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"ESTUDIO PARA DETERMINAR UN PROCEDIMIENTO QUE DISMINUYA LA POROSIDAD EN EL ALUMINIO DURANTE EL PROCESO DE FUNDICIÓN PARA MEJORAR SUS PROPIEDADES MECÁNICAS."

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APROBACIÓN DEL TUTOR

En mi calidad de tutor del trabajo de investigación sobre el tema: "ESTUDIO PARA DETERMINAR UN PROCEDIMIENTO QUE DISMINUYA LA POROSIDAD EN EL ALUMINIO DURANTE EL PROCESO DE FUNDICIÓN PARA MEJORAR SUS PROPIEDADES MECÁNICAS." del estudiante Julio Cesar Jurado, considero que dicho informe investigativo reúne los requisitos y méritos suficientes para ser sometido a la evaluación del jurado examinador designado por el H. Consejo Directivo.

Ambato, julio 31 del 2011

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Los criterios emitidos en el presente trabajo de investigación “ESTUDIO PARA DETERMINAR UN PROCEDIMIENTO QUE DISMINUYA LA POROSIDAD EN EL ALUMINIO DURANTE EL PROCESO DE FUNDICIÓN PARA MEJORAR SUS PROPIEDADES MECÁNICAS”, como también los contenidos, ideas, análisis, conclusiones y propuesta son de exclusiva responsabilidad de mi persona, como autor de este trabajo de grado.

Ambato, julio 31 del 2011

EL AUTOR

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DEDICATORIA

Con respeto: A mis padres Julio y Yoli, por su infinita colaboración, paciencia y por su apoyo incondicional durante toda mi vida y especialmente el tiempo que duró esta investigación. A mi hermana Pamela por su preocupación e interés, los amo.

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El Autor

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RESUMEN EJECUTIVO

En la actualidad, la porosidad en las fundiciones de aluminio causa inconvenientes a las personas dedicadas a la fundición y a los ingenieros de diseño; debido a que la porosidad disminuye drásticamente las propiedades mecánicas de las piezas fundidas con este material; por tal motivo el presente trabajo investigativo está enfocado en mejorar las propiedades mecánicas del aluminio adicionando el compuesto químico nitrito de sodio durante la fundición, el mismo que por sus características higroscópicas ha permitido reducir los niveles de solubilidad del hidrógeno en el aluminio fundido y en consecuencia reducir el índice de porosidad, facilitando a las industrias de fundición, al pequeño artesano fundidor y a las personas involucradas con este tema a perfeccionar los procesos de fundición optimizando de esta manera recursos económicos, tecnológicos y humanos.

INTRODUCCIÓN

El presente trabajo investigativo tiene por finalidad encontrar un método para reducir el nivel de Hidrógeno en el aluminio que es altamente soluble durante los procesos de fundición con este metal, lo cual genera porosidades. La finalidad de reducir la porosidad es mejorar las propiedades mecánicas que satisfagan las necesidades más exigentes de los usuarios, por tal situación esta investigación contiene información del aluminio como su historia, obtención, propiedades físicas, mecánicas, fundición y aplicaciones. Posteriormente se detalla cada proceso realizado, como primer paso realizamos la fundición en molde de arena con diferentes elementos químicos que tienen como función reducir el nivel de hidrógeno; obteniendo las muestras necesarias para realizar los ensayos de dureza, tracción y metalográfico, según las normas respectivamente establecidas por la ASTM, como siguiente paso se maquinan las probetas de acuerdo a las normas para proceder a realizar los ensayos de tracción, dureza, metalográfico y cuantificación física de la porosidad sobre la superficie del aluminio. Luego se detallan los valores obtenidos en cada ensayo para posteriormente evaluarlos, permitiendo seleccionar el compuesto químico más idóneo para reducir la porosidad en las fundiciones de aluminio que es el nitrito de sodio, un compuesto manipulable y fácil y obtener en nuestro medio. Con el uso del nitrito de sodio disminuyó la porosidad considerablemente, se aumentó el tamaño de grano a 4,9, se incrementó el módulo de elasticidad a 55,1MPa (10.000Ksi), mejoró la ductilidad al 16% y aumentó la dureza a 24,9HB en el aluminio.

CAPÍTULO 1
EL PROBLEMA

1.1.TEMA

Estudio de un procedimiento que disminuya la porosidad en el aluminio durante el proceso de fundición para mejorar sus propiedades mecánicas.

1.2. PLANTEAMIENTO DEL PROBLEMA

1.2.1. CONTEXTUALIZACIÓN

Con el transcurso del tiempo se ha podido observar que las aplicaciones del aluminio a nivel mundial han aumentado notablemente debido a sus características físicas, químicas, mecánicas, y uno de los grandes problemas con los que se enfrentan las empresas de fundición en el mundo es la porosidad, razón por la cual es necesario mejorar las propiedades de este elemento para brindar las características necesarias que permitan lograr un desempeño óptimo durante su utilización.

La Industria del aluminio en el Ecuador se ha desarrollado notablemente razón por la cual existen varias empresas dedicadas a la producción de material para la construcción, la misma que es un área explotada y resulta importante mejorar las propiedades de este elemento.

Con el estudio de este procedimiento se pretende beneficiar a pequeños talleres de fundición de aluminio de la ciudad de Ambato, permitiendo que los procesos de fundición sean óptimos para eliminar la porosidad del aluminio y de esta manera se pueda fabricar un producto con mayor calidad.

1.2.2. ANÁLISIS CRÍTICO

El aluminio es un metal que debido a características como: su peso y punto de fusión (660ºC) nos brinda una infinidad de aplicaciones industriales, este punto de fusión relativamente bajo, junto a otras propiedades químicas, físicas y mecánicas hacen del aluminio un elemento con el cual se pueda trabajar en pequeñas Empresas de Fundición.

Pero durante el proceso de fundición del aluminio se genera porosidad la misma que causa un producto de baja calidad y limita sus aplicaciones. La formación de porosidad se atribuye generalmente a la formación de burbujas de gas de Hidrógeno, debido a una repentina disminución en la solubilidad del Hidrógeno durante la solidificación. El Hidrógeno es el único gas que tiene una solubilidad apreciable en el Aluminio y en sus aleaciones, su solubilidad varia directamente con la temperatura y la raíz cuadrada de la presión.

La determinación del grado en que la porosidad afecta las respuestas mecánicas del aluminio no es una cuestión de interés exclusivamente académico sino que atañe, a todas las personas que están involucradas en la industria del aluminio, Es por eso; que esta investigación se centra en el estudio de un procedimiento que logre disminuir la porosidad de este elemento durante su fundición.

1.2.3. PROGNOSIS

El presente trabajo investigativo se efectúa para el desarrollo de la industria del aluminio, evitando los problemas que se presentan durante su fundición y colado, en consecuencia se podrá elevar la calidad del producto y mejorar sus niveles producción.

1.2.4. FORMULACIÓN DEL PROBLEMA

¿Cómo se pueden mejorar las propiedades mecánicas del Aluminio en la fundición?

1.2.5. PREGUNTAS DIRECTRICES

¿Los procedimientos de fundición son los adecuados?
¿Influye la humedad de las herramientas utilizadas durante la fundición?
¿Se puede disminuir el número de piezas defectuosas?
¿Qué elementos están disponibles en nuestro medio para mejorar la fundición?

1.2.6. DELIMITACIÓN DEL OBJETO DE INVESTIGACIÓN

1.2.6.1. DELIMITACIÓN DE CONTENIDO

El presente proyecto investigativo está relacionado con las Áreas de: Fundición de metales, metalografía, química y ensayo de materiales.

1.2.6.2. DELIMITACIÓN ESPACIAL

El presente trabajo investigativo comprende el desarrollo de una técnica que permita disminuir la porosidad que se genera en el aluminio durante su fundición, así como el análisis metalográfico, y ensayos mecánicos (tracción, dureza). Para lo cual la investigación se lo hará en la Facultad de Ingeniería Civil y Mecánica (F.I.C.M.) y los ensayos en el Laboratorio de materiales de la Carrera de Ingeniería Mecánica de la Universidad Técnica de Ambato, el mismo que se encuentra ubicado en la ciudad de Ambato provincia del Tungurahua en el sector de Huachi Chico.

1.2.6.3. DELIMITACIÓN TEMPORAL

El presente trabajo de investigación será realizado en el periodo de Diciembre del 2009 y Junio del 2010.

1.3. JUSTIFICACIÓN

Este trabajo de investigación surge a partir de la necesidad que tienen las Empresas de Fundición y los Institutos de Educación Superior para de una forma eficiente

disminuir al máximo la porosidad del aluminio durante el proceso de fundición, lo cual permitirá perfeccionar las propiedades mecánicas de este metal y en consecuencia se podrán mejorar los estándares de calidad requeridos a nivel profesional, aumentando los niveles de producción, disminuyendo de esta manera las pérdidas que causa este problema. Con el presente trabajo se pretende impulsar el desarrollo investigativo, profesional y productivo de la Industria de Fundición de Aluminio dando una solución práctica al problema que se presenta durante este proceso.

1.4. OBJETIVOS

1.4.1. GENERAL

Solucionar la deficiencia que tienen las Empresas de Fundición de aluminio al presentar porosidades en las piezas fundidas.

1.4.2. ESPECÍFICOS

- Disminuir el contenido de hidrógeno en el aluminio.
- Mejorar los procedimientos de fundición.
- Conocer las propiedades del aluminio y sus aleaciones.
- Controlar los niveles de solubilidad del hidrógeno.

CAPÍTULO 2
MARCO TEÓRICO

2.1. ANTECEDENTES INVESTIGATIVOS

El aluminio es un metal que presenta múltiples propiedades muy apreciadas como son ligereza, notable dureza y resistencia, fácil mecanizado, excelente conductividad, así como un extraordinario aspecto decorativo, estas propiedades le han permitido ocupar un lugar destacado en las más modernas aplicaciones industriales.

Aunque el aluminio es un material muy abundante en nuestro planeta, raramente se encuentra en estado libre; su forma más frecuente es el oxido hidratado de aluminio conocido comúnmente como bauxita en honor a la localidad " Les Baux " en Francia de donde se extrajo por primera vez. La extracción de la bauxita es el primer paso en el ciclo productivo del aluminio, se llevan a cabo explotaciones a cielo abierto que una vez en desuso son devueltas a su estado original incluyendo la restitución del manto vegetal.

Durante la mayor parte de la historia de la humanidad el uso de este metal ligero y resistente resulto prácticamente imposible, hasta que descubrimos como producir en masa el aluminio. El acero fue el metal del siglo XIX pero en el siglo XX se topo con el aluminio que ha acelerado el progreso tecnológico en los pocos años que se han trabajado con él, lo cual es una suerte; ya que el aluminio no es solo el metal más abundante en la tierra si no que también es el tercer elemento más común y constituye más del 8 por ciento de la corteza terrestre.

El hombre primitivo poco uso le daba al aluminio ya que aparecía en una amalgama similar a la arcilla; denominada bauxita. Después de descubierto el aluminio puro en 1825 se le considero un metal precioso con un valor a la par del valor del oro , el aluminio resulta útil porque es ligero, maleable y resulta sencillo hacer hilos con él, no es magnético ni propenso a las chispas, conduce la electricidad lo cual hace que

sea útil para fabricar líneas de conducción eléctrica, es un metal decorativo y se enlaza fácilmente con otros para crear aleaciones mucho más fuertes y resistentes que el aluminio puro, pero durante la mayor parte de la historia de la humanidad solo pudo fabricarse en pequeñas cantidades.

El proceso ordinario de obtención del metal consta de dos etapas: la obtención de alúmina por proceso Bayer a partir de la bauxita y la posterior electrolisis de este oxido para obtener el aluminio.

El aluminio así obtenido es conformado en función de la aplicación posterior del mismo como puede ser: placa de laminación, lingote para fundición, alambre para cable y tocho para extrusión tras esta primera etapa de conformado el aluminio ha adquirido su aspecto metálico y está preparado para ser trabajado mediante los procesos de estirado, fundición, laminación y forja.

2.2. FUNDAMENTACIÓN FILOSÓFICA

EL ALUMINIO

"… El aluminio es un elemento metálico, de símbolo Al, número atómico 13, peso atómico 26.9815u, que pertenece al grupo IIIA del sistema periódico. El aluminio puro es blando y tiene poca resistencia mecánica, pero puede formar aleaciones con otros elementos para aumentar su resistencia y adquirir varias propiedades útiles. Las aleaciones de aluminio son ligeras, fuertes, y de fácil formación para muchos procesos de producción; son fáciles de ensamblar, fundir o maquinar y aceptan gran variedad de acabados. Por sus propiedades físicas, químicas y metalúrgicas, el aluminio se ha convertido en el metal no ferroso de mayor uso.

El aluminio es el elemento metálico más abundante en la Tierra y en la Luna, pero nunca se encuentra en forma libre en la naturaleza. Se halla ampliamente distribuido en las plantas y en casi todas las rocas, sobre todo en las ígneas, que contienen aluminio en forma de minerales de alúmino silicato. Cuando estos minerales se disuelven, según las condiciones químicas, es posible precipitar el aluminio en forma

de arcillas minerales, hidróxidos de aluminio o ambos. En esas condiciones se forman las bauxitas que sirven de materia prima fundamental en la producción de aluminio.

El aluminio es un metal plateado con una densidad de 2.70 g/cm3 a 20ºC (1.56 oz/in3 a 68ºF). El aluminio cristaliza en una estructura cúbica centrada en las caras, con lados de longitud de 4.0495 angstroms. (0.40495 nanómetros). El aluminio se conoce por su alta conductividad eléctrica y térmica, lo mismo que por su gran reflectividad.

La configuración electrónica del elemento es 1s2 2s2 2p6 3s2 3p1. El aluminio muestra una valencia de 3+ en todos sus compuestos, exceptuadas unas cuantas especies monovalentes y divalentes gaseosas a altas temperaturas. El aluminio es estable al aire y resistente a la corrosión por el agua de mar, a muchas soluciones acuosas y otros agentes químicos. Esto se debe a la protección del metal por una capa impenetrable de óxido.

A una pureza superior al 99.95%, resiste el ataque de la mayor parte de los ácidos, pero se disuelve en agua regia. Su capa de óxido se disuelve en soluciones alcalinas y la corrosión es rápida. El aluminio es anfótero y puede reaccionar con ácidos minerales para formar sales solubles con desprendimiento de hidrógeno. El aluminio fundido puede tener reacciones explosivas con agua. El metal fundido no debe entrar en contacto con herramientas ni con contenedores húmedos. A temperaturas altas, reduce muchos compuestos que contienen oxígeno, sobre todo los óxidos metálicos. Estas reacciones se aprovechan en la manufactura de ciertos metales y aleaciones. … [1]

2.2.1. CARACTERÍSTICAS

2.2.1.1. CARACTERÍSTICAS FÍSICAS

"… Entre las características físicas del aluminio, destacan las siguientes:

- Es un metal ligero, cuya densidad es de 2700 kg/m^3 (2,7 veces la densidad del agua), un tercio de la del acero.
- Tiene un punto de fusión bajo: 660 °C (933 K).
- El peso atómico del aluminio es de 26,9815 u.
- Es de color blanco brillante, con buenas propiedades ópticas y un alto poder de reflexión de radiaciones luminosas y térmicas.
- Tiene una elevada conductividad eléctrica comprendida entre 34 y 38 m/(Ω mm^2) y una elevada conductividad térmica (80 a 230 W/(m·K)).
- Resistente a la corrosión, a los productos químicos, a la intemperie y al agua de mar, gracias a la capa de Al_2O_3 formada.
- Abundante en la naturaleza. Es el tercer elemento más común en la corteza terrestre, tras el oxígeno y el silicio.
- Su producción metalúrgica a partir de minerales es muy costosa y requiere gran cantidad de energía eléctrica.
- Material fácil y barato de reciclar.

2.2.1.2. CARACTERÍSTICAS QUÍMICAS

- Debido a su elevado estado de oxidación se forma rápidamente al aire una fina capa superficial de óxido de aluminio (Alúmina Al_2O_3) impermeable y adherente que detiene el proceso de oxidación, lo que le proporciona resistencia a la corrosión y durabilidad. Esta capa protectora, de color gris mate, puede ser ampliada por electrólisis en presencia de oxalatos. Ciertas aleaciones de alta dureza presentan problemas graves de corrosión intercristalina.
- El aluminio tiene características anfóteras. Esto significa que se disuelve tanto en ácidos (formando sales de aluminio) como en bases fuertes (formando aluminatos con el anión $[Al(OH)_4]^-$) liberando hidrógeno.
- La capa de óxido formada sobre el aluminio se puede disolver en ácido cítrico formando citrato de aluminio.
- El principal y casi único estado de oxidación del aluminio es +III como es de esperarse por sus tres electrones en la capa de valencia "…[2]

2.2.1.3. CARACTERÍSTICAS MECÁNICAS

- **Resistencia a la ruptura:** El aluminio puro comercial posee una resistencia a la ruptura sobre los 90 MPa, y este valor puede aproximarse al doble cuando es trabajado en frío. Sus propiedades mejoran largamente al someter al aluminio a aleaciones con pequeños porcentajes de otros metales como el cobre, magnesio, silicio, manganeso o zinc. Algunas de estas aleaciones pueden incrementar su resistencia y dureza mediante tratamiento térmico, especialmente con aleaciones de silicio - magnesio.

- **Resistencia a la tensión:** El aluminio posee una resistencia a la tensión de aproximadamente 300 Mpa, en condiciones normales de tratamiento térmico, sobre el 70% de la resistencia que posee el acero.

- **Resistencia a la flexión:** La resistencia típica a la flexión de la aleación 6061 - T6 es de 270 Mpa, igual que la resistencia del acero. Esta aleación estructural posee una alta resistencia considerando su reducida masa. Cuando esta es combinada con la versatilidad del proceso de extrusión, permite que el metal se distribuya sobre su eje neutral con una máxima eficiencia, lo que hace posible diseñar en aluminio con igual resistencia que el acero, pero con una masa equivalente al 50% de éste. Esto es aplicable a largas estructuras donde es más importante la menor masa posible que su contenido, debido a que la economía es significativamente mayor.

- **Dureza:** La dureza del aluminio es la capacidad de resistencia a la penetración que éste posee.

- **Elongación:** Cuantifica el alargamiento lineal permanente del aluminio por efectos de una carga que actúa en tensión.

- **Módulo de elasticidad:** Medida de la rigidez de un material. El módulo de elasticidad se mantiene constante sobre el rango elástico de un material, actuando del mismo modo para aleaciones de aluminio. En consecuencia,

todas las estructuras de aleación de aluminio de la misma dimensión, sufrirán igual flexión sobre una carga, sin embargo la rigidez y la tensión no serán de igual magnitud. Con un tratamiento térmico o trabajo en frío, se incrementa el límite de resistencia a la tensión de una aleación, mas no altera su módulo de elasticidad.

- **Resistencia máxima a la tensión:** Es la máxima resistencia que un material es capaz de soportar en tensión bajo la aplicación de una fuerza gradual y uniforme.

2.2.2. PRODUCCIÓN DE ALUMINIO

Para la obtención del aluminio se usan menas que contienen Al_2O_3. Entre estas están las:

- Bauxitas: Las bauxitas contienen el equivalente a 30-57% de Al_2O_3 en forma de hidróxido de aluminio $Al(OH)_3$; 17-35% de Fe_2O_3 ; 3-13% de SiO_2 ; 2-4% de TiO_2 ; hasta 3% de CaO y 10-18% de H_2O
- Nefelinas: Las nefelinas contienen cerca de 30% de Al_2O_3 ; 20% de Na_2O+K_2O ; 40-45% de SiO_2 ; 2-4% de CaO y 2-4% de Fe_2O_3.
- Alunitas: Las alunitas contienen 20-21% Al_2O_3 ; 4.5-5% de Na_2O+K_2O ; 22-23% de SO_3 ; 41-42% de SiO_2 ; 4-5% de Fe_2O_3 y 6-7% de H_2O.
- Caolines.

Las menas principales para la producción de aluminio son las bauxitas y las nefelinas. Al usarse las nefelinas para la producción de aluminio se obtienen valiosos productos derivados; la potasa y la sosa caústica. El proceso tecnológico para la elaboración del aluminio se divide en dos etapas:

1. La obtención de la alúmina (Al_2O_3) a partir de la mena.
2. La obtención del aluminio a partir de la alúmina.

2.2.2.1. OBTENCIÓN DE LA ALÚMINA

Para obtener la alúmina desde la mena se usan diferentes procedimientos, dos de los cuales son:

- Tratamiento con sosa caústica.
- Tratamiento con carbonatos.

Tratamiento con sosa caústica

Este método es más conveniente cuando la cantidad de sílice (SiO_2) es menor del 5% en la mena. Según este procedimiento, la bauxita se muele y se carga a unos autoclaves para su lixiviación. A los autoclaves se agrega una disolución de sosa caústica y se da vapor hasta una presión de trabajo de 12 atm y una temperatura de 160-170^oC.

La alúmina, que se encuentra en la bauxita en forma de hidróxido de aluminio, reacciona con la sosa y pasa a la disolución en forma de aluminato sódico ($Na_2O{\cdot}Al_2O_3$):

$$2Al(OH)_3 + 2NaOH \Longrightarrow Na_2O{\cdot}Al_2O_3 + 4H_2O$$

Los óxidos de hierro presentes, no reaccionan y pasan a los lodos.
El sílice reacciona con la sosa caústica y pasa a la disolución en forma de silicato sódico ($Na_2O{\cdot}SiO_2$):

$$SiO_2 + 2Na(OH) \Longrightarrow Na_2O{\cdot}SiO_2 + H_2O$$

El silicato sódico, actúa con el aluminato sódico en la disolución y forma el alumino-silicato sódico insoluble ($Na_2O{\cdot}SiO_2{\cdot}2SiO_2{\cdot}2H_2O$):

$Na_2O{\cdot}Al_2O_3 + 2Na_2O{\cdot}SiO_2 + 4H_2O \Longrightarrow Na_2O{\cdot}SiO_2{\cdot}2SiO_2{\cdot}2H_2O + 4NaOH$
Como resultado de esta reacción, la disolución se limpia de sílice y finalmente se ha

obtenido el aluminato sódico ($Na_2O{\cdot}Al_2O_3$) como una masa pastosa en el autoclave. Del autoclave se envía a un aparato de evaporación especial, donde la masa se enfría y se hidroliza el aluminato sódico para obtener el hidróxido de aluminio ($Al(OH)_3$) cristalino precipitado. Este proceso se inocula con cristales de hidróxido de aluminio para servir de centros de cristalización.

$$Na_2O{\cdot}Al_2O_3 + 4H_2O <==> NaOH + 2Al(OH)_3$$

Finalmente se hace la calcinación a 1200^{o}C del hidróxido obtenido en hornos rotatorios para convertirlo en alúmina (Al_2O_3):

$$2Al(OH)_3 ==> Al_2O_3 + H_2O$$

El rendimiento de la alúmina partir de la mena por este procedimiento es cerca del 85%.

Tratamiento con carbonatos

Las menas se trituran y se mezclan con carbonato de sodio, carbonato de calcio y se sinteriza a 1100^{o}C, como resultado se obtiene el aluminato sódico sólido ($Na_2O{\cdot}Al_2O_3$), así como el silicato cálcico ($CaO{\cdot}SiO_2$) y la ferrita sódica ($Fe_2O_3{\cdot}Na_2O$), según las reacciones.

$$Al_2O_3 + Na_2CO_3 ==> Na_2O{\cdot}Al_2O_3 + CO_2$$

$$2CaCO_3 + SiO_2 ==> CaO{\cdot}SiO_2 + 2CO_2$$

$$2Fe_2O_3 + Na_2CO_3 ==> 2Fe_2O_3{\cdot}Na_2O + CO_2$$

Después de la sinterización la masa se muele y se somete a la lixiviación, durante la cual pasan a la disolución el aluminato sódico ($Na_2O{\cdot}Al_2O_3$) y la ferrita sódica ($2Fe_2O_3{\cdot}Na_2O$), el silicato cálcico ($CaO{\cdot}SiO_2$) precipita, así como algunas otras impurezas. Con el tiempo posterior la ferrita sódica en disolución se hidroliza y

forma hidróxido de hierro insoluble ($Fe(OH)_3$) que precipita, y sosa cáustica (NaOH) que pasa a la disolución, según la reacción:

$$Fe_2O_3 \cdot Na_2O + 4H_2O \Longrightarrow 2Fe(OH)_3 + 2NaOH$$

Luego el aluminato de sodio se somete a la carbonatación con CO_2 para formar hidróxido de aluminio ($Al(OH)_3$) insoluble que precipita y carbonato de sodio (Na_3CO_3) que pasa a la disolución; la reacción es la siguiente:

$$Na_2O \cdot Al_2O_3 + CO_2 + 3H_2O \Longrightarrow 2Al(OH)_3 + Na_3CO_3$$

Finalmente se hace la calcinación del hidróxido de aluminio para obtener alúmina (Al_2O_3) pura, igual que en caso anterior.

$$2Al(OH)_3 \Longrightarrow Al_2O_3 + H_2O$$

En ambos procesos el resultado final es la alúmina, base para la producción del aluminio metálico.

2.2.2.2. OBTENCIÓN DEL ALUMINIO

El óxido deshidratado del aluminio tiene una temperatura de fusión de 2050 ^oC y de ebullición de 2980 ^oC sin descomposición resulta una sustancia muy estable. La reducción del óxido a aluminio resulta imposible con carbono o con monóxido de carbono ya que este proceso lleva a la formación de carburos (Al_4C_3). Tampoco se logra obtener aluminio por disolución acuosa de sales, ya que en el cátodo se desprende solo hidrógeno. Por eso, el aluminio se obtiene por electrólisis, a partir de la alúmina disuelta en criolita (Na_3AlF_6) fundida, la que a su vez se produce usando fluorita (CaF_2), el hidróxido de aluminio, el carbonato sódico y el ácido sulfúrico.

El baño electrolítico se compone de una caja de acero recubierta interiormente con ladrillos termo aislantes, el fondo de la caja está recubierta de bloques de carbón

conductor y que sirven como uno de los electrodos (cátodo). Por encima de la cuba se colocan otros electrodos de carbón y se conectan a la corriente directa de 5 a 10 V.

Con ello se produce la circulación de una corriente muy elevada, que además de producir la electrólisis, calienta la solución de alúmina en la criolita fundida hasta 950-1000^{o}C, manteniéndola líquida. Se acepta que el proceso electrolítico transcurre de la siguiente manera:

Bajo la acción de la corriente la criolita fundida se disocia en iones.

$$Na_3AlF_6 \Longrightarrow 3Na^{+} + AlF_6^{3-}$$

La alúmina disuelta también se disocia en iones.

$$Al_2O_3 \Longrightarrow Al^{3+} + AlO_3^{3-}$$

De manera que son transportados al cátodo los iones $3Na^{+}$ y Al^{3+}, como el ion de aluminio tiene un potencial negativo menor que el sódico, se descarga allí solo el aluminio, convirtiéndose en aluminio metálico que precipita en el fondo del baño caliente en forma líquida. Los iones de sodio reaccionan con el anión AlO_3^{3-} para formar aluminato sódico según:

$$3Na^{+} + AlO_3^{3-} \Longrightarrow Na_3AlO_3$$

Los iones negativos o aniones se dirigen al ánodo, se forma allí alúmina y se desprende oxígeno, según:

$$2AlO_3^{3-} - 6_e \Longrightarrow Al_2O_3 + {}^{3}/_{2}O_2$$

El oxigeno desprendido reacciona con el carbón para formar CO y CO_2 que se desprenden del baño como gases. El aluminio líquido se extrae de tiempo en tiempo desde el fondo por sifón. Por este método, para obtener una tonelada de aluminio se

usan 2 toneladas de alúmina, 100 kg de criolita, hasta 600 kg de los electrodos de carbón y de 16,500 a 18,500 Kwh de energía eléctrica.

Afinación del aluminio

El aluminio obtenido de las cubas de electrólisis de la alúmina contiene cierta cantidad de impurezas, alúmina, criolita y gases, por lo que para obtener aluminio de alta pureza (99.85-99.9%) se someten a un proceso de afinación.

Hay dos vías principales de afinar el aluminio:

1. La clorinación: Por este método se insufla cloro a la masa de aluminio fundido a temperatura de entre 750-770^{o}C, durante unos 10-15 minutos. Durante la insuflación las impurezas reaccionan con el cloro y se separan del aluminio, aunque una parte (1%) del aluminio reacciona también y se separa, produciendo pérdidas del material.
2. La afinación electrolítica: Para afinar el aluminio por el método electrolítico, las barras de aluminio impuro se colocan como ánodos en un baño de sales de cloro y flúor y este se descarga a pureza muy elevada en cátodos hechos de aluminio puro.

2.2.3. DEFECTOS EN ALUMINIO

"… Para satisfacer las demandas de hoy de fundición de aluminio en el mercado, las fundiciones se han centrado en la mejora de la calidad del metal fundido mediante el desarrollo de procesos para producir el metal limpio. Estos procesos se centran en la eliminación de una serie de impurezas (es decir, inclusiones porosidad) que plantean graves problemas en la producción de piezas fundidas de calidad. En la vanguardia de estas impurezas esta hidrógeno, el único gas soluble en aluminio fundido, porque crea la porosidad en las piezas moldeadas.

El aluminio al igual que sus aleaciones son ampliamente usadas en la industria, esto debido a sus buenas propiedades mecánicas, bajo peso, buena soldabilidad, buena conductibilidad térmica, relativamente alta resistencia a alta temperatura, excelente

resistencia a la corrosión, así como excelente fluidez al vaciado. La porosidad causa costosas pérdidas por chatarra (producto de mala calidad) y puede limitar el uso de los vaciados en ciertas aplicaciones. La porosidad por contracción y gas puede ocurrir separadamente o junta, produciendo indeseables defectos en los vaciados. Uno de los mayores problemas asociados con las aleaciones de Aluminio vaciadas es la formación de cavidades a escala micrométrica, llamadas como microporosidad. La microporosidad causa la reducción de las propiedades mecánicas, particularmente la resistencia a la fatiga, así como una pérdida de presión por tensión y una degradación de la superficie aparente en las partes vaciadas. La formación de microporosidad se atribuye generalmente a dos factores:

- Contracción acompañada con una falta de alimentación interdendrítica durante la solidificación de la zona pastosa (poros por contracción).

- Evolución de burbujas de gas de Hidrógeno, debido a una repentina disminución en la solubilidad del Hidrógeno durante la solidificación.

El Hidrógeno es el único gas que tiene una solubilidad apreciable en el Aluminio y en sus aleaciones, su solubilidad varia directamente con la temperatura y la raíz cuadrada de la presión. En el Aluminio puro, hay un incremento de solubilidad en el punto de fusión de aproximadamente 0.02 ml/100 g de Al en la fase sólida a 0.7 ml/100 g de Al en la fase líquida. En el estado líquido, también se observa una fuerte dependencia con la temperatura. En la solidificación, casi todo el Hidrógeno disuelto en el líquido es rechazado por el enfriamiento del sólido.

Con más frecuencia este Hidrógeno rechazado forma una fase gaseosa que resulta en porosidad en los productos solidificados. Poco Hidrógeno es absorbido de la atmósfera, la mayor cantidad se obtiene de la disociación del vapor de agua en la superficie del metal líquido, o de la humedad de los aditivos de fisión, crisoles o herramientas. Los gases de combustión de hornos que queman gas también pueden ser una significante fuente de Hidrógeno. El Hidrógeno liberado esta en forma atómica, el cual es muy reactivo y rápidamente es absorbido por el Aluminio fundido.

La absorción del Hidrógeno se puede minimizar mediante técnicas de fusión apropiadas, y en adición, el Hidrógeno disuelto se puede remover mediante el uso de técnicas de desgasificación. "…[3]

"… En la actualidad las demandas que existen a nivel industrial del Aluminio ha obligado a investigar y desarrollar nuevos métodos de desgasificación, es por eso que en la actualidad se utilizan el Argón o Nitrógeno para desgasificar este elemento, por tal motivo la desgasificación del aluminio ha logrado substanciales mejoras, como incrementos en niveles de producción.

Los desgasificantes tradicionales como cloro, hexacloroetano y diclorodifluorometano (Freón 12), tienden a ser sustituidos debido a su alta emisión de contaminantes que atacan la capa de ozono. Esto ha impulsado el desarrollo de nuevos métodos de desgasificación, tales como, el uso de gases inertes los cuales tienen definitivamente una influencia directa sobre el aumento de la calidad del producto, y en la completa eliminación de los gases contaminantes.

El aluminio y sus aleaciones son muy susceptibles a absorber Hidrógeno durante la fusión y la colada. Debido a que la solubilidad del Hidrógeno en el aluminio se incrementa exponencialmente al aumentar la temperatura, una gran cantidad de Hidrógeno es captado por el aluminio durante la fusión, mismo que es expulsado durante la solidificación formando burbujas; un porcentaje de éstas salen a la atmósfera, pero la cantidad remanente permanece en el aluminio causando porosidades en la pieza sólida. La formación de estas porosidades es promovida por la presencia de inclusiones en el metal, éstas actúan como nucleantes para las burbujas durante la solidificación, de ahí que el objetivo de la desgasificación sea tanto reducir el nivel del Hidrógeno en el metal líquido, como el de reducir el número de inclusiones.

El proceso de desgasificación del aluminio consiste en la inyección de un flujo de gas de arrastre (Argón o Nitrógeno) en el aluminio fundido; dicha inyección debe llevarse a cabo antes de iniciar la colada del metal fundido. El mecanismo de desgasificación, consiste en la difusión del Hidrógeno a las burbujas del gas de

arrastre, esto debido a las diferencias de presión parcial de Hidrógeno entre el gas de arrastre y el aluminio líquido. Uno de los parámetros más importantes de la desgasificación del aluminio y que determina el grado de la eficiencia en la desgasificación, es el tamaño de la burbuja inyectada; cuando el tamaño de dicha burbuja es grande la desgasificación resulta inadecuada. La tabla que se presenta a continuación, muestra el efecto del tamaño de la burbuja en la eficiencia del desgasificado. Otros de los factores importantes en la desgasificación del aluminio son: el suministro de un número suficiente de burbujas y la protección de la superficie del metal líquido; esto, para evitar la reabsorción del Hidrógeno.

Nitrógeno.- El Nitrógeno es un gas incoloro, no corrosivo y no flamable, es inerte excepto cuando es calentado a muy altas temperaturas. Como es un gas no corrosivo, no se requieren materiales especiales para su almacenamiento y control. El Nitrógeno ha sido usado como desgasificante con buenos resultados, su costo es inferior al del Argón, pero los tiempos de desgasificación son más prolongados y consecuentemente se reducen los niveles de producción y aumentan los costos de energía.

Argón.- El Argón es un gas monoatómico, incoloro, inodoro, no corrosivo y no flamable. El Argón no reacciona con ningún elemento ni compuesto, por lo que no requiere tanques de almacenamiento ni equipos de control de flujo especiales. Su eficiencia como desgasificante es muy alta y su emisión de contaminantes es nula; la remoción de Hidrógeno es mayor y los tiempos de desgasificación son menores que los del Nitrógeno. "…[4]

2.2.4. APLICACIONES DEL ALUMINIO

"… El aluminio se utiliza rara vez 100% puro y casi siempre se usa aleado con otros metales para mejorar alguna de sus características. El aluminio puro se emplea principalmente en la fabricación de espejos, tanto para uso doméstico como para telescopios reflectores.

Los principales usos industriales de las aleaciones metálicas de aluminio son:

- Transporte; como material estructural en aviones, automóviles, tanques, superestructuras de buques y bicicletas.
- Estructuras de aluminio en edificios
- Embalaje de alimentos; papel de aluminio, latas, *tetrabriks*, etc.
- Carpintería metálica; puertas, ventanas, cierres, armarios, etc.
- Bienes de uso doméstico; utensilios de cocina, herramientas, etc.
- Transmisión eléctrica. Un conductor de aluminio de misma longitud y peso es más conductivo que uno de cobre y más barato. Sin embargo el cable sería más grueso. Medida en volumen la conductividad eléctrica es tan sólo el 60% de la del cobre. Su mayor ligereza reduce el esfuerzo que deben soportar las torres de alta tensión y permite una mayor separación entre torres, disminuyendo los costes de la infraestructura. En aeronáutica también sustituye al cobre.
- Recipientes criogénicos (hasta -200 °C), ya que contrariamente al acero no presenta temperatura de transición dúctil a frágil. Por ello la tenacidad del material es mejor a bajas temperaturas.

Debido a su gran reactividad química, el aluminio se usa finamente pulverizado como combustible sólido de cohetes espaciales y para aumentar la potencia de los explosivos. También se usa como ánodo de sacrificio y en procesos de aluminotermia (termita) para la obtención y soldadura de metales. "…[5]

2.2.5. FUNDICIÓN

"… Se denomina fundición al proceso de fabricación de piezas, comúnmente metálicas pero también de plástico, consiste en fundir un material e introducirlo en una cavidad, llamada molde, donde se solidifica.

El proceso tradicional es la fundición en arena, por ser ésta un material refractario muy abundante en la naturaleza y que, mezclada con arcilla, adquiere cohesión y moldeabilidad sin perder la permeabilidad que posibilita evacuar los gases del molde al tiempo que se vierte el metal fundido.

La fundición en arena consiste en colar un metal fundido, típicamente aleaciones de hierro, acero, aluminio, bronce, latón y otros, en un molde de arena, dejarlo solidificar y posteriormente romper el molde para extraer la pieza fundida.

Para la fundición con metales como el hierro o el plomo, que son significativamente más pesados que el molde de arena, la caja de moldeo es a menudo cubierta con una chapa gruesa para prevenir un problema conocido como "flotación del molde", que ocurre cuando la presión del metal empuja la arena por encima de la cavidad del molde, causando que el proceso no se lleve a cabo de forma satisfactoria.

2.2.5.1. ETAPAS DE LA FUNDICIÓN

2.2.5.2. DISEÑO DEL MODELO

La fundición en arena requiere un modelo a tamaño natural de madera, plástico y metales que define la forma externa de la pieza que se pretende reproducir y que formará la cavidad interna en el molde. En lo que atañe a los materiales empleados para la construcción del modelo, se puede emplear desde madera o plásticos como el uretano y el poliestireno expandido (EPS) hasta metales como el aluminio o el hierro fundido. Para el diseño del modelo se debe tener en cuenta una serie de medidas derivadas de la naturaleza del proceso de fundición:

- Debe ser ligeramente más grande que la pieza final, ya que se debe tener en cuenta la contracción de la misma una vez se haya enfriado a temperatura ambiente. El porcentaje de reducción depende del material empleado para la fundición. A esta dimensión se debe dar una sobremedida en los casos en el que se dé un proceso adicional de maquinado o acabado por arranque de viruta.
- Las superficies del modelo deberán respetar unos ángulos mínimos con la dirección de desmoldeo (la dirección en la que se extraerá el modelo), con objeto de no dañar el molde de arena durante su extracción. Este ángulo se denomina ángulo de salida. Se recomiendan ángulos entre 0,5º y 2º.

- Incluir todos los canales de alimentación y mazarotas necesarios para el llenado del molde con el metal fundido.

- Si es necesario incluirá portadas, que son prolongaciones que sirven para la colocación del macho. Los moldes, generalmente, se encuentran divididos en dos partes, la parte superior denominada cope y la parte inferior denominada draga que se corresponden a sendas partes del molde que es necesario fabricar.

Los moldes se pueden distinguir entre los siguientes:

- Moldes de arena verde: estos moldes contienen arena húmeda.

- Moldes de arena fría: usa aglutinantes orgánicos e inorgánicos para fortalecer el molde. Estos moldes no son cocidos en hornos y tienen como ventaja que son más precisos dimensionalmente pero también más caros que los moldes de arena verde.

- Moldes no horneados: estos moldes no necesitan ser cocidos debido a sus aglutinantes (mezcla de arena y resina). Las aleaciones metálicas que típicamente se utilizan con estos moldes son el latón, el hierro y el aluminio.

Las etapas que se diferencian en la fabricación de una pieza metálica por fundición en arena comprende:

- Compactación de la arena alrededor del modelo en la caja de moldeo. Para ello primeramente se coloca cada semi modelo en una tabla, dando lugar a las llamadas tablas modelo, que garantizan que posteriormente ambas partes del molde encajarán perfectamente. Actualmente se realiza el llamado moldeo mecánico, consistente en la compactación de la arena por medios automáticos, generalmente mediante pistones (uno o varios) hidráulicos o neumáticos.

- Colocación del macho o corazones. Si la pieza que se quiere fabricar es hueca, será necesario disponer machos, también llamados corazones que eviten que el metal fundido rellene dichas oquedades. Los machos se elaboran con arenas especiales debido a que deben ser más resistentes que el molde, ya que es necesario manipularlos para su colocación en el molde. Una vez colocado, se juntan ambas caras del molde y se sujetan. Siempre que sea posible, se debe prescindir del uso de estos corazones ya que aumentan el tiempo para la fabricación de una pieza y también su costo.

- Colada. Vertido del material fundido. La entrada del metal fundido hacia la cavidad del molde se realiza a través de la copa o bebedero de colada y varios canales de alimentación. Estos serán eliminados una vez solidifique la pieza. Los gases y vapores generados durante el proceso son eliminados a través de la arena permeable.

- Enfriamiento y solidificación. Esta etapa es crítica de todo el proceso, ya que un enfriamiento excesivamente rápido puede provocar tensiones mecánicas en la pieza, e incluso la aparición de grietas, mientras que si es demasiado lento disminuye la productividad. Además un enfriamiento desigual provoca diferencias de dureza en la pieza. Para controlar la solidificación de la estructura metálica, es posible localizar placas metálicas enfriadas en el molde. También se puede utilizar estas placas metálicas para promover una solidificación direccional. Además, para aumentar la dureza de la pieza que se va a fabricar se pueden aplicar tratamientos térmicos.

- Desmoldeo. Rotura del molde y extracción de la pieza. En el desmoldeo también debe retirarse la arena del macho. Toda esta arena se recicla para la construcción de nuevos moldes.

- Desbarbado. Consiste en la eliminación de los conductos de alimentación, mazarota y rebarbas procedentes de la junta de ambas caras del molde.

- Acabado y limpieza de los restos de arena adheridos. Posteriormente la pieza puede requerir mecanizado, tratamiento térmico, etc "...[6]

2.2.6. ENSAYO A TRACCIÓN

"… El ensayo a tracción es la forma básica de obtener información sobre el comportamiento mecánico de los materiales. Mediante una máquina de ensayos se deforma una muestra o probeta del material a estudiar, aplicando la fuerza uniaxialmente en el sentido del eje de la muestra. A medida que se va deformando la muestra, se va registrando la fuerza (carga), llegando generalmente hasta la fractura de la pieza. Así pues, el resultado inmediato es una curva de carga vs. alargamiento, que transformados en tensión y deformación, en función de la geometría de la probeta ensayada, aportan una información más general.

El ensayo de tracción tiene por objetivo definir la resistencia elástica, resistencia última y plasticidad del material cuando se le somete a fuerzas uniaxiales. Se requiere una máquina universal, ó prensa hidráulica por lo general, capaz de:

a) Alcanzar la fuerza suficiente para producir la fractura de la probeta.

b) Controlar la velocidad de aumento de fuerzas.

c) Registrar las fuerzas, F, que se aplican y los alargamientos, ΔL, que se observan en la probeta.

La máquina de ensayo impone la deformación desplazando el cabezal móvil a una velocidad seleccionable. La celda de carga conectada a la mordaza fija entrega una señal que representa la carga aplicada, las máquinas están conectadas a un ordenador que registra el desplazamiento y la carga leída.

La probeta a ensayar se sujeta por sus extremos al cabezal móvil de la máquina de ensayos y a la célula de carga, respectivamente. Las mordazas de sujeción deben mantener firme a la muestra durante el ensayo, mientras se aplica la carga,

impidiendo el deslizamiento. A su vez, no deben influir en el ensayo introduciendo tensiones que causen la rotura en los puntos de sujeción. Para que el ensayo se considere válido la rotura debe ocurrir dentro de la longitud calibrada, en la parte central de la probeta.

A partir de las dimensiones iniciales de la probeta, se transforman la fuerza en tensión y el alargamiento en deformación, que nos permite caracterizar las propiedades mecánicas que se derivan de este ensayo. La interpretación de la curva de la Figura N^{o} 2.1. nos lleva a:

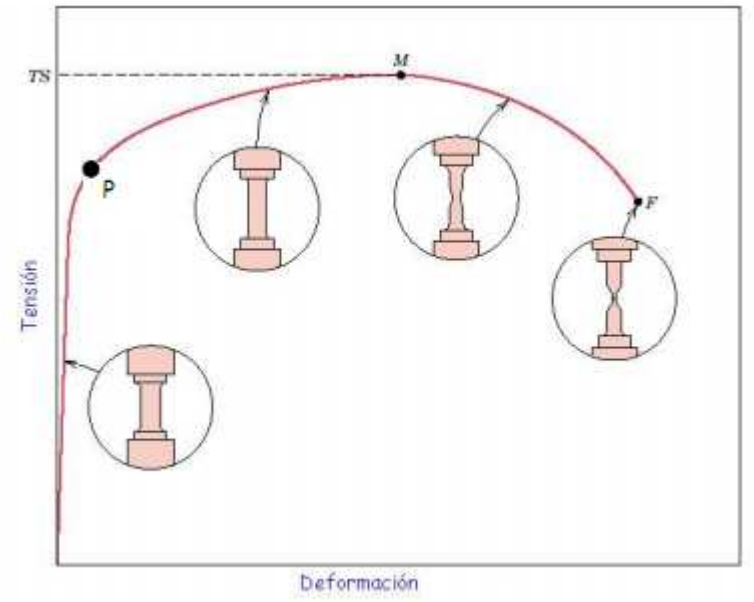


FIG N^{o} 2.1. Diagrama tensión vs deformación

Fuente:[7]

1.- En la curva podemos distinguir dos regiones:

- Zona elástica: La región a bajas deformaciones (hasta el punto P), donde se cumple la Ley de Hooke: $\sigma = E\,\varepsilon$ (E = modulo elástico).

- Zona plástica: A partir del punto P. Se pierde el comportamiento lineal, el valor de tensión para el cual esta transición ocurre, es decir, se pasa de deformación elástica a plástica, es el Límite de Elasticidad, σy, del material.

2.- Después de iniciarse la deformación plástica, la tensión necesaria para continuar la deformación en los metales aumenta hasta un máximo, punto M, Resistencia a tracción (RT ó TS), y después disminuye hasta que finalmente se produce la fractura, punto F. La Resistencia a Tracción es la tensión en el máximo del diagrama tensión-deformación nominales. Esto corresponde a la máxima tensión que puede ser soportada por una estructura a tracción; si esta tensión es aplicada y mantenida, se producirá la rotura. Hasta llegar a este punto, toda la deformación es uniforme en la región estrecha de la probeta. Sin embargo, cuando se alcanza la tensión máxima, se empieza a formar una disminución localizada en el área de la sección transversal en algún punto de la probeta, lo cual se denomina estricción, y toda la deformación subsiguiente está confinada en la estricción. La fractura ocurre en la estricción. La tensión de fractura o bien de rotura corresponde a la tensión en la fractura.

2.2.6.1. DEFORMACIÓN ELÁSTICA

Definimos elasticidad como la propiedad de un material en virtud de la cual las deformaciones causadas por la aplicación de una fuerza desaparecen cuando cesa la acción de la fuerza. "Un cuerpo completamente elástico se concibe como uno de los que recobra completamente su forma y dimensiones originales al retirarse la carga". ej: caso de un resorte al cual le aplicamos una fuerza. El grado con que una estructura se deforma depende de la magnitud de la tensión impuesta. Para muchos metales sometidos a esfuerzos de tracción pequeños, la tensión y la deformación son proporcionales según la relación:

$$\sigma = E\varepsilon$$

Esta relación se conoce con el nombre de ley de Hooke, y la constante de proporcionalidad, E (MPa) es el módulo de elasticidad, o módulo de Young. Cuando se cumple que la deformación es proporcional a la tensión, la deformación se denomina deformación elástica; al representar la tensión en el eje de coordenadas en función de la deformación en el eje de abscisas se obtiene una relación lineal como se muestra en la figura N^{o}2.2.

FIG N^{o} 2.2 Pendiente del módulo de elasticidad

Fuente: [7]

La pendiente de este segmento lineal corresponde al módulo de elasticidad E, puede ser interpretado como rigidez, o sea, la resistencia de un material a la deformación elástica. Cuanto mayor es el módulo, más rígido es el material, o sea, menor es la deformación elástica originada cuando se aplica una determinada tensión.

2.2.6.2. DEFORMACIÓN PLÁSTICA

Definimos como plasticidad a aquella propiedad que permite al material soportar una deformación permanente sin fracturarse. Todo cuerpo al soportar una fuerza aplicada trata de deformarse en el sentido de aplicación de la fuerza. En el caso del ensayo de tracción, la fuerza se aplica en dirección del eje de ella y por eso se denomina axial, la probeta se alargara en dirección de su longitud y se encogerá en el sentido o plano perpendicular. Aunque el esfuerzo y la deformación ocurren simultáneamente en el ensayo, los dos conceptos son completamente distintos. Para la mayoría de los materiales metálicos, la deformación elástica únicamente persiste hasta deformaciones de alrededor de 0.005. A medida que el material se deforma más allá de este punto, la tensión deja de ser proporcional a la deformación y ocurre deformación plástica, la cual es permanente, es decir no recuperable. En la figura N^{o}2.3. se traza esquemáticamente el comportamiento tensión deformación en la región plástica para un metal típico.

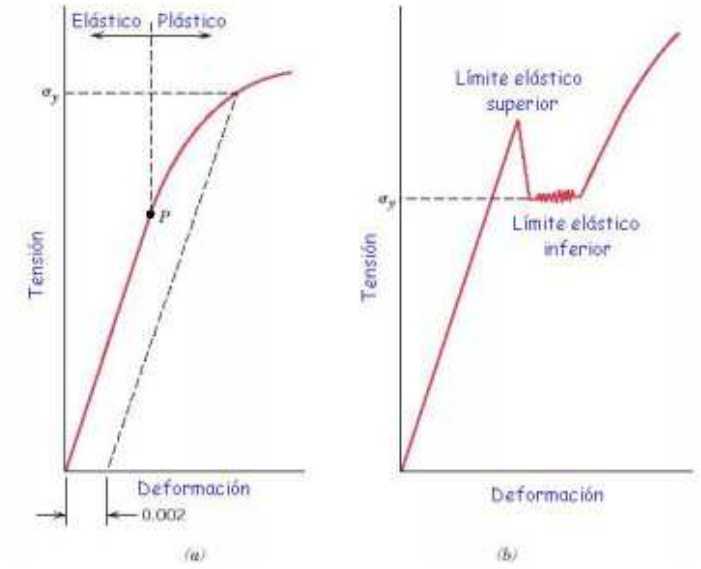


FIG N°2.3. (A) curva de tracción típica de un metal que muestra las deformaciones elástica y plástica, el limite proporcional p y el limite elástico σy, determinado como la tensión para una deformación plástica del 0.002. (b) curva de tracción típica de algunos aceros que presentan el fenómeno de la discontinuidad de la fluencia.

Fuente: [7]

La transición elastoplástica es gradual para la mayoría de los metales; se empieza a notar cierta curvatura al comienzo de la deformación plástica, la cual aumenta rápidamente al aumentar la carga.

2.2.6.3. CÁLCULO DEL LÍMITE ELÁSTICO

Para conocer el nivel de tensiones en el que empieza la deformación elástica, debemos que tener en cuenta dos tipos de transición elastoplástica:

1.- Los metales que experimentan esta transición de forma gradual. El punto de fluencia puede determinarse como la desviación inicial de la linealidad de la curva tensión-deformación (punto P en la figura N° 2.3a). En tales casos, la posición de este punto no puede ser determinada con precisión, por este motivo se ha establecido una convención por la cual se traza una línea recta paralela a la línea recta paralela a la línea elástica del diagrama de la tensión-deformación desplazada por una

determinada deformación, usualmente 0.002. La tensión correspondiente a la intersección de esta línea con el diagrama tensión deformación cuando éste se curva se denomina límite elástico, σy.

2.- Para aquellos materiales que tienen una región elástica no lineal, la utilización del método anterior no es posible, y la práctica usual es definir el límite elástico como la tensión necesaria para producir una determinada deformación plástica. Algunos aceros y otros materiales exhiben el tipo de diagrama tensión deformación mostrado en la figura N^{o} 2.3b. La transición elastoplástica está muy bien definida y ocurre de forma abrupta y se denomina fenómeno de discontinuidad del punto de fluencia. En el límite de fluencia superior, la deformación plástica se inicia con una disminución de la tensión. La deformación prosigue bajo una tensión que fluctúa ligeramente alrededor de un valor constante, denominado punto de fluencia inferior. En los metales en que ocurre este fenómeno, el límite elástico se toma como el promedio de la tensión asociada con el límite de fluencia inferior, ya que está bien definido y es poco sensible al procedimiento seguido en el ensayo.

2.2.6.4. DUCTILIDAD

La ductilidad es otra importante propiedad mecánica. Es una medida del grado de deformación plástica que puede ser soportada hasta la fractura. Un material que experimenta poca o ninguna deformación plástica se denomina frágil. La ductilidad puede expresarse cuantitativamente como alargamiento relativo porcentual, o bien mediante el porcentaje de reducción de área. El alargamiento relativo porcentual a rotura se da por:

$$\%\, alargamiento = \frac{lf - lo}{lo} \times 100$$

Donde *lf* es la longitud en el momento de la fractura y *lo* es la longitud de prueba original.

2.2.6.5. TENACIDAD

La tenacidad de un material es un término mecánico que se utiliza en varios contextos; en sentido amplio, es una medida de la capacidad de un material de absorber energía antes de la fractura. La geometría de la probeta así como la manera con que se aplica la carga son importantes en la determinación de la tenacidad.

2.2.6.6. RESILIENCIA

Medida de la capacidad de un material de absorber energía elástica antes de la deformación plástica.”...[7]

2.2.7. ENSAYO DE DUREZA

“… El ensayo de dureza mide la resistencia de la superficie del material a la penetración de un objeto duro. Dureza es un término que no se define con precisión. Dependiendo del contexto, puede representar resistencia al rayado o penetración y una medida cualitativa de la resistencia del material. En el gráfico No. 2.4. se muestra un durómetro. Se han inventado varios ensayos de dureza, pero los que se usan con mayor frecuencia son el Rockwell y Brinell.

FIG Nº 2.4. Durómetro.

Fuente: [8]

2.2.7.1. ENSAYO DE DUREZA BRINELL

En el ensayo de dureza brinell, se comprime una esfera de acero duro, por lo general de 10mm de diámetro, contra la superficie del material. Se mide el diámetro de la impresión, que suele ser de 2 a 6mm, y se calcula el numero de dureza brinell que se abrevia HB o HBN,por sus siglas en ingles con la siguiente ecuación:

$$HB = \frac{2F}{\pi D(D - \sqrt[2]{D^{2-d^2}})}$$

Donde F es la carga aplicada en kilogramos, D es el diámetro del penetrador en milímetros y d es el diámetro de la impresión, la dureza brinell tiene unidades de esfuerzo es decir kg/mm^2.

Los números de dureza brinell se usan principalmente como base cualitativa de comparación entre materiales o en especificaciones para tratamiento térmico en la manufactura o control de calidad y para correlacionar con otras propiedades de los materiales; por ejemplo, la dureza brinell se relaciona estrechamente con la resistencia a la tensión del acero, con la siguiente ecuación:

Resistencia a la tensión (p s i) = 500 HB

Donde HB tiene las unidades en kg/mm^2

1. Se puede obtener un número de dureza brinell solo en pocos minutos, casi sin preparar el espécimen y sin romper el componente; es decir, se considera que es un ensayo no destructivo y proporciona una aproximación muy cercana a la resistencia a la tensión. La dureza se correlaciona bien con la resistencia al desgaste (Para medir la resistencia al desgaste hay, además, un ensayo especial). Un material que se puede romper o moler minerales debe ser muy duro, para asegurar que no se desgaste o erosione con esos minerales.”…[9]

2.2.8. METALOGRAFÍA

"… La metalografía consiste en el estudio de la constitución y la estructura de los metales y las aleaciones. La forma más sencilla de hacer dicho estudio es examinando las superficies metálicas a simple vista, pudiendo determinar de esta forma las características macroscópicas. Este examen se denomina macrográfico del cual se pueden obtener datos sobre los tratamientos mecánicos sufridos por el material (es decir se puede determinar si el material fue trefilado, laminado, forjado, etc.) o comprobar la distribución de defectos (como grietas superficiales, rechupes, partes soldadas, etc). Para el examen macroscópico, dependiendo del estudio a realizar, se utilizan criterios para el tipo de corte a realizar (transversal o longitudinal) para extraer la muestra (por ejemplo un corte transversal para determinar la naturaleza del material, homogeneidad, segregaciones, procesos de fabricación de caños, etc., y un corte longitudinal: para controlar los procesos de fabricación de piezas, tipo y calidad de la soldadura, etc.).

Con la ayuda del microscopio podemos realizar un ensayo micrográfico con el cual es posible determinar el tamaño de grano, y el tamaño, forma y distribución de las distintas fases e inclusiones que tienen gran efecto sobre las propiedades mecánicas del material. La microestructura revelará el tratamiento mecánico y térmico del metal y podrá predecirse cómo se comportará mecánicamente. El examen micrográfico, es una técnica más avanzada que el macrográfico y necesita de una preparación más especial y cuidadosa de la muestra. Se basa en la amplificación de la superficie mediante instrumentos ópticos (microscopio) para observar las características estructurales microscópicas (microestructura). Este tipo de examen permite realizar el estudio o controlar el proceso térmico al que ha sido sometido un metal, debido a que los mismos nos ponen en evidencia la estructura o los cambios estructurales que sufren en dicho proceso. Como consecuencia de ello también es posible deducir las variaciones que experimentan sus propiedades mecánicas (dependiendo de los constituyentes metalográficos presentes en la estructura).

El examen de la microestructura es muy útil para determinar si un metal o aleación satisface las especificaciones en relación a trabajos mecánicos, tratamientos térmicos

y composición general. La microestructura es un instrumento para analizar las fallas metálicas y para controlar procesos industriales. Si bien para un estudio de la estructura microscópica se necesita una preparación aún más cuidadosa de la superficie, el procedimiento de preparación de la superficie es básicamente el mismo para ambos ensayos metalográficos (microscópico y macroscópico). Los cuatro pasos básicos que se requieren para preparar la superficie para su observación son:

2.2.8.1. CORTE TRANSVERSAL

Por lo general, se deben cortar varios trozos pequeños del material a examinar. La ubicación de las muestras y la forma en que se corten afectarán los resultados y su interpretación. Dependiendo del tipo de pieza a examinar se determina el lugar de dónde extraer las muestras. Por ejemplo: Si se estudian perfiles o barras laminadas, deben extraerse probetas de sus extremos y parte media. En una varilla de acero estirado en frío se pueden obtener las muestras de tal forma que quede expuesta una sección transversal o una longitudinal, y ambas secciones variarán notablemente su aspecto. Cuando el material a examinar es blando (acero al carbono recocido, aleaciones blandas de Al o de Cu), el corte se realizará con una sierra a mano y de diente grande (mientras más blando sea el material, más grande debe ser el diente de la sierra a utilizar, con el objeto de que la viruta sea fácilmente extraída de la zona de corte, evitando que al agruparse se adhiera a la superficie a estudiar, falseando la observación posterior). Los materiales duros (aceros aleados, templados, no ferrosos endurecidos) deben cortarse con discos abrasivos muy delgados de carbundum a altas velocidades y gran refrigeración. Los metales frágiles como fundición blanca, aceros templados, bronces ricos en estaño, etc, pueden romperse con golpe de martillo para extraer la probeta. En el caso del acero (y de algunas otras aleaciones), es necesario evitar el calentamiento de la muestra al hacer el corte.

2.2.8.2. MONTAJE

Si la muestra que va a examinarse es lo suficientemente grande como para que pueda sujetarse bien con la mano, no es necesario montarla. Siempre que se pueda se eligen probetas de 20 x 20 mm y alturas de 15 mm. No obstante la mayoría de las veces la

muestra es demasiado pequeña como para que pueda sostenerse de esta forma (por ejemplo un tramo de varilla, alambre, lámina), mientras se esmerila o pule. El montaje puede efectuarse de varias maneras. Con sujetadores tipo tenazas .La muestra puede también encerrarse en una resina epóxica de dos compuestos, que se solidifican después de que se mezclan; asimismo pueden usarse resinas termoplásticas transparentes. Al emplear esta técnica, la muestra se coloca en el molde con plástico en polvo, luego se aplica presión y calor, hasta que el plástico se suaviza y densifica.

2.2.8.3. DESBASTE GRUESO

Este se logra mejor en un esmeril húmedo de banco usando esmeriles de granos 120, 140, 160 (este número resulta de dividir la cantidad de líneas del tamiz de selección de granos- sobre la superficie del mismo). El objetivo del esmerilado es obtener una superficie plana, libre de toda huella de marcas de herramientas, y en la que todas las marcas del esmerilado sigan la misma dirección. Se puede esmerilar en seco a condición de no producir cambios estructurales por el calentamiento de la muestra. También se deben evitar presiones excesivas que calienten o distorsionen la superficie a observar. Luego, la muestra se lava y se seca antes de pasar a la próxima etapa de esmerilado.

2.2.8.4. DESBASTE FINO

Este proceso se efectúa utilizando granos cada vez más finos de lija metalográfica para esmerilar. Se utilizan papeles de grano 240 en adelante. La lija se sostiene sobre una superficie plana y dura, que puede ser acero o vidrio, y la muestra se pasa sobre el papel de lija sin seguir un movimiento rotatorio. Cuando se termina de esmerilar con un papel de lija, las marcas deben estar todas en la misma dirección. Antes de proseguir con la siguiente lija más fina, deben lavarse la muestra como las manos del operario. Ahora la muestra debe desplazarse en forma tal que las rayas hechas por las distintas lijas formen ángulos rectos con las del inmediatamente anterior. Así, puede verse con claridad si se han eliminado las rayas más gruesas que se hicieron en la operación anterior. El desbaste se da por terminado cuando se obtiene una cara

perfectamente plana, con rayas muy finas en toda la superficie, producidas en un solo sentido, por el papel de esmeril de mayor finura. Cuando más blando es el material, mayor es la finura del grano del papel de esmeril utilizado en último término.

2.2.8.5. PULIDO

Se procede a hacer el pulido solo después de lavar con sumo cuidado tanto las manos como la muestra, a fin de evitar cualquier contaminación en el plato de pulido. Este procedimiento se basa en el uso de un plato cubierto con una tela (o paño), cargada con una suspensión de alúmina (Al_2O_3). Al principio, la muestra se sostiene en una posición sobre la rueda, sin girar la muestra, hasta que se hayan eliminado la mayoría de las rayas anteriores producidas en el desbaste. Luego puede hacerse girar con lentitud en sentido contrario al de rotación de la rueda, hasta que solo puedan verse las marcas de alúmina. La rotación de la muestra reduce a un mínimo el peligro de formación de ranuras. Los resultados del pulido pueden mejorarse si esta última etapa de pulido se realiza sobre la rueda girando a baja velocidad. El aspecto de la superficie debe ser igual al de un espejo.

2.2.8.6. ATAQUE

Este permite poner en evidencia la estructura del metal o aleación. Existen diversos métodos de ataque pero el más utilizado es el ataque químico, que puede hacerse sumergiendo la muestra en un reactivo adecuado, o pasar sobre la cara pulida un algodón humedecido en dicho reactivo. Luego se lava la probeta con agua, se enjuaga con alcohol o éter y se seca en corriente de aire. El fundamento se basa en que el constituyente metalográfico de mayor velocidad de reacción se ataca más rápido y se verá más oscuro al microscopio, y el menos atacable permanecerá más brillante, reflejará más luz y se verá más brillante en el microscopio.

Por otro lado, en los metales con un solo constituyente metalográfico, los límites de grano están sujetos a ataques selectivos, puesto que representan zonas de imperfección cristalina e impurezas que aceleran el ataque local. Además los granos con orientaciones distintas son atacados con diferente intensidad, dado que esta diferencia en la orientación provoca velocidades de ataque diferentes. Se debe evitar

el sobreataque, dado que la superficie se puede manchar y tapar la estructura o producirse manchas de corrosión. En caso de que esto sucediera se deberá proceder a un nuevo desbaste y pulido (dependiendo del grado de sobreataque).

Un reactivo común utilizado para atacar hierros y aceros al carbono en general es el nital, que consiste en 5% de ácido nítrico concentrado en alcohol etílico (en 100cm3de alcohol etílico 95% agregar 5 cm3 de NO3H concentrado). Para su aplicación, se toma la muestra con unas pinzas con la cara pulida hacia arriba, se vierte unas gotas de nital sobre la muestra (lavada y secada previamente) asegurándose que el nital cubra toda la cara (con algunos movimientos de la pinza). Por lo común es adecuado de 3 a 5 segundos para que el ataque químico sea adecuado.

Otro método de ataque muy utilizado en aleaciones no ferrosas y que actualmente se está introduciendo en el campo de las ferrosas, especialmente en los aceros inoxidables es el ataque electrolítico. Se hace generalmente a continuación del pulido electrolítico pero con un voltaje mucho menor. La diferencia con el pulido es que en el pulido la disolución anódica es indiferenciada y ahora es selectiva.

2.2.8.7. EXAMEN MICROSCÓPICO

La muestra se coloca en la placa de un microscopio metalúrgico, de modo que la superficie de la muestra sea perpendicular al ojo óptico. Puede observarse con ampliaciones diferentes, y elegir la adecuada. Si se examina con un aumento de 500x deben aparecer claramente el constituyente perlita, en una muestra de acero completamente recocido. Puede tomarse una imagen de la microestructura. Si la muestra no ha sido bien atacada por el ácido, el aspecto de la perlita será prácticamente invisible o muy débil. Si el ataque ha sido excesivo la perlita tendrá un aspecto muy negro. Se puede hacer un repulido rápido y un nuevo ataque.

Todo lo explicado en el procedimiento anterior es válido para un examen macroscópico teniendo en cuenta para este examen algunas salvedades

- Generalmente no es necesario la colocación de la muestra en soportes especiales dado que su tamaño es fácil de manipular.

- No es necesario esmerilado fino ni pulido. Con esmerilado grueso y mediano basta. El grado de pulido necesario depende del reactivo de ataque y de lo que se quiere poner de manifiesto. Reactivos más energéticos requieren superficie más grosera. Cuanto más fino sea el grado de detalle alcanzado, mayor será el pulimiento.

2.2.8.8. EL MICROSCOPIO METALOGRÁFICO

Se analizar muy brevemente los principios del microscopio metalúrgico. En comparación con uno de tipo biológico, el microscopio metalúrgico difiere en la manera en que la muestra es iluminada. Como una muestra metalográfica es opaca a la luz, la misma debe ser iluminada por luz reflejada. Un haz de luz horizontal de alguna fuente de luz es reflejado, por medio de un reflector de vidrio plano, hacia abajo a través del objetivo del microscopio sobre la superficie de la muestra. Un poco de esta luz incidente reflejada desde la superficie de la muestra se amplificará al pasar a través del sistema inferior de lentes, el objetivo, y continuará hacia arriba a través del reflector de vidrio plano; luego, una vez más lo amplificará el sistema superior de lentes, el ocular. Cada objetivo posee un aumento propio característico, es decir, capacidad para dar una imagen un número determinado de veces mayor que el objeto. El poder de amplificación inicial del objetivo y del ocular está generalmente grabado en la base de la lente. Cuando se utiliza una combinación particular de objetivo y ocular y la longitud adecuada de tubo, la amplificación total es igual al producto de las amplificaciones del objetivo y del ocular. Es decir, con un objetivo 60x y un ocular 10x se obtiene una amplificación de 600x

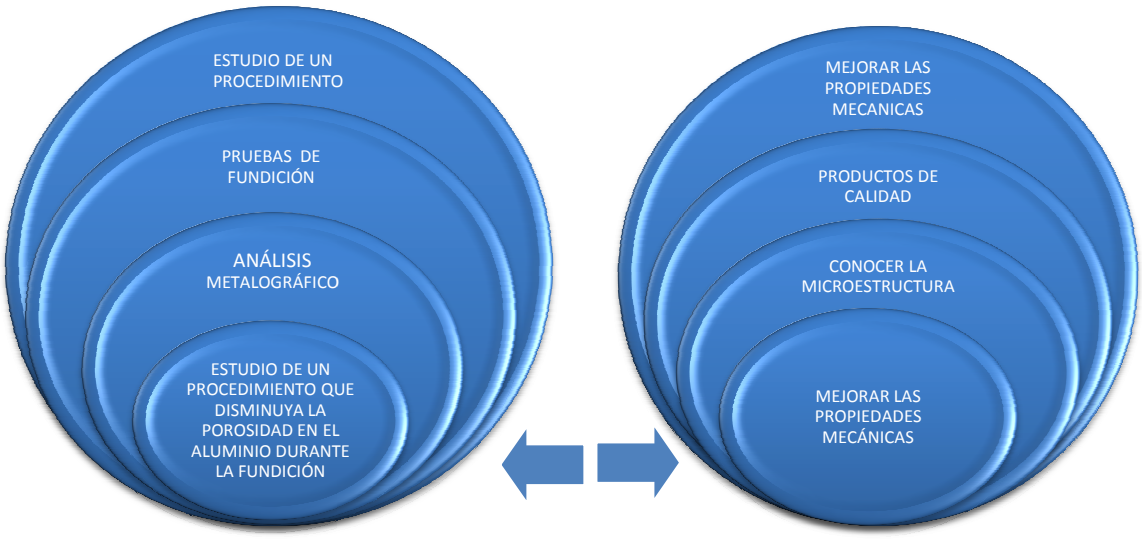
De los tres elementos esenciales que constituyen un microscopio (objetivo, ocular e iluminador) el objetivo es el más crítico, por su influencia sobre la calidad de la imagen observada. Es esencial que los distintos elementos ópticos se hallen escrupulosamente limpios y libres de huellas dactilares, polvo, películas de grasa, que perjudican la calidad de las imágenes. El polvo se puede quitar de las superficies

ópticas soplando aire sobre ellas, mediante una pera de goma, con un pincel de pelo blando de camello o frotando suave con una tela o papel apropiado. En estas operaciones hay que tener cuidado de no rayar la superficie ni deteriorarla por abrasión. La grasa y las huellas dactilares se quitan frotando con una tela o papel de los citados, impregnados en xilol (nunca alcohol ni otros disolventes orgánicos), secando luego con otros papeles limpios, y finalmente, soplando aire con una pera de goma para quitar las fibras del papel. Este método es ideal para quitar el aceite que queda adherido a los objetivos de inmersión y debe realizarse inmediatamente después del uso. En ningún caso se deben desmontar los elementos ópticos, y en particular los objetivos para su limpieza. Todos los elementos ópticos se deben manipular con cuidado. No deben estar expuestos a cambios bruscos de temperatura"… [10]

2.3. FUNDAMENTACIÓN LEGAL.

Para el desarrollo del presente trabajo investigativo y después del proceso de recolección de información podemos concluir que no existen investigaciones o proyectos que estén relacionados específicamente con la disminución de porosidad en la fundición de aluminio, siendo este trabajo de mi total autoría.

2.4. CATEGORÍAS FUNDAMENTALES



Variable Independiente **Variable Dependiente**

2.5. HIPÓTESIS

El estudio de un procedimiento que disminuya la porosidad en el aluminio durante la fundición mejorará las propiedades mecánicas de las piezas fundidas con este material.

2.6. SEÑALAMIENTO DE VARIABLES

VARIABLE INDEPENDIENTE

Estudio de un procedimiento que disminuya la porosidad en el aluminio durante la fundición.

VARIABLE DEPENDIENTE

Propiedades mecánicas de las piezas fundidas con este material.

TÉRMINO DE RELACIÓN

Mejorará

CAPÍTULO 3
METODOLOGÍA

3.1. ENFOQUE

En la presente investigación van a predominar los datos cuantitativos por que se realizarán varios ensayos, los cuales nos entregarán diversos resultados a los mismos que se les realizará análisis estadísticos y cualitativos ya que nos permitirán identificar que propiedades mecánicas del aluminio han variado de acuerdo a cada ensayo.

3.2. MODALIDAD BÁSICA DE LA INVESTIGACIÓN

Debido a que el presente trabajo investigativo no tiene la suficiente información bibliográfica, la indagación se la realizará mediante la búsqueda de documentos relacionados con el tema por internet, mientras que los conceptos básicos se los obtendrá de libros, revistas, trípticos y distintos documentos que puedan servir de ayuda para la solución del problema, la otra modalidad básica es la investigación experimental con la cual se podrá ensayar diferentes métodos que nos permitan desarrollar una técnica simple y económica para la solución del problema. La experimentación se la realizará en el Laboratorio de Materiales de la Carrera de Ingeniería Mecánica en la Facultad de Ingeniería Civil y Mecánica de la Universidad Técnica de Ambato que cuenta con la infraestructura y equipos necesarios para cumplir con esta investigación.

3.3. NIVEL O TIPO DE INVESTIGACIÓN

Los niveles de Investigación que se utilizarán en el presente trabajo serán: Exploratorios, ya que este tema ha sido poco estudiado y no cuenta con la información y experimentación necesaria para dar una solución al problema de la porosidad en el Aluminio, otro nivel de investigación será el descriptivo porque

necesitamos cuantificar, especificar y describir cada resultado de los ensayos realizados en el laboratorio de la Facultad, y explicativos ya que facilitará a las personas interesadas en este trabajo descubrir causas del problema e implementar alguna técnica que permita reducir el nivel de porosidad en las fundiciones de Aluminio.

3.4. OPERACIONALIZACIÓN DE LAS VARIABLES

3.4.1 VARIABLE INDEPENDIENTE

Estudio de un procedimiento que disminuya la porosidad en el aluminio durante el proceso de fundición

TABLA No. 3.1. Variable independiente

DESCRIPCIÓN	DIMENSIÓN	INDICADORES	ITEMS	TÉCNICAS E INSTRUMENTOS
La investigación pretende disminuir la porosidad que se genera en el aluminio durante su fundición, de esta forma se desea a aprovechar al máximo la materia prima elevando los niveles de producción y aumentando la cartera de cliente a niveles rentables	Hidrógeno Atmósferas no controladas Presión de vaciado	Porosidad Piezas defectuosas	¿Cuál es el procedimiento de fundición más adecuado para obtener piezas de mejor calidad?	Normas ASTM Equipos y horno para fundición Ensayos Observación

3.4.2 VARIABLE DEPENDIENTE

Mejorar las propiedades mecánicas.

TABLA No. 3.2. Variable dependiente

DESCRIPCIÓN	DIMENSIÓN	INDICADORES	ITEMS	TÉCNICAS E INSTRUMENTOS
Las propiedades mecánicas del aluminio son de gran importancia ya que nos permiten conocer el comportamiento del material durante sus aplicaciones y después de ellas	Propiedades mecánicas Comportamiento del material	Confiabilidad en aplicaciones	¿Cómo conocer el comportamiento del material? ¿Cómo determinar si el material está listo para las diferentes aplicaciones?	Ensayos Observación

3.5. PLAN DE RECOLECCIÓN DE INFORMACIÓN

La información existente sobre la porosidad en el aluminio, sus causas y consecuencias es sumamente escasa, por tal motivo para el presente trabajo investigativo vamos a acudir a documentales que se encuentran publicados en la web, artículos de libros, revistas, periódicos y de toda la información que se pueda recabar a lo largo del tiempo que dure esta investigación para de esta forma concluir con una técnica que permita eliminar la porosidad en el Aluminio.

3.6. PLAN DE PROCESAMIENTO DE LA INFORMACIÓN

Una vez finalizada la recopilación de la información se analizará los aspectos más importantes y relevantes acerca del tema, los mismos que permitirán realizar ensayos en el laboratorio aportando al desarrollo de una técnica con la que se pueda eliminar la porosidad en el Aluminio durante el proceso de fundición.

CAPÍTULO 4
ANÁLISIS E INTERPRETACIÓN DE RESULTADOS

4.1. PROCESO DE OBTENCIÓN Y ANÁLISIS DE LOS RESULTADOS

Las fundiciones realizadas en arena de aluminio puro, y con diferentes elementos reductores como: cloruro de sodio [NaCl], calcio [Ca], azufre [S], fosfato de calcio [$Ca_3(PO_4)_2$] y nitrito de sodio [$NaNO_2$] nos ha permitido generar las muestras necesarias para poder determinar: la porosidad por unidad de superficie, realizar los ensayos metalográficos, a tracción y de dureza de seis fundiciones diferentes, las mismas que están identificadas mediante un código alfanumérico; de las cuales se han obtenido varios resultados interesantes que nos ayudarán a seleccionar el elemento reductor más apropiado para realizar una fundición de aluminio con un mínimo índice de porosidad y con propiedades mecánicas mejoradas que la fundición base que consta solamente de aluminio.

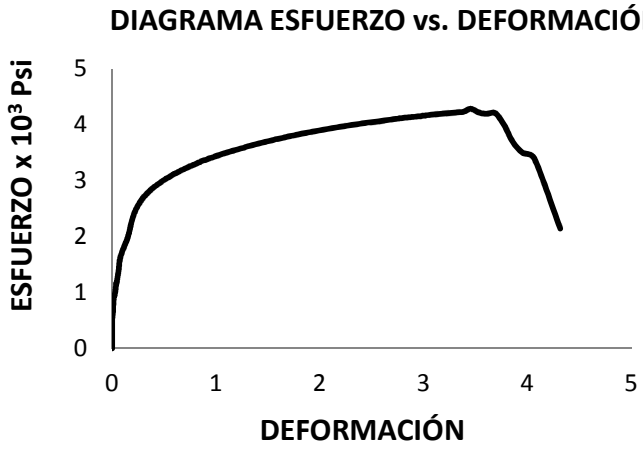
Luego de haber realizado varias pruebas, se ha podido definir un diagrama lógico que permitirá desarrollar cada ensayo y analizar los resultados obtenidos, el cual se muestra a continuación.

PRESENTACIÓN DE LOS RESULTADOS

Debido a que los resultados de las probetas ensayadas arrojan extensos valores, es lo más apropiado filtrar los datos que van a permitir identificar las características y propiedades de cada fundición. Para eso se establecido formatos que permitan al diseñador interpretar de una manera directa los datos obtenidos de los ensayos como son: la dureza, ductilidad, módulo de elasticidad, tamaño de grano y el índice de porosidad.

ENSAYO A TRACCIÓN

DATOS INFORMATIVOS	
Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 0	**Ensayo en P-0** : 1 / 4
Material : Aluminio	**Elemento reductor :** Ninguno
Fundido en : Arena	**Tratamiento térmico :** Ninguno
DATOS PARA EL ENSAYO	
Norma : ASTM	**Designación :** E-08
Probeta : Cilíndrica	**Especimen :** No. 1
RESULTADOS DEL ENSAYO	
Longitud de estudio : 50mm	**Sección de estudio :** 119,6 mm^2
Esfuerzo fluencia : 19MPa / 2,8x10^3Psi	**Carga máxima :** 4217N / 948Lbf
Resistencia tracción : 35MPa / 5,1x10^3Psi	**Módulo de elasticidad :** 40GPa / 5000x10^3Psi
% Elongación en 50mm : 4,3	



RESULTADOS: El ensayo a tracción realizado en la probeta P-0; que es una fundición de aluminio sin elementos reductores, nos da resultados que permiten tenerlos como parámetros de comparación con las probetas que se ensayarán posteriormente, entre los valores más destacados de este ensayo tenemos: un esfuerzo de fluencia de 2,8 x 10^3Psi y una Ductilidad del 4,3%; Los valores de obtención del gráfico Esfuerzo vs. Deformación están tabulados en el Anexo B-1.

ENSAYO DE DUREZA

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 0	**Ensayo en P-0** : 2 / 4
Material : Aluminio	**Elemento reductor :** Ninguno
Fundido en : Arena	**Tratamiento térmico :** Ninguno

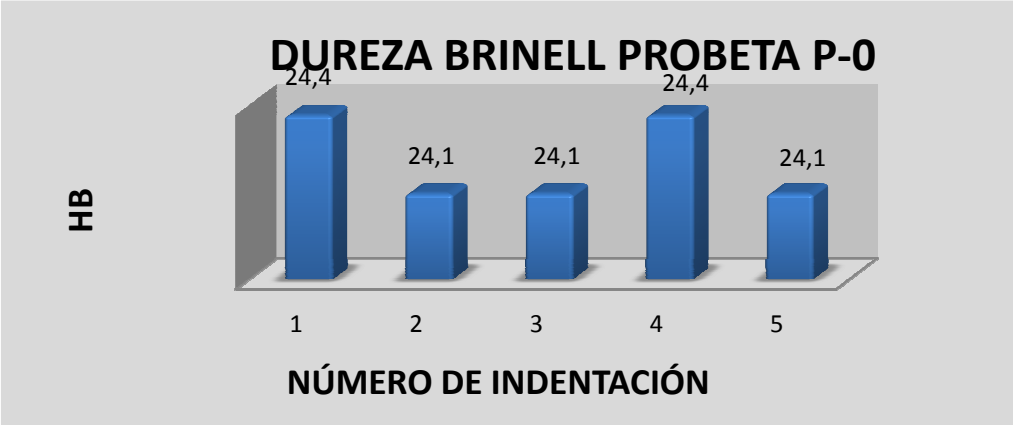
DATOS PARA EL ENSAYO

Dureza : Brinell		
Norma : ASTM	**Designación :** E-10	**Espesor Probeta:** 20 mm
Carga : 613N/62,5Kgf	**Tiempo de indentación :** 15 s	**Ø del indentador :** 5 mm

RESULTADOS DEL ENSAYO

No. De indentación	Ø de la indentación (mm)	Dureza (HB)
1	1,80	24,4
2	1,81	24,1
3	1,81	24,1
4	1,80	24,4
5	1,81	24,1

Mínimo : 24,1HB	**Máximo :** 24,4 HB	**Dureza :** 24,2 HB



RESULTADOS: El ensayo de dureza realizado en la probeta P-0; la misma que es una fundición de aluminio sin elementos reductores, arrojó un resultado de dureza de 24,2 HB (ver Anexo C-1); valor a partir del cual se realizarán comparaciones de esta propiedad mecánica con las fundiciones que contienen elementos reductores.

ENSAYO METALOGRÁFICO

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 0	**Ensayo en P-0** : 3 / 4
Material : Aluminio	**Elemento reductor :** Ninguno
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO

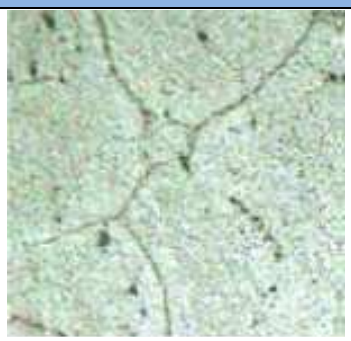
Norma : ASTM	**Designación :** E-112
Pulido : Mecánico	
Reactivo : Ácido hidrofluórico	**Tiempo ataque :** 10 s

RESULTADOS DEL ENSAYO

N. ins = 1 *N. int = 5*

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$
$$N_{AE} = 2\left(1 + \frac{5}{2}\right)$$
$$N_{AE} = 7$$

$$G = 1{,}000 + 3{,}3219 \log 7$$
$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$
$$\boldsymbol{G = 3{,}8}$$



Tamaño de grano : 3,8

Aluminio a 100X, atacado con Ácido hidrofluórico durante 10 s.

- POROSIDAD
- GRANO
- INCLUSION

RESULTADOS:

El ensayo microestructural realizado en la probeta P-0, la misma que es una fundición de aluminio sin elementos reductores arrojó un tamaño de grano de 3,8 según la norma ASTM E-112; el mismo que se considera un grano grueso, a partir de este valor se realizarán las comparaciones con las otras fundiciones.(ver Anexo D-1)

ÍNDICE DE POROSIDAD

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 0	**Ensayo en P - 0** : 4 / 4
Material : Aluminio	**Elemento reductor :** Ninguno
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO

Para determinar la porosidad superficial del material tomamos como referencia la probeta utilizada en el ensayo metalográfico, la superficie pulida de la probeta ayuda a visualizar de mejor manera el índice de porosidad, en la que se tomará como referencia un cuadrado de 1 cm de lado; el mismo que da una superficie para inspección visual de 1 cm^2.

RESULTADOS DEL ENSAYO

Imagen de la probeta metalográfica P-0 para realizar la inspección visual

Escala 1:5

Conteo de poros en la superficie de la probeta metalográfica P-0

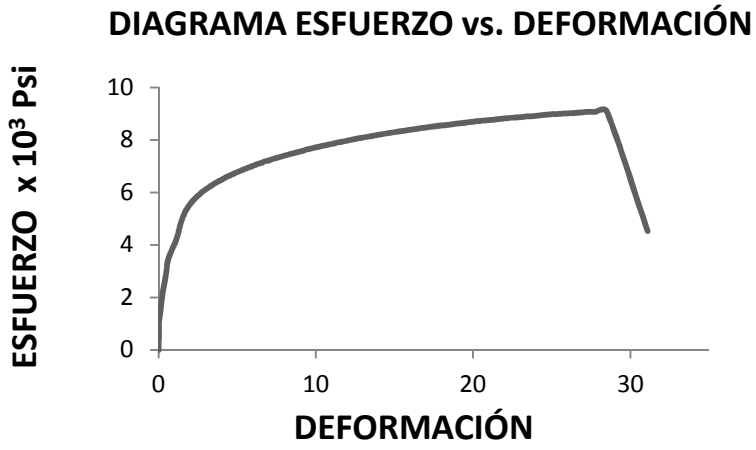
Escala 1:5

Superficie de estudio : 1cm^2	**Número de poros :** 25

RESULTADOS: Al realizar una inspección visual en la superficie de la probeta P-0; sobre una área de 1cm^2 podemos visualizar con claridad que existe porosidad bien acentuada, encontrando 25 poros (ver Anexo E).

ENSAYO A TRACCIÓN

DATOS INFORMATIVOS	
Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 1	**Ensayo en P - 1:** 1 / 4
Material : Aluminio	**Elemento reductor :** Cloruro de sodio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno
DATOS PARA EL ENSAYO	
Norma : ASTM	**Designación :** E - 08
Probeta : Cilíndrica	**Espécimen :** No. 1
RESULTADOS DEL ENSAYO	
Longitud de estudio : 50mm	**Sección de estudio :** 120 mm^2
Esfuerzo fluencia : 26MPa / 3,7x10^3Psi	**Carga máxima :** 7509N/ 1688Lbf
Resistencia tracción : 63MPa / 9,1x10^3Psi	**Módulo de elasticidad :** 43GPa / 6200x10^3Psi
% Elongación en 50mm : 25,7	



RESULTADOS: El ensayo a tracción realizado en la probeta P-1; de aluminio con Cloruro de sodio como elemento reductor; nos ha permitido obtener un esfuerzo de fluencia de 3,7 x 10^3 Psi y un valor de ductilidad del 25,7%. Los valores para obtener el gráfico Esfuerzo vs. Deformación de P-1 se encuentran tabulados en el Anexo B-2.

ENSAYO DE DUREZA

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 1	**Ensayo en P - 1** : 2 / 4
Material : Aluminio	**Elemento reductor :** Cloruro de sodio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

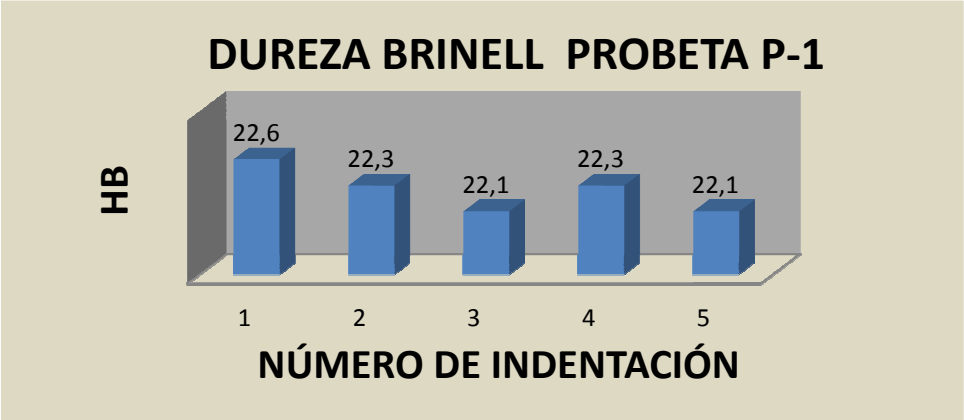
DATOS PARA EL ENSAYO

Dureza : Brinell		
Norma : ASTM	**Designación :** E-10	**Espesor Probeta:** 20 mm
Carga : 613N/62,5Kgf	**Tiempo de indentación :** 15 s	**Ø del indentador :** 5 mm

RESULTADOS DEL ENSAYO

No. De indentación	Ø de la indentación (mm)	Dureza (HB)
1	1,87	22,6
2	1,88	22,3
3	1,89	22,1
4	1,88	22,3
5	1,89	22,1

Mínimo : 22,1HB	**Máximo :** 22,6 HB	**Dureza :** 22,3 HB



RESULTADOS:

Luego de haber realizado 5 indentaciones sobre la probeta P-1, que es una fundición de aluminio con cloruro de sodio como elemento reductor; se tuvo un diámetro promedio de indentación igual a 1,88 mm que da una dureza de 22,3 HB.(Ver Anexo C-2).

ENSAYO METALOGRÁFICO

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 1	**Ensayo en P - 1** : 3 / 4
Material : Aluminio	**Elemento reductor :** Cloruro de sodio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO

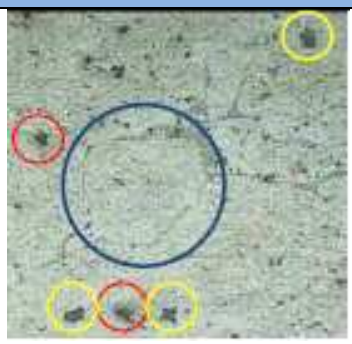
Norma : ASTM	**Designación :** E-112
Pulido : Mecánico	
Reactivo : Ácido hidrofluórico	**Tiempo ataque :** 12 s

RESULTADOS DEL ENSAYO

N ins = 6 *N int = 6*

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$
$$N_{AE} = 2\left(6 + \frac{6}{2}\right)$$
$$N_{AE} = 18$$

$$G = 1{,}000 + 3{,}3219 \log 18$$
$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$
$$\boldsymbol{G = 5{,}2}$$



Tamaño de grano : 5,2

Aluminio con cloruro de sodio (reductor) a 100X, atacado con Ácido hidrofluórico durante 12 s.

- POROSIDAD
- GRANO
- INCLUSION

RESULTADOS:

El ensayo microestructural realizado en la probeta P-1 de aluminio con cloruro de sodio como elemento reductor determinó un tamaño de grano de 5,2 según la norma ASTM E-112; el mismo que se considera un grano medio.(ver Anexo D-2)

ÍNDICE DE POROSIDAD

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 1	**Ensayo en P - 1** : 4 / 4
Material : Aluminio	**Elemento reductor :** Cloruro de sodio
Fundido en : Arena	**Tratamiento térmico :** Ninguno

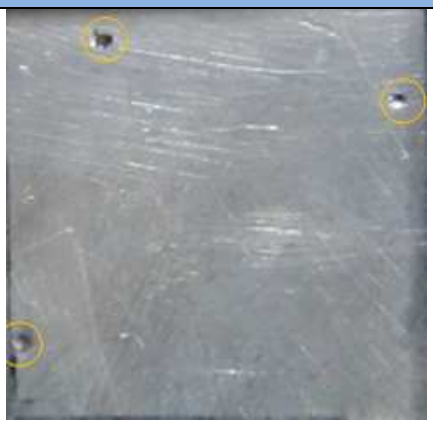
DATOS PARA EL ENSAYO

Para determinar la porosidad superficial del material tomamos como referencia la probeta utilizada en el ensayo metalográfico, la superficie pulida de la probeta ayuda a visualizar de mejor manera el índice de porosidad, en la se tomará como referencia un cuadrado de 1 cm de lado; el mismo que da una superficie para inspección visual de 1 cm^2.

RESULTADOS DEL ENSAYO

Imagen de la probeta metalográfica P-0 para realizar la inspección visual

Escala 1:5



Conteo de poros en la superficie de la probeta metalográfica P-0

Escala 1:5

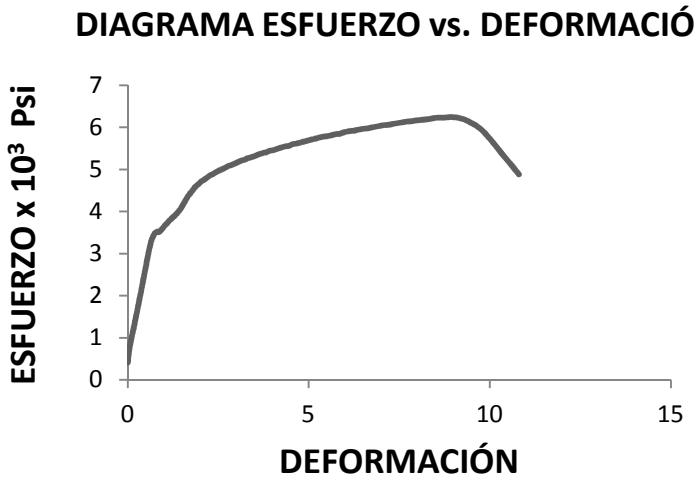
Superficie de estudio : 1cm^2	**Número de poros :** 3

RESULTADOS:

Al realizar una inspección visual en la superficie de la probeta P-1 sobre un área de 1 cm^2, se observan 3 pequeños poros (Ver Anexo E).

ENSAYO A TRACCIÓN

DATOS INFORMATIVOS	
Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 2	**Ensayo en P - 2:** 1 / 4
Material : Aluminio	**Elemento reductor :** Calcio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno
DATOS PARA EL ENSAYO	
Norma : ASTM	**Designación :** E-08
Probeta : Cilíndrica	**Espécimen :** No. 1
RESULTADOS DEL ENSAYO	
Longitud de estudio : 50mm	**Sección de estudio :** 120 mm^2
Esfuerzo fluencia : 28MPa/3,5 $x10^3$Psi	**Carga máxima :** 5231N/ 1176Lbf
Resistencia tracción : 43MPa/6,2 $x10^3$Psi	**Módulo de elasticidad :** 41,4GPa/6000 $x10^3$Psi
% Elongación en 50mm : 9,8	



RESULTADOS:

El ensayo a tracción realizado en la probeta P-2; de aluminio con Calcio como elemento reductor; nos ha permitido obtener un esfuerzo de fluencia a 3,5 x 10^3 Psi y la ductilidad al 9,8%. Los valores para obtener el gráfico Esfuerzo vs. Deformación de la probeta P-2 se encuentran tabulados en el Anexo B-3.

ENSAYO DE DUREZA

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 2	**Ensayo en P - 2** : 2 / 4
Material : Aluminio	**Elemento reductor :** Calcio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

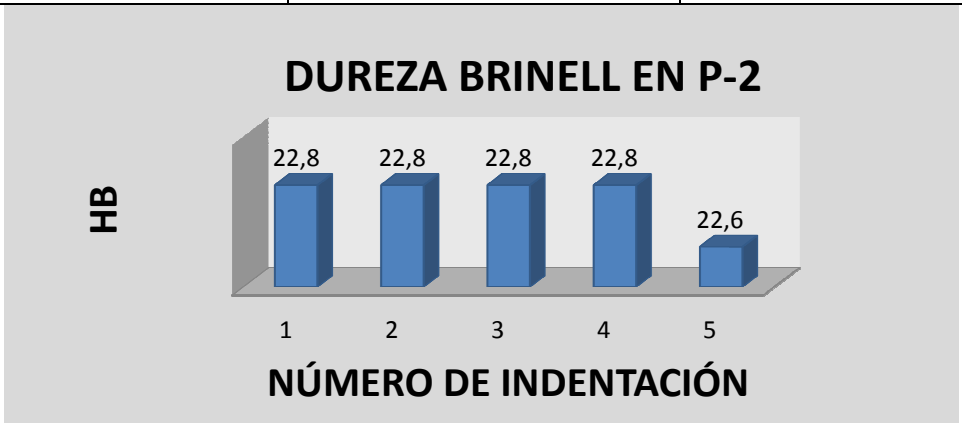
DATOS PARA EL ENSAYO

Dureza : Brinell		
Norma : ASTM	**Designación :** E-10	**Espesor Probeta:** 20mm
Carga : 613N/62,5Kgf	**Tiempo de indentación :** 15 s	**Ø del indentador :** 5 mm

RESULTADOS DEL ENSAYO

No. De indentación	Ø de la indentación (mm)	Dureza (HB)
1	1,86	22,8
2	1,86	22,8
3	1,86	22,8
4	1,86	22,8
5	1,87	22,6

Mínimo : 22,6 HB	**Máximo :** 22,8 HB	**Dureza :** 22,8 HB



RESULTADOS:

Luego de haber realizado 5 indentaciones sobre la probeta P-2, que es una fundición de aluminio con calcio como elemento reductor; se tuvo un diámetro promedio de indentación igual a 1,86 mm que da una dureza de 22,8 HB.(Ver Anexo C-3).

ENSAYO METALOGRÁFICO

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 2	**Ensayo en P - 2** : 3 / 4
Material : Aluminio	**Elemento reductor :** Calcio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO

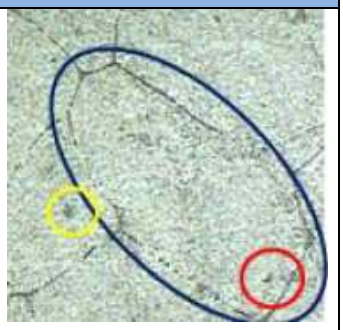
Norma : ASTM	**Designación :** E-112
Pulido : Mecánico	
Reactivo : Ácido hidrofluórico	**Tiempo ataque :** 15 s

RESULTADOS DEL ENSAYO

N ins = 1 *N int = 7*

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$
$$N_{AE} = 2\left(1 + \frac{7}{2}\right)$$
$$N_{AE} = 9$$

$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$
$$G = 1{,}000 + 3{,}3219 \log 9$$
$$\boldsymbol{G = 4{,}2}$$



Tamaño de grano : 4,2

Aluminio con Calcio (reductor) a 100X, atacado con Ácido hidrofluórico durante 15 s.

- POROSIDAD
- GRANO
- INCLUSION

RESULTADOS:

El ensayo microestructural realizado en la probeta P-2 de aluminio con calcio como elemento reductor determinó un tamaño de grano de 4,2 según la norma ASTM E-112; el mismo que se considera un grano medio. (Ver Anexo D-3).

ÍNDICE DE POROSIDAD

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 2	**Ensayo en P - 2** : 4 / 4
Material : Aluminio	**Elemento reductor :** Calcio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

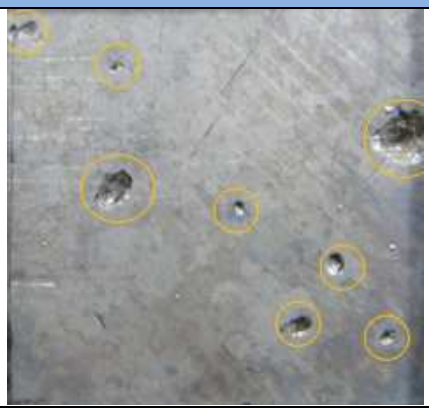
DATOS PARA EL ENSAYO

Para determinar la porosidad superficial del material tomamos como referencia la probeta utilizada en el ensayo metalográfico, la superficie pulida de la probeta ayuda a visualizar de mejor manera el índice de porosidad, en la se tomará como referencia un cuadrado de 1 cm de lado; el mismo que da una superficie para inspección visual de 1 cm^2.

RESULTADOS DEL ENSAYO

Imagen de la probeta metalográfica P-2 para realizar la inspección visual

Escala 1:5



Conteo de poros en la superficie de la probeta metalográfica P-2

Escala 1:5

Superficie de estudio : 1cm^2	**Número de poros :** 8

RESULTADOS:

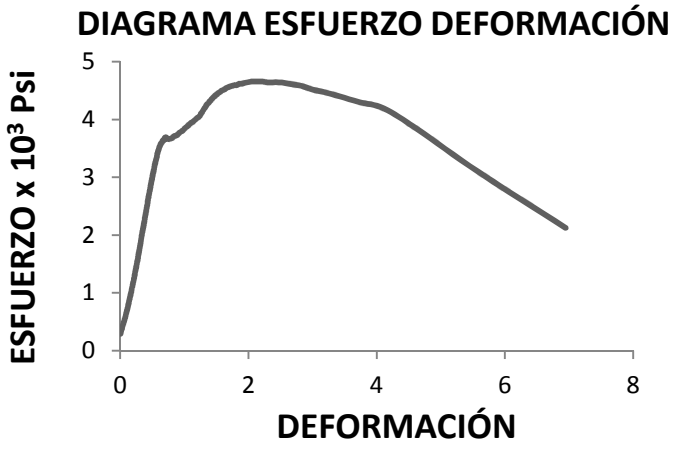
Al realizar una inspección visual en la superficie de la probeta P-2 sobre un área de 1 cm^2, podemos observar 8 poros, 2 de los cuales son más grandes que los otros.(Ver Anexo E)

ENSAYO A TRACCIÓN

DATOS INFORMATIVOS	
Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 3	**Ensayo en P - 3:** 1 / 4
Material : Aluminio	**Elemento reductor :** Azufre 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO	
Norma : ASTM	**Designación :** E-08
Probeta : Cilíndrica	**Espécimen :** No. 1

RESULTADOS DEL ENSAYO	
Longitud de estudio : 50mm	**Sección de estudio :** 120,6 mm^2
Esfuerzo fluencia : 26MPa/3,8 $x10^3$Psi	**Carga máxima :** 3812N/ 857Lbf
Resistencia tracción : 32MPa/4,6 $x10^3$Psi	**Módulo de elasticidad :** 41,4GPa/6000 $x10^3$Psi
% Elongación en 50mm : 6,9	



RESULTADOS: El ensayo a tracción realizado en la probeta P-3; de aluminio con Azufre como elemento reductor; nos ha permitido obtener un esfuerzo de fluencia de 3,8 x 10^3 Psi y una ductilidad de 6,9%. Los valores para obtener el gráfico Esfuerzo vs. Deformación de la probeta P-3 se encuentran tabulados en el Anexo B-4.

ENSAYO DE DUREZA

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 3	**Ensayo en P - 3** : 2 / 4
Material : Aluminio	**Elemento reductor :** Azufre 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

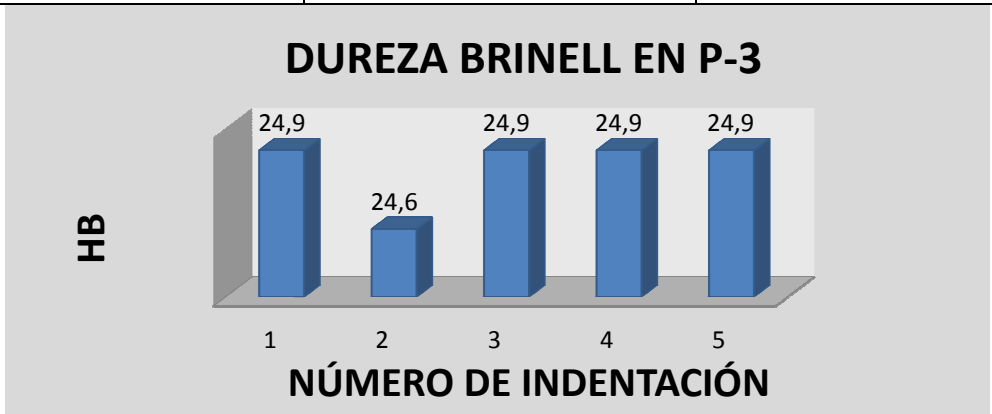
DATOS PARA EL ENSAYO

Dureza : Brinell		
Norma : ASTM	**Designación :** E-10	**Espesor Probeta:** 20mm
Carga : 613N/62,5Kgf	**Tiempo de indentación :** 15 s	**Ø del indentador :** 5 mm

RESULTADOS DEL ENSAYO

No. De indentación	Ø de la indentación (mm)	Dureza (HB)
1	1,78	24,9
2	1,79	24,6
3	1,78	24,9
4	1,78	24,9
5	1,78	24,9

Mínimo : 24,6HB	**Máximo :** 24,9HB	**Dureza :** 24,9 HB



RESULTADOS:

Luego de haber realizado 5 indentaciones sobre la probeta P-3, que es una fundición de aluminio con Azufre como elemento reductor; se tuvo un diámetro promedio de indentación igual a 1,78 mm que da una dureza de 24,9 HB.(Ver Anexo C-4).

ENSAYO METALOGRÁFICO

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 3	**Ensayo en P - 3** : 3 / 4
Material : Aluminio	**Elemento reductor :** Azufre 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO

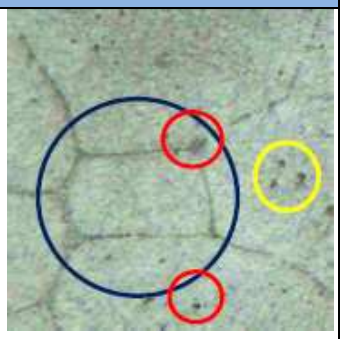
Norma : ASTM	**Designación :** E-112
Pulido : Mecánico	
Reactivo : Ácido hidrofluórico	**Tiempo ataque :** 11 s

RESULTADOS DEL ENSAYO

N ins = 1 *N int = 5*

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$
$$N_{AE} = 2\left(1 + \frac{5}{2}\right)$$
$$N_{AE} = 7$$

$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$
$$G = 1{,}000 + 3{,}3219 \log 7$$
$$\boldsymbol{G = 3{,}8}$$



Tamaño de grano : 3,8

Aluminio con azufre (reductor) a 100X, atacado con Ácido hidrofluórico durante 11 s.

- POROSIDAD
- GRANO
- INCLUSION

RESULTADOS:

El ensayo microestructural realizado en la probeta P-3 de aluminio con Azufre como elemento reductor determinó un tamaño de grano de 3,8 según la norma ASTM E-112; el mismo que se considera un grano grueso.(ver Anexo D-4).

ÍNDICE DE POROSIDAD

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 3	**Ensayo en P - 3** : 4 / 4
Material : Aluminio	**Elemento reductor :** Azufre 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

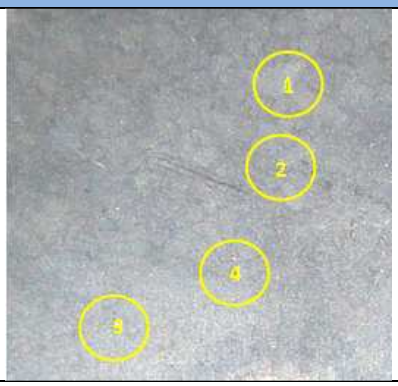
DATOS PARA EL ENSAYO

Para determinar la porosidad superficial del material tomamos como referencia la probeta utilizada en el ensayo metalográfico, la superficie pulida de la probeta ayuda a visualizar de mejor manera el índice de porosidad, en la que se tomará como referencia un cuadrado de 0,4 cm de lado; el mismo que da una superficie para inspección visual de $0{,}16 cm^2$.

RESULTADOS DEL ENSAYO

Imagen de la probeta metalográfica P-3 para realizar la inspección visual

Escala 1:15



Conteo de poros en la superficie de la probeta metalográfica P-3

Escala 1:15

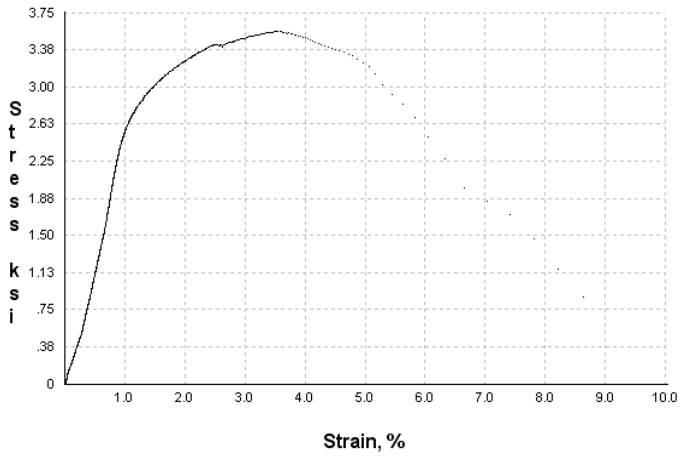
Superficie de estudio : $0{,}16 cm^2$	**Número de poros :** 4

RESULTADOS:

Al realizar una inspección visual en la superficie de la probeta P-3 sobre un área de $0{,}16\ cm^2$, podemos observar 4 poros de pequeñas dimensiones (Ver Anexo E).

ENSAYO A TRACCIÓN

DATOS INFORMATIVOS	
Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 4	**Ensayo en P - 4:** 1 / 4
Material : Aluminio	**Elemento reductor :** Fosfato de calcio5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno
DATOS PARA EL ENSAYO	
Norma : ASTM	**Designación :** E-08
Probeta : Cilíndrica	**Espécimen :** No. 1
RESULTADOS DEL ENSAYO	
Longitud de estudio : 50mm	**Sección de estudio :** 119,6 mm^2
Esfuerzo fluencia : 22MPa/3,3 $x10^3$Psi	**Carga máxima :** 3016N/ 678Lbf
Resistencia tracción : 25MPa/3,6 $x10^3$Psi	**Módulo de elasticidad :** 42MPa/6100 $x10^3$Psi
% Elongación en 50mm : 5,4	



RESULTADOS: El ensayo a tracción realizado en la probeta P-4; de aluminio con Fosfato de calcio como elemento reductor; nos ha permitido obtener un esfuerzo de fluencia a 3,3 x 10^3 Psi y una de ductilidad 5,4%. Los valores para obtener el gráfico Esfuerzo vs. Deformación de la probeta P-4 se encuentran tabulados en el Anexo B-5.

ENSAYO DE DUREZA

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 4	**Ensayo en P - 4** : 2 / 4
Material : Aluminio	**Elemento reductor :** Fosfato de calcio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

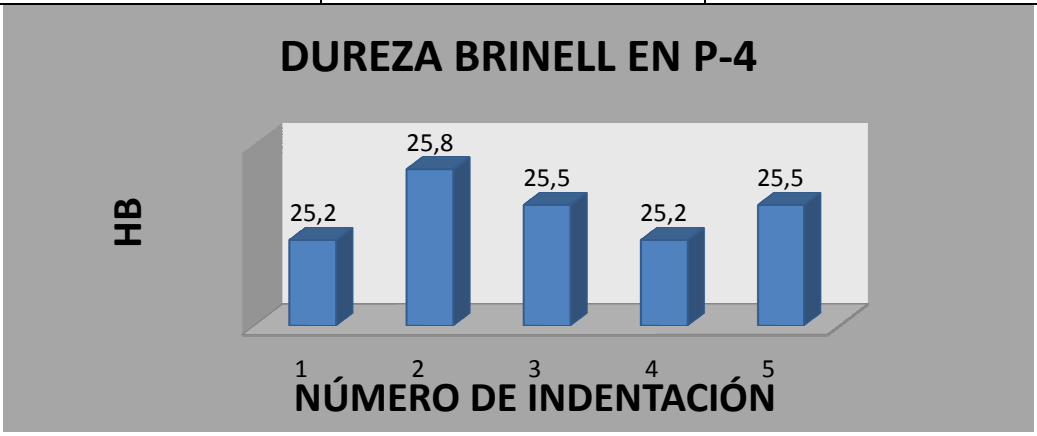
DATOS PARA EL ENSAYO

Dureza : Brinell		
Norma : ASTM	**Designación :** E-10	**Espesor Probeta:** 20mm
Carga : 613N/62,5Kgf	**Tiempo de indentación :** 15 s	**Ø del indentador :** 5 mm

RESULTADOS DEL ENSAYO

No. De indentación	Ø de la indentación (mm)	Dureza (HB)
1	1,77	25,2
2	1,75	25,8
3	1,76	25,5
4	1,77	25,2
5	1,76	25,5

Mínimo : 25,2HB	**Máximo :** 25,8HB	**Dureza :** 25,4 HB



RESULTADOS:

Luego de haber realizado 5 indentaciones sobre la probeta P-4, que es una fundición de aluminio con fosfato de calcio como elemento reductor; se tuvo un diámetro promedio de indentación igual a 1,76 mm que da una dureza de 25,4 HB.(Ver Anexo C-5).

ENSAYO METALOGRÁFICO

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 4	**Ensayo en P - 4** : 3 / 4
Material : Aluminio	**Elemento reductor :** Fosfato de calcio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO

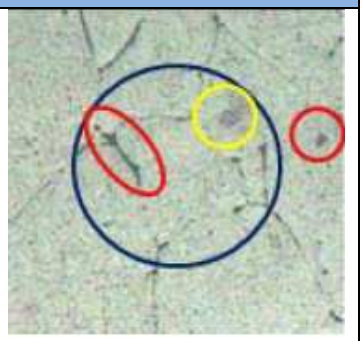
Norma : ASTM	**Designación :** E-112
Pulido : Mecánico	
Reactivo : Ácido hidrofluórico	**Tiempo ataque :** 10 s

RESULTADOS DEL ENSAYO

N ins = 1 *N ins = 8*

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$
$$N_{AE} = 2\left(1 + \frac{8}{2}\right)$$
$$N_{AE} = 10$$

$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$
$$G = 1{,}000 + 3{,}3219 \log 10$$
$$\boldsymbol{G = 4{,}3}$$



Tamaño de grano : 4,3

Aluminio con fosfato de calcio (reductor) a 100X, atacado con Ácido hidrofluórico durante 10 s.

- POROSIDAD
- GRANO
- INCLUSION

RESULTADOS:

El ensayo microestructural realizado en la probeta P-4 de aluminio con Fosfato de calcio como elemento reductor determinó un tamaño de grano de 4,3 según la norma ASTM E-112; el mismo que se considera un grano medio.(ver Anexo D-5)

ÍNDICE DE POROSIDAD

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 4	**Ensayo en P - 4** : 4 / 4
Material : Aluminio	**Elemento reductor :** Fosfato de calcio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO

Para determinar la porosidad superficial del material tomamos como referencia la probeta utilizada en el ensayo metalográfico, la superficie pulida de la probeta ayuda a visualizar de mejor manera el índice de porosidad, en la que se tomará como referencia un cuadrado de 1 cm de lado; el mismo que da una superficie para inspección visual de 1 cm^2.

RESULTADOS DEL ENSAYO

Imagen de la probeta metalográfica P-4 para realizar la inspección visual

Escala 1:5

Conteo de poros en la superficie de la probeta metalográfica P-4

Escala 1:5

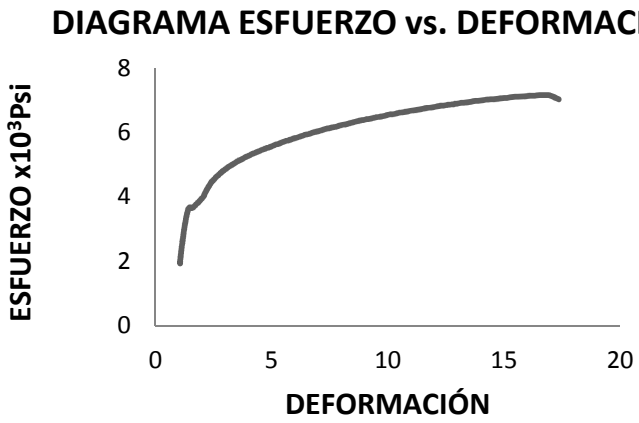
Superficie de estudio : 1cm^2	**Número de poros :** 4

RESULTADOS:

Al realizar una inspección visual en la superficie de la probeta P-4 sobre un área de 1 cm^2, podemos observar 4 poros. (Ver Anexo E).

ENSAYO A TRACCIÓN

DATOS INFORMATIVOS	
Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 5	**Ensayo en P - 5** : 1 / 4
Material : Aluminio	**Elemento reductor :** Nitrito de sodio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno
DATOS PARA EL ENSAYO	
Norma : ASTM	**Designación :** E-08
Probeta : Cilíndrica	**Especimen :** No. 1
RESULTADOS DEL ENSAYO	
Longitud de estudio : 50mm	**Sección de estudio :** 122,3 mm^2
Esfuerzo fluencia : 25MPa/3,6 $x10^3$Psi	**Carga máxima :** 5943N/ 1336Lbf
Resistencia tracción : 49MPa/7 $x10^3$Psi	**Módulo de elasticidad :** 55,1GPa/10000 $x10^3$Psi
% Elongación en 50mm : 16,6	



RESULTADOS: El ensayo a tracción realizado en la probeta P-5; de aluminio con Nitrito de sodio como elemento reductor; nos ha permitido obtener un esfuerzo de fluencia de 3,6 x 10^3 Psi y una ductilidad de 16,6%. Los valores para obtener el gráfico Esfuerzo vs. Deformación de la probeta P-5 se encuentran tabulados en el Capítulo 6 (Página 90).

ENSAYO DE DUREZA

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 5	**Ensayo en P - 5** : 2 / 4
Material : Aluminio	**Elemento reductor :** Nitrito de sodio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

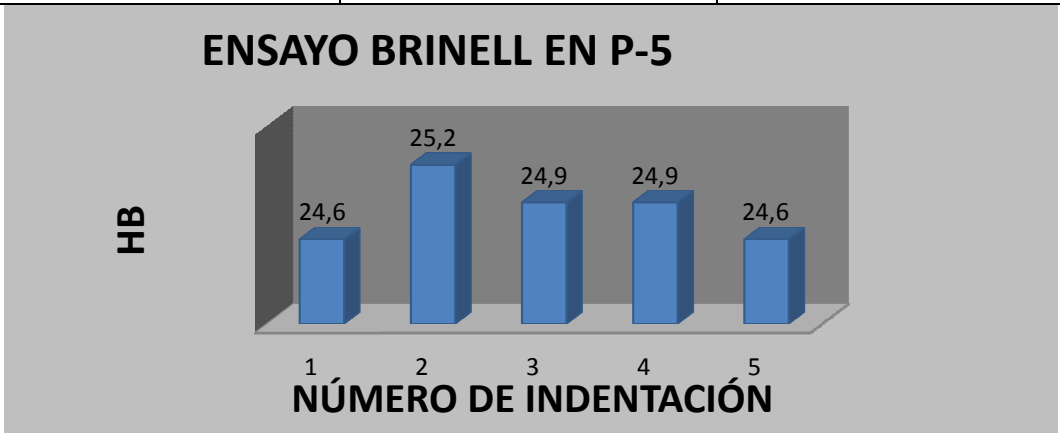
DATOS PARA EL ENSAYO

Dureza : Brinell		
Norma : ASTM	**Designación :** E-10	**Espesor Probeta:** 20 mm
Carga : 613N/62,5Kgf	**Tiempo de indentación :** 15 s	**Ø del indentador :** 5 mm

RESULTADOS DEL ENSAYO

No. De indentación	Ø de la indentación (mm)	Dureza (HB)
1	1,79	24,6
2	1,77	25,2
3	1,78	24,9
4	1,78	24,9
5	1,79	24,6

Mínimo : 24,6 HB	**Máximo :** 25,2 HB	**Dureza :** 24,9 HB



RESULTADOS:

Luego de haber realizado 5 indentaciones sobre la probeta P-5, que es una fundición de aluminio con nitrito de sodio como elemento reductor; se tuvo un diámetro promedio de indentación igual a 1,78 mm que da una dureza de 24,9 HB. Ver Capítulo 6 (Página 96).

ENSAYO METALOGRÁFICO

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 5	**Ensayo en P - 5** : 3 / 4
Material : Aluminio	**Elemento reductor :** nitrito de sodio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO

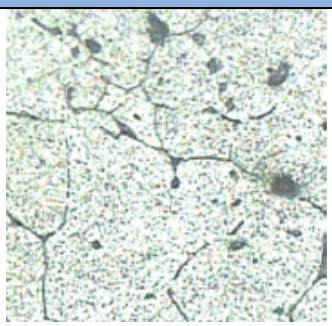
Norma : ASTM	**Designación :** E-112
Pulido : Mecánico	
Reactivo : Ácido hidrofluórico	**Tiempo ataque :** 10 s

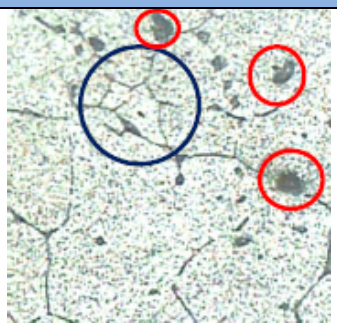
RESULTADOS DEL ENSAYO

N ins = 3 *N int = 9*

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$
$$N_{AE} = 2\left(3 + \frac{9}{2}\right)$$
$$N_{AE} = 15$$

$$G = 1{,}000 + 3{,}3219\, log\, N_{AE}$$
$$G = 1{,}000 + 3{,}3219\, log\, 15$$
$$\boldsymbol{G = 4{,}9}$$





Tamaño de grano : 4,9

Aluminio a 100X, atacado con Ácido hidrofluórico durante 10 s.

- POROSIDAD
- GRANO
- INCLUSION

RESULTADOS:

El ensayo microestructural realizado en la probeta P-5 de aluminio con Nitrito de sodio como elemento reductor determinó un tamaño de grano de 4,9 según la norma ASTM E-112; el mismo que se considera un grano medio. Ver Capítulo 6 (Página 97).

ÍNDICE DE POROSIDAD

DATOS INFORMATIVOS

Lugar de análisis : Lab. de materiales FICM-UTA	**Fecha:** 27 mayo 2011
Solicitado por :	**Realizado por :** Julio César Jurado
Supervisado por :	**Aprobado por :**
Probeta : P - 5	**Ensayo en P - 5** : 4 / 4
Material : Aluminio	**Elemento reductor :** Nitrito de sodio 5%
Fundido en : Arena	**Tratamiento térmico :** Ninguno

DATOS PARA EL ENSAYO

Para determinar la porosidad superficial del material tomamos como referencia la probeta utilizada en el ensayo metalográfico, la superficie pulida de la probeta ayuda a visualizar de mejor manera el índice de porosidad, en la que se tomará como referencia un cuadrado de 1 cm de lado; el mismo que da una superficie para inspección visual de 1 cm^2.

RESULTADOS DEL ENSAYO

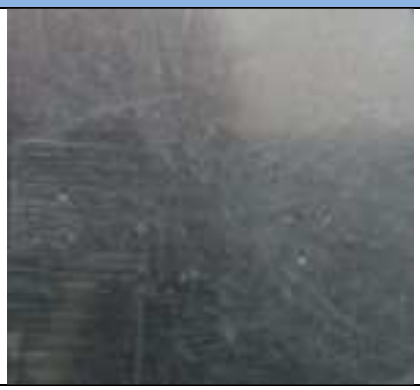


Imagen de la probeta metalográfica P-5 para realizar la inspección visual

Escala 1:5

Conteo de poros en la superficie de la probeta metalográfica P-5

Escala 1:5

Superficie de estudio : 1 cm^2	**Número de poros :** 2

RESULTADOS:

Al realizar una inspección visual en la superficie de la probeta P-5 sobre un área de 1 cm^2, se observa 2 poros de pequeñas dimensiones .Ver Capítulo 6 (Página 97).

4.2. INTERPRETACIÓN DE DATOS

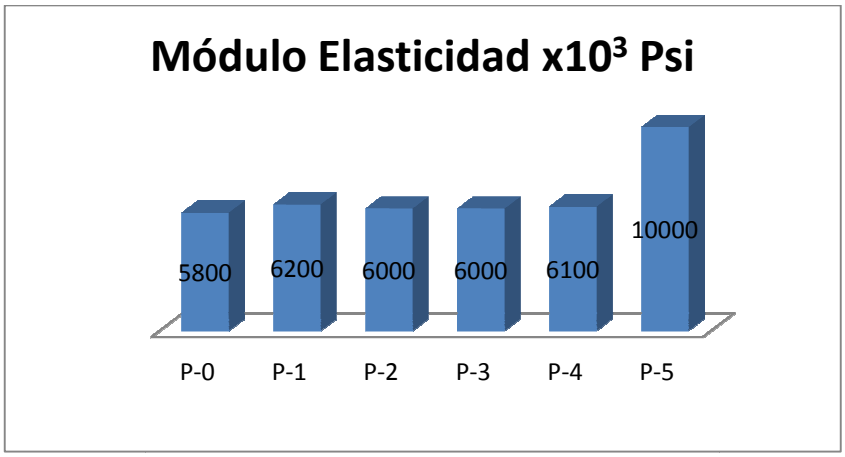


Fig No. 4.2.1 (Fuente: El Autor)

En la figura No. 4.2.1. se observa que mediante la aplicación de diferentes elementos reductores se ha logrado aumentar el módulo de elasticidad del aluminio de $5800x10^3$Psi en la probeta P-0 a $10000x10^3$Psi en la probeta P-5, es decir se ha aumentado la rigidez del material.

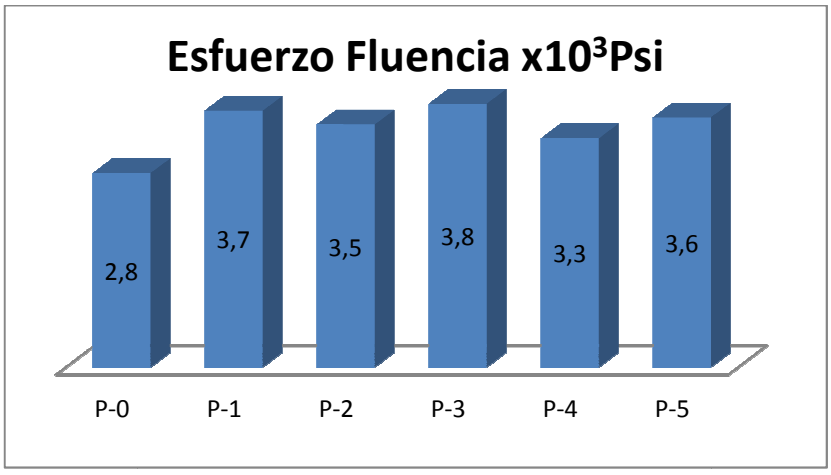


Fig No. 4.2.2. (Fuente: El Autor)

El esfuerzo de fluencia es uno de los parámetros mecánicos más importantes para el diseño en ingeniería, el mismo que se ha aumentado con todos los elementos reductores, siendo P-3 el que mejores resultados arrojó, logrando un aumento de 2,8 $x10^3$Psi en P-0 a 3,8 $x10^3$Psi en P-3, según la figura No. 4.2.2.

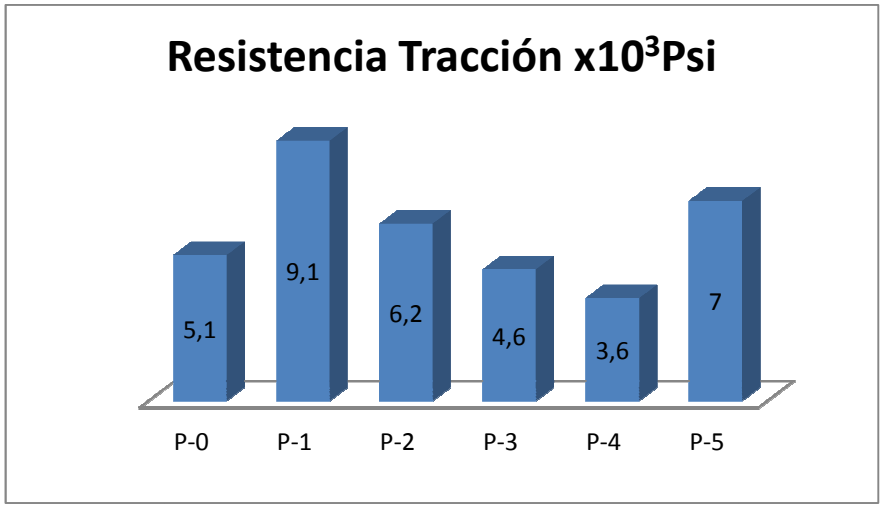


Fig No. 4.2.3. (Fuente: El Autor)

La resistencia a la tracción es el esfuerzo máximo en el diagrama Esfuerzo vs. Deformación, justamente en este valor, se forma un cuello de botella en el material denominada estricción, en la figura No. 4.2.3. se puede observar el valor obtenido con P-0 es de 5,1 x10^3Psi y con P-1 de 9,1 x10^3Psi.

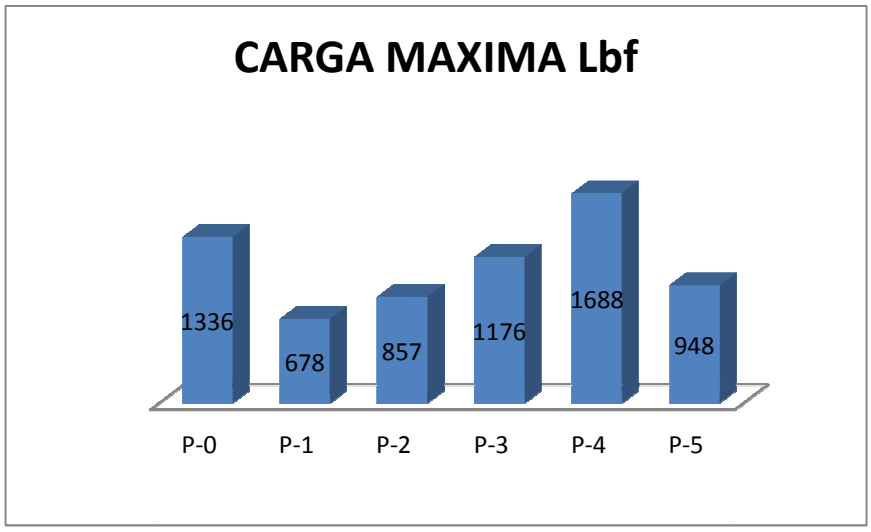


Fig No. 4.2.4. (Fuente: El Autor)

En la figura No. 4.2.4. Se visualiza que en la probeta P-0 la carga máxima registrada es de 1336 Lbf, con la probeta P-4 se registró una carga máxima a 1688 Lbf.

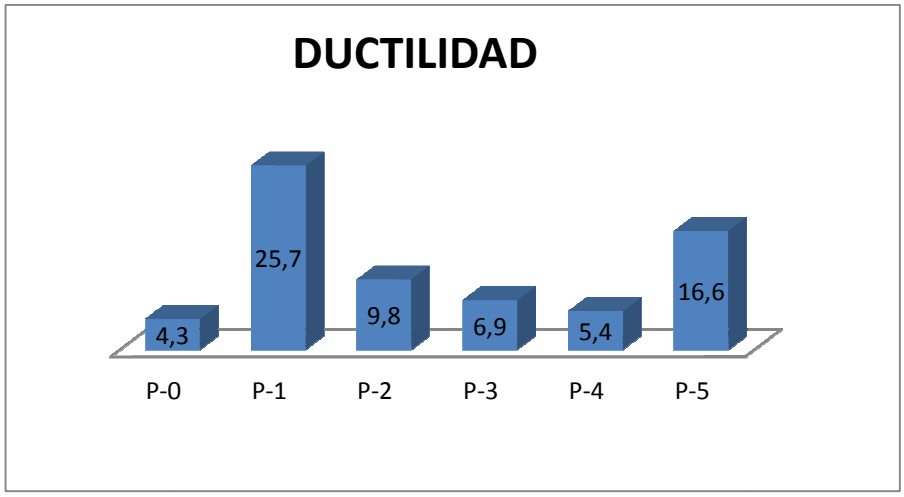


Fig No. 4.2.5. (Fuente: El Autor)

En la figura No. 4.2.5. Se observa que los valores de ductilidad han aumentado con cada elemento reductor, obteniendo una ductilidad de 25,7% en la probeta P-1.

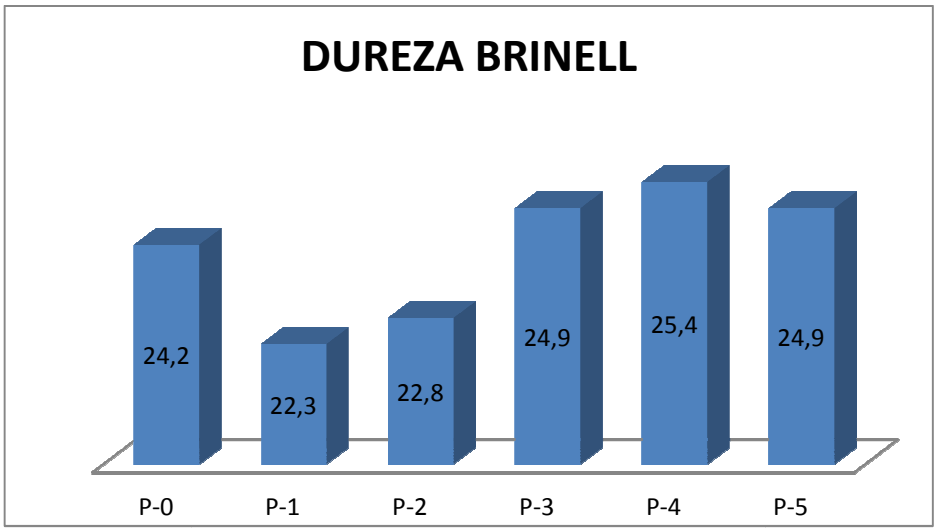


Fig No. 4.2.6. (Fuente: El Autor)

La dureza brinell es uno de los parámetros en el que no existe diferencia relativamente grande en todos los ensayos; con la probeta P-0 se obtuvo una dureza de 24,2HB, con P-1 disminuyó a 22,3HB, mientras que con P-4 se obtuvo el mayor valor de dureza 25,4HB; estos valores se pueden observar en la figura No. 4.2.6.

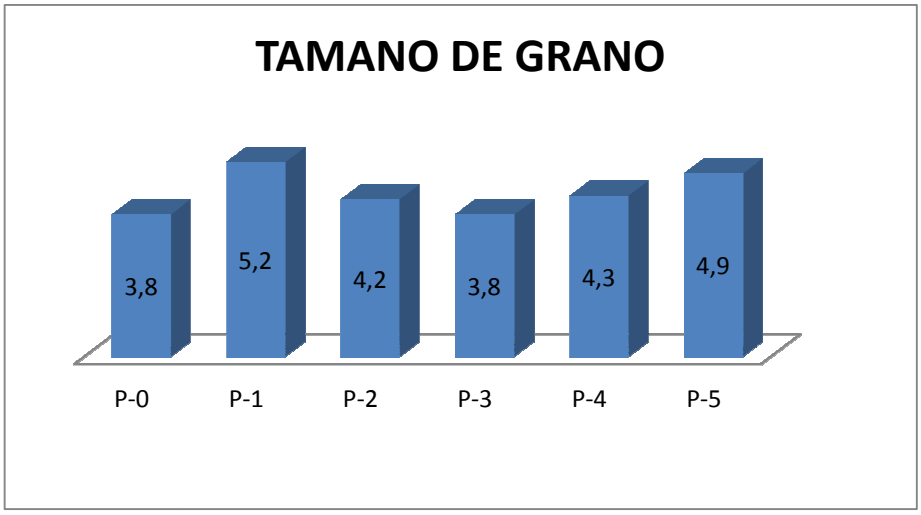
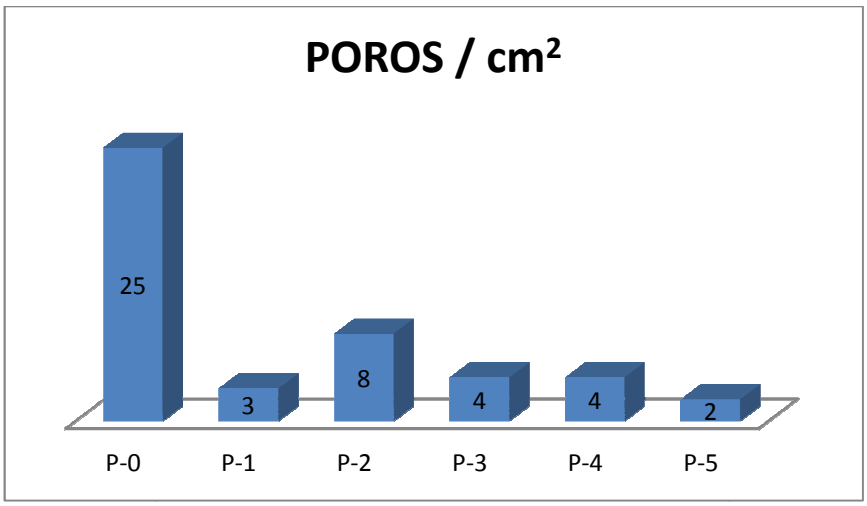


Fig No. 4.2.7. (Fuente: El Autor)

El tamaño de grano es otro de los parámetros de gran importancia para conocer las propiedades mecánicas del material, teniendo un tamaño de grano mayor se mejoran las propiedades mecánicas del material, por lo tanto con P-0 se obtuvo 3,8 y con P-1 se logró aumentar el tamaño de grano a 5,2. En la figura No. 4.2.7. Se puede observar los valores de tamaño de grano de cada probeta.



NOTA: En la probeta P-3 el índice de porosidad se lo determina sobre un área de 0,16cm^2

Fig No. 4.2.8. (Fuente: El Autor)

De la figura No.4.2.8. Concluimos que la porosidad en el aluminio se ha reducido con todos los elementos utilizados durante la fundición, siendo la probeta P-5 arrojó mejores resultados reduciendo la porosidad 2 poros/cm^2.

4.3. VERIFICACIÓN DE LA HIPÓTESIS

Con los ensayos realizados en la presente investigación se determinó que las probetas ensayadas con distintos elementos reductores como: cloruro de sodio, calcio, azufre, fosfato de calcio y nitrito de sodio han presentado una notable mejoría en las propiedades mecánicas con respecto al aluminio que no tiene ningún elemento reductor. En la figura No. 4.2.2. Observamos que el esfuerzo de fluencia ha mejorado con todos estos elementos, principalmente en las fundiciones que tiene como reductor al cloruro de sodio y azufre. En lo que respecta a la ductilidad que es otro parámetro de importancia para el diseño podemos mirar en la tabla No. 4.2.5. Que también se han aumentado los valores con respecto a P-0; obteniendo un valor máximo de 25,7% de ductilidad con la probeta P-1. Analizando la porosidad superficial del material concluimos que se ha disminuido con la aplicación de todos los elementos reductores, pero el compuesto químico con el cual se obtuvo mejores resultados es el nitrito de sodio, realizando una inspección visual sobre la superficie de la probeta P-5 la porosidad disminuyó de forma aceptable. Aunque la aplicación de los otros elementos presentaron valores mayores en algunas características mecánicas con respecto a la probeta P-5, se selecciona al **nitrito de sodio** como el compuesto más idóneo por haber reducido más que los otros elementos el índice de porosidad; comprobando la hipótesis de la investigación.

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CAPÍTULO 5
CONCLUSIONES Y RECOMENDACIONES

5.1. CONCLUSIONES

- La presente investigación ha tenido resultados positivos, mediante la selección adecuada de ciertos elementos químicos se ha logrado reducir el índice de porosidad en las fundiciones de aluminio moldeado en arena.

- Conociendo que el elemento que genera porosidad en las fundiciones de aluminio es el hidrógeno, es de vital importancia eliminar la excesiva humedad en el molde de arena, para que permita obtener una pieza fundida de calidad.

- La porosidad tiene una relación directa con las propiedades mecánicas del material, por tal motivo reduciendo el índice de porosidad se ha logrado mejorar propiedades mecánicas.

- El uso de elementos higroscópicos durante la fundición mejora las propiedades mecánicas del aluminio.

- De los compuestos químicos utilizados en los ensayos el nitrito de sodio ha permitido mejorar propiedades mecánicas como son: esfuerzo de fluencia y la ductilidad del aluminio.

5.2. RECOMENDACIONES

- Utilizar elementos de seguridad apropiados durante el proceso de fundición para evitar quemaduras y lesiones.

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- No humedecer en exceso la arena, esta debe tener un nivel determinado de humedad para darle una consistencia que permita moldear con facilidad.

- Si la arena del molde está muy húmeda, es necesario calentarlo en un horno para eliminar el exceso de humedad.

- Al momento de colar el aluminio fundido es primordial realizarlo continuamente para que no existan defectos posteriores en las piezas.

- Fabricar las probetas para ensayo a tracción con un buen acabado y acorde a las dimensiones de la norma.

- Dar un buen acabado superficial a las probetas para el ensayo de dureza con el objeto de tener una visibilidad óptima del contorno de la huella.

- Las muestras tomadas para el ensayo metalográfico deben ser pulidas de tal forma que no existan rayas en la superficie, ya que no permitirá visualizar correctamente los contornos de grano en el microscopio.

- Durante el pulido manual no se debe presionar en exceso la muestra al paño; ya que produce rayaduras y provocará que el tiempo de pulido sea demasiado extenso.

- Cuando se ataque a la muestra con ácido hidrofluórico hay que tener precaución en no quemar la muestra.

- Atacar correctamente la muestra; esta es atacada de manera adecuada cuando cambia su coloración y en el microscopio se visualiza con facilidad los contornos de grano.

- Conocer a fondo las características de los instrumentos para evitar inconvenientes durante la realización de los ensayos.

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CAPÍTULO 6
PROPUESTA

DEMOSTRAR QUE EL USO DEL NITRITO DE SODIO COMO ELEMENTO REDUCTOR DISMINUYE EL ÍNDICE DE POROSIDAD EN LA FUNDICIÓN DE ALUMINIO EN MOLDES DE ARENA.

6.1. DATOS INFORMATIVOS

El resultado de la presente investigación va a ser de beneficio para todas las personas que sientan interés por la de fundición de metales y especialmente por temas que estén relacionados con el aluminio, para estudiantes que están cursando la Carrera de Ingeniería Mecánica y deseen reforzar sus conocimientos, para las pequeñas y grandes industrias de fundición de aluminio ubicadas en la zona centro del país que busquen mejorar las características mecánicas de sus fundiciones.

La fundición al igual que el análisis y ensayos se los realizó en el Laboratorio de Materiales de la Facultad de Ingeniería Civil y Mecánica ubicados en el Campus Universitario de la Avenida los Chasquis sector de Huachi Chico.

Esta investigación consta de varios pasos a seguir para obtener resultados, los mismos son: Fundición de las piezas, maquinado de las probetas, realización de los ensayos a tracción, de dureza, análisis metalográfico, estudio del índice porosidad y procesamiento de datos obtenidos.

Después de haber ejecutado los ensayos de tracción, dureza, metalografico, haber determinado el índice de porosidad y analizado los resultados se determinó que el compuesto químico más óptimo es el nitrito de sodio; pues mejoró las propiedades mecánicas del aluminio.

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6.2. ANTECEDENTES DE LA PROPUESTA

En la Universidad Técnica de Ambato, Facultad de Ingeniería Civil y Mecánica, Carrera de Ingeniería Mecánica, no se han realizado investigaciones sobre fundición de aluminio realizando ensayos a tracción, dureza, metalográfico, y determinando el índice de porosidad utilizando nitrito de sodio durante la fundición que es un compuesto químico que se lo usa en la industria.

6.3. JUSTIFICACIÓN

Esta investigación aporta con conocimientos útiles, sencillos y poco costosos que tranquilamente pueden ser utilizados por el pequeño artesano dedicado a la fundición al igual que grandes industrias.

Existe un método técnicamente desarrollado que reduce el índice de porosidad en las fundiciones de aluminio por medio de una máquina desgasificadora, el mismo que es un proceso muy costoso y debido a la economía de nuestro país resulta difícil que empresas de fundición adquieran este tipo de máquina, y más aun el pequeño artesano que se dedica a la fundición de metales esencialmente de aluminio. Por tal motivo está completamente justificado este proyecto, el cual busca la utilización del compuesto químico nitrito de sodio [$NaNO_2$], durante la fundición, el mismo que en pequeñas cantidades es manipulable, además es poco costoso y se lo puede obtener con facilidad.

6.4. OBJETIVOS

6.4.1. OBJETIVO GENERAL

Demostrar que el uso del nitrito de sodio [$NaNO_2$] como elemento reductor disminuye el índice de porosidad en la fundición de aluminio en moldes de arena.

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6.4.2. OBJETIVOS ESPECÍFICOS

- Determinar que el uso del nitrito de sodio [$NaNO_2$] disminuye la porosidad.

- Evaluar los resultados obtenidos en los ensayos metalográfico, dureza, a tracción, e índice de porosidad en la probeta P-5.

- Comprobar que las fundiciones de aluminio realizadas han mejorado sus propiedades mecánicas.

6.5. ANÁLISIS DE FACTIBILIDAD

6.5.1. FACTIBILIDAD TECNOLÓGICA

Para el proceso de fundición no se necesita de equipos sofisticados o herramientas complejas y se lo puede realizar mediante los procedimientos básicos de fundición, se recomienda para la fundición el uso de un pirómetro, el mismo que permitirá controlar la temperatura, o utilizar un horno automático

La realización de los ensayos son complemento para esta investigación, y para realizarlos se necesitan máquinas específicas para cada uno de ellos como son: la máquina universal para el ensayo a tracción, el durómetro para el ensayo de dureza, y todo el equipo para el análisis metalográfico.

6.5.2. FACTIBILIDAD ECONÓMICA

La tabla No. 6.1. Nos presenta el detalle de todos los elementos necesarios para realizar los ensayos, el valor total de materiales y uso de equipos es algo costoso, cabe recalcar que gracias a la Facultad de Ingeniería Civil y Mecánica se pudo realizar los ensayos de cada probeta sin costo alguno en el Laboratorio de Materiales, por tal motivo se puede decir que es un proyecto económicamente realizable.

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TABLA No. 6.1. Costos para una probeta

NUMERO	PROCESO	ELEMENTOS USADOS	CANTIDAD	COSTO (USD)
1	FUNDICIÓN	Aluminio	500gr	2,00
		Nitrito de sodio	25gr	4,00
2	MOLDEO	Caja para moldeo	1	10,00
		Arena	12 kg	50,00
		Tamiz	1	10,00
		Accesorios de moldeo	-	10,00
3	MAQUINADO	Probeta ensayo a tracción	1	20,00
		Probeta ensayo dureza	1	10,00
4	DESBASTE PROBETA METALOGRÁFICA	LIJAS No. 240	1 pliego	0,60
		LIJAS No. 320	1 pliego	0,60
		LIJAS No. 600	1 pliego	0,60
		LIJAS No. 1000	1 pliego	0,60
5	PULIDO PROBETA METALOGRÁFICA	Paño metalográfico	$0,5m^2$	6,00
		Alúmina	10 gr	3,00
6	ATAQUE QUÍMICO	Reactivo Acido hidrofluorihídrico	1 ml	0,60
7	ANÁLISIS			15,00
8	PRESENTACIÓN DEL INFORME FINAL			10,00
			TOTAL:	**153,00**

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6.5.3. FACTIBILIDAD AMBIENTAL

El compuesto químico nitrito de sodio usado como reductor en la fundición no representa peligro para el medio ambiente debido a que se lo usa en pequeñas cantidades, y aunque el manejo de este compuesto químico en pequeñas cantidades no represente un riesgo para la salud; la persona que trabaje con nitrito de sodio deberá utilizar los medios de protección necesarios como: mascarillas, gafas, guantes.

6.5.4. FACTIBILIDAD LEGAL

Todos los ensayos han sido realizados bajo las siguientes normas:

- ASTM E-08 método estándar para ensayos de tensión en materiales metálicos
- ASTM E-10 método estándar para ensayo de dureza brinell en materiales metálicos
- ASTM E-112 método estándar para determinar el tamaño de grano.

6 .6. METODOLOGÍA

El proceso que ha permitido obtener los resultados más satisfactorios reduciendo la porosidad en las fundiciones de aluminio consta de varios pasos a seguir los cuales detallamos a continuación:

El primer paso es la obtención del material base, el cual será el aluminio utilizado en las redes de distribución eléctrica, el mismo que es seleccionado por ser el más puro que podemos conseguir en nuestro medio, ya que no contiene tantos elementos aleantes.

`

FIG N^{o} 6.6.1. Aluminio. (Fuente: El Autor)

El siguiente paso es clasificar el aluminio, eliminando aquellos que contengan elementos considerados como impurezas y que pueden generar problemas durante la fundición, en caso de ser necesario se deberá secar el aluminio para eliminar el exceso de humedad.

Otro paso es la preparación de la arena, la cual consiste en tamizarla para obtener una arena muy fina que permitirá dar un acabado superficial bueno a la pieza fundida para lo cual utilizaremos un tamizador con malla fina. Después del tamizado es necesario agregar una cantidad suficiente de agua que permita moldear la arena en la caja con facilidad, hay que tener en cuenta de no humedecer excesivamente la arena.

FIG N^{o} 6.6.2. Arena para moldeo. (Fuente: [11])

Después de haber preparado la arena se procede a confeccionar el molde, esto se lo realiza en una caja, la misma que consta de dos partes que encajan embonan entre sí, entonces ubicamos el modelo (que tiene la forma de la pieza que obtendremos de la fundición) en el interior de la caja y comenzamos a poner la arena hasta llenarla la caja.

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FIG N^{o} 6.6.3. Caja para moldeo. (Fuente: El Autor)

Luego ubicamos la otra parte de la caja añadiendo los bebederos cerca del modelo y vamos agregando arena hasta llenar el molde. A medida que vamos poniendo arena dentro de la caja es necesario ir compactándola para evitar que existan espacios vacíos, ya que estos al final podrían causar el deterioro del molde de arena y se debería volver a repetir esta operación. Finalmente retiramos los bebederos y el modelo del molde de madera.

FIG N^{o} 6.6.4. Molde terminado. (Fuente: El Autor)

Procedemos a eliminar la humedad de la arena moldeada, para lo cual dejamos secar el molde en un horno; el tiempo de secado variará según la cantidad de agua que se

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puso para moldear, pero el tiempo estimado para secado será de una hora y media a dos. Una vez secado completamente el molde comenzamos la fundición del aluminio con la ayuda de un pequeño quemador o un horno, la cantidad de aluminio que ubicamos dentro del crisol es aproximadamente 500gr; con el uso de un pirómetro vamos controlando la temperatura en la que se encuentra el aluminio dentro del crisol, al momento que la temperatura del aluminio sea 670 grados centígrados agregamos 25 gr de nitrito de sodio mezclamos bien, sacamos las impurezas y procedemos a colar el material en los moldes.

FIG N^{o} 6.6.5. Fundición del Aluminio. (Fuente: El Autor)

El colado del aluminio en el molde de arena también es un paso fundamental; debido a que si no lo realizamos correctamente la pieza fundida tendrá defectos como: vacíos, rechupes, por tal motivo este paso se lo debe realizar de manera que el aluminio salga continuamente del crisol en un tiempo no muy prolongado.

FIG N^{o} 6.6.6 Piezas fundidas de Aluminio. (Fuente: El Autor)

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Una vez fundidas las piezas se las maquinará de acuerdo a las formas y dimensiones que exijan las normas ASTM: E-08 para ensayo a tracción, E-10 para ensayo de dureza, y E-112 para la medición del tamaño de grano.

De todos los ensayos descritos el que se realizará primero es el de tracción, debido a que presenta el diseño más complejo de todas las probetas, se la maquinará en un torno de acuerdo a la norma ASTM E-08, espécimen N°1 de sección redonda, con rosca de ¾ de pulgada para sujeción.

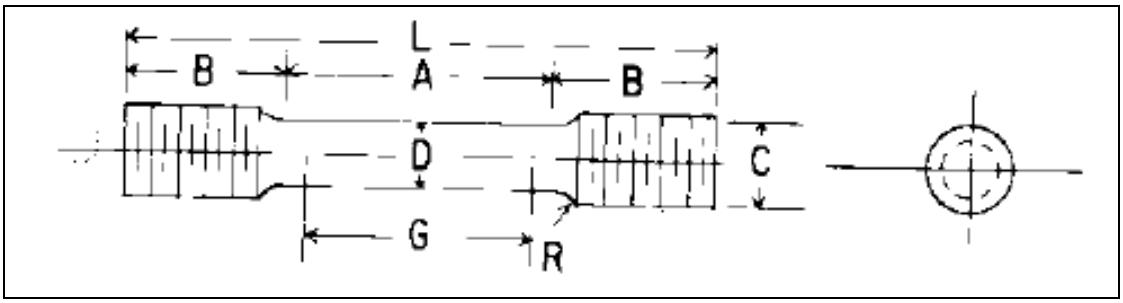

FIG N° 6.6.7. Forma probeta de ensayo a tracción según norma.
(Fuente: Norma ASTM E-08)

TABLA No. 6.2. Dimensiones de la probeta. (Fuente: El Autor)

ESPECIMEN No.1	
DESIGNACIÓN	**DIMENSION (mm)**
G	62.5
D	12.5
R	10
A	75 mínimo
L	145
B	35 aproximadamente
C	20

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FIG N^{o} 6.6.8. Probetas para los ensayo a tracción. (Fuente: El Autor)

Maquinada la probeta, la montamos en los soportes de la Máquina universal, una vez asegurada la probeta vamos aplicando cargas continuamente para obtener los valores correspondientes de esfuerzo para cada valor de carga.

FIG N^{o} 6.6.9. Ensayo a tracción. (Fuente: El Autor)

FIG N^{o} 6.6.10. Probeta ensayada. (Fuente: El Autor)

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El siguiente ensayo a realizar es de dureza, en el cual la norma ASTM E-10 no especifica una probeta; ni dimensiones determinadas, simplemente para realizar este ensayo se debe tomar en cuenta el siguiente aspecto: para evitar que el efecto de la indentación aparezca en el lado opuesto de la probeta, el espesor de ésta debe ser al menos 10 veces más que la profundidad de la indentación. Tomando en cuenta este aspecto y con la ayuda del durómetro aplicamos una carga de 613N (62,5Kgf) sobre la probeta de aluminio con una bola de acero de 5mm de diámetro durante 15 segundos. Realizado esto se procede a medir la indentación y calcular la dureza mediante la fórmula.

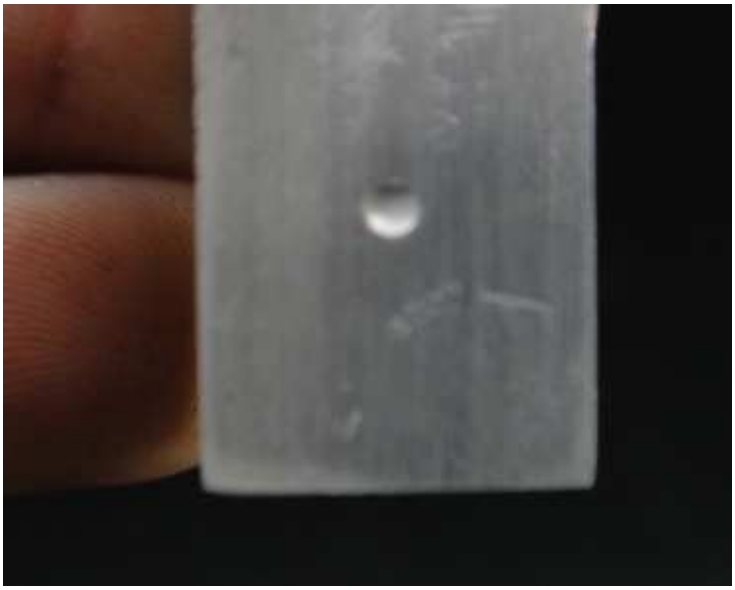

FIG N^{o} 6.6.11. Probetas para el ensayo de dureza. (Fuente: El Autor)

Para el ensayo metalográfico, realizamos la probeta con la ayuda de una máquina especialmente diseñada para esto que consta de una prensa hidráulica y unas niquelinas que proporcionan calor; alcanzando una temperatura interior de 170 ºC , luego tomamos un pedazo de aluminio y lo ponemos en el compartimiento, echamos una cantidad de baquelita y tapamos; ejercemos presión hasta tener un valor comprendido entre 2000 y 3000 P.S.I., encendemos máquina la por un periodo de 6 minutos, transcurrido este tiempo dejamos refrigerar la máquina por 2 minutos y luego sacamos la probeta para dejarla enfriar.

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FIG N^{o} 6.6.12. Máquina para montaje de la probeta de ensayo metalográfico. (Fuente: El Autor)

FIG N^{o} 6.6.13. Probetas para el ensayo metalográfico. (Fuente: El Autor)

Luego procedemos a realizar el desbaste de la muestra, en la que utilizamos lijas de de 240, 320, 600 y 1000 la primera es para desbastar las imperfecciones más acentuadas en la probeta, luego vamos avanzando con el número de lija y finalmente terminamos con la lija 1000 que dará un mejor acabado a la superficie, hay que tener en cuenta que el lijado se lo realiza en una dirección es decir de arriba hacia abajo y cuando se avanza a una lija superior hay que rotar la probeta 90 grados.

`

FIG N^{o} 6.6.14. Máquina para desbaste de la probeta. (Fuente: El Autor)

Para concluir esta etapa; el pulido fino se lo realiza en una máquina pulidora que básicamente es un disco giratorio que se lo calibra entre 250 y 300 r.p.m. y se presiona suavemente la probeta sobre el paño y se va agregando alúmina que ayuda al pulido, en este proceso hay que tener en cuenta de no presionar mucho la muestra ya que pueden aparecer rayas o sobrecalentamientos en el material los mismos que deberán ser eliminados con el uso de lijas antes mencionado.

FIG N^{o} 6.6.15. Máquina Pulido fino. (Fuente: El Autor)

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Una vez que la probeta tenga una superficie similar a un espejo esta lista para ser atacada con el reactivo Acido Hidrofluórico, esto se lo realiza durante unos segundos en este caso el tiempo de ataque fue de 10 segundos, este tiempo de ataque dependerá del material a atacar, pero se puede decir que la muestra está atacada cuando la superficie cambia de color.

FIG N^{o} 6.6.16. Elementos para ataque químico. (Fuente: El Autor)

Una vez que ha cambiado de color la muestra se lo rocía agua ó alcohol y se lo seca con flujo de aire y finalmente se podrá ubicar en el microscopio para obtener las imágenes necesarias para analizarlas.

FIG N^{o} 6.6.17. Microscopio digital. (Fuente: El Autor)

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TABULACIÓN DE RESULTADOS PROBETA P-5

ENSAYO A TRACCIÓN

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
1	369,55	1,0591	1,9495
2	366,81	1,0591	1,935
3	371,15	1,0591	1,9579
4	375,26	1,0591	1,9796
5	378,23	1,0591	1,9953
6	383,26	1,063	2,0218
7	387,14	1,065	2,0422
8	391,48	1,0669	2,0651
9	395,36	1,0709	2,0856
10	400,61	1,0728	2,1133
11	404,5	1,0748	2,1338
12	407,24	1,0807	2,1483
13	412,26	1,0827	2,1748
14	416,6	1,0866	2,1977
15	420,94	1,0906	2,2206
16	425,05	1,0945	2,2422
17	429,16	1,0984	2,2639
18	434,65	1,1024	2,2929
19	438,76	1,1043	2,3145
20	442,64	1,1102	2,335
21	447,89	1,1122	2,3627
22	452,23	1,1181	2,3856
23	459,08	1,122	2,4218
24	461,37	1,126	2,4338
25	465,94	1,1299	2,4579
26	470,5	1,1358	2,482
27	475,07	1,1398	2,5061
28	479,64	1,1457	2,5302
29	484,21	1,1496	2,5543
30	488,78	1,1516	2,5784
31	491,06	1,1575	2,5905
32	497,91	1,1594	2,6266
33	500,2	1,1654	2,6386
34	507,05	1,1693	2,6748
35	509,33	1,1752	2,6868
36	513,9	1,1791	2,7109
37	520,75	1,1831	2,7471
38	523,04	1,187	2,7591

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NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
39	527,6	1,1929	2,7832
40	532,17	1,1969	2,8073
41	536,74	1,2008	2,8314
42	541,31	1,2047	2,8555
43	545,88	1,2106	2,8796
44	550,44	1,2126	2,9037
45	555,01	1,2165	2,9278
46	559,58	1,2224	2,9519
47	564,15	1,2283	2,976
48	568,72	1,2323	3,0001
49	573,28	1,2402	3,0242
50	577,85	1,2441	3,0483
51	582,42	1,25	3,0724
52	586,99	1,2559	3,0965
53	591,56	1,2598	3,1206
54	593,84	1,2657	3,1326
55	598,41	1,2697	3,1567
56	602,98	1,2776	3,1808
57	607,54	1,2835	3,2049
58	612,11	1,2874	3,229
59	616,68	1,2933	3,2531
60	621,25	1,2992	3,2772
61	625,82	1,3051	3,3013
62	630,38	1,3091	3,3254
63	634,95	1,315	3,3495
64	639,52	1,3228	3,3736
65	641,8	1,3268	3,3857
66	646,37	1,3346	3,4098
67	650,94	1,3425	3,4339
68	655,51	1,3504	3,458
69	660,08	1,3543	3,482
70	662,36	1,3622	3,4941
71	669,21	1,372	3,5302
72	673,78	1,3799	3,5543
73	676,06	1,3878	3,5664
74	680,63	1,3957	3,5905
75	685,2	1,4016	3,6146
76	687,48	1,4134	3,6266
77	689,77	1,4232	3,6387
78	689,77	1,437	3,6387
79	692,05	1,4567	3,6507
80	696,62	1,4783	3,6748

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NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
81	692,05	1,5059	3,6507
82	692,05	1,5492	3,6507
83	694,34	1,6043	3,6628
84	701,19	1,6575	3,6989
85	708,04	1,7028	3,7351
86	714,89	1,748	3,7712
87	719,46	1,7894	3,7953
88	724,03	1,8307	3,8194
89	730,88	1,8701	3,8556
90	735,45	1,9075	3,8797
91	742,3	1,9449	3,9158
92	746,87	1,9803	3,9399
93	751,44	2,0118	3,964
94	756	2,0472	3,9881
95	762,86	2,0768	4,0242
96	769,71	2,1004	4,0604
97	776,56	2,1142	4,0965
98	781,13	2,1339	4,1206
99	785,7	2,1516	4,1447
101	790,26	2,17	4,1688
102	794,83	2,185	4,1929
103	799,4	2,2008	4,217
104	803,97	2,2146	4,2411
105	806,25	2,2323	4,2532
106	810,82	2,252	4,2773
107	815,39	2,2697	4,3014
108	819,96	2,2874	4,3255
109	826,81	2,3252	4,3616
110	831,38	2,3465	4,3857
111	835,94	2,3642	4,4098
112	840,51	2,3878	4,4339
113	845,08	2,4094	4,458
114	849,65	2,435	4,4821
115	851,93	2,4626	4,4941
116	856,5	2,4902	4,5182
117	861,07	2,5157	4,5423
118	865,64	2,5472	4,5664
119	870,2	2,5768	4,5905
120	874,77	2,6083	4,6146
121	879,34	2,6378	4,6387
122	881,62	2,6654	4,6508
123	886,19	2,7047	4,6749

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NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
124	890,76	2,7382	4,699
125	895,33	2,7717	4,7231
126	899,9	2,8071	4,7472
127	902,18	2,8445	4,7592
128	909,03	2,8799	4,7953
129	911,32	2,9154	4,8074
130	915,88	2,9547	4,8315
131	920,45	2,9941	4,8556
132	922,74	3,0335	4,8676
133	927,3	3,0748	4,8917
134	931,87	3,1142	4,9158
135	936,44	3,1575	4,9399
136	938,72	3,2028	4,952
137	943,29	3,248	4,9761
138	947,86	3,2933	5,0002
139	950,14	3,3386	5,0122
140	954,71	3,3878	5,0363
141	959,28	3,435	5,0604
142	963,85	3,4941	5,0845
143	968,42	3,5374	5,1086
144	970,7	3,5906	5,1207
145	975,27	3,6457	5,1448
146	977,55	3,6988	5,1568
147	982,12	3,7539	5,1809
148	986,69	3,8091	5,205
149	991,26	3,8681	5,2291
150	995,82	3,9252	5,2532
151	998,11	3,9764	5,2652
152	1002,68	4,0551	5,2893
153	1007,24	4,1142	5,3134
154	1011,81	4,1732	5,3375
155	1014,1	4,2323	5,3496
156	1018,66	4,311	5,3737
157	1023,23	4,3701	5,3978
158	1025,52	4,4291	5,4098
159	1030,08	4,5079	5,4339
160	1034,65	4,5866	5,458
161	1036,94	4,6457	5,4701
162	1041,5	4,7244	5,4942
163	1046,07	4,8031	5,5183
164	1048,36	4,8819	5,5303
165	1052,92	4,9606	5,5544

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NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
166	1057,49	5,0394	5,5785
167	1062,06	5,1181	5,6026
168	1066,63	5,1969	5,6267
169	1068,91	5,2756	5,6388
170	1073,48	5,3543	5,6628
171	1078,05	5,4331	5,6869
172	1082,62	5,5315	5,711
173	1087,18	5,6102	5,7351
174	1089,47	5,7087	5,7472
175	1094,04	5,7874	5,7713
176	1098,6	5,8858	5,7954
177	1103,17	5,9646	5,8195
178	1105,46	6,063	5,8315
179	1110,02	6,1614	5,8556
180	1114,59	6,2598	5,8797
181	1119,16	6,3583	5,9038
182	1123,73	6,4567	5,9279
183	1126,01	6,5551	5,94
184	1130,58	6,6535	5,9641
185	1135,15	6,752	5,9882
186	1139,72	6,8504	6,0123
187	1142	6,9488	6,0243
188	1146,57	7,0669	6,0484
189	1151,14	7,1654	6,0725
190	1155,7	7,2835	6,0966
191	1160,27	7,3819	6,1207
192	1162,56	7,5	6,1327
193	1167,12	7,6181	6,1568
194	1169,41	7,7362	6,1689
195	1173,98	7,8346	6,193
196	1178,54	7,9528	6,2171
197	1183,11	8,0709	6,2412
198	1185,4	8,2087	6,2532
199	1189,96	8,3268	6,2773
200	1194,53	8,4449	6,3014
201	1199,1	8,5827	6,3255
202	1203,67	8,7008	6,3496
203	1208,24	8,8386	6,3737
204	1210,52	8,9567	6,3858
205	1215,09	9,0945	6,4099
206	1217,37	9,2323	6,4219
207	1221,94	9,3701	6,446

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NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
208	1226,51	9,5079	6,4701
209	1228,79	9,6457	6,4822
210	1233,36	9,8031	6,5063
211	1237,93	9,9409	6,5303
212	1242,5	10,0787	6,5544
213	1244,78	10,2362	6,5665
214	1249,35	10,3937	6,5906
215	1253,92	10,5512	6,6147
216	1256,2	10,7087	6,6267
217	1260,77	10,8661	6,6508
218	1265,34	11,0236	6,6749
219	1267,62	11,1811	6,687
220	1272,19	11,3583	6,7111
221	1276,76	11,5157	6,7352
222	1281,32	11,6929	6,7593
223	1283,61	11,8701	6,7713
224	1288,18	12,0472	6,7954
225	1292,74	12,2244	6,8195
226	1295,03	12,4016	6,8316
227	1299,6	12,5984	6,8557
228	1301,88	12,7559	6,8677
229	1306,45	12,9724	6,8918
230	1311,02	13,1693	6,9159
231	1313,3	13,3661	6,928
232	1317,87	13,5827	6,9521
233	1322,44	13,7795	6,9761
234	1324,72	13,9961	6,9882
235	1329,29	14,2126	7,0123
236	1331,57	14,4291	7,0243
237	1333,86	14,6654	7,0364
238	1338,42	14,9016	7,0605
239	1340,71	15,1378	7,0725
240	1345,28	15,374	7,0966
241	1347,56	15,6102	7,1087
242	1349,84	15,8661	7,1207
243	1352,13	16,1417	7,1328
244	1354,41	16,3976	7,1448
245	1356,7	16,6929	7,1569
246	1354,41	16,9882	7,1448
247	1331,57	17,3622	7,0243

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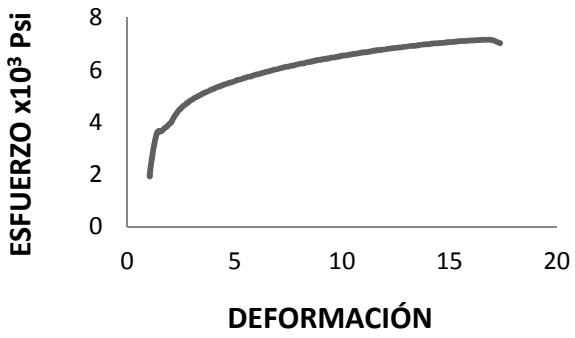
DIAGRAMA ESFUERZO VS. DEFORMACIÓN DE LA PROBETA P-5



$$\boldsymbol{E} = \frac{\sigma}{\varepsilon} = \frac{3385Ksi}{0{,}3268} = 10360 \times 10^3 \text{Psi}$$

$$\boldsymbol{Ductilidad} = \frac{lf - lo}{lo} \times 100 = \frac{58{,}3 - 50}{50} \times 100 = 16{,}6\%$$

VALORES OBTENIDOS LUEGO DEL ENSAYO A TRACCIÓN DE LA PROBETA P-5
ESFUERZO FLUENCIA: 25MPa/3,6 x10^{3}Psi
RESISTENCIA TRACCIÓN: 49MPa/7 x10^{3}Psi
MÓDULO ELASTICIDAD : 55,1GPa/10000 x10^{3}Psi
CARGA MÁXIMA : 5943N/1336lbf
% ELONGACIÓN EN 50mm :16,6

ENSAYO DE DUREZA EN P-5

F= 613N D= 5 mm d= 1,7 7 mm

$$\boldsymbol{HB} = 0{,}102 \frac{2F}{\pi D(D - \sqrt[2]{D^2 - d^2})}$$

$$\boldsymbol{HB} = 0{,}102 \frac{2 * 613}{\pi * 5(5 - \sqrt[2]{5^2 - 1{,}7\,7^{\,2}})}$$

$$\boldsymbol{HB} = 25{,}2$$

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TAMAÑO DE GRANO MÉTODO PLANIMÉTRICO EN P-5

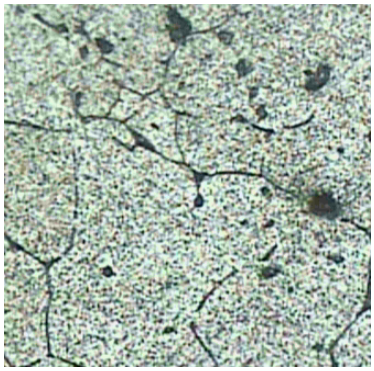
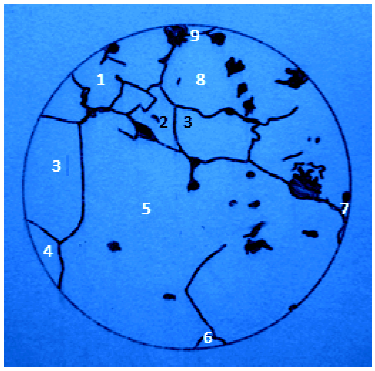


Imagen de la probeta P-5, Aluminio con nitrito de sodio como reductor a 100X, atacado con ácido hidrofluórico durante 10 s.



Conteo de granos en la Probeta P-5

Fuente: El Autor

N interceptados = 9

N internos = 3

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$

$$N_{AE} = 2\left(3 + \frac{9}{2}\right)$$

$$N_{AE} = 15$$

$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$

$$G = 1{,}000 + 3{,}3219 \log 15$$

$$G = 4{,}9$$

ÍNDICE DE POROSIDAD EN P-5

	
Imagen de la probeta metalográfica P-5 para realizar la inspección visual Escala 1:5	Conteo de poros en la superficie de la probeta metalográfica P-5 Escala 1:5
Superficie de estudio : 1 cm^2	**Número de poros :** 2

Tabla No.6.3. Cuadro comparativo de las propiedades mecánicas de las fundiciones. **(Fuente: El Autor)**

PROBETA	MÓDULO ELASTICIDAD		ESFUERZO FLUENCIA		RESISTENCIA TRACCIÓN		CARGA MÁXIMA		% DUCTILIDAD EN 50 mm	TAMAÑO GRANO G	DUREZA HB	Poros / cm^2
	GPa	x10^3 Psi	MPa	x10^3 Psi	MPa	x10^3 Psi	N	Lbf				
P-0	40	5000	19	2,8	35	5,1	4217	948	4,3	3,8	24,2	25
P-1	43	6200	26	3,7	63	9,1	7509	1688	25,7	5,2	22,3	3
P-2	41,4	6000	28	3,5	43	6,2	5231	1176	9,8	4,2	22,8	8
P-3	41,4	6000	26	3,8	32	4,6	3812	857	6,9	3,8	24,9	4
P-4	42	6100	22	3,3	25	3,6	3016	678	5,4	4,3	25,4	4
P-5	55,1	10000	25	3,6	49	7	5943	1336	16,6	4,9	24,9	2

NOTA: El índice de porosidad en las probetas se lo realizó sobre una superficie de 1cm^2 a excepción de la probeta P-3 que se ejecutó en un área de 0,16cm^2

La tabla No.6.3. Nos proporciona un resumen de los valores obtenidos de los ensayos realizados en las probetas P-0, P-1, P-2, P-3, P-4 y P-5, permitiéndonos realizar una comparación entre la probeta P-0 (fundición de aluminio sin elemento reductor) y la probeta P-5 (fundición de aluminio con nitrito de sodio como elemento reductor). Realizando una comparación del índice de porosidad sobre una superficie de $1cm^2$ entre las probetas P-0 y P-5 podemos concluir que la porosidad ha disminuido. De acuerdo a los valores de la probeta P-5 podemos determinar que cada una de las características mecánicas de esta fundición han sido mejoradas, se ha aumentado el esfuerzo de fluencia, la ductilidad, dureza y tamaño de grano con respecto a P-0. Y con los otros compuestos químicos utilizados como elementos reductores de la misma forma se han mejorado las propiedades mecánicas del aluminio a excepción de la dureza que en algunos casos ha disminuido.

6.7. ADMINISTRACIÓN

6.7.1. PLANEACIÓN

Es necesario que la persona que desee realizar estos análisis tenga conocimiento de varios aspectos con el fin de no tener inconvenientes:

- Seleccionar el aluminio con el fin de que no existen impurezas o elementos no deseados que afecten la calidad del aluminio fundido.

- Maquinar las probetas de ensayo a tracción y dureza de acuerdo a las dimensiones fijadas por la norma ASTM E08 y ASTM E-10 respectivamente.

- Realizar un pulido óptimo en la probeta para ensayo de dureza con el fin de poder observar y medir con exactitud el contorno de la huella dejada por la indentación.

- El pulido de la probeta es esencial en el ensayo metalográfico para poder observar con facilidad los contornos de los granos formados en el metal.

- Atacar la muestra es fundamental, el tiempo de ataque variará con cada una, la muestra estará atacada cuando la superficie cambie de tonalidad, si al observar en el microscopio los contornos de grano no están bien definidos; se deberá volver atacar la muestra.

6.7.2. ORGANIZACIÓN

Después de haber realizado los ensayos de varias fundiciones con distintos elementos y compuestos químicos podemos describir a continuación el proceso con el cual podemos llegar a la finalización de esta práctica.

6.7.3. DIRECCIÓN

La persona que realice esta práctica deberá tener los conocimientos suficientes sobre procedimientos de fundición, ensayos según normas ASTM y normas de seguridad, e indispensablemente deberá tener una persona que guíe y supervise cada procedimiento a realizar.

6.7.4. CONTROL

Mientras se cumpla lo dispuesto por las normas durante la fundición, ensayos; y de acuerdo a la experiencia que se vaya adquiriendo en cada proceso podremos obtener mejores resultados y de esta manera prever cualquier situación que genere conflictos para el análisis correcto de los resultados.

6.8. PREVISIÓN DE LA EVALUACIÓN

Es necesario tener presente para el desarrollo de esta práctica aspectos como: Los elementos necesarios para la fundición, el aluminio y el nitrito de sodio son fáciles de obtener en nuestro medio, de esta manera se podrá utilizar este compuesto químico como reductor, el mismo que reduce la solubilidad del hidrógeno en el aluminio.

Se podrían utilizar otros compuestos químicos para obtener resultados similares o mejores que los obtenidos con el nitrito de sodio; teniendo en cuenta siempre los efectos que pueda causar al medio ambiente y a la salud del personal que trabajará con estos compuestos químicos.

El acabado superficial de las probetas es de vital importancia para obtener resultados confiables durante los ensayos y hay que tener un cuidado muy especial en el manejo de la probeta de ensayo metalográfico puesto que cualquier imperfección, rayadura o mancha causará problemas al momento de analizarla en el microscopio. Los equipos necesarios para los ensayos deberán estar con sus calibraciones adecuadas y listas para ejecutar los ensayos.

1.-BIBLIOGRAFÍA

[1]. www.aluminioplus.com/archivo.php?dato=11

[2]. www.es.wikipedia.org/wiki/Aluminio

[3].www74.125.65.132/translate_c?hl=es&langpair=en|es&u=http://www.allbusiness.com/manufacturing/fabricated-metal-product-manufacturing/]

[4]. www.infra.com.mx/sectores/sectores/metalurgica/desgasificado_aluminio.html

[5].www.es.wikipedia.org/wiki/Aluminio

[6]. www.es.wikipedia.org

[7]. www.webpages.ull.es/users/mhdezm/nautica/traccion.pdf

[8]. www.importecnica.com.br/durometros.html

[9]. ASKELAND, Donald y PHULE, Pradeep. (2004). Ciencia e Ingeniería de los Materiales. Thompson Editores. Mexico.

[10]. www.web.fi.uba.ar/~jmoya/Metalografia.pdf

[11]. www.ilarduya.com/arenas.htm

[12]. GROOVER, Mikell. (1997). Fundamentos de manufactura moderna. Editorial Prentice-Hall Hispanoamericana. Mexico.

[13]. KALPAKJIAN, Serope y SCHMID, Steven. (2002). Manufactura ingeniería y tecnología. Cuarta Edición. Editorial Pearson Education. Mexico.

[14]. HOUSECROFT, Catherine y SHARPE, Alan. (2006). Química Inorgánica. Editorial Pearson. Madrid-España.

[15]. BURRIEL, Martí y otros. (2006).Química Analítica y Cualitativa. Editorial Paraninfo. España

[16]. NARANJO, Galo y otros. (2004). Tutoría de Investigación Científica. Producción Diemerino Editores. Segunda Edición. Quito – Ecuador.

[17]. SÁNCHEZ, María (2010). Tecnología de los materiales. Editorial Trillas. México.

[18]. Norma ASTM E-08

[19]. Norma ASTM E-10

[20]. Norma ASTM E-112

[21]. www.foros.emagister.com/tema-desgasificacion_de_alumini-13752-683015-1.htm

[22]. www.infra.com.mx/sectores/sectores/metalurgica/desgasificado_aluminio.html

[23]. www.talleriscj.com.ar/material/Mecanica/Materiales/Metales%20No%20ferrosos.pdf

[24]. www.ciasem2009.com.ar/upload_extended/ea118584__userid-13.pdf

[25]. www.biblioteca.uson.mx/digital/tesis/docs/9310/Capitulo4.pdf

[26]. www.icei.es/aleaciones.pdf

[27]. www.alu-stock.es/catalogo/cap.11_Aleaciones.pdf

[28]. www.cividino.com.ar

[29]. www.foseco.es

[30]. www.webpages.ull.es/users/mhdezm/nautica/traccion.pdf

[31]. www.importecnica.com.br/durometros.html

[32]. www.ilarduya.com/arenas.htm

ANEXOS

ANEXO A-1

NORMA ASTM E-08

Designation: E 8M – 00b
METRIC

An American National Standard

Standard Test Methods for Tension Testing of Metallic Materials [Metric][1]

This standard is issued under the fixed designation E 8M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope *

1.1 These test methods cover the tension testing of metallic materials in any form at room temperature, specifically, the methods of determination of yield strength, yield point elongation, tensile strength, elongation, and reduction of area.

NOTE 1—These test methods are the metric companion of Test Methods E 8. Committee E-28 was granted an exception in 1997 by the Committee on Standards to maintain E8 and E8M as separate companion standards rather than combining standards as recommended by the Form and Style manual.

NOTE 2—These metric test methods are essentially the same as those in Test Methods E 8, and are compatible in technical content except that gage lengths are required to be 5D for most round specimens rather than 4D as specified in Test Methods E 8. Test specimens made from powder metallurgy (P/M) materials are exempt from this requirement by industry-wide agreement to keep the pressing of the material to a specific projected area and density.

NOTE 3—Exceptions to the provisions of these test methods may need to be made in individual specifications or test methods for a particular material. For examples, see Test Methods and Definitions A 370 and Test Methods B 557M.

NOTE 4—Room temperature shall be considered to be 10 to 38°C unless otherwise specified.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

A 356/A356M Specification for Steel Castings, Carbon, Low Alloy, and Stainless Steel, Heavy-Walled for Steam Turbines[2]

A 370 Test Methods and Definitions for Mechanical Testing of Steel Products[3]

B 557M Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products [Metric][4]

E 4 Practices for Force Verification of Testing Machines[5]

E 6 Terminology Relating to Methods of Mechanical Testing[5]

E 8 Test Methods for Tension Testing of Metallic Materials[5]

E 29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications[6]

E 83 Practice for Verification and Classification of Extensometers[5]

E 345 Test Methods of Tension Testing of Metallic Foil[5]

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[6]

E 1012 Practice for Verification of Specimen Alignment Under Tensile Loading[5]

3. Terminology

3.1 *Definitions*—The definitions of terms relating to tension testing appearing in Terminology E 6 shall be considered as applying to the terms used in these test methods of tension testing. Additional terms being defined are as follows:

3.1.1 *discontinuous yielding*—a hesitation or fluctuation of force observed at the onset of plastic deformation, due to localized yielding. (The stress-strain curve need not appear to be discontinuous.)

3.1.2 *lower yield strength, LYS [FL^{-2}]*—the minimum stress recorded during discontinuous yielding, ignoring transient effects.

3.1.3 *upper yield strength, UYS [FL^{-2}]*—the first stress maximum (stress at first zero slope) associated with discontinuous yielding.

3.1.4 *yield point elongation, YPE*—the strain (expressed in percent) separating the stress-strain curve's first point of zero slope from the point of transition from discontinuous yielding to uniform strain hardening. If the transition occurs over a range of strain, the YPE end point is the intersection between (*a*) a horizontal line drawn tangent to the curve at the last zero slope and (*b*) a line drawn tangent to the strain hardening portion of the stress-strain curve at the point of inflection. If there is no point at or near the onset of yielding at which the

[1] These test methods are under the jurisdiction of ASTM Committee E28 on Mechanical Testing and are the direct responsibility of Subcommittee E28.04 on Uniaxial Testing.

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[2] *Annual Book of ASTM Standards*, Vol 01.02.

[3] *Annual Book of ASTM Standards*, Vol 01.03.

[4] *Annual Book of ASTM Standards*, Vol 02.02.

[5] *Annual Book of ASTM Standards*, Vol 03.01.

[6] *Annual Book of ASTM Standards*, Vol 14.02.

***A Summary of Changes section appears at the end of this standard.**

slope reaches zero, the material has 0 % YPE.

4. Significance and Use

4.1 Tension tests provide information on the strength and ductility of materials under uniaxial tensile stresses. This information may be useful in comparisons of materials, alloy development, quality control, and design under certain circumstances.

4.2 The results of tension tests of specimens machined to standardized dimensions from selected portions of a part or material may not totally represent the strength and ductility properties of the entire end product or its in-service behavior in different environments.

4.3 These test methods are considered satisfactory for acceptance testing of commercial shipments. The test methods have been used extensively in the trade for this purpose.

5. Apparatus

5.1 *Testing Machines*—Machines used for tension testing shall conform to the requirements of Practices E 4. The forces used in determining tensile strength and yield strength shall be within the verified force application range of the testing machine as defined in Practices E 4.

5.2 *Gripping Devices*:

5.2.1 *General*—Various types of gripping devices may be used to transmit the measured force applied by the testing machine to the test specimens. To ensure axial tensile stress within the gage length, the axis of the test specimen should coincide with the center line of the heads of the testing machine. Any departure from this requirement may introduce bending stresses that are not included in the usual stress computation (force divided by cross-sectional area).

NOTE 5—The effect of this eccentric force application may be illustrated by calculating the bending moment and stress thus added. For a standard 12.5-mm diameter specimen, the stress increase is 1.5 % for each 0.025 mm of eccentricity. This error increases to about 2.5 %/0.025 mm for a 9-mm diameter specimen and to about 3.2 %/0.025 mm for a 6-mm diameter specimen.

NOTE 6—Alignment methods are given in Practice E 1012.

5.2.2 *Wedge Grips*—Testing machines usually are equipped with wedge grips. These wedge grips generally furnish a satisfactory means of gripping long specimens of ductile metal and flat plate test specimens such as those shown in Fig. 1. If, however, for any reason, one grip of a pair advances farther than the other as the grips tighten, an undesirable bending stress may be introduced. When liners are used behind the wedges, they must be of the same thickness and their faces must be flat and parallel. For best results, the wedges should be supported over their entire lengths by the heads of the testing machine. This requires that liners of several thicknesses be available to cover the range of specimen thickness. For proper gripping, it is desirable that the entire length of the serrated face of each wedge be in contact with the specimen. Proper alignment of wedge grips and liners is illustrated in Fig. 2. For short specimens and for specimens of many materials, it is generally necessary to use machined test specimens and to use a special means of gripping to ensure that the specimens, when under load, shall be as nearly as possible in uniformly distributed pure axial tension (see 5.2.3, 5.2.4, and 5.2.5).

5.2.3 *Grips for Threaded and Shouldered Specimens and Brittle Materials*—A schematic diagram of a gripping device for threaded-end specimens is shown in Fig. 3, while Fig. 4 shows a device for gripping specimens with shouldered ends. Both of these gripping devices should be attached to the heads of the testing machine through properly lubricated spherical-seated bearings. The distance between spherical bearings should be as great as feasible.

5.2.4 *Grips for Sheet Materials*—The self-adjusting grips shown in Fig. 5 have proved satisfactory for testing sheet materials that cannot be tested satisfactorily in the usual type of wedge grips.

5.2.5 *Grips for Wire*—Grips of either the wedge or snubbing types as shown in Fig. 5 and Fig. 6 or flat wedge grips may be used.

5.3 *Dimension-Measuring Devices*—Micrometers and other devices used for measuring linear dimensions shall be accurate and precise to at least one half the smallest unit to which the individual dimension is required to be measured.

5.4 *Extensometers*—Extensometers used in tension testing shall conform to the requirements of Practice E 83 for the classifications specified by the procedure section of this test method. Extensometers shall be used and verified to include strains corresponding to the yield strength and elongation at fracture (if determined).

5.4.1 Extensometers with gage lengths equal to or shorter than the nominal gage length of the specimen (dimensions shown as “G-Gage Length” in the accompanying figures) may be used to determine the yield behavior. For specimens without a reduced section (for example, full cross sectional area specimens of wire, rod, or bar), the extensometer gage length for the determination of yield behavior shall not exceed 80 % of the distance between grips. For measuring elongation at fracture with an appropriate extensometer the gage length of the extensometer shall be equal to the nominal gage length required for the specimen being tested.

6. Test Specimens

6.1 *General*:

6.1.1 *Specimen Size*—Test specimens shall be either substantially full size or machined, as prescribed in the product specifications for the material being tested.

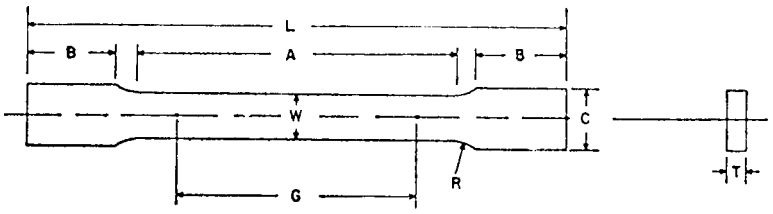
6.1.2 *Location*—Unless otherwise specified, the axis of the test specimen shall be located within the parent material as follows:

6.1.2.1 At the center for products 40 mm or less in thickness, diameter, or distance between flats.

6.1.2.2 Midway from the center to the surface for products over 40 mm in thickness, diameter, or distance between flats.

6.1.3 *Specimen Machining*—Improperly prepared test specimens often are the reason for unsatisfactory and incorrect test results. It is important, therefore, that care be exercised in the preparation of specimens, particularly in the machining, to maximize precision and minimize bias in test results.

6.1.3.1 The reduced sections of prepared specimens should be free of cold work, notches, chatter marks, grooves, gouges, burrs, rough surfaces or edges, overheating, or any other condition which may deleteriously affect the properties to be measured.



Nominal Width	Dimensions, mm		
	Standard Specimens		Subsize Specimen
	Plate-Type 40 mm	Sheet-Type 12.5 mm	6 mm
G— Gage length (Note 1 and Note 2)	200.0 ± 0.2	50.0 ± 0.1	25.0 ± 0.1
W— Width (Note 3 and Note 4)	40.0 ± 2.0	12.5 ± 0.2	6.0 ± 0.1
T— Thickness (Note 5)		thickness of material	
R— Radius of fillet, min (Note 6)	25	12.5	6
L— Overall length, (Note 2, Note 7 and Note 8)	450	200	100
A— Length of reduced section, min	225	57	32
B— Length of grip section, (Note 8)	75	50	30
C— Width of grip section, approximate (Note 4 and Note 9)	50	20	10

NOTE 1—For the 40-mm wide specimen, punch marks for measuring elongation after fracture shall be made on the flat or on the edge of the specimen and within the reduced section. Either a set of nine or more punch marks 25 mm apart, or one or more pairs of punch marks 200 mm apart, may be used.

NOTE 2—When elongation measurements of 40-mm wide specimens are not required, a minimum length of reduced section (*A*) of 75 mm may be used with all other dimensions similar to the plate-type specimen.

NOTE 3—For the three sizes of specimens, the ends of the reduced section shall not differ in width by more than 0.10, 0.05 or 0.02 mm, respectively. Also, there may be a gradual decrease in width from the ends to the center, but the width at each end shall not be more than 1 % larger than the width at the center.

NOTE 4—For each of the three sizes of specimens, narrower widths (*W* and *C*) may be used when necessary. In such cases the width of the reduced section should be as large as the width of the material being tested permits; however, unless stated specifically, the requirements for elongation in a product specification shall not apply when these narrower specimens are used.

NOTE 5—The dimension *T* is the thickness of the test specimen as provided for in the applicable material specifications. Minimum thickness of 40-mm wide specimens shall be 5 mm. Maximum thickness of 12.5-mm and 6-mm wide specimens shall be 19 mm and 6 mm, respectively.

NOTE 6—For the 40-mm wide specimen, a 13-mm minimum radius at the ends of the reduced section is permitted for steel specimens under 690 MPa in tensile strength when a profile cutter is used to machine the reduced section.

NOTE 7—The dimension shown is suggested as a minimum. In determining the minimum length, the grips must not extend in to the transition section between Dimensions A and B, see Note 9.

NOTE 8—To aid in obtaining axial force application during testing of 6-mm wide specimens, the overall length should be as large as the material will permit, up to 200 mm.

NOTE 9—It is desirable, if possible, to make the length of the grip section large enough to allow the specimen to extend into the grips a distance equal to two thirds or more of the length of the grips. If the thickness of 12.5-mm wide specimens is over 10 mm, longer grips and correspondingly longer grip sections of the specimen may be necessary to prevent failure in the grip section.

NOTE 10—For the three sizes of specimens, the ends of the specimen shall be symmetrical in width with the center line of the reduced section within 2.5, 0.25, and 0.13 mm, respectively. However, for referee testing and when required by product specifications, the ends of the 12.5-mm wide specimen shall be symmetrical within 0.2 mm.

NOTE 11—For each specimen type, the radii of all fillets shall be equal to each other within a tolerance of 1.25 mm, and the centers of curvature of the two fillets at a particular end shall be located across from each other (on a line perpendicular to the centerline) within a tolerance of 2.5 mm.

NOTE 12—Specimens with sides parallel throughout their length are permitted, except for referee testing, provided: (*a*) the above tolerances are used; (*b*) an adequate number of marks are provided for determination of elongation; and (*c*) when yield strength is determined, a suitable extensometer is used. If the fracture occurs at a distance of less than 2*W* from the edge of the gripping device, the tensile properties determined may not be representative of the material. In acceptance testing, if the properties meet the minimum requirements specified, no further testing is required, but if they are less than the minimum requirements, discard the test and retest.

FIG. 1 Rectangular Tension Test Specimens

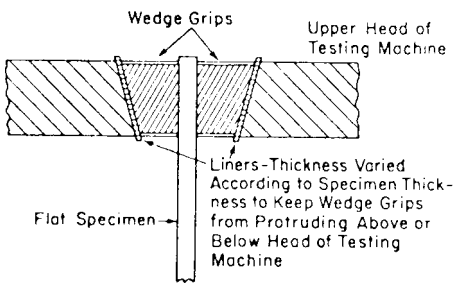


FIG. 2 Wedge Grips with Liners for Flat Specimens

NOTE 7—Punching or blanking of reduced section may produce significant cold work or shear burrs, or both, along the edges which should be removed by machining.

6.1.3.2 Within the reduced section of rectangular specimens, edges or corners should not be ground or abraded in a manner which could cause the actual cross-sectional area of the specimen to be significantly different from the calculated area.

6.1.3.3 For brittle materials, large radius fillets at the ends of the gage length should be used.

6.1.3.4 The cross-sectional area of the specimen should be smallest at the center of the reduced section to ensure fracture

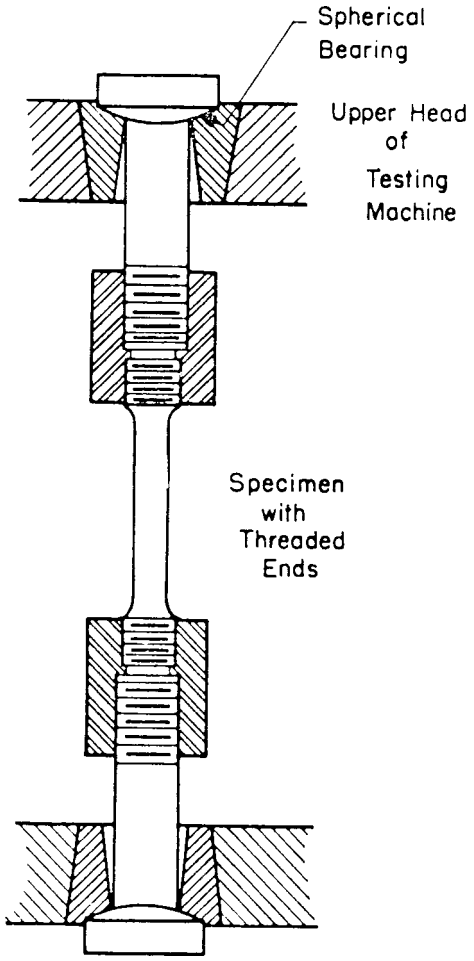


FIG. 3 Gripping Device for Threaded-End Specimens

within the gage length. For this reason, a small taper is permitted in the reduced section of each of the specimens described in the following sections.

6.1.4 *Specimen Surface Finish*—When materials are tested with surface conditions other than as manufactured, the surface finish of the test specimens shall be as provided in the applicable product specifications.

NOTE 8—Particular attention should be given to the uniformity and quality of surface finish of specimens for high strength and very low ductility materials, since this has been shown to be a factor in the variability of test results.

6.2 *Plate-Type Specimens*—The standard plate-type specimen is shown in Fig. 1. This specimen is used for testing metallic materials in the form of plate, shapes, and flat material having a nominal thickness of 5 mm or over. When product specifications so permit, other types of specimens may be used, as provided in 6.3, 6.4, and 6.5.

6.3 *Sheet-Type Specimens*:

6.3.1 The standard sheet-type test specimen is shown in Fig. 1. This specimen is used for testing metallic materials in the form of sheet, plate, flat wire, strip, band, hoop, rectangles, and shapes ranging in nominal thickness from 0.13 to 19 mm. When product specifications so permit, other types of specimens may be used as provided in 6.2, 6.4, and 6.5.

NOTE 9—Test Methods E 345 may be used for tension testing of materials in thicknesses up to 0.150 mm.

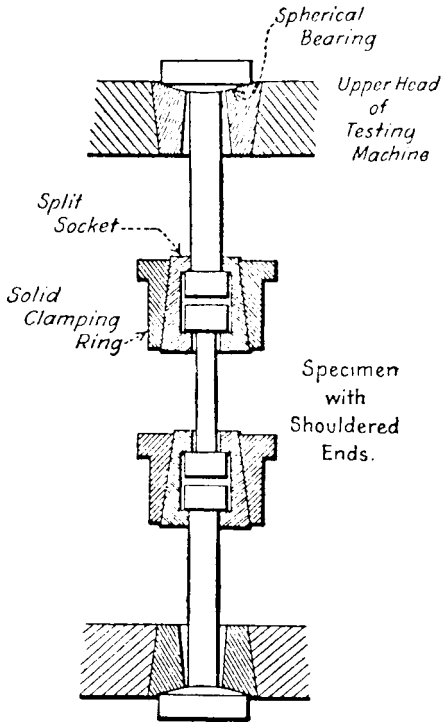


FIG. 4 Gripping Device for Shouldered-End Specimens

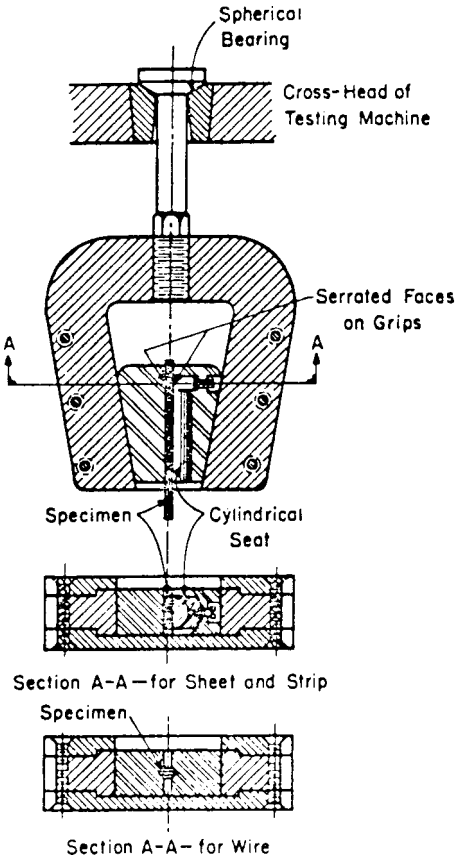


FIG. 5 Gripping Devices for Sheet and Wire Specimens

6.3.2 Pin ends as shown in Fig. 7 may be used. In order to avoid buckling in tests of thin- and high-strength materials, it

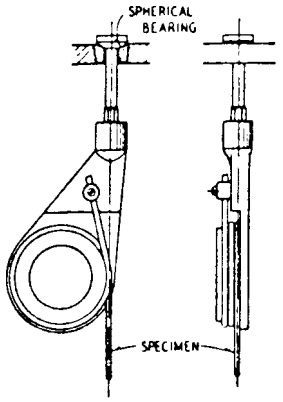


FIG. 6 Snubbing Device for Testing Wire

may be necessary to use stiffening plates at the grip ends.

6.4 *Round Specimens*:

6.4.1 The standard 12.5-mm diameter round test specimen shown in Fig. 8 is used quite generally for testing metallic materials, both cast and wrought.

6.4.2 Fig. 8 also shows small-size specimens proportional to the standard specimen. These may be used when it is necessary to test material from which the standard specimen or specimens shown in Fig. 1 cannot be prepared. Other sizes of small, round specimens may be used. In any such small-size specimen, it is important that the gage length for measurement of elongation be five times the diameter of the specimen.

6.4.3 The shape of the ends of the specimen outside of the gage length shall be suitable to the material and of a shape to fit the holders or grips of the testing machine so that the forces may be applied axially. Fig. 9 shows specimens with various types of ends that have given satisfactory results.

6.5 *Specimens for Sheet, Plate, Flat Wire, and Strip*—In testing sheet, plate, flat wire, and strip one of the following types of specimens shall be used:

6.5.1 For material ranging in nominal thickness from 0.13 to 19 mm, use the sheet-type specimen described in 6.3.

NOTE 10—Attention is called to the fact that either of the flat specimens described in 6.2 and 6.3 may be used for material from 5 to 19 mm in thickness, and one of the round specimens described in 6.4 may also be used for material 12.5 mm or more in thickness.

6.5.2 For material having a nominal thickness of 5 mm or over (Note 10), use the plate-type specimen described in 6.2.

6.5.3 For material having a nominal thickness of ½ in. or over (Note 10), use the largest practical size of specimen described in 6.4. When product specifications so permit, a sheet-type ½ in. wide specimen conforming to the geometry of Fig. 1 is appropriate, provide the T-Thickness dimension is machined to .400 in., ± .020 in. and this machined thickness is uniform within .004 in. throughout the reduced section. In the event of disagreement, referee specimens shall be the round specimen.

6.6 *Specimens for Wire, Rod, and Bar*:

6.6.1 For round wire, rod, and bar, test specimens having the full cross-sectional area of the wire, rod, or bar shall be used wherever practicable. The gage length for the measurement of elongation of wire less than 4 mm in diameter shall be as prescribed in product specifications. In testing wire, rod, or bar that has a 4 mm or larger diameter, unless otherwise specified, a gage length equal to five times the diameter shall be used. The total length of the specimens shall be at least equal to the gage length plus the length of material required for the full use of the grips employed.

6.6.2 For wire of octagonal, hexagonal, or square cross section, for rod or bar of round cross section where the specimen required in 6.6.1 is not practicable, and for rod or bar of octagonal, hexagonal, or square cross section, one of the following types of specimens shall be used:

6.6.2.1 *Full Cross Section* (Note 11)—It is permissible to reduce the test section slightly with abrasive cloth or paper, or machine it sufficiently to ensure fracture within the gage marks. For material not exceeding 5 mm in diameter or distance between flats, the cross-sectional area may be reduced to not less than 90 % of the original area without changing the shape of the cross section. For material over 5 mm in diameter or distance between flats, the diameter or distance between flats may be reduced by not more than 0.25 mm without changing the shape of the cross section. Square, hexagonal, or octagonal wire or rod not exceeding 5 mm between flats may be turned to a round having a cross-sectional area not smaller than 90 % of the area of the maximum inscribed circle. Fillets, preferably with a radius of 10 mm, but not less than 3 mm, shall be used at the ends of the reduced sections. Square, hexagonal, or octagonal rod over 5 mm between flats may be turned to a round having a diameter no smaller than 0.25 mm less than the original distance between flats.

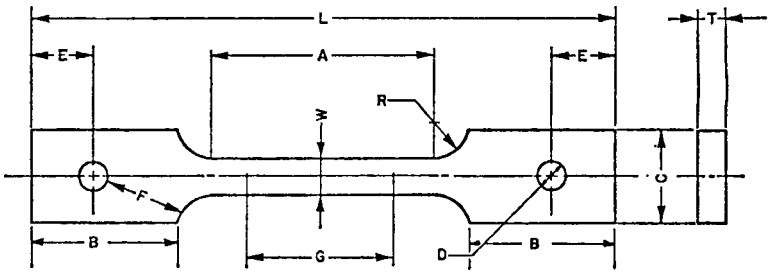
NOTE 11—The ends of copper or copper alloy specimens may be flattened 10 to 50 % from the original dimension in a jig similar to that shown in Fig. 10, to facilitate fracture within the gage marks. In flattening the opposite ends of the test specimen, care shall be taken to ensure that the four flattened surfaces are parallel and that the two parallel surfaces on the same side of the axis of the test specimen lie in the same plane.

6.6.2.2 For rod and bar, the largest practical size of round specimen as described in 6.4 may be used in place of a test specimen of full cross section. Unless otherwise specified in the product specification, specimens shall be parallel to the direction of rolling or extrusion.

6.7 *Specimens for Rectangular Bar*— In testing rectangular bar one of the following types of specimens shall be used:

6.7.1 *Full Cross Section*—It is permissible to reduce the width of the specimen throughout the test section with abrasive cloth or paper, or by machining sufficiently to facilitate fracture within the gage marks, but in no case shall the reduced width be less than 90 % of the original. The edges of the midlength of the reduced section not less than 20 mm in length shall be parallel to each other and to the longitudinal axis of the specimen within 0.05 mm. Fillets, preferably with a radius of 10 mm but not less than 3 mm, shall be used at the ends of the reduced sections.

6.7.2 Rectangular bars of thickness small enough to fit the grips of the testing machine but of too great width may be reduced in width by cutting to fit the grips, after which the cut surfaces shall be machined or cut and smoothed to ensure failure within the desired section. The reduced width shall be not less than the original bar thickness. Also, one of the types of specimens described in 6.2, 6.3, and 6.4 may be used.



Dimensions, mm	
G— Gage length	50.0 ± 0.1
W— Width (Note 1)	12.5 ± 0.2
T— Thickness, max (Note 2)	12.5
R— Radius of fillet, min (Note 3)	13
L— Overall length, min	200
A— Length of reduced section, min	57
B— Length of grip section, min	50
C— Width of grip section, approximate	50
D— Diameter of hole for pin, min (Note 4)	13
E— Edge distance from pin, approximate	40
F— Distance from hole to fillet, min	15

NOTE 1—The ends of the reduced section shall differ in width by not more than 0.1 mm. There may be a gradual taper in width from the ends to the center, but the width at each end shall be not more than 1 % greater than the width at the center.

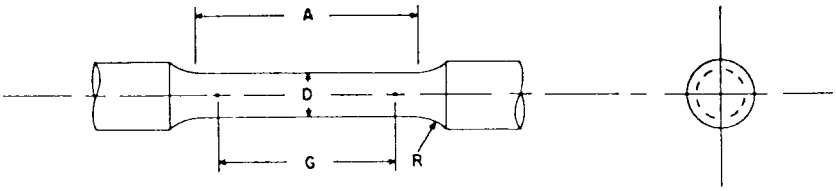
NOTE 2—The dimension *T* is the thickness of the test specimen as stated in the applicable product specifications.

NOTE 3—For some materials, a fillet radius *R* larger than 13 mm may be needed.

NOTE 4—Holes must be on center line of reduced section, within ± 0.1 mm.

NOTE 5—Variations of dimensions *C*, *D*, *E*, *F*, and *L* may be used that will permit failure within the gage length.

FIG. 7 Pin-Loaded Tension Test Specimen with 50-mm Gage Length



Dimensions, mm					
	Standard Specimen	Small-Size Specimens Proportional To Standard			
	12.5	9	6	4	2.5
G—Gage length	62.5 ± 0.1	45.0± 0.1	30.0 ± 0.1	20.0± 0.1	12.5 ± 0.1
D—Diameter (Note 1)	12.5 ± 0.2	9.0 ± 0.1	6.0 ± 0.1	4.0 ± 0.1	2.5 ± 0.1
R—Radius of fillet, min	10	8	6	4	2
A—Length of reduced section, min (Note 2)	75	54	36	24	20

NOTE 1—The reduced section may have a gradual taper from the ends toward the center, with the ends not more than 1 % larger in diameter than the center (controlling dimension).

NOTE 2—If desired, the length of the reduced section may be increased to accommodate an extensometer of any convenient gage length. Reference marks for the measurement of elongation should, nevertheless, be spaced at the indicated gage length.

NOTE 3—The gage length and fillets shall be as shown, but the ends may be of any form to fit the holders of the testing machine in such a way that the load may be axial (see Fig. 9). If the ends are to be held in wedge grips it is desirable, if possible, to make the length of the grip section great enough to allow the specimen to extend into the grips a distance equal to two thirds or more of the length of the grips.

NOTE 4—On the round specimens in Figs. 8 and 9, the gage lengths are equal to five times the nominal diameter. In some product specifications other specimens may be provided for, but the 5-to-1 ratio is maintained within dimensional tolerances, the elongation values may not be comparable with those obtained from the standard test specimen.

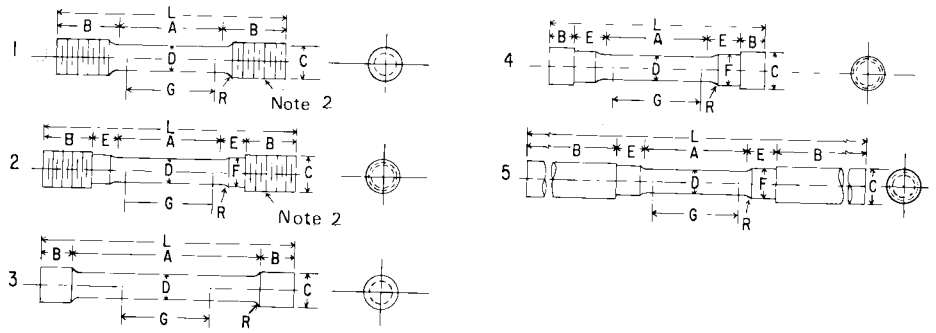
NOTE 5—The use of specimens smaller than 6 mm in diameter shall be restricted to cases when the material to be tested is of insufficient size to obtain larger specimens or when all parties agree to their use for acceptance testing. Smaller specimens require suitable equipment and greater skill in both machining and testing.

FIG. 8 Standard 12.5-mm Round Tension Test Specimen with Gage Lengths Five Times the Diameters (5D), and Examples of Small-Size Specimens Proportional to the Standard Specimen

6.8 *Shapes, Structural and Other*—In testing shapes other than those covered by the preceding sections, one of the types of specimens described in 6.2, 6.3, and 6.4 shall be used.

6.9 *Specimens for Pipe and Tube* (Note 12):

6.9.1 For all small tube (Note 12), particularly sizes 25 mm and under in nominal outside diameter, and frequently for



	Dimensions, mm				
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
G—Gage length	62.5 ± 0.1	62.5± 0.1	62.5 ± 0.1	62.5 ± 0.1	62.5 ± 0.1
D—Diameter (Note 1)	12.5 ± 0.2	12.5 ± 0.2	12.5 ± 0.2	12.5± 0.2	12.5 ± 0.2
R—Radius of fillet, min	10	10	2	10	10
A—Length of reduced section	75, min	75, min	100, approximately	75, min	75, min
L—Overall length, approximate	145	155	140	140	255
B—Length of end section (Note 3)	35, approximately	25, approximately	20, approximately	15, approximately	75, min
C—Diameter of end section	20	20	20	22	20
E—Length of shoulder and fillet section, approximate	... .	15	... .	20	15
F—Diameter of shoulder	... .	15	... .	15	15

NOTE 1—The reduced section may have a gradual taper from the ends toward the center with the ends not more than 1 % larger in diameter than the center.

NOTE 2—On Specimens 1 and 2, any standard thread is permissible that provides for proper alignment and aids in assuring that the specimen will break within the reduced section.

NOTE 3—On Specimen 5 it is desirable, if possible, to make the length of the grip section great enough to allow the specimen to extend into the grips a distance equal to two thirds or more of the length of the grips.

FIG. 9 Various Types of Ends for Standard Round Tension Test Specimens

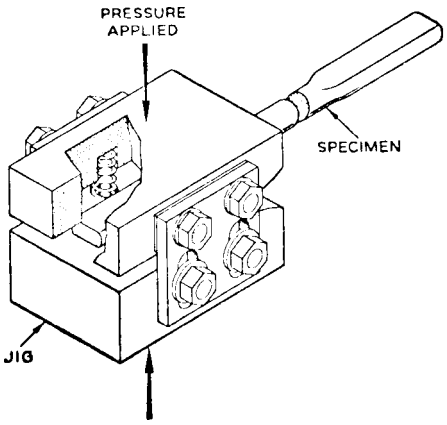
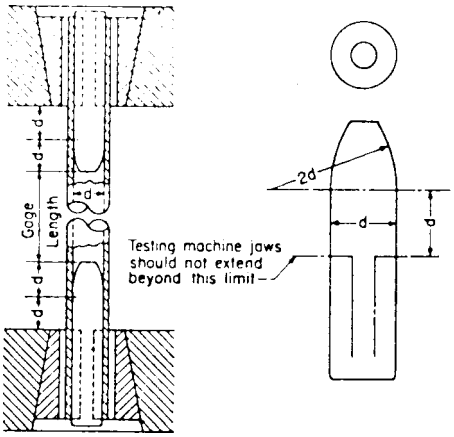


FIG. 10 Squeezing Jig for Flattening Ends of Full-Size Tension Test Specimens



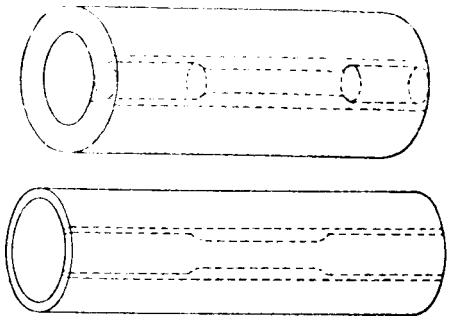
NOTE 1—The diameter of the plug shall have a slight taper from the line limiting the testing machine jaws to the curved section.

FIG. 11 Metal Plugs for Testing Tubular Specimens, Proper Location of Plugs in Specimen and of Specimen in Heads of Testing Machine

larger sizes, except as limited by the testing equipment, it is standard practice to use tension test specimens of full-size tubular sections. Snug-fitting metal plugs shall be inserted far enough into the ends of such tubular specimens to permit the testing machine jaws to grip the specimens properly. The plugs shall not extend into that part of the specimen on which the elongation is measured. Elongation is measured over a length of 5D unless otherwise stated in the product specification. Fig. 11 shows a suitable form of plug, the location of the plugs in the specimen, and the location of the specimen in the grips of the testing machine.

NOTE 12—The term "tube" is used to indicate tubular products in general, and includes pipe, tube, and tubing.

6.9.2 For large-diameter tube that cannot be tested in full section, longitudinal tension test specimens shall be cut as indicated in Fig. 12. Specimens from welded tube shall be located approximately 90° from the weld. If the tube-wall thickness is under 20 mm, either a specimen of the form and dimensions shown in Fig. 13 or one of the small-size specimens proportional to the standard 12.5-mm specimen, as



NOTE 1—The edges of the blank for the specimen shall be cut parallel to each other.

FIG. 12 Location from Which Longitudinal Tension Test Specimens Are to Be Cut from Large-Diameter Tube

mentioned in 6.4.2 and shown in Fig. 8, shall be used. Specimens of the type shown in Fig. 13 may be tested with grips having a surface contour corresponding to the curvature of the tube. When grips with curved faces are not available, the ends of the specimens may be flattened without heating. If the tube-wall thickness is 20 mm or over, the standard specimen shown in Fig. 8 shall be used.

NOTE 13—In clamping of specimens from pipe and tube (as may be done during machining) or in flattening specimen ends (for gripping), care must be taken so as not to subject the reduced section to any deformation or cold work, as this would alter the mechanical properties.

6.9.3 Transverse tension test specimens for tube may be taken from rings cut from the ends of the tube as shown in Fig. 14. Flattening of the specimen may be either after separating as in *A*, or before separating as in *B*. Transverse tension test specimens for large tube under 20 mm in wall thickness shall be either of the small-size specimens shown in Fig. 8 or of the form and dimensions shown for Specimen 2 in Fig. 13. When using the latter specimen, either or both surfaces of the specimen may be machined to secure a uniform thickness, provided not more than 15 % of the normal wall thickness is removed from each surface. For large tube 20 mm and over in wall thickness, the standard specimen shown in Fig. 8 shall be used for transverse tension tests. Specimens for transverse tension tests on large welded tube to determine the strength of welds shall be located perpendicular to the welded seams, with the welds at about the middle of their lengths.

6.10 *Specimens for Forgings*—For testing forgings, the largest round specimen described in 6.4 shall be used. If round specimens are not feasible, then the largest specimen described in 6.5 shall be used.

6.10.1 For forgings, specimens shall be taken as provided in the applicable product specifications, either from the predominant or thickest part of the forging from which a coupon can be obtained, or from a prolongation of the forging, or from separately forged coupons representative of the forging. When not otherwise specified, the axis of the specimen shall be parallel to the direction of grain flow.

6.11 *Specimens for Castings*—In testing castings either the standard specimen shown in Fig. 8 or the specimen shown in Fig. 15 shall be used unless otherwise provided in the product specifications.

6.11.1 Test coupons for castings shall be made as shown in Fig. 16 and Table 1.

6.12 *Specimen for Malleable Iron*—For testing malleable iron the test specimen shown in Fig. 17 shall be used, unless otherwise provided in the product specifications.

6.13 *Specimen for Die Castings*—For testing die castings the test specimen shown in Fig. 18 shall be used unless otherwise provided in the product specifications.

6.14 *Specimens for Powder Metallurgy (P/M) Materials*—For testing powder metallurgy (P/M) materials the test specimens shown in Fig. 19 and Fig. 20 shall be used, unless otherwise provided in the product specifications. When making test specimens in accordance with Fig. 19, shallow transverse grooves, or ridges, may be pressed in the ends to allow gripping by jaws machined to fit the grooves or ridges. Because of shape and other factors, the flat unmachined tensile test specimen (Fig. 19) in the heat-treated condition will have an ultimate tensile strength of 50 % to 85 % of that determined in a machined round tensile test specimen (Fig. 20) of like composition and processing.

7. Procedures

7.1 *Preparation of the Test Machine*— Upon startup or following a prolonged period of machine inactivity, the test machine should be exercised or warmed up to normal operating temperatures to minimize errors that may result from transient conditions.

7.2 *Measurement of Dimensions of Test Specimens*:

7.2.1 To determine the cross-sectional area of a test specimen, measure the dimensions of the cross section at the center of the reduced section. For referee testing of specimens under 5 mm in their least dimension, measure the dimensions where the least cross-sectional area is found. Measure and record the cross-sectional dimensions of tension test specimens 5 mm and over to the nearest 0.02 mm; the cross-sectional dimensions less than 5 mm and not less than 2.5 mm to the nearest 0.01 mm; the cross-sectional dimensions less than 2.5 mm and not less than 0.50 mm to the nearest 0.002 mm; and when practical, the cross-sectional dimensions less than 0.50 mm to at least the nearest 1 % but in all cases to at least the nearest 0.002 mm.

NOTE 14—Accurate and precise measurement of specimen dimensions can be one of the most critical aspects of tension testing, depending on specimen geometry. See Appendix X2 for additional information.

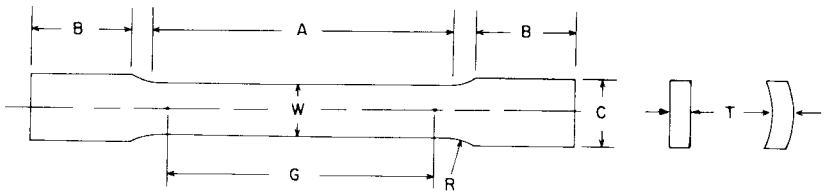
NOTE 15—Rough surfaces due to the manufacturing process such as hot rolling, metallic coating, etc., may lead to inaccuracy of the computed areas greater than the measured dimensions would indicate. Therefore, cross-sectional dimensions of tension test specimens with rough surfaces due to processing may be measured and recorded to the nearest 0.02 mm.

NOTE 16—See X2.9 for cautionary information on measurements taken from coated metal products.

7.2.2 Determine cross-sectional areas of full-size test specimens of nonsymmetrical cross sections by weighing a length not less than 20 times the largest cross-sectional dimension and using the value of density of the material. Determine the weight to the nearest 0.5 % or less.

7.2.3 For materials where the specified elongation is 3 % or less, measure the original gage length to the nearest 0.05 mm prior to testing.

7.2.4 When using specimens of the type shown in Fig. 13



Nominal Width	Dimensions, mm						
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6	Specimen 7
	12.5	40	40	20	20	25	25
G—Gage length	50.0 ± 0.1	50.0 ± 0.1	200.0 ± 0.2	50.0 ± 0.1	100.0 ± 0.1	50.0 ± 0.1	100.0 ± 0.1
W—Width (Note 1)	12.5 ± 0.2	40.0± 2.0	40.0 ± 2.0	20.0 ± 0.7	20.0 ± 0.7	25.0 ± 1.5	25.0 ± 1.5
T—Thickness	measured thickness of specimen						
R—Radius of fillet, min	12.5	25	25	25	25	25	25
A—Length of reduced section, min	60	60	230	60	120	60	120
B—Length of grip section, min (Note 2)	75	75	75	75	75	75	75
C—Width of grip section, approximate (Note 3)	20	50	50	25	25	40	40

NOTE 1—The ends of the reduced section shall not differ in width by more than 0.1 mm for specimens 1–7. There may be a gradual taper in width from the ends to the center, but the width at each end shall be not more than 1 % greater than the width at the center.

NOTE 2—It is desirable, if possible, to make the length of the grip section great enough to allow the specimen to extend into the grips a distance equal to two thirds or more of the length of the grips.

NOTE 3—The ends of the specimen shall be symmetrical with the center line of the reduced section within 1.0 mm for specimens 1, 4, and 5 and 2.5 mm for specimens 2, 3, 6, and 7.

NOTE 4—For circular segments, the cross-sectional area may be calculated by multiplying W and *T*. If the ratio of the dimension *W* to the diameter of the tubular section is larger than about ⅙, the error in using this method to calculate cross-sectional area may be appreciable. In this case, the exact equaton (see 7.2.3) must be used to determine the area.

NOTE 5—For each specimen type, the radii of all fillets shall be equal to each other within a tolerance of 1.25 mm, and the centers of curvature of the two fillets at a particular end shall be located across from each other (on a line perpendicular to the centerline) within a tolerance of 2.5 mm.

NOTE 6—Specimens with sides parallel throughout their length are permitted, except for referee testing and where prohibited by product specification, provided: (*a*) the above tolerances are used; (*b*) an adequate number of marks are provided for determination of elongation; and (*c*) when yield strength is determined, a suitable extensometer is used. If the fracture occurs at a distance of less than 2*W* from the edge of the gripping device, the tensile properties determined may not be representative of the material. If the properties meet the minimum requirements specified, no further testing is required, but if they are less than the minimum requirements, discard the test and retest.

FIG. 13 Tension Test Specimens for Large-Diameter Tubular Products

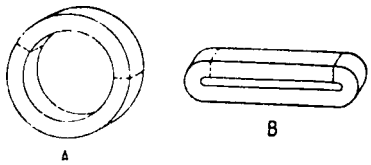


FIG. 14 Location of Transverse Tension Test Specimen in Ring Cut from Tubular Products

taken from tubes, the cross-sectional area shall be determined as follows:

If $D/W \leq 6$:

$$A = [(W/4) \times (D^2 - W^2)^{1/2}] + [(D^2/4) \times \arcsin (W/D)] - [(W/4) \times ((D - 2T)^2 - W^2)^{1/2}] - [((D - 2T)/2)^2 \times \arcsin (W/(D - 2T))] \quad (1)$$

where:

A = exact cross-sectional area, mm^2,
W = width of the specimen in the reduced section, mm,
D = measured outside diameter of the tube, mm, and
T = measured wall thickness of the specimen, mm.

arcsin values to be in radians

If $D/W > 6$, the exact equation or the following equation may be used:

$$A = W \times T \quad (2)$$

where:

A = approximate cross-sectional area, mm^2,
W = width of the specimen in the reduced section, mm, and
T = measured wall thickness of the specimen, mm.

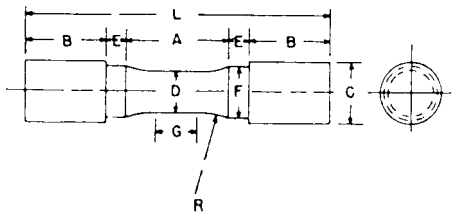
NOTE 17—See X2.8 for cautionary information on measurements and calculations for specimens taken from large-diameter tubing.

7.3 *Gage Length Marking of Test Specimens*:

7.3.1 The gage length for the determination of elongation shall be in accordance with the product specifications for the material being tested. Gage marks shall be stamped lightly with a punch, scribed lightly with dividers or drawn with ink as preferred. For material that is sensitive to the effect of slight notches and for small specimens, the use of layout ink will aid in locating the original gage marks after fracture.

7.4 *Zeroing of the Testing Machine*:

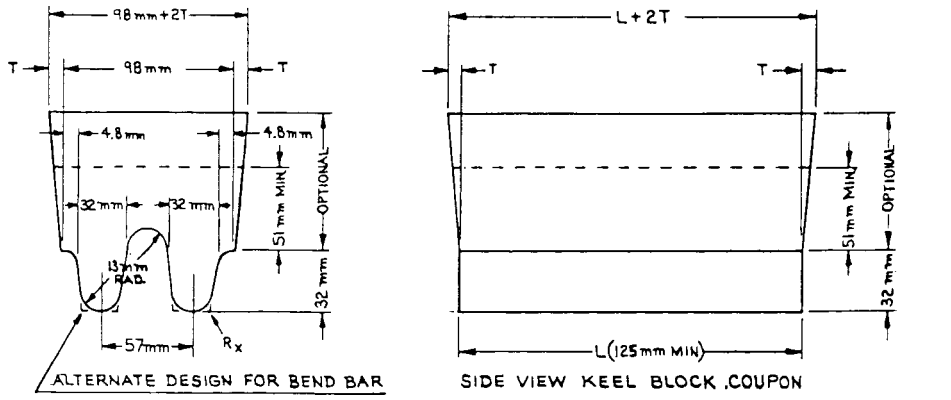
7.4.1 The testing machine shall be set up in such a manner that zero force indication signifies a state of zero force on the specimen. Any force (or preload) imparted by the gripping of the specimen (see Note 18) must be indicated by the force measuring system unless the preload is physically removed prior to testing. Artificial methods of removing the preload on the specimen, such as taring it out by a zero adjust pot or removing it mathematically by software, are prohibited because these would affect the accuracy of the test results.



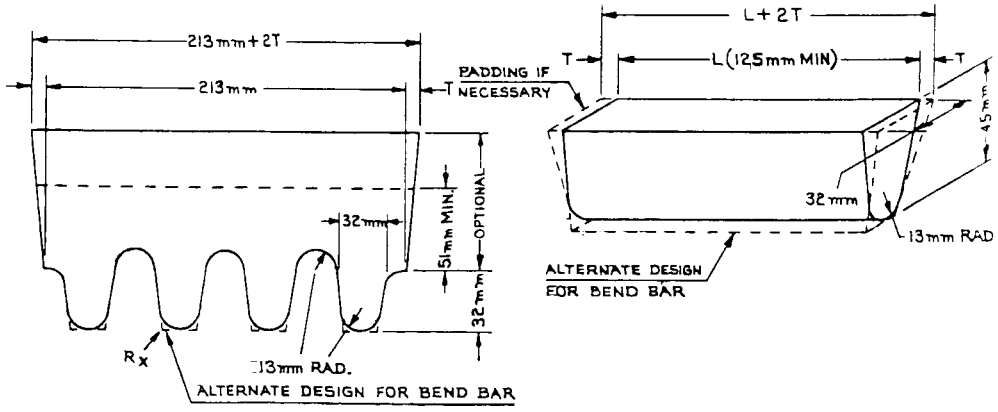
Nominal Diameter	Dimensions, mm		
	Specimen 1	Specimen 2	Specimen 3
	12.5	20	30
G—Length of parallel	Shall be equal to or greater than diameter *D*		
D—Diameter	12.5 ± 0.2	20.0 ± 0.4	30.0 ± 0.6
R—Radius of fillet, min	25	25	50
A—Length of reduced section, min	32	38	60
L—Overall length, min	95	100	160
B—Length of end section, approximate	25	25	45
C—Diameter of end section, approximate	20	30	48
E—Length of shoulder, min	6	6	8
F—Diameter of shoulder	16.0 ± 0.4	24.0± 0.4	36.5 ± 0.4

NOTE 1—The reduced section and shoulders (dimensions *A, D, E, F, G,* and *R*) shall be as shown, but the ends may be of any form to fit the holders of the testing machine in such a way that the force shall be axial. Commonly the ends are threaded and have the dimensions *B* and *C* given above.

FIG. 15 Standard Tension Test Specimen for Cast Iron



(*a*) **Design for Double Keel Block Coupon**



(*b*) **Design for Multiple Keel Block Coupon (4 Legs)** (*c*) **Design for "Attached" Coupon**

FIG. 16 Test Coupons for Castings (see Table 1 for Details of Design)

NOTE 18—Preloads generated by gripping of specimens may be either tensile or compressive in nature and may be the result of such things as:

— grip design

— malfunction of gripping apparatus (sticking, binding, etc.)

— excessive gripping force

— sensitivity of the control loop

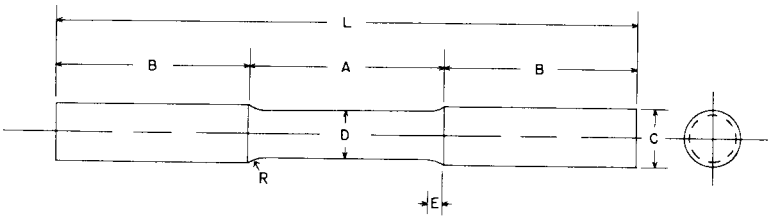
NOTE 19—It is the operator's responsibility to verify that an observed preload is acceptable and to ensure that grips operate in a smooth manner.

TABLE 1 Details of Test Coupon Design for Castings (See Fig. 16)

NOTE 1—*Test Coupons for Large and Heavy Steel Castings:* The test coupons in Fig. 16 are to be used for large and heavy steel castings. However, at the option of the foundry the cross-sectional area and length of the standard coupon may be increased as desired. This provision does not apply to Specification A 356/A 356M.

NOTE 2—*Bend Bar:* If a bend bar is required, an alternate design (as shown by dotted lines in Fig. 16) is indicated.

	Log Design (125 mm)		Riser Design
1. *L* (length)	A 125-mm minimum length will be used. This length may be increased at the option of the foundry to accommodate additional test bars (see Note 1).	1. *L* (length)	The length of the riser at the base will be the same as the top length of the leg. The length of the riser at the top therefore depends on the amount of taper added to the riser.
2. End taper	Use of and size of end taper is at the option of the foundry.	2. Width	The width of the riser at the base of a multiple-leg coupon shall be *n* (57 mm) − 16 mm where *n* equals the number of legs attached to the coupon. The width of the riser at the top is therefore dependent on the amount of taper added to the riser.
3. Height	32 mm		
4. Width (at top)	32 mm (see Note 1).		
5. Radius (at bottom)	13 mm max		
6. Spacing between legs	A 13-mm radius will be used between the legs.		
7. Location of test bars	The tensile, bend, and impact bars will be taken from the lower portion of the leg (see Note 2).		
8. Number of legs	The number of legs attached to the coupon is at the option of the foundry providing they are equispaced according to Item 6.	3. *T* (riser taper) Height	Use of and size is at the option of the foundry. The minimum height of the riser shall be 51 mm. The maximum height is at the option of the foundry for the following reasons: (*a*) many risers are cast open, (*b*) different compositions may require variation in risering for soundness, or (*c*) different pouring temperatures may require variation in risering for soundness.
9. R_s	Radius from 0 to approximately 2 mm		



Dimensions, mm	
D—Diameter	16
R—Radius of fillet	8
A—Length of reduced section	64
L—Overall length	190
B—Length of end section	64
C—Diameter of end section	20
E—Length of fillet	5

FIG. 17 Standard Tension Test Specimen for Malleable Iron

Unless otherwise specified, it is recommended that momentary (dynamic) forces due to gripping not exceed 20 % of the material's nominal yield strength and that static preloads not exceed 10 % of the material's nominal yield strength.

7.5 *Gripping of the Test Specimen*:

7.5.1 For specimens with reduced sections, gripping of the specimen shall be restricted to the grip section, because gripping in the reduced section or in the fillet can significantly affect test results.

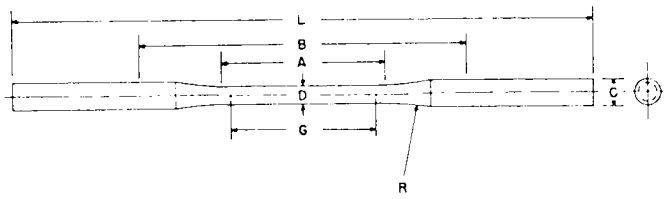
7.6 *Speed of Testing*:

7.6.1 Speed of testing may be defined in terms of (*a*) rate of straining of the specimen, (*b*) rate of stressing of the specimen, (*c*) rate of separation of the two heads of the testing machine during a test, (*d*) the elapsed time for completing part or all of the test, or (*e*) free-running crosshead speed (rate of movement of the crosshead of the testing machine when not under load).

7.6.2 Specifying suitable numerical limits for speed and selection of the method are the responsibilities of the product committees. Suitable limits for speed of testing should be specified for materials for which the differences resulting from the use of different speeds are of such magnitude that the test results are unsatisfactory for determining the acceptability of the material. In such instances, depending upon the material and the use for which the test results are intended, one or more of the methods described in the following paragraphs is recommended for specifying speed of testing.

NOTE 20—Speed of testing can affect test values because of the rate sensitivity of materials and the temperature-time effects.

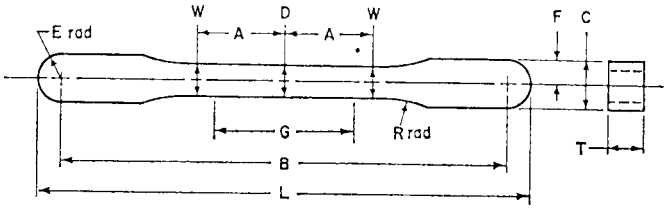
7.6.2.1 *Rate of Straining*—The allowable limits for rate of straining shall be specified in metres per metre per second. Some testing machines are equipped with pacing or indicating



Dimensions, mm	
G—Gage length	50.0 ± 0.1
D—Diameter (see Note)	6.4 ± 0.1
R—Radius of fillet, min	75
A—Length of reduced section, min	60
L—Overall length, min	230
B—Distance between grips, min	115
C—Diameter of end section, approximate	10

NOTE 1—The reduced section may have a gradual taper from the ends toward the center, with the ends not more than 0.1 mm larger in diameter than the center.

FIG. 18 Standard Tension Test Specimen for Die Castings



Pressing Area = 645 mm^2

NOTE 1—Dimensions specified, except *G* and *T*, are those of the die.

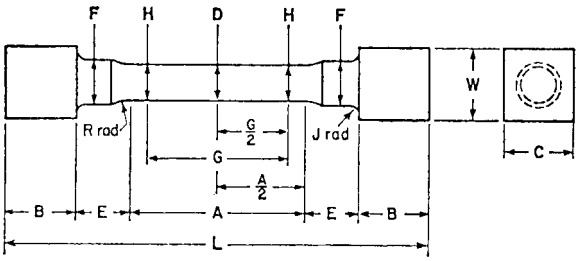
Dimensions, mm	
G—Gage length	25.40 ± 0.8
D—Width at center	5.72 ± 0.03
W—Width at end of reduced section	5.97 ± 0.03
T—Compact to this thickness	3.56 to 6.35
R—Radius of fillet	25.4
A—Half-length of reduced section	15.88
B—Grip length	80.95 ± 0.03
L—Overall length	89.64 ± 0.03
C—Width of grip section	8.71 ± 0.03
F—Half-width of grip section	4.34 ± 0.03
E—End radius	4.34 ± 0.03

FIG. 19 Standard Flat Unmachined Tension Test Specimen for Powder Metallurgy (P/M) Products

devices for the measurement and control of rate of straining, but in the absence of such a device the average rate of straining can be determined with a timing device by observing the time required to effect a known increment of strain.

7.6.2.2 *Rate of Stressing*—The allowable limits for rate of stressing shall be specified in megapascals per second. Many testing machines are equipped with pacing or indicating devices for the measurement and control of the rate of stressing, but in the absence of such a device the average rate of stressing can be determined with a timing device by observing the time required to apply a known increment of stress.

7.6.2.3 *Rate of Separation of Heads During Tests*—The allowable limits for rate of separation of the heads of the testing machine, during a test, shall be specified in metres per metre of length of reduced section (or distance between grips for specimens not having reduced sections) per second. The



Approximate Pressing Area of Unmachined Compact = 752 mm^2

Machining Recommendations

1. Rough machine reduced section to 6.35 mm diameter
2. Finish turn 4.75/4.85 mm diameter with radii and taper
3. Polish with 00 emery cloth
4. Lap with crocus cloth

Dimensions, mm	
G—Gage length	25.40 ± 0.8
D—Diameter at center of reduced section	4.75± 0.03
H—Diameter at ends of gage length	4.85± 0.03
R—Radius of fillet	6.35 ± 0.13
A—Length of reduced section	47.63 ± 0.13
L—Overall length (die cavity length)	75, nominal
B—Length of end section	7.88 ± 0.13
C—Compact to this end thickness	10.03 ± 0.13
W—Die cavity width	10.03 ± 0.08
E—Length of shoulder	6.35 ± 0.13
F—Diameter of shoulder	7.88 ± 0.03
J—End fillet radius	1.27 ± 0.13

NOTE 1—The gage length and fillets of the specimen shall be as shown. The ends as shown are designed to provide a practical minimum pressing area. Other end designs are acceptable, and in some cases are required for high-strength sintered materials.

NOTE 2—It is recommended that the test specimen be gripped with a split collet and supported under the shoulders. The radius of the collet support circular edge is to be not less than the end fillet radius of the test specimen.

NOTE 3—Diameters *D* and *H* are to be concentric within 0.03 mm total indicator runout (T.I.R.), and free of scratches and tool marks.

FIG. 20 Standard Round Machined Tension Test Specimen for Powder Metallurgy (P/M) Products

limits for the rate of separation may be further qualified by specifying different limits for various types and sizes of specimens. Many testing machines are equipped with pacing or indicating devices for the measurement and control of the rate of separation of the heads of the machine during a test, but in the absence of such a device the average rate of separation of the heads can be experimentally determined by using suitable length-measuring and timing devices.

7.6.2.4 *Elapsed Time*—The allowable limits for the elapsed time from the beginning of force application (or from some specified stress) to the instant of fracture, to the maximum force, or to some other stated stress, shall be specified in minutes or seconds. The elapsed time can be determined with a timing device.

7.6.2.5 *Free-Running Crosshead Speed*—The allowable limits for the rate of movement of the crosshead of the testing machine, with no force applied by the testing machine, shall be specified in metres per metre of length of reduced section (or distance between grips for specimens not having reduced sections) per second. The limits for the crosshead speed may be further qualified by specifying different limits for various types and sizes of specimens. The average crosshead speed can be

experimentally determined by using suitable length-measuring and timing devices.

NOTE 21—For machines not having crossheads or having stationary crossheads, the phrase "free-running crosshead speed" may be interpreted to mean the free-running rate of grip separation.

7.6.3 *Speed of Testing When Determining Yield Properties*—Unless otherwise specified, any convenient speed of testing may be used up to one half the specified yield strength or up to one quarter the specified tensile strength, whichever is smaller. The speed above this point shall be within the limits specified. If different speed limitations are required for use in determining yield strength, yield point elongation, tensile strength, elongation, and reduction of area, they should be stated in the product specifications. In the absence of any specified limitations on speed of testing, the following general rules shall apply:

NOTE 22—In the previous and following paragraphs, the yield properties referred to include yield strength and yield point elongation.

7.6.3.1 The speed of testing shall be such that the forces and strains used in obtaining the test results are accurately indicated.

7.6.3.2 When performing a test to determine yield properties, the rate of stress application shall be between 1.15 and 11.5 MPa/s.

NOTE 23—When a specimen being tested begins to yield, the stressing rate decreases and may even become negative in the case of a specimen with discontinuous yielding. To maintain a constant stressing rate in this case would require the testing machine to operate at extremely high speeds and, in many cases, this is not practical. The speed of the testing machine shall not be increased in order to maintain a stressing rate when the specimen begins to yield. In practice, it is simpler to use either a strain rate, a rate of separation of the heads, or a free-running crosshead speed which approximates the desired stressing rate. As an example, use a strain rate that is less than 11.5 MPa/s divided by the nominal Young's Modulus of the material being tested. As another example, find a rate of separation of the heads through experimentation which would approximate the desired stressing rate prior to the onset of yielding, and maintain that rate of separation of the heads through the region that yield properties are determined. While both of these methods will provide similar rates of stressing and straining prior to the onset of yielding, the rates of stressing and straining may be different in the region where yield properties are determined. This difference is due to the change in the rate of elastic deformation of the testing machine, before and after the onset of yielding. In addition, the use of any of the methods other than rate of straining may result in different stressing and straining rates when using different testing machines, due to differences in the stiffness of the testing machines used.

7.6.4 *Speed of Testing When Determining Tensile Strength*—In the absence of any specified limitations on speed of testing, the following general rules shall apply for materials with expected elongations greater than 5 %. When determining only the tensile strength, or after the yield behavior has been recorded, the speed of the testing machine shall be set between 0.05 and 0.5 m/m of the length of the reduced section (or distance between the grips for specimens not having reduced sections) per minute. Alternatively, an extensometer and strain rate indicator may be used to set the strain between 0.05 and 0.5 m/m/min.

NOTE 24—For materials with expected elongations less than or equal to 5 %, the speed of the testing machine may be maintained throughout the test at the speed used to determine yield properties.

NOTE 25—Tensile strength and elongation are sensitive to test speed for many materials (see Appendix XI) to the extent that variations within the range of test speeds given above can significantly affect results.

7.7 *Determination of Yield Strength*— Determine yield strength by any of the methods described in 7.7.1 to 7.7.4. Where extensometers are employed, use only those which are verified over a strain range in which the yield strength will be determined (see 5.4).

NOTE 26—For example, a verified strain range of 0.2 to 2.0 % is appropriate for use in determining the yield strengths of many metals.

NOTE 27—Determination of yield behavior on materials which cannot support an appropriate extensometer (thin wire, for example) is problematic and outside the scope of this standard.

7.7.1 *Offset Method*—To determine the yield strength by the offset method, it is necessary to secure data (autographic or numerical) from which a stress-strain diagram may be drawn. Then on the stress-strain diagram (Fig. 21) lay off *Om* equal to the specified value of the offset, draw *mn* parallel to *OA*, and thus locate *r*, the intersection of *mn* with the stress-strain diagram (Note 33). In reporting values of yield strength obtained by this method, the specified value of offset used should be stated in parentheses after the term yield strength, as follows:

$$\text{yield strength (offset} = 0.2\ \%) = 360\ \text{MPa} \quad (3)$$

In using this method, a Class B2 or better extensometer (see Practice E 83) shall be used.

NOTE 28—There are two general types of extensometers, averaging and non-averaging, the use of which is dependent on the product tested. For most machined specimens, there are minimal differences. However, for some forgings and tube sections, significant differences in measured yield strength can occur. For these cases, it is recommended that the averaging type be used.

NOTE 29—When there is a disagreement over yield properties, the

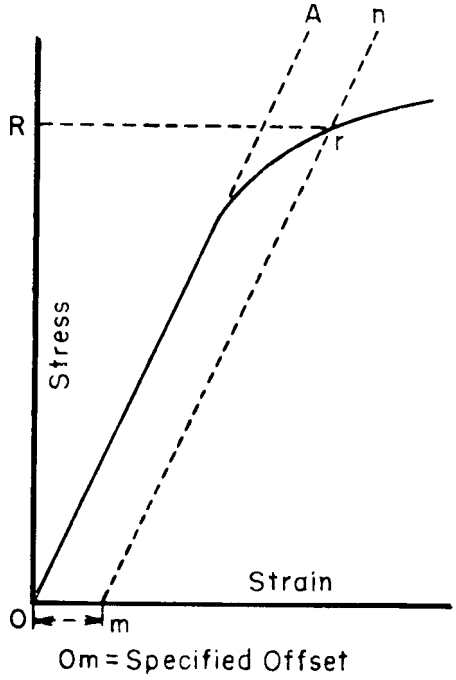


FIG. 21 Stress-Strain Diagram for Determination of Yield Strength by the Offset Method

offset method for determining yield strength is recommended as the referee method.

7.7.2 *Extension-Under-Load Method*—Yield strength by the extension-under-load method may be determined by: (*1*) using autographic or numerical devices to secure stress-strain data, and then analyzing this data (graphically or using automated methods) to determine the stress value at the specified value of extension, or (*2*) using devices that indicate when the specified extension occurs, so that the stress then occurring may be ascertained (Note 31). Any of these devices may be automatic. This method is illustrated in Fig. 22. The stress at the specified extension shall be reported as follows:

$$\text{yield strength (EUL} = 0.5\ \%) = 360\ \text{MPa} \quad (4)$$

Extensometers and other devices used in determination of the extension shall meet Class B2 requirements (see Practice E 83) at the strain of interest, except where use of low-magnification Class C devices is helpful, such as in facilitating measurement of YPE if observed. If Class C devices are used, this must be reported along with the results.

NOTE 30—The appropriate value of the total extension must be specified. For steels with nominal yield strengths of less than 550 MPa, an appropriate value is 0.005 mm/mm (0.5 %) of the gage length. For higher strength steels, a greater extension or the offset method should be used.

NOTE 31—When no other means of measuring elongation are available, a pair of dividers or similar device can be used to determine a point of detectable elongation between two gage marks on the specimen. The gage length shall be 50 mm. The stress corresponding to the load at the instant of detectable elongation may be recorded as the *approximate* extension-under-load yield strength.

7.7.3 *Autographic Diagram Method (for materials exhibiting discontinuous yielding)*—Obtain stress-strain (or force-elongation) data or construct a stress-strain (or load-elongation) diagram using an autographic device. Determine the upper or lower yield strength as follows:

7.7.3.1 Record the stress corresponding to the maximum force at the onset of discontinuous yielding as the upper yield strength. This is illustrated in Fig. 23 and Fig. 24.

NOTE 32—If multiple peaks are observed at the onset of discontinuous yielding, the first is considered the upper yield strength. (See Fig. 24.)

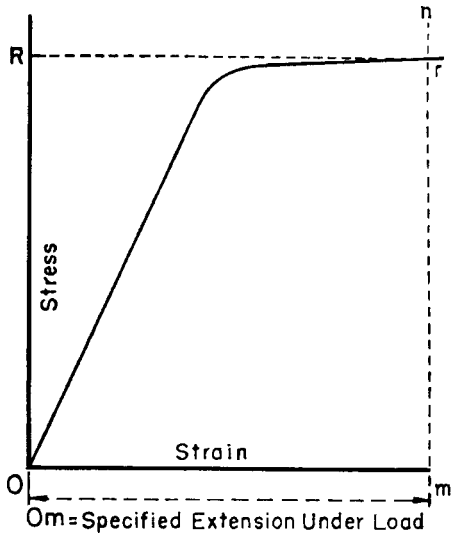


FIG. 22 Stress-Strain Diagram for Determination of Yield Strength by the Extension-Under-Load Method

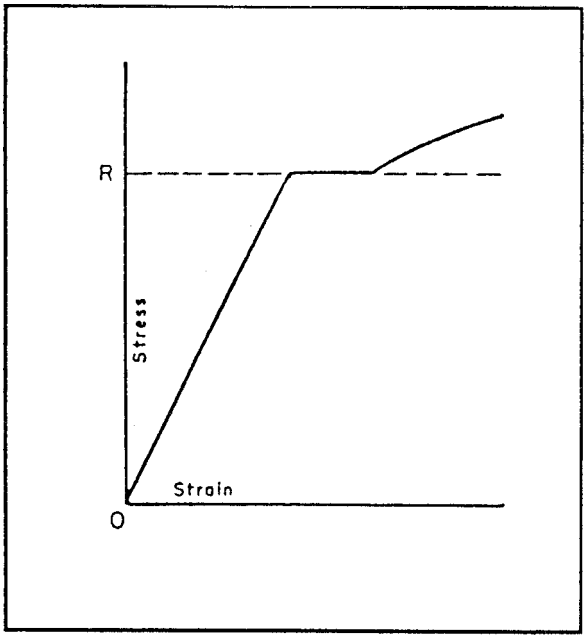


FIG. 23 Stress-Strain Diagram Showing Upper Yield Strength Corresponding with Top of Knee

7.7.3.2 Record the minimum stress observed during discontinuous yielding (ignoring transient effects) as the lower yield strength. This is illustrated in Fig. 24.

NOTE 33—Yield properties of materials exhibiting yield point elongation are often less repeatable and less reproducible than those of similar materials having no YPE. Offset and EUL yield strengths may be significantly affected by force fluctuations occurring in the region where the offset or extension intersects the stress-strain curve. Determination of upper or lower yield strengths (or both) may therefore be preferable for such materials, although these properties are dependent on variables such as test machine stiffness and alignment. Speed of testing may also have a significant effect, regardless of the method employed.

NOTE 34—Where low-magnification autographic recordings are needed to facilitate measurement of yield point elongation for materials which may have discontinuous yielding, Class C extensometers may be employed. When this is done but the material exhibits no discontinuous yielding, the extension-under-load yield strength may be determined instead, using the autographic recording (see Extension-Under-Load Method).

7.7.4 *Halt-of-the-Force Method (for materials exhibiting discontinuous yielding)*—Apply an increasing force to the specimen at a uniform deformation rate. When the force hesitates, record the corresponding stress as the upper yield strength.

NOTE 35—The Halt-of-the-Force Method was formerly known as the Halt-of-the-Pointer Method, the Drop-of-the-Beam Method, and the Halt-of-the-Load Method.

7.8 *Yield Point Elongation*—Calculate the yield point elongation from the stress-strain diagram or data by determining the difference in strain between the upper yield strength (first zero slope) and the onset of uniform strain hardening (see definition of YPE and Fig. 24).

NOTE 36—The stress-strain curve of a material exhibiting only a hint of the behavior causing YPE may have an inflection at the onset of yielding

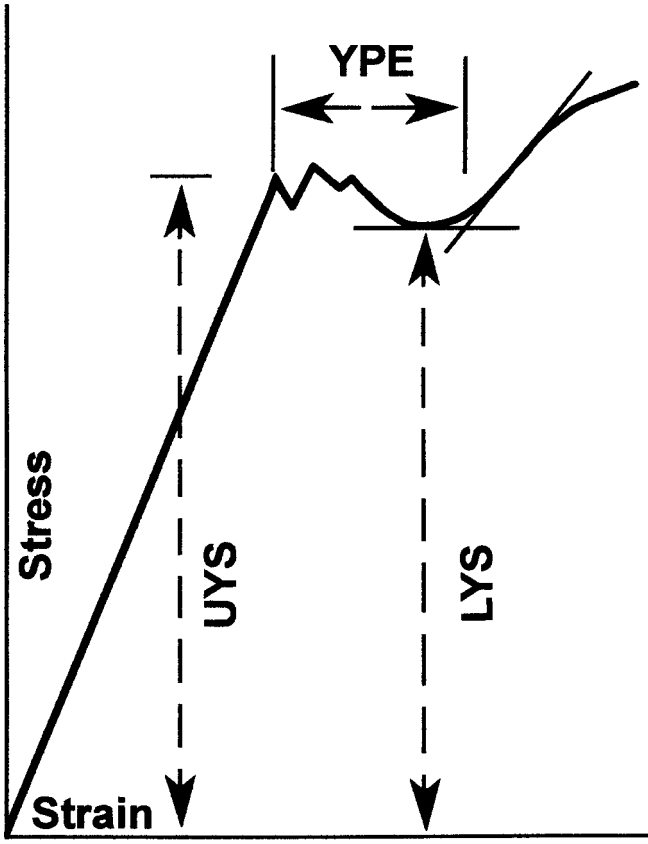


FIG. 24 Stress-Strain Diagram Showing Yield Point Elongation and Upper and Lower Yield Strengths

with no point where the slope reaches zero (Fig. 25). Such a material has no YPE, but may be characterized as exhibiting an *inflection*. Materials exhibiting inflections, like those with measurable YPE, may, in certain applications, acquire an unacceptable surface appearance during forming.

7.9 *Tensile Strength*—Calculate the tensile strength by dividing the maximum force carried by the specimen during the tension test by the original cross-sectional area of the specimen.

NOTE 37—If the upper yield strength is the maximum stress recorded, and if the stress-strain curve resembles that of Fig. 26, it is recommended that the maximum stress *after discontinuous yielding* be reported as the tensile strength. Where this may occur, determination of the tensile strength should be in accordance with the agreement between the parties involved.

7.10 *Elongation*:

7.10.1 In reporting values of elongation, give both the original gage length and the percentage increase. If any device other than an extensometer is placed in contact with the specimen's reduced section during the test, this shall also be noted.

Example: elongation = 30 % increase (50−mm gage length) (5)

NOTE 38—Elongation results are very sensitive to variables such as: (*a*) speed of testing, (*b*) specimen geometry (gage length, diameter, width, and thickness), (*c*) heat dissipation (through grips, extensometers, or other devices in contact with the reduced section), (*d*) surface finish in reduced section (especially burrs or notches), (*e*) alignment, and (*f*) fillets and tapers. Parties involved in comparison or conformance testing should standardize the above items, and it is recommended that use of ancillary devices (such as extensometer supports) which may remove heat from specimens be avoided. See Appendix X1. for additional information on the effects of these variables.

7.10.2 When the specified elongation is greater than 3 %, fit ends of the fractured specimen together carefully and measure the distance between the gage marks to the nearest 0.25 mm for gage lengths of 50 mm and under, and to at least the nearest 0.5 % of the gage length for gage lengths over 50 mm. A percentage scale reading to 0.5 % of the gage length may be used.

7.10.3 When the *specified* elongation is 3 % or less, determine the elongation of the specimen using the following procedure, except that the procedure given in 7.10.2 may be used instead when the *measured* elongation is greater than 3 %.

7.10.3.1 Prior to testing, measure the original gage length of the specimen to the nearest 0.05 mm.

7.10.3.2 Remove partly torn fragments that will interfere with fitting together the ends of the fractured specimen or with making the final measurement.

7.10.3.3 Fit the fractured ends together with matched surfaces and apply a force along the axis of the specimen sufficient to close the fractured ends together. If desired, this force may then be removed carefully, provided the specimen remains intact.

NOTE 39—The use of a force of approximately 15 MPa has been found to give satisfactory results on test specimens of aluminum alloy.

7.10.3.4 Measure the final gage length to the nearest 0.05 mm and report the elongation to the nearest 0.2 %.

7.10.4 Elongation measured per paragraph 7.10.2 or 7.10.3

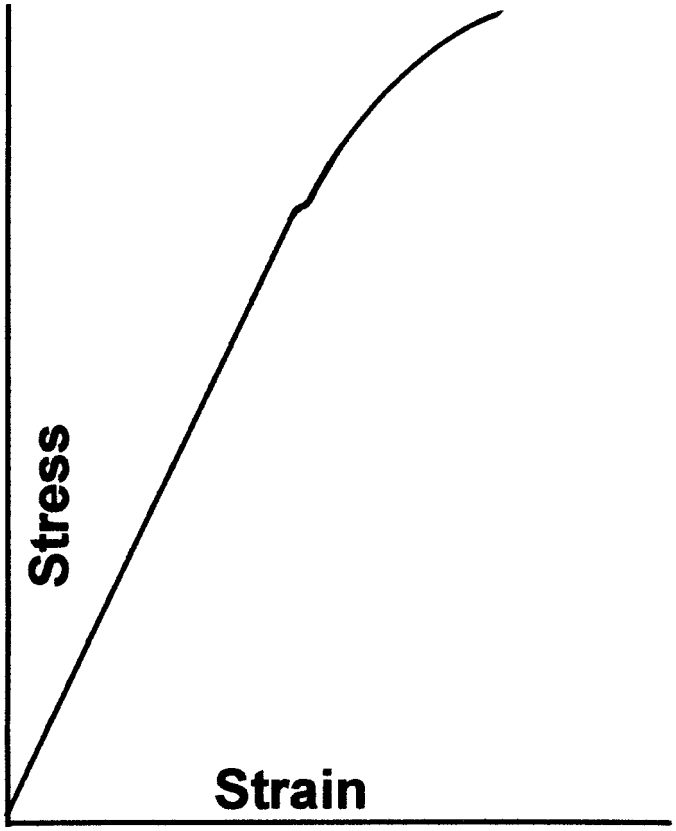


FIG. 25 Stress-Strain Diagram With an Inflection, But No YPE

may be affected by location of the fracture, relative to the marked gage length. If any part of the fracture occurs outside the gage marks or is located less than 25 % of the elongated gage length from either gage mark, the elongation value obtained using that pair of gage marks may be abnormally low and non-representative of the material. If such an elongation measure is obtained in acceptance testing involving only a minimum requirement and meets the requirement, no further testing need be done. Otherwise, discard the test and retest the material.

7.10.5 Elongation at fracture is defined as the elongation measured just prior to the sudden decrease in force associated with fracture. For many ductile materials not exhibiting a sudden decrease in force, the elongation at fracture can be taken as the strain measured just prior to when the force falls below 10 % of the maximum force encountered during the test.

7.10.5.1 Elongation at fracture shall include elastic and plastic elongation and may be determined with autographic or automated methods using extensometers verified over the strain range of interest (see 5.4). Use a class B2 or better extensometer for materials having less than 5 % elongation, a class C or better extensometer for materials having elongation greater than or equal to 5 % but less than 50 %, and a class D or better extensometer for materials having 50 % or greater elongation. In all cases, the extensometer gage length shall be the nominal gage length required for the specimen being tested. Due to the lack of precision in fitting fractured ends together, the elongation after fracture using the manual methods of the preceding paragraphs may differ from the elongation at fracture determined with extensometers.

7.10.5.2 Percent elongation at fracture may be calculated directly from elongation at fracture data and be reported instead of percent elongation as calculated in paragraphs 7.10.2 to 7.10.3. However, these two parameters are not interchangeable. Use of the elongation at fracture method generally provides more repeatable results.

NOTE 40—When disagreements arise over the percent elongation results, agreement must be reached on which method to use to obtain the results.

7.11 *Reduction of Area*:

7.11.1 The reduced area used to calculate reduction of area (see 7.11.2 and 7.11.3) shall be the minimum cross section at the location of fracture.

7.11.2 *Specimens With Originally Circular Cross Sections*—Fit the ends of the fractured specimen together and measure the reduced diameter to the same accuracy as the original measurement.

NOTE 41—Because of anisotropy, circular cross sections often do not remain circular during straining in tension. The shape is usually elliptical, thus, the area may be calculated by $\pi \cdot d_1 \cdot d_2/4$, where d_1 and d_2 are the major and minor diameters, respectively.

7.11.3 *Specimens With Originally Rectangular Cross Sections*—Fit the ends of the fractured specimen together and measure the thickness and width at the minimum cross section to the same accuracy as the original measurements.

NOTE 42—Because of the constraint to deformation that occurs at the corners of rectangular specimens, the dimensions at the center of the original flat surfaces are less than those at the corners. The shapes of these surfaces are often assumed to be parabolic. When this assumption is made,

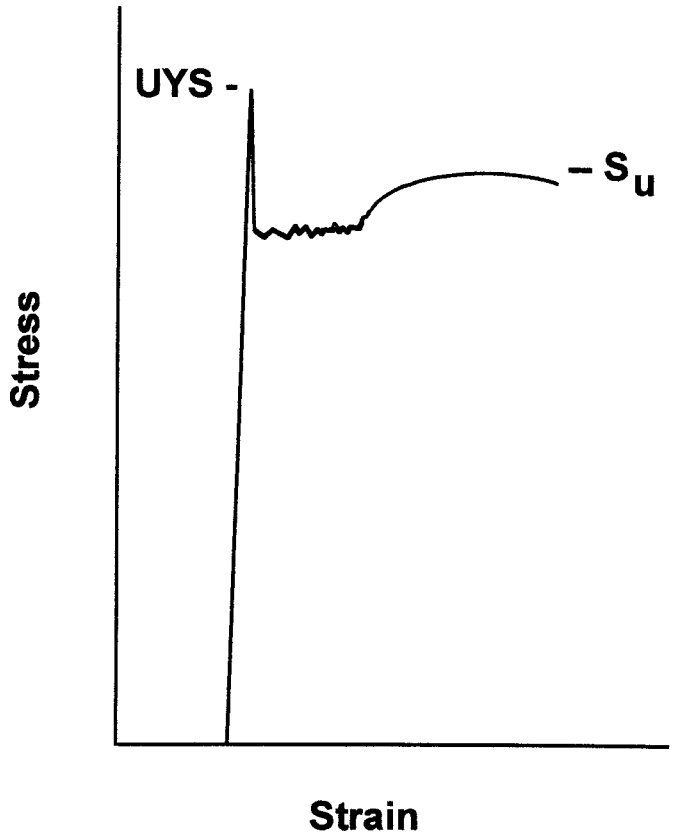


FIG. 26 Stress-Strain Diagram in Which the Upper Yield Strength is the Maximum Stress Recorded

an effective thickness, t_e, may be calculated by: $(t_1 + 4t_2 + t_3)/6$, where t_1 and t_3 are the thicknesses at the corners, and t_2 is the thickness at the mid-width. An effective width may be similarly calculated.

7.11.4 Calculate the reduced area based upon the dimensions determined in 7.11.2 or 7.11.3. The difference between the area thus found and the area of the original cross section expressed as a percentage of the original area is the reduction of area.

7.11.5 If any part of the fracture takes place outside the middle half of the reduced section or in a punched or scribed gage mark within the reduced section, the reduction of area value obtained may not be representative of the material. In acceptance testing, if the reduction of area so calculated meets the minimum requirements specified, no further testing is required, but if the reduction of area is less than the minimum requirements, discard the test results and retest.

7.11.6 Results of measurements of reduction of area shall be rounded using the procedures of Practice E 29 and any specific procedures in the product specifications. In the absence of a specified procedure, it is recommended that reduction of area test values in the range from 0 to 10 % be rounded to the nearest 0.5 % and test values of 10 % and greater to the nearest 1 %.

7.12 *Rounding Reported Test Data for Yield Strength and Tensile Strength*—Test data should be rounded using the procedures of Practice E 29 and the specific procedures in the product specifications. In the absence of a specified procedure for rounding the test data, one of the procedures described in the following paragraphs is recommended.

7.12.1 For test values up to 500 MPa, round to the nearest 1 MPa; for test values of 500 MPa and up to 1000 MPa, round to the nearest 5 MPa; for test values of 1000 MPa and greater, round to the nearest 10 MPa.

NOTE 43—For steel products, see Test Methods and Definitions A 370.

7.12.2 For all test values, round to the nearest 1 MPa.

NOTE 44—For aluminum- and magnesium-alloy products, see Methods B 557M.

7.12.3 For all test values, round to the nearest 5 MPa.

7.13 *Replacement of Specimens*—A test specimen may be discarded and a replacement specimen selected from the same lot of material in the following cases:

7.13.1 The original specimen had a poorly machined surface,

7.13.2 The original specimen had the wrong dimensions,

7.13.3 The specimen's properties were changed because of poor machining practice,

7.13.4 The test procedure was incorrect,

7.13.5 The fracture was outside the gage length,

7.13.6 For elongation determinations, the fracture was outside the middle half of the gage length, or

7.13.7 There was a malfunction of the testing equipment.

NOTE 45—The tension specimen is inappropriate for assessing some types of imperfections in a material. Other methods and specimens employing ultrasonics, dye penetrants, radiography, etc., may be considered when flaws such as cracks, flakes, porosity, etc., are revealed during a test and soundness is a condition of acceptance.

8. Report

8.1 Test information on materials not covered by a product specification should be reported in accordance with 8.2 or both 8.2 and 8.3.

8.2 Test information to be reported shall include the following when applicable:

8.2.1 Material and sample identification.

8.2.2 Specimen type (Section 6).

8.2.3 Yield strength and the method used to determine yield strength (see 7.7).

8.2.4 Yield point elongation (see 7.8).

8.2.5 Tensile strength (see 7.9).

8.2.6 Elongation (report original gage length, percentage increase, and method used to determine elongation) (see 7.10).

8.2.7 Reduction of area (see 7.11).

8.3 Test information to be available on request shall include:

8.3.1 Specimen test section dimension(s).

8.3.2 Formula used to calculate cross-sectional area of specimens taken from large-diameter tubular products.

8.3.3 Speed and method used to determine speed of testing (see 7.6).

8.3.4 Method used for rounding of test results (see 7.12).

8.3.5 Reasons for replacement specimens (see 7.13).

9. Precision and Bias [7]

9.1 *Precision*—An interlaboratory test program gave the following values for coefficients of variation for the most commonly measured tensile properties:

Coefficient of Variation, %

	Tensile Strength	Yield Strength Offset = 0.02 %	Yield Strength Offset = 0.2 %	Elongation Gage Length = 5 Diameters	Reduction of Area
$CV\%_r$	0.9	2.7	1.4	3.0	2.8
$CV\%_R$	1.3	4.5	2.3	6.4	4.6

$CV\%_r$ = repeatability coefficient of variation in percent within a laboratory
$CV\%_R$ = repeatability coefficient of variation in percent between laboratories

9.1.1 The values shown are the averages from tests on six frequently tested metals, selected to include most of the normal range for each property listed above. When these materials are compared, a large difference in coefficient of variation is found. Therefore, the values above should not be tightness; width; workmanship used to judge whether the difference between duplicate tests of a specific material is larger than expected. The values are provided to allow potential users of this test method to assess, in general terms, its usefulness for a proposed application.

9.2 *Bias*—The procedures in Test Methods E 8M for measuring tensile properties have no bias because these properties can only be defined in terms of a test method.

10. Keywords

10.1 accuracy; bending stress; discontinuous yielding; drop-of-the-beam; eccentric force application; elastic extension; elongation; extension-under-load; extensometer; force; free-running crosshead speed; gage length; halt-of-the force; percent elongation; plastic extension; preload; rate of stressing; rate of straining; reduced section; reduction of area; sensitivity; strain; stress; taring; tensile strength; tension testing; yield point elongation; yield strength

[7] Supporting data can be found in Appendix I and additional data are available from ASTM Headquarters. Request RR: E28-1004 and E28-1006.

APPENDIXES

(Nonmandatory Information)

X1. FACTORS AFFECTING TENSION TEST RESULTS

X1.1 The precision and bias of tension test strength and ductility measurements depend on strict adherence to the stated test procedure and are influenced by instrumental and material factors, specimen preparation, and measurement/testing errors.

X1.2 The consistency of agreement for repeated tests of the same material is dependent on the homogeneity of the material, and the repeatability of specimen preparation, test conditions, and measurements of the tension test parameters.

X1.3 Instrumental factors that can affect test results include: the stiffness, damping capacity, natural frequency, and mass of moving parts of the tensile test machine; accuracy of force indication and use of forces within the verified range of the machine; rate of force application, alignment of the test specimen with the applied force, parallelness of the grips, grip pressure, nature of the force control used, appropriateness and calibration of extensometers, heat dissipation (by grips, extensometers, or ancillary devices), and so forth.

X1.4 Material factors that can affect test results include: representativeness and homogeneity of the test material, sampling scheme, and specimen preparation (surface finish, dimensional accuracy, fillets at the ends of the gage length, taper in the gage length, bent specimens, thread quality, and so forth).

X1.4.1 Some materials are very sensitive to the quality of the surface finish of the test specimen (see Note 8) and must be ground to a fine finish, or polished to obtain correct results.

X1.4.2 Test results for specimens with as-cast, as-rolled, as-forged, or other non-machined surface conditions can be affected by the nature of the surface (see Note 15).

X1.4.3 Test specimens taken from appendages to the part or component, such as prolongs or risers, or from separately produced castings (for example, keel blocks) may produce test results that are not representative of the part or component.

X1.4.4 Test specimen dimensions can influence test results. For cylindrical or rectangular specimens, changing the test specimen size generally has a negligible effect on the yield and tensile strength but may influence the upper yield strength, if one is present, and elongation and reduction of area values. Comparison of elongation values determined using different specimens requires that the following ratio be controlled:

$$L_0/(A_0)^{1/2} \quad \text{(X1.1)}$$

where:

L_0 = original gage length of specimen, and
A_0 = original cross-sectional area of specimen.

X1.4.4.1 Specimens with smaller $L_0/(A_0)^{1/2}$ ratios generally give greater elongation and reduction in area values. This is the case, for example, when the width or thickness of a rectangular tensile test specimen is increased.

X1.4.4.2 Holding the $L_0/(A_0)^{1/2}$ ratio constant minimizes, but does not necessarily eliminate, differences. Depending on material and test conditions, increasing the size of the proportional specimen of Fig. 8 may be found to increase or decrease elongation and reduction in area values somewhat.

X1.4.5 Use of a taper in the gage length, up to the allowed 1 % limit, can result in lower elongation values. Reductions of as much as 15 % have been reported for a 1 % taper.

X1.4.6 Changes in the strain rate can affect the yield strength, tensile strength, and elongation values, especially for materials which are highly strain rate sensitive. In general, the yield strength and tensile strength will increase with increasing strain rate, although the effect on tensile strength is generally less pronounced. Elongation values generally decrease as the strain rate increases.

X1.4.7 Brittle materials require careful specimen preparation, high quality surface finishes, large fillets at the ends of the gage length, oversize threaded grip sections, and cannot tolerate punch or scribe marks as gage length indicators.

X1.4.8 Flattening of tubular products to permit testing does alter the material properties, generally nonuniformity, in the flattened region which may affect test results.

X1.5 Measurement errors that can affect test results include: verification of the test force, extensometers, micrometers, dividers, and other measurement devices, alignment and zeroing of chart recording devices, and so forth.

X1.5.1 Measurement of the dimensions of as-cast, as-rolled, as-forged, and other test specimens with non-machined surfaces may be imprecise due to the irregularity of the surface flatness.

X1.5.2 Materials with anisotropic flow characteristics may exhibit non-circular cross sections after fracture and measurement precision may be affected, as a result (see Note 37).

X1.5.3 The corners of rectangular test specimens are subject to constraint during deformation and the originally flat surfaces may be parabolic in shape after testing which will affect the precision of final cross-sectional area measurements (see Note 42).

X1.5.4 If any portion of the fracture occurs outside of the middle of the gage length, or in a punch or scribe mark within the gage length, the elongation and reduction of area values may not be representative of the material. Wire specimens that break at or within the grips may not produce test results representative of the material.

X1.5.5 Use of specimens with shouldered ends (“button-head” tensiles) will produce lower 0.02 % offset yield strength values than threaded specimens.

X1.6 Because standard reference materials with certified tensile property values are not available, it is not possible to rigorously define the bias of tension tests. However, by the use of carefully designed and controlled interlaboratory studies, a reasonable definition of the precision of tension test results can be obtained.

X1.6.1 An interlaboratory test program[7] was conducted in which six specimens each, of six different materials were prepared and tested by each of six different laboratories. Tables X1.1-X1.5 present the precision statistics, as defined in Practice E 691, for: tensile strength, 0.02 % yield strength, 0.2 % yield strength, % elongation in 5D, and % reduction in area. In each table, the first column lists the six materials tested, the second column lists the average of the average results obtained by the laboratories, the third and fifth columns list the repeatability and reproducibility standard deviations, the fourth and sixth columns list the coefficients of variation for these standard deviations, and the seventh and eighth columns list the 95 % repeatability and reproducibility limits.

X1.6.2 The averages (below columns four and six in each

TABLE X1.1 Precision Statistics—Tensile Strength, MPa

NOTE 1— X is the average of the cell averages, that is, the grand mean for the test parameter,
s_r is the repeatability standard deviation (within-laboratory precision),
s_r/X is the coefficient of variation in %,
s_R is the reproducibility standard deviation (between-laboratory precision),
s_R/X is the coefficient of variation, %,
r is the 95 % repeatability limits,
R is the 95 % reproducibility limits.

Material	X	s_r	s_r/X,%	s_R	s_R/X, %	r	R
EC-H19	176.9	4.3	2.45	4.3	2.45	12.1	12.1
2024-T351	491.3	6.1	1.24	6.6	1.34	17.0	18.5
ASTM A105	596.9	4.1	0.69	8.7	1.47	11.6	24.5
AISI 316	694.6	2.7	0.39	8.4	1.21	7.5	23.4
Inconel 600	685.9	2.9	0.43	5.0	0.72	8.2	13.9
SAE 51410	1253.0	3.2	0.25	7.9	0.63	8.9	22.1
		Averages:	0.91		1.30		

TABLE X1.2 Precision Statistics—0.02 % Yield Strength, MPa

Material	X	s_r	s_r/X,%	s_R	s_R/X, %	r	R
EC-H19	111.4	4.5	4.00	8.2	7.37	12.5	23.0
2024-T351	354.2	5.8	1.64	6.1	1.73	16.3	17.2
ASTM A105	411.4	8.3	2.02	13.1	3.18	23.2	36.6
AISI 316	336.1	16.7	4.97	31.9	9.49	46.1	89.0
Inconel 600	267.1	3.2	1.18	5.2	1.96	8.8	14.7
SAE 51410	723.2	16.6	2.29	21.9	3.02	46.4	61.2
		Averages:	2.68		4.46		

TABLE X1.3 Precision Statistics—0.2 % Yield Strength, MPa

Material	X	s_r	s_r/X,%	s_R	s_R/X, %	r	R
EC-H19	158.4	3.3	2.06	3.3	2.07	9.2	9.2
2024-T351	362.9	5.1	1.41	5.4	1.49	14.3	15.2
ASTM A105	402.4	5.7	1.42	9.9	2.47	15.9	27.8
AISI 316	481.1	6.6	1.36	19.5	4.06	18.1	54.7
Inconel 600	268.3	2.5	0.93	5.8	2.17	7.0	16.3
SAE 51410	967.5	8.9	0.92	15.9	1.64	24.8	44.5
		Averages:	1.35		2.32		

TABLE X1.4 Precision Statistics— % Elongation in 5D

NOTE 1—Length of reduced section = 6D.

Material	X	s_r	s_r/X,%	s_R	s_R/X, %	r	R
EC-H19	14.60	0.59	4.07	0.66	4.54	1.65	1.85
2024-T351	17.99	0.63	3.48	1.71	9.51	1.81	4.81
ASTM A105	25.63	0.77	2.99	1.30	5.06	2.15	3.63
AISI 316	35.93	0.71	1.98	2.68	7.45	2.00	7.49
Inconel 600	41.58	0.67	1.61	1.60	3.86	1.88	4.49
SAE 51410	12.39	0.45	3.61	0.96	7.75	1.25	2.69
		Averages:	2.96		6.36		

TABLE X1.5 Precision Statistics— % Reduction in Area

Material	X	s_r	s_r/X,%	s_R	s_R/X, %	r	R
EC-H19	79.15	1.93	2.43	2.01	2.54	5.44	5.67
2024-T351	30.41	2.09	6.87	3.59	11.79	5.79	10.01
ASTM A105	65.59	0.84	1.28	1.26	1.92	2.35	3.53
AISI 316	71.49	0.99	1.39	1.60	2.25	2.78	4.50
Inconel 600	59.34	0.67	1.14	0.70	1.18	1.89	1.97
SAE 51410	50.49	1.86	3.69	3.95	7.81	5.21	11.05
		Averages:	2.80		4.58		

table) of the coefficients of variation permit a relative comparison of the repeatability (within-laboratory precision) and reproducibility (between-laboratory precision) of the tension test parameters. This shows that the ductility measurements exhibit less repeatability and reproducibility than the strength measurements. The overall ranking from the least to the most repeatable and reproducible is: % elongation in 5D, % reduction in area, 0.02 % offset yield strength, 0.2 % offset yield strength, and tensile strength. Note that the rankings are in the same order for the repeatability and reproducibility average coefficients of variation and that the reproducibility (between-laboratory precision) is poorer than the repeatability (within-laboratory precision), as would be expected.

X1.6.3 No comments about bias can be made for the interlaboratory study due to the lack of certified test results for these specimens. However, examination of the test results showed that one laboratory consistently exhibited higher than average strength values and lower than average ductility values for most of the specimens. One other laboratory had consistently lower than average tensile strength results for all specimens.

X2. MEASUREMENT OF SPECIMEN DIMENSIONS

X2.1 Measurement of specimen dimensions is critical in tension testing, and it becomes more critical with decreasing specimen size, as a given absolute error becomes a larger relative (percent) error. Measuring devices and procedures should be selected carefully, so as to minimize measurement error and provide good repeatability and reproducibility.

X2.2 Relative measurement error should be kept at or below 1 %, where possible. Ideally, this 1 % error should include not only the resolution of the measuring device but also the variability commonly referred to as repeatability and reproducibility. (Repeatability is the ability of any operator to obtain similar measurements in repeated trials. Reproducibility is the ability of multiple operators to obtain similar measurements.)

X2.3 Formal evaluation of gage repeatability and reproducibility (GR and R) by way of a GR and R study is highly recommended. A GR and R study involves having multiple operators each take two or three measurements of a number of parts—in this case, test specimens. Analysis, usually done by computer, involves comparing the observed measurement variations to a tolerance the procedure is to determine conformance to. High GR and R percentages (more than 20 %) indicate much variability relative to the tolerance, whereas low percentages (10 % or lower) indicate the opposite. The analysis also estimates, independently, the repeatability and reproducibility.

X2.4 GR and R studies in which nontechnical personnel used different brands and models of hand-held micrometers have given results varying from about 10 % (excellent) to nearly 100 % (essentially useless), relative to a dimensional tolerance of 0.075 mm. The user is, therefore, advised to be very careful in selecting devices, setting up measurement procedures, and training personnel.

X2.5 With a 0.075 mm tolerance, a 10 % GR and R result (exceptionally good, even for digital hand-held micrometers reading to 0.001 mm) indicates that the total variation due to repeatability and reproducibility is around 0.0075 mm. This is less than or equal to 1 %, only if all dimensions to be measured are greater than or equal to 0.75 mm. The relative error in using this device to measure thickness of a 0.25 mm flat tensile specimen would be 3 %, which is considerably more than that allowed for load or strain measurement.

X2.6 Dimensional measurement errors can be identified as the cause of many *out-of-control* signals, as indicated by statistical process control (SPC) charts used to monitor tension testing procedures. This has been the experience of a production laboratory employing SPC methodology and the best hand-held micrometers available (from a GR and R standpoint) in testing of 0.45 mm to 6.35 mm flat-rolled steel products.

X2.7 Factors which affect GR and R, sometimes dramatically, and which should be considered in the selection and evaluation of hardware and procedures include:

X2.7.1 Resolution,
X2.7.2 Verification,
X2.7.3 Zeroing,
X2.7.4 Type of anvil (flat, rounded, or pointed),
X2.7.5 Cleanliness of part and anvil surfaces,
X2.7.6 User-friendliness of measuring device,
X2.7.7 Stability/temperature variations,
X2.7.8 Coating removal,
X2.7.9 Operator techique, and
X2.7.10 Ratchets or other features used to regulate the clamping force.

X2.8 Flat anvils are generally preferred for measuring the dimensions of round or flat specimens which have relatively smooth surfaces. One exception is that rounded or pointed anvils must be used in measuring the thickness of curved specimens taken from large-diameter tubing (see Fig. 13), to prevent overstating the thickness. (Another concern for these curved specimens is the error that can be introduced through use of the equation $A = W \times T$; see 7.2.4.)

X2.9 Heavy coatings should generally be removed from at least one grip end of flat specimens taken from coated products to permit accurate measurement of base metal thickness, assuming (*a*) the base metal properties are what are desired, (*b*) the coating does not contribute significantly to the strength of the product, and (*c*) coating removal can be easily accomplished (some coatings may be easily removed by chemical stripping). Otherwise, it may be advisable to leave the coating intact and determine the base metal thickness by an alternate method. Where this issue may arise, all parties involved in comparison or conformance testing should agree as to whether or not coatings are to be removed before measurement.

X2.10 As an example of how the considerations identified above affect dimensional measurement procedures, consider the case of measuring the thickness of 0.40 mm painted, flat rolled steel specimens. The paint should be removed prior to measurement, if possible. The measurement device used should have flat anvils, must read to 0.001 mm or better, and must have excellent repeatability and reproducibility. Since GR and R is a significant concern, it will be best to use a device which has a feature for regulating the clamping force used, and devices without digital displays should be avoided to prevent reading errors. Before use of the device, and periodically during use, the anvils should be cleaned, and the device should be verified or zeroed (if an electronic display is used) or both. Finally, personnel should be trained and audited periodically to ensure that the measuring device is being used correctly and consistently by all.

SUMMARY OF CHANGES

This section identifies the principal changes to this standard that have been incorporated since the last issue.

(1) Note 16 was inserted, susequent notes renumbered.
(2) X2.9 was revised.
(3) 7.10.4 was revised.
(4) 6.5.3 was revised.
(5) In Fig. 1, Note 7 was added and subsequent notes of this figure were renumbered. The new note was to eliminate a minimum requirement for the length of the test specimen.

ANEXO A-2

NORMA ASTM E-10

Designation: E 10 – 01

American Association State Highway
and Transportation Officials Standard
AASHTO No.: T70–86
An American National Standard

Standard Test Method for Brinell Hardness of Metallic Materials[1]

This standard is issued under the fixed designation E 10; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This test method (Test Method A) covers the determination of the Brinell hardness of metallic materials, including methods for the verification of Brinell hardness testing machines (Test Method B) and the calibration of standardized hardness test blocks (Test Method C).

1.2 The values stated in SI units are to be regarded as the standard.

NOTE 1—In common terminology, the equivalent force in kgf is substituted for N.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 4 Practices for Force Verification of Testing Machines[2]

E 29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications[3]

E 74 Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines[2]

E 140 Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Rockwell Superficial Hardness, Knoop Hardness, and Scleroscope Hardness[2]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *Brinell hardness number*—a number, which is proportional to the quotient obtained by dividing the test force by the curved surface area of the indentation which is assumed to be spherical and of the diameter of the ball.

$$\text{HBW} = 0.102 \times \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})} \quad \text{(See Table 1)} \qquad (1)$$

where:

D = diameter of the ball, mm,
F = test force, N, and
d = mean diameter of the indentation, mm.

The Brinell hardness is denoted by the symbol: HBW.

3.1.1.1 *Discussion*—In former standards, a steel ball was allowed for hardness values below 450. In cases when a steel ball was used, the Brinell hardness was denoted by HB or HBS.

3.1.1.2 *Discussion*—The symbol HBW is preceded by the hardness value. When conditions other than those specified in 11.1.2 are used, the hardness value is supplemented by an index indicating the test conditions in the order:

(*1*) Diameter of the ball, in mm,
(*2*) A value representing the test force in kg/f (see Table 3), and,
(*3*) Duration of loading, in s.

Examples:
350 HBW 5/750 = Brinell hardness of 350 determined with a ball of 5-mm diameter and with a test force of 7.355 kN (750 kgf) applied for 10 to 15 s.
600 HBW 1/30/20 = Brinell hardness of 600 determined with a ball of 1-mm diameter and with a test force of 294.2 N (30 kgf) applied for 20 s.

3.1.1.3 *Discussion*—Brinell hardness numbers vary with the test force used; however, test results will generally be in agreement when the ratio of the test force to the square of the ball diameter is held constant (see Table 3).

3.1.1.4 *Discussion*—Table 2 lists the Brinell hardness numbers corresponding to various diameters of indentations for 29.4 kN (3000 kgf), 14.7 kN (1500 kgf), and 4.90 kN (500 kgf) test forces making it unnecessary to calculate for each test the value of the Brinell hardness number by the above equation in Table 1 when these forces are used with a 10-mm diameter ball.

3.1.2 *Brinell hardness test*—an indenter (tungsten carbide ball with diameter *D*) is forced into the surface of a test piece and the diameter of the indentation *d* left in the surface after removal of the test force, *F*, is measured. (see Table 1 and Figs. 1 and 2.)

3.1.2.1 *Discussion*—The tungsten carbide ball may be used for materials with a Brinell hardness not exceeding 650.

3.1.3 *calibration*—adjustment of the significant parameters by comparison with values indicated by a reference instrument or by a set of reference standards.

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[1] This test method is under the jurisdiction of ASTM Committee E28 on Mechanical Testing and is the direct responsibility of Subcommittee E28.06 on Indentation Hardness Testing.

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[2] *Annual Book of ASTM Standards*, Vol 03.01.

[3] *Annual Book of ASTM Standards*, Vol 14.02.

TABLE 1 Symbols and Designations

NOTE 1— Constant $= \frac{1}{g_n} = \frac{1}{9.806\,65} = 0.102$

Symbol	Designation
D	Diameter of the ball, mm
F	Test force, N
d	Mean diameter of the indentation, mm
h	Depth of the indentation, mm $= \frac{D - \sqrt{D^2 - d^2}}{2}$
HBW	Brinell hardness $= \text{Constant} \times \frac{\text{Test force}}{\text{Surface area of indentation}}$ $= 0.102 \times \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})}$

3.1.4 *verification*—checking or testing to assure conformance with the specification.

4. Significance and Use

4.1 The Brinell hardness test is an empirical indentation hardness test. Brinell hardness tests provide useful information about metallic materials. This information may correlate to tensile strength, wear resistance, ductility, or other physical characteristics of metallic materials, and may be useful in quality control and selection of materials. Brinell hardness testing at the specific location on a part may not represent the physical characteristics of the whole part or end product. Brinell hardness tests are considered satisfactory for acceptance testing of commercial shipments, and they have been used extensively in industry for this purpose.

TEST METHOD A—GENERAL DESCRIPTION AND TEST PROCEDURE FOR BRINELL HARDNESS TESTS

5. Apparatus

5.1 *Testing Machine*—Equipment for Brinell hardness testing usually consists of a testing machine which supports the test specimen and applies an indenting force to a ball in contact with the specimen. The design of the testing machines shall be such that no rocking or lateral movement of the indenter or specimen occurs while the force is being applied. The design of the testing machine shall ensure that the force to the indenter shall be applied smoothly and without impact forces. Precautions shall be taken to prevent a momentary high test force caused by the inertia of the system, hydraulic system overshoot, etc. See equipment manufacturer's instruction manual for a description of the machine's characteristics, limitations, and respective operating procedure.

5.2 *Brinell Balls*:

5.2.1 The standard ball for Brinell hardness testing shall be 10.000 mm in diameter with a deviation from this value of not more than 0.005 mm in any diameter. The ball shall be polished and free of surface defects. Smaller balls having the diameters and tolerances indicated in Table 4 may be used also provided the precautions set forth in 8.1 are observed.

5.2.2 The tungsten carbide ball indenter shall have a minimum hardness of 1500 HV10.

NOTE 2—**Caution:** The Brinell test is not recommended for material having hardness over 650 HBW (see 8.1).

5.2.2.1 The chemical composition of tungsten carbide balls shall be:

Tungsten Carbide (WC)	Balance
Cobalt (Co)	5.0 to 7.0 %
Total other Carbides	2.0 % max

5.2.2.2 The use of hardened steel ball indenters has been eliminated from this test method. Only tungsten carbide balls may now be used for this test method.

5.2.3 If a ball is used to test a specimen which shows a Brinell hardness greater than 650, the result should be considered suspect and the ball inspected for damage. If there is any evidence of damage, the ball shall be replaced.

5.3 *Measuring Device*—The divisions of the micrometer scale of the microscope or other measuring devices used for the measurement of the diameter of the indentations shall be such as to permit the direct measuring of the diameter to 0.1 mm and the estimation of the diameter to 0.05 mm.

NOTE 3—This requirement applies to the construction of the device only and is not a requirement for measurement of the indentation.

6. Test Specimen

6.1 There is no standard shape or size for a Brinell test specimen. The specimen upon which the indentation is made shall conform to the following:

6.1.1 *Thickness*—The thickness of the specimen tested shall be such that no bulge or other marking showing the effect of the test force appears on the side of the piece opposite the indentation. As a general rule, the thickness of the specimen shall be at least ten times the depth of the indentation (Table 5).

6.1.2 The minimum width shall conform with the requirements of 8.3.

6.1.3 *Finish*—When necessary, the surface on which the indentation is to be made shall be filed, ground, machined or polished with abrasive material so that the edge of the indentation shall be clearly defined to permit the measurement of the diameter to the specified accuracy (see 9.1). Care should be taken to avoid overheating or cold working the surface.

7. Verification of Testing Machine

7.1 *Verification Methods*—The hardness testing machine shall be verified in accordance with one of the two acceptable methods of verifying Brinell hardness testing machines as given in Test Method B.

7.2 *Test Force Range*—When direct verification is used, the Brinell hardness testing machine is acceptable for use over a test force range within which the error in test force does not exceed ±1 %. When indirect verification is used, the Brinell hardness machine is acceptable for use over a test force range within which the mean hardness value obtained is within ±3 % of the Brinell hardness of the standardized test blocks used.

8. Procedure

8.1 *Magnitude of Test Force*—Typically, the force in the standard Brinell test shall be 29.42 kN (3000 kgf), 14.7 kN (1500 kgf), or 4.90 kN (500 kgf). It is recommended that the diameter of the indentation be between 24 and 60 % of the ball diameter. A lower limit in indentation diameter is necessary

TABLE 2 Brinell Hardness Numbers[A]

(Ball 10 mm in Diameter, Applied Forces of 500, 1500, and 3000 kgf)

NOTE 1—The values given in this table for Brinell hardness numbers are merely solutions of the equation given in the definition in 3.1.1, and include values for impression diameters outside the ranges recommended in 8.1. These values are indicated by italics.

Diameter of Indentation, mm	Brinell Hardness Number			Diameter of Indentation, mm	Brinell Hardness Number			Diameter of Indentation, mm	Brinell Hardness Number			Diameter of Indentation, mm	Brinell Hardness Number		
	500-kgf Force	1500-kgf Force	3000-kgf Force		500-kgf Force	1500-kgf Force	3000-kgf Force		500-kgf Force	1500-kgf Force	3000-kgf Force		500-kgf Force	1500-kgf Force	3000-kgf Force
2.00	*158*	*473*	*945*	2.60	92.6	278	555	3.20	60.5	182	363	3.80	42.4	127	255
2.01	*156*	*468*	*936*	2.61	91.8	276	551	3.21	60.1	180	361	3.81	42.2	127	253
2.02	*154*	*463*	*926*	2.62	91.1	273	547	3.22	59.8	179	359	3.82	42.0	126	252
2.03	*153*	*459*	*917*	2.63	90.4	271	543	3.23	59.4	178	356	3.83	41.7	125	250
2.04	*151*	*454*	*908*	2.64	89.7	269	538	3.24	59.0	177	354	3.84	41.5	125	249
2.05	*150*	*450*	*899*	2.65	89.0	267	534	3.25	58.6	176	352	3.85	41.3	124	248
2.06	*148*	*445*	*890*	2.66	88.4	265	530	3.26	58.3	175	350	3.86	41.1	123	246
2.07	*147*	*441*	*882*	2.67	87.7	263	526	3.27	57.9	174	347	3.87	40.9	123	245
2.08	*146*	*437*	*873*	2.68	87.0	261	522	3.28	57.5	173	345	3.88	40.6	122	244
2.09	*144*	*432*	*865*	2.69	86.4	259	518	3.29	57.2	172	343	3.89	40.4	121	242
2.10	*143*	*428*	*856*	2.70	85.7	257	514	3.30	56.8	170	341	3.90	40.2	121	241
2.11	*141*	*424*	*848*	2.71	85.1	255	510	3.31	56.5	169	339	3.91	40.0	120	240
2.12	*140*	*420*	*840*	2.72	84.4	253	507	3.32	56.1	168	337	3.92	39.8	119	239
2.13	*139*	*416*	*832*	2.73	83.8	251	503	3.33	55.8	167	335	3.93	39.6	119	237
2.14	*137*	*412*	*824*	2.74	83.2	250	499	3.34	55.4	166	333	3.94	39.4	118	236
2.15	*136*	*408*	*817*	2.75	82.6	248	495	3.35	55.1	165	331	3.95	39.1	117	235
2.16	*135*	*404*	*809*	2.76	81.9	246	492	3.36	54.8	164	329	3.96	38.9	117	234
2.17	*134*	*401*	*802*	2.77	81.3	244	488	3.37	54.4	163	326	3.97	38.7	116	232
2.18	*132*	*397*	*794*	2.78	80.8	242	485	3.38	54.1	162	325	3.98	38.5	116	231
2.19	*131*	*393*	*787*	2.79	80.2	240	481	3.39	53.8	161	323	3.99	38.3	115	230
2.20	*130*	*390*	*780*	2.80	79.6	239	477	3.40	53.4	160	321	4.00	38.1	114	229
2.21	*129*	*386*	*772*	2.81	79.0	237	474	3.41	53.1	159	319	4.01	37.9	114	228
2.22	*128*	*383*	*765*	2.82	78.4	235	471	3.42	52.8	158	317	4.02	37.7	113	226
2.23	*126*	*379*	*758*	2.83	77.9	234	467	3.43	52.5	157	315	4.03	37.5	113	225
2.24	*125*	*376*	*752*	2.84	77.3	232	464	3.44	52.2	156	313	4.04	37.3	112	224
2.25	*124*	*372*	*745*	2.85	76.8	230	461	3.45	51.8	156	311	4.05	37.1	111	223
2.26	*123*	*369*	*738*	2.86	76.2	229	457	3.46	51.5	155	309	4.06	37.0	111	222
2.27	*122*	*366*	*732*	2.87	75.7	227	454	3.47	51.2	154	307	4.07	36.8	110	221
2.28	*121*	*363*	*725*	2.88	75.1	225	451	3.48	50.9	153	306	4.08	36.6	110	219
2.29	*120*	*359*	*719*	2.89	74.6	224	448	3.49	50.6	152	304	4.09	36.4	109	218
2.30	*119*	*356*	*712*	2.90	74.1	222	444	3.50	50.3	151	302	4.10	36.2	109	217
2.31	*118*	*353*	*706*	2.91	73.6	221	441	3.51	50.0	150	300	4.11	36.0	108	216
2.32	*117*	*350*	*700*	2.92	73.0	219	438	3.52	49.7	149	298	4.12	35.8	108	215
2.33	*116*	*347*	*694*	2.93	72.5	218	435	3.53	49.4	148	297	4.13	35.7	107	214
2.34	*115*	*344*	*688*	2.94	72.0	216	432	3.54	49.2	147	295	4.14	35.5	106	213
2.35	*114*	*341*	*682*	2.95	71.5	215	429	3.55	48.9	147	293	4.15	35.3	106	212
2.36	*113*	*338*	*676*	2.96	71.0	213	426	3.56	48.6	146	292	4.16	35.1	105	211
2.37	*112*	*335*	*670*	2.97	70.5	212	423	3.57	48.3	145	290	4.17	34.9	105	210
2.38	*111*	*332*	*665*	2.98	70.1	210	420	3.58	48.0	144	288	4.18	34.8	104	209
2.39	*110*	*330*	*659*	2.99	69.6	209	417	3.59	47.7	143	286	4.19	34.6	104	208
2.40	*109*	*327*	*653*	3.00	69.1	207	415	3.60	47.5	142	285	4.20	34.4	103	207
2.41	108	324	648	3.01	68.6	206	412	3.61	47.2	142	283	4.21	34.2	103	205
2.42	107	322	643	3.02	68.2	205	409	3.62	46.9	141	282	4.22	34.1	102	204
2.43	106	319	637	3.03	67.7	203	406	3.63	46.7	140	280	4.23	33.9	102	203
2.44	105	316	632	3.04	67.3	202	404	3.64	46.4	139	278	4.24	33.7	101	202
2.45	104	313	627	3.05	66.8	200	401	3.65	46.1	138	277	4.25	33.6	101	201
2.46	104	311	621	3.06	66.4	199	398	3.66	45.9	138	275	4.26	33.4	100	200
2.47	103	308	616	3.07	65.9	198	395	3.67	45.6	137	274	4.27	33.2	99.7	199
2.48	102	306	611	3.08	65.5	196	393	3.68	45.4	136	272	4.28	33.1	99.2	198
2.49	101	303	606	3.09	65.0	195	390	3.69	45.1	135	271	4.29	32.9	98.8	198
2.50	100	301	601	3.10	64.6	194	388	3.70	44.9	135	269	4.30	32.8	98.3	197
2.51	99.4	298	597	3.11	64.2	193	385	3.71	44.6	134	268	4.31	32.6	97.8	196
2.52	98.6	296	592	3.12	63.8	191	383	3.72	44.4	133	266	4.32	32.4	97.3	195
2.53	97.8	294	587	3.13	63.3	190	380	3.73	44.1	132	265	4.33	32.3	96.8	194
2.54	97.1	291	582	3.14	62.9	189	378	3.74	43.9	132	263	4.34	32.1	96.4	193
2.55	96.3	289	578	3.15	62.5	188	375	3.75	43.6	131	262	4.35	32.0	95.9	192
2.56	95.5	287	573	3.16	62.1	186	373	3.76	43.4	130	260	4.36	31.8	95.5	191
2.57	94.8	284	569	3.17	61.7	185	370	3.77	43.1	129	259	4.37	31.7	95.0	190
2.58	94.0	282	564	3.18	61.3	184	368	3.78	42.9	129	257	4.38	31.5	94.5	189
2.59	93.3	280	560	3.19	60.9	183	366	3.79	42.7	128	256	4.39	31.4	94.1	188

because of the risk in damaging the ball and difficulty measuring the indentation. The upper limit is necessary because of a reduction in sensitivity as the diameter of the indentation approaches the ball diameter. The thickness and spacing requirements of 6.1.1, 6.1.2, and 8.3 may determine the maximum permissible diameter of indentation for a specific test. Table 6 gives standard test forces and approximate Brinell hardness numbers for the above range of indentation diameters.

TABLE 2 *Continued*

Diameter of Indentation, mm	Brinell Hardness Number			Diameter of Indentation, mm	Brinell Hardness Number			Diameter of Indentation, mm	Brinell Hardness Number			Diameter of Indentation, mm	Brinell Hardness Number		
	500-kgf Force	1500-kgf Force	3000-kgf Force		500-kgf Force	1500-kgf Force	3000-kgf Force		500-kgf Force	1500-kgf Force	3000-kgf Force		500-kgf Force	1500-kgf Force	3000-kgf Force
4.40	31.2	93.6	187	5.05	23.3	69.8	140	5.70	17.8	53.5	107	6.35	*14.0*	*42.0*	*84.0*
4.41	31.1	93.2	186	5.06	23.2	69.5	139	5.71	17.8	53.3	107	6.36	*13.9*	*41.8*	*83.7*
4.42	30.9	92.7	185	5.07	23.1	69.2	138	5.72	17.7	53.1	106	6.37	*13.9*	*41.7*	*83.4*
4.43	30.8	92.3	185	5.08	23.0	68.9	138	5.73	17.6	52.9	106	6.38	*13.8*	*41.5*	*83.1*
4.44	30.6	91.8	184	5.09	22.9	68.6	137	5.74	17.6	52.7	105	6.39	*13.8*	*41.4*	*82.8*
4.45	30.5	91.4	183	5.10	22.8	68.3	137	5.75	17.5	52.5	105	6.40	*13.7*	*41.2*	*82.5*
4.46	30.3	91.0	182	5.11	22.7	68.0	136	5.76	17.4	52.3	105	6.41	*13.7*	*41.1*	*82.2*
4.47	30.2	90.5	181	5.12	22.6	67.7	135	5.77	17.4	52.1	104	6.42	*13.6*	*40.9*	*81.9*
4.48	30.0	90.1	180	5.13	22.5	67.4	135	5.78	17.3	51.9	104	6.43	*13.6*	*40.8*	*81.6*
4.49	29.9	89.7	179	5.14	22.4	67.1	134	5.79	17.2	51.7	103	6.44	*13.5*	*40.6*	*81.3*
4.50	29.8	89.3	179	5.15	22.3	66.9	134	5.80	17.2	51.5	103	6.45	*13.5*	*40.5*	*81.0*
4.51	29.6	88.8	178	5.16	22.2	66.6	133	5.81	17.1	51.3	103	6.46	*13.4*	*40.4*	*80.7*
4.52	29.5	88.4	177	5.17	22.1	66.3	133	5.82	17.0	51.1	102	6.47	*13.4*	*40.2*	*80.4*
4.53	29.3	88.0	176	5.18	22.0	66.0	132	5.83	17.0	50.9	102	6.48	*13.4*	*40.1*	*80.1*
4.54	29.2	87.6	175	5.19	21.9	65.8	132	5.84	16.9	50.7	101	6.49	*13.3*	*39.9*	*79.8*
4.55	29.1	87.2	174	5.20	21.8	65.5	131	5.85	16.8	50.5	101	6.50	*13.3*	*39.8*	*79.6*
4.56	28.9	86.8	174	5.21	21.7	65.2	130	5.86	16.8	50.3	101	6.51	*13.2*	*39.6*	*79.3*
4.57	28.8	86.4	173	5.22	21.6	64.9	130	5.87	16.7	50.2	100	6.52	*13.2*	*39.5*	*79.0*
4.58	28.7	86.0	172	5.23	21.6	64.7	129	5.88	16.7	50.0	99.9	6.53	*13.1*	*39.4*	*78.7*
4.59	28.5	85.6	171	5.24	21.5	64.4	129	5.89	16.6	49.8	99.5	6.54	*13.1*	*39.2*	*78.4*
4.60	28.4	85.4	170	5.25	21.4	64.1	128	5.90	16.5	49.6	99.2	6.55	*13.0*	*39.1*	*78.2*
4.61	28.3	84.8	170	5.26	21.3	63.9	128	5.91	16.5	49.4	98.8	6.56	*13.0*	*38.9*	*78.0*
4.62	28.1	84.4	169	5.27	21.2	63.6	127	5.92	16.4	49.2	98.4	6.57	*12.9*	*38.8*	*77.6*
4.63	28.0	84.0	168	5.28	21.1	63.3	127	5.93	16.3	49.0	98.0	6.58	*12.9*	*38.7*	*77.3*
4.64	27.9	83.6	167	5.29	21.0	63.1	126	5.94	16.3	48.8	97.7	6.59	*12.8*	*38.5*	*77.1*
4.65	27.8	83.3	167	5.30	20.9	62.8	126	5.95	16.2	48.7	97.3	6.60	*12.8*	*38.4*	*76.8*
4.66	27.6	82.9	166	5.31	20.9	62.6	125	5.96	16.2	48.5	96.9	6.61	*12.8*	*38.3*	*76.5*
4.67	27.5	82.5	165	5.32	20.8	62.3	125	5.97	16.1	48.3	96.6	6.62	*12.7*	*38.1*	*76.2*
4.68	27.4	82.1	164	5.33	20.7	62.1	124	5.98	16.0	48.1	96.2	6.63	*12.7*	*38.0*	*76.0*
4.69	27.3	81.8	164	5.34	20.6	61.8	124	5.99	16.0	47.9	95.9	6.64	*12.6*	*37.9*	*75.7*
4.70	27.1	81.4	163	5.35	20.5	61.5	123	6.00	*15.9*	*47.7*	*95.5*	6.65	*12.6*	*37.7*	*75.4*
4.71	27.0	81.0	162	5.36	20.4	61.3	123	6.01	*15.9*	*47.6*	*95.1*	6.66	*12.5*	*37.6*	*75.2*
4.72	26.9	80.7	161	5.37	20.3	61.0	122	6.02	*15.8*	*47.4*	*94.8*	6.67	*12.5*	*37.5*	*74.9*
4.73	26.8	80.3	161	5.38	20.3	60.8	122	6.03	*15.7*	*47.2*	*94.4*	6.68	*12.4*	*37.3*	*74.7*
4.74	26.6	79.9	160	5.39	20.2	60.6	121	6.04	*15.7*	*47.0*	*94.1*	6.69	*12.4*	*37.2*	*74.4*
4.75	26.5	79.6	159	5.40	20.1	60.3	121	6.05	*15.6*	*46.8*	*93.7*	6.70	*12.4*	*37.1*	*74.1*
4.76	26.4	79.2	158	5.41	20.0	60.1	120	6.06	*15.6*	*46.7*	*93.4*	6.71	*12.3*	*36.9*	*73.9*
4.77	26.3	78.9	158	5.42	19.9	59.8	120	6.07	*15.5*	*46.5*	*93.0*	6.72	*12.3*	*36.8*	*73.6*
4.78	26.2	78.5	157	5.43	19.9	59.6	119	6.08	*15.4*	*46.3*	*92.7*	6.73	*12.2*	*36.7*	*73.4*
4.79	26.1	78.2	156	5.44	19.8	59.3	119	6.09	*15.4*	*46.2*	*92.3*	6.74	*12.2*	*36.6*	*73.1*
4.80	25.9	77.8	156	5.45	19.7	59.1	118	6.10	*15.3*	*46.0*	*92.0*	6.75	*12.1*	*36.4*	*72.8*
4.81	25.8	77.5	155	5.46	19.6	58.9	118	6.11	*15.3*	*45.8*	*91.7*	6.76	*12.1*	*36.3*	*72.6*
4.82	25.7	77.1	154	5.47	19.5	58.6	117	6.12	*15.2*	*45.7*	*91.3*	6.77	*12.1*	*36.2*	*72.3*
4.83	25.6	76.8	154	5.48	19.5	58.4	117	6.13	*15.2*	*45.5*	*91.0*	6.78	*12.0*	*36.0*	*72.1*
4.84	25.5	76.4	153	5.49	19.4	58.2	116	6.14	*15.1*	*45.3*	*90.6*	6.79	*12.0*	*35.9*	*71.8*
4.85	25.4	76.1	152	5.50	19.3	57.9	116	6.15	*15.1*	*45.2*	*90.3*	6.80	*11.9*	*35.8*	*71.6*
4.86	25.3	75.8	152	5.51	19.2	57.7	115	6.16	*15.0*	*45.0*	*90.0*	6.81	*11.9*	*35.7*	*71.3*
4.87	25.1	75.4	151	5.52	19.2	57.5	115	6.17	*14.9*	*44.8*	*89.6*	6.82	*11.8*	*35.5*	*71.1*
4.88	25.0	75.1	150	5.53	19.1	57.2	114	6.18	*14.9*	*44.7*	*89.3*	6.83	*11.8*	*35.4*	*70.8*
4.89	24.9	74.8	150	5.54	19.0	57.0	114	6.19	*14.8*	*44.5*	*89.0*	6.84	*11.8*	*35.3*	*70.6*
4.90	24.8	74.4	149	5.55	18.9	56.8	114	6.20	*14.7*	*44.3*	*88.7*	6.86	*11.7*	*35.2*	*70.4*
4.91	24.7	74.1	148	5.56	18.9	56.6	113	6.21	*14.7*	*44.2*	*88.3*	6.86	*11.7*	*35.1*	*70.1*
4.92	24.6	73.8	148	5.57	18.8	56.3	113	6.22	*14.7*	*44.0*	*88.0*	6.87	*11.6*	*34.9*	*69.9*
4.93	24.5	73.5	147	5.58	18.7	56.1	112	6.23	*14.6*	*43.8*	*87.7*	6.88	*11.6*	*34.8*	*69.6*
4.94	24.4	73.2	146	5.59	18.6	55.9	112	6.24	*14.6*	*43.7*	*87.4*	6.89	*11.6*	*34.7*	*69.4*
4.95	24.3	72.8	146	5.60	18.6	55.7	111	6.25	*14.5*	*43.5*	*87.1*	6.90	*11.5*	*34.6*	*69.2*
4.96	24.2	72.5	145	5.61	18.5	55.5	111	6.26	*14.5*	*43.4*	*86.7*	6.91	*11.5*	*34.5*	*68.9*
4.97	24.1	72.2	144	5.62	18.4	55.2	110	6.27	*14.4*	*43.2*	*86.4*	6.92	*11.4*	*34.3*	*68.7*
4.98	24.0	71.9	144	5.63	18.3	55.0	110	6.28	*14.4*	*43.1*	*86.1*	6.93	*11.4*	*34.2*	*68.4*
4.99	23.9	71.6	143	5.64	18.3	54.8	110	6.29	*14.3*	*42.9*	*85.8*	6.94	*11.4*	*34.1*	*68.2*
5.00	23.8	71.3	143	5.65	18.2	54.6	109	6.30	*14.2*	*42.7*	*85.5*	6.95	*11.3*	*34.0*	*68.0*
5.01	23.7	71.0	142	5.66	18.1	54.4	109	6.31	*14.2*	*42.6*	*85.2*	6.96	*11.3*	*33.9*	*67.7*
5.02	23.6	70.7	141	5.67	18.1	54.2	108	6.32	*14.1*	*42.4*	*84.9*	6.97	*11.3*	*33.8*	*67.5*
5.03	23.5	70.4	141	5.68	18.0	54.0	108	6.33	*14.1*	*42.3*	*84.6*	6.98	*11.2*	*33.6*	*67.3*
5.04	23.4	70.1	140	5.69	17.9	53.7	107	6.34	*14.0*	*42.1*	*84.3*	6.99	*11.2*	*33.5*	*67.0*

[A] Prepared by the Engineering Mechanics Section, National Bureau of Standards.

It is not mandatory that the Brinell test conform to these hardness ranges, but it should be realized that different Brinell hardness numbers may be obtained for a given material by using different forces on a 10-mm diameter ball. For the purpose of obtaining a continuous scale of values it may be desirable, however, to use a single force to cover the complete

TABLE 3 Test Conditions

Hardness Symbol	Ball Diameter *D*, mm	0.102 *F* / D^2	Test Force *F* Nominal Value	
HBW 10/3000	10	30	29.42	kN − (3000 kgf)
HBW 10/1500	10	15	14.71	kN − (1500 kgf)
HBW 10/1000	10	10	9.807	kN − (1000 kgf)
HBW 10/500	10	5	4.903	kN − (500 kgf)
HBW 10/250	10	2.5	2.452	kN − (250 kgf)
HBW 10/125	10	1.25	1.226	kN − (125 kgf)
HBW 10/100	10	1	980.7	N − (100 kgf)
HBW 5/750	5	30	7.355	kN − (750 kgf)
HBW 5/250	5	10	2.452	kN − (250 kgf)
HBW 5/125	5	5	1.226	kN − (125 kgf)
HBW 5/62.5	5	2.5	612.9	N − (62.5 kgf)
HBW 5/31.25	5	1.25	306.5	N − (31.25 kgf)
HBW 5/25	5	1	245.2	N − (25 kgf)
HBW 2.5/187.5	2.5	30	1.839	kN − (187.5 kgf)
HBW 2.5/62.5	2.5	10	612.9	N − (62.5 kgf)
HBW 2.5/31.25	2.5	5	306.5	N − (31.25 kgf)
HBW 2.5/15.625	2.5	2.5	153.2	N − (15.625 kgf)
HBW 2.5/7.812.5	2.5	1.25	76.61	N − (7.8125 kgf)
HBW 2.5/6.25	2.5	1	61.29	N − (6.25 kgf)
HBW 2/120	2	30	1.177	kN − (120 kgf)
HBW 2/40	2	10	392.3	N − (40 kgf)
HBW 2/20	2	5	196.1	N − (20 kgf)
HBW 2/10	2	2.5	98.07	N − (10 kgf)
HBW 2/5	2	1.25	49.03	N − (5 kgf)
HBW 2/4	2	1	39.23	N − (4 kgf)
HBW 1/30	1	30	294.2	N − (30 kgf)
HBW 1/10	1	10	98.07	N − (10 kgf)
HBW 1/5	1	5	49.03	N − (5 kgf)
HBW 1/2.5	1	2.5	24.52	N − (2.5 kgf)
HBW 1/1.25	1	1.25	12.26	N − (1.25 kgf)
HBW 1/1	1	1	9.807	N − (1 kgf)

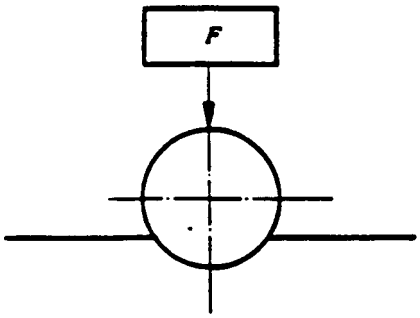


FIG. 1 Principle of Test

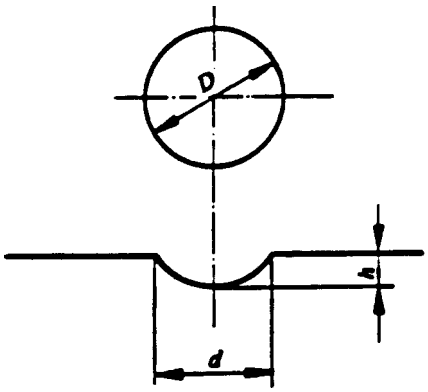


FIG. 2 Principle of Test

TABLE 4 Tolerances for Brinell Hardness Balls

Ball Diameter, mm	Tolerance, mm
10	±0.005
5	±0.004
2.5	±0.003
2	±0.003
1	±0.003

TABLE 5 Minimum Thickness Requirements for Brinell Hardness Tests

Minimum Thickness of Specimen		Minimum Hardness for Which the Brinell Test May Safely Be Made		
in.	mm	3000-kgf Force	1500-kgf Force	500-kgf Force
1/16	1.6	602	301	100
1/8	3.2	301	150	50
3/16	4.8	201	100	33
1/4	6.4	150	75	25
5/16	8.0	120	60	20
3/8	9.6	100	50	17

TABLE 6 Standard Test Forces

Ball Diameter, mm	Force	Recommended Range, HBW
10	29.42 kN (3000 kgf)	96 to 600
10	14.7 kN (1500 kgf)	48 to 300
10	4.90 kN (500 kgf)	16 to 100

range of hardness for a given class of materials. For softer metals, forces of 2.45 kN (250 kgf), 1.23 kN (125 kgf), or 0.981 kN (100 kgf) are sometimes used. The force used shall be specifically stated in the test report (see 11.1.2).

TABLE 7 Hardness Ranges Used By Standard Test Block Method

100 to 200 HBW
300 to 400 HBW
500 to 600 HBW

8.1.1 For testing thin or small specimens, a ball less than 10 mm in diameter is sometimes used. Such tests, which are not to be regarded as standard tests, will approximate the standard tests more closely if the relation between the applied force, *F*, measured in N, and the diameter of the ball, *D*, measured in mm is the same as in the standard tests,

where:

$0.102F/D^2$ = 30 for 29.42 kN (3000 kgf) force and 10-mm ball,

$0.102F/D^2$ = 15 for 14.72 kN (1500 kgf) force and 10-mm ball, and

$0.102F/D^2$ = 5 for 4.90 kN (500 kgf) force and 10-mm ball.

8.1.1.1 *Example*—A 1.23-kN (125-kgf) test force on a 5-mm diameter ball would approximate a standard 4.90-kN (500-kgf) test force on a 10-mm diameter ball.

8.1.2 Tests for soft metals often are made with the following force-diameter ratios:

$$0.102F/D^2 = 2.5 \quad (2)$$

$$0.102F/D^2 = 1.25$$

$$0.102F/D^2 = 1.0$$

8.1.3 When balls smaller than 10 mm in diameter are used, both the test force and ball size shall be specifically stated in the test report (see 3.1.1, 3.1.1.1, and 11.1.2).

8.2 *Radius of Curvature*—When indentations are made on a curved surface, the minimum radius of curvature of the surface shall be not less than 2½ times the diameter of the ball. Indentations made on curved surfaces may be slightly elliptical rather than circular in shape. The measurements of the indentation shall be taken as the mean of the major and minor axes.

8.3 *Spacing of Indentations*—The distance of the center of the indentation from the edge of the specimen or edge of another indentation shall be at least two and one half times the diameter of the indentation.

8.4 *Application of Test Force*—Apply the force to the specimen uniformly taking precautions to prevent a momentary overload of the system. Apply the full test force for 10 to 15 s.

8.4.1 If a duration of test force application other than 10 to 15 s is used, results of the test shall be reported using the nomenclature outlined in 4.2 and 11.1.2.

8.5 *Alignment*—The angle between the indenter force line and the surface of the specimen should be 90 ± 2°. (see 9.1)

9. Measurement of Indentation

9.1 *Diameter*—In the Brinell hardness test, two diameters of the indentation at right angles to each other shall be measured and their mean value used as a basis for calculation of the Brinell hardness number for flat specimens. If the largest and smallest diameters for two readings of the same indentation differ by 0.1 mm or more, refer to the material specifications for further guidance. For routine tests and for tests to determine compliance with a material or product specification, the diameter of the indentation shall be estimated to 0.05 mm (0.0020 in.).

NOTE 4—These measurements are usually made with a low-magnification portable measuring device (approximately 20×) having a fixed scale in the eyepiece. If a more accurate determination is needed, as in referee or standardization tests, a laboratory comparator such as a micrometer measuring device is required.

10. Conversion to Other Hardness Scales or Tensile Strength Values

10.1 There is no general method for accurately converting Brinell hardness numbers to other hardness scales or tensile strength values. Such conversion are, at best, approximations and, therefore, should be avoided except for special cases where a reliable basis for the approximate conversion has been obtained by comparison tests.

NOTE 5—Hardness Conversion Tables E 140 for Metals give approximate hardness conversion values for specific materials such as steel, austenitic stainless steel, nickel and high-nickel alloys, and cartridge brass.

11. Report

11.1 Whenever a Brinell hardness number is used, provide the following information:

11.1.1 The Brinell hardness number, which shall be reported rounded to three significant digits in accordance with rounding method in Practice E 29 (for example, 125 HBW, 99.2 HBW).

11.1.2 The test conditions when the Brinell hardness number is determined from forces other than 29.42 kN (3000 kgf), ball diameters other than 10 mm, and test force applications other than 10 to 15 s (see 3.1.1 and 8.4).

12. Precision and Bias

12.1 *Precision*—An interlaboratory comparison program is now in progress which, when completed, will be the basis of a statement on precision.

12.2 *Bias*—There is no basis for defining the bias for this test method.

TEST METHOD B—VERIFICATION OF BRINELL HARDNESS TESTING MACHINES

13. Scope

13.1 Test Method B covers two procedures for the verification of Brinell hardness testing machines. These are as follows:

13.1.1 *Direct Verification*—Separate verification of force application, indenter, and the measuring device for measuring the diameter of the indentation.

13.1.2 *Indirect Verification*—Verification by the standardized test block method.

13.2 New or rebuilt machines shall be initially checked by the direct verification method (see 13.1.1) before being placed in service.

13.3 Machines used for routine testing may be checked by either verification method.

14. General Requirements

14.1 Before a Brinell hardness testing machine is verified,

the machine shall be examined to ensure that:

14.1.1 The machine is set up properly.

14.1.2 The ball holder, with a new ball whose nominal diameter has been checked (see 15.1.2), is mounted firmly in the plunger.

14.1.3 The force will be applied and removed without shock or vibration.

14.2 If the measuring device is integral with the machine, the machine shall be examined to ensure the following:

14.2.1 The change from test force application to measuring does not influence the readings.

14.2.2 The method of illumination does not affect the readings.

14.2.3 The center of the indentation is in the center of the field of view.

15. Verification

15.1 *Direct Verification*—Separate verification of force application, indenter, and measuring device:

15.1.1 *Force Application*—Brinell hardness testing machines shall be verified at the test force(s) at which it is used. The test forces will be checked periodically with a force measuring device traceable to national standards (in the United States, National Institute of Standards and Technology) in the manner described in Practices E 4. A Brinell hardness testing machine is acceptable for use when the test force error does not exceed ±1 %.

15.1.2 *Indenter*—The indenter to be verified shall be a new ball selected at random from a lot meeting the hardness requirements specified in 5.2. The diameter of each ball shall be verified at not less than three positions and the mean of these readings shall not differ from the nominal diameter by more than the tolerance specified in Table 4.

15.1.3 *Measuring Device*—The measuring device used to determine the diameter of the indentation shall be verified at five intervals over the working range by the use of an accurate scale such as a stage micrometer. The adjustment of the device shall be such that, throughout the range covered, the difference between the scale divisions of the device and of the calibrating scale does not exceed 0.01 mm (0.0004 in.).

15.1.4 The verification is incomplete if a verification report is not issued.

15.2 *Indirect Verification*—Verification by standardized test block method.

15.2.1 A Brinell hardness testing machine also may be checked by making a series of at least five indentations on standardized hardness test blocks (Test Method C).

15.2.2 If the machine is to be used at conditions other than 10/29.42 kN (3000 kgf)/15, the machine also shall be verified at those other conditions.

15.2.3 The testing machine shall be verified for each test force and for each size of ball used. For each test force, standardized blocks within the hardness ranges given in Table 7, shall be used.

NOTE 6—When the hardness test in question makes it impossible to reach the higher hardness range defined in Table 7 (for $0.102/F/D^2 = 5$ or 10), the verification may be carried out with two blocks from the lower hardness range.

15.2.3.1 Verification shall be carried out using a tungsten carbide ball and this verification will be valid for hardnesses ≤ 650 HBW.

15.2.4 *Repeatability*—For each standardized block, let $d_1, d_2, \ldots, d_n$ be the mean values of the measured diameter of the indentations, arranged in increasing order of magnitude. The repeatability of the testing machine under the particular verification conditions is determined by the following quantity:

$$d_n - d_1 \tag{3}$$

The repeatability of the testing machine verified is not considered satisfactory unless it satisfies the conditions given in Table 8.

15.2.5 *Error*—The error of the testing machine under the particular verification conditions is characterized by the following quantity:

$$\bar{H} - H \tag{4}$$

where:

error = $\bar{H} - H$

$$\bar{H} = \frac{H_1 + H_2 \ldots H_n}{n} \tag{5}$$

$H_1, H_2, \ldots, H_n$ = the hardness values corresponding to $d_1, d_2, \ldots, d_n$, and

H = specified hardness of the standardized block.

15.2.6 The Brinell hardness testing machine shall be considered verified if the mean hardness differs by no more than 3 % from the hardness value of the standardized hardness test block.

15.2.7 The verification is incomplete if a verification report is not issued.

15.3 *Verification Report*—The test report shall include the following information:

15.3.1 Reference to this ASTM test method,

15.3.2 Method of verification (direct or indirect),

15.3.3 Identification of the hardness testing machine,

15.3.4 Means of verification (test blocks, elastic proving devices, etc.),

15.3.5 Diameter of indenter ball and test force,

15.3.6 The result obtained,

15.3.7 Date of verification and reference to the calibration institution, and

15.3.8 Identity of person performing the verification.

16. Procedure for Periodic Checks by the User

16.1 Verification by the standardized test block method (15.2) is too lengthy for daily use. Instead, the following is recommended:

TABLE 8 Repeatability of Testing Machine

Hardness of Standardized Block HBW	Repeatability of the Testing Machine, max	HBW	
		H	H_1–H_5, max
<225	0.04 $\bar{d}$	100	9
		200	17
>225	0.02 $\bar{d}$	300	12
		400	17
		500	20
		600	24

16.1.1 Make at least one routine check in accordance with 16.1.2 each day that the testing machine is used.

16.1.2 Consult the machine manufacturer's start-up procedures. Select the force, indenter, and measuring device that will be used for the routine testing. Make at least two indentations on a standardized hardness test block. If the mean of these two values falls within the tolerances required (see 15.2.6), the hardness machine may be regarded as producing satisfactory hardness results. If not, the hardness machine shall be verified as described in 15.2.

TEST METHOD C—CALIBRATION OF STANDARDIZED HARDNESS TEST BLOCKS FOR BRINELL HARDNESS TESTING MACHINES

17. Scope

17.1 This test method covers the calibration of standardized hardness test blocks for the verification of Brinell hardness testing machines as described in Test Method B.

18. Manufacture

18.1 Each metal block to be calibrated shall be not less than 16 mm (⅝ in.) in thickness for 10-mm balls, 12 mm (½ in.) thick for 5-mm balls, and 6 mm (¼in.) thick for smaller balls.

18.1.1 The maximum surface area of the test block shall be 40 cm^2 (6 $in.^2$) for balls less than 5 mm in diameter, and 150 cm^2 (24 $in.^2$) for balls equal to or greater than 5 mm in diameter.

18.2 Each block shall be specially prepared and heat treated to give the necessary homogeneity and stability of structure.

18.3 The maximum error in parallelism shall not exceed 0.0008 mm/mm (in./in.) for blocks when used with balls having a diameter greater than or equal to 5 mm and 0.0002 mm/mm (in./in.) for blocks when used with balls having a diameter less than 5 mm. The maximum deviation in flatness of the block surfaces shall not exceed 0.02 mm (0.0008 in.) and 0.005 mm (0.0002 in.) for balls having diameters equal to or greater than 5 mm and less than 5 mm, respectively.

18.4 The supporting surface of the test block shall have a ground finish and shall have a mean surface roughness height rating that shall not exceed 0.0008-mm (32-µin.) centerline average.

18.5 The test surface shall be free of scratches which would interfere with measurements of the diameters of the indentation.

18.5.1 The mean surface roughness height of the test surface rating shall not exceed 0.0003-mm (12-µin.) center line average for the standard 10-mm ball. For smaller balls a maximum mean test surface roughness height rating of 0.00015 mm (6 µin.) is recommended.

18.6 To permit checking that no material is subsequently removed from the standardized block, its thickness at the time of standardization shall be marked on it to the nearest 0.1 mm (0.004 in.), or an identifying mark shall be made on the test surface. (See Section 24.)

18.7 Each block, if of steel, shall be demagnetized by the manufacturer and maintained demagnetized by the user.

18.8 Each block must be uniquely serialized by the manufacturer for traceability.

19. Standardizing Procedure

19.1 The standardized blocks shall be calibrated on a Brinell hardness testing machine which was verified in accordance with the requirements of 15.1.

19.2 The mechanism that controls the application of the force shall ensure that the speed of approach immediately before the ball touches the specimen and the speed of penetration does not exceed 1 mm/s (0.040 in./s).

19.3 The test force shall be within 0.25 % of the nominal force. Use of a Practice E 74 Class AA device will be required to verify the force.

19.4 The test force shall be applied for 10 to 15 s.

19.5 The standardized blocks shall be calibrated at a temperature of 23 ± 5°C, using the general procedure described in Test Method A.

20. Indenter

20.1 A ball conforming to the requirements of 15.1.2 shall be used for calibrating standardized hardness test blocks.

21. Number of Indentations

21.1 At least five uniformly distributed indentations shall be made on the test surface of the block.

22. Measurement of the Diameters of the Indentation

22.1 The illuminating system of the measuring device shall be adjusted to give uniform intensity over the field of view and maximum contrast between the indentations and the undisturbed surface of the block.

22.2 The measuring device shall be graduated to read 0.002 mm (0.00008 in.) for indentations made with balls of 5-mm diameter or larger and 0.001 mm (0.00004 in.) for indentations made with balls of smaller diameter.

22.3 The measuring device shall be checked by a stage micrometer, or by other suitable means to ensure that the difference between readings corresponding to any two divisions of the instrument is within ±0.001 mm (0.00004 in.) for balls of less than 5-mm diameter and within ±0.002 mm (0.00008 in.) for balls of larger diameter.

23. Uniformity of Hardness

23.1 If d_1, d_2, . . ., d_n are the mean values of the measured diameters as determined by one observer and arranged in increasing order of magnitude, the range of the hardness readings, measured from the last block, is defined as $d_n - d_1$ where n = at least five indentations.

23.2 The range of hardness readings shall be equal to or less than 2 % of the mean diameter for Brinell hardness numbers equal to or less than 225 and 1 % for Brinell hardness number values greater than 225.

24. Marking

24.1 Each standardized block shall be marked with the following:

24.1.1 The arithmetic mean of the hardness values found in the standardizing test and the type of ball used.

24.1.2 The name or mark of the supplier.

24.1.3 The serial number or other unique identification of the block.

24.1.4 Name or mark of the calibrating agency if different from supplier.

24.1.5 The thickness of the block or an official mark on the test surface (see 18.6).

24.1.6 The year of calibration. It is sufficient that the year of calibration be incorporated into the serial number of the block.

24.2 All of the markings except the official mark should be placed outside of the test area or on the side of the block. When the markings are on the side of the block, the markings shall be upright when the test surface is the upper face.

24.3 Each block shall be supplied with a certificate showing the results of the individual standardizing tests and the arithmetic mean of those tests, including the following:

24.3.1 Date of standardization,

24.3.2 Serial number of block, and

24.3.3 Name of manufacturer or mark of supplier.

25. Keywords

25.1 Brinell hardness; metallic

SUMMARY OF CHANGES

Committee E28 has identified the location of selected changes to this standard since the last issue E 10-00a that may impact the use of this standard. The numbering system used in this Summary reflects current numbering of this edition of E 10.

NOTE 7—Most of the changes listed below resulted from the new requirement for using only tungsten-carbide indenter balls and disallowing the use of steel indenter balls (see 5.2.2.2

(1) 2.1 –E 74 title revised.
(2) 3 –definitions alphabetized and new numbering structure used.
(3) 3.1 –new title added.
(4) 3.1.1 (formerly 3.2) - revised
(5) Equation 1– editorial correction
(6) 3.1.1.1 (formerly Note 2) - revised
(7) 3.1.1.2 (formerly Note 3) - revised
(8) 3.1.1.3 (formerly part of Note 3)
(9) 3.1.1.4 (formerly part of Note 3)
(10) 3.1.2 (formerly 3.2) - revised
(11) 3.1.2.1 (formerly Discussion 1) - revised
(12) Former Discussion 2–deleted)
(13) Former Discussion 3 – deleted
(14) Table 1–revised and editorially corrected
(15) 3.1.3 (formerly 3.4)
(16) 3.1.4 (formerly 3.3)
(17) 5.2.2–replaced
(18) Former Note 5–deleted
(19) 5.2.2.2–added
(20) 5.2.3–revised
(21) Table 2–revised
(22) Table 3–revised
(23) Table 5–revised
(24) Table 6 (formerly Table 7) - revised
(25) Table 7 (formerly Table 6) - revised
(26) Former Table 8 - deleted
(27) 8.5-revised
(28) 11.1.1–revised
(29) 15.2.3–revised
(30) 15.2.3.1–revised
(31) 15.3.5- revised
(32) Table 9–renumbered as Table 8 and revised
(33) Summary of Changes added.

ANEXO A-3

NORMA ASTM E-112

Designation: E 112 – 96ε1

An American National Standard

Standard Test Methods for Determining Average Grain Size[1]

This standard is issued under the fixed designation E 112; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

ε[1] NOTE—Equations A1.4, A1.5 and A1.6 were editorially revised in April 2000.

INTRODUCTION

These test methods of determination of average grain size in metallic materials are primarily measuring procedures and, because of their purely geometric basis, are independent of the metal or alloy concerned. In fact, the basic procedures may also be used for the estimation of average grain, crystal, or cell size in nonmetallic materials. The comparison method may be used if the structure of the material approaches the appearance of one of the standard comparison charts. The intercept and planimetric methods are always applicable for determining average grain size. However, the comparison charts cannot be used for measurement of individual grains.

1. Scope

1.1 These test methods cover the measurement of average grain size and include the comparison procedure, the planimetric (or Jeffries) procedure, and the intercept procedures. These test methods may also be applied to nonmetallic materials with structures having appearances similar to those of the metallic structures shown in the comparison charts. These test methods apply chiefly to single phase grain structures but they can be applied to determine the average size of a particular type of grain structure in a multiphase or multiconstituent specimen.

1.2 These test methods are used to determine the average grain size of specimens with a unimodal distribution of grain areas, diameters, or intercept lengths. These distributions are approximately log normal. These test methods do not cover methods to characterize the nature of these distributions. Characterization of grain size in specimens with duplex grain size distributions is described in Test Methods E 1181. Measurement of individual, very coarse grains in a fine grained matrix is described in Test Methods E 930.

1.3 These test methods deal only with determination of planar grain size, that is, characterization of the two-dimensional grain sections revealed by the sectioning plane. Determination of spatial grain size, that is, measurement of the size of the three-dimensional grains in the specimen volume, is beyond the scope of these test methods.

1.4 These test methods describe techniques performed manually using either a standard series of graded chart images for the comparison method or simple templates for the manual counting methods. Utilization of semi-automatic digitizing tablets or automatic image analyzers to measure grain size is described in Test Methods E 1382.

1.5 These test methods deal only with the recommended test methods and nothing in them should be construed as defining or establishing limits of acceptability or fitness of purpose of the materials tested.

1.6 The measured values are stated in SI units, which are regarded as standard. Equivalent inch-pound values, when listed, are in parentheses and may be approximate.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.8 The paragraphs appear in the following order:

[1] These test methods are under the jurisdiction of ASTM Committee E-4 on Metallography and are the direct responsibility of Subcommittee E04.08 on Grain Size.

Current edition approved May 10, 1996. Published July 1996. Originally published as E 112 – 55 T. Last previous edition E 112 – 95.

2. Referenced Documents

2.1 *ASTM Standards:*

E 3 Practice for Preparation of Metallographic Specimens[2]

E 7 Terminology Relating to Metallography[2]

E 407 Practice for Microetching Metals and Alloys[2]

E 562 Practice for Determining Volume Fraction by Systematic Manual Point Count[2]

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[3]

E 883 Guide for Reflected-Light Photomicrography[2]

E 930 Test Methods for Estimating the Largest Grain Observed in a Metallographic Section (ALA Grain Size)[2]

E 1181 Test Methods for Characterizing Duplex Grain Sizes[2]

E 1382 Test Methods for Determining Average Grain Size Using Semiautomatic and Automatic Image Analysis[2]

2.2 ASTM Adjuncts:

2.2.1 For a complete adjunct list, see Appendix X2

3. Terminology

3.1 *Definitions*—For definitions of terms used in these test methods, see Terminology E 7.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *ASTM grain size number*—the ASTM grain size number, *G*, was originally defined as:

$$N_{AE} = 2^{G-1} \quad (1)$$

where N_{AE} is the number of grains per square inch at 100X magnification. To obtain the number per square millimetre at 1X, multiply by 15.50.

3.2.2 *grain*—that area within the confines of the original (primary) boundary observed on the two-dimensional plane-of-polish or that volume enclosed by the original (primary) boundary in the three-dimensional object. In materials containing twin boundaries, the twin boundaries are ignored, that is, the structure on either side of a twin boundary belongs to the grain.

3.2.3 *grain boundary intersection count*—determination of the number of times a test line cuts across, or is tangent to, grain boundaries (triple point intersections are considered as 1-½ intersections).

3.2.4 *grain intercept count*—determination of the number of times a test line cuts through individual grains on the plane of polish (tangent hits are considered as one half an interception; test lines that end within a grain are considered as one half an interception).

3.2.5 *intercept length*—the distance between two opposed, adjacent grain boundary intersection points on a test line segment that crosses the grain at any location due to random placement of the test line.

3.3 *Symbols:Symbols:*

α	=	matrix grains in a two phase (constituent) microstructure.
A	=	test area.
$\overline{A}$	=	mean grain cross sectional area.
AI_ℓ	=	grain elongation ratio or anisotropy index for a longitudinally oriented plane.
$\overline{d}$	=	mean planar grain diameter (Plate III).
$\overline{D}$	=	mean spatial (volumetric) grain diameter.
f	=	Jeffries multiplier for planimetric method.
G	=	ASTM grain size number.
ℓ	=	mean lineal intercept length.
$\overline{\ell}_\alpha$	=	mean lineal intercept length of the α matrix phase in a two phase (constituent) microstructure.
$\overline{\ell}_\ell$	=	mean lineal intercept length on a longitudinally oriented surface for a non-equiaxed grain structure.
$\overline{\ell}_t$	=	mean lineal intercept length on a transversely oriented surface for a non-equiaxed grain structure.
$\overline{\ell}_p$	=	mean lineal intercept length on a planar oriented surface for a non-equiaxed grain structure.
ℓ_0	=	base intercept length of 32.00 mm for defining the relationship between G and ℓ (and N_L) for macroscopically or microscopically determined grain size by the intercept method.
L	=	length of a test line.
M	=	magnification used.
M_b	=	magnification used by a chart picture series.
n	=	number of fields measured.
N_α	=	number of α grains intercepted by the test line in a two phase (constituent) microstructure.
N_A	=	number of grains per mm^2 at 1X.
$N_{A\alpha}$	=	number of α grains per mm^2 at 1X in a two phase (constituent) microstructure.
N_{AE}	=	number of grains per inch^2 at 100X.
$N_{A\ell}$	=	N_A on a longitudinally oriented surface for a non-equiaxed grain structure.
N_{At}	=	N_A on a transversely oriented surface for a non-equiaxed grain structure.

[2] *Annual Book of ASTM Standards*, Vol 03.01.

[3] *Annual Book of ASTM Standards*, Vol 14.02.

N_{Ap} = N_A on a planar oriented surface for a non-equiaxed grain structure.
N_i = number of intercepts with a test line.
N_{Inside} = number of grains completely within a test circle.
$N_{\text{Intercepted}}$ = number of grains intercepted by the test circle.
N_L = number of intercepts per unit length of test line.
$N_{L\ell}$ = N_L on a longitudinally oriented surface for a non-equiaxed grain structure.
N_{Lt} = N_L on a transversely oriented surface for a non-equiaxed grain structure.
N_{Lp} = N_L on a planar oriented surface for a non-equiaxed grain structure.
P_i = number of grain boundary intersections with a test line.
P_L = number of grain boundary intersections per unit length of test line.
$P_{L\ell}$ = P_L on a longitudinally oriented surface for a non-equiaxed grain structure.
P_{Lt} = P_L on a transversely oriented surface for a non-equiaxed grain structure.
P_{Lp} = P_L on a planar oriented surface for a non-equiaxed grain structure.
Q = correction factor for comparison chart ratings using a non-standard magnification for microscopically determined grain sizes.
Q_m = correction factor for comparison chart ratings using a non-standard magnification for macroscopically determined grain sizes.
s = standard deviation.
S_V = grain boundary surface area to volume ratio for a single phase structure.
$S_{V\alpha}$ = grain boundary surface area to volume ratio for a two phase (constituent) structure.
t = students' t multiplier for determination of the confidence interval.
$V_{V\alpha}$ = volume fraction of the α phase in a two phase (constituent) microstructure.
95 % CI = 95 % confidence interval.
% RA = percent relative accuracy.

4. Significance and Use

4.1 These test methods cover procedures for estimating and rules for expressing the average grain size of all metals consisting entirely, or principally, of a single phase. The test methods may also be used for any structures having appearances similar to those of the metallic structures shown in the comparison charts. The three basic procedures for grain size estimation are:

4.1.1 *Comparison Procedure*—The comparison procedure does not require counting of either grains, intercepts, or intersections but, as the name suggests, involves comparison of the grain structure to a series of graded images, either in the form of a wall chart, clear plastic overlays, or an eyepiece reticle. There appears to be a general bias in that comparison grain size ratings claim that the grain size is somewhat coarser (½ to 1 *G* number lower) than it actually is (see X1.3.5). Repeatability and reproducibility of comparison chart ratings are generally ±1 grain size number.

4.1.2 *Planimetric Procedure*—The planimetric method involves an actual count of the number of grains within a known area. The number of grains per unit area, N_A , is used to determine the ASTM grain size number, *G*. The precision of the method is a function of the number of grains counted. A precision of ±0.25 grain size units can be attained with a reasonable amount of effort. Results are free of bias and repeatability and reproducibility are less than ±0.5 grain size units. An accurate count does require marking off of the grains as they are counted.

4.1.3 *Intercept Procedure*—The intercept method involves an actual count of the number of grains intercepted by a test line or the number of grain boundary intersections with a test line, per unit length of test line, used to calculate the mean lineal intercept length, $\overline{\ell}$. $\overline{\ell}$ is used to determine the ASTM grain size number, *G*. The precision of the method is a function of the number of intercepts or intersections counted. A precision of better than ±0.25 grain size units can be attained with a reasonable amount of effort. Results are free of bias; repeatability and reproducibility are less than ±0.5 grain size units. Because an accurate count can be made without need of marking off intercepts or intersections, the intercept method is faster than the planimetric method for the same level of precision.

4.2 For specimens consisting of equiaxed grains, the method of comparing the specimen with a standard chart is most convenient and is sufficiently accurate for most commercial purposes. For higher degrees of accuracy in determining average grain size, the intercept or planimetric procedures may be used. The intercept procedure is particularly useful for structures consisting of elongated grains.

4.3 In case of dispute, the intercept procedure shall be the referee procedure in all cases.

4.4 No attempt should be made to estimate the average grain size of heavily cold-worked material. Partially recrystallized wrought alloys and lightly to moderately cold-worked material may be considered as consisting of non-equiaxed grains, if a grain size measurement is necessary.

4.5 *Individual grain measurements should not be made based on the standard comparison charts*. These charts were constructed to reflect the typical log-normal distribution of grain sizes that result when a plane is passed through a three-dimensional array of grains. Because they show a distribution of grain dimensions, ranging from very small to very large, depending on the relationship of the planar section and the three-dimensional array of grains, the charts are not applicable to measurement of individual grains.

5. Generalities of Application

5.1 It is important, in using these test methods, to recognize that the estimation of average grain size is not a precise measurement. A metal structure is an aggregate of three-dimensional crystals of varying sizes and shapes. Even if all these crystals were identical in size and shape, the grain cross

sections, produced by a random plane (surface of observation) through such a structure, would have a distribution of areas varying from a maximum value to zero, depending upon where the plane cuts each individual crystal. Clearly, no two fields of observation can be exactly the same.

5.2 The size and location of grains in a microstructure are normally completely random. No nominally random process of positioning a test pattern can improve this randomness, but random processes can yield poor representation by concentrating measurements in part of a specimen. *Representative* implies that all parts of the specimen contribute to the result, not, as sometimes has been presumed, that fields of average grain size are selected. Visual selection of fields, or casting out of extreme measurements, may not falsify the average when done by unbiased experts, but will in all cases give a false impression of high precision. For representative sampling, the area of the specimen is mentally divided into several equal coherent sub-areas and stage positions prespecified, which are approximately at the center of each sub-area. The stage is successively set to each of these positions and the test pattern applied blindly, that is, with the light out, the shutter closed, or the eye turned away. No touch-up of the position so selected is allowable. Only measurements made on fields chosen in this way can be validated with respect to precision and bias.

6. Sampling

6.1 Specimens should be selected to represent average conditions within a heat lot, treatment lot, or product, or to assess variations anticipated across or along a product or component, depending on the nature of the material being tested and the purpose of the study. Sampling location and frequency should be based upon agreements between the manufacturers and the users.

6.2 Specimens should not be taken from areas affected by shearing, burning, or other processes that will alter the grain structure.

7. Test Specimens

7.1 In general, if the grain structure is equiaxed, any specimen orientation is acceptable. However, the presence of an equiaxed grain structure in a wrought specimen can only be determined by examination of a plane of polish parallel to the deformation axis.

7.2 If the grain structure on a longitudinally oriented specimen is equiaxed, then grain size measurements on this plane, or any other, will be equivalent within the statistical precision of the test method. If the grain structure is not equiaxed, but elongated, then grain size measurements on specimens with different orientations will vary. In this case, the grain size should be evaluated on at least two of the three principle planes, transverse, longitudinal, and planar (or radial and transverse for round bar) and averaged as described in Section 16 to obtain the mean grain size. If directed test lines are used, rather than test circles, intercept counts on non-equiaxed grains in plate or sheet type specimens can be made using only two principle test planes, rather than all three as required for the planimetric method.

7.3 The surface to be polished should be large enough in area to permit measurement of at least five fields at the desired magnification. In most cases, except for thin sheet or wire specimens, a minimum polished surface area of 160 mm^2 (0.25 $in.^2$) is adequate.

7.4 The specimen shall be sectioned, mounted (if necessary), ground, and polished according to the recommended procedures in Practice E 3. The specimen shall be etched using a reagent, such as listed in Practice E 407, to delineate most, or all, of the grain boundaries (see also Annex A3).

TABLE 1 Suggested Comparison Charts for Metallic Materials

NOTE 1—These suggestions are based upon the customary practices in industry. For specimens prepared according to special techniques, the appropriate comparison standards should be selected on a structural-appearance basis in accordance with 8.2.

Material	Plate Number	Basic Magnification
Aluminum	I	100X
Copper and copper-base alloys (see Annex A4)	III or IV	75X, 100X
Iron and steel:		
Austenitic	II or IV	100X
Ferritic	I	100X
Carburized	IV	100X
Stainless	II	100X
Magnesium and magnesium-base alloys	I or II	100X
Nickel and nickel-base alloys	II	100X
Super-strength alloys	I or II	100X
Zinc and zinc-base alloys	I or II	100X

8. Calibration

8.1 Use a stage micrometer to determine the true linear magnification for each objective, eyepiece and bellows, or zoom setting to be used within ±2 %.

8.2 Use a ruler with a millimetre scale to determine the actual length of straight test lines or the diameter of test circles used as grids.

9. Preparation of Photomicrographs

9.1 When photomicrographs are used for estimating the average grain size, they shall be prepared in accordance with Guide E 883.

10. Comparison Procedure

10.1 The comparison procedure shall apply to completely recrystallized or cast materials with equiaxed grains.

10.2 When grain size estimations are made by the more convenient comparison method, repeated checks by individuals as well as by interlaboratory tests have shown that unless the appearance of the standard reasonably well approaches that of the sample, errors may occur. To minimize such errors, the comparison charts are presented in four categories as follows:[4]

10.2.1 *Plate I*—Untwinned grains (flat etch). Includes grain size numbers 00, 0, ½, 1, 1½, 2, 2½, 3, 3½, 4, 4½, 5, 5½, 6, 6½, 7, 7½, 8, 8½, 9, 9½, 10, at 100X.

10.2.2 *Plate II*—Twinned grains (flat etch). Includes grain size numbers, 1, 2, 3, 4, 5, 6, 7, 8, at 100X.

[4] Plates I, II, III, and IV are available from ASTM Headquarters. Order Adjunct: ADJE011201 (Plate I), ADJE011202 (Plate II), ADJE011203 (Plate III), and ADJE011204 (Plate IV). A combination of all four plates is also available. Order Adjunct: ADJE011214.

10.2.3 *Plate III*—Twinned grains (contrast etch). Includes nominal grain diameters of 0.200, 0.150, 0.120, 0.090, 0.070, 0.060, 0.050, 0.045, 0.035, 0.025, 0.020, 0.015, 0.010, 0.005 mm at 75X.

10.2.4 *Plate IV*—Austenite grains in steel (McQuaid-Ehn). Includes grain size numbers 1, 2, 3, 4, 5, 6, 7, 8, at 100X.

10.3 Table 1 lists a number of materials and the comparison charts that are suggested for use in estimating their average grain sizes. For example, for twinned copper and brass with a contrast etch, use Plate III.

NOTE 1—Examples of grain-size standards from Plates I, II, III, and IV are shown in Fig. 1, Fig. 2, Fig. 3, and Fig. 4.

10.4 The estimation of microscopically-determined grain size should usually be made by direct comparison at the same magnification as the appropriate chart. Accomplish this by comparing a projected image or a photomicrograph of a representative field of the test specimen with the photomicrographs of the appropriate standard grain-size series, or with suitable reproductions or transparencies of them, and select the photomicrograph which most nearly matches the image of the test specimen or interpolate between two standards. Report this estimated grain size as the ASTM grain size number, or grain diameter, of the chart picture that most closely matches the image of the test specimen or as an interpolated value between two standard chart pictures.

10.5 Good judgment on the part of the observer is necessary to select the magnification to be used, the proper size of area (number of grains), and the number and location in the specimen of representative sections and fields for estimating the characteristic or average grain size. It is not sufficient to visually select what appear to be areas of average grain size. Recommendations for choosing appropriate areas for all procedures have been noted in 5.2.

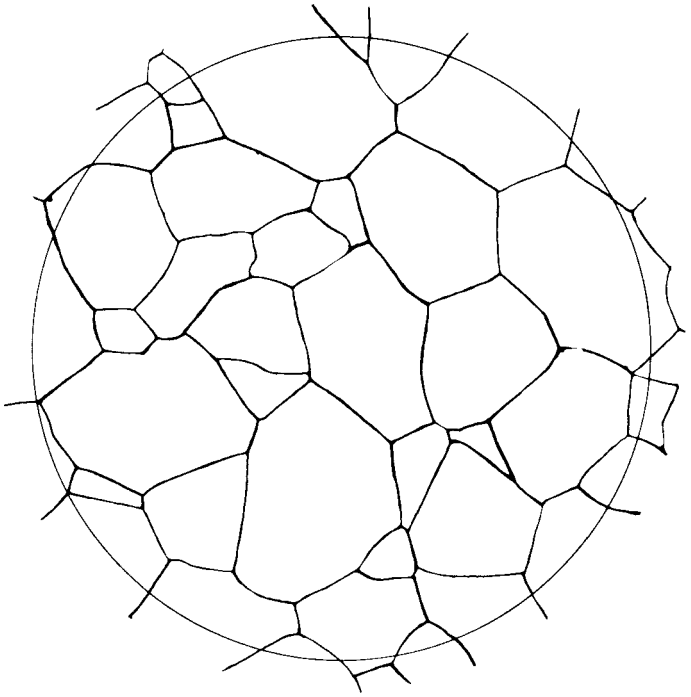


FIG. 1 Example of Untwinned Grains (Flat Etch) from Plate I. Grain Size No. 3 at 100X

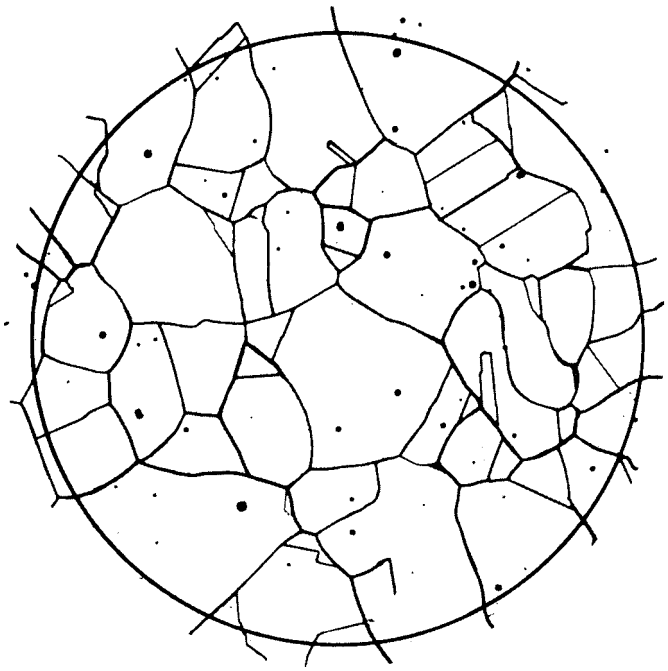


FIG. 2 Example of Twin Grains (Flat Etch) from Plate II. Grain Size No. 3 at 100X

FIG. 3 Example of Twin Grains (Contrast Etch) from Plate III. Grain Size 0.090 mm at 75X

10.6 Grain size estimations shall be made on three or more representative areas of each specimen section.

10.7 When the grains are of a size outside the range covered by the standard photographs, or when magnifications of 75X or 100X are not satisfactory, other magnifications may be employed for comparison by using the relationships given in Note 2 and Table 2. It may be noted that alternative magnifications

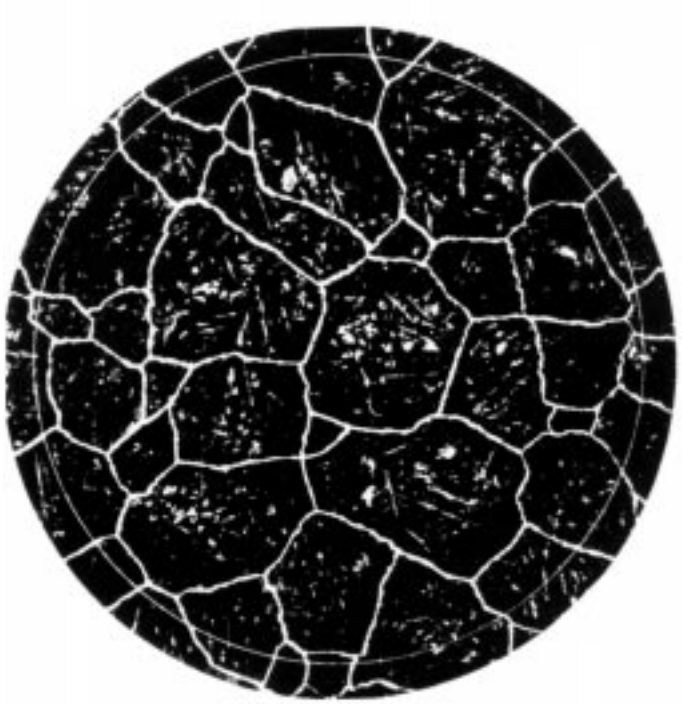


FIG. 4 Example of Austenite Grains in Steel from Plate IV. Grain Size No. 3 at 100X

10.8 The small number of grains per field at the coarse end of the chart series, that is, size 00, and the very small size of the grains at the fine end make accurate comparison ratings difficult. When the specimen grain size falls at either end of the chart range, a more meaningful comparison can be made by changing the magnification so that the grain size lies closer to the center of the range.

10.9 The use of transparencies[5] or prints of the standards, with the standard and the unknown placed adjacent to each other, is to be preferred to the use of wall chart comparison with the projected image on the microscope screen.

10.10 No particular significance should be attached to the fact that different observers often obtain slightly different results, provided the different results fall within the confidence limits reasonably expected with the procedure used.

10.11 There is a possibility when an operator makes repeated checks on the same specimen using the comparison method that they will be prejudiced by their first estimate. This disadvantage can be overcome, when necessary, by changes in magnification, through bellows extension, or objective or eyepiece replacement between estimates **(1)**.[6]

10.12 Make the estimation of macroscopically-determined grain sizes (extremely coarse) by direct comparison, at a magnification of 1X, of the properly prepared specimen, or of a photograph of a representative field of the specimen, with

TABLE 2 Microscopically Determined Grain Size Relationships Using Plate III at Various Magnifications

NOTE 1—First line—mean grain diameter, d, in mm; in parentheses—equivalent ASTM grain size number, G.
NOTE 2—Magnification for Plate III is 75X (row 3 data).

Magnification	Chart Picture Number (Plate III)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
25X	0.015	0.030	0.045	0.060	0.075	0.105	0.135	0.150	0.180	0.210	0.270	0.360	0.451	0.600
	(9.2)	(7.2)	(6.0)	(5.2)	(4.5)	(3.6)	(2.8)	(2.5)	(2.0)	(1.6)	(0.8)	(0)	(0/00)	(00 +)
50X	0.0075	0.015	0.0225	0.030	0.0375	0.053	0.0675	0.075	0.090	0.105	0.135	0.180	0.225	0.300
	(11.2)	(9.2)	(8.0)	(7.2)	(6.5)	(5.6)	(4.8)	(4.5)	(4.0)	(3.6)	(2.8)	(2.0)	(1.4)	(0.5)
75X	0.005	0.010	0.015	0.020	0.025	0.035	0.045	0.050	0.060	0.070	0.090	0.120	0.150	0.200
	(12.3)	(10.3)	(9.2)	(8.3)	(7.7)	(6.7)	(6.0)	(5.7)	(5.2)	(4.7)	(4.0)	(3.2)	(2.5)	(1.7)
100X	0.00375	0.0075	0.0112	0.015	0.019	0.026	0.034	0.0375	0.045	0.053	0.067	0.090	0.113	0.150
	(13.2)	(11.2)	(10.0)	(9.2)	(8.5)	(7.6)	(6.8)	(6.5)	(6.0)	(5.6)	(4.8)	(4.0)	(3.4)	(2.5)
200X	0.0019	0.00375	0.0056	0.0075	0.009	0.013	0.017	0.019	0.0225	0.026	0.034	0.045	0.056	0.075
	(15.2)	(13.2)	(12.0)	(11.2)	(10.5)	(9.6)	(8.8)	(8.5)	(8.0)	(7.6)	(6.8)	(6.0)	(5.4)	(4.5)
400X	—	0.0025	0.0037	0.005	0.006	0.009	0.011	0.0125	0.015	0.0175	0.0225	0.030	0.0375	0.050
		(14.3)	(13.2)	(12.3)	(11.7)	(10.7)	(10.0)	(9.7)	(9.2)	(8.7)	(8.0)	(7.2)	(6.5)	(5.7)
500X	—	—	0.003	0.004	0.005	0.007	0.009	0.010	0.012	0.014	0.018	0.024	0.030	0.040
			(13.8)	(13.0)	(12.3)	(11.4)	(10.6)	(10.3)	(9.8)	(9.4)	(8.6)	(7.8)	(7.2)	(6.3)

are usually simple multiples of the basic magnifications.

NOTE 2—If the grain size is reported in ASTM numbers, it is convenient to use the relationship:

$$Q = 2 \log_2 (M/M_b) \quad (2)$$

$$= 6.64 \log_{10} (M/M_b)$$

where Q is a correction factor that is added to the apparent micro-grain size of the specimen, as viewed at the magnification, M, instead of at the basic magnification, M_b (75X or 100X), to yield the true ASTM grain-size number. Thus, for a magnification of 25X, the true ASTM grain-size number is four numbers lower than that of the corresponding photomicrograph at 100X ($Q = -4$). Likewise, for 400X, the true ASTM grain-size number is four numbers higher ($Q = +4$) than that of the corresponding photomicrograph at 100X. Similarly, for 300X, the true ASTM grain-size number is four numbers higher than that of the corresponding photomicrograph at 75X.

photographs of the standard grain series shown in Plate I (for untwinned material) and Plates II and III (for twinned material). Since the photographs of the standard grain size series

[5] Transparencies of the various grain sizes in Plate I are available from ASTM Headquarters. Order Adjunct: ADJE112010 for the set. Transparencies of individual grain size groupings are available on request. Order Adjunct: ADJE011205 (Grain Size 00), ADJE012206 (Grain Size 0), ADJE012207 (Grain Size 0.5), ADJE011208 (Grain Size 1.0), ADJE011209 (Grain Size 1.5), ADJE11210 (Grain Size 2.0), ADJE011211 (Grain Size 2.5), ADJE011212 (Grain Sizes 3.0, 3.5, and 4.0), ADJE011213 (Grain Sizes 4.5, 5.0, and 5.5), ADJE011214 (Grain Sizes 6.0, 6.5, and 7.0), ADJE011215 (Grain Sizes 7.5, 8.0, and 8.5), and ADJE011216 (Grain Sizes 9.0, 9.5, and 10.0). Charts illustrating grain size numbers 00 to 10 are on 8½by 11 in. (215.9 by 279.4 mm) film. Transparencies for Plates II, III, and IV are not available.

[6] The boldface numbers in parentheses refer to the list of references appended to these test methods.

TABLE 3 Macroscopic Grain Size Relationships Computed for Uniform, Randomly Oriented, Equiaxed Grains

NOTE 1—Macroscopically determined grain size numbers M-12.3, M-13.3, M-13.8 and M-14.3 correspond, respectively, to microscopically determined grain size numbers (*G*) 00, 0, 0.5 and 1.0.

Macro Grain Size No.	$\bar{N}_A$ Grains/Unit Area		$\bar{A}$ Average Grain Area		$\bar{d}$ Average Diameter		$\bar{\ell}$ Mean Intercept		$\bar{N}_L$	$\bar{N}$
	No./mm^2	No./in.^{2}	mm^2	in.^{2}	mm	in.	mm	in.	mm^{-1}	100 mm
M-0	0.0008	0.50	1290.3	2.00	35.9	1.41	32.00	1.2	0.031	3.13
M-0.5	0.0011	0.71	912.4	1.41	30.2	1.19	26.91	1.0	0.037	3.72
M-1.0	0.0016	1.00	645.2	1.00	25.4	1.00	22.63	0.89	0.044	4.42
M-1.5	0.0022	1.41	456.2	0.707	21.4	0.841	19.03	0.74	0.053	5.26
M-2.0	0.0031	2.00	322.6	0.500	18.0	0.707	16.00	0.63	0.063	6.25
M-2.5	0.0044	2.83	228.1	0.354	15.1	0.595	13.45	0.53	0.074	7.43
M-3.0	0.0062	4.00	161.3	0.250	12.7	0.500	11.31	0.44	0.088	8.84
M-3.5	0.0088	5.66	114.0	0.177	10.7	0.420	9.51	0.37	0.105	10.51
M-4.0	0.0124	8.00	80.64	0.125	8.98	0.354	8.00	0.31	0.125	12.50
M-4.5	0.0175	11.31	57.02	0.0884	7.55	0.297	6.73	0.26	0.149	14.87
M-5.0	0.0248	16.00	40.32	0.0625	6.35	0.250	5.66	0.22	0.177	17.68
M-5.5	0.0351	22.63	28.51	0.0442	5.34	0.210	4.76	0.18	0.210	21.02
M-6.0	0.0496	32.00	20.16	0.0312	4.49	0.177	4.00	0.15	0.250	25.00
M-6.5	0.0701	45.26	14.26	0.0221	3.78	0.149	3.36	0.13	0.297	29.73
M-7.0	0.099	64.00	10.08	0.0156	3.17	0.125	2.83	0.11	0.354	35.36
M-7.5	0.140	90.51	7.13	0.0110	2.67	0.105	2.38	0.093	0.420	42.05
				$\times10^{-3}$		$\times10^{-3}$		$\times10^{-3}$		
M-8.0	0.198	128.0	5.04	7.812	2.25	88.4	2.00	78.7	0.500	50.00
M-8.5	0.281	181.0	3.56	5.524	1.89	74.3	1.68	66.2	0.595	59.46
M-9.0	0.397	256.0	2.52	3.906	1.59	62.5	1.41	55.7	0.707	70.71
M-9.5	0.561	362.1	1.78	2.762	1.33	52.6	1.19	46.8	0.841	84.09
M-10.0	0.794	512.0	1.26	1.953	1.12	44.2	1.00	39.4	1.00	100.0
M-10.5	1.122	724.1	0.891	1.381	0.994	37.2	0.841	33.1	1.19	118.9
M-11.0	1.587	1024.1	0.630	0.977	0.794	31.2	0.707	27.8	1.41	141.4
M-11.5	2.245	1448.2	0.0445	0.690	0.667	26.3	0.595	23.4	1.68	168.2
M-12.0	3.175	2048.1	0.315	0.488	0.561	22.1	0.500	19.7	2.00	200.0
M-12.3	3.908	2521.6	0.256	0.397	0.506	19.9	0.451	17.7	2.22	221.9
M-12.5	4.490	2896.5	0.223	0.345	0.472	18.6	0.420	16.6	2.38	237.8
M-13.0	6.349	4096.3	0.157	0.244	0.397	15.6	0.354	13.9	2.83	282.8
M-13.3	7.817	5043.1	0.128	0.198	0.358	14.1	0.319	12.5	3.14	313.8
M-13.5	8.979	5793.0	0.111	0.173	0.334	13.1	0.297	11.7	3.36	336.4
M-13.8	11.055	7132.1	0.091	0.140	0.301	11.8	0.268	10.5	3.73	373.2
M-14.0	12.699	8192.6	0.079	0.122	0.281	11.0	0.250	9.84	4.00	400.0
M-14.3	15.634	10086.3	0.064	0.099	0.253	9.96	0.225	8.87	4.44	443.8

were made at 75 and 100 diameters magnification, grain sizes estimated in this way do not fall in the standard ASTM grain-size series and hence, preferably, should be expressed either as diameter of the average grain or as one of the macro-grain size numbers listed in Table 3. For the smaller macroscopic grain sizes, it may be preferable to use a higher magnification and the correction factor given in Note 3, particularly if it is desirable to retain this method of reporting.

NOTE 3—If the grain size is reported in ASTM macro-grain size numbers, it is convenient to use the relationship:

$$Q_m = 2 \log_2 M \quad (3)$$
$$= 6.64 \log_{10} M$$

where Q_M is a correction factor that is added to the apparent grain size of the specimen, when viewed at the magnification *M*, instead of at 1X, to yield the true ASTM macro-grain size number. Thus, for a magnification of 2X, the true ASTM macro-grain size number is two numbers higher ($Q = +2$), and for 4X, the true ASTM macro-grain size number is four numbers higher ($Q = +4$) than that of the corresponding photograph.

10.13 The comparison procedure shall be applicable for estimating the austenite grain size in ferritic steel after a McQuaid-Ehn test (see Annex A3, A3.2), or after the austenite grains have been revealed by any other means (see Annex A3, A3.3). Make the grain-size measurement by comparing the microscopic image, at magnification of 100X, with the standard grain size chart in Plate IV, for grains developed in a McQuaid-Ehn test (see Annex A3); for the measurement of austenite grains developed by other means (see Annex A3), measure by comparing the microscopic image with the plate having the most nearly comparable structure observed in Plates I, II, or IV.

10.14 The so-called "Shepherd Fracture Grain Size Method" of judging grain size from the appearance of the fracture of hardened steel **(2)**, involves comparison of the specimen under investigation with a set of standard fractures.[7] It has been found that the arbitrarily numbered fracture grain size series agree well with the correspondingly numbered ASTM grain sizes presented in Table 4. This coincidence makes the fracture grain sizes interchangeable with the austenitic grain sizes determined microscopically. The sizes observed microscopically shall be considered the primary standard, since they can be determined with measuring instruments.

[7] A photograph of the Shepherd standard fractures can be obtained from ASTM Headquarters. Order Adjunct: ADJE011224.

TABLE 4 Grain Size Relationships Computed for Uniform, Randomly Oriented, Equiaxed Grains

Grain Size No. G	$\bar{N}_A$ Grains/Unit Area		$\bar{A}$ Average Grain Area		$\bar{d}$ Average Diameter		$\bar{\ell}$ Mean Intercept		$\bar{N}_L$
	No./in.^{2} at 100X	No./mm^2 at 1X	mm^2	μm^2	mm	μm	mm	μm	No./mm
00	0.25	3.88	0.2581	258064	0.5080	508.0	0.4525	452.5	2.21
0	0.50	7.75	0.1290	129032	0.3592	359.2	0.3200	320.0	3.12
0.5	0.71	10.96	0.0912	91239	0.3021	302.1	0.2691	269.1	3.72
1.0	1.00	15.50	0.0645	64516	0.2540	254.0	0.2263	226.3	4.42
1.5	1.41	21.92	0.0456	45620	0.2136	213.6	0.1903	190.3	5.26
2.0	2.00	31.00	0.0323	32258	0.1796	179.6	0.1600	160.0	6.25
2.5	2.83	43.84	0.0228	22810	0.1510	151.0	0.1345	134.5	7.43
3.0	4.00	62.00	0.0161	16129	0.1270	127.0	0.1131	113.1	8.84
3.5	5.66	87.68	0.0114	11405	0.1068	106.8	0.0951	95.1	10.51
4.0	8.00	124.00	0.00806	8065	0.0898	89.8	0.0800	80.0	12.50
4.5	11.31	175.36	0.00570	5703	0.0755	75.5	0.0673	67.3	14.87
5.0	16.00	248.00	0.00403	4032	0.0635	63.5	0.0566	56.6	17.68
5.5	22.63	350.73	0.00285	2851	0.0534	53.4	0.0476	47.6	21.02
6.0	32.00	496.00	0.00202	2016	0.0449	44.9	0.0400	40.0	25.00
6.5	45.25	701.45	0.00143	1426	0.0378	37.8	0.0336	33.6	29.73
7.0	64.00	992.00	0.00101	1008	0.0318	31.8	0.0283	28.3	35.36
7.5	90.51	1402.9	0.00071	713	0.0267	26.7	0.0238	23.8	42.04
8.0	128.00	1984.0	0.00050	504	0.0225	22.5	0.0200	20.0	50.00
8.5	181.02	2805.8	0.00036	356	0.0189	18.9	0.0168	16.8	59.46
9.0	256.00	3968.0	0.00025	252	0.0159	15.9	0.0141	14.1	70.71
9.5	362.04	5611.6	0.00018	178	0.0133	13.3	0.0119	11.9	84.09
10.0	512.00	7936.0	0.00013	126	0.0112	11.2	0.0100	10.0	100.0
10.5	724.08	11223.2	0.000089	89.1	0.0094	9.4	0.0084	8.4	118.9
11.0	1024.00	15872.0	0.000063	63.0	0.0079	7.9	0.0071	7.1	141.4
11.5	1448.15	22446.4	0.000045	44.6	0.0067	6.7	0.0060	5.9	168.2
12.0	2048.00	31744.1	0.000032	31.5	0.0056	5.6	0.0050	5.0	200.0
12.5	2896.31	44892.9	0.000022	22.3	0.0047	4.7	0.0042	4.2	237.8
13.0	4096.00	63488.1	0.000016	15.8	0.0040	4.0	0.0035	3.5	282.8
13.5	5792.62	89785.8	0.000011	11.1	0.0033	3.3	0.0030	3.0	336.4
14.0	8192.00	126976.3	0.000008	7.9	0.0028	2.8	0.0025	2.5	400.0

11. Planimetric (or Jeffries') (3) Procedure

11.1 In the planimetric procedure inscribe a circle[8] or rectangle of known area (usually 5000 mm^2 to simplify the calculations) on a micrograph or on the ground-glass screen of the metallograph. Select a magnification which will give at least 50 grains in the field to be counted. When the image is focused properly, count the number of grains within this area. The sum of all the grains included completely within the known area plus one half the number of grains intersected by the circumference of the area gives the number of equivalent whole grains, measured at the magnification used, within the area. If this number is multiplied by the Jeffries' multiplier, *f*, in the second column of Table 5 opposite the appropriate magnification, the product will be the number of grains per square millimetre N_A. Count a minimum of three fields to ensure a reasonable average. The number of grains per square millimetre at 1X, N_A, is calculated from:

$$N_A = f\left(N_{\text{Inside}} + \frac{N_{\text{Intercepted}}}{2}\right) \quad (4)$$

where *f* is the Jeffries' multiplier (see Table 5), N_{Inside} is the number of grains completely inside the test circle and $N_{\text{Intercepted}}$ is the number of grains that intercept the test circle. The average grain area, $\bar{A}$, is the reciprocal of N_A, that is, $1/N_A$, while the mean grain diameter, $\bar{d}$, as listed on Plate III (see 10.2.3), is the square root of $\bar{A}$. This grain diameter has no physical significance because it represents the side of a square grain of area $\bar{A}$, and grain cross sections are not square.

TABLE 5 Relationship Between Magnification Used and Jeffries' Multiplier, *f*, for an Area of 5000 mm^2 (a Circle of 79.8-mm Diameter) ($f = 0.0002\ M^2$)

Magnification Used, *M*	Jeffries' Multiplier, *f*, to Obtain Grains/mm^2
1	0.0002
10	0.02
25	0.125
50	0.5
75[A]	1.125
100	2.0
150	4.5
200	8.0
250	12.5
300	18.0
500	50.0
750	112.5
1000	200.0

[A] At 75 diameters magnification, Jeffries' multiplier, *f*, becomes unity if the area used is 5625 mm^2 (a circle of 84.5-mm diameter).

11.2 To obtain an accurate count of the number of grains completely within the test circle and the number of grains intersecting the circle, it is necessary to mark off the grains on the template, for example, with a grease pencil or felt tip pen. The precision of the planimetric method is a function of the number of grains counted (see Section 19). The number of grains within the test circle, however, should not exceed about 100 as counting becomes tedious and inaccurate. Experience suggests that a magnification that produces about 50 grains within the test circle is about optimum as to counting accuracy per field. Because of the need to mark off the grains to obtain an accurate count, the planimetric method is less efficient than

[8] A transparent grid for the planimetric method is available from ASTM Headquarters. The transparency consists of two test circles, one with a diameter of 79.8 mm (5000 mm^2 area) and the other with a diameter of 159.6 mm (20 000 mm^2 area). Order Adjunct: ADJE011223.

the intercept method (see Section 12).

11.3 Fields should be chosen at random, without bias, as described in 5.2. Do not attempt to choose fields that appear to be typical. Choose the fields blindly and select them from different locations on the plane of polish.

11.4 By original definition, a microscopically-determined grain size of No. 1 has 1.000 grains/in.^{2} at 100X, hence 15.500 grains/mm^2 at 1X. For areas other than the standard circle, determine the actual number of grains per square millimetre, N_A, and find the nearest size from Table 4. The ASTM grain size number, G, can be calculated from N_A (number of grains per mm^2 at 1X) using (Eq 1) in Table 6.

12. General Intercept Procedures

12.1 Intercept procedures are more convenient to use than the planimetric procedure. These procedures are amenable to use with various types of machine aids. It is strongly recommended that at least a manual tally counter be used with all intercept procedures in order to prevent normal errors in counting and to eliminate bias which may occur when counts appear to be running higher or lower than anticipated.

12.2 Intercept procedures are recommended particularly for all structures that depart from the uniform equiaxed form. For anisotropic structures, procedures are available either to make separate size estimates in each of the three principal directions, or to rationally estimate the average size, as may be appropriate.

12.3 There is no direct mathematical relationship between the ASTM grain size number, G, and the mean lineal intercept, unlike the exact relationship between G, N_{AE}, N_A and $\bar{A}$ (Eq 1) for the planimetric method. The relationship

$$\ell = \left(\frac{\pi}{4}\bar{A}\right)^{1/2} \tag{5}$$

between the mean lineal intercept, ℓ, and the average grain area, $\bar{A}$, is exact for circles but not quite exact for a structure of uniform equiaxed grains (see A2.2.2). Consequently, the relationship between the ASTM grain size number G and the mean lineal intercept has been defined so that ASTM No. 0 has a mean intercept size of precisely 32.00 mm for the macroscopically determined grain size scale and of 32.00 mm on a field of view at 100X magnification for the microscopically determined grain size scale. Thus:

$$G = 2\log_2\frac{\ell_0}{\bar{\ell}} \tag{6}$$

TABLE 6 Grain Size Equations Relating Measured Parameters to the Microscopically Determined ASTM Grain Size, *G*

NOTE 1—Determine the ASTM Grain Size, G, using the following equations:

NOTE 2—The second and third equations are for single phase grain structures.

NOTE 3—To convert micrometres to millimetres, divide by 1000.

NOTE 4—A calculated G value of −1 corresponds to ASTM G = 00.

Equation	Units
$G = (3.321928 \log_{10}\bar{N}_A) - 2.954$	$\bar{N}_A$ in mm^{-2}
$G = (6.643856 \log_{10}\bar{N}_L) - 3.288$	$\bar{N}_L$ in mm^{-1}
$G = (6.643856 \log_{10}P_L) - 3.288$	P_L in mm^{-1}
$G = (-6.643856 \log_{10}\ell) - 3.288$	ℓ in mm

$$G = 10.00 - 2\log_2\ell \tag{7}$$

$$G = 10.00 + 2\log_2\bar{N}_L \tag{8}$$

where ℓ_0 is 32 mm and $\bar{\ell}$ and $\bar{N}_L$ are in millimetres at 1X or number of intercepts per mm for the macroscopically determined grain size numbers and in millimetres or number per mm on a field at 100X for the microscopically determined grain size numbers. Using this scale, measured grain size numbers are within about 0.01 G units of grain size numbers determined by the planimetric method, that is, well within the precision of the test methods. Additional details concerning grain size relationships are given in Annex A1 and Annex A2.

12.4 The mean intercept distance, $\bar{\ell}$, measured on a plane section is an unbiased estimate of the mean intercept distance within the solid material in the direction, or over the range of directions, measured. The grain boundary surface area-to-volume ratio is given exactly by $S_v = 2\,N_L$ when N_L is averaged over three dimensions. These relations are independent of grain shape.

13. Heyn (4) Lineal Intercept Procedure

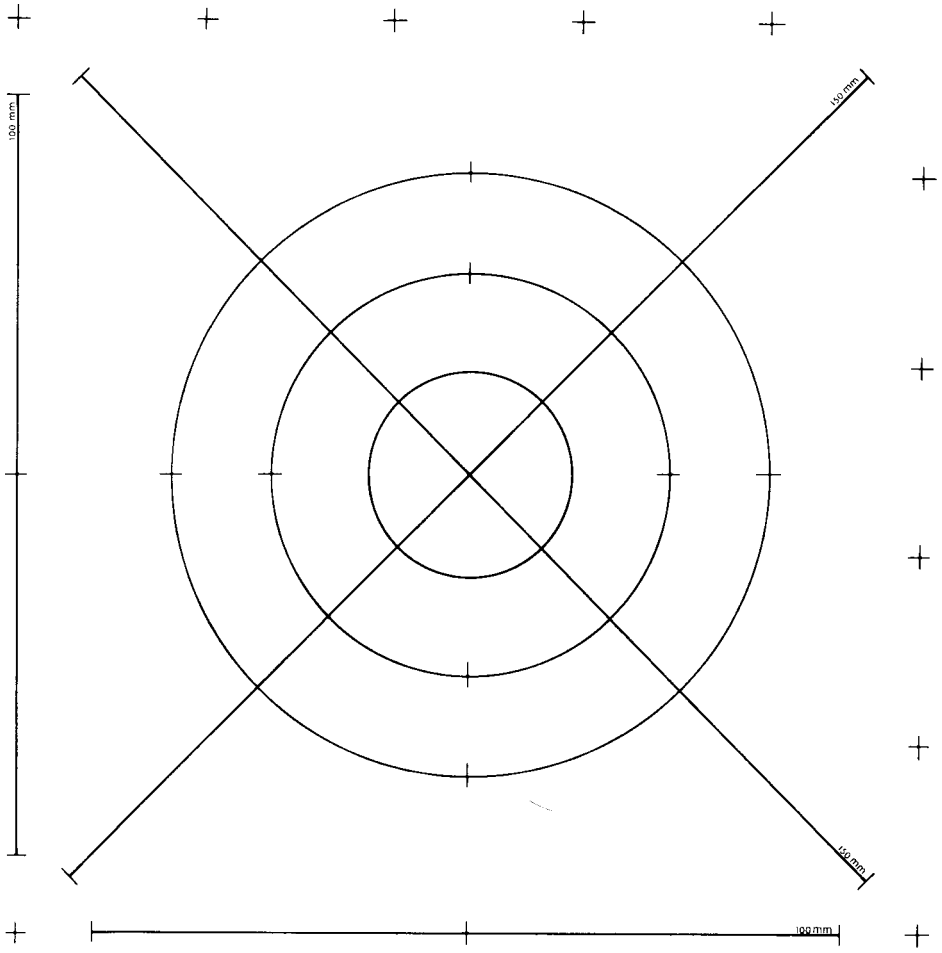
13.1 Estimate the average grain size by counting (on the ground-glass screen, on a photomicrograph of a representative field of the specimen, or on the specimen itself) the number of grains intercepted by one or more straight lines sufficiently long to yield at least 50 intercepts. It is desirable to select a combination of test line length and magnification such that a single field will yield the required number of intercepts. One such test will nominally allow estimation of grain size to the nearest whole ASTM size number, at the location tested. Additional lines, in a predetermined array, should be counted to obtain the precision required. The precision of grain size estimates by the intercept method is a function of the number of grain interceptions counted (see Section 19). Because the ends of straight test lines will usually lie inside grains (see 14.3), precision will be reduced if the average count per test line is low. If possible, use either a longer test line or a lower magnification.

13.2 Make counts first on three to five blindly selected and widely separated fields to obtain a reasonable average for the specimen. If the apparent precision of this average (calculated as indicated in Section 15) is not adequate, make counts on sufficient additional fields to obtain the precision required for the specimen average.

13.3 An *intercept* is a segment of test line overlaying one grain. An *intersection* is a point where a test line is cut by a grain boundary. Either may be counted, with identical results in a single phase material. When counting intercepts, segments at the end of a test line which penetrate into a grain are scored as half intercepts. When counting intersections, the end points of a test line are not intersections and are not counted except when the end appears to exactly touch a grain boundary, when ½ intersection should be scored. A tangential intersection with a grain boundary should be scored as one intersection. An intersection apparently coinciding with the junction of three grains should be scored as 1½. With irregular grain shapes, the test line may generate two intersections with different parts of the same grain, together with a third intersection with the

intruding grain. The two additional intersections are to be counted.

making separate size determinations along parallel line arrays that coincide with all three principal directions of the speci-



NOTE 1—If reproduced to make straight lines marked length:
Straight lines total: 500 mm

Circles are:	Circumference, mm,	Diameter, mm
	250.0	79.58
	166.7	53.05
	83.3	26.53
	Total 500.0	

NOTE 2—See Footnote 9.

FIG. 5 Test Pattern for Intercept Counting

13.4 The effects of moderate departure from an equiaxed structure may be eliminated by making intercept counts on a line array containing lines having four or more orientations. The four straight lines of Fig. 5[9] may be used. The form of such arrays is not critical, provided that all portions of the field are measured with approximately equal weight. An array of lines radiating from a common point is therefore not suitable. The number of intercepts is to be counted for the entire array and single values of N_L and ℓ determined for each array as a whole.

13.5 For distinctly non-equiaxed structures such as moderately worked metals, more information can be obtained by men. Longitudinal and transverse specimen sections are normally used, the normal section being added when necessary. Either of the 100-mm lines of Fig. 5 may be applied five times, using parallel displacements, placing the five " + " marks at the same point on the image. Alternatively, a transparent test grid with systematically spaced parallel test lines of known length can be made and used.

14. Circular Intercept Procedures

14.1 Use of circular test lines rather than straight test lines has been advocated by Underwood **(5)**, Hilliard **(6)**, and Abrams **(7)**. Circular test arrays automatically compensate for departures from equiaxed grain shapes, without overweighting any local portion of the field. Ambiguous intersections at ends of test lines are eliminated. Circular intercept procedures are

[9] A true-size transparency of Fig. 5 is available from ASTM Headquarters. Order Adjunct:ADJE011217.

most suitable for use as fixed routine manual procedures for grain size estimation in quality control.

14.2 *Hilliard Single-Circle Procedure* **(6)** *:*

14.2.1 When the grain shape is not equiaxed but is distorted by deformation or other processes, obtaining an average lineal intercept value using straight test lines requires averaging of values made at a variety of orientations. If this is not done carefully, bias may be introduced. Use of a circle as the test line eliminates this problem as the circle will test all orientations equally and without bias.

14.2.2 Any circle size of exactly known circumference may be used. Circumferences of 100, 200, or 250 mm are usually convenient. The test circle diameter should never be smaller than the largest observed grains. If the test circle is smaller than about three times the mean lineal intercept, the distribution of the number of intercepts or intersections per field will not be Gaussian. Also, use of small test circles is rather inefficient as a great many fields must be evaluated to obtain a high degree of precision. A small reference mark is usually placed at the top of the circle to indicate the place to start and stop the count. Blindly apply the selected circle to the microscope image at a convenient known magnification and count the number of grain boundaries intersecting the circle for each application. Apply the circle only once to each field of view, adding fields in a representative manner, until sufficient counts are obtained to yield the required precision. The variation in counts per test circle application decreases as the circle size increases and, of course, is affected by the uniformity of the grain size distribution.

14.2.3 As with all intercept procedures, the precision of the measurement increases as the number of counts increases (see Section 19). The precision is based on the standard deviation of the counts of the number of intercepts or intersections per field. In general, for a given grain structure, the standard deviation is improved as the count per circle application and the total count (that is, the number of applications) increase. Hilliard recommended test conditions that produce about 35 counts per circle with the test circle applied blindly over as large a specimen area as feasible until the desired total number of counts is obtained.

14.3 *Abrams Three-Circle Procedure* **(7)** *:*

14.3.1 Based on an experimental finding that a total of 500 counts per specimen normally yields acceptable precision, Abrams developed a specific procedure for routine average grain size rating of commercial steels. Use of the chi-square test on real data demonstrated that the variation of intercept counts is close to normal, allowing the observations to be treated by the statistics of normal distributions. Thus both a measure of variability and the confidence limit of the result are computed for each average grain size determination.

14.3.2 The test pattern consists of three concentric and equally spaced circles having a total circumference of 500 mm, as shown in Fig. 5. Successively apply this pattern to at least five blindly selected and widely spaced fields, separately recording the count of intersections per pattern for each of the tests. Then, determine the mean lineal intercept, its standard deviation, 95 % confidence limit, and percent relative accuracy. For most work, a relative accuracy of 10 % or less represents an acceptable degree of precision. If the calculated relative accuracy is unacceptable for the application, count additional fields until the calculated percent relative accuracy is acceptable. The specific procedure is as follows:

14.3.2.1 Examine the grain structure and select a magnification that will yield from 40 to 100 intercepts or intersection counts per placement of the three circle test grid. Because our goal is to obtain a total of about 400 to 500 counts, the ideal magnification is that which yields about 100 counts per placement. However, as the count per placement increases from 40 to 100, errors in counting become more likely. Because the grain structure will vary somewhat from field to field, at least five widely spaced fields should be selected. Some metallographers feel more comfortable counting 10 fields with about 40 to 50 counts per field. For most grain structures, a total count of 400 to 500 intercepts or intersections over 5 to 10 fields produces better than 10 % relative accuracy. Fig. 6 shows the relationship between the average intercept count and the microscopically determined ASTM grain size number as a function of magnification.

14.3.2.2 Blindly select one field for measurement and apply the test pattern to the image. A transparency of the pattern may be applied directly to the ground glass, or to a photomicrograph when permanent records are desired. Direct counting using a properly sized reticle in the eyepiece is allowable, but it may here be expected that some operators will find difficulty in counting correctly at the count density recommended. Completely count each circle in turn, using a manually operated counter to accumulate the total number of grain boundary intersections with the test pattern. The manual counter is necessary to avoid bias toward unreal agreement between applications or toward a desired result, and to minimize memory errors. The operator should avoid keeping a mental score. When a tally counter is used, score any intersection of the circle with the junction of three grains as two rather than the correct value of 1½; the error introduced is very small.

14.3.3 For each field count, calculate N_L or P_L according to:

$$\bar{N}_L = \frac{N_i}{L/M} \tag{9}$$

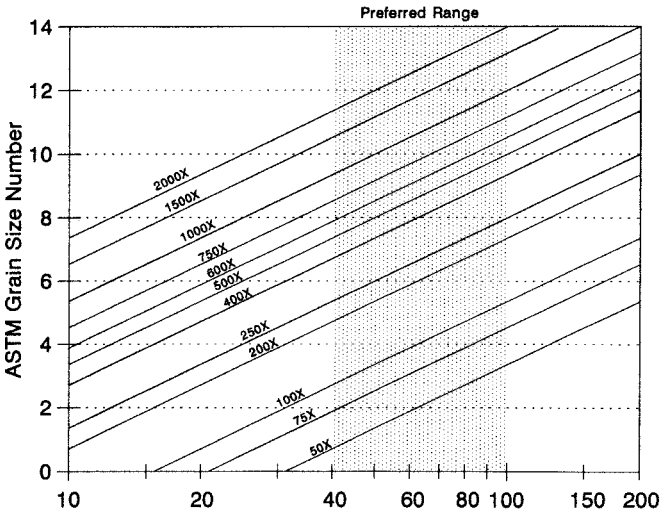


FIG. 6 Average Intercept Counts on 500 mm Test Pattern

$$\bar{P}_L = \frac{P_i}{L/M} \tag{10}$$

where N_i and P_i are the number of intercepts or intersections counted on the field, L is the total test line length (500 mm) and M is the magnification.

14.3.4 Calculate the mean lineal intercept value for each field, $\bar{\ell}$ by:

$$\bar{\ell} = \frac{1}{\bar{N}_L} = \frac{1}{\bar{P}_L} \tag{11}$$

The average value of n determinations of N_L , P_L , or $\bar{\ell}$ is used to determine the microscopically measured ASTM grain size using the equations in Table 6, the data shown graphically in Fig. 6, or the data in Table 4.

15. Statistical Analysis

15.1 No determination of average grain size can be an exact measurement. Thus, no determination is complete without also calculating the precision within which the determined size may, with normal confidence, be considered to represent the actual average grain size of the specimen examined. In accordance with common engineering practice, this section assumes normal confidence to represent the expectation that the actual error will be within the stated uncertainty 95 % of the time.

15.1.1 Many specimens vary measurably in grain size from one field of view to another, this variation being responsible for a major portion of the uncertainty. Minimum effort in manual methods, to obtain a required precision, justifies individual counts whose precision is comparable to this natural variability **(6)**. The high local precision that may be obtained by machine methods often will yield only a small increase in overall precision unless many fields also are measured, but does help distinguish natural variability from inaccuracies of counting.

15.2 After the desired number of fields have been measured, calculate the mean value of $\bar{N}_A$ or $\bar{\ell}$ from the individual field values according to:

$$\bar{X} = \frac{\Sigma X_i}{n} \tag{12}$$

where X_i represents an individual value, $\bar{X}$ is the mean and n is the number of measurements.

15.3 Calculate the standard deviation of the individual measurements according to the usual equation:

$$s = \left[\frac{\Sigma (X_i - \bar{X})^2}{n - 1} \right]^{1/2} \tag{13}$$

where s is the standard deviation.

15.4 Calculate the 95 % confidence interval, 95 % CI, of each measurement according to:

$$95\ \%\ \text{CI} = \frac{t \cdot s}{\sqrt{n}} \tag{14}$$

where the · indicates a multiplication operation. Table 7 lists values of t as a function of n.

15.5 Calculate the percent relative accuracy, % RA, of the measurements by dividing the 95 % CI value by the mean and expressing the results as a percentage, that is:

TABLE 7 95 % Confidence Internal Multipliers, *t*

No. of Fields, *n*	*t*	No. of Fields, *n*	*t*
5	2.776	13	2.179
6	2.571	14	2.160
7	2.447	15	2.145
8	2.365	16	2.131
9	2.306	17	2.120
10	2.262	18	2.110
11	2.228	19	2.101
12	2.201	20	2.093

$$\%\ \text{RA} = \frac{95\ \%\ \text{CI}}{\bar{X}} \cdot 100 \tag{15}$$

15.6 If the % RA is considered to be too high for the intended application, more fields should be measured and the calculations in 15.1-15.5 should be repeated. As a general rule, a 10 % RA (or lower) is considered to be acceptable precision for most purposes.

15.7 Convert the mean value of $\bar{N}_A$ or $\bar{\ell}$ to the ASTM grain size number, G, using Table 4 or the Eqs in Table 6.

16. Specimens with Non-equiaxed Grain Shapes

16.1 If the grain shape was altered by processing so that the grains are no longer equiaxed in shape, grain size measurements should be made on longitudinal (ℓ), transverse (t) and planar (p) oriented surfaces for rectangular bar, plate or sheet type material. For round bars, radial longitudinal and transverse sections are used. If the departure from equiaxed is not too great (see 16.2.2), a reasonable estimate of the grain size can be determined using a longitudinal specimen and the circular test grid. If directed test lines are used for the analysis, measurements in the three principal directions can be made using only two of the three principal test planes.

16.2 *Planimetric Method*:

16.2.1 When the grain shape is not equiaxed but elongated, make grain counts on each of the three principal planes, that is, planes of polish on longitudinal, transverse and planar-oriented surfaces. Determine the number of grains per mm^2 at 1X on the longitudinal, transverse, and planar oriented surfaces, $\bar{N}_{A\,\ell}$, $\bar{N}_{At}$ and $\bar{N}_{Ap}$, respectively, and calculate the mean number of grains per unit area, $\bar{N}_A$, from the three $\bar{N}_A$ values from the principal planes:

$$\bar{N} = (\bar{N}_{A\ell} \cdot \bar{N}_{At} \cdot \bar{N}_{Ap})^{1/3} \tag{16}$$

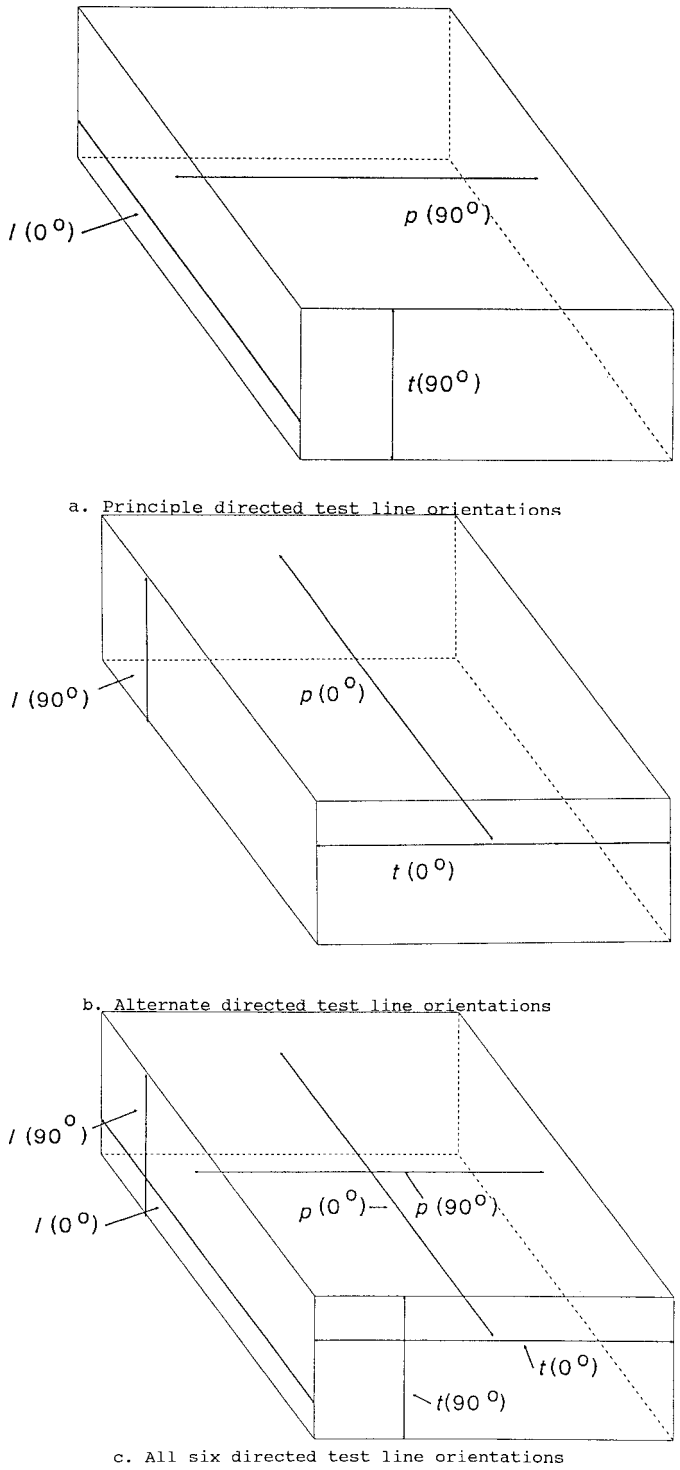
where · indicates a multiplication operation and the bar above each quantity indicates an average value.

16.2.2 A reasonable estimate of the grain size can be made from $\bar{N}_{A\ell}$ alone if the departure from an equiaxed shape is not excessive ($\leq$3:1 aspect ratio).

16.2.3 Calculate G from the mean value of $\bar{N}_A$ from the averages made on each field. Perform the statistical analysis (15.1-15.5) only on the individual measurements on each field.

16.3 *Intercept Method*:

16.3.1 To assess the grain size of non-equiaxed grain structures, measurements can be made using circular test grids or randomly placed test lines on each of the three principal test planes, or by use of directed test lines in either three or six of the principal directions using either two or three of the principal test planes, see Fig. 7. For specimens where the



NOTE 1—Measurements of rectangular bar, plate, strip or sheet type specimens with non-equiaxed grain structures.

FIG. 7 Schematic Showing the Six Possible Directed Test Line Orientations for Grain Size Measurement

departure from an equiaxed shape is not severe (≤3:1 aspect ratio), a reasonable estimate of the grain size can be made using a circular test grid on the longitudinal plane only.

16.3.2 The grain size can be determined from measurements of the mean number of grain boundary intersections per unit length, $\bar{P}_L$, or the mean number of grains intercepted per unit length, $\bar{N}_L$. Both methods yield the same results for a single phase grain structure. $\bar{P}_L$ or $\bar{N}_L$ can be determined using either test circles on each of the principal planes or directed test lines in either three or six of the principal test directions shown in Fig. 7.

16.3.3 For the case of randomly determined values of $\bar{P}_L$ or $\bar{N}_L$ on the three principal planes, compute the average value according to:

$$\bar{P} = (\bar{P}_{L\ell} \cdot \bar{P}_{Lt} \cdot \bar{P}_{Lp})^{1/3} \quad (17)$$

or

$$\bar{N} = (\bar{N}_{L\ell} \cdot \bar{N}_{Lt} \cdot \bar{N}_{Lp})^{1/3} \quad (18)$$

Alternatively, calculate ℓ_ℓ, $\bar{\ell}_t$ and $\bar{\ell}_p$ from the $\bar{P}_L$ or $\bar{N}_L$ values on each plane using (Eq 11). Then, calculate the overall mean value of $\bar{\ell}$ from:

$$\bar{\ell} = (\bar{\ell}_\ell \cdot \bar{\ell}_t \cdot \bar{\ell}_p)^{1/3} \quad (19)$$

16.3.4 If directed test lines are used in the principal directions on the principal planes, only two of the principal planes are required to perform directed counts in the three principal directions and obtain an estimate of the grain size.

16.3.5 Additional information on grain shape may be obtained by determining $\bar{\ell}$parallel (0°) and perpendicular (90°) to the deformation axis on a longitudinally oriented surface. The grain elongation ratio, or the anisotropy index, *AI*, can be determined from:

$$AI_\ell = \bar{\ell}_{\ell(0°)} / \bar{\ell}_{\ell(90°)} \quad (20)$$

16.3.5.1 The three-dimensional mean grain size and shape may also be defined by the directed mean lineal intercept values on the three principal planes. These values would be expressed as:

$$\bar{\ell}_{\ell(0°)} : \bar{\ell}_{\ell(90°)} : \bar{\ell}_{\ell(90°)} \quad (21)$$

16.3.5.2 Another approach that can be used is to normalize the three results by dividing each by the value of the smallest with the results expressed as ratios.

16.3.6 The mean value of $\bar{\ell}$ for the measurements in the three principal test directions is obtained by averaging the directed $\bar{N}_L$, or $\bar{P}_L$ values (as shown in (Eq 22)) and then computing $\bar{\ell}$ from this mean value; or, by calculating directed $\bar{\ell}$ values in each of the three principal directions and then averaging them according to (Eq 23):

$$\overline{P} = (\bar{P}_{L\ell(0°)} \cdot \bar{P}_{Lt(90°)} \cdot \bar{P}_{Lp(90°)})^{1/3} \quad (22)$$

This is done in like manner for $\bar{N}_L$. For computing the grand mean $\bar{\ell}$ from the directed mean values, use:

$$\bar{\ell} = (\bar{\ell}_{\ell(0°)} \cdot \bar{\ell}_{t(90°)} \cdot \bar{\ell}_{p(90°)})^{1/3} \quad (23)$$

where the · indicates a multiplication operation.

16.3.7 The mean grain size is determined from the overall averages of $\bar{P}_L$, $\bar{N}_L$ or ℓ using Table 4 or the equations in Table 6. Additional information on the measurement of grain size for non-equiaxed structures can be found in Annex A1 of Test Methods E 1382.

16.4 Statistical analysis should be performed on the data

from each plane or each principal test direction according to the procedure in 15.1-15.5.

17. Specimens Containing Two or More Phases or Constituents

17.1 Minor amounts of second phase particles, whether desireable or undesireable features, may be ignored in the determination of grain size, that is, the structure is treated as a single phase material and the previously described planimetric or intercept methods are used to determine the grain size. Unless stated otherwise, the effective average grain size shall be presumed to be the size of the matrix phase.

17.2 The identity of each measured phase and the percentage of field area occupied by each phase shall be determined and reported. The percentage of each phase can be determined according to Practice E 562.

17.3 *Comparison Method*—The comparison chart rating procedure may provide acceptable precision for most commercial applications if the second phase (or constituent) consists of *islands* or *patches* of essentially the same size as the matrix grains; or, the amount and size of the second phase particles are both small and the particles are located primarily along grain boundaries.

17.4 *Planimetric Method*—The planimetric method may be applied if the matrix grain boundaries are clearly visible and the second phase (constituent) particles are mainly present between the matrix grains rather than within the grains. Determine the percentage of the test area occupied by the second phase, for example, by Practice E 562. Always determine the amount of the phase of least concentration, usually the second phase or constituent. Then, determine the matrix phase by difference. Next, count the number of matrix grains completely within the test areas and the number of matrix grains intersecting the test area boundary, as described in Section 11. The test area must be reduced to that covered only by the matrix phase grains. The effective average grain size is then determined from the number of grains per unit net area of the matrix phase. Statistically analyze the number of grains per unit area of the α matrix phase, N_A α, from each field measurement using the approach described in Section 15. Then, from the overall average, $\bar{N}_A$ α, determine the effective grain size of the matrix using Table 4 or the appropriate equation in Table 6.

17.5 *Intercept Method*—The same restrictions regarding applicability, as stated in 17.4, pertain to this method. Again, the amount of the matrix phase must be determined, as described in 17.4. A test grid consisting of one or more test circles, such as shown in Fig. 5, is used. For this application, count the number of matrix grains, N_α, intercepted by the test line. Determine the mean intercept length of the matrix phase according to:

$$\bar{\ell}_\alpha = \frac{(V_{V\alpha})(L/M)}{N_\alpha} \tag{24}$$

where the volume fraction of the α matrix, $V_{V\alpha}$, is expressed as a fraction, L is the test line length and M is the magnification. The grain size of the α grains is determined using Table 4 or the equation in Table 6. In practice, it is inconvenient to manually determine the volume fraction of the α phase and the number of α grains intercepting the test line for each field. If this is done, the mean lineal intercept length of the α phase for each field can be determined and this data can be statistically analyzed for each field according to the procedure described in Section 15. If $V_{V\alpha}$ and N_α are not measured simultaneously for the same fields, then the statistical analysis can only be performed on the $V_{V\alpha}$ and N_α data.

17.6 It is also possible to determine $\bar{\ell}_\alpha$ by measurement of individual intercept lengths using parallel straight test lines applied randomly to the structure. Do not measure the partial intercepts at the ends of the test lines. This method is rather tedious unless it can be automated in some way. The individual intercepts are averaged and this value is used to determine G from Table 4 or the equation in Table 6. The individual intercepts may be plotted in a histogram, but this is beyond the scope of these test methods.

18. Report

18.1 The test report should document all of the pertinent identifying information regarding the specimen, its composition, specification designation or trade name, customer or data requester, date of test, heat treatment or processing history, specimen location and orientation, etchant and etch method, grain size analysis method, and so forth, as required.

18.2 List the number of fields measured, the magnification, and field area. The number of grains counted or the number of intercepts or intersections counted, may also be recorded. For a two-phase structure, list the area fraction of the matrix phase.

18.3 A photomicrograph illustrating the typical appearance of the grain structure may be provided, if required or desired.

18.4 List the mean measurement value, its standard deviation, 95 % confidence interval, percent relative accuracy, and the ASTM grain size number.

18.4.1 For the comparison method, list only the estimated ASTM grain size number.

18.5 For a non-equiaxed grain structure, list the method of analysis, planes examined, directions evaluated (if applicable), the grain size estimate per plane or direction, the grand mean of the planar measurements, and the computed or estimated ASTM grain size number.

18.6 For a two-phase structure, list the method of analysis, the amount of the matrix phase (if determined), the grain size measurement of the matrix phase (and the standard deviation, 95 % confidence interval, and percent relative accuracy), and the computed or estimated ASTM grain size number.

18.7 If it is desired to express the average grain size of a group of specimens from a lot, do not simply average the ASTM grain size numbers. Instead, compute an arithmetic average of the actual measurements, such as, the $\bar{N}_A$ or $\bar{\ell}$ values per specimen. Then, from the lot average, calculate or estimate the ASTM grain size for the lot. The specimen values of $\bar{N}_A$ or $\bar{\ell}$ may also be statistically analyzed, according to the approach in Section 15, to evaluate the grain size variability within the lot.

19. Precision and Bias

19.1 The precision and bias of grain size measurements depend on the representativeness of the specimens selected and the areas on the plane-of-polish chosen for measurement. If the

grain size varies within a product, specimen and field selection must adequately sample this variation.

19.2 The relative accuracy of the grain size measurement of the product improves as the number of specimens taken from the product increases. The relative accuracy of the grain size measurement of each specimen improves as the number of fields sampled and the number of grains or intercepts counted increase.

19.3 Bias in measurements will occur if specimen preparation is inadequate. The true structure must be revealed and the grain boundaries must be fully delineated for best measurement precision and freedom from bias. As the percentage of non-delineated grain boundaries increases, bias increases and precision, repeatability, and reproducibility become poorer.

19.4 Inaccurate determination of the magnification of the grain structure will produce bias.

19.5 If the grain structure is not equiaxed in shape, for example, if the grain shape is elongated or flattened by deformation, measurement of the grain size on only one plane, particularly the plane perpendicular to the deformation direction, will bias test results. Grain shape distortion is best detected using a test plane parallel to the deformation direction. The size of the deformed grains should be based on measurements made on two or three of the principal planes which are averaged as described in Section 16.

19.6 Specimens with a unimodal grain size distribution are measured for average grain size using the methods described in these test methods. Specimens with bimodal (or more complex) size distributions should not be tested using a method that yields a single average grain size value; they should be characterized using the methods described in Test Methods E 1181 and measured using the methods described in Test Methods E 112. The size of individual very large grains in a fine grained matrix should be determined using Test Methods E 930.

19.7 When using the comparison chart method, the chart selected should be consistent with the nature of the grains (that is, twinned or non-twinned, or carburized and slow cooled) and the etch (that is, flat etch or grain contrast etch) for best precision.

19.8 Grain size ratings using the comparison chart method by an individual metallographer will vary within ± 0.5 *G* units. When a number of individuals rate the same specimen, the spread in ratings may be as great as 1.5 to 2.5 *G* units.

19.9 The fracture grain size method is only applicable to hardened, relatively brittle, tool steels. Specimens should be in the as-quenched or lightly tempered condition so that the fracture surface is quite flat. An experienced metallographer can rate the prior-austenite grain size of a tool steel within ± 0.5 *G* units by the Shepherd fracture grain size method.

19.10 A round robin test program (see Appendix X1), analyzed according to Practice E 691, revealed a rather consistent bias between comparison chart ratings using Plate I and grain size measurements using both the planimetric and intercept methods. Chart ratings were 0.5 to 1 *G* unit coarser, that is, lower *G* numbers, than the measured values.

19.11 Grain sizes determined by either the planimetric or intercept methods produced similar results with no observed bias.

19.12 The relative accuracy of grain size measurements improved as the number of grains or intercepts counted increased. For a similar number of counts, the relative accuracy of intercept measurements was better than that of planimetric measurements of grain size. For the intercept method, 10 % RA (or less) was obtained with about 400 intercept or intersection counts while for the planimetric method, to obtain 10 % RA, or less, about 700 grains had to be counted. Repeatability and reproducibility of measurements improved as the number of grains or intercepts counted increased and was better for the intercept method than for the planimetric method for the same count.

19.13 The planimetric method requires a marking off of the grains during counting in order to obtain an accurate count. The intercept method does not require marking in order to get an accurate count. Hence, the intercept method is easier to use and faster. Further, the round robin test showed that the intercept method provides better statistical precision for the same number of counts and is, therefore, the preferred measurement method.

19.14 An individual metallographer can usually repeat planimetric or intercept grain size measurements within ± 0.1 *G* units. When a number of metallographers measure the same specimen, the spread of grain sizes is usually well within ± 0.5 *G* units.

20. Keywords

20.1 ALA grain size; anisotropy index; area fraction; ASTM grain size number; calibration; equiaxed grains; etchant; grain boundary; grains; grain size; intercept count; intercept length; intersection count; non-equiaxed grains; twin boundaries

ANNEXES

(Mandatory Information)

A1. BASIS OF ASTM GRAIN SIZE NUMBERS

A1.1 Descriptions of Terms and Symbols

A1.1.1 The general term *grain size* is commonly used to designate size estimates or measurements made in several ways, employing various units of length, area, or volume. Of the various systems, only the ASTM grain size number, *G*, is essentially independent of the estimating system and measurement units used. The equations used to determine *G* from recommended measurements, as illustrated in Fig. 6 and Table 2 and Table 4, are given in A1.2 and A1.3. The nominal relationships between commonly used measurements are given in Annex A2. Measurements that appear in these equations, or in equations in the text, are as follows:

A1.1.1.1 N = Number of grain sections counted on a known test area, A, or number of intercepts counted on a known test array of length = L, at some stated magnification, M. The average of counts on several fields is designated as $\bar{N}$.

A1.1.1.2 After correction for magnification, N_A is the number of grain sections per unit test area (mm ^{2}) at 1X; N_L is the number of grains intercepted per unit length (mm) of test lines at 1X; and P_L is the number of grain boundary intersections per unit length (mm) of test line at 1X.

A1.1.1.3 $\bar{\ell} = 1/N_L = 1/P_L$ where $\bar{\ell}$ is the mean lineal intercept length in mm at 1X.

A1.1.1.4 $\bar{A} = 1/N_A$ where $\bar{A}$ is the mean area of the grain sections (mm^2) at 1X. The mean grain diameter, $\bar{d}$, is the square root of $\bar{A}$. Grain size values on Plate III are expressed in terms of $\bar{d}$. Note that Table 2 lists the equivalent ASTM grain size number for each chart picture and for several different magnifications.

A1.1.1.5 The letters ℓ, t and p are used as subscripts when assessing the grain size of specimens with non-equiaxed grain structures. The three subscripts represent the principal planes for rectangular bar, plate, sheet, or strip specimens, that is, the longitudinal (ℓ), transverse (t) and planar (p) surfaces. They are mutually perpendicular to each other. On each plane, there are two principal directions that are perpendicular to each other (as illustrated in Fig. 7).

A1.1.1.6 The number of fields measured is designated by n.

A1.1.1.7 Other specific designations are defined by equations which follow.

A1.2 *Intercept Methods:*

A1.2.1 Metric units, $\bar{\ell}$ in millimetres at 100X for microscopically determined grain sizes and $\bar{\ell}_m$ at 1X for macroscopically determined grain sizes, are used with the following equation relating $\bar{\ell}$ or $\bar{\ell}_m$ to G. For macroscopically determined grain sizes, $\bar{\ell}_m$ is in mm at 100X:

$$G = 2 \log_2 \frac{\ell_0}{\bar{\ell}_m} \quad \text{(A1.1)}$$

for $G = 0$, ℓ_0 is established as 32.00 and $\log_2 \ell_0 = 5$.

$$G = +10.000 - 2 \log_2 \ell_m \quad \text{(A1.2)}$$

$$G = +10.0000 - 6.6439 \log_{10} \bar{\ell}_m \quad \text{(A1.3)}$$

For microscopically determined grain sizes, $\bar{\ell}$ is in millimetres at 1X and:

$$G = -3.2877 - 6.6439 \log_{10} \bar{\ell} \quad \text{(A1.4)}$$

$$G = -3.2877 + 2 \log_2 \bar{N}_L \quad \text{(A1.5)}$$

$$G = -3.2877 + 6.6439 \log_{10} \bar{N}_L \quad \text{(A1.6)}$$

If $\bar{P}_L$ is determined instead of $\bar{N}_L$, substitute $\bar{P}_L$ for $\bar{N}_L$ in Eq A1.5 and Eq A1.6.

A1.3 *Planimetric Method:*

A1.3.1 English units, $\bar{N}_{AE}$ in number per square inches at 100X for microscopically determined grain sizes and at 1X for macroscopically determined grain sizes, are used with the following equations relating $\bar{N}_{AE}$ to G:

$$G = 1.000 + \log_2 \bar{N}_{AE} \quad \text{(A1.7)}$$

$$G = 1.000 + 3.3219 \log_{10} \bar{N}_{AE} \quad \text{(A1.8)}$$

If $\bar{N}_A$ is expressed in terms of the number of grains per square millimetres at 1X, for microscopically determined grain sizes, then:

$$G = 2.9542 + 3.3219 \log_{10} \bar{N}_A \quad \text{(A1.9)}$$

A2. EQUATIONS FOR CONVERSIONS AMONG VARIOUS GRAIN SIZE MEASUREMENTS

A2.1 *Change of Magnification*—If the apparent grain size has been observed at magnification M, but determined as if at the basic magnification M_b (100X or 1X), then the size value at the basic magnification is as follows:

A2.1.1 *Planimetric Count*:

$$N_A = N_{A0} (M/M_b)^2 \quad \text{(A2.1)}$$

where $N_{A\,0}$ is the number of grains per unit area at magnification M_b.

A2.1.2 *Intercept Count*:

$$N_i = N_{i0} (M/M_b) \quad \text{(A2.2)}$$

where $N_{i\,0}$ is the number of grains intercepted by the test line (the equation for P_i and $P_{i\,0}$ is the same) at magnification M_b.

A2.1.3 *Any Length*:

$$\bar{\ell} = \bar{\ell}_0 M_b / M \quad \text{(A2.3)}$$

where $\bar{\ell}_0$ is the mean lineal intercept at magnification M_b .

A2.1.4 *ASTM Grain Size Number*:

$$G = G_0 + Q \quad \text{(A2.4)}$$

where:

$Q = 2 \log_2 (M/M_b)$
$= 2 (\log_2 M - \log_2 M_b)$
$= 6.6439 (\log_{10} M - \log_{10} M_b)$

where G_0 is the apparent ASTM grain size number at magnification M_b .

A2.1.5 Grains per mm^2 at 1X from grains per in.^{2} at 100X:

$$N_A = N_{AE} (100/25.4)^2 \quad \text{(A2.5)}$$

$$N_A = 15.5\, N_{AE} \quad \text{(A2.6)}$$

where N_A is the number of grains per mm^2 at 1X and N_{AE} is the number of grains per in.^{2} at 100X.

A2.2 Other measurements shown in the tables may be computed from the following equations:

A2.2.1 *Area of Average Grain*:

$$\bar{A} = 1/N_A \quad \text{(A2.7)}$$

where $\bar{A}$ is the average grain cross sectional area.

A2.2.2 *Intercept Width of a Circular Grain Section*:

$$\bar{\ell} = \left(\frac{\pi}{4} \bar{A}\right)^{1/2} \quad \text{(A2.8)}$$

The mean intercept distance for polygonal grains varies about this theoretical value, being decreased by anisotropy but increased by a range of section sizes. The width computed by (Eq A2.8) is 0.52 % smaller than the width assigned to G by (Eq A1.4) in A1.2.1 (Δ = + 0.015 ASTM No.).

A2.3 Other useful size indications are given by the following equations:

A2.3.1 The volumetric (spatial) diameter, $\bar{D}$, of similar size spheres in space is:

$$\bar{D} = 1.5 \bar{\ell} \quad \text{(A2.9)}$$

Similar relationships between $\bar{\ell}$, determined on the two-dimensional plane of polish, and the spatial diameter, $\bar{D}$, have been derived for a variety of potential grain shapes, and various assumptions about their size distribution. A number of formulae, such as equation (Eq A2.7), have been proposed with different multiplying factors. A reasonable estimate of the spatial diameter, $\bar{D}$, based upon the tetrakaidecahedron shape model and a grain size distribution function **(8)**, is:

$$\bar{D} = 1.571\, \bar{\ell} \quad \text{(A2.10)}$$

A2.3.2 For a single phase microstructure, the grain boundary surface area per unit volume, S_V , has been shown to be an exact function of P_L or N_L :

$$S_V = 2P_L = 2N_L \quad \text{(A2.11)}$$

while for a two phase microstructure, the phase boundary surface area per unit volume of the α phase, $S_V \alpha$, is:

$$S_{V\alpha} = 2P_L = 4N_L \quad \text{(A2.12)}$$

A3. AUSTENITE GRAIN SIZE, FERRITIC AND AUSTENITIC STEELS

A3.1 Scope

A3.1.1 Because it is sometimes necessary to subject material to special treatments or techniques in order to develop certain grain characteristics prior to the estimation of grain size, the essential details of these treatments are set forth in the following sections.

A3.2 Establishing Austenite Grain Size

A3.2.1 *Ferritic Steels*— Unless otherwise specified, austenite grain size shall be established by one of the following procedures:

NOTE A3.1—The indications of carbon contents in the procedure headings are advisory only. Numerous methods are in use for establishing austenite grain size, and a knowledge of grain growth and grain coarsening behavior is helpful in deciding which method to use. The size of austenite grains, in any particular steel, depends primarily on the temperature to which that steel is heated and the time it is held at the temperature. It should be remembered that the atmosphere in heating may affect the grain growth at the outside of the piece. Austenite grain size is also influenced by most previous treatments to which the steel may have been subjected as, for example, austenitizing temperature, quenching, normalizing, hot working, and cold working. It is therefore advisable, when testing for austenite grain size, to consider the effects of prior or subsequent treatments, or both, on the precise piece (or typical piece) that is under consideration.

A3.2.1.1 *Correlation Procedure (Carbon and Alloy Steels)*—Test conditions should correlate with the actual heat-treatment cycle used to develop the properties for actual service. Heat the specimens at a temperature not over 50°F (28°C) above the normal heat-treating temperature and for not over 50 % more than the normal heat-treating time and under normal heat-treating atmosphere, the normal values being those mutually agreed upon. The rate of cooling depends on the method of treatment. Make the microscopical examination in compliance with Table 1.

A3.2.1.2 *Carburizing Procedure (Carbon and Alloy Steels; Carbon Generally Below 0.25 %)*—This procedure is usually referred to as the McQuaid—Ehn Test. Unless otherwise specified, carburize the specimens at 1700 ± 25°F (927± 14°C) for 8 h or until a case of approximately 0.050 in. (1.27 mm) is obtained. The carburizing compound must be capable of producing a hypereutectoid case in the time and at the temperature specified. Furnace cool the specimen to a temperature below the lower critical at a rate slow enough to precipitate cementite in the austenite grain boundaries of the hypereutectoid zone of the case. When cool, section the specimen to provide a fresh-cut surface, polish, and suitably etch to reveal the grain size of the hypereutectoid zone of the case. Make a microscopical examination in compliance with Table 1. While

the McQuaid-Ehn test was designed for evaluating the grain growth characteristics of steels intended for carburizing applications, usually steels with <0.25 % carbon, it is frequently used to evaluate steels with higher carbon contents that will not be carburized. It must be recognized that the grain size of such steels when heat treated from austenitizing temperatures below 1700°F may be finer in size than that obtained by the McQuaid-Ehn test.

A3.2.1.3 *Mock Carburizing Procedure*—The heat treatment described in A3.2.1.2 is performed but a carburizing atmosphere is not used and the specimen must be quenched from the mock carburizing temperature at a rate fast enough to form martensite, rather than slowly cooled after carburizing. The specimen is sectioned (careful abrasive cut-off cutting is required to prevent burning), polished and etched with a reagent that will reveal the prior-austenite grain boundaries (such as saturated aqueous picric acid with a wetting agent, see Practice E 407). Mock carburizing is sometimes preferred because the depth of the carburized case produced by the McQuaid-Ehn test may be quite thin with some steels. With a mock carburized specimen, all of the grains on the cross section can be examined. Problems such as banded grain size, duplex or ALA grains (see Test Methods E 1181) are more easily detected with a mock carburized specimen due to the much greater surface area for examination.

A3.2.1.4 *Hypoeutectoid Steels (Carbon and Alloy Steels 0.25 to 0.60 % Carbon)*—Unless otherwise specified, heat specimens of steels with a carbon content of 0.35 % or less at 1625 ± 25°F (885± 14°C); heat specimens of steel with a carbon content of over 0.35 % at 1575 ± 25°F (857 ± 14°C) for a minimum of 30 min and cool in air or quench in water. The higher carbon steels in this range and alloy steels over approximately 0.40 % carbon may require an adjustment in cooling practice to outline clearly the austenite grain boundaries with ferrite. In such cases it is recommended that after holding the specimen for the required time at a hardening temperature, the temperature be reduced to approximately 1340 ± 25°F (727 ± 14°C) for 10 min, followed by water or oil quench. When cool, section the specimen to provide a fresh-cut surface, polish, and suitably etch to reveal the austenite grain size as outlined by precipitated ferrite in the grain boundaries. Make the microscopical examination in compliance with Table 1.

A3.2.1.5 *Oxidation Procedure (Carbon and Alloy Steels 0.25 to 0.60 % Carbon)*—Polish one of the surfaces of the specimen (approximately 400-grit or 15-µm abrasive). Place the specimen with the polished side up in a furnace, and, unless otherwise specified, heat at 1575 ± 25°F (857 ± 14°C) for 1 h and quench in cold water or brine. Polish the quenched specimen to reveal the austenite grain size as developed in the oxidized surface. Make the microscopical examination in compliance with Table 1.

A3.2.1.6 *Direct Hardening Steels (Carbon and Alloy Steels; Carbon Generally Below 1.00 %)*—Unless otherwise specified, heat specimens of steels with a carbon content of 0.35 % or less at 1625± 25°F (885 ± 14°C); heat specimens of steels with a carbon content of over 0.35 % at 1575 ± 25°F (857 ± 14°C) for sufficient time and quench at a rate to produce full hardening. Polish the quenched specimen and etch to reveal the martensitic structure. Tempering for 15 min at 450 ± 25°F (232 ± 14°C) prior to etching improves the contrast. Make the microscopical examination in compliance with Table 1.

A3.2.1.7 *Hypereutectoid Steels (Carbon and Alloy Steels; Carbon Generally Over 1.00 %)*—Use a specimen approximately 1 in. (25.4 mm) in diameter or 1 in. square for this test. Unless otherwise specified, heat the specimen at 1500 ± 25°F (816 ± 14°C) for a minimum of 30 min, and furnace cool to a temperature below the lower critical temperature at a rate slow enough to precipitate cementite in the austenite grain boundaries. When cool, section the specimen to provide a fresh-cut surface, polish, and suitably etch to reveal the austenite grain size as outlined by precipitated cementite in the grain boundaries. Make the microscopical examination in compliance with Table 1.

A3.2.2 *Austenitic Steels*—With austenitic materials, the actual grain size of the metal has been established by prior heat-treatment.

A3.3 Revealing the Grain Size

A3.3.1 *Ferritic Steels*— For revealing austenite grain size the following methods (see Note A3.1) are generally used:

A3.3.1.1 *Outlining the Grains with Cementite*—In the hypereutectoid zone of a carburizing (McQuaid—Ehn test) procedure or in hypereutectoid steels cooled from the austenitic condition, the austenite grain size is outlined by the cementite which precipitated in the grain boundaries. It is therefore possible to rate the grain size by etching the micrographic specimen with a suitable etchant,[10] such as nital, picral, or alkaline sodium picrate.

A3.3.1.2 *Outlining the Grains with Ferrite*—In the hypoeutectoid zone of a carburized specimen, the austenite grain size is outlined by the ferrite that precipitated in the grain boundaries. Ferrite similarly outlines the former austenite grains in a medium-carbon steel (approximately 0.50 % carbon), when it has been cooled slowly from the austenite range. In low-carbon steels (approximately 0.20 % carbon), cooling slowly from the austenite range to room temperature, the amount of ferrite is so large that the former austenite grain size is masked; in this case, the steel may be cooled slowly to an intermediate temperature, to allow only a small amount of ferrite to precipitate, followed by quenching in water; an example would be a piece previously heated to 1675°F (913°C), transferred to a furnace at between 1350 to 1450°F (732 to 788°C), held at this temperature for perhaps 3 to 5 min, and then quenched in water; the austenite grain size would be revealed by small ferrite grains outlining low-carbon martensite grains.

A3.3.1.3 *Outlining the Grains by Oxidation*—The oxidation method depends on the fact that when steels are heated in an oxidizing atmosphere, oxidation takes place in part preferentially along the grain boundaries. A common procedure, therefore, is to polish the test specimen to a metallographic polish, heat it in air at the desired temperature for the desired length of time, and then repolish the specimen lightly so as merely to remove scale; whereupon the austenite grain boundaries are visible as outlined by oxide.

[10] See Practice E 407.

A3.3.1.4 *Outlining Martensite Grains with Fine Pearlite*—A method applicable particularly to eutectoid steels, which cannot be judged so readily by some other methods, is either to harden a bar of such a size that it is fully hardened at the outside but not quite fully hardened in the interior, or to employ a *gradient quench* in which the heated piece is for a portion of its length immersed in water and therefore fully hardened, the remainder of the piece projecting above the quenching bath, being therefore not hardened. With either method there will be a small zone which is almost but not quite fully hardened. In this zone, the former austenite grains will consist of martensite grains surrounded by small amounts of fine pearlite, thus revealing the grain size. These methods are also applicable to steels somewhat lower and higher than the eutectoid composition.

A3.3.1.5 *Etching of Martensite Grains*—The former austenite grain size may be revealed in steels fully hardened to martensite by using an etching reagent that develops contrast between the martensite grains. Tempering for 15 min at 450°F (232°C) prior to etching distinctly improves the contrast. A reagent that has been recommended is 1 g of picric acid, 5 mL of HCl (sp gr 1.19), and 95 mL of ethyl alcohol. An alternate approach is to use an etchant that reveals the prior-austenite grain boundaries preferentially. Many etchants have been developed for this purpose (see Practice E 407 and standard text books). The most successful consists of saturated aqueous picric acid containing a wetting agent, usually sodium tridecylbenzene sulfonate (the dodecyl version also works well). Specimens should be in the as-quenched condition or tempered not above about 1000°F. Success with this etchant depends upon the presence of phosphorus in the alloy (≥0.005 % P required). Results may be enhanced by tempering the steel between 850 and 900°F for 8 h or more to drive phosphorus to the grain boundaries. For steels with substantial alloy additions, it may be necessary to add a few drops of hydrochloric acid to the etchant (per 100 mL of etchant). Etching usually takes at least 5 min. The etchant will attack sulfide inclusions. Lightly re-polishing the specimen on a stationary wheel to remove some of the unimportant background detail may make it easier to see the grain boundaries.

A3.3.2 *Austenitic Steels*—For revealing the grain size in austenitic materials, a suitable etching technique shall be used to develop grain size. Recognizing that twinning tends to confuse reading of grain size, the etching should be such that a minimum amount of twinning is evident.

A3.3.2.1 *Stabilized Material*—The specimen, as the anode, may be electrolytically etched in a water solution composed of 60 % concentrated nitric acid by volume, at ambient temperature. To minimize the appearance of twinning, a low voltage (1 to 1½ V) should be used. This etchant is also recommended for revealing ferrite grain boundaries in ferritic stainless steels and is used identically.

A3.3.2.2 *Unstabilized Material*—The grain boundary may be developed through precipitation of carbides by heating within the sensitizing temperature range, 482 to 704°C (900 to 1300°F). Any suitable carbide-revealing etchant should be used.

A3.4 Reporting the Grain Size

A3.4.1 *Ferritic Steels*— Duplex, or mixed grain-sized structure (see Test Methods E 1181) when observed, shall be reported with two representative ranges of grain size numbers. Whenever heat-treatments other than the carburizing (McQuaid—Ehn test) procedure are employed to develop austenite grain size, a complete report shall be made which includes:

A3.4.1.1 Temperature used in establishing the grain size,

A3.4.1.2 Time at temperature used in establishing the grain size,

A3.4.1.3 Method of revealing grain size, and

A3.4.1.4 Grain size.

A3.4.2 *Austenitic Steels*—In determining the size of austenitic grains, the twin boundaries within a grain shall not be counted.

A4. FRACTURE GRAIN SIZE METHOD[11]

A4.1 The fracture grain size method, developed by Arpi **(9)**, and Shepherd **(2)**, employs a graded series of ten fractured specimens to estimate the prior-austenite grain size of steel specimens (see Footnote 11 for applicable materials) by comparison. Carburized cases of carbon and alloy steels may also be evaluated for prior-austenite grain size by this method (but not the low-carbon core).

A4.2 The ten fractured specimens are numbered from one to ten where the numbers correspond to ASTM grain size numbers. The sample to be rated is fractured, usually transverse to the hot working direction, and the fracture is compared to the ten test fractures of the Shepherd series.[12] The fracture appearance of the specimen is rated to the nearest whole number of the standard, but interpolation to one-half numbers is permitted. It is also possible to rate duplex conditions when the fracture exhibits two different fracture patterns.

A4.3 Specimens can be fractured by striking the free end, while restraining the other end, or by three-point bending using a press, or a tensile machine (loaded in compression) or any other suitable method. Notching of specimens or refrigeration prior to fracturing, or both, helps to ensure a flat fracture. For further information see Vander Voort **(10)**.

A4.4 The specimen to be rated must be predominantly

[11] This method is applicable only to high-hardness, brittle steels with a predominantly martensite microstructure, such as tool steels, high-carbon steels and martensitic stainless steels, and should be done with the specimen in the as-quenched or lightly tempered condition.

[12] For those individuals who do not possess a Shepherd standard series, a photographic reproduction is available from ASTM Headquarters. Order PCN 12-501124-23.

martensitic, although large amounts of retained austenite do not invalidate the results. Appreciable amounts of residual carbide are also permitted. However, diffusion controlled transformation products, such as bainite, pearlite, or ferrite, if present in amounts more than a few percent, change the nature of the fracture appearance and invalidate fracture grain size ratings. Excessive tempering of martensitic tool steel structures also alters the fracture appearance and invalidates fracture grain size ratings. Ratings are most accurate for as-quenched or lightly tempered specimens. Flat, brittle fractures are desired to obtain the best accuracy.

A4.5 Studies have shown that fracture grain size ratings of fully hardened, as-quenched tool steels correlate well with microscopically measured prior-austenite grain size ratings. For most tool steels, the fracture grain size rating will be within ± 1 unit of the microscopically determined prior-austenite grain size number, *G*.

A4.6 The fracture grain size method cannot be used to rate grain sizes finer than ten. Fractures of specimens with prior-austenite grain sizes finer than ten cannot be discriminated by eye and will be rated as if they were a ten grain size. Fractures coarser than a grain size number of one will appear to be coarser than one but cannot be accurately rated by this method.

A5. REQUIREMENTS FOR WROUGHT COPPER AND COPPER-BASE ALLOYS

A5.1 For wrought copper and copper-base alloy products under the jurisdiction of Committee B-5 on Copper and Copper Alloys, it is mandatory that the following procedures be followed:

A5.1.1 The specimen shall be prepared in accordance with Practice E 3.

A5.1.2 The specimen used for the comparison method shall be contrast etched, and compared with Plate III, or, if given a flat etch, compared with Plate II.

A5.1.3 The grain size shall be expressed as the average grain diameter in millimetres; for example, 0.025-mm average grain diameter. The meaning of this expression is the diameter of the average cross section of grains lying in the plane of the metal being examined.

A5.1.4 Mixed grain sizes (see Test Methods E 1181) are sometimes encountered, particularly in hot-worked metal. These shall be expressed by giving the estimated area percentages occupied by the two ranges of sizes. For example, 50 % of 0.015 mm; and 50 % of 0.070 mm; or, if a range exists, 40 % of 0.010 to 0.020 mm; and 60 % of 0.090 to 0.120 mm.

A5.1.5 For determining compliance of requirements for grain size with the specified limits, the estimated value shall be rounded in accordance with:

Grain Size	Calculated or Observed Value to Which Grain Size Should be Rounded
Up to 0.055 mm, incl	to the nearest multiple of 0.005 mm
Over 0.055 mm	to the nearest 0.010 mm

A6. APPLICATION TO SPECIAL SITUATIONS

A6.1 Numerous specific practices for grain size measurement have become established in various segments of the metals and materials industries. The present listing of standard methods is not intended to imply that any such specific practice should be abandoned when experience has shown that practice to be adequate for the intended application. It is, however, strongly recommended that the statistical procedure of Section 15 be applied to the data from these traditional practices in order to ensure that they yield a confidence limit that is adequate for current requirements.

A6.2 It is characteristic of many special practices that they report a numerical result that is not conveniently related to commonly used size scales such as are shown in Table 4. Continued usage of the customary numbers is justified on the grounds that either they have inherent meaning in their own community, or that they have acquired meaning through long usage. It is, however, strongly recommended that such measurements be made comprehensible to a wider audience first by reexpression on one of the preferred metric scales (as used in Table 4), and then by conversion to the corresponding ASTM grain size numbers. Where the original measurements represent some form of intercept or planimetric count it may be said that the ASTM grain size number has in fact been determined. Where the original data are of a different nature, it should be stated that the measurement is equivalent to ASTM grain size No. “x”. Conversions may be made either through Table 4 or through the relations shown in Annex A1 and Annex A2.

A6.3 *Examples:*

A6.3.1 *Example 1*—The Snyder and Graff procedure **(11)** remains in general usage for estimating the austenitic grain size of tool steels. This is a specific version of the Heyn intercept method (see 13.1) in which the reported number is the average number of intercepts with a 5-in. (127-mm) test line applied to an image at 1000X. This count is more immediately useful than the ASTM grain size number itself, as important changes of quality are associated with a change of about two ASTM size numbers, which difference is not well resolved on the logarithmic size scale or by comparison or planimetric methods. The Snyder and Graff size number will become meaningful to others by multiplying by the factor 7.874 to yield N_L per millimetre, after which Table 4 will indicate, for example, that S&G No. 15 is ASTM grain size No. 10.5. Furthermore, as the

precision of this practice does not attain 2 % of the count, the 5-in. (127-mm) test line could be replaced by a 125-mm test line without invalidating past records, making the multiplier 8.0, whereupon the total intercept count on eight test lines equals N_L directly. The confidence limit evaluation in Section 15 can be applied to single test lines, or to totals on fixed numbers of lines in each local area.

APPENDIXES

(Nonmandatory Information)

X1. RESULTS OF INTERLABORATORY GRAIN SIZE DETERMINATIONS[13]

X1.1 This interlaboratory test program was conducted to develop precision and bias estimates for the measurement of grain size by the chart comparison method, by the planimetric method, and by the intercept method.

X1.2 Procedure

X1.2.1 Photomicrographs (8 by 10 in.) of two different ferritic stainless steels, four of one specimen at different magnifications and three of the other specimen at different magnifications, were rated for grain size using the chart method with Plate I and by the planimetric and intercept methods. A drawing of the grain boundaries of a specimen of austenitic Hadfield's manganese steel, with a grain contrast etch, was also evaluated by all three methods. A number of other micrographs were rated only by the comparison method. In each case, the grain boundaries were clearly and fully delineated.

X1.2.2 For the planimetric method, each rater was given an 8 by 10 in. clear plastic template with five 79.8 mm diameter test circles and a grease pencil. For the intercept method, each rater was given a single three-circle template.

X1.2.3 For the planimetric method, the template was dropped onto the photograph and taped down to prevent movement. Because the circles grid and the micrograph were nearly the same size, grid placement should be rather consistent between raters. For the intercept method, the raters dropped their grid onto the micrograph five times at random. It was assumed that this difference in placement method would reduce the variability of the planimetric method relative to the intercept method.

X1.3 Results

X1.3.1 Figs. X1.1 and X1.2 show the grain size ratings for

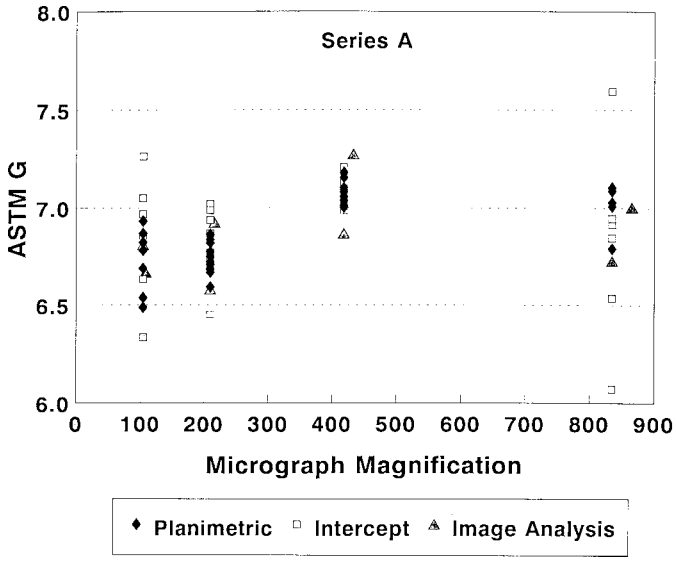


FIG. X1.1 Grain Size Measurements for the Series A Ferritic Stainless Steel Specimens

the two ferritic stainless steels, identified as Series A and B, as a function of the magnification of the micrographs, for the planimetric and intercept methods. Three people also made image analysis measurements of the images. As can be seen, the tightest spread occurred, for both sets of micrographs, at a magnification of about 400X where the average grain count per planimetric measurement was about 30 to 35 and the average number of intercepts or intercepts was about 40 to 50 per three-circle application.

X1.3.2 Figs. X1.3 and X1.4 show how the percent relative accuracy of the measurements varied with the number of grains counted, Fig. X1.3, and with the number of intercepts or intersections counted, Fig. X1.4. All of the measurement data are included. Note that a percent RA of 10 %, or less, is obtained when about 700 or more grains are counted by the

[13] Supporting data have been filed at ASTM Headquarters and may be obtained by requesting RR:E 04-1005.

TABLE X1.1 Results of ASTM Grain Size Round Robin (Planimetric Method)

Image	No./sq. mm	ASTM *G*	Average No.	Repeatability 95 % CL	Reproducibility 95 % CL	Repeatability % RA	Reproducibility % RA
A1	846.64	6.77	1918.0	106.11	266.56	12.53	31.49
A2	831.61	6.75	474.5	209.68	239.88	25.21	28.85
A3	1046.98	7.08	150.5	499.42	489.10	47.70	46.72
A4	978.49	6.98	35.5	785.07	765.18	80.23	78.20
B1	1054.12	7.09	608.5	342.21	344.35	32.46	32.67
B2	1069.41	7.11	152.5	464.60	452.27	43.44	42.29
B3	1184.01	7.26	41.5	435.21	403.98	36.76	34.12

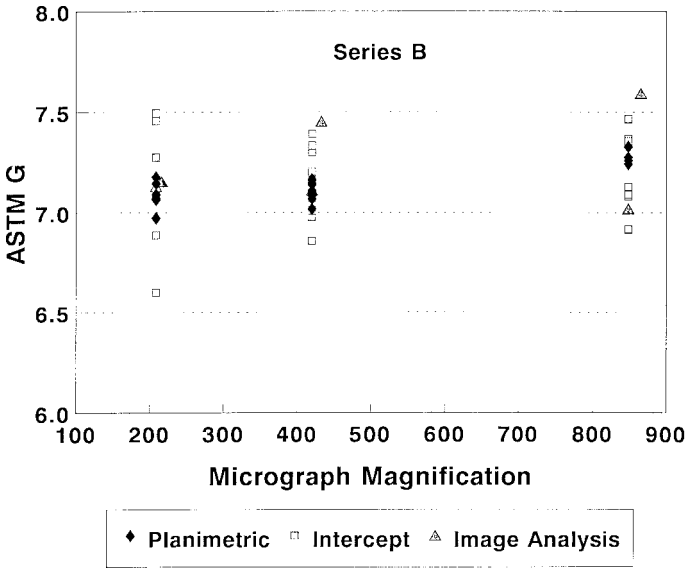
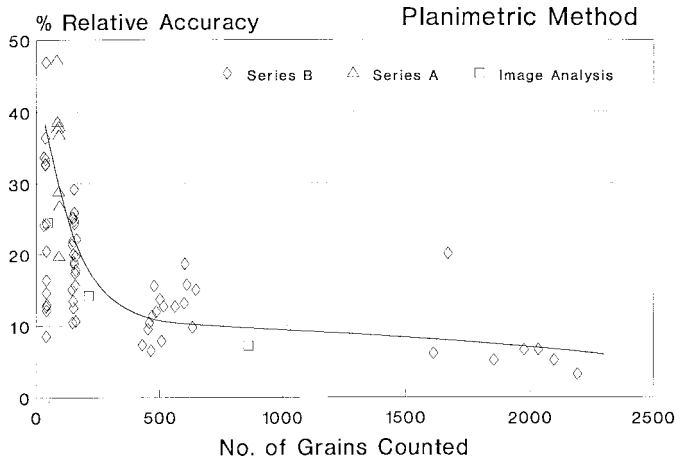


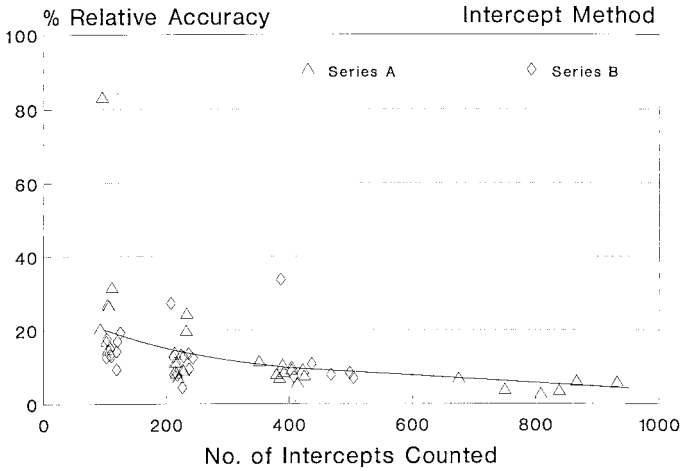
FIG. X1.2 Grain Size Measurements for the Series B Ferritic Stainless Steel Specimens



NOTE 1—The image analysis results for the same micrographs.

FIG. X1.3 Relationship Between the Number of Grains Counted and the Percent Relative Accuracy for the Planimetric Method

planimetric method and when about 400 grain boundary intersections or grain intercepts are counted for the intercept method. Because the grains must be marked off on the template as they are counted to ensure counting accuracy in the



NOTE 1—The image analysis results for the same micrographs.

FIG. X1.4 Relationship Between the Number of Intercepts or Intersections Counted and the Percent Relative Accuracy for the Intercept Method

planimetric method, while marking is not needed for the intercept method, it is clear that the intercept method is a more efficient method.

X1.3.3 Tables X1.1 and X1.2 list the results of the analysis of repeatability and reproducibility according to Practice E 691. In general, the intercept method outperformed the planimetric method in this study.

X1.3.4 Fig. X1.5 shows a plot of the planimetric versus the intercept grain size rating for each micrograph by each rater. Note that the data are scattered at random around the one-to-one trend line. This indicates that there was no bias in the grain size measurements by either method.

X1.3.5 Each micrograph that was rated for grain size could be considered in two ways, first as a rating for the true magnification of the micrograph and second for a rating as if the micrograph was at 100X. For evaluation of the comparison method, it was assumed that each micrograph was at 100X. The intercept and planimetric data were also computed using this assumption. Figs. X1.6 and X1.7 show plots of the chart comparison ratings versus the planimetric and intercept ratings, assuming all micrographs were at 100X. Note that the data are not scattered at random around the one-to-one trend line. This clearly shows that bias is occurring in the chart comparison ratings, which were typically 0.5 to 1 *G* unit lower, that is, coarser, than the planimetric or intercept measurements. The source of this bias is under study.

TABLE X1.2 Results of ASTM Grain Size Round Robin (Intercept Method)

Image	$\bar{\ell}$ (μm)	ASTM *G*	Average Intercepts	Repeatability 95 % CL	Reproducibility 95 % CL	Repeatability % RA	Reproducibility % RA
A1	29.9	6.84	811.5	3.25	9.37	10.87	31.35
A2	29.8	6.85	396.0	5.65	6.33	18.96	21.24
A3	27.2	7.11	222.5	8.28	8.16	30.43	30.00
A4	29.0	6.93	102.0	14.90	16.46	51.37	56.77
B1	26.1	7.23	450.0	4.96	7.96	19.01	30.51
B2	26.7	7.17	223.5	6.19	7.01	23.20	26.26
B3	26.6	7.18	113.0	8.84	9.86	33.24	37.08

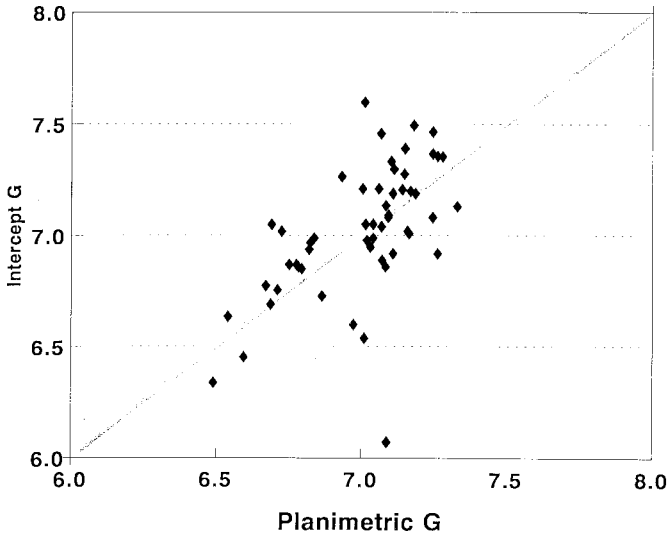
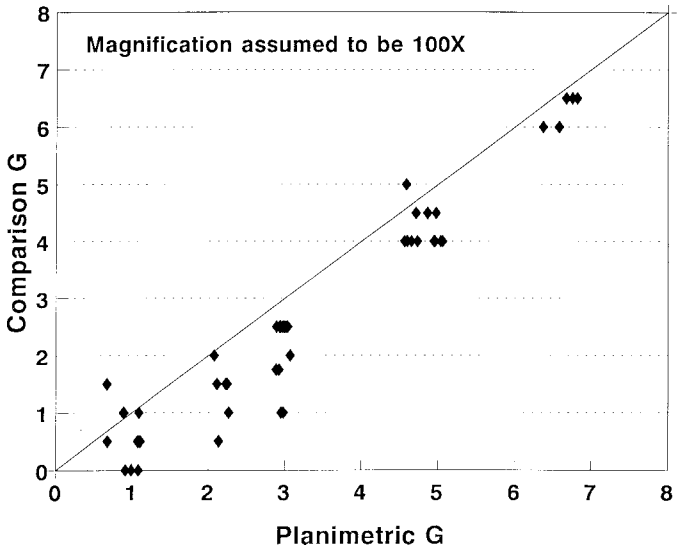


FIG. X1.5 Comparison of the Grain Size Measurements for Each Micrograph by Each Operator by the Planimetric and Intercept Methods



NOTE 1—Chart plots by each rater and assumes the micrographs are at 100X magnification. The data generally fall to one side of the one to one trend line indicating a bias.

FIG. X1.6 Plot of the Comparison Chart Grain Size Ratings for Each Micrograph Versus the Planimetric Method Rating for Each Micrograph

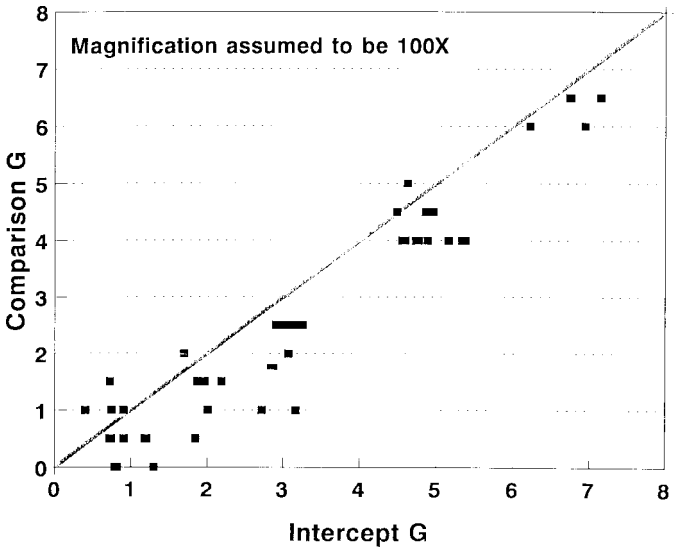


FIG. X1.7 Plot of the Comparison Chart Grain Size Ratings for Each Micrograph Versus the Intercept Method Rating for Each Micrograph

X2. REFERENCED ADJUNCTS

X2.1 The following is a complete and updated list of adjuncts referenced in Test Methods E 112. All adjuncts are available from ASTM.

Adjunct:	Order Adjunct:
Combination of 23 Components	ADJE011223
Combination of Plates I, II, III, and IV	ADJE011214
Plate I only	ADJE011201
Plate II only	ADJE01102
Plate III only	ADJE011203
Plate IV only	ADJE011204
Combination Transparencies, (Plate I) 00 through 10	ADJE112010
Transparency, Grain Size 00	ADJE011205
Transparency, Grain Size 0	ADJE011206
Transparency, Grain Size 0.5	ADJE011207
Transparency, Grain Size 1.0	ADJE011208
Transparency, Grain Size 1.5	ADJE011209
Transparency, Grain Size 2.0	ADJE011210
Transparency, Grain Size 2.5	ADJE011211
Transparency, Grain Sizes 3.0, 3.5, and 4.0	ADJE011212
Transparency, Grain Sizes 4.5, 5.0, and 5.5	ADJE011213
Transparency, Grain Sizes 6.0, 6.5, and 7.0	ADJE011214
Transparency, Grain Sizes 7.5, 8.0, and 8.5	ADJE011215
Transparency, Grain Sizes 9.0, 9.5, and 10.0	ADJE011216

Adjunct:	Order ADJ:
Fig. 5 only	E0011217

Adjunct:	Order ADJ:
Shepherd Series Reproduction	ADJE011224

REFERENCES

(**1**) Hull, F. C., *Transactions*, "A New Method for Making Rapid and Accurate Estimates of Grain Size," American Institute of Mining and Metallurgical Engineers, Vol 172, 1947, p. 439.

(**2**) Shepherd, B. F., "The P-F Characteristic of Steel," *Transactions*, American Institute of Mining and Metallurgical Engineers, Vol 22, December 1934, pp. 979–1016.

(**3**) Jeffries, Z., Kline, A. H., and Zimmer, E. B., "The Determination of the Average Grain Size in Metals," *Transactions*, American Institute of Mining and Metallurgical Engineers, Vol 54, 1917, pp. 594–607.

(**4**) Heyn, E., "Short Reports from the Metallurgical Laboratory of the Royal Mechanical and Testing Institute of Charlottenburg," *Metallographist*, Vol 5, 1903, pp. 37–64.

(**5**) Underwood, E. E., and Coons, W. C., "The Role of Quantitative Stereology in Deformation Twinning," *Deformation Twinning*, Gordon and Breach, New York, 1965, pp. 405–429.

(**6**) Hilliard, J., "Estimating Grain Size by the Intercept Method," *Metal Progress*, Vol 85, May 1964.

(**7**) Abrams, H., "Grain Size Measurement by the Intercept Method," *Metallography*, Vol 4, 1971, pp. 59–78.

(**8**) Mendelson, M. I., "Average Grain Size in Polycrystalline Ceramics," *J. American Ceramic Society*, Vol 52, August 1969, pp. 443–446.

(**9**) Arpi, R., "The Fracture Test as Used for Tool Steel in Sweden," *Metallurgia*, Vol 11, No. 65, March 1935, pp. 123–127.

(**10**) Vander Voort, G. F., "Grain Size Measurement," *Practical Applications of Quantitative Metallography*, ASTM STP 839, 1984, pp. 85–181.

(**11**) Snyder, R. W., and Graff, H. F., "Study of Grain Size in Hardened High Speed," *Metal Progress*, Vol 33, 1938, pp. 377–380.

ANEXO B-1

TABULACIÓN DE RESULTADOS DEL ENSAYO A TRACCIÓN EN LA PROBETA P-0

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
1	0	0	0
2	97,915	0	0,53
3	100,686	0	0,545
4	101,61	0,002	0,55
5	105,305	0,003	0,57
6	109	0,004	0,59
7	114,542	0,005	0,62
8	115,096	0,007	0,623
9	120,823	0,008	0,654
10	123,779	0,009	0,67
11	127,474	0,01	0,69
12	147,796	0,011	0,8
13	149,644	0,012	0,81
14	157,033	0,013	0,85
15	160,728	0,014	0,87
16	164,423	0,015	0,89
17	166,271	0,016	0,9
18	168,118	0,017	0,91
19	169,966	0,018	0,92
20	170,335	0,018	0,922
21	170,889	0,019	0,925
22	173,106	0,02	0,937
23	173,476	0,021	0,939
24	173,845	0,022	0,941
25	174,03	0,023	0,942
26	175,139	0,024	0,948
27	176,062	0,025	0,953
28	179,572	0,026	0,972
29	182,159	0,027	0,986
30	184,745	0,028	1
31	188,255	0,03	1,019
32	191,766	0,031	1,038
33	193,428	0,032	1,047
34	196,938	0,033	1,066
35	199,71	0,035	1,081
36	212,457	0,036	1,15
37	214,305	0,037	1,16

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
38	215,044	0,039	1,164
39	215,228	0,04	1,165
40	215,598	0,042	1,167
41	216,152	0,043	1,17
42	220,586	0,045	1,194
43	224,096	0,047	1,213
44	226,682	0,048	1,227
45	230,193	0,05	1,246
46	232,964	0,051	1,261
47	236,474	0,053	1,28
48	239,984	0,054	1,299
49	243,494	0,055	1,318
50	246,081	0,057	1,332
51	250,415	0,058	1,351
52	253,937	0,06	1,37
53	257,458	0,061	1,389
54	260,98	0,063	1,408
55	263,575	0,064	1,422
56	267,097	0,065	1,441
57	270,619	0,066	1,46
58	274,14	0,067	1,479
59	277,662	0,067	1,498
60	281,184	0,068	1,517
61	283,779	0,069	1,531
62	286,374	0,07	1,545
63	289,896	0,071	1,564
64	292,491	0,071	1,578
65	293,417	0,073	1,583
66	295,086	0,075	1,592
67	299,534	0,077	1,616
68	302,129	0,078	1,63
69	303,983	0,08	1,64
70	306,578	0,082	1,654
71	309,173	0,084	1,668
72	311,768	0,087	1,682
73	314,548	0,09	1,697
74	317,143	0,093	1,711
75	320,665	0,096	1,73
76	323,26	0,099	1,744
77	325,855	0,102	1,758
78	329,376	0,105	1,777

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
79	331,971	0,109	1,791
80	334,752	0,112	1,806
81	338,273	0,116	1,825
82	341,795	0,119	1,844
83	344,39	0,123	1,858
84	347,912	0,127	1,877
85	350,507	0,131	1,891
86	354,029	0,134	1,91
87	356,624	0,138	1,924
88	360,145	0,142	1,943
89	363,667	0,145	1,962
90	367,189	0,149	1,981
91	370,711	0,152	2
92	374,232	0,154	2,019
93	376,827	0,157	2,033
94	380,349	0,16	2,052
95	383,871	0,163	2,071
96	387,392	0,165	2,09
97	390,914	0,168	2,109
98	394,436	0,17	2,128
99	397,958	0,173	2,147
101	401,479	0,174	2,166
102	404,074	0,176	2,18
103	407,596	0,179	2,199
104	410,191	0,18	2,213
105	413,713	0,182	2,232
106	416,308	0,184	2,246
107	419,83	0,187	2,265
108	422,61	0,189	2,28
109	425,205	0,191	2,294
110	427,8	0,193	2,308
111	431,322	0,196	2,327
112	433,917	0,198	2,341
113	436,512	0,201	2,355
114	440,033	0,204	2,374
115	442,814	0,207	2,389
116	445,409	0,21	2,403
117	448,004	0,212	2,417
118	451,525	0,216	2,436
119	453,194	0,22	2,445
120	456,715	0,223	2,464

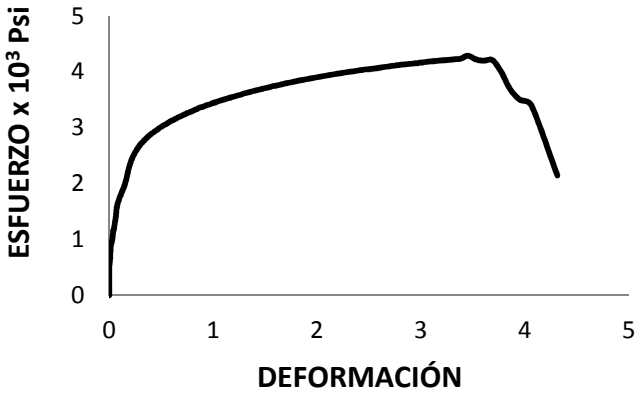
NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
121	460,237	0,227	2,483
122	463,017	0,231	2,498
123	466,539	0,236	2,517
124	469,134	0,24	2,531
125	471,729	0,245	2,545
126	475,251	0,25	2,564
127	477,846	0,254	2,578
128	480,441	0,259	2,592
129	483,963	0,265	2,611
130	486,743	0,27	2,626
131	489,338	0,275	2,64
132	492,86	0,282	2,659
133	494,528	0,288	2,668
134	498,05	0,293	2,687
135	500,645	0,3	2,701
136	503,425	0,307	2,716
137	506,02	0,314	2,73
138	508,615	0,321	2,744
139	511,21	0,33	2,758
140	514,732	0,336	2,777
141	516,585	0,343	2,787
142	519,18	0,352	2,801
143	521,775	0,36	2,815
144	525,297	0,368	2,834
145	527,892	0,378	2,848
146	530,672	0,386	2,863
147	533,267	0,396	2,877
148	535,862	0,406	2,891
149	538,457	0,416	2,905
150	541,052	0,427	2,919
151	543,832	0,436	2,934
152	546,427	0,448	2,948
153	549,022	0,459	2,962
154	551,617	0,47	2,976
155	555,139	0,482	2,995
156	557,734	0,493	3,009
157	560,514	0,506	3,024
158	563,109	0,518	3,038
159	565,704	0,532	3,052
160	567,558	0,545	3,062
161	571,08	0,559	3,081

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
162	573,675	0,573	3,095
163	577,196	0,586	3,114
164	579,791	0,6	3,128
165	581,459	0,616	3,137
166	584,981	0,631	3,156
167	586,835	0,646	3,166
168	590,356	0,661	3,185
169	592,951	0,678	3,199
170	595,546	0,695	3,213
171	598,141	0,711	3,227
172	600,922	0,73	3,242
173	604,443	0,746	3,261
174	606,112	0,764	3,27
175	609,633	0,784	3,289
176	611,487	0,802	3,299
177	615,009	0,821	3,318
178	617,604	0,841	3,332
179	621,125	0,86	3,351
180	623,72	0,881	3,365
181	625,389	0,902	3,374
182	628,91	0,923	3,393
183	631,691	0,943	3,408
184	633,359	0,966	3,417
185	636,881	0,988	3,436
186	639,476	1,011	3,45
187	642,071	1,035	3,464
188	644,851	1,059	3,479
189	647,446	1,082	3,493
190	650,041	1,107	3,507
191	652,636	1,132	3,521
192	655,416	1,157	3,536
193	658,011	1,184	3,55
194	660,606	1,21	3,564
195	663,201	1,238	3,578
196	665,796	1,266	3,592
197	669,318	1,293	3,611
198	672,098	1,323	3,626
199	674,693	1,352	3,64
200	677,288	1,381	3,654
201	679,883	1,411	3,668
202	682,478	1,443	3,682

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
203	685,258	1,475	3,697
204	687,853	1,507	3,711
205	690,448	1,541	3,725
206	693,97	1,574	3,744
207	695,824	1,607	3,754
208	698,419	1,642	3,768
209	701,94	1,678	3,787
210	704,535	1,714	3,801
211	707,13	1,752	3,815
212	709,725	1,789	3,829
213	712,506	1,828	3,844
214	715,101	1,867	3,858
215	717,696	1,906	3,872
216	720,291	1,948	3,886
217	722,885	1,989	3,9
218	725,666	2,032	3,915
219	728,261	2,075	3,929
220	730,856	2,12	3,943
221	733,451	2,166	3,957
222	736,231	2,211	3,972
223	738,826	2,259	3,986
224	741,421	2,307	4
225	744,016	2,357	4,014
226	746,611	2,409	4,028
227	749,391	2,46	4,043
228	751,059	2,511	4,052
229	753,654	2,566	4,066
230	756,435	2,621	4,081
231	759,03	2,677	4,095
232	761,625	2,734	4,109
233	764,22	2,786	4,123
234	766,815	2,856	4,137
235	768,668	2,911	4,147
236	771,263	2,981	4,161
237	773,858	3,036	4,175
238	776,639	3,106	4,19
239	778,307	3,175	4,199
240	780,902	3,245	4,213
241	782,755	3,314	4,223
242	785,35	3,384	4,237
243	795,174	3,453	4,29

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
244	782,199	3,536	4,22
245	778,492	3,606	4,2
246	780,346	3,689	4,21
247	741,421	3,773	4
248	685,814	3,856	3,7
249	648,743	3,953	3,5
250	397,958	4,314	2,147

DIAGRAMA ESFUERZO VS. DEFORMACIÓN DE LA PROBETA P-0



$$\boldsymbol{E} = \frac{\sigma}{\varepsilon} = \frac{3137Ksi}{0{,}616} = 5093 \times 10^3 Psi$$

$$\boldsymbol{Ductilidad} = \frac{lf - lo}{lo} \times 100 = \frac{52{,}1 - 50}{50} \times 100 = 4{,}3\%$$

VALORES OBTENIDOS LUEGO DEL ENSAYO A TRACCIÓN DE LA PROBETA P-0
ESFUERZO FLUENCIA: 19MPa/2,8 x10^3Psi
RESISTENCIA TRACCIÓN: 35MPa/5,1x10^3Psi
MÓDULO ELASTICIDAD : 40GPa/5000x10^3Psi
CARGA MÁXIMA : 4217N/948lbf
% ELONGACIÓN EN 50mm : 4,3

ANEXO B-2

TABULACIÓN DE RESULTADOS DEL ENSAYO A TRACCIÓN EN LA PROBETA P-1

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
1	0	0	0
2	203,774	0,028	1,103
3	210,794	0,038	1,141
4	218,554	0,048	1,183
5	224,835	0,061	1,217
6	232,779	0,069	1,26
7	239,615	0,076	1,297
8	245,896	0,086	1,331
9	253,84	0,094	1,374
10	261,045	0,102	1,413
11	267,511	0,109	1,448
12	273,608	0,117	1,481
13	280,443	0,122	1,518
14	287,464	0,13	1,556
15	294,484	0,137	1,594
16	300,211	0,145	1,625
17	306,862	0,15	1,661
18	314,806	0,158	1,704
19	321,087	0,165	1,738
20	326,814	0,17	1,769
21	334,204	0,178	1,809
22	339,377	0,185	1,837
23	346,028	0,191	1,873
24	353,048	0,198	1,911
25	359,514	0,206	1,946
26	365,241	0,213	1,977
27	371,338	0,219	2,01
28	378,728	0,226	2,05
29	384,27	0,234	2,08
30	389,813	0,241	2,11
31	397,202	0,251	2,15
32	404,592	0,262	2,19
33	408,287	0,269	2,21
34	415,677	0,277	2,25
35	421,219	0,287	2,28
36	428,609	0,297	2,32
37	434,151	0,307	2,35
38	441,541	0,318	2,39

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
39	445,236	0,327	2,41
40	452,626	0,338	2,45
41	460,016	0,35	2,49
42	465,558	0,363	2,52
43	472,948	0,373	2,56
44	478,49	0,384	2,59
45	485,88	0,396	2,63
46	491,422	0,406	2,66
47	498,812	0,417	2,7
48	506,202	0,427	2,74
49	513,592	0,437	2,78
50	519,134	0,447	2,81
51	528,262	0,458	2,85
52	535,677	0,47	2,89
53	543,091	0,478	2,93
54	550,505	0,488	2,97
55	556,066	0,495	3
56	563,48	0,503	3,04
57	570,894	0,511	3,08
58	578,308	0,518	3,12
59	585,723	0,523	3,16
60	593,137	0,528	3,2
61	598,697	0,533	3,23
62	604,258	0,538	3,26
63	611,672	0,546	3,3
64	617,233	0,552	3,33
65	619,087	0,561	3,34
66	622,794	0,577	3,36
67	632,061	0,589	3,41
68	637,622	0,599	3,44
69	641,329	0,615	3,46
70	646,89	0,627	3,49
71	652,45	0,645	3,52
72	658,011	0,663	3,55
73	663,572	0,683	3,58
74	669,132	0,704	3,61
75	676,547	0,726	3,65
76	682,107	0,747	3,68
77	687,668	0,772	3,71
78	695,082	0,795	3,75
79	700,643	0,82	3,78
80	706,204	0,843	3,81

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
81	713,618	0,871	3,85
82	721,032	0,897	3,89
83	726,593	0,923	3,92
84	734,007	0,95	3,96
85	739,567	0,978	3,99
86	746,982	1,005	4,03
87	752,542	1,031	4,06
88	759,957	1,057	4,1
89	767,371	1,083	4,14
90	774,785	1,107	4,18
91	782,199	1,13	4,22
92	789,613	1,148	4,26
93	795,174	1,169	4,29
94	802,588	1,189	4,33
95	810,002	1,212	4,37
96	817,417	1,229	4,41
97	824,831	1,247	4,45
98	832,245	1,262	4,49
99	839,659	1,28	4,53
101	847,074	1,293	4,57
102	852,634	1,308	4,6
103	860,048	1,323	4,64
104	865,609	1,336	4,67
105	873,023	1,349	4,71
106	878,584	1,364	4,74
107	885,998	1,382	4,78
108	891,559	1,397	4,81
109	897,119	1,415	4,84
110	902,68	1,43	4,87
111	910,094	1,448	4,91
112	915,655	1,466	4,94
113	921,216	1,486	4,97
114	928,63	1,506	5,01
115	934,19	1,527	5,04
116	939,751	1,547	5,07
117	945,312	1,567	5,1
118	952,726	1,593	5,14
119	956,433	1,618	5,16
120	963,847	1,643	5,2
121	971,262	1,671	5,24
122	976,822	1,702	5,27
123	984,236	1,735	5,31

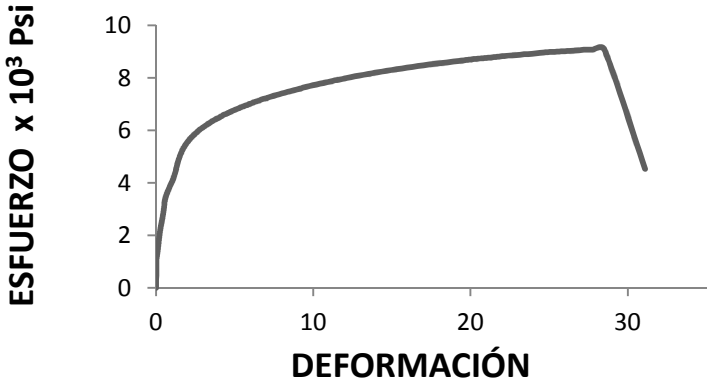
NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
124	989,797	1,765	5,34
125	995,358	1,798	5,37
126	1002,772	1,834	5,41
127	1008,333	1,868	5,44
128	1013,893	1,905	5,47
129	1021,307	1,946	5,51
130	1026,868	1,984	5,54
131	1032,429	2,02	5,57
132	1039,843	2,07	5,61
133	1043,55	2,11	5,63
134	1050,964	2,15	5,67
135	1056,525	2,2	5,7
136	1062,086	2,25	5,73
137	1067,646	2,3	5,76
138	1073,207	2,35	5,79
139	1078,768	2,41	5,82
140	1086,182	2,46	5,86
141	1089,889	2,51	5,88
142	1095,45	2,57	5,91
143	1101,01	2,63	5,94
144	1108,424	2,69	5,98
145	1113,985	2,76	6,01
146	1119,546	2,82	6,04
147	1125,106	2,89	6,07
148	1130,667	2,96	6,1
149	1136,228	3,03	6,13
150	1141,788	3,11	6,16
151	1147,349	3,18	6,19
152	1152,91	3,26	6,22
153	1158,47	3,34	6,25
154	1164,031	3,42	6,28
155	1171,445	3,51	6,32
156	1177,006	3,59	6,35
157	1182,567	3,68	6,38
158	1188,127	3,77	6,41
159	1193,688	3,87	6,44
160	1197,395	3,96	6,46
161	1204,809	4,06	6,5
162	1210,37	4,16	6,53
163	1217,784	4,26	6,57
164	1223,345	4,36	6,6
165	1227,052	4,47	6,62

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
166	1234,466	4,58	6,66
167	1238,173	4,69	6,68
168	1245,587	4,8	6,72
169	1251,148	4,92	6,75
170	1256,709	5,04	6,78
171	1262,269	5,16	6,81
172	1267,83	5,29	6,84
173	1275,244	5,41	6,88
174	1278,951	5,54	6,9
175	1286,365	5,68	6,94
176	1290,073	5,81	6,96
177	1297,487	5,95	7
178	1303,047	6,09	7,03
179	1310,462	6,23	7,07
180	1316,022	6,38	7,1
181	1319,729	6,53	7,12
182	1327,144	6,68	7,16
183	1332,704	6,83	7,19
184	1336,411	6,99	7,21
185	1343,826	7,15	7,25
186	1349,386	7,32	7,28
187	1354,947	7,49	7,31
188	1360,508	7,66	7,34
189	1366,068	7,83	7,37
190	1371,629	8,01	7,4
191	1377,19	8,19	7,43
192	1382,75	8,37	7,46
193	1388,311	8,56	7,49
194	1393,872	8,75	7,52
195	1399,432	8,95	7,55
196	1404,993	9,15	7,58
197	1412,407	9,35	7,62
198	1417,968	9,56	7,65
199	1423,528	9,77	7,68
200	1429,089	9,98	7,71
201	1434,65	10,2	7,74
202	1440,21	10,43	7,77
203	1445,771	10,66	7,8
204	1451,332	10,89	7,83
205	1456,892	11,13	7,86
206	1464,307	11,37	7,9
207	1468,014	11,61	7,92

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
208	1473,574	11,86	7,95
209	1480,988	12,12	7,99
210	1486,549	12,38	8,02
211	1492,11	12,65	8,05
212	1497,67	12,92	8,08
213	1503,231	13,2	8,11
214	1508,792	13,48	8,14
215	1514,352	13,76	8,17
216	1519,913	14,06	8,2
217	1525,474	14,36	8,23
218	1531,034	14,67	8,26
219	1536,595	14,98	8,29
220	1542,156	15,3	8,32
221	1547,716	15,63	8,35
222	1553,277	15,96	8,38
223	1558,838	16,3	8,41
224	1564,398	16,65	8,44
225	1569,959	17,01	8,47
226	1575,52	17,38	8,5
227	1581,08	17,75	8,53
228	1584,787	18,12	8,55
229	1590,348	18,51	8,58
230	1595,909	18,91	8,61
231	1601,469	19,31	8,64
232	1607,03	19,72	8,67
233	1612,591	20,1	8,7
234	1618,151	20,6	8,73
235	1621,858	21	8,75
236	1627,419	21,5	8,78
237	1632,98	21,9	8,81
238	1638,54	22,4	8,84
239	1642,248	22,9	8,86
240	1647,808	23,4	8,89
241	1651,515	23,9	8,91
242	1657,076	24,4	8,94
243	1662,637	24,9	8,97
244	1666,344	25,5	8,99
245	1670,051	26	9,01
246	1673,758	26,6	9,03
247	1679,319	27,2	9,06
248	1681,172	27,8	9,07
249	1683,026	28,5	9,08

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
250	839,659	31,1	4,53

DIAGRAMA ESFUERZO VS. DEFORMACIÓN DE LA PROBETA P-1



$$\boldsymbol{E} = \frac{\sigma}{\varepsilon} = \frac{2850Ksi}{0{,}458} = 6223 \times 10^3 Psi$$

$$\boldsymbol{Ductilidad} = \frac{lf - lo}{lo} \times 100 = \frac{62{,}8 - 50}{50} \times 100 = 25{,}7\%$$

VALORES OBTENIDOS LUEGO DEL ENSAYO A TRACCIÓN DE LA PROBETA P-1
ESFUERZO FLUENCIA: 26MPa/3,7 x10^3Psi
RESISTENCIA TRACCIÓN: 63MPa/9,1 x10^3Psi
MÓDULO ELASTICIDAD : 43MPa/6200 x10^3Psi
CARGA MÁXIMA : 7509N/1688lbf
% ELONGACIÓN EN 50mm : 25,7

ANEXO B-3

TABULACIÓN DE RESULTADOS DEL ENSAYO A TRACCIÓN EN LA PROBETA P-2

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
1	77,56	0,0025	0,4122
2	81,38	0,0075	0,4325
3	86,77	0,01	0,4611
4	92,17	0,0125	0,4898
5	97,56	0,015	0,5185
6	101,83	0,0186	0,5412
7	106,11	0,0225	0,5639
8	111,73	0,025	0,5937
9	116,22	0,0275	0,6176
10	121,62	0,0325	0,6463
11	126,11	0,035	0,6702
12	131,06	0,04	0,6965
13	135,33	0,0451	0,7192
14	139,38	0,0474	0,7407
15	144,77	0,0526	0,7694
16	148,59	0,0596	0,7897
17	152,86	0,0624	0,8124
18	157,36	0,0675	0,8363
19	162,76	0,0724	0,8649
20	166,8	0,0799	0,8864
21	171,75	0,085	0,9127
22	176,47	0,0925	0,9378
23	181,86	0,0974	0,9665
24	185,91	0,1049	0,988
25	191,08	0,11	1,0155
26	196,48	0,1175	1,0441
27	200,97	0,1224	1,068
28	205,69	0,1299	1,0931
29	210,86	0,135	1,1206
30	215,81	0,1425	1,1469
31	221,43	0,15	1,1767
32	225,7	0,1575	1,1994
33	231,09	0,1624	1,2281
34	234,69	0,1701	1,2472
35	240,76	0,175	1,2795
36	245,03	0,1825	1,3022
37	250,65	0,1874	1,332
38	254,92	0,1951	1,3547

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
39	260,54	0,2	1,3846
40	265,71	0,2075	1,4121
41	270,88	0,2124	1,4396
42	274,93	0,2175	1,4611
43	280,33	0,225	1,4897
44	285,27	0,2299	1,516
45	290,67	0,2374	1,5447
46	294,71	0,2449	1,5662
47	299,88	0,25	1,5937
48	305,73	0,2575	1,6247
49	309,77	0,265	1,6462
50	316,07	0,2701	1,6797
51	320,34	0,275	1,7024
52	325,51	0,2825	1,7299
53	330,68	0,2874	1,7573
54	335,4	0,2951	1,7824
55	340,8	0,3	1,8111
56	344,84	0,3075	1,8326
57	350,24	0,3124	1,8613
58	355,86	0,3175	1,8911
59	360,35	0,3224	1,915
60	364,85	0,3299	1,9389
61	369,57	0,335	1,964
62	375,42	0,3425	1,9951
63	379,69	0,3474	2,0178
64	384,86	0,3549	2,0453
65	389,35	0,36	2,0692
66	393,85	0,3675	2,093
67	399,24	0,3724	2,1217
68	405,09	0,3776	2,1528
69	409,14	0,385	2,1743
70	414,76	0,39	2,2042
71	419,25	0,3976	2,228
72	425,1	0,4016	2,2591
73	429,37	0,4075	2,2818
74	434,99	0,4154	2,3117
75	439,26	0,4193	2,3344
76	444,43	0,4252	2,3618
77	449,15	0,4291	2,3869
78	454,1	0,437	2,4132
79	458,59	0,4429	2,4371
80	463,09	0,4508	2,461

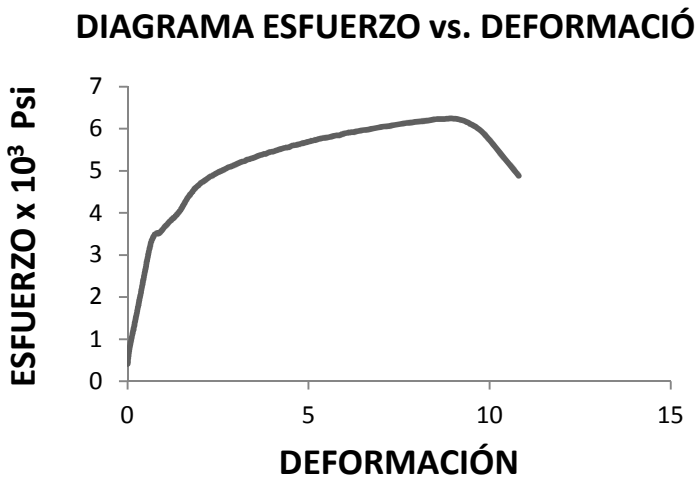
NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
81	469,83	0,4567	2,4968
82	474,33	0,4626	2,5207
83	478,82	0,4665	2,5446
84	483,32	0,4724	2,5685
85	490,06	0,4803	2,6044
86	492,31	0,4843	2,6163
87	499,06	0,4921	2,6521
88	503,55	0,498	2,676
89	508,05	0,502	2,6999
90	512,54	0,5098	2,7238
91	519,29	0,5157	2,7597
92	523,78	0,5197	2,7836
93	528,28	0,5256	2,8075
94	535,02	0,5295	2,8433
95	537,27	0,5374	2,8552
96	544,02	0,5433	2,8911
97	548,51	0,5492	2,915
98	553,01	0,5571	2,9389
99	557,5	0,563	2,9628
101	564,25	0,5669	2,9986
102	566,5	0,5728	3,0105
103	573,24	0,5807	3,0464
104	577,74	0,5846	3,0703
105	582,23	0,5925	3,0942
106	586,73	0,5984	3,1181
107	591,22	0,6043	3,142
108	595,72	0,6122	3,1659
109	600,22	0,6181	3,1897
110	606,96	0,626	3,2256
111	609,21	0,6319	3,2375
112	615,95	0,6398	3,2734
113	620,45	0,6476	3,2973
114	624,94	0,6575	3,3212
115	629,44	0,6654	3,3451
116	631,69	0,6752	3,357
117	636,18	0,685	3,3809
118	640,68	0,6949	3,4048
119	645,18	0,7067	3,4287
120	647,42	0,7205	3,4406
121	651,92	0,7323	3,4645
122	656,42	0,75	3,4884
123	658,66	0,7677	3,5004

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
124	660,91	0,7933	3,5123
125	663,16	0,8169	3,5243
126	660,91	0,8602	3,5123
127	667,66	0,9016	3,5481
128	674,4	0,9409	3,584
129	681,14	0,9783	3,6198
130	687,89	1,0118	3,6557
131	694,63	1,0433	3,6915
132	699,13	1,0748	3,7154
133	703,62	1,1043	3,7393
134	710,37	1,1339	3,7751
135	714,86	1,1654	3,799
136	719,36	1,1969	3,8229
137	723,86	1,2283	3,8468
138	730,6	1,2598	3,8827
139	732,85	1,2933	3,8946
140	739,59	1,3209	3,9304
141	744,09	1,3583	3,9543
142	750,83	1,3878	3,9902
143	755,33	1,4173	4,0141
144	762,07	1,4429	4,0499
145	766,57	1,4665	4,0738
146	773,31	1,4902	4,1096
147	777,81	1,5098	4,1335
148	784,55	1,5256	4,1694
149	789,05	1,5453	4,1933
150	793,54	1,565	4,2172
151	798,04	1,5827	4,2411
152	804,78	1,5984	4,2769
153	809,28	1,6142	4,3008
154	813,78	1,6319	4,3247
155	818,27	1,6516	4,3486
156	822,77	1,6693	4,3725
157	827,26	1,6909	4,3964
158	831,76	1,7106	4,4202
159	836,26	1,7303	4,4441
160	840,75	1,7559	4,468
161	845,25	1,7776	4,4919
162	849,74	1,8031	4,5158
163	856,49	1,8268	4,5517
164	860,98	1,8543	4,5756
165	865,48	1,8819	4,5994

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
166	869,98	1,9134	4,6233
167	874,47	1,9429	4,6472
168	878,97	1,9724	4,6711
169	883,46	2,0059	4,695
170	887,96	2,0374	4,7189
171	892,46	2,0728	4,7428
172	894,7	2,1083	4,7548
173	899,2	2,1417	4,7786
174	903,7	2,1791	4,8025
175	908,19	2,2165	4,8264
176	912,69	2,2598	4,8503
177	917,18	2,2992	4,8742
178	919,43	2,3406	4,8862
179	923,93	2,3858	4,9101
180	928,42	2,4291	4,934
181	932,92	2,4783	4,9578
182	937,42	2,5236	4,9817
183	939,66	2,5748	4,9937
184	944,16	2,624	5,0176
185	948,66	2,6791	5,0415
186	953,15	2,7323	5,0654
187	957,65	2,7894	5,0893
188	959,9	2,8465	5,1012
189	964,39	2,9075	5,1251
190	968,89	2,9665	5,149
191	973,38	3,0295	5,1729
192	977,88	3,0945	5,1968
193	982,38	3,1634	5,2207
194	984,62	3,2283	5,2326
195	991,37	3,2992	5,2685
196	993,62	3,372	5,2804
197	998,11	3,4449	5,3043
198	1.002,61	3,5197	5,3282
199	1.007,10	3,5965	5,3521
200	1.011,60	3,6752	5,376
201	1.016,10	3,7559	5,3999
202	1.018,34	3,8346	5,4118
203	1.025,09	3,9193	5,4477
204	1.027,34	4,0157	5,4596
205	1.031,83	4,0945	5,4835
206	1.036,33	4,1732	5,5074
207	1.040,82	4,2717	5,5313

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
208	1.045,32	4,3701	5,5552
209	1.047,57	4,4685	5,5671
210	1.054,31	4,5472	5,603
211	1.056,56	4,6457	5,6149
212	1.061,06	4,7441	5,6388
213	1.065,55	4,8622	5,6627
214	1.070,05	4,9606	5,6866
215	1.074,54	5,0591	5,7105
216	1.079,04	5,1772	5,7344
217	1.083,54	5,2756	5,7583
218	1.088,03	5,3937	5,7822
219	1.090,28	5,5118	5,7941
220	1.094,78	5,6299	5,818
221	1.099,27	5,748	5,8419
222	1.101,52	5,8661	5,8538
223	1.108,26	5,9843	5,8897
224	1.112,76	6,122	5,9136
225	1.115,01	6,2402	5,9255
226	1.119,50	6,378	5,9494
227	1.124,00	6,5157	5,9733
228	1.126,25	6,6535	5,9853
229	1.130,74	6,7913	6,0091
230	1.135,24	6,9291	6,033
231	1.139,74	7,0669	6,0569
232	1.141,98	7,2244	6,0689
233	1.146,48	7,3819	6,0928
234	1.150,98	7,5394	6,1167
235	1.155,47	7,6969	6,1406
236	1.157,72	7,8543	6,1525
237	1.162,22	8,0315	6,1764
238	1.164,46	8,2087	6,1883
239	1.168,96	8,3858	6,2122
240	1.173,46	8,563	6,2361
241	1.173,46	8,7598	6,2361
242	1.175,70	8,9567	6,2481
243	1.171,21	9,1732	6,2242
244	1.153,22	9,4488	6,1286
245	1.108,26	9,8425	5,8897
246	919,43	10,8071	4,8862

DIAGRAMA ESFUERZO VS. DEFORMACIÓN DE LA PROBETA P-2



$$\boldsymbol{E} = \frac{\sigma}{\varepsilon} = \frac{1811Ksi}{0{,}300} = 5960 \times 10^3 Psi$$

$$\boldsymbol{Ductilidad} = \frac{lf - lo}{lo} \times 100 = \frac{54{,}9 - 50}{50} \times 100 = 9{,}8\%$$

VALORES OBTENIDOS LUEGO DEL ENSAYO A TRACCIÓN DE LA PROBETA P-2
ESFUERZO FLUENCIA: 28MPa/3,5 x10^3Psi
RESISTENCIA TRACCIÓN: 43MPa/6,2 x10^3Psi
MÓDULO ELASTICIDAD: 41,4GPa/6000 x10^3Psi
CARGA MÁXIMA : 5231N/1176lbf
% ELONGACIÓN EN 50 mm: 9,8

ANEXO B-4

TABULACIÓN DE RESULTADOS PROBETA P-3

ENSAYO A TRACCIÓN

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
1	55,27	0,0025	0,2957
2	57,79	0,005	0,3091
3	60,75	0,01	0,325
4	63,5	0,0125	0,3397
5	67,38	0,0175	0,3604
6	69,66	0,0225	0,3727
7	72,63	0,0275	0,3885
8	75,83	0,03	0,4057
9	80,4	0,035	0,4301
10	84,51	0,0425	0,4521
11	87,48	0,0474	0,468
12	91,82	0,0526	0,4912
13	95,7	0,0598	0,512
14	99,58	0,065	0,5327
15	103,47	0,0701	0,5535
16	106,21	0,075	0,5682
17	110,55	0,0799	0,5914
18	115,11	0,085	0,6158
19	119,22	0,09	0,6378
20	122,65	0,0951	0,6561
21	127,9	0,1	0,6842
22	130,87	0,1049	0,7001
23	135,21	0,11	0,7233
24	138,41	0,115	0,7404
25	142,52	0,1201	0,7624
26	146,86	0,1224	0,7856
27	150,97	0,1276	0,8076
28	154,4	0,1325	0,826
29	158,28	0,135	0,8467
30	163,53	0,14	0,8748
31	166,73	0,1447	0,8919
32	169,93	0,1474	0,9091
33	174,5	0,1526	0,9335
34	178,15	0,1575	0,953
35	182,26	0,1624	0,975
36	186,83	0,165	0,9995
37	189,34	0,1701	1,0129
38	193,45	0,175	1,0349

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
39	197,79	0,1776	1,0581
40	201,91	0,1799	1,0801
41	205,79	0,185	1,1009
42	208,99	0,19	1,118
43	212,87	0,1925	1,1388
44	217,21	0,1974	1,162
45	220,18	0,2	1,1779
46	224,29	0,2049	1,1999
47	228,4	0,2093	1,2218
48	232,74	0,2126	1,2451
49	236,39	0,2175	1,2646
50	239,36	0,2201	1,2805
51	244,62	0,2224	1,3086
52	247,81	0,2276	1,3257
53	251,47	0,2299	1,3453
54	255,12	0,2325	1,3648
55	259,23	0,2376	1,3868
56	263,57	0,24	1,41
57	266,31	0,2451	1,4247
58	270,88	0,2474	1,4491
59	275,22	0,2526	1,4723
60	277,96	0,2549	1,487
61	282,53	0,26	1,5114
62	286,87	0,2626	1,5346
63	290,75	0,2675	1,5554
64	294,64	0,2701	1,5762
65	298,52	0,275	1,597
66	303,09	0,2776	1,6214
67	305,83	0,2799	1,6361
68	309,94	0,2825	1,658
69	314,28	0,285	1,6813
70	317,02	0,29	1,6959
71	321,36	0,2925	1,7191
72	325,24	0,2974	1,7399
73	329,12	0,3	1,7607
74	332,32	0,3026	1,7778
75	337,12	0,3071	1,8034
76	340,09	0,31	1,8193
77	344,43	0,3126	1,8425
78	348,31	0,315	1,8633
79	352,42	0,3201	1,8853
80	356,53	0,3224	1,9073

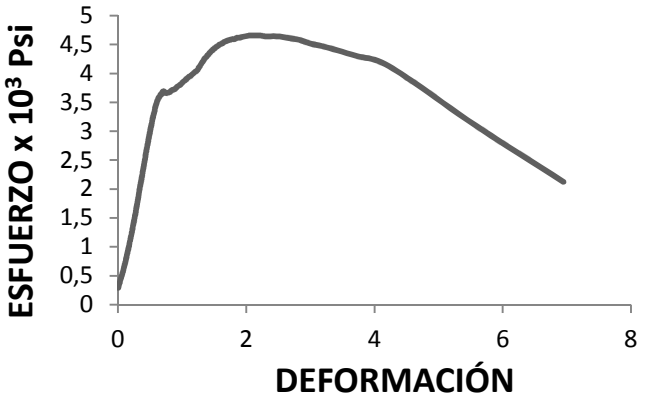
NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
81	360,19	0,325	1,9269
82	363,61	0,3276	1,9452
83	366,58	0,3299	1,9611
84	371,15	0,3325	1,9855
85	375,03	0,3374	2,0063
86	378,69	0,34	2,0258
87	382,34	0,3425	2,0454
88	386	0,3474	2,0649
89	390,34	0,35	2,0881
90	394,22	0,3526	2,1089
91	397,42	0,3575	2,126
92	402,21	0,36	2,1517
93	405,18	0,365	2,1676
94	409,52	0,3675	2,1908
95	413,63	0,3701	2,2128
96	416,37	0,375	2,2274
97	420,94	0,3776	2,2519
98	423,68	0,3799	2,2665
99	428,94	0,3825	2,2946
101	431,22	0,385	2,3068
102	435,79	0,39	2,3313
103	439,21	0,3925	2,3496
104	443,1	0,3957	2,3704
105	446,75	0,3996	2,3899
106	450,86	0,4016	2,4119
107	454,06	0,4055	2,429
108	459,08	0,4094	2,4559
109	463,65	0,4134	2,4803
110	465,94	0,4154	2,4926
111	470,5	0,4193	2,517
112	472,79	0,4232	2,5292
113	477,36	0,4252	2,5537
114	481,92	0,4272	2,5781
115	484,21	0,4291	2,5903
116	488,78	0,4331	2,6147
117	493,34	0,437	2,6392
118	495,63	0,4409	2,6514
119	500,2	0,4429	2,6758
120	504,76	0,4469	2,7003
121	507,05	0,4508	2,7125
122	511,62	0,4547	2,7369
123	516,18	0,4567	2,7614

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
124	518,47	0,4626	2,7736
125	523,04	0,4646	2,798
126	527,6	0,4705	2,8225
127	529,89	0,4724	2,8347
128	534,46	0,4744	2,8591
129	539,02	0,4783	2,8836
130	541,31	0,4823	2,8958
131	545,88	0,4843	2,9202
132	550,44	0,4902	2,9446
133	555,01	0,4921	2,9691
134	557,3	0,498	2,9813
135	561,86	0,5	3,0057
136	566,43	0,502	3,0302
137	568,72	0,5079	3,0424
138	573,28	0,5098	3,0668
139	575,57	0,5157	3,0791
140	580,14	0,5177	3,1035
141	582,42	0,5217	3,1157
142	586,99	0,5256	3,1401
143	591,56	0,5295	3,1646
144	596,12	0,5335	3,189
145	598,41	0,5354	3,2012
146	602,98	0,5394	3,2257
147	605,26	0,5453	3,2379
148	609,83	0,5472	3,2623
149	614,4	0,5531	3,2868
150	616,68	0,5571	3,299
151	621,25	0,563	3,3234
152	623,53	0,565	3,3356
153	628,1	0,5709	3,3601
154	632,67	0,5748	3,3845
155	637,24	0,5768	3,4089
156	639,52	0,5827	3,4212
157	644,09	0,5866	3,4456
158	646,37	0,5925	3,4578
159	650,94	0,5984	3,4823
160	653,22	0,6024	3,4945
161	657,79	0,6083	3,5189
162	660,08	0,6122	3,5311
163	662,36	0,6201	3,5434
164	666,93	0,626	3,5678
165	669,21	0,6319	3,58

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
166	671,5	0,6398	3,5922
167	673,78	0,6496	3,6044
168	678,35	0,6594	3,6289
169	680,63	0,6693	3,6411
170	680,63	0,6791	3,6411
171	687,48	0,6909	3,6778
172	689,77	0,7028	3,69
173	689,77	0,7165	3,69
174	685,2	0,7362	3,6655
175	685,2	0,7717	3,6655
176	687,48	0,8071	3,6778
177	694,34	0,8445	3,7144
178	696,62	0,8819	3,7266
179	703,47	0,9154	3,7633
180	708,04	0,9449	3,7877
181	712,61	0,9783	3,8122
182	719,46	1,0079	3,8488
183	724,03	1,0335	3,8732
184	728,6	1,061	3,8977
185	733,16	1,0846	3,9221
186	737,73	1,1102	3,9466
187	740,02	1,1319	3,9588
188	744,58	1,1575	3,9832
189	749,15	1,1811	4,0077
190	753,72	1,2047	4,0321
191	756	1,2244	4,0443
192	760,57	1,2441	4,0687
193	767,42	1,2618	4,1054
194	771,99	1,2776	4,1298
195	776,56	1,2894	4,1543
196	781,13	1,3031	4,1787
197	785,7	1,3169	4,2031
198	787,98	1,3268	4,2154
199	792,55	1,3406	4,2398
200	797,12	1,3524	4,2642
201	799,4	1,3681	4,2765
202	801,68	1,3799	4,2887
203	806,25	1,3917	4,3131
204	808,54	1,4075	4,3253
205	813,1	1,4232	4,3498
206	815,39	1,435	4,362
207	819,96	1,4528	4,3864

NÚMERO	CARGA (Lbf)	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
208	822,24	1,4705	4,3986
209	826,81	1,4882	4,4231
210	829,09	1,5079	4,4353
211	833,66	1,5295	4,4597
212	835,94	1,5531	4,472
213	840,51	1,5768	4,4964
214	842,8	1,6004	4,5086
215	845,08	1,628	4,5208
216	849,65	1,6535	4,5453
217	851,93	1,6831	4,5575
218	854,22	1,7126	4,5697
219	856,5	1,7441	4,5819
220	858,78	1,7795	4,5941
221	858,78	1,815	4,5941
222	863,35	1,8524	4,6186
223	863,35	1,8957	4,6186
224	865,64	1,937	4,6308
225	867,92	1,9882	4,643
226	870,2	2,0374	4,6552
227	870,2	2,0945	4,6552
228	870,2	2,1535	4,6552
229	870,2	2,2224	4,6552
230	867,92	2,2953	4,643
231	867,92	2,3799	4,643
232	867,92	2,4724	4,643
233	865,64	2,5748	4,6308
234	861,07	2,6909	4,6064
235	856,5	2,8248	4,5819
236	845,08	2,9862	4,5208
237	835,94	3,187	4,472
238	822,24	3,4272	4,3986
239	803,97	3,7303	4,3009
240	783,41	4,1142	4,1909
241	714,89	4,6457	3,8244
242	577,85	5,5906	3,0913
243	397,64	6,9488	2,1272

DIAGRAMA ESFUERZO VS. DEFORMACIÓN DE LA PROBETA P-3



$$\boldsymbol{E} = \frac{\sigma}{\varepsilon} = \frac{3164Ksi}{0{,}5295} = 5977 \times 10^3 Psi$$

$$\boldsymbol{Ductilidad} = \frac{lf - lo}{lo} \times 100 = \frac{53{,}4 - 50}{50} \times 100 = 6{,}9\%$$

VALORES OBTENIDOS LUEGO DEL ENSAYO A TRACCIÓN DE LA PROBETA P-3
ESFUERZO FLUENCIA: 26MPa/3,8 x10^3Psi
RESISTENCIA TRACCIÓN: 32MPa/4,6 x10^3Psi
MÓDULO ELASTICIDAD : 41,4MPa/6000 x10^3Psi
CARGA MÁXIMA : 3812N/857lbf
% ELONGACIÓN EN 50 mm : 6,9

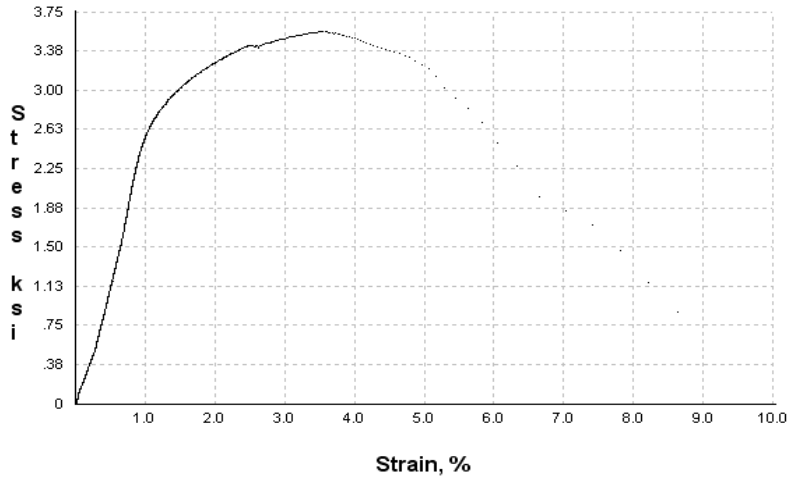
ANEXO B-5

TABULACIÓN DE RESULTADOS PROBETA P-4

ENSAYO A TRACCIÓN

NÚMERO	DEFORMACIÓN (mm)	ESFUERZO ($x10^3$Psi)
1	0	0
2	0,25	0,5
3	0,5	1,15
4	0,75	1,9
5	1	2,65
6	1,25	2,88
7	1,5	3,08
8	1,75	3,2
9	2	3,29
10	2,25	3,4
11	2,5	3,45
12	2,75	3,5
13	3	3,52
14	3,25	3,55
15	3,5	3,56
16	3,75	3,55
17	4	3,5
18	4,25	3,45
19	4,5	3,4
20	4,75	3,35
21	5	3,25
22	5,25	3,05
23	5,5	2,9
24	5,75	2,75
25	6	2,55

DIAGRAMA ESFUERZO VS. DEFORMACIÓN DE LA PROBETA P-4



$$\boldsymbol{Ductilidad} = \frac{lf - lo}{lo} \times 100 = \frac{52{,}7 - 50}{50} \times 100 = 5{,}4\%$$

ALORES OBTENIDOS LUEGO DEL ENSAYO A TRACCIÓN DE LA PROBETA P-4
ESFUERZO FLUENCIA: 22MPa/3,3 x10^3Psi
RESISTENCIA TRACCIÓN: 25MPa/3,6 x10^3Psi
MÓDULO ELASTICIDAD : 42MPa/6100 x10^3Psi
CARGA MÁXIMA : 3016N/678lbf
% ELONGACIÓN EN 50 mm :5,4

ANEXO C-1

CÁLCULO DE DUREZA EN LA PROBETA P-0

NORMA : ASTM E-10
MATERIAL : aluminio
CARGA : 613 N (62,5 Kgf)
Ø DEL INDENTADOR : 5 mm
TIEMPO DE INDENTACIÓN : 15 seg

RESULTADOS DEL ENSAYO		
No. De indentación	**Ø de la indentación (mm)**	**Dureza (HB)**
1	1,80	24,4
2	1,81	24,1
3	1,81	24,1
4	1,80	24,4
5	1,81	24,1
	Ø Promedio = 1,81 mm	**Dureza Promedio : 24,2 HB**

$$HB = 0{,}102\ \frac{2F}{\pi D(D - \sqrt[2]{D^2 - d^2})}$$

$$HB = 0{,}102\ \frac{2 \times 613}{\pi \times 5(5 - \sqrt[2]{5^2 - 1{,}81^2})}$$

$$\boldsymbol{HB = 24{,}2}$$

ANEXO C-2

CÁLCULO DE DUREZA EN LA PROBETA P-1

NORMA : ASTM E-10
MATERIAL : aluminio con cloruro de sodio 5%
CARGA : 613 N (62,5 Kgf)
Ø DEL INDENTADOR : 5 mm
TIEMPO DE INDENTACIÓN : 15 seg

RESULTADOS DEL ENSAYO		
No. De indentación	**Ø de la indentación (mm)**	**Dureza (HB)**
1	1,87	22,6
2	1,88	22,3
3	1,89	22,1
4	1,88	22,3
5	1,89	22,1
	Ø Promedio = 1,88 mm	**Dureza Promedio : 22,3 HB**

$$HB = 0{,}102\ \frac{2F}{\pi D(D - \sqrt[2]{D^2 - d^2})}$$

$$HB = 0{,}102\ \frac{2 \times 613}{\pi \times 5(5 - \sqrt[2]{5^2 - 1{,}88^2})}$$

$$\boldsymbol{HB = 22{,}3}$$

ANEXO C-3

CÁLCULO DE DUREZA EN LA PROBETA P-2

NORMA : ASTM E-10
MATERIAL : aluminio con calcio 5%
CARGA : 613 N (62,5 Kgf)
Ø DEL INDENTADOR : 5 mm
TIEMPO DE INDENTACIÓN : 15 seg

RESULTADOS DEL ENSAYO		
No. De indentación	**Ø de la indentación (mm)**	**Dureza (HB)**
1	1,86	22,8
2	1,86	22,8
3	1,86	22,8
4	1,86	22,8
5	1,87	22,6
	Ø Promedio = 1,86 mm	**Dureza Promedio : 22,8 HB**

$$HB = 0{,}102\ \frac{2F}{\pi D(D - \sqrt[2]{D^2 - d^2})}$$

$$HB = 0{,}102\ \frac{2 \times 613}{\pi \times 5(5 - \sqrt[2]{5^2 - 1{,}86^2})}$$

$$\boldsymbol{HB = 22{,}8}$$

ANEXO C-4

CÁLCULO DE DUREZA EN LA PROBETA P-3

NORMA : ASTM E-10
MATERIAL : aluminio con azufre 5%
CARGA : 613 N (62,5 Kgf)
Ø DEL INDENTADOR : 5 mm
TIEMPO DE INDENTACIÓN : 15 seg

RESULTADOS DEL ENSAYO		
No. De indentación	**Ø de la indentación (mm)**	**Dureza (HB)**
1	1,78	24,9
2	1,79	24,6
3	1,78	24,9
4	1,78	24,9
5	1,78	24,9
Mínimo : 24,6HB	**Ø Promedio = 1,78 mm**	**Dureza Promedio : 24,9 HB**

$$HB = 0{,}102\ \frac{2F}{\pi D(D - \sqrt[2]{D^2 - d^2})}$$

$$HB = 0{,}102\ \frac{2 \times 613}{\pi \times 5(5 - \sqrt[2]{5^2 - 1{,}78^2})}$$

$$\boldsymbol{HB = 24,9}$$

ANEXO C-5

CÁLCULO DE DUREZA EN LA PROBETA P-4

NORMA : ASTM E-10
MATERIAL : aluminio con fosfato de calcio 5%
CARGA : 613 N (62,5 Kgf)
Ø DEL INDENTADOR : 5 mm
TIEMPO DE INDENTACIÓN : 15 seg

RESULTADOS DEL ENSAYO		
No. De indentación	**Ø de la indentación (mm)**	**Dureza (HB)**
1	1,77	25,2
2	1,75	25,8
3	1,76	25,5
4	1,77	25,2
5	1,76	25,5
	Ø Promedio = 1,76 mm	**Dureza Promedio : 25,4 HB**

$$HB = 0{,}102\ \frac{2F}{\pi D(D - \sqrt[2]{D^2 - d^2})}$$

$$HB = 0{,}102\ \frac{2 \times 613}{\pi \times 5(5 - \sqrt[2]{5^2 - 1{,}76^2})}$$

$$\boldsymbol{HB = 25{,}4}$$

ANEXO D-1

CÁLCULO DEL TAMAÑO DE GRANO POR EL MÉTODO PLANIMÉTRICO EN LA PROBETA P-0

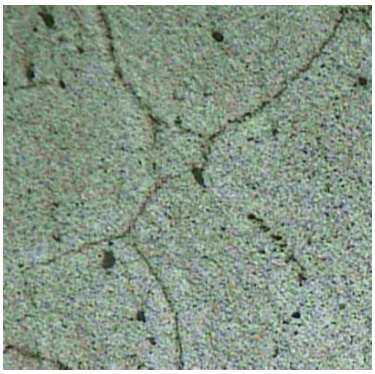
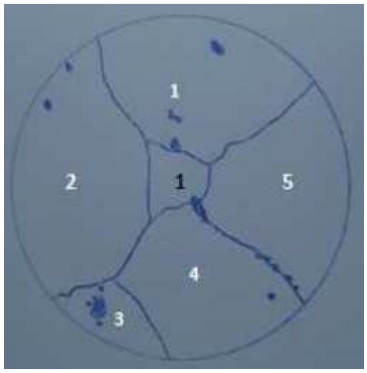


Imagen de la probeta P-0 de Aluminio a 100X, atacado con ácido hidrofluórico durante 10 s.



Conteo de granos en la Probeta P-0

Fuente: El Autor

N granos internos = 1

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$

$$N_{AE} = 2\left(1 + \frac{5}{2}\right)$$

$$N_{AE} = 7$$

N granos interceptados = 5

$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$

$$G = 1{,}000 + 3{,}3219 \log 7$$

$$\boldsymbol{G = 3{,}8}$$

ANEXO D-2

CÁLCULO DEL TAMAÑO DE GRANO POR EL MÉTODO PLANIMÉTRICO EN LA PROBETA P-1

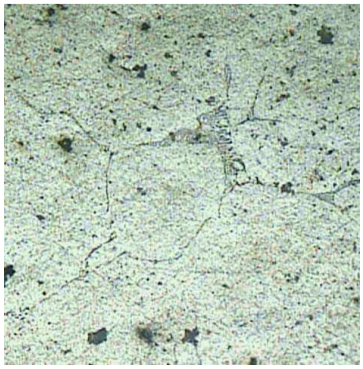
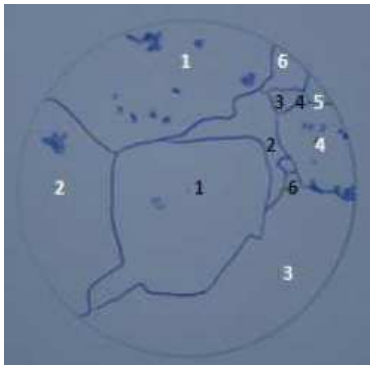


Imagen de la probeta P-1, Aluminio con cloruro de sodio como reductor a 100X, atacado con ácido hidrofluórico durante 12 s.



Conteo de granos en la Probeta P-1

Fuente: El Autor

N granos internos = 6

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$

$$N_{AE} = 2\left(6 + \frac{6}{2}\right)$$

$$N_{AE} = 18$$

N granos interceptados = 6

$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$

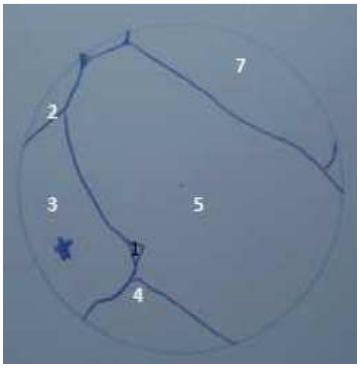
$$G = 1{,}000 + 3{,}3219 \log 18$$

$$\boldsymbol{G = 5{,}2}$$

ANEXO D-3

CÁLCULO DEL TAMAÑO DE GRANO POR EL MÉTODO PLANIMÉTRICO EN LA PROBETA P-2

Imagen de la probeta P-2, Aluminio con calcio como reductor a 100X, atacado con ácido hidrofluórico durante 15 s.



Conteo de granos en la Probeta P-2

Fuente: El Autor

N granos internos = 1

N granos interceptados = 7

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$

$$N_{AE} = 2\left(1 + \frac{7}{2}\right)$$

$$N_{AE} = 9$$

$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$

$$G = 1{,}000 + 3{,}3219 \log 9$$

$$\boldsymbol{G = 4{,}2}$$

ANEXO D-4

CÁLCULO DEL TAMAÑO DE GRANO POR EL MÉTODO PLANIMÉTRICO EN LA PROBETA P-3

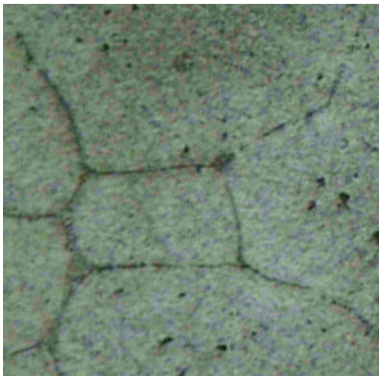
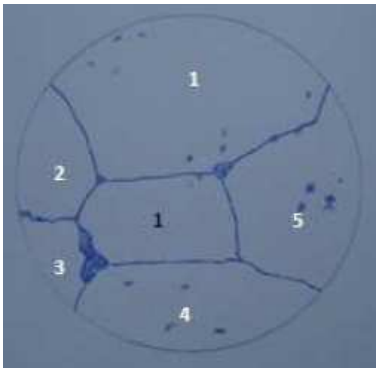


Imagen de la probeta P-3, Aluminio con Azufre como reductor a 100X, atacado con ácido hidrofluórico durante 11 s.



Conteo de granos en la Probeta P-3

Fuente: El Autor

N granos internos = 1

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$

$$N_{AE} = 2\left(1 + \frac{5}{2}\right)$$

$$N_{AE} = 7$$

N granos interceptados = 5

$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$

$$G = 1{,}000 + 3{,}3219 \log 7$$

$$\boldsymbol{G = 3{,}8}$$

ANEXO D-5

CÁLCULO DEL TAMAÑO DE GRANO POR EL MÉTODO PLANIMÉTRICO EN LA PROBETA P-4

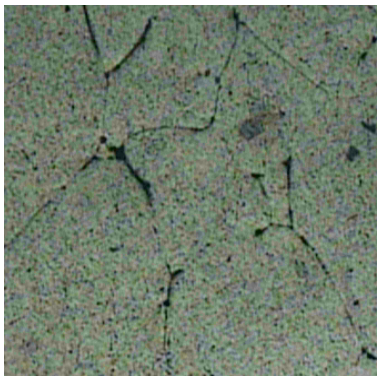
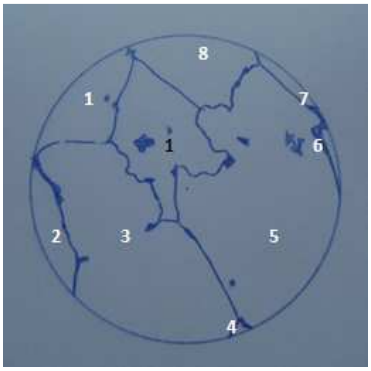


Imagen de la probeta P-4, Aluminio con Fosfato de calcio como reductor a 100X, atacado con ácido hidrofluórico durante 10 s.



Conteo de granos en la probeta P-4

Fuente: El Autor

N granos internos = 1

N granos interceptados = 8

$$N_{AE} = f\left(N_{inside} + \frac{N_{intercepted}}{2}\right)$$

$$N_{AE} = 2\left(1 + \frac{8}{2}\right)$$

$$N_{AE} = 10$$

$$G = 1{,}000 + 3{,}3219 \log N_{AE}$$

$$G = 1{,}000 + 3{,}3219 \log 10$$

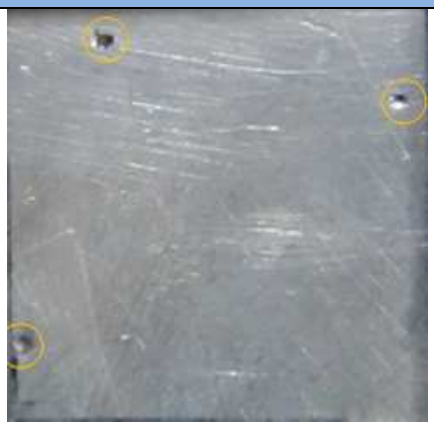
$$\boldsymbol{G = 4{,}3}$$

ANEXO E

➢ ÍNDICE DE POROSIDAD EN LA PROBETA P-0

INSPECCIÓN VISUAL EN LA PROBETA P-0	
	
Imagen de la probeta metalográfica P-0 para realizar la inspección visual Escala 1:5	Conteo de poros en la superficie de la probeta metalográfica P-0 Escala 1:5
Superficie de estudio : 1cm^2	**Número de poros :** 25

➢ ÍNDICE DE POROSIDAD EN LA PROBETA P-1

INSPECCIÓN VISUAL EN LA PROBETA P-1	
	
Imagen de la probeta metalográfica P-1 para realizar la inspección visual Escala 1:5	Conteo de poros en la superficie de la probeta metalográfica P-1 Escala 1:5
Superficie de estudio : 1 cm^2	**Número de poros :** 3

➢ ÍNDICE DE POROSIDAD EN LA PROBETA P-2

INSPECCIÓN VISUAL EN LA PROBETA P-2	

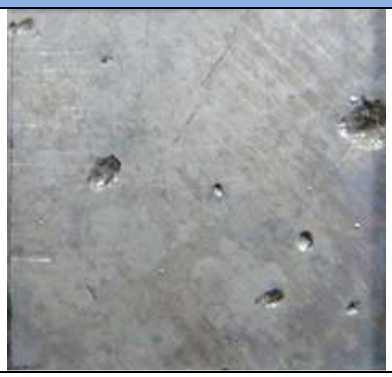
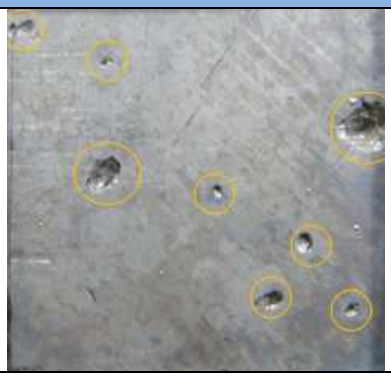
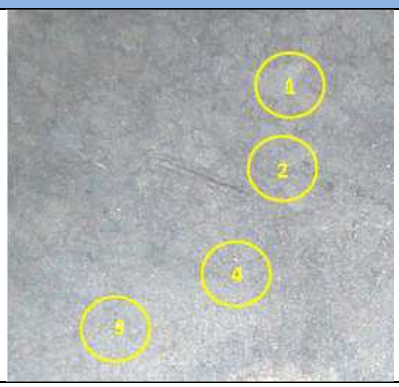

	

Imagen de la probeta metalográfica P-2 para realizar la inspección visual Escala 1:5	Conteo de poros en la superficie de la probeta metalográfica P-2 Escala 1:5
Superficie de estudio : 1 cm^2	**Número de poros :** 8

➢ ÍNDICE DE POROSIDAD EN LA PROBETA P-3

INSPECCIÓN VISUAL EN LA PROBETA P-3	
	
Imagen de la probeta metalográfica P-3 para realizar la inspección visual Escala 1:15	Conteo de poros en la superficie de la probeta metalográfica P-3 Escala 1:15
Superficie de estudio : 0,16cm^2	**Número de poros :** 4

- **ÍNDICE DE POROSIDAD EN LA PROBETA P-4**

INSPECCIÓN VISUAL EN LA PROBETA P-4	
	
Imagen de la probeta metalográfica P-4 para realizar la inspección visual Escala 1:5	Conteo de poros en la superficie de la probeta metalográfica P-4 Escala 1:5
Superficie de estudio : 1cm^2	**Número de poros :** 4

ANEXO F

Importadora de Químicos Dúnamis S.A.

NITRITO DE SODIO TÉCNICO

ANALISIS	ESTÁNDAR	UNIDAD
PUREZA(NO_2Na) en base seca	99.0 min.	%
NITRATO SODIO($NaNO_3$) en base seca	0.80 max.	%
CLORUROS	0.10 max.	
INSOLUBLES EN AGUA	0.05 max.	%
HUMEDAD:	1.5 max.	%
FECHA DE MANUFACTURA: En el empaque		
FECHA DE EXPIRACION: En el empaque		

FORMULA QUIMICA:

NO_2Na (Sales Diazotantes)

DEFINICION:

Cristales o polvo ligeramente amarillo o blanco, soluble en agua, ligeramente soluble en alcohol y éter.

PRECAUCIONES

Riesgo de incendio y explosión cuando se calienta a mas 538 ºC., o en contacto con materia orgánica. Agente oxidante

USOS:
Industria química: obtención de compuestos nitrosos, hidoxilamina,; para la diazotación, catalizador en la obtención de alcohilsulfonatos, estabilizador de color de las resinas de vinilo.; Fabricación de colorantes: obtención de colorantes azóicos, para la diazotación en la tintura y estampado.; Reactivo fotográfico, teñido y estampado de tejidos; Industria metalúrgica(tratamiento de metales) ; Productos farmacéuticos, Adobo de carnes, y en medicina(USP-FCC)

PROCEDENCIA

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