# UNIVERSIDAD CATÓLICA SANTA MARIA

FACULTAD DE CIENCIAS E INGENIERIAS FÍSICAS Y FORMALES

PROGRAMA PROFESIONAL DE INGENIERIA MECÁNICA, MECÁNICA ELECTRICA Y MECATRÓNICA

## TESIS

# “EVALUACIÓN Y OPTIMIZACIÓN DE LOS PARÁMETROS DE OPERACIÓN DEL TRATAMIENTO TÉRMICO DE BONIFICADO DE UN ACERO DE MEDIO CARBONO C 45E-EN 10083”.

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# DEDICATORIA

La presente tesis se la dedico a mis padres Abelardo Vega Palma y Rosa Cruz Pinares, también a mi familia que siempre han estado a mi lado apoyándome para que siga adelante y no rendirme, los amo.

A Dios por darme fuerzas e iluminarme en los momentos más duros.

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A mi asesor de tesis que con mucho empeño logramos concluir este trabajo.

Finalmente, gracias al apoyo de mi compañero de Universidad Josiph P.

Homero Vega

# DEDICATORIA

La presente tesis la dedico principalmente a Dios y al Diviño Niño Jesús, por haberme dado la vida y permitirme el haber llegado hasta este momento tan importante de mi formación profesional. A mi madre, por ser el pilar más importante y por demostrarme siempre su amor y apoyo incondicional. A mi padre, por estar siempre presente y permitirme lograr esta meta. A mis hermanos, por confiar siempre en mí. A mis 3 amores: Fiorella, Ariana y Fernanda, ellas hicieron que me esfuerce cada día más. Y por último a mi gran amigo Josiph, mi gran hermano del alma, gracias LOCO.

# RESUMEN

Dado los constantes cambios en las industrias en conjunto con el incremento económico de algunos sectores, actualmente se ha observado que uno de los problemas que más afecta en la industria son las fallas de componentes provocados por desgaste y rotura, los cuales están ligados con los procesos de fabricación de las muestras o piezas de acero C 45E-EN 10083, en los cuales intervienen los tratamiento térmicos de recocido, templado y revenido.

A fin de mejorar las propiedades mecánicas de un acero C 45E-EN 10083, se realiza el siguiente trabajo de investigación, cuya finalidad es el estudio de la temperatura de temple, el tiempo de permanencia de la austenización y la temperatura de revenido.

# ABSTRACT

Given the constant changes in the industries in conjunction with the economic growth of some sectors, currently it has been observed that one of the problems that affect the industry are component failures caused by wear and tear, which are linked to processes manufacturing samples or pieces of steel C 45E-EN 10083, in which the thermal annealing treatment, quenching and tempering involved.

To improve the mechanical properties of a steel C 45E-EN 10083, the following research work aimed at studying the quenching temperature is performed, the time spent for the austenitising and the tempering temperature.

# PRESENTACIÓN

Se ha observado que uno de los problemas que más afecta en la elaboración de muestras o piezas de acero C 45E-EN 10083, es en las aplicaciones de pernos, tuercas, pines, ejes, piñones, engranajes, émbolos, árbol de transmisión, partes de maquinaria y repuestos de dimensiones medianas, etc., son los tratamiento térmicos de recocido, de templado y revenido cuya deficiencia provoca fallas de desgaste y rotura.

Por tal motivo en el presente trabajo de investigación se centra el estudio en el efecto de la temperatura de temple, tiempo de permanencia a la temperatura de austenización y temperatura de revenido en las propiedades mecánicas de dureza.

Para determinar experimentalmente los mejores valores de dureza se ha trabajado en muestras según normas ASTM, para el ensayo de dureza se ha elaborado muestras de 20 mm de diámetro por 20 mm de altura.

La temperatura de temple fue 820°C, 850°C y 880°C, utilizándose como medio de temple aceite Shell SÁE 40, y la temperatura de revenido estuvo entre 250°C, 300°C y 350°C, según catálogos de Boehler, teniendo como medio de enfriamiento el aire a temperatura ambiente.

Los mejores resultados promedios obtenidos a 820°C, con 45 minutos de austenización y 250°C de temperatura de revenido se tienen una dureza de 103 HRB.

A 850°C con 30 minutos de austenización y 300°C de temperatura de revenido se tiene una dureza de 110 HRB. Y a 880°C con 15 y 45 minutos de austenización y 350°C de temperatura de revenido se tiene una dureza de 110 HRB.

Se concluye finalmente que el experimento a 850°C con un tiempo de 30 minutos de austenización y a una temperatura de 300°C de revendo, es lo más adecuado o recomendado en esta serie de experimentos, está de más indicar que los factores de mayor a menor efecto sobre la dureza es la temperatura de revenido, tiempo de austenización y temperatura de temple.

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# CAPITULO I

# ASPECTOS GENERALES DEL PROYECTO

## 1.1 FORMULACIÓN DEL PROBLEMA

El Perú un país en vías de desarrollo industrial en sus diferentes sectores de la minería, metal mecánica, automotriz, etc., en el cual el reemplazo de piezas determinadas es inevitable al uso y deterioro de las mismas.

La carencia de estas piezas con el mismo tipo de acero y con las propiedades mecánicas requeridas, han causado grandes problemas técnicos y económicos en la industria del medio y a veces es necesario importarlos y ello genera alternativas de solución para menguar la falta de estas piezas, haciendo uso de la materia prima disponible y dándole el tratamiento térmico adecuado, siendo de gran utilidad la evaluación de la temperatura de temple, tiempo de permanencia a la temperatura de temple y temperatura de revenido en el acero C 45E-EN 10083, para la obtención de las propiedades mecánicas y así contribuir al desarrollo y progreso de la industria.

De manera particular los tratamiento térmicos de temple y revenido se han convertido en tratamiento de gran aplicación por los beneficios técnicos y económicos que ofrece, así como también ayudan a alargar la vida de servicio de las piezas y/o autopartes, corno engranajes, árbol de transmisión, pines, émbolos, etc.

El propósito de realizar el presente trabajo es el desarrollar y aplicar en forma correcta el proceso de temple y revenido, de esta manera incentivar a las empresas que de alguna forma se encuentran involucradas con el desarrollo de estos procesos, como un aporte de los tratamientos térmicos en la solución de este tipo de problemas.

La formulación del problema consiste en decir, que efecto tiene la temperatura de temple, tiempo de permanencia a la temperatura de temple y temperatura de revenido sobre las principales propiedades mecánicas del acero C 45E-EN 10083.

## 1.2 PLANTEAMIENTO DE LA HIPÓTESIS

Controlando adecuadamente la temperatura de temple, tiempo de permanencia a la temperatura de temple y temperatura de revenido, nos permita incrementa las principales propiedades mecánicas en el acero C 45E-EN 10083.

## 1.3 DETERMINACIÓN DE OBJETIVOS

### 1.3.1 OBJETIVO GENERAL

Determinar experimentalmente el efecto de la temperatura de temple y temperatura de revenido en la dureza, resistencia a la tracción, microestructura y resiliencia del acero C 45E-EN 10083.

### 1.3.2 OBJETIVOS ESPECÍFICOS

1. Experimentar a nivel de elaboración, la influencia de los parámetros de operación de los tratamientos térmicos de temple y revenido.

2. Construir gráficas que nos permita analizar el efecto de la temperatura de temple, permanencia y temperatura de revenido en la dureza, resiliencia, microestructura y resistencia a la tracción.

# CAPITULO II

# ACEROS AL CARBONO

## 2.1 EL ACERO

Fundamentalmente todos los aceros son mezclas de hierro y carbono (máx. 2.00%). Los aceros comunes al carbono también tienen pequeñas cantidades de otros elementos como manganeso. Silicio, fósforo y azufre. Por ejemplo el acero C 45E-EN 10083 tiene 0.45% C ,0.75% Mn, 0.040% P, 0.050% S y 0.22% Si.

Aceros aleados son aquellos que tienen cantidades específicas de otros elementos en su composición química. Los elementos más comúnmente aleados con el acero son el níquel, cromo, molibdeno, vanadio y tungsteno; el manganeso también cae en esta categoría cuando se encuentra en cantidades arriba del 1%. Sin embargo el carbono es el elemento principal de la mayoría de los aceros, debido a que la cantidad de carbono presente en el acero común, tiene un efecto pronunciado en sus propiedades y en la selección del tratamiento térmico, recomendable para obtener ciertas propiedades deseadas.

## 2.2 ESTRUCTURA DEL ACERO

Todos los metales por naturaleza son cristalinos. En la solidificación del acero, se forman pequeños cristales

Todos los granos o cristales están compuestos de átomos ligados en un patrón definido. Esta estructura atómica es llamada red espacial. A una temperatura determinada los átomos en un grano están espaciados una distancia definida y esta no puede ser cambiada.

Existen catorce formas de ordenar puntos en el espacio. Los metalurgistas necesitan conocer solamente dos la cúbica de cuerpo centrado y la cúbica de caras centradas, Fig. N° 2.1 .a y 2.1 .b.

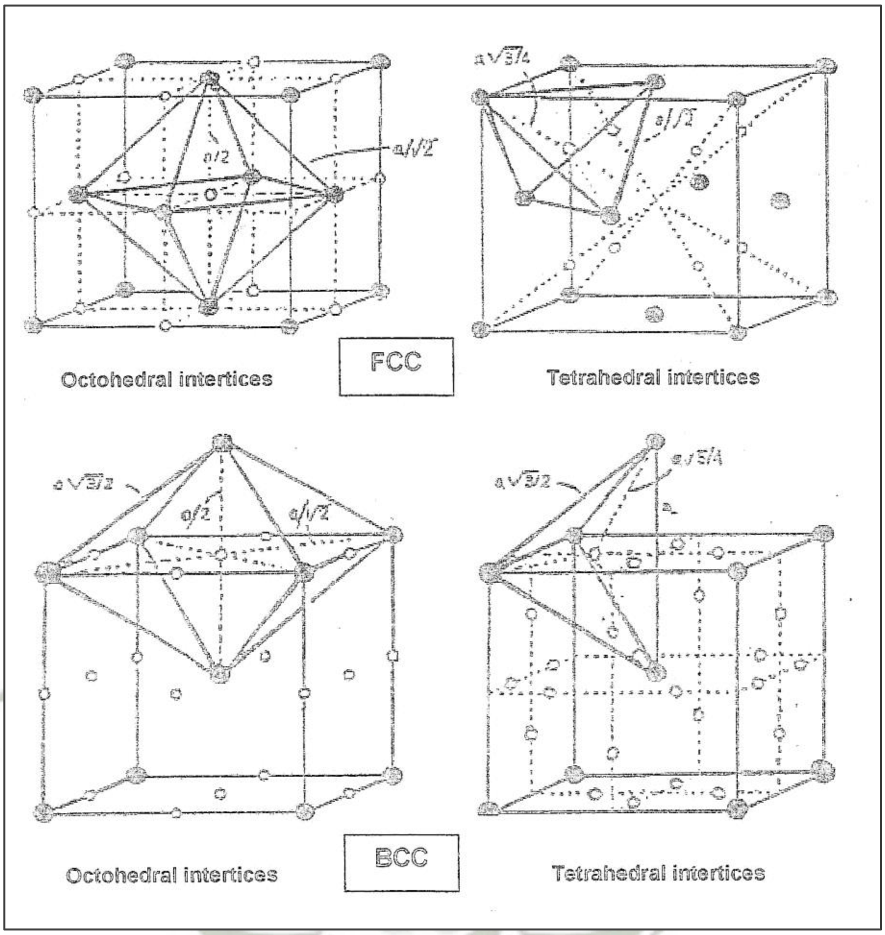


**Figura N° 2.1.a, 2.1.b.**
**Estructura del acero**

La cúbica centrada en el cuerpo se abrevia BCC, tiene un átomo en cada esquina del cubo y uno en el centro del cuerpo. La cúbica centrada en las caras se abrevia FCC, tiene un átomo en cada esquina del cubo y uno en el centro de cada una de las caras.

El hierro puro y el acero al carbono tienen la estructura BCC, a la temperatura ambiente mientras que a altos rangos de temperatura el arreglo es FCC. Hay un re-arreglo de átomos en los granos del hierro o del acero, al ser calentados a ciertos valores de temperatura, donde ocurren cambios de BCC a FCC este reacomodo de átomos es llamado cambio alotrópico. La temperatura a la cual estos cambios ocurren, se llama Temperatura de transformación. La ciencia del tratamiento térmico del acero depende de la alotropía del hierro y la variación de la solubilidad del carbono en cada forma cristalina de hierro.

## 2.3 ALOTROPIA DEL HIERRO

Dado que el hierro es el elemento predominante en las aleaciones hierro-carbono, es conveniente hacer un estudio de los cambios alotrópicos de hierro por ser de gran importancia en el tratamiento térmico del acero.

En la Fig. N° 2.2 se observa que arriba de 1540°C el hierro es líquido; a 1540°C el hierro comienza a solidificar y la temperatura se mantiene constante hasta que solidifique totalmente. Después de solidificar el hierro la temperatura comienza a descender a una razón uniforme hasta que alcanza 1395°C, a esta temperatura hay una ligera pertenencia, comparada con la que se tuvo a 1540°C.

Entre 1540°C y 1395°C, el hierro es conocido como hiero delta, con una estructura BCC a 1395°C la curva de enfriamiento indica que hay un cambio de hierro delta (BCC) a hierro gama (FCC) esta transformación no es de importancia en los tratamientos térmicos; porque no se aplican a estas temperaturas.

Cuando termina la transformación a 1395°C la temperatura comienza a descender nuevamente a una razón constante hasta los 915°C donde nuevamente hay una permanencia por un corto tiempo; y a esta temperatura el hierro gama (FCC) cambia a hierro alfa (BCC). Esta transformación es de gran importancia en el tratamiento térmico del acero.

La permanencia a 770°C no tiene importancia en los tratamientos térmicos ya que representan un cambio en las propiedades magnéticas del hierro, al pasar de no-magnético a magnético y se llama punto de Curie.

**Tabla N° 2.1.**
**Estados Alotrópicos del Hierro**

| ALOTROPÍA | CALENTADO | ENFRIADO | ESTRUCTURA | PROPIEDAD |
|---|---|---|---|---|
| Hierro α | 0°C a 768°C | 768°C a 0°C | BCC | MUY MAG |
| Hierro β | 768°C a 910°C | 898°C a 768°C | BCC | DÉBIL MAG |
| Hierro γ | 910°C a 1401°C | 1401°C a 898°C | FCC | NO MAG |
| Hierro δ | 1401°C a 1535°C | 1528°C a1401°C | BCC | DÉBIL MAG |

Fuente: Apraiz Ramiro, Madrid, 1961

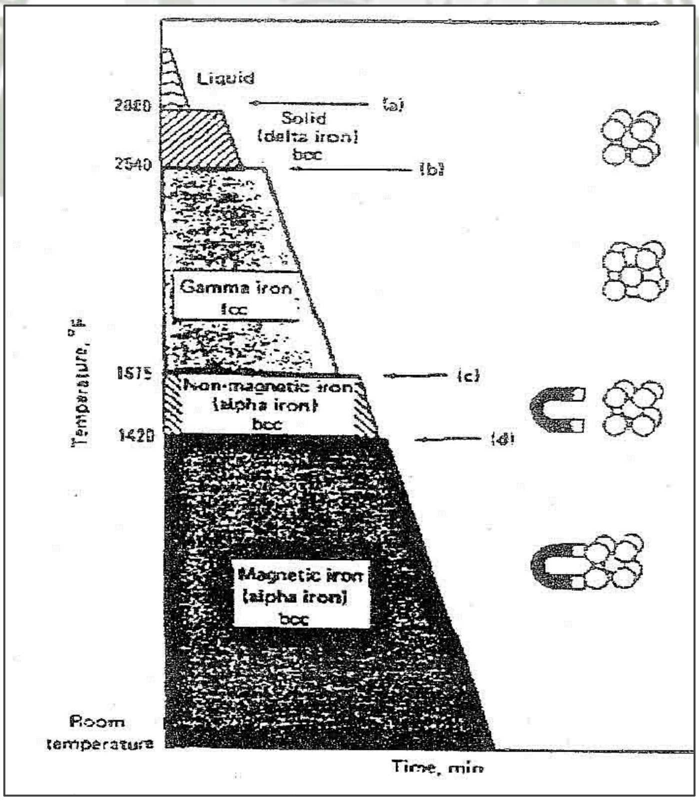


**Figura N° 2.2.**
**Cambios alotrópicos del hierro**

## 2.4 DIAGRAMA DE FASES Fe-Fe$_3$C : ACEROS

- En el Diagrama Fe-Fe3C es un diagrama meta-estable por la cementita.
- La cementita no es una fase de equilibrio en el diagrama.
- El eje de ordenadas representa las temperaturas de transformación de fases.
- El eje de abscisas inferior, representa las proporciones en peso del carbono y hierro.
- El eje de abscisas superior, representa el porcentaje atómico.
- El punto de fusión del Fe es 1539°C.
- El punto de fusión de la cementita es 1250°C.
- El punto de fusión del C es 3500°C.
- La línea continua representa al diagrama meta-estable.
- Las líneas punteadas representan el diagrama de equilibrio.
- La línea de líquidos está representada por: A, B, C, D.
- La línea de sólidos está representada por las letras A, H, J, G, C, F, D.

El diagrama presenta tres líneas horizontales:
- Horizontal peritéctica a 1492°C línea HJB
- Horizontal eutéctica a 1147°C línea ECF
- Horizontal eutectoide a 723°C línea PSK

a. 1492°C (línea HJB) se produce la reacción peritéctica
D (0.08%C) + líquido (0.55%C) ←→ (0.18%C) y

b. 1147°C (línea SCF) la reacción eutéctica
Líquido (4.3%C) ←→ y (2.06%C) + Fe3C (6.67%C)

c. 723°C (línea PSK) la reacción eutectoide
$\gamma$ (0.80%C) ←→ (0.23%C) Fe3C (6.67%C)

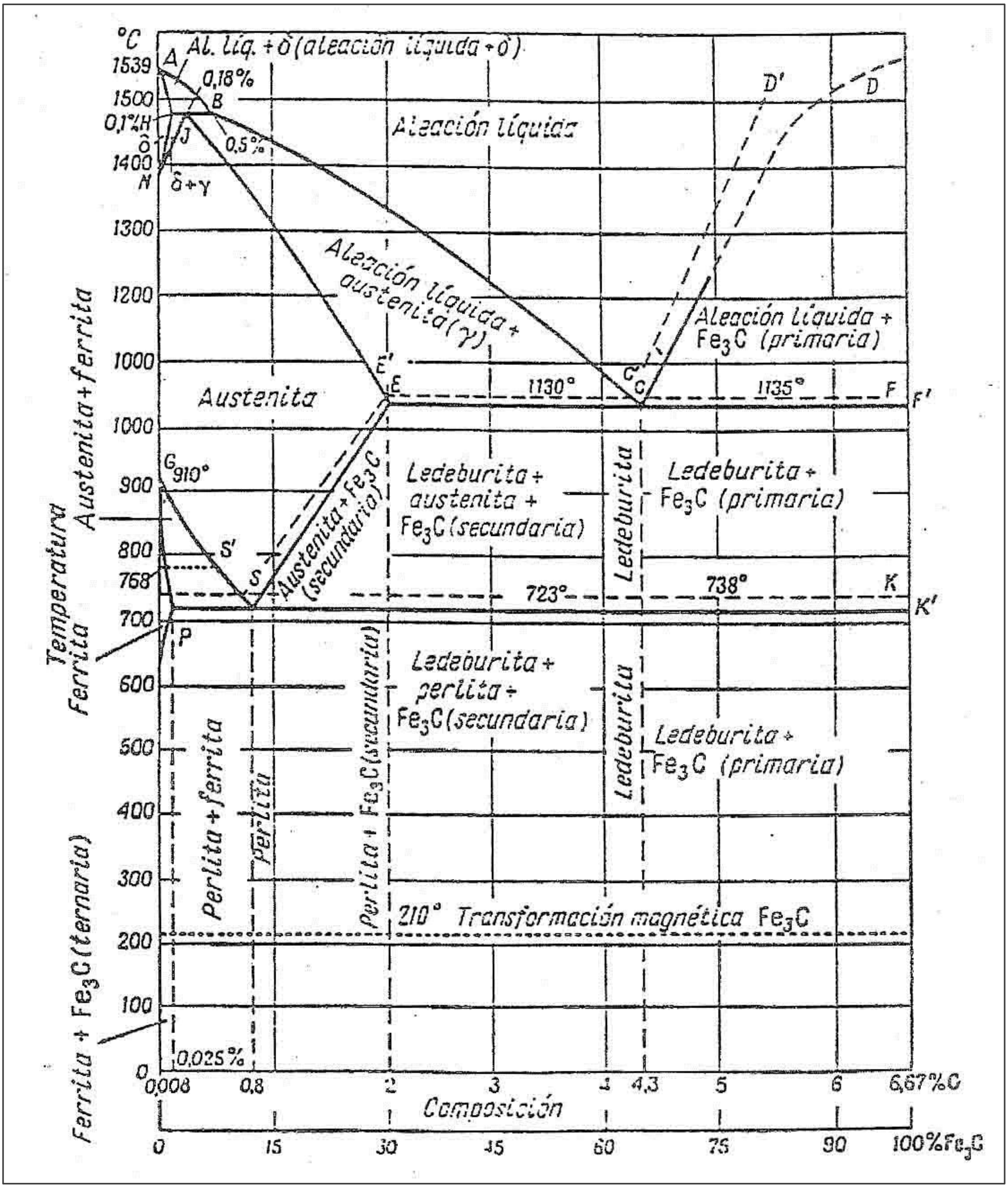


**Figura N° 2.3.**

**Diagrama de Equilibrio de las aleaciones de hierro-carbono; las líneas gruesas se refieren al sistema de Fe-$Fe_3C$; las líneas punteadas (horizontales e inclinadas) se refieren al sistema de Fe-C.**

- Los puntos G (910°C) y N (1403°C) corresponden a las transformaciones alotrópicas del Fe puro.
- Por debajo de 910°C al Fe es CC y a = 2.866 Å se conoce como ferrita (Fe$\alpha$).
- Entre 910°C y 1403°C el Fe es CCC y a = 3.656 Å y se conoce como austenita (Fe$\gamma$).
- Por encima de 1403°C el Fe es CC y a = 2.94 Å y se conoce como ferrita delta (Fe$\delta$).
- La diferencia básica entre aceros y fundiciones se encuentra en el diagrama de fases.
- Los aceros tiene un punto de fusión por encima de 1539°C.
- Las fundiciones requieren temperaturas inferiores 1350°C.
- La parte inferior está conformada por la línea G-S-E, P-S-K, son reacciones en estado sólido.
- En el eje de la abscisa se define cuatro puntos:
    - El límite de diagrama D-F-K-L (6.67%C).
    - Punto C denominado eutéctico (4.3%C) se llama ledeburita (a la izquierda fundición blanca hipoeutéctica y a la derecha fundición hipereuéctica.
    - El punto E marca la máxima solubilidad del carbono en hierro gama.
    - El punto S, punto eutectoide, la reacción se llama perlita, a la izquierda aceros hipoeutectoides, a la derecha aceros hipereutectoides, puntos S acero eutectoide.

- Otros puntos a considerar:

Puntos críticos subiendo la temperatura.

| | |
|---|---|
| $AC_1$ | Inicio de la transformación de ferrita en austenita con C < 0.83%. Transformación de la perlita en austenita, para C > 0.83%. |
| $AC_2$ | Desaparece el magnetismo. |
| $AC_3$ | Final de la transformación de la ferrita en austenita. |
| $AC_4$ | Principio de la transformación de la austenita en solución sólida delta. |
| $AC_{cm}$ | Final de la transformación de la cementita secundaria en austenita. |

Puntos críticos bajando la temperatura.

| | |
|---|---|
| $Ar_{cm}$ | Principia la segregación de cementita secundaria de la austenita. |
| $Ar_4$ | Final de la transformación de la solución sólida delta en austenita. |
| $Ar_3$ | Principia la transformación de la austenita en ferita. |
| $Ar_2$ | Aparece el magnetismo. |
| $Ar_1$ | Transformación de la austenita en perlita. |

Es posible encontrar variaciones de la definición de los puntos críticos entre diferentes autores, estas diferencias no deben atribuirse solamente a los errores inherentes a los procesos de determinación experimental, sino también al grado de pureza de los elementos básicos Fe y C que se han utilizado.

**Tabla N° 2.2.**

**Puntos críticos del diagrama Fe-$Fe_3C$**

| Punto | Temperatura | C% |
|---|---|---|
| A | 1535 | 0,00 |
| B | 1492 | 0,55 |
| H | 1492 | 0,08 |
| J | 1492 | 0,18 |
| N | 1405 | 0,00 |
| E | 1147 | 2,06 |
| C | 1147 | 4,3 |
| F | 1147 | 6,67 |
| D | 1250 | 6,67 |
| G | 910 | 0,00 |
| P | 723 | 0,023 |
| S | 423 | 0,80 |
| K | 423 | 6,67 |

Fuente: Segundo Muñiz, OEA 1994

En la determinación de los puntos críticos, las aleaciones son estudiadas en procesos repetidos de calentamiento y enfriamiento, registrándose la transformación mediante la medición de una propiedad física (dilatación, variación de la resistencia óhmica; calor liberados o absorbidos en la transformación).

Si bien el ciclado térmico en torno a los puntos críticos se efectúa muy lentamente, cercanos al equilibrio termodinámico, se debe una energía libre adicional mediante un sub-enfriamiento o sobrecalentamiento para que la transformación de fase se produzca, es por ello que los puntos críticos se encuentran a temperaturas inferiores, cuando son obtenidos por enfriamiento y superiores en caso contrario. Esto se muestra en la Fig. N° 2.4, donde las velocidades de calentamiento y enfriamiento son de 0,125°C/minuto.

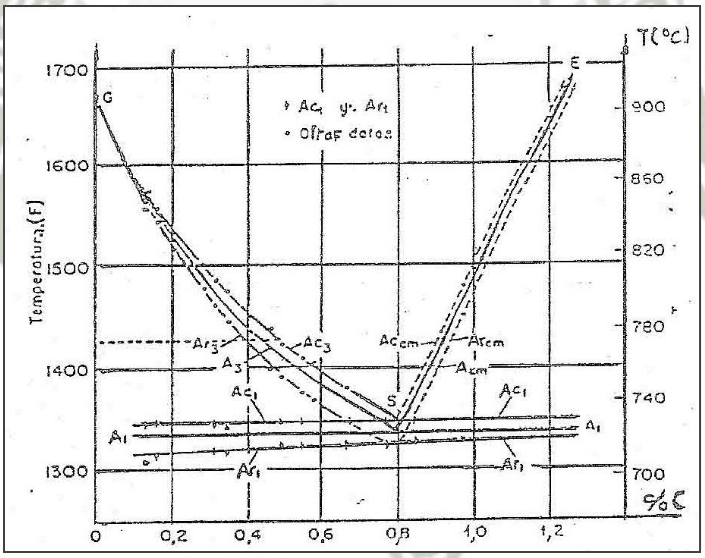


**Figura Nº 2.4.**
**Puntos Críticos**

Las líneas $A_3$, $A_1$ y $A_{cm}$ se han obtenido como medias de las líneas designadas como $A_c$ (c = "chauffage"= calentamiento) y $A_r$ (r = "refroidissement" = enfriamiento), siendo adoptadas como temperaturas de equilibrio en la transformación.

Cuando el hierro puro alcanza la transformación a 915°C, lo hace a temperatura constante. Arriba de 915°C el hierro es (FCC) y abajo de esta temperatura es (BCC). Cuando hay átomos de carbono presente dos cambios tienen lugar. La temperatura de esta transformación es menor y la transformación ocurre en un rango de temperaturas y no a temperatura constante. Esta información ha sido condensada en el diagrama de equilibrio Fig. N° 2.3. Una fase es una porción de materia física, Química y cristal o gráficamente homogénea, la cual está separada de las otras fases por límites de grano.

Las siguientes fases ocurren en aleaciones hierro-carbono: aleación fundida, austenita, ferrita, cementita y grafito. Estas fases también son llamadas constituyentes. No todos los constituyentes como la perlita o la boinita, son fases, dado que, algunas son mezclas y no son totalmente homogéneas.

Un diagrama de fases es una representación gráfica de la temperatura de equilibrio y la composición de las fases. En el sistema hierro-cementita, la temperatura es colocada verticalmente y la composición horizontalmente. En un sistema metálico, la presión, es usual mente considerada constante, o puede ser tomada como una variable adicional en casos raros. Este diagrama es llamado incorrectamente diagrama de equilibrio hierro-carbono, porque la fase del lado derecho es cementita y no carbono o grafito, y el término equilibrio, no es apropiado porque la fase cementita no es realmente estable.

En otras palabras, dando suficiente tiempo el carburo de hierro o cementita, se descompone a hierro y grafito. El acero grafitiza. Esto es una reacción perfectamente natural y solamente el diagrama hierro-grafito es propiamente llamando diagrama de equilibrio.

En el diagrama hierro - cementita se indican, que fases están presentes a cada temperatura y los límites de composición de cada una de ellas. En el diagrama la temperatura es colocada verticalmente y la composición horizontal.

Es más fácil aceptar el hecho que el carbono se disuelve uniformemente en el hierro fundido, de la misma manera que la sal se disuelve en agua. Sin embargo es difícil esquematizar o dibujar al carbono sólido o al carburo de hierro disuelto en el hierro sólido.

La habilidad del hierro y carbono para formar soluciones sólidas hace posible el tratamiento térmico del acero.

Refiriéndonos al diagrama hierro - cementita si área marcada como austenita, es un área donde el hierro retiene mucho carbono disuelto.

De hecho, la mayoría de los tratamientos térmicos, como el recocido, normalizado y temple empieza con el calentamiento del acero dentro del rango austenítico, para disolver el carburo en el hierro.

### 2.4.1 AUSTENITA

Es el término aplicable a la solución sólida intersticial de carbono en hierro FCC como otros constituyentes en el diagrama, la austenita tiene una solubilidad definida por el carbono, la cual depende de la temperatura. El área sombreada en el diagrama limitado por AGFDE, es donde se encuentra la austenita. Como se muestra en el diagrama, el contenido de carbono puede variar de 0 a 2%. Dado que uno de los límites del área de la austenita es hierro en hierro gama. Bajo condiciones normales la austenita no puede existir a temperaturas elevadas, en la zona del diagrama limitada por la línea AGFED.

Los límites de solubilidad para el carbono, en la estructura BCC del hierro son mostrados por la línea ABC del diagrama. Esta área del diagrama se conoce como alfa y la fase es llamada ferrita. La máxima solubilidad del carbono en el hierro $\alpha$ es 25% y ocurre a 725°C, a temperatura ambiente solamente disuelve .008% de carbono.

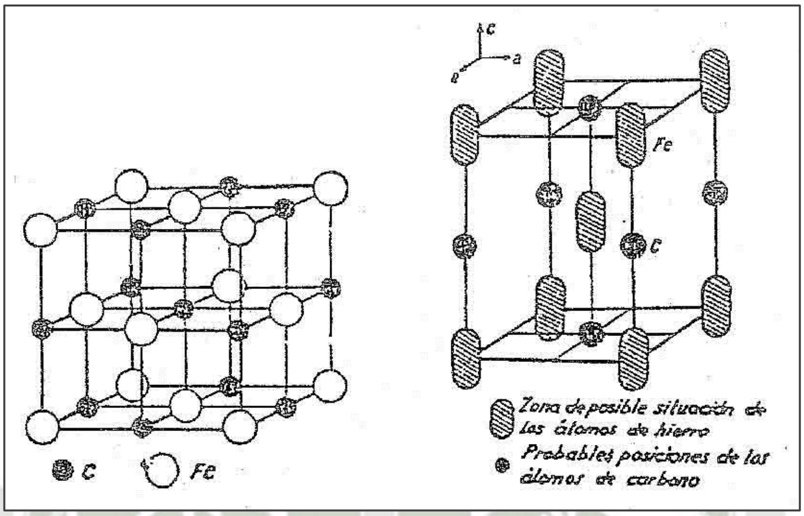


**Figura N° 2.5.**
**Transformación de la austenita en martensita**

### 2.4.2 ESTRUCTURA DE LA CEMENTITA

Como se ha señalado en el diagrama de estado Fe-$Fe_3C$, en el límite de solubilidad del C en Fe y en el $Fe_3$ tanto en la reacción eutectoide, precipita una segunda fase, carburo de hierro (cementita). La fórmula química $Fe_3C$, no significa que la cementita forme moléculas $Fe_3C$, sino simplemente que la red cristalina contiene átomos de C en proporción de 3:1. Fig. N° 2.6.

El $Fe_3C$ tiene una celda unitaria tetragonal de 12 átomos de Fe y 4 átomos de C por celda.

La cementita no experimenta transformaciones alotrópicas, tiene una gran dureza (>HB 800). La cementita es apta para formar soluciones sólidas de sustitución. Los átomos de C pueden ser sustituidos por átomos no metálicos como N, O; los átomos de Fe, por metales como Mn, Mo, Cr, W, etc.

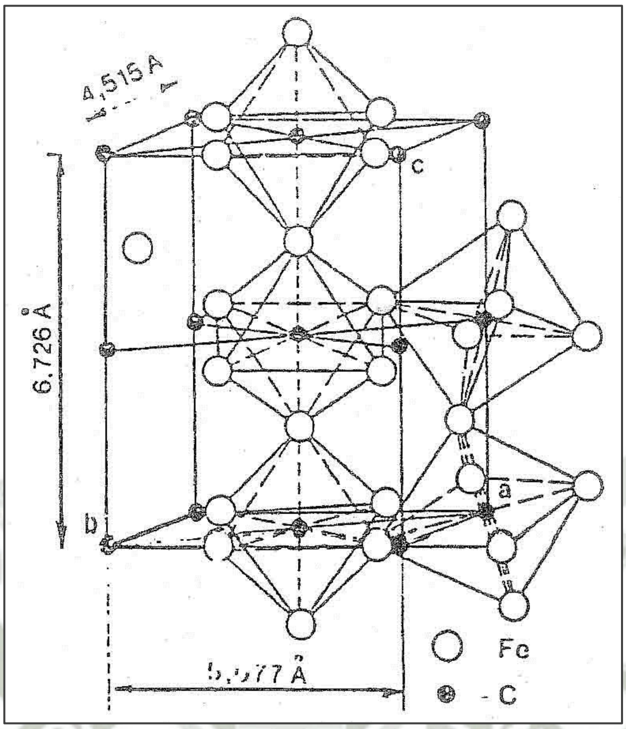


**Figura N°2.6.**
**Estructura cristalina de la cementita**

Desde el punto de vista termodinámico, la cementita es un compuesto inestable puesto que su energía libre de formación es ligeramente superior de las fases Fe y C libre (grafito), Sin embargo, se necesita elevada temperatura por debajo de la eutéctica y largos tiempos de tratamiento (con un contenido relativamente alto de Si, elemento grafitizante) para descomponer el carburo de grafito y ferrita
Fe$\alpha$ ←→ 3Fe $\alpha$ + (grafito).

## 2.5 TRANSFORMACIÓN DE LA AUSTENITA

La transformación de la austenita a ferrita y cementita puede dar diferentes microestructuras dependiendo de la composición y la velocidad de enfriamiento.

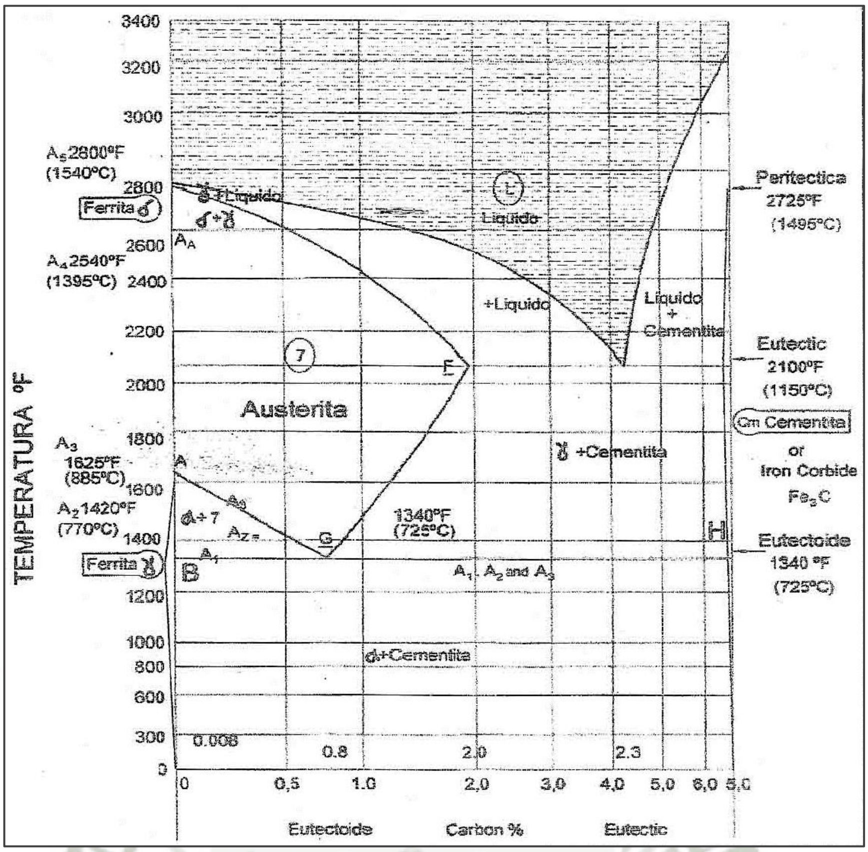


**Figura N° 2.7.a.**
**Diagrama de fase de hierro - cementita**

### 2.5.1 ACERO HIPOEUTECTOIDE

Los aceros que contengan menos de 0.77% C son conocidos como aceros hipoeutectoides. A temperatura ambiente las fases presentes son ferrita y perlita.

El contenido de ferrita en estos aceros, es inversamente proporcional al contenido de carbono del acero y el contenido de perlita es directamente proporcional.

La línea BG del diagrama Fig. N° 2.7.a. es llamada crítica inferior $A_1$ y la línea AG es llamada línea crítica superior $A_3$.

### 2.5.2 ACERO EUTECTOIDE

Un acero al carbono conteniendo 0.77% de carbono es una solución sólida en el rango de la temperatura austenitica, entre 725°C a 1370°C. Todo el carbono esta disuelto en la austenita. Cuando esta solución sólida se enfría lentamente, ocurren varios cambios a 725°C. Esta temperatura es de transformación o temperatura critica del sistema hierro-cementita. A esta temperatura el acero se transforma de una solución sólida homogénea a dos nuevas fases distintas. Este cambio ocurre a temperatura constante y con generación de calor. Las nuevas fases de ferrita y cemente, formadas simultáneamente; sin embargo, esto ocurre a una sola composición punto "G" en la Fig. N° 2.7.a.

Estos dos nuevos constituyentes pueden desarrollarse separadamente de la austenita en otros aceros. La transformación en el punto "G" es conocido como reacción eutectoide y por esta razón el acero de 0.77% C es llamado acero eutectoide. La ferrita y cementita formada en la reacción eutectoide es llamada perlita. La Fig. N° 2.7. a y b muestra la microestructura de la perlita y cementita a diferentes porcentajes de carbono. La perlita está compuesta de placas alternadas de ferrita y cementita. Se llama perlita porque muestra un color similar al de la madre perla el acero de 0.77% C tiene 100% perlita a temperatura ambiente y mediante enfriamiento lento.

### 2.5.3 ACERO HIPEREUTECTOIDE

Los aceros que contengan entre 0.77 C y 2% de carbono son llamados aceros hipereutectoides.

La línea GF del diagrama Fig. N° 2.7.a es llamada línea crítica $A_{cm}$ o línea de la solubilidad de la cementita y la línea GH es llamada línea crítica inferior $A_{3-1.}$

Las temperaturas críticas mostradas en el diagrama se obtienen a condiciones de enfriamiento y calentamiento muy lento. Sin embargo en la práctica comercial las razones de calentamiento exceden las condiciones obtenidas en laboratorio por lo que los cambios ocurren a temperaturas de unos cuantos grados arriba de las indicadas en la Fig. N° 2.7.a son conocidas como temperaturas $A_c$ el subíndice c viene de la palabra en francés chauffage, que significa calentamiento.

Por otra parte en la práctica comercial del enfriamiento, las transformaciones ocurren a unos cuantos grados por abajo de las temperaturas mostradas en la Fig. N° 2.7.a y estas son conocidas como Ar, el subíndice r viene de la palabra en Francés refroidissement, que significa enfriamiento.
La diferencia entra las temperaturas de transformación en el calentamiento o en el enfriamiento varia con la rapidez del ccalentamiento y de enfriamiento. Entre más rápido se caliente varia con la rapidez de calentamiento y del enfriamiento. Entre más rápido se caliente el acero más alta será la temperatura $A_c$. Y entre más rápido se enfríe menor será la temperatura $A_r$.

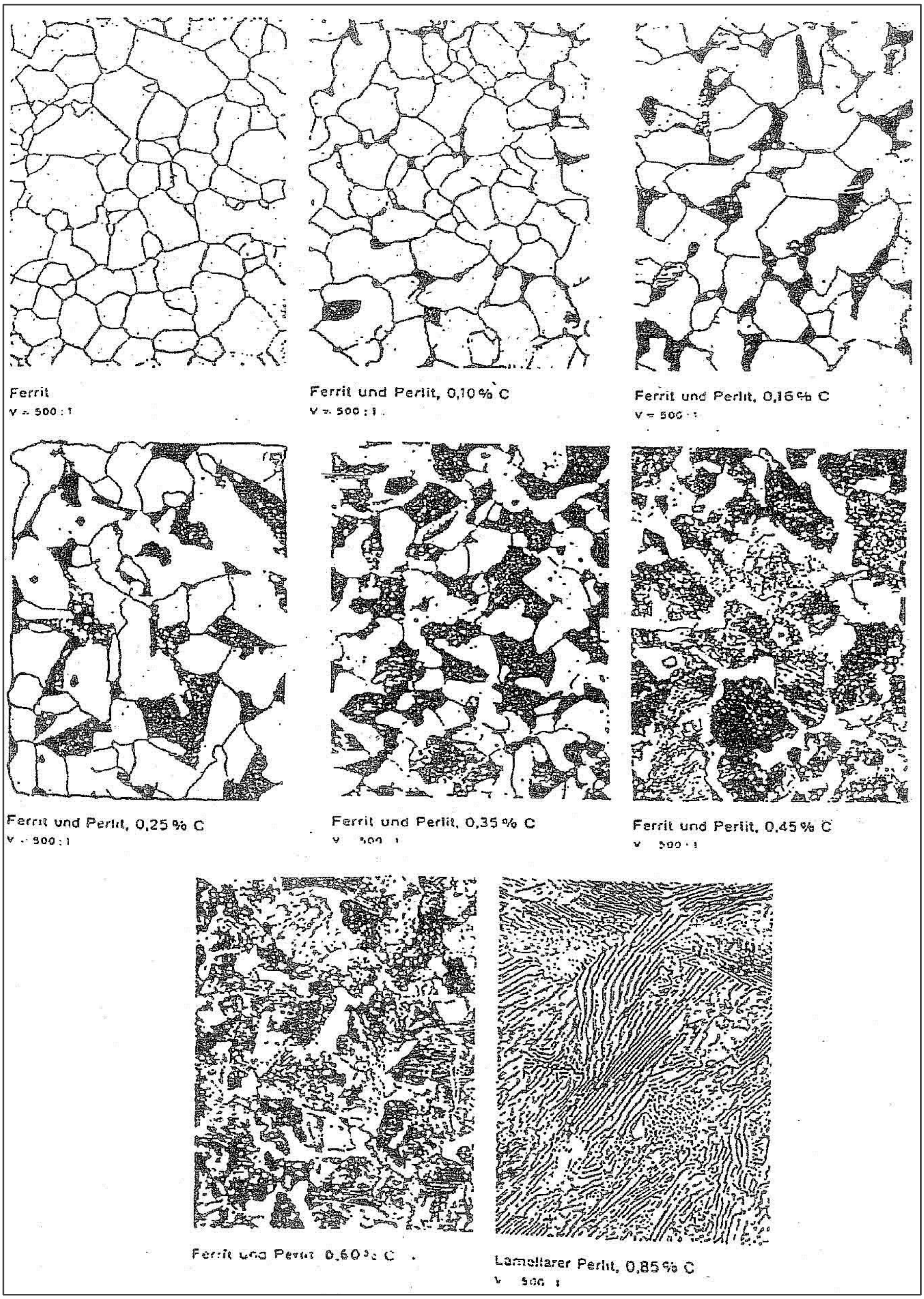
El diagrama hierro-cementita solamente muestra las fases que existen en equilibrio. Cuando las razones de calentamiento y de enfriamiento son muy lentas, se permite una completa transformación de los constituyentes. Si el calentamiento es muy rápido, la solución y difusión del carbono no puede presentarse adecuadamente, y esto puede provocar resultados desastrosos.
Para corregir esta condición, la temperatura debe ser elevada y dar un tiempo suficiente para permitir que la difusión del carbono ocurra,

y se distribuya uniformemente en la austenita. Esto es llamado homogenización, Fig. N° 2.8.

La temperatura de transformación: durante el primer paso del calentamiento, la temperatura de la probeta se incrementa a una razón uniforme. A temperatura $T_1$ la razón de calor absorbido se decrementa hasta que la temperatura $T_2$ es alcanzada, después de este punto de razón se incrementa nuevamente. La temperatura $T_1$ es la temperatura crítica e indica el comienzo de la transformación de ferrita a austenita. Y la temperatura $T_2$ indica la total transformación a austenita. En el enfriamiento ocurren los efectos inversos.

Las fases representadas en el diagrama hierro- cementita son fases metaestabies. Las temperaturas en las cuates ocurren las trasformaciones son determinadas por condiciones de calentamiento y enfriamiento lento. Condiciones de enfriamiento rápido, se alejan de las condiciones de equilibrio, y produce estructuras metaestabies, y la relación mostrada en el diagrama de fase hierro cementita debe ser modificado.

No hay dificultad en comprender por qué en el enfriamiento rápido de un acero hipoeutectoide se obtiene un exceso de perlita. La trasformación de la austenita a ferrita y perlita es un proceso de difusión, el cual involucra el movimiento de átomos de carbono. La velocidad de difusión depende del tiempo y de la temperatura. Bajo condiciones de enfriamiento rápido, la temperatura crítica $A_3$ se pasa muy rápido y se cuenta con un tiempo muy corto para que los átomos de carbono se difundan. Cuando la temperatura es menor a la temperatura critica $A_3$ habrá más austenita que se transforme en perlita, esto sucede hasta antes de alcanzar la temperatura crítica $A_1$.



Ferrit
V = 500 : 1

Ferrit und Perlit, 0,10 % C
V = 500 : 1

Ferrit und Perlit, 0,16 % C
V = 500 : 1

Ferrit und Perlit, 0,25 % C
V = 500 : 1

Ferrit und Perlit, 0,35 % C
V = 500 : 1

Ferrit und Perlit, 0,45 % C
V = 500 : 1

Ferrit und Perlit 0,60 % C

Lamellarer Perlit, 0,85 % C
V = 500 : 1

**Figura Nº 2.7.b.**
**Microestructura de los aceros hipereutectoides y otros**

En muchas ocasiones es posible estimar, el contenido de carbono de un acero, mediante el examen de microestructura, es decir, determinándola cantidad de perlita presente en dicho acero. De lo anterior se deduce que es importante conocer la historia previa del acero para hacer una estimación correcta. Un acero que se enfría rápidamente tendrá más perlita que uno que se enfría más lento, por lo que el contenido de carbono en relación con el contenido de perlita no es correcto.

El diagrama de fase hierro-cementita es también útil para estimar el contenido de carbono del acero, mediante el examen de la microestructura.

Cálculos de contenido de carbono mediante el examen de la microestructura, se hacen ocasionalmente. Los métodos químicos son más rápidos y exactos

## 2.6 TRANSFORMACIÓN ISOTÉRMICA DE LA AUSTENITA

Cuando en un acero eutectoide. La transformación de la austenita se lleva a cabo, los átomos de carbono se difunden de tal manera que el producto es perlita. Esta si es vista al microscopio tiene la apariencia de capas alternadas. Con velocidades de enfriamiento muy lento, la distancia entra las capas es mayor que en el caso de enfriamiento más rápido. La razón del poco espaciamiento, se debe a una baja velocidad de difusión. Y hay poco tiempo para la difusión del carbono. La distancia de traslación de los átomos de carbono es pequeña, por lo tanto, el espaciamiento de las capas de cementita es pequeño.

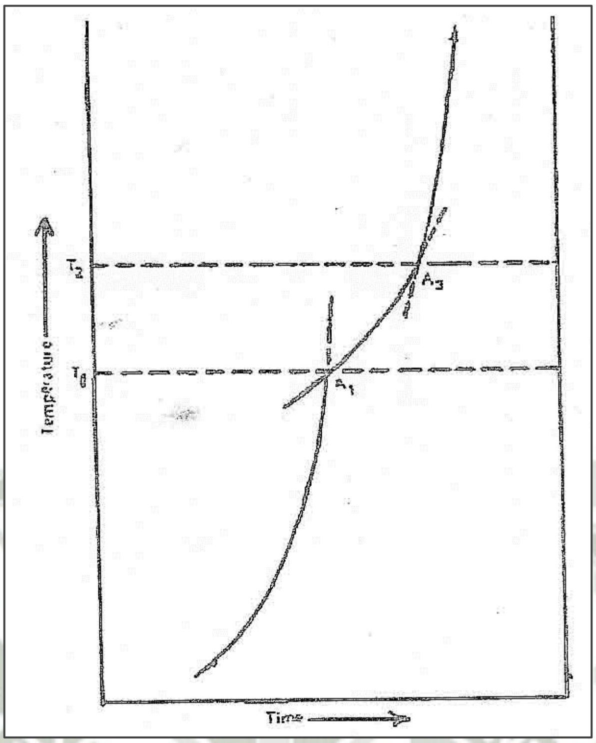


**Figura N° 2.8.**
**Curva del calentamiento de un acero hipoeutectoide**

La formación de perlita a partir de la austenita es un proceso de nucleación y crecimiento. Como en todo proceso de nucleación, se requiere cierto tiempo para que los átomos tengan la energía suficiente y así efectuar el proceso de crecimiento. Al empezar a empujar una rueda en una superficie, se requiere de una energía extra, por algunos segundos, para ponerla en movimiento, pero una vez que empezó a moverse no es difícil mantenerla en esa condición. De manera similar sucede en la formación de la perlita, la energía extra viene siendo un sobreenfriamiento por debajo de la temperatura crítica A1.

Con el siguiente experimento se puede mostrar el fenómeno de la formación de la perlita en un acero eutectoide. Del diagrama de fases hierro-carburo de hierro se observa que la transformación completa del acero eutectoide a austenita es a los 725°C, sin embargo para asegurar que todas las partes del metal estén arriba de $Ac_1$, las probetas se calentaran hasta 760°C y rápidamente se ponen en un baño de sales fundidas a 875°C. Después de medio segundo se saca una probeta, a un segundo la segunda, a dos segundos la tercera y las otras a 4, 8, 16, 32, 63, 125, 250, 500 y 1000 segundos, y éstas son enfriadas inmediatamente en agua fría. Las probetas se examinan metalográficamente para determinar, el tiempo necesario para nuclear la perlita y el tiempo necesario para completar la formación de la perlita.

En la Fig. N° 2.8 se observa la microestructura de las muestras examinadas, que no revelan perlita en los primeros segundos, pero en los subsiguientes, se ve un aumento en la cantidad de perlita. En la última probeta toda la microestructura es perlita. Posteriormente en una segunda y tercera serie de probetas, son colocadas en baños de sales fundidas a temperaturas de 620°C y 565°C; respectivamente y se aplica el mismo procedimiento. Estas probetas se examinan para determinar el inicio y el final de la transformación a perlita. De los datos obtenidos en la Fig. N° 2.8 se obtiene la gráfica de la Fig. N° 2.9.

En la gráfica de la Fig. N° 2.9, se observa cuanto tiempo es necesario para iniciar y completar la formación de la perlita a cada temperatura.

La línea $P_s$ indica el tiempo que se necesita para que inicie la formación de la perlita y la línea $P_f$ indica cuando toda la austenita ha sido transformada a perlita.

La perlita formada a 585°C es perlita fina, es decir el espaciamiento entre las capas alternadas de ferrita y cementita es pequeño. Las probetas que se mantuvieron a temperaturas altas producen perlita mucho más gruesa.

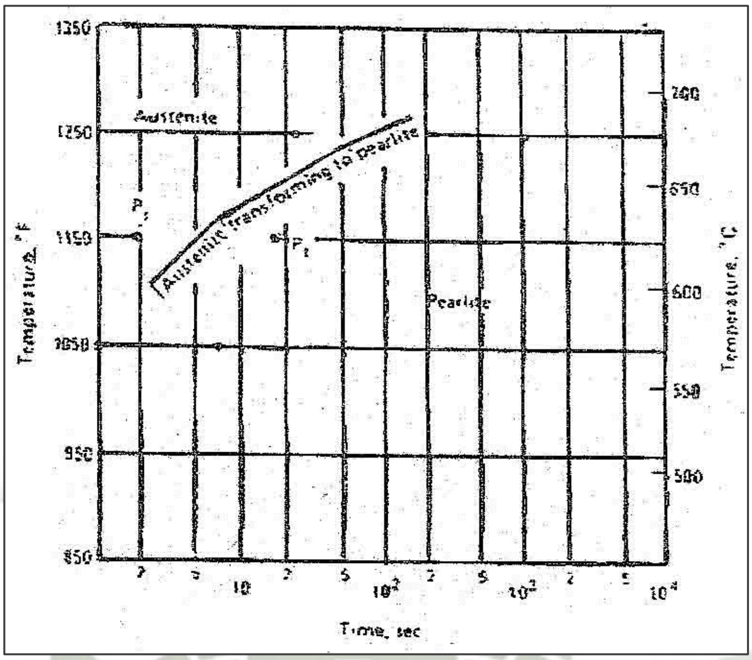


**Figura N° 2.9.**
**Tiempos de transformación- descomposición de la austenita**

En el diagrama de fases hierro-cementita se observa que a 725°C la probeta tiene una micro estructura austenítica en condiciones de equilibrio. Cuando la pieza se enfría por debajo de 725°C, la austenita tiene una alta inercia para cambiar a perlita. Sin embargo la facilidad con la cual la austenita puede transformarse a perlita viene cada vez a menos conforme es más baja la temperatura. Hay que recordar que al aumentar la temperatura se incrementa la velocidad de reacción, y al bajar la temperatura se reduce la velocidad de reacción. La mayor cantidad de austenita que sea enfriada por debajo de 725°C, los átomos de carbono se moverán con más dificultad. Esto es, hay dos formas opositoras durante la transformación de la austenita. Una es el incremento de inercia de la austenita para transformarse en perlita (nucleación). La otra es el decremento de la habilidad de la austenita para transformarse, a temperaturas por debajo de la temperatura critica, y decremento en la movilidad de los átomos de carbono, es decir velocidad de crecimiento bajo.

En la Fig. N° 2.9 se observa que a la temperatura ele 675°C la austenita no tiene prisa en transformarse, por otra parte, la temperatura es lo suficientemente alta para permitir una fácil difusión en los átomos de carbono y después de un tiempo suficientemente grande la transformación será completa, formándose perlita gruesa. La difusión de los átomos de carbono es más difícil a 565°C, la tendencia de la austenita para transformarse es suficientemente alta, pero como los átomos de carbono no se pueden mover fácilmente, por lo tanto la perlita formada es extremadamente fina.

### 2.6.1 BAINITA

El proceso que permite a la austenita transformarse isotérmicamente puede ser llevado hasta temperaturas más bajas de 565°C. A bajas temperaturas sin embargo la inercia de la austenita para transformarse y la poca movilidad de los átomos de carbono, hace que no se transforme a perlita, en lugar de esta transformación se obtiene otro producto que se llama Bainita.

Dependiendo de la temperatura de formación, esta micro estructura varía desde una mezcla fina de ferrita y cementita hasta agujas no visibles de ferrita y cementita.

En la Fig. N° 1.10.a, b, c, el lado izquierdo de la curva debajo de la rodilla, indica el inicio de la formación de la bainita y el lado derecho indica el final de transformación. La temperatura a la cual se forma este micro estructura es entre 525 y 275°C, para el acero eutectoide.

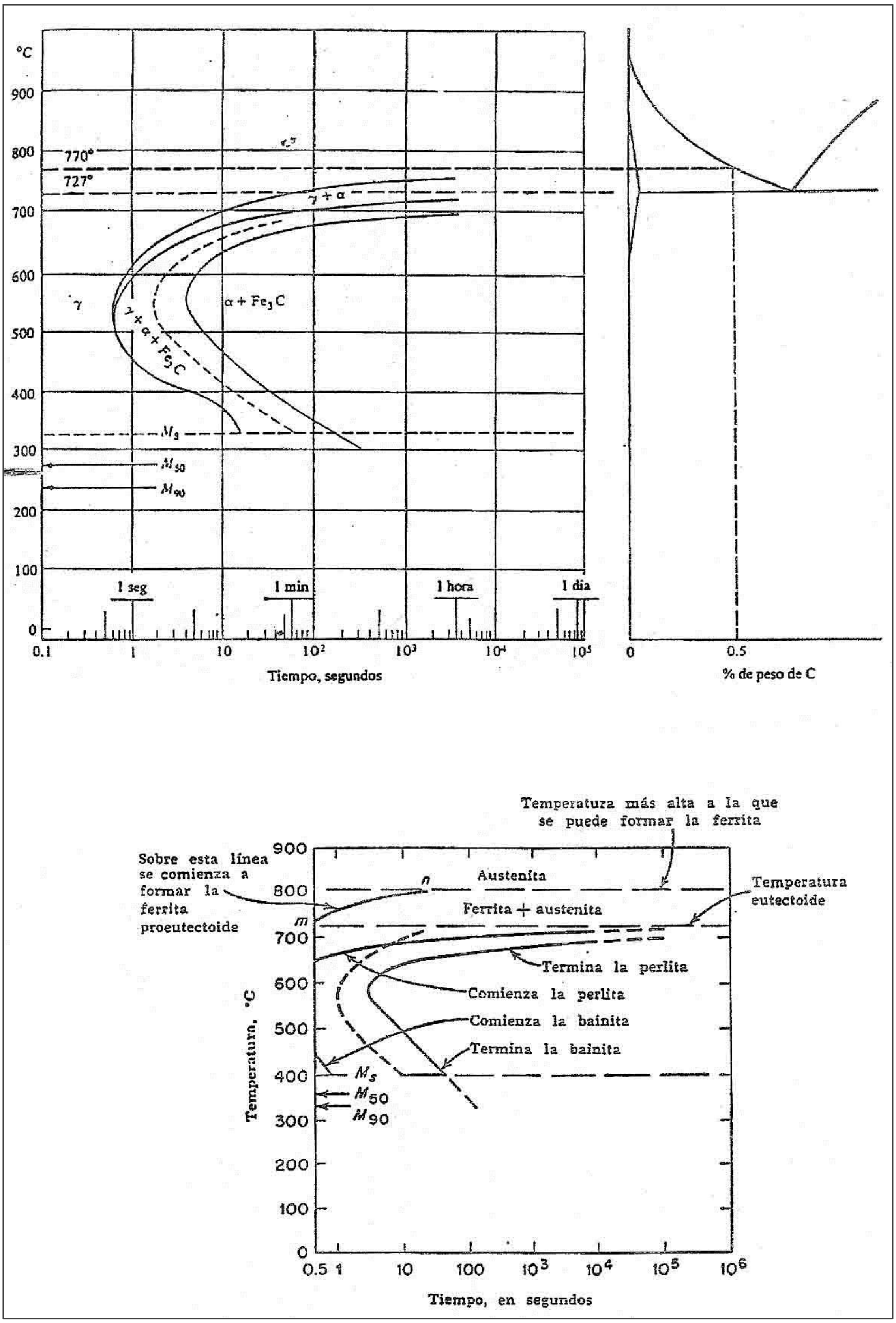


**Figura Nº 2.10.a.**
**Diagrama de transformación isotérmica para un acero hipoeutectoide**

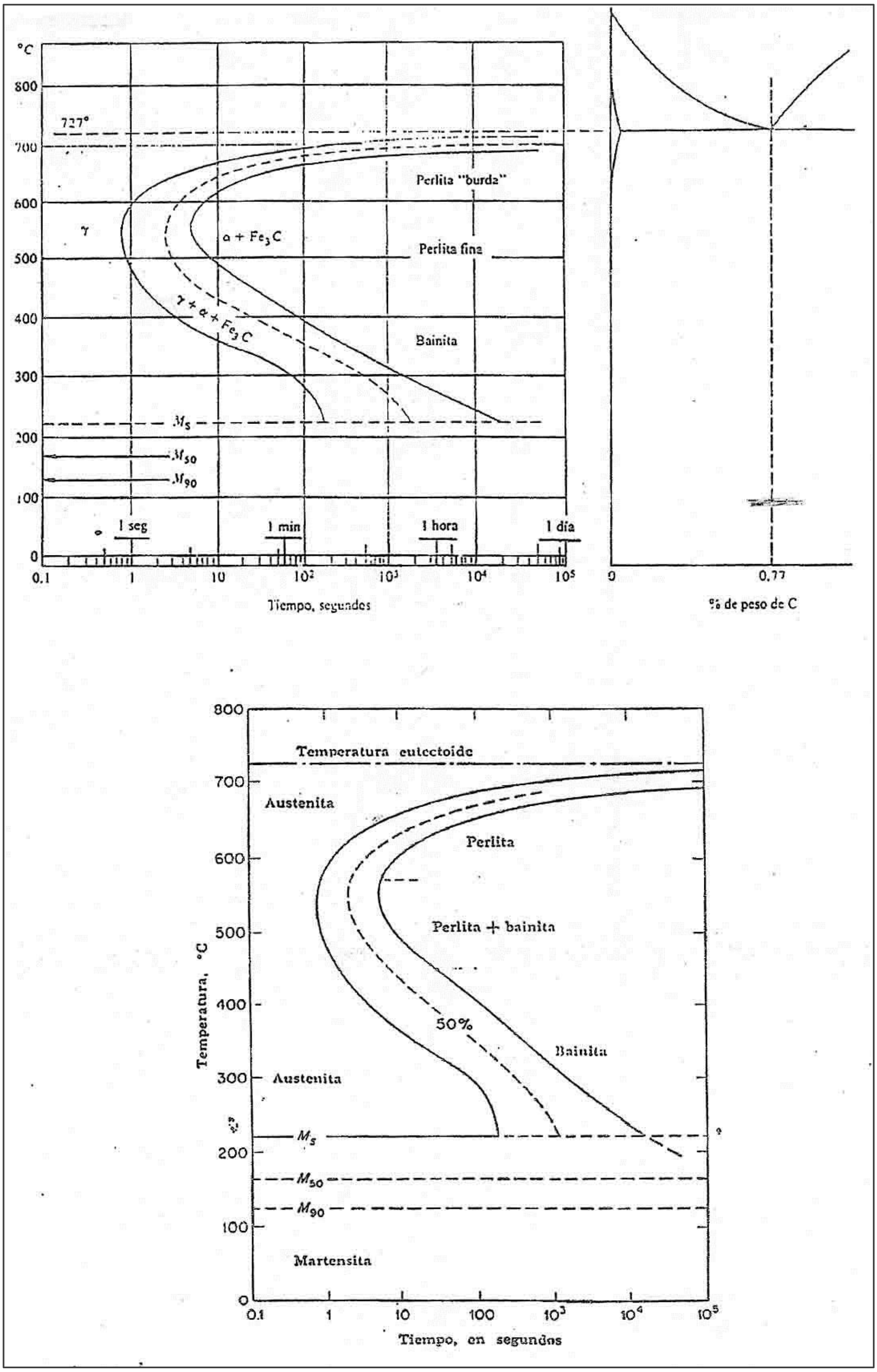


**Figura Nº 2.10.b.**
**Diagrama de Transformación Isotérmica para un acero eutectoide.**

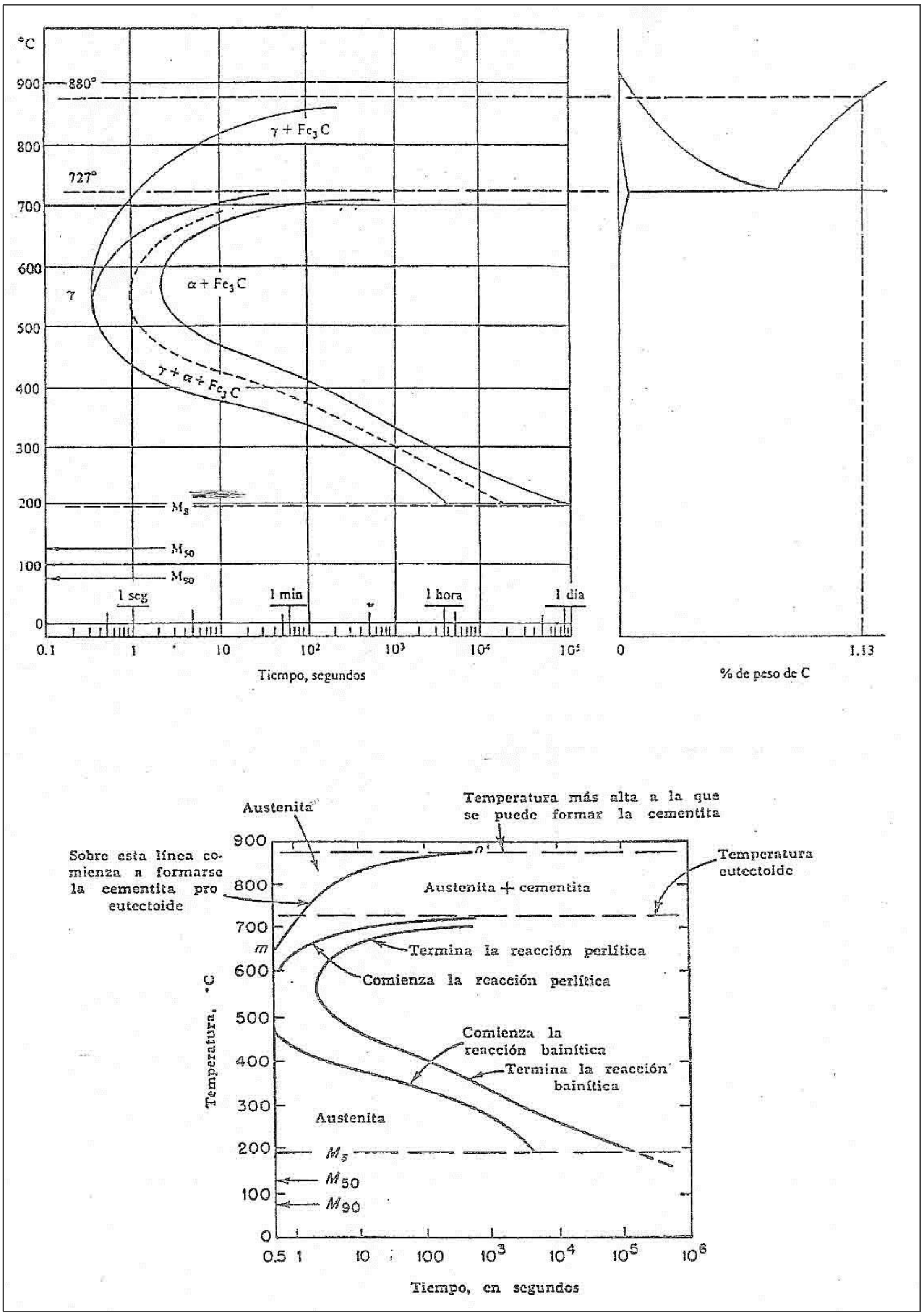


**Figura Nº 2.10.c.**
**Diagrama de Transformación isotérmica para un acero hipereutectoide.**

### 2.6.2 MARTENSITA

Enfriamiento a temperaturas por debajo de 275°C, se obtiene otro producto de transformación que se llama martensita. La estructura es muy similar a la de la bainita formada a bajas temperaturas. Esto es, tiene apariencia de agujas.

En la Fig. N° 2.11.a, b, c se observan las micro estructuras de la vainita superior e inferior y de la martensita. La Martensita es llamada martensita acicular, lo que significa aspecto de agujas.

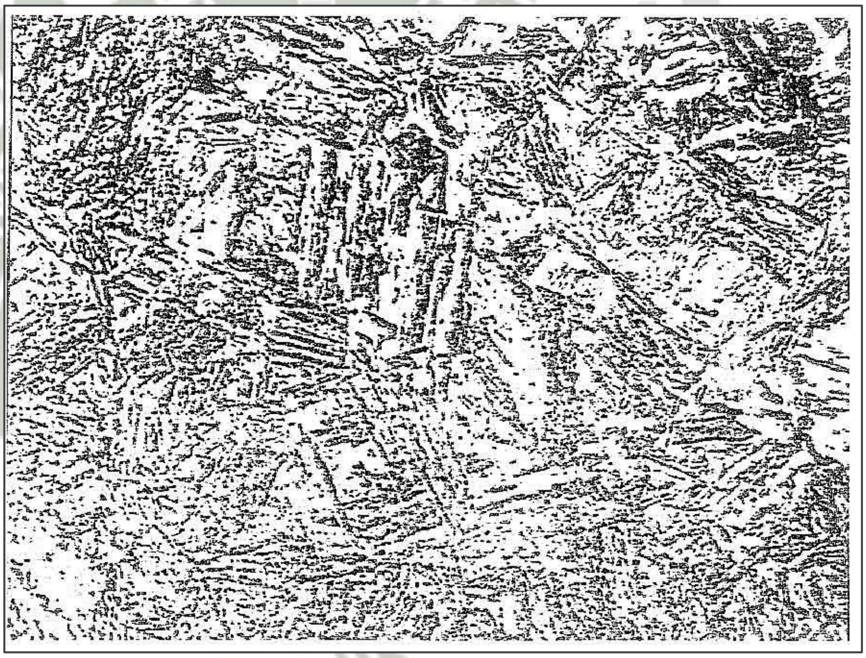


**Figura Nº 2.11.a.**
**Estructura de martensita a 750X**

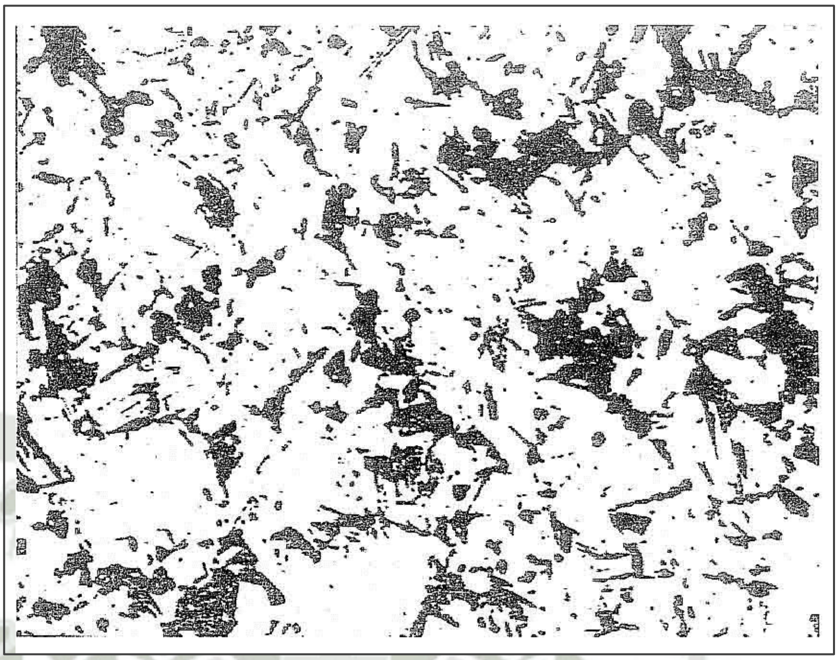


**Figura Nº 2.11.b.**
**Estructura de Bainita superior a 750X**

**Figura Nº 2.11.c.**
**Estructura de Bainita inferior a 750X**

Las curvas de transformación a rnartensita no pueden dibujarse ($M_s$ y $M_f$), porque la formación de la rnartensita no depende de un intervalo de tiempo a una temperatura dada, pero si comienza a formarse cuando se alcanza una temperatura definida. La transformación continúa hasta la línea $M_f$. Si el enfriamiento es interrumpido la transformación de la martensita también se interrumpe.

La curva mostrada en la Fig. N° 2.10.a, b, c, es llamada diagrama de transformación isotérmica, diagrama tiempo-temperatura-transformación, o simplemente curva TTT.

## 2.7 PROPIEDADES DE LOS ACEROS

Como se ha visto en las transformaciones del acero, la austenita se transforma a perlita gruesa, perlita fina o bainita, pero si el acero es hipoeutectoide, este puede contener ferrita con perlita, bainita o martensita.

En los aceros hipereutectoides, éstos contienen cementita con perlita, bainita o martensita.

Las propiedades de dureza, tenacidad, ductilidad y resistencia a la tensión, son dependientes del porcentaje de carbono y de los productos de transformación que contiene el acero.

Es posible obtener un amplio rango de dureza en el acero, mediante el control de la cantidad de ferrita, perlita, bainita, cementita y martensita obtenida. Cada fase contribuye a la dureza del acero. Esta contribución es proporcional a la cantidad de fase presente. La proporción de cada fase está relacionada con el porcentaje de carbono y el tratamiento térmico.

La dureza máxima alcanzada en el acero es función directa del porcentaje de carbono.

# CAPÍTULO III

# TRATAMIENTOS TÉRMICOS

Los tratamientos térmicos más usados son: el Recocido, Temple, Revenido Normalizado, Cementado, Nitrurado, Temple en baño de sales, Temple en baño de plomo, etc.

## 3.1 RECOCIDO

Con éste nombre se conocen varios tratamientos cuyo objetivo principal es ablandar el acero; otras veces también se desea además regenerar su estructura o eliminar tensiones internas. Consiste en calentar a temperaturas adecuadas, seguidos generalmente de enfriamientos lentos. Los diferentes tipos de recocido que se emplean en la industria se pueden clasificar en tres grupos: recocidos con austenización completa, recocidos subcriticos y recocidos con austenización incompleta. Fig. N° 3.1.

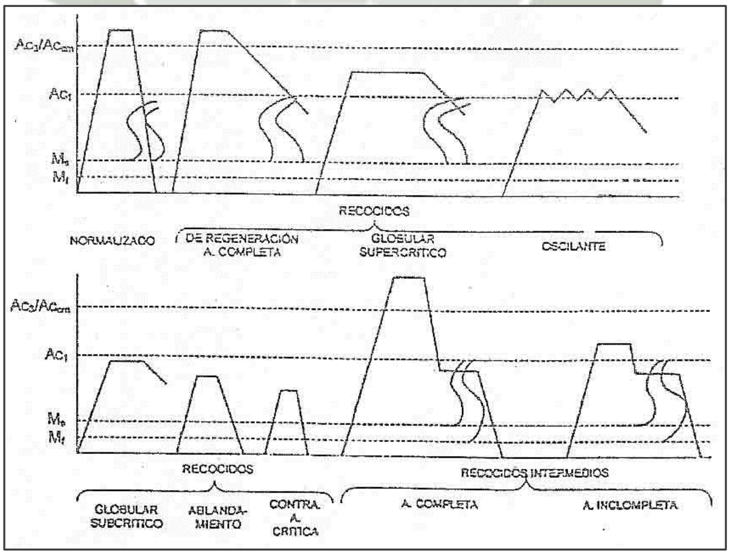


**Figura N° 3.1.**
**Recocido y normalizado**

### 3.1.1 RECOCIDO DE AUSTENIZACION COMPLETA

En este caso el calentamiento se hace a una temperatura ligeramente más elevada que la crítica superior y luego el material se enfría muy lentamente. Sirve para ablandar y regenerar su estructura. Tabla N° 3.1.

**Tabla N° 3.1.**

**Temperatura recomendable para el recocido de regeneración de los aceros al carbono**

| Composición % de C | Austenización completa °C | Composición % de C | Austenización completa °C |
|---|---|---|---|
| 0.10 | 910° | 0.70 | 775° |
| 0.20 | 980° | 0.80 | 760° |
| 0.30 | 860° | 0.90 | 760° |
| 0.40 | 840° | 1.00 | 825° |
| 0.50 | 820° | 1.10 | 860° |
| 0.60 | 800° | 1.20 | 900° |

Fuente: Apraiz Barrero, Madrid 1961

### 3.1.2 RECOCIDO SUBCRITICO

El calentamiento se hace por debajo de la temperatura critica inferior, no teniendo tanta importancia como en el caso anterior la velocidad de enfriamiento, pudiendo incluso enfriarse el acero al aire sin que se endurezca. Por medio de este tratamiento se eliminan las tensiones del material y se aumenta su ductilidad.

Se puede distinguir tres clases de reconocidos subcríticos: de ablandamiento, contra acritud y globular.

### 3.1.3 RECOCIDO DE ABLANDAMIENTO

Su principal objetivo es ablandar el acero por un procedimiento rápido y económico. Con este tratamiento no se suelen obtener las menores durezas, pero e muchos casos las que se consiguen son suficientes para mecanizar fácilmente las piezas. El proceso consiste en calentar el acero hasta una temperatura, que siendo inferior a la crítica Ac1, sea lo más elevada posible y enfriar luego al aire. Las durezas que se obtienen en ciertos aceros de herramientas y de construcción de alta aleación de éste tratamiento, suelen ser algunas veces demasiado elevadas para el mecanizado.

### 3.1.4 RECOCIDO CONTRA ACRITUD

Se efectúa a temperaturas de 550 a 650°C, y tiene por objeto aumentar la ductilidad de los aceros de poco contenido de carbono (menos de 0.40%) estirados en frío. Con el calentamiento a esa temperatura se destruye la cristalización alargada de la ferrita, apareciendo nuevos cristales poliédricos más dúctiles que los primitivos, que permiten estirar o laminar nuevamente el material sin dificultad. El enfriamiento se suele hacer al aire.

### 3.1.5 RECOCIDO SUBCRITICO GLOBULAR

En ocasiones para obtener en los aceros al carbono y de baja aleación una estructura globular de baja dureza, en cierto modo parecida a la que se obtiene en el recocido globular de austenización incompleta, se le somete a los aceros a un calentamiento a temperaturas inferiores pero muy próximas a la crítica $Ac_1$, debiendo luego enfriarse el acero lentamente en el horno.

### 3.1.6 RECOCIDO DE AUSTENIZACION INCOMPLETA

Son tratamientos que se suelen dar a los aceros al carbono o aleados, de más de 0.50% de carbono, para ablandarlos y mejorar su maquinabilidad. Consisten en calentamientos prolongados a temperaturas intermedias entre la crítica superior y la inferior, seguidos siempre de un enfriamiento lento. El fin que se persigue con estos recocidos es obtener la menor dureza posible y una estructura microscópica favorable para el mecanizado de las piezas. Por medio de estos tratamientos se consigue con bastante facilidad en los aceros hipereutectoides que la cementita y los carburos de aleación adopten una disposición más o menos globular que da para cada composición una dureza muy inferior a cualquier otra micro estructura, incluso la perlita laminar.

Algunas veces se hace el recocido empleando un ciclo oscilante de temperaturas que son unas veces superiores y otras inferiores a $Ac_1$ Otras veces (que suelen ser la mayoría) se emplean temperaturas ligeramente superiores a $Ac_1$. Al primero de estos tratamientos se le suele llamar recocido globular oscilante y el segundo se le llama recocido globular de austenización globular incompleta.

## 3.2 NORMALIZADO

Este tratamiento consiste en un calentamiento a temperatura ligeramente más elevada que la crítica superior, seguido de un enfriamiento en aire tranquilo. De esta forma, se deja el acero con una estructura y propiedades que arbitrariamente se consideran como normales y características de su composición. Se suele utilizar para piezas que han sufrido trabajos en caliente, trabajos en frió, enfriamientos irregulares o sobrecalentamientos, y también sirve para corregir los efectos de un tratamiento anterior defectuoso.

Por medio del normalizado, se eliminan las tensiones internas y se uniformiza el tamaño de grano del acero. Se emplea casi exclusivamente para los aceros de construcción al carbono o de baja aleación.

## 3.3 TEMPLE

El temple tiene por objeto endurecer y aumentar la resistencia de los aceros. Para ello, se calienta en general a una temperatura ligeramente más elevada que la crítica superior y se enfría rápidamente (según la composición y el tamaño de la pieza) en un medio conveniente, agua, aceite, etc. Fig. N° 3.2.

El temple es un proceso de calentamiento y enfriamiento realizado a una velocidad mínima denominado crítica, el fin es transformar la austenita en martensita.
En la práctica no toda la austenita se transforma en martensita ya que es imposible conseguir una velocidad de enfriamiento lo suficientemente rápida en piezas grandes y en otros no interesa tener martensita sino otras como la vainita, el temple abarca tres etapas:

### A. PRIMERA ETAPA: CALENTAMIENTO

Para activar el proceso, es necesario alcanzar la temperatura de austenización por tanto se deberán calentar las piezas por encima de $Ac_3$ y $Ac_1$ o $A_{cm}$.

### B. SEGUNDA ETAPA: PERMANENCIA

Es necesario permanecer a la temperatura de austenización, hasta que toda la masa sea austenita homogénea, su valor es función del espesor de la pieza, de la temperatura de calentamiento y de la composición del acero. Fig. N° 3.2.

### C. TERCERA ETAPA: ENFRIAMIENTO

Se caracteriza por la velocidad de enfriamiento y se clasifica en:

- Lentos Ve < 50°C / seg. se originan estructuras estables.
- Intermedios 50 < Ve < 250°C /seg., se origina sorbita de temple.
- Rápidos 250 < Ve < 500°C /seg., se originan mezclas de troostita y martensita.
- Muy rápido Ve > 500°C /seg. Se obtiene martensita.

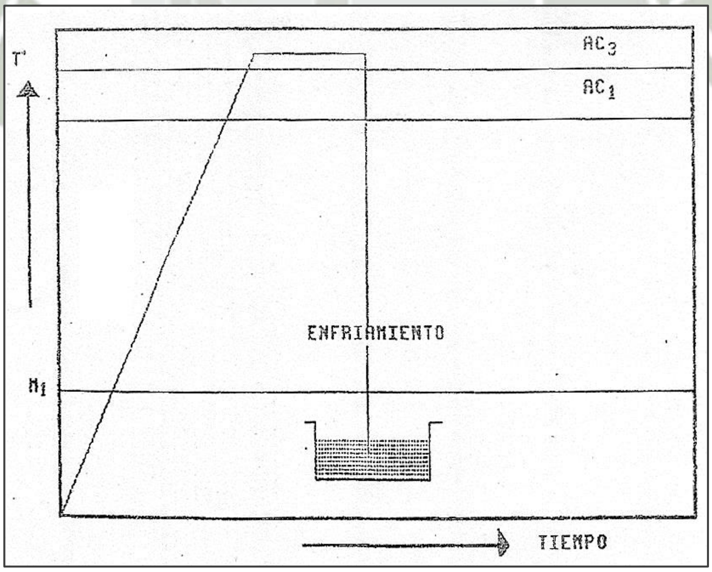


**Figura Nº 3.2.**
**Representación de un temple ordinario**

### 3.3.1 FACTORES QUE INFLUYEN EN EL TEMPLE

#### A. EL TAMAÑO DE LA PIEZA

En los perfiles delgados tanto en el calentamiento como en el enfriamiento se observa muy poca diferencia de temperatura entre la periferia y el interior de las muestras.

En muestras de gran de gran espesor o gran diámetro la temperatura en el interior es inferior en el calentamiento y superior en el enfriamiento a la de su periferia ya que el calor no se transmite directamente al interior sino a través del espesor de la muestra por tanto en el calentamiento es necesario aumentar la duración del proceso hasta una temperatura determinada.

#### B. INFLUENCIA DE LA COMPOSICIÓN

El contenido del carbono del acero influye a la vez en la temperatura y en la velocidad crítica del temple, la temperatura del temple es tanto más baja cuanto más se aproxima el acero a la composición eutectoide.

La velocidad crítica de temple disminuye cuando el contenido de carbono aumenta, para las mismas condiciones de enfriamiento el temple obtenido es más energético y la dureza de los aceros al carbono templados, es mayor cuanto más alto es su porcentaje de carbono.

#### C. INFLUENCIA DEL TAMAÑO DE GRANO

El tamaño de grano influye, principalmente en la velocidad crítica de temple. A igualdad de composición, las velocidades críticas de temple de los acero de grano grueso son inferiores a las velocidades críticas de los aceros de grano fino.

### D. INFLUENCIA DEL MEDIO DE ENFRIAMIENTO

Al sumergir una barra de acero a aita temperatura en un líquido, tiene lugar las siguientes etapas:

**Primera etapa**: ES enfriamiento se produce por conducción y radiación a través de la capa gaseosa.

**Segunda etapa**: El enfriamiento se produce por transporte de vapor.

**Tercera etapa**: El enfriamiento se produce por conducción y convección del líquido.

Los temples pueden ser austenización completa y de austenización incompleta, en los primeros el constituyente final del acero es martensita y en los segundos los componentes son martensita y cementita.

## 3.4 REVENIDO

Es un tratamiento que se da a las piezas de acero que han sido previamente templadas.

Con este tratamiento, que consiste en un calentamiento a temperatura inferior a la crítica $Ac_1$, se disminuye la dureza y resistencia de los aceros templados, se eliminan las tensiones creadas en el temple y se mejora su tenacidad, quedando el acero con la dureza o resistencia deseada.

No interesa prolongar la duración del revenido más de una hora, pues no se obtiene beneficios apreciables que compensen el costo.

### 3.4.1 ETAPAS DEL PROCESO DE REVENIDO

Existen cuatro etapas fundamentales:

**A. PRIMERA ETAPA de 100 a 200 °C**

- Diminución del porcentaje de carbono en la martensita.
- Pérdida parcial de tetragonalidad de la martensita.
- Las agujas de martensita después del temple es de color claro.
- Las agujas de martensita después del revenido es de color oscuro.
- La martensita formada en aceros de 0.3 a 1.5%C no es estable a temperatura ambiente.

**B. SEGUNDA ETAPA DE 200 A 300°C**

- Descomposición de la austenita retenida en vainita, ferrita y cementita.
- En aceros de 0.5%C la austenita retenida es < a dos 2%.
- En aceros de 0.8%C la austenita retenida es de 6%.
- En aceros de 1.25%C la austenita retenida es de 30%.

**C. TERCERA ETAPA DE 300 A 350 °C**

- Reemplazo de carburo por la cementita.
- Pérdida de la tetragonalidad de la martensita.
- La cementita aparece como la estructura de widmanstetten.
- La cementita se esferoidiza en los límites de grano.
- Hay desaparición de tetragonalidad de la matriz, quedando una matriz ferrítica.

**D. CUARTA ETAPA POR ENCIMA DE 350°C**

- Granulación y esferoidización de la cementita a 300 y 400 °C.
- Recuperación y recristalización de la ferrita.
- A los 700 °C los listones martensiticos son reemplazados por límites de granos ferríticos, mediante el proceso de recristalización.
- Finalmente, quedan granos ferríticos equiaxiales con partículas esferoidizadas de cementita parcialmente precipitados en los bordes de grano.

## 3.5 BONIFICADO O MEJORADO

### 3.5.1 TRATAMIENTO ISOTERMICO DE LOS ACEROS

Reciben este nombre ciertos tratamientos, en los que el enfriamiento de las piezas no se hacen de una forma regular y progresiva, sino que se interrumpe o modifica a diversas temperaturas durante ciertos intervalos, en los que permanece el material a temperatura constante durante un tiempo, que depende de la composición del acero, de la masa de las piezas y de los resultados que se quieren obtener.

Después de los estudios realizados sobre la curva "S" de los aceros, se han desarrollado éstos tratamientos, que se usan en la actualidad para el temple de los troqueles, herramientas, engranajes, muelles, etc. Se obtiene de esta forma una gran tenacidad, pequeñas deformaciones y se elimina de ésta ciase, que recibe el nombre de recocido isotérmico, para el ablandamiento de los aceros.

### 3.5.2 AUSTEMPERING

Este tratamiento consiste en calentar el acero a una temperatura ligeramente más elevada que la crítica superior y luego enfriarlo rápidamente en plomo o sales fundidas, a temperaturas comprendidas entre 250 y 600°C, permaneciendo el acero en el baño a ésta temperatura durante el tiempo suficiente para que se verifique la transformación completa de la austenita en otros constituyentes a temperatura constante. Fig. N° 3.3.

Un tratamiento de esta ciase, denominado "patenting", se aplica desde hace mucho tiempo para la fabricación de alambres de alta resistencia, que se conocen generalmente con el nombre de "cuerda de piano". En este caso el enfriamiento se suele hacer en baño de plomo, quedando el acero con una tenacidad y ductilidad excepcionales.

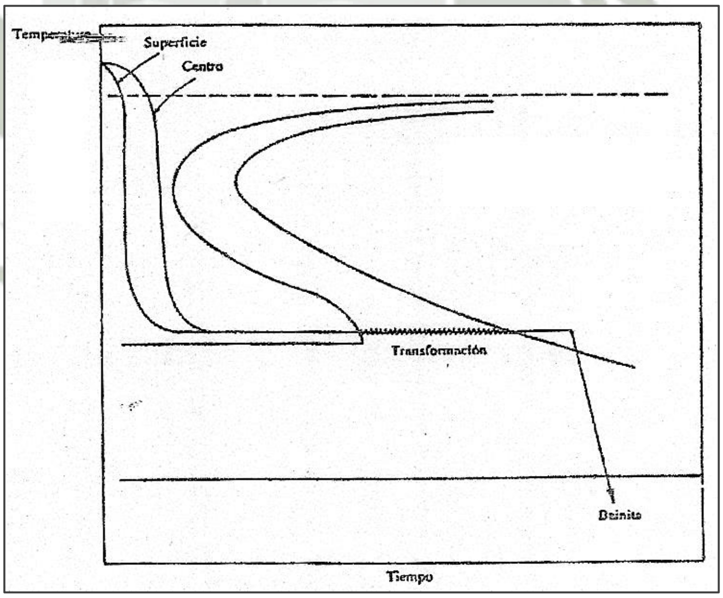


**Figura N° 3.3.**
**Austempering**

### 3.5.3 MARTEMPERING

Es un tratamiento que ha comenzado a desarrollarse también recientemente. Es un temple escalonado en el que el material caliente, a una temperatura ligeramente más elevada que la crítica superior, se enfría en un baño de sales, también caliente, a temperaturas comprendidas entre 200 y 400 °C, permaneciendo las piezas en el baño, durante un tiempo que debe controlarse cuidadosamente y que debe ser suficiente para que iguale la temperatura en toda la masa, antes de que en ninguna parte de ella se inicie la transformación de la austenita, y luego se enfría al aire. De esta forma se consigue que la transformación de toda la masa del acero se verifique casi al mismo tiempo, evitándose desiguales y peligrosas dilataciones que ocurren en los temples ordinarios, en los que las transformaciones de las distintas zonas del material ocurren en momentos diferentes. Fig. N° 3.4.

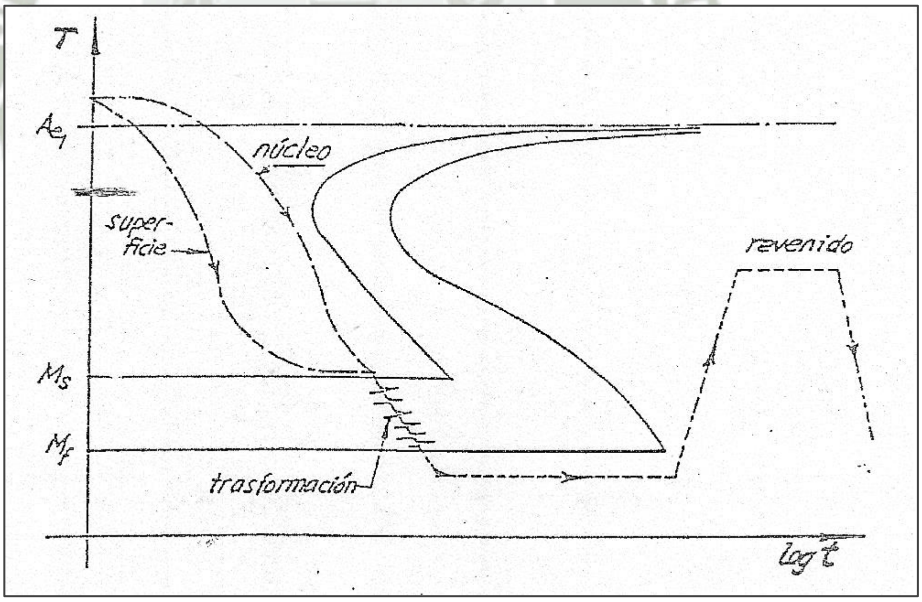


**Figura Nº 3.4.**
**Recocido isotérmico en el Diagrama TTT**

### 3.5.4 RECOCIDOS ISOTÉRMICOS

Son tratamientos de ablandamiento que consisten en calentar el acero por encima de la temperatura critica superior o inferior según los caso (generalmente de 470 a 880 °C) y luego enfriar hasta una temperatura de 600 a 700 °C, manteniéndose constante durante varias horas, para conseguir la completa transformación isotérmica de la austenita, y finalmente se enfría al aire. Este enfriamiento es rápido y se obtienen durezas muy bajas. El calentamiento se suele hacer con austenización completa en los aceros hipoeutectoides y austenización incompleta en los aceros hipereutectoides. En cierto modo estos tratamientos pueden considerarse como casos particulares de los recocidos de austenización completa e incompleta. Fig. N° 3.5.

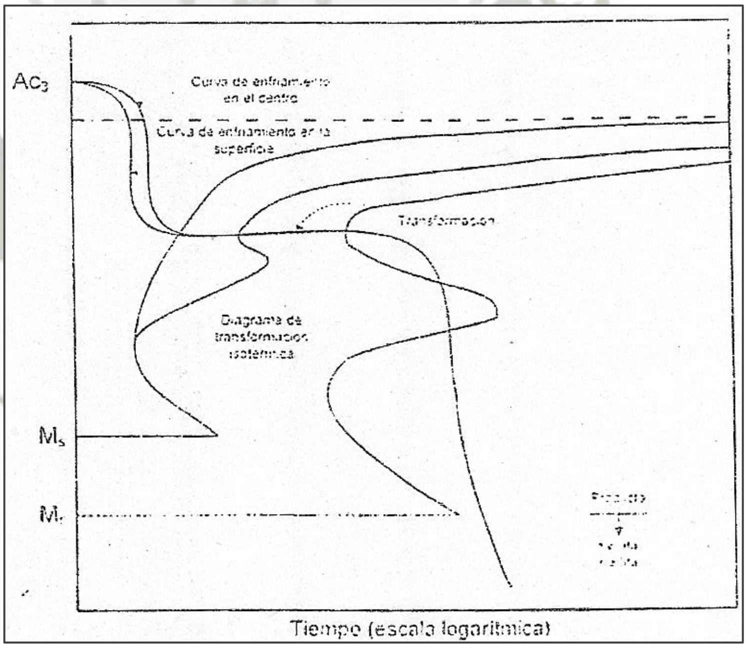


**Figura N° 3.5.**
**Recocido isotérmico en el Diagrama TTT**

## 3.6 TEMPLE SUPERFICIAL

Se ha desarrollado éste procedimiento en el que se endurece únicamente la capa superficial de las piezas. El calentamiento se puede hacer por llama o por corrientes inducidas de alta frecuencia, pudiéndose regular en ambos casos perfectamente la profundidad del calentamiento y con ello la penetración de la dureza. Una vez conseguida la temperatura de temple, se enfría generalmente en agua.

## 3.7 TRATAMIENTOS TERMOQUÍMICOS

En esta clase de tratamientos, además de considerar el tiempo y la temperatura como factores fundamentales, hay que tener también en cuenta el medio o atmósfera que envuelve el metal durante el calentamiento y enfriamiento. Estos tratamientos se suelen utilizar para obtener piezas que deben tener gran dureza superficial para resistir el desgaste y buena tenacidad en el núcleo. Los tratamientos pertenecientes a este grupo son: Cementación, Cianuración, Sulfinización y Nitruración.

### 3.7.1 CEMENTACIÓN

Por medio de este tratamiento se modifica la composición de las piezas, aumentando el, contenido en carbono de la superficie, obteniéndose después, por medio de temple y revenido, una gran dureza superficial.

### 3.7.2 CIANURACIÓN

Es un tratamiento parecido a la cementación, en el que el acero absorbe carbono y nitrógeno en la zona superficial, quedando luego esa zona periférica muy dura después de un temple final.

### 3.7.3 SULFINIZACIÓN

Es un tratamiento que se da a los aceros a 565°C aproximadamente en baño de sales de composición especial y que se mejora extraordinariamente la resistencia al desgaste. Esa mejora se consigue por la incorporación de azufre a la superficie de las piezas de acero sin que ello aumente mucho la dureza.

### 3.7.4 NITRURACIÓN

Es un tratamiento de endurecimiento superficial a baja temperatura, en el que las piezas de acero templadas y revenidas, al ser calentadas a 500°C en contacto con una corriente de amoniaco, se introduce en la caja de nitrurar, absorben nitrógeno, formándose en la capa superficial nitruros de gran dureza, quedando las piezas muy duras sin necesidad de ningún otro tratamiento posterior.

## 3.8 OBJETIVO DE LOS TRATAMIENTOS TÉRMICOS.

El tratamiento térmico del acero es generalmente aplicado para Segar alguno de los siguientes objetivos:

- Eliminar esfuerzos inducidos por el trabajo en frio o por enfriamiento no uniforme de metales calientes.
- Refinar el tamaño de grano de aceros trabajados en caliente, los cuales pudieron haber incrementado el tamaño de grano.
- Obtener una estructura de grano apropiado.
- Disminuir la dureza e incrementar la ductilidad.
- incrementar la tenacidad, esto es producir un acero que tenga ambos alta resistencia a la tensión y buena ductilidad, es decir alta resistencia al impacto.
- Mejorar la maquinabilidad.
- Mejorar las propiedades de corte en aceros de herramientas.
- Mejorar las propiedades eléctricas.
- Modificar las propiedades magnéticas.

# CAPITULO IV

# PROCEDIMIENTO EXPERIMENTAL

Se ha realizado el tratamiento térmico de bonificado o mejorado sobre muestras de acero de medio carbono C 45E-EN 10083, a fin de evaluar y optimizar el proceso para aceros fabricados y comercializados en el mercado nacional. Para lograr este propósito se han realizado pruebas de dureza, resiliencia, tracción y un detenido y exhaustivo ensayo metalográfico antes y después del bonificado dirigido a evaluar los cambios microestructurales producidos con el bonificado.

**Figura 4.1.**
**Laboratorio de ensayo materiales - UCSM**

## 4.1 HORNOS PARA TRATAMIENTO TÉRMICO

Los hornos para tratamientos térmicos varían en tamaño, diseño, modo de calentamiento, etc. Por lo tanto no es posible tener una clasificación precisa. Hay hornos en los cuales se usa un combustible y la carga está expuesta a los gases de la combustión, mientras que en otros la carga se calienta indirectamente, esto es la cámara de combustión está separada de la carga. Hay hornos que se calientan por resistencias eléctricas.

Los hornos para calentamiento industrial, clasifica los equipos en: estufas y hornos. Esta separación se hace en base de la temperatura de operación; si la temperatura de operación llega a 600 °C es una estufa, pero si la temperatura de operación es mayor de 600 °C, se llama horno.

Esta separación basada en la temperatura de operación es relacionada con el modo de calentamiento. Hay básicamente tres modos de transmisión de calor, que son: conducción, convección y radiación.

### A. CONDUCCIÓN

La conducción de calor en un sólido, es debido a la influencia de un gradiente de temperatura y sin apreciable desplazamiento de las partículas.

Si la temperatura de la superficie de una pieza es elevada, el calor fluye al centro de la misma por un mecanismo molecular. La conducción de calor involucra la transferencia de energía cinética de una molécula a otra en una reacción en cadena. El calor fluye continuamente hasta que se logra el equilibrio térmico.

El tiempo depende de la conductividad térmica del metal, pero en general la velocidad de conducción de calor en los metales es relativamente rápida.

En la mayoría de los procesos de tratamiento térmico la conducción de calor juega un papel mínimo en la transferencia de calor desde la fuente a la pieza de trabajo

Una excepción a la regla es: sales fundidas, metales fundidos y cama fluidizada, en estos el medio de calentamiento está en contacto directo con la superficie de la pieza.

### B. CONVECCIÓN

Involucra el calentamiento a través de un líquido o un gas. El movimiento del fluido puede ser debido a la diferencia de densidad ocasionada por la diferencia de temperatura a la cual se le llama convección natural o también puede producirse por medios mecánicos y se llama convección forzada.

En el revenido del acero es común la aplicación del calentamiento por convección.

### C. RADIACIÓN

Un cuerpo emite energía radiante en todas direcciones por medio de ondas electromagnéticas, el rango de longitud de onda varia de 4 a 7 micrómetros.

Cuando esta energía toca otro cuerpo, algo de la energía es absorbida e incrementa el nivel de actividad molecular, produciendo calor. Algo de la energía es reflejada, la cantidad de energía absorbida depende de la emisividad de la superficie de la pieza reflectora; si dos piezas de metal, una caliente y una fría, colocadas en una cámara aislada; la caliente se enfría y la fría se calienta. El intercambio de energía se lleva a efecto hasta que ambas piezas lleguen al equilibrio o sea, hasta que alcancen la misma temperatura. La transferencia de calor por radiación está relacionada directamente con la emisividad. La cual es igual a la razón de perdida de calor por unidad de área de la superficie de una temperatura dada a la razón de perdida de calor por unidad de área de un cuerpo negro a la misma temperatura. El significado práctico es que cuando la carga es colocada en el horno y expuesta a un calor radiante, su razón de calentamiento depende de la superficie; una pieza altamente reflejante (acero inoxidable pulido), absorbe menor cantidad de calor que una pieza oxidada.

Siendo los hornos más adecuados a los tratamientos térmicos: Hornos de sales fundidas, hornos de metales fundidos, hornos- de cama fluidizada, hornos de atmósfera controlada y hornos al vacío.

### 4.1.1 HORNOS DE SALES FUNDIDAS

Estos hornos tienen las siguientes ventajas:

- Hay sales disponibles para baja temperatura (175°C) y de alta temperatura (1260°C).
- Las piezas no se oxidan porque están protegidas por las sales fundidas.
- Una pequeña capa de sales fundidas permanece en la pieza durante la transferencia de calor en el enfriamiento, tal que el endurecimiento es favorecido.
- Una amplia variedad de sales están disponibles. Además, hay sales que cambian la composición química de la superficie del acero.

La principal desventaja de calentar piezas en sales fundidas es la necesidad de limpiar la pieza después del tratamiento térmico, pero esto es difícil en piezas de diseño complejo.

#### 4.1.1.1 TIPOS DE BAÑOS DE SALES FUNDIDAS

La forma más simple de baños de sales fundidas, es un crisol el cual puede ser calentado por medios eléctricos o mediante la combustión de un combustible. Las sales deben de ser de baja temperatura de fusión, por lo general ele 175° a 345°C. Al incrementarse la temperatura de fusión de las sales, es necesario equipo más sofisticado.

Si el calentamiento del horno es externo, tiene la desventaja de que el crisol que contiene las sales fundidas tiene la menor durabilidad al aumentar la temperatura de operación. Si el calentamiento es por medio de un combustible (gas o líquido), su temperatura de operación no es mayor de 900°C. La vida útil del crisol se puede incrementar si se utiliza un acero aleado al cromo - níquel.

Los hornos de baños de sales fundidas calientan por conducción y radiación, pero los de tipo de electrodos (inmersos y sumergidos), también calientan por convección.

Por tanto, la razón de calentamiento en este tipo de hornos es mucho mayor que en los hornos convencionales.

### 4.1.2 HORNOS DE METALES FUNDIDOS.

Este tipo de hornos ya son obsoletos por las siguientes razones:

- El plomo fundido es pesado por lo tanto las piezas de acero flotan.
- El plomo se adhiere al acero, el cual dificulta la acción de enfrentamiento y causa problemas de limpieza.

### 4.1.3 HORNOS DE CAMA FLUIDIZADA

En estos hornos de calentamiento del metal se lleva a efecto por medio de partículas móviles inertes, generalmente oxido de aluminio; estas partículas son suspendidas por los gases de la combustión de la mezcla aire - combustible que fluyen a través de la cama. Las piezas son inmersas en la cama fluid izada, y ésta actuara corno si fuera un líquido. Las piezas se calientan diez veces más rápido por este método comparándolo con un horno de calentamiento convencional.

Hay dos tipos de hornos de cama fluidizada:

- Los calentados internamente, se usan para altas temperaturas (760°a1215°C).
- Los calentados exteriormente, se usa para bajas temperaturas (<780°C).

### 4.1.4 HORNOS DE ATMOSFERA CONTROLADA.

La función principal de una atmosfera controlada, en el tratamiento térmico del acero, es asegurar el control de la composición química de la superficie.

Básicamente la atmosfera es requerida para lograr una o más de las siguientes funciones:

- Proteger la superficie del metal y prevenir del deterioro de la misma durante el tratamiento térmico. Es decir obtener un "endurecimiento limpio", por supuesto la atmosfera no solo se elimina la formación de óxido, sino que también previene la pérdida de carbono de la superficie de la pieza, debido a la reacción entre las fases metal- gas.

- Para limpiar la superficie del metal o prevenir manchado pos-oxidación, debido a superficies contaminadas.

- Para activar reacciones con la superficie del metal ya si mejorar propiedades químicas o físicas. Los procesos de carburizado, carbonitrurado y nitrurado son ejemplos donde el carbono y/o nitrógeno son tomados por el acero y lograr incrementar la dureza del acero.

### 4.1.4.1 TIPO DE ATMÓSFERA

Fundamentalmente, hay seis clases de gases usados en atmósferas controladas para el tratamiento térmico del acero.

En todos los casos, estos gases son generados fuera del horno, posteriormente son introducidos a la cámara.

Para lograr la protección se requiere condiciones muy cuidadosas de control. Pocas de estas atmósferas solamente son utilizadas para el tratamiento térmico de aceros para herramientas. Los tipos de atmósferas utilizadas son:

- Gas exotérmico
- Gas endotérmico
- Nitrógeno
- Amonta disociada
- Hidrogeno, helio y argón
- Atmosfera de vapor

**Figura N° 4.2.**
**Atmósferas Controladas**

### 4.1.5 HORNOS AL VACÍO.

En este tipo de hornos, el calentamiento es el vacío y representa un nuevo desarrollo en el campo de la metalurgia, pero en particular en los tratamientos térmicos. El tratamiento térmico al vacío puede ser utilizado en:

- Prevenir reacciones en la superficie de trabajo de la pieza, como lo es la oxidación o decarburación.
- Quitar contaminantes superficiales, como son las películas de óxidos.
- Agregar .sustancias en la superficie de trabajo, como es el carburizado, el nitrurado, etc.
- Eliminar sustancias contaminantes de los metates mediante, el efecto desgasificante del vacío; para eliminar el oxígeno hidrogeno, etc.

Los tratamientos térmicos en hornos al vacío son: templado, revenido, recocido y alivio de esfuerzos.

En los hornos al vacío, conseguir un vacío completo es virtualmente imposible.

**Figura N° 4.3.**
**Hornos al Vacío**

## 4.2 MEDIOS DE ENFRIAMIENTO

Muchos medios de enfriamiento pueden ser usados para obtener resultados específicos según el tratamiento térmico. Muchos de ellos están incluidos en la siguiente lista:

- Agua
- Salmuera
- Soluciones cáusticas
- Aceites
- Sales fundidas
- Metales fundidos

- Aire
- Gases
- Horno

## 4.3 MATERIALES

- **Materias y Equipo**

  Se hará mención al material de estudio y a los equipos que se utilizó para realizar las pruebas.

- **Material**

  Acero C 45E-EN 10083

Las características que se han tomado de las muestras son:

### A. Composición Química

**Tabla Nº 4.1.**

**Composición Química**

| Elemento | % |
|---|---|
| C | 0.45 |
| Si | 0.22 |
| Mn | 0.75 |
| P | 0.04 |
| S | 0.05 |

Fuente: Talleres Córdova.-Arequipa 2013

### B. Dimensiones

El dimensionamiento de las muestras para el temple, revenido y ensayo de dureza es de 2.0 cm x 2.0 cm.

Reactivos y materiales consumibles

**a) Reactivos**

- ✓ Para ataque químico: Nital al 2%
- ✓ Para encapsular: Resina epóxico o dental

**b) Materiales Consumibles**

- ✓ Material de corte: sierra, disco abrasivo.
- ✓ Material de desbaste y pulido: lijas # 220, 280, 400, 600, 1000
- ✓ Alúmina: 1 micrón, 5.5 micrón.
- ✓ Materiales para ataque químico: alcohol, algodón.
- ✓ Materiales para microfotografías.
- ✓ Material Para Tratamiento Térmico: Aceite SHELL SAE 40.
- ✓ Material para desengrase: Gasolina, NaOH.

Equipos e Instrumentos:

**A) Equipos**

- ✓ Máquina de corte muestras
- ✓ Horno: Tipo mufla para tratamiento térmico con calentamiento con resistencia eléctrica con control de temperatura automático.
- ✓ Microscopio: Metalograftas Metaval
- ✓ Durómetro: Rockwell B
- ✓ Devastadora: Metasinex 20V.3.3A.60 H2.
- ✓ Pulidora rotativa: 220v. 1. 9a. 1. 9A. 60Hz.
- ✓ Termopares
- ✓ Máquina Universal de ensayos (Tracción)
- ✓ Péndulo de Charpy

**B) Instrumentos**

- ✓ Tenazas.
- ✓ Cubas.

## 4.4 DISEÑO EXPERIMENTAL DE LAS PRUEBAS

El diseño estadístico de experimentos significa planificar la realización de una serie de pruebas en los cuales se induce cambios deliberadamente en las variables independientes de tal manera que nos permita observar e identificar las causas de los cambios en la variable dependiente o variable respuesta.

Las variables o factores que presentan mayor efecto en el tratamiento térmico de temple y revenido son:

- Velocidad de calentamiento
- Temperatura de permanencia a la temperatura de temple
- Velocidad de enfriamiento
- Temperatura de revenido
- Composición química de la muestra

Para el presente trabajo solamente consideramos las siguientes variables:

### A. VARIABLES INDEPENDIENTES

- Temperatura de temple
- Tiempo de permanencia a la temperatura de temple
- Temperatura de revenido

### B. VARIABLE DEPENDIENTE (RESPUESTA)

- Dureza

### C. SELECCIÓN DEL TAMAÑO DE LA MUESTRA

La ejecución de un experimento demanda tiempo, disponibilidad de material, equipo y presupuesto; esto a su vez implica una selección de los experimento más adecuado.

## 4.5 DISEÑO FACTORIAL

El modelo experimental usado con la finalidad de recolectar nuestros datos, que nos lleve a la contrastación de nuestra hipótesis fue un diseño factorial $2^3$ con tres niveles y tres repeticiones en el centro, para dar a nuestros datos de dureza mayor confiabilidad.

Las variables fueron temperatura de temple (A), tiempo de sostenimiento a la temperatura de temple (B) y temperatura de revenido (C), la siguiente tabla muestra el circuito experimental.

**Tabla N° 4.2.**

**Diseño Factorial $2^3$**

| **Factores** | **Unidad °C** | **NIVEL (-)** | **NIVEL (o)** | **NIVEL (+)** |
|---|---|---|---|---|
| A.- Temperatura temple | **°C** | 820 | 850 | 880 |
| B.- Tiempo de permanencia | **minutos** | 15 | 30 | 45 |
| C- Temperatura de revenido | **°C** | 250 | 300 | 350 |

Fuente: Elaboración inédita del autor.-Arequipa.-2014

**Tabla N° 4.3.**

**Matriz del Diseño Factorial $2^3$**

| **Muestra** | **A** | **B** | **C** |
|---|---|---|---|
| 01 | -1 | -1 | -1 |
| 02 | +1 | -1 | -1 |
| 03 | -1 | +1 | -1 |
| 04 | +1 | +1 | -1 |
| 05 | -1 | -1 | +1 |
| 06 | +1 | -1 | +1 |
| 07 | -1 | +1 | +1 |
| 08 | +1 | +1 | +1 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

La Tabla N° 4.3. Muestra la ejecución de las pruebas experimentadas que sigue la secuencia de todas las combinaciones posibles entre los niveles de los factores del diseño factorial.

**Tabla N° 4.4.**

**Muestra aleatoria**

| Muestra | A | B | C |
|---|---|---|---|
| 01 | 820°C | 45 min | 350°C |
| 02 | 820°C | 45 min | 250°C |
| 03 | 820°C | 15 min | 250°C |
| 04 | 820°C | 45 min | 350°C |
| 05 | 850°C | 30 min | 300°C |
| 06 | 850°C | 30 min | 300°C |
| 07 | 850°C | 30 min | 300°C |
| 08 | 880°C | 45 min | 250°C |
| 09 | 880°C | 15 min | 350°C |
| 10 | 880°C | 15 min | 250°C |
| 11 | 880°C | 45 min | 350°C |

Fuente: Elaboración inédita del autor.-Arequipa 2014

Para el presente estudio seleccionamos 08 muestras de 2,0 cm por 2.0 cm, con tres repeticiones en el centro haciendo, un total de 11 muestras como base y una repetición igual, para dar mayor confiabilidad a los valores de dureza.

Cabe indicar que se ha experimentado con 22 muestras para asegurar los valores de dureza.

## 4.6 MEDICIÓN DE LA DUREZA

Para evaluar las condiciones mecánicas del acero C45E-EN10083, en el recocido, templado en aceite a diferentes temperaturas y tiempos y finalmente revenidos, se utilizó una máquina para prueba de dureza Rockwel B, diámetro de bola 1/16".

### 4.6.1 PREPARACIÓN DE LAS MUESTRAS

De las varillas de acero C45E-EN10083 se cortan probetas cilíndricas de dimensiones de 2.0 x 2.0 cm, para temple, revenido y dureza, las cuales son sometidas a desbaste, pulidos y análisis metalográfico para determinar la estructura característica del material.

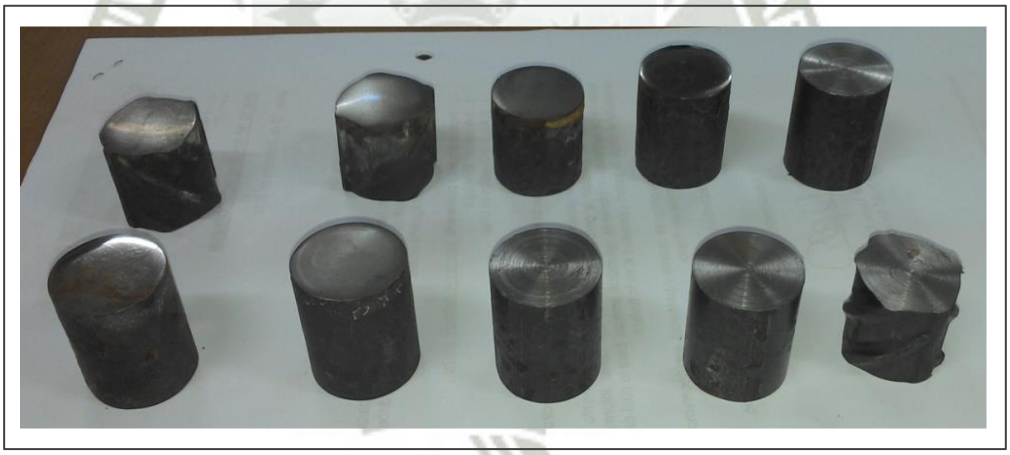


**Figura N° 4.4.**
**Probetas: acero C 45E-EN 10083**

### A. TRATAMIENTOS TÉRMICOS

Las muestras antes de ser revenidas son previamente recocidas a 650°C y luego templadas en aceite. Para el caso del acero C45E-

EN10083, en el mercado se encuentra en estado bonificado por lo que en algunos casos su aplicación es directa sin tratamiento térmico adicional.

### B. FUNCIONAMIENTO DEL HORNO

- Verificar que el sistema de control automático de temperaturas esté debidamente instalado y en perfecto funcionamiento.
- Introducir las muestras al horno.
- Subir la llave cuchilla.
- Presionar el botón de encendido del horno.
- Ubicar el selector a la temperatura de operaciones.
- Verificar la temperatura de trabajo y controlar este mediante el selector de temperatura.
- Esperar el tiempo necesario de calentamiento de las muestras a la temperatura de operación.
- Sacar las piezas calientes del horno y seguidamente introducir al medio de temple y posteriormente revenir. Concluidas las pruebas apagar el horno.

## 4.6.2 BONIFICADO

### 4.6.2.1 TEMPLE DE LAS MUESTRAS.

Las piezas antes de ser introducidas al horno para su respectivo calentamiento son previamente sometidos a una limpieza de grasa, aceites, etc., utilizando disolventes apropiados y son colocados en el interior del horno para su calentamiento y austenización de acuerdo a la temperatura y tiempo diseñado

Las pruebas experimentales se realizaron de acuerdo con el diseño planteado, por ejemplo, para el temple a 850°C calentamos en el horno tres probetas; una vez alcanzada esta temperatura se controla el tiempo de austenización, para este caso 15 min, y luego la probeta es retirada del horno para su templado en aceite. Finalmente se realizó el ensayo de dureza.

**Figura 4.5.**
**Enfriamiento de la probeta en forma de 8**

### 4.6.2.2. REVENIDO DE LAS MUESTRAS

Después que las muestras fueron templadas, estas se colocaron en el interior del horno para su calentamiento hasta alcanzar la temperatura de revenido y permanencia durante el tiempo determinado.

Las pruebas experimentales se realizaron de acuerdo al diseño planteado, por ejemplo si se elige como temperatura de trabajo de revenido 350°C, introducimos dos probetas correspondientes a 15, y 45 min., de tiempo permanencia a la temperatura de temple, y una vez alcanzado la temperatura de revenido, al cabo de 60 minutos, se retira del horno y se deja enfriar al aire.

**Figura 4.6.**
**Revenido de la Muestra**

Finalmente se realizan los correspondientes ensayos de dureza

**Figura 4.7.**
**Prueba de Dureza**

Se tomaron medidas de dureza en cada probeta recocida y luego las templadas en aceite a diferentes temperaturas y tiempos y por último las revenidas en diferentes lugares superficiales de la misma y obteniendo un promedio de lectura de valores de dureza en cada uno de las probetas.

**Tabla N° 4.5.**
**Dureza de los tratamientos térmicos en HRB**

| Muestra | S/T | T ºC | T. min | Recocido | Temple | Revenido |
|---|---|---|---|---|---|---|
| 01 | 98.26 | 820 | 45 | 94.87 | 97.95 | 96.26 |
| 02 | 98.96 | 820 | 45 | 95.77 | 105.33 | 103.17 |
| 03 | 99.63 | 820 | 15 | 96.03 | 98.06 | 97.67 |
| 04 | 98.50 | 820 | 15 | 95.94 | 97.80 | 96.17 |
| 05 | 99.60 | 850 | 30 | 95.60 | 111.53 | 109.50 |
| 06 | 98.66 | 850 | 30 | 94.80 | 99.33 | 100.70 |
| 07 | 99.46 | 850 | 30 | 96.43 | 111.30 | 110.87 |
| 08 | 97.73 | 880 | 45 | 95.10 | 101.87 | 101.43 |
| 09 | 98.70 | 880 | 15 | 95.57 | 111.27 | 109.73 |
| 10 | 99.40 | 880 | 15 | 95.50 | 110.53 | 104.80 |
| 11 | 99.10 | 880 | 45 | 96.23 | 110.43 | 110.10 |
| 12 | 98.90 | S/T | S/T | 00 | 00 | 00 |

Fuente: Elaboración inédita del autor.-Arequipa.- 2014

La Tabla N° 4.5. Muestra las durezas de muestras sin tratamiento térmico tal como fue adquirido, así como las durezas de las muestras recocidas a 650°C, las durezas de los muestras templadas en aceite a diferentes tiempos y temperaturas, y como las durezas de las muestras recocidas, se tomaron cinco durezas en cada muestra, la tabla presenta los valores promedios

### Tabla N° 4.6.
### Dureza HRB para revenido-Temple 820°C

| Muestra | T. Temple °C | Tiempo T.T | T. Revenido | Dureza (HB) |
|---|---|---|---|---|
| 01 | 820 | 45 min | 350°C | 96.27 |
| 02 | 820 | 45 min | 250°C | 103.17 |
| 03 | 820 | 15 min | 250°C | 97.67 |
| 04 | 820 | 15 min | 350°C | 96.17 |

Fuente Elaboración inédita del autor.-Arequipa 2014

La Tabla N° 4.6. Denota que los mejores valores de dureza se obtienen a 820°C, con un tiempo de austenización de 45 minutos y una temperatura de revenido de 250°C por espacio de sesenta minutos.

### Tabla N° 4.7.
### Dureza HRB para revenido-Temple 850°C

| Muestra | T. Temple °C | Tiempo T.T | T. Revenido | Dureza (HB) |
|---|---|---|---|---|
| 05 | 850 | 30 min | 300°C | 109.50 |
| 06 | 850 | 30 min | 300°C | 100.70 |
| 07 | 850 | 30 min | 300°C | 110.87 |

Fuente: Elaboración inédita del autor.- Arequipa 2014

La Tabla N° 4.7. Denota que los mejores valores de dureza se obtienen a una temperatura de 850°C, con un tiempo de austenización de 30 minutos y a una temperatura de revenido de 300°C por espacio de sesenta minutos.

**Tabla N° 4.8.**

**Dureza HRB para revenido-Temple 880°C**

| Muestra | T. Temple ºC | Tiempo T.T | T. Revenido | Dureza (HB) |
|---|---|---|---|---|
| 08 | 880 | 45 min | 250 °C | 101.43 |
| 09 | 880 | 15 min | 350° C | 109.73 |
| 10 | 880 | 15 min | 250 °C | 104.60 |
| 11 | 880 | 45 min | 350 °C | 110.10 |

Fuente: Elaboración inédita del autor.- Arequipa 2014

La Tabla N° 4.8. Denota que son mejores valores de dureza se obtienen a una temperatura de 880°C con un tiempo de austenización de 15 y 45 minutos a una temperatura de revenido de 350°C por espacio de sesenta minutos.

## 4.7 METALOGRAFÍA

Es la realización de una reseña histórica del material o metal usado, buscando su microestructura, inclusiones, tratamiento térmico a los que haya sido sometido, con el fin de determinar si dicho acero C 45E-EN10083 cumple con los requisitos para los cuales ha sido diseñado.

Los análisis de las microestructuras del acero C 45E-EN 10083, se ha hecho sobre probetas que fueron sometidas al proceso de bonificado, es decir probetas que fueron templadas a las temperaturas de 820°C, 850°C, 680°C, con 15 min., 30 min y 45 min, de austenización respectivo y probetas revenidas a 250°C, 300°C, 350°C de temperatura y 1 hora de sostenimiento en cada una de las temperaturas respectivamente.

Los ensayos metalográficos, corresponden las siguientes operaciones:

Toma de muestra, seccionado, desbaste, pulido, ataque químico, observación de la microestructura en un microscopio y fotografiado de la microestructura.

### 4.7.1 PREPARACIÓN DE PROBETAS METALOGRÁFICAS

#### 4.7.1.1 CORTE DEL MATERIAL

La muestra debe tener un tamaño adecuado de tal manera que pueda ser manipulado con facilidad para el pulido y el ataque químico. La muestra ha de mantenerse a temperatura ambiente durante la operación de corte para ello se debe usar un fluido refrigerante colocado correctamente al momento de cortar las probetas.

#### 4.7.1.2 DESBASTE GRUESO

Este tipo de desbaste permite la remoción de rebabas y todas las rayaduras producidas en el corte, esto se logra ejerciendo una presión uniforme de la probeta sobre el disco de la desbastadora provista de lija número 80. Durante ésta operación se debe regular el caudal de agua para mantener fría la probeta.

#### 4.7.1.3 DESBASTE FINO

En éste tipo de desbaste el objetivo es remover la zona deformada causada por los procesos anteriores, para ello se utilizó el equipo para desbastado fino que contiene lijas número 240, 320, 400, 600 granos/pulg ordenadas de forma secuencial. Para obtener buenos resultados de deslizará la probeta en dirección opuesta al operario de manera que se formen líneas en una sola dirección y que conforme se aumente de número de lija se trate de eliminar las rayaduras aún presentes.

**Figura N° 4.8.**
**Desbastado Grueso a Fino**

### 4.7.1.4 PULIDO GRUESO

En ésta operación de pulido se utiliza la pulidora de paño en la que se emplea como abrasivo alúmina de 1 micrón en suspensión. El objetivo es remover mediante la abrasión las zonas de metal deformado causado por el desbaste fino.

**Figura N° 4.9.**
**Pulido Grueso**

### 4.7.1.5 PULIDO FINO

En ésta operación de pulido se utiliza alúmina de 0.3 micrones en suspensión en agua con lo que se obtiene las condiciones de superficie adecuadas para la observación de la microestructura ya que el efecto abrasivo se ha reducido de tal manera que la posibilidad de causar deformaciones en la superficie metalográfica es mínima. El movimiento de la probeta metalográfica en éste tipo de operación deberá ser en forma circular para evitar la formación de colas de cometa y conseguir una excelente apreciación de la microestructura.

**Figura N° 4.10.**
**Pulido Fino**

### 4.7.1.6 ATAQUE QUÍMICO

El objetivo del ataque químico es hacer visibles las características estructurales del metal en la muestra metalográfica, el proceso debe permitir observar claramente y diferenciar las partes de la microestructura. Para lograr esto se utiliza un reactivo apropiado que somete a la superficie pulida a una acción química. Las muestras pueden atacarse sumergiéndolas en un recipiente que contenga el reactivo durante el tiempo adecuado para evitar el sobreataque o sino utilizando un gotero que dosifique el reactivo sobre la muestra metalográfica.

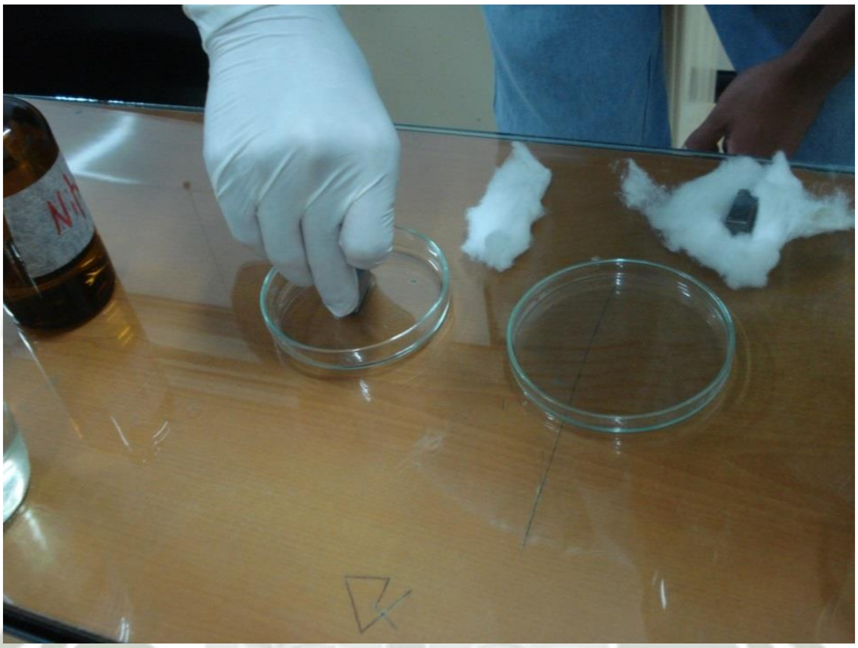


**Figura N° 4.11.**
**Ataque Químico**

### 4.7.2 EQUIPO PARA LA PREPARACIÓN DE PROBETAS METALOGRÁFICAS

Para la preparación de las probetas metalográficas se utilizó los equipos disponibles en el Laboratorio de Ensayo de Materiales, en la sección de Metalografía del Programa Profesional de Ingeniería Mecánica, Mecánica-Eléctrica y Mecatrónica de la Universidad Católica de Santa María, que se muestran en las tablas y fotografías correspondientes.

### 4.7.3 MICROSCOPIO METALOGRÁFICO

El principal instrumento para la realización de un examen metalográfico lo constituye el microscopio metalográfico, con el cual es posible examinar una muestra con aumentos que varían entre 50X y 500X.

El microscopio metalográfico, debido a la opacidad de los metales y aleaciones, opera con la luz reflejada por el metal. Por lo que para poder observar la muestra es necesario preparar una probeta y pulir a espejo la superficie.

Muchas veces es necesario variar a voluntad la incidencia de la luz, pues el aspecto de la imagen varía mucho con la incidencia con pequeños elementos, debe operarse con incidencia normal o casi normal desde el momento que la superficie presenta gráneles accidentes de relieve, y con aumentos altos cuando el relieve es mínimo, se utiliza una incidencia muy oblicua, casi rasante.

El enfoque se efectúa por desplazamiento de la platina, es decir, del objeto paralelamente al eje óptico del microscopio. Este movimiento se realiza con ayuda de una cremallera, un desplazamiento con el enfoque grosero permite ubicarse en las cercanías de la posición correcta, un movimiento con el enfoque fino permite regular la distancia objetivo-objetivo de manera precisa. Cada objetivo posee un aumento propio característico, o sea, capacidad para dar una imagen, a un aumento determinado de veces mayor que el objeto.

En todos los microscopios metalográficos modernos, se puede pasar rápidamente de la observación ocular a la observación fotográfica.

**Figura 4.12.**

**Análisis Metalográfico**

## 4.8 APLICACIÓN:

En partes de maquinaria y repuestos de dimensiones medianas con grandes exigencias mecánicas como alta dureza, resistencia a la tracción y alta tensión y también ciertos elementos para la construcción de motores, engranajes, pernos, tuercas, pines, émbolos, árbol de trasmisión, eje de bombas, etc.

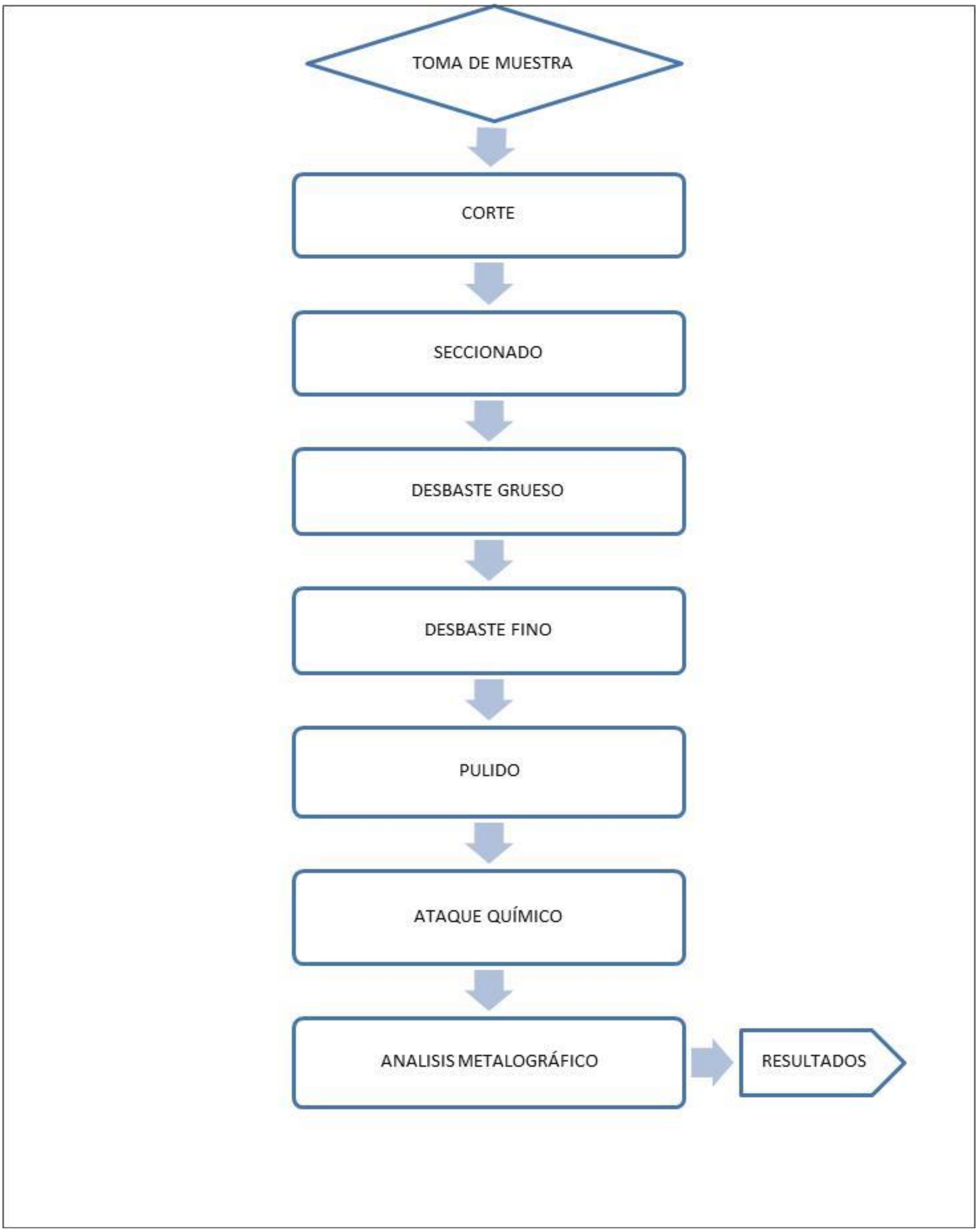


**Figura Nº 4.13.**
**Diagrama de Bloques Preparación Metalográfica**

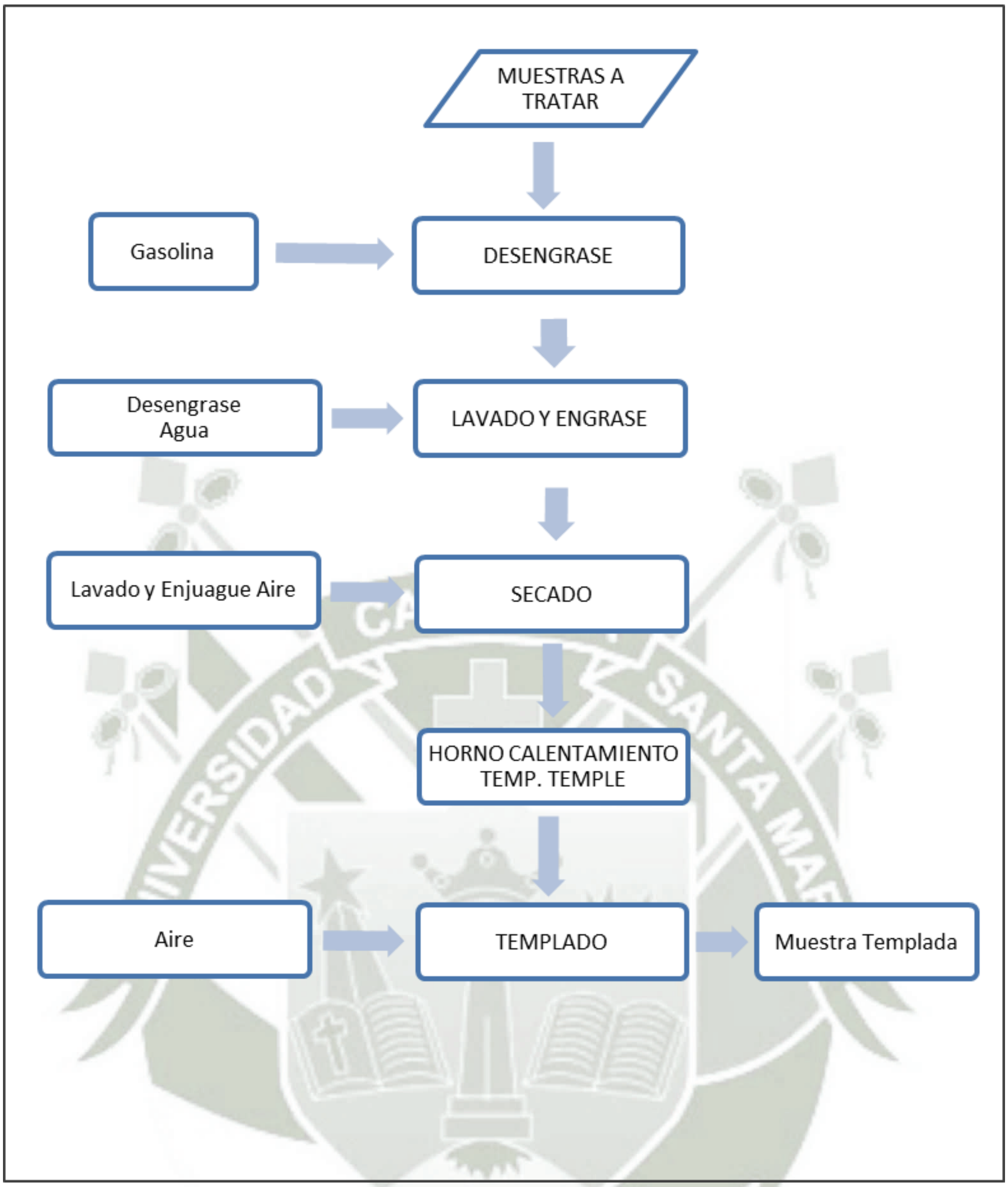


**Figura Nº 4.14.**
**Diagrama de Bloques del Proceso de Temple**

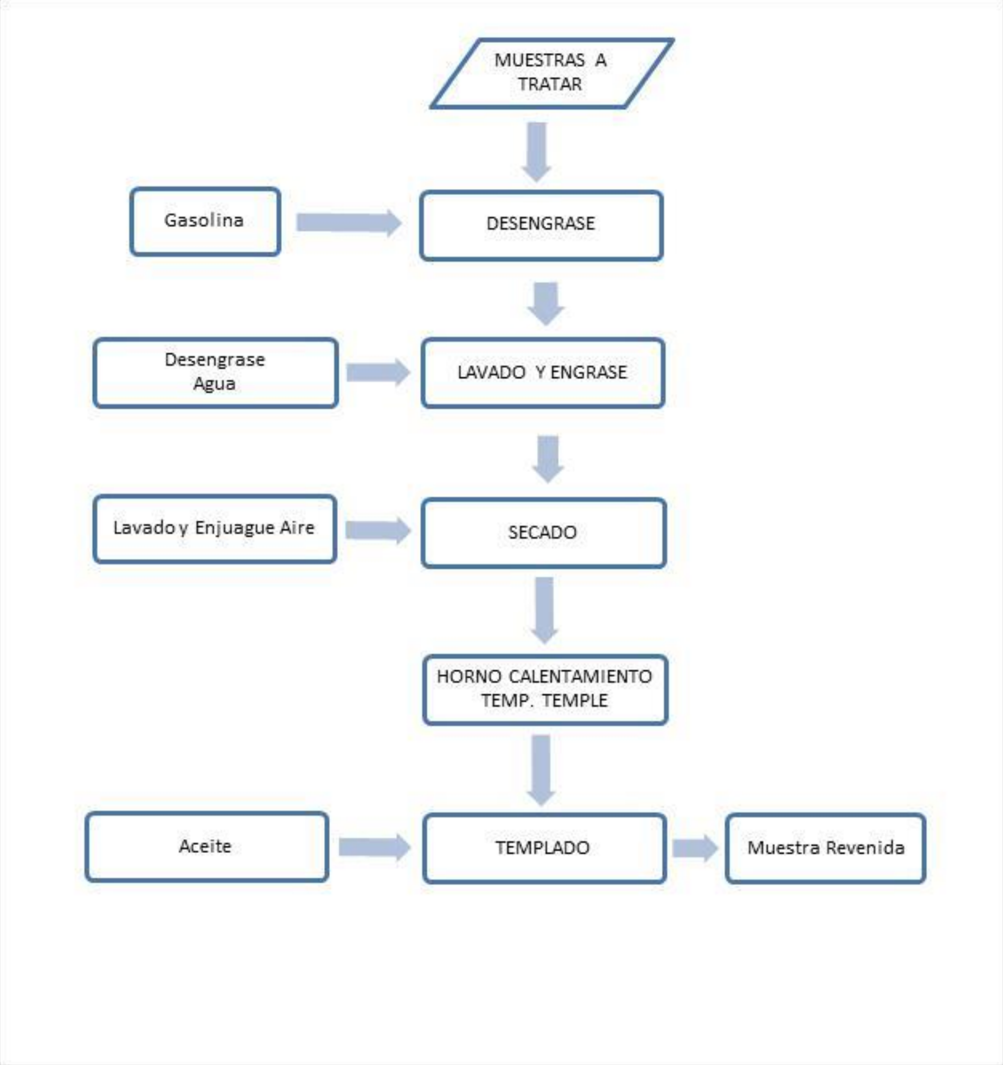


**Figura Nº 4.15.**
**Diagrama de Bloques del Proceso de Revenido**

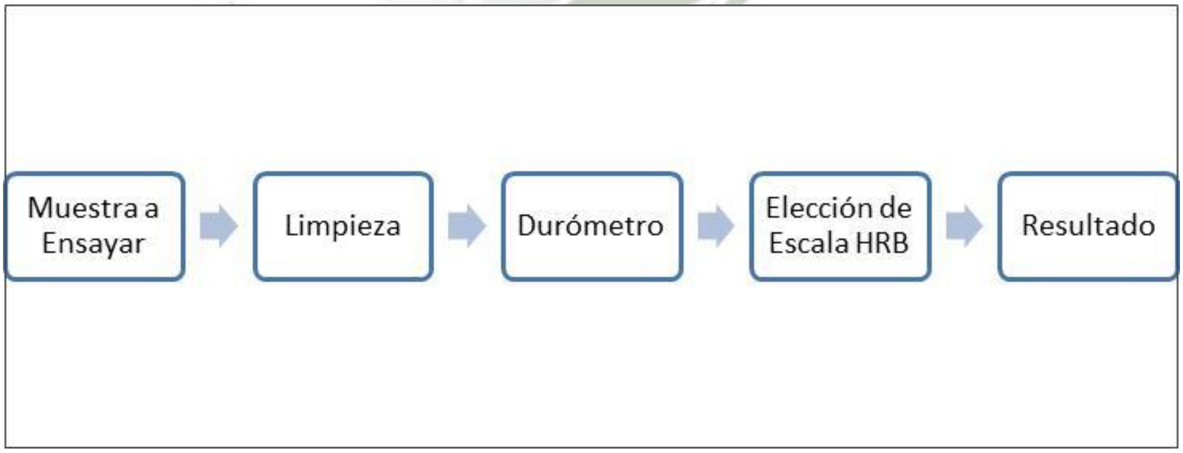


**Figura Nº 4.16.**
**Diagrama de Bloques del Proceso del Ensayo de Dureza**

# CAPÍTULO V

# ANÁLISIS DE RESULTADOS

Las condiciones y resultados correspondientes a las pruebas experimentales son detallados en las gráficas y fotos que a continuación se presentan.

## 5.1 ANÁLISIS EXPERIMENTAL DEL TEMPLE A 850°C

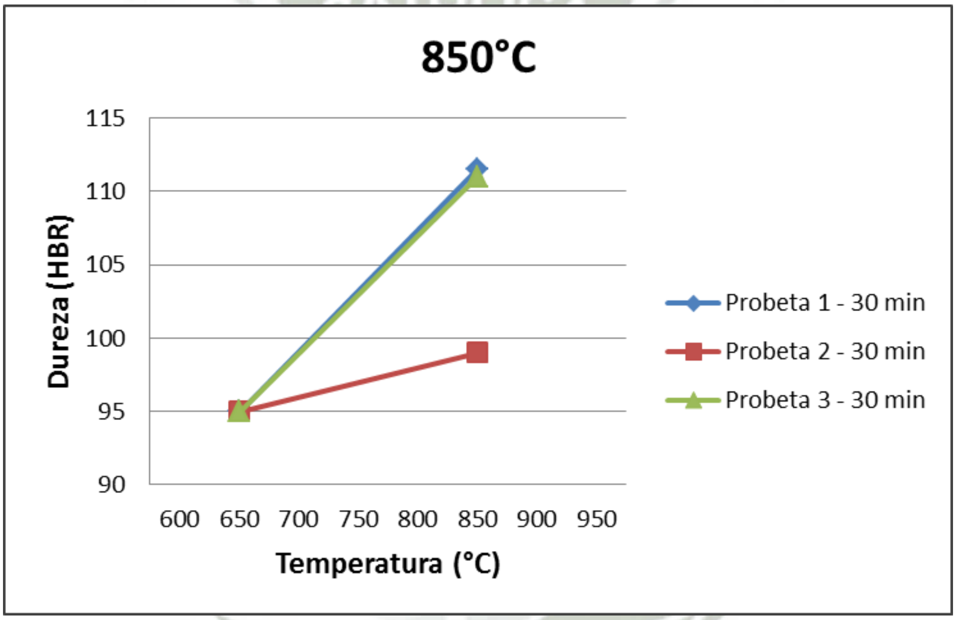


**Gráfico N° 5.1.**
**Muestra las condiciones y resultados experimentales de temple, donde se observa que la dureza promedio más alta es 111.53 HRB, con una temperatura de temple de 850°C y un tiempo de austenización de 30 minutos.**

## 5.2 ANÁLISIS EXPERIMENTAL DEL TEMPLE A 820°C

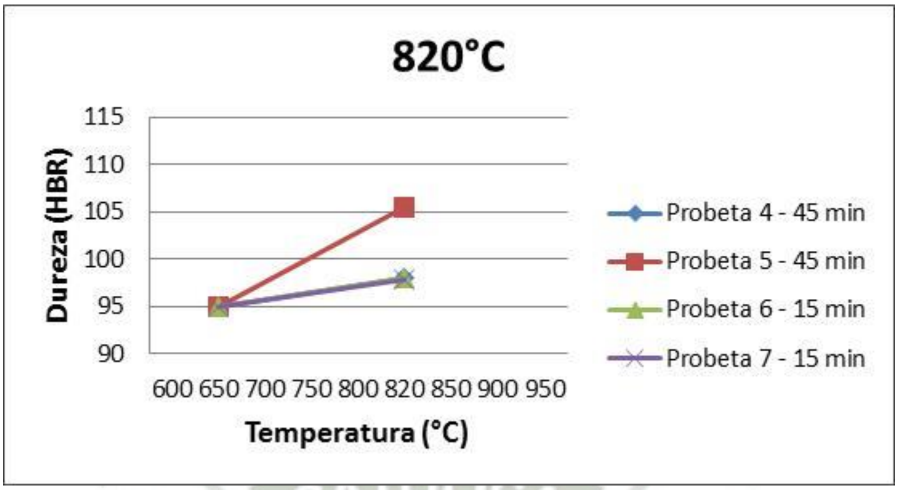


**Gráfico N° 5.2.**
**Muestra las condiciones y resultados experimentales de temple, donde podemos observar que la dureza promedio más alta es 105.53 HRB con una temperatura de temple de 820°C y un tiempo de austenización de 45 minutos.**

## 5.3 ANÁLISIS EXPERIMENTAL DEL TEMPLE A 880°C

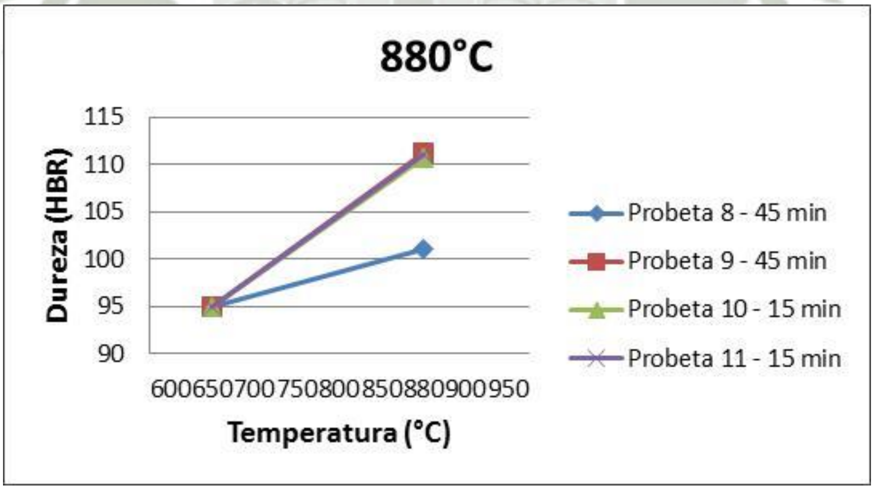


**Gráfico N° 5.3.**
**Muestra las condiciones y resultados experimentales de temple, donde podemos observar que la dureza promedio es 111.26 HRB con una temperatura de temple de 880°C y un tiempo de austenización de 15 minutos.**

## 5.4 ANÁLISIS EXPERIMENTAL DEL REVENIDO A 300°C

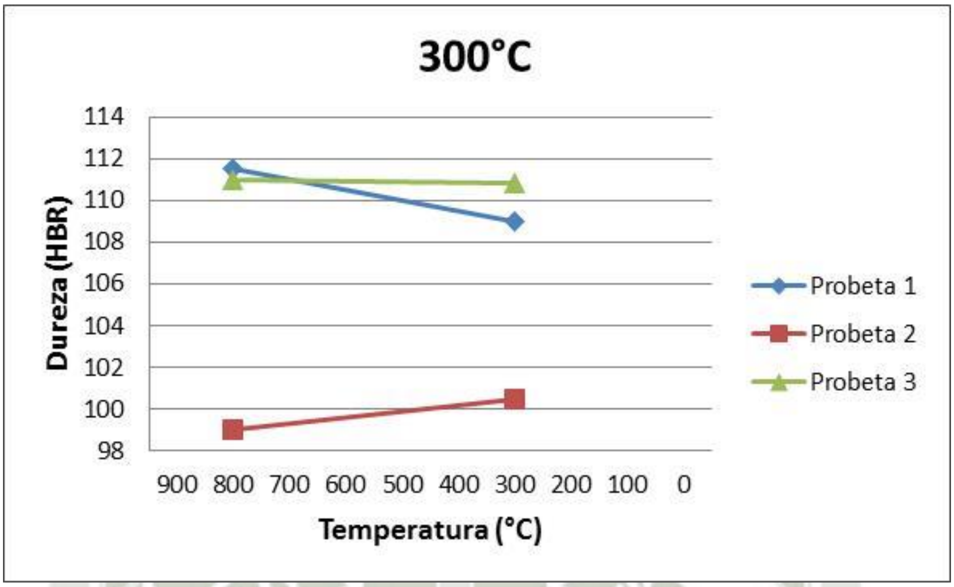


**Gráfico N° 5.4.**
**Muestra las condiciones y resultados experimentales del revenido de las muestras templadas a 850°C en donde la dureza promedio más alta que se obtuvo es 110.86 HRB con un tiempo de austenización de 30 minutos y una temperatura de revenido de 300°C.**

## 5.5 ANÁLISIS EXPERIMENTAL DEL REVENIDO A 250°C

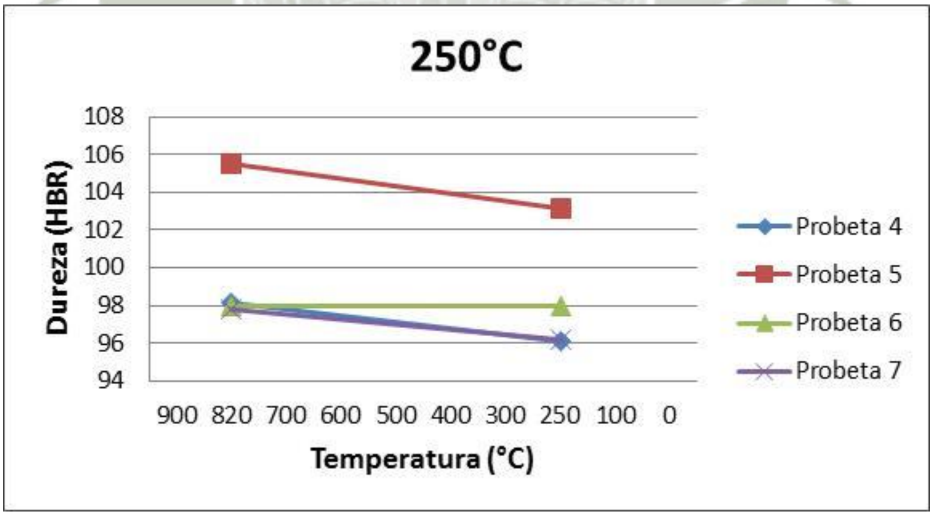


**Gráfico N° 5.5.**
**Muestra las condiciones y resultados experimentales del revenido en las muestras templadas a 820°C, en donde la dureza promedio más alta que se obtuvo es 103.16 HRB con un tiempo de austenización de 45 minutos y una temperatura de revenido de 250°C**

## 5.6 ANÁLISIS EXPERIMENTAL DEL REVENIDO A 350°C

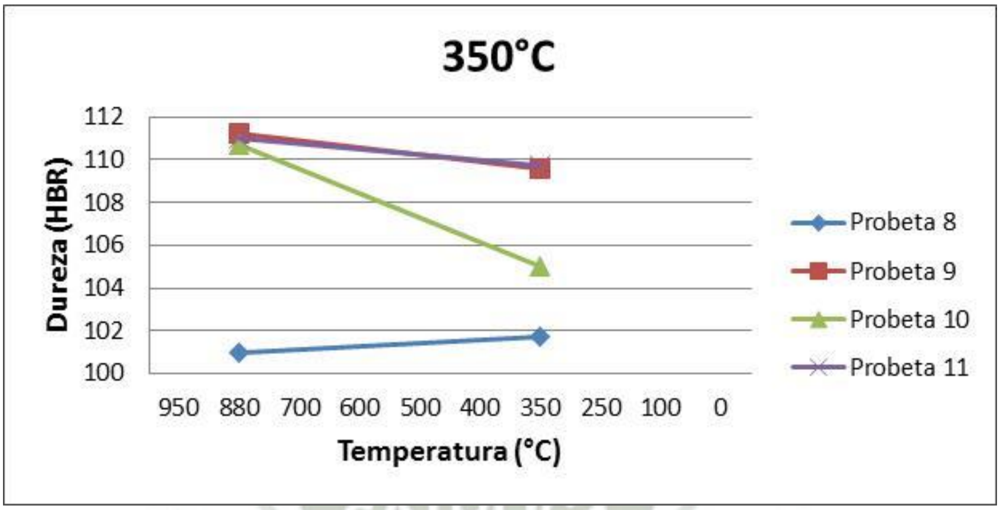


**Gráfico N° 5.6.**
**Muestra las condiciones y resultados experimentales del revenido en las muestras templadas a 880°C en donde la dureza promedio más alta que se obtuvo es 109.73 HRB con un tiempo de austenización de 15 minutos y una temperatura de revenido de 350°C.**

## 5.7 ANÁLISIS DEL DISEÑO FACTORIAL CON INTERACCIONES

**Tabla 5.1 Efectos estimados para Dureza (Dureza HRB)**

| EFECTO | ESTIMADO | ERROR ESTD. | V.I.F. |
|---|---|---|---|
| Promedio | 103.701 | 1.66399 | 1.0 |
| A: Temp | 8.02 | 3.90241 | 1.0 |
| B: Tiempo | 0.575 | 3.90241 | 1.0 |
| C: Temp_Rev | 1.475 | 3.90241 | 1.0 |
| AB | -1.975 | 3.90241 | 1.0 |
| AC | 5.425 | 3.90241 | 1.0 |
| BC | -0.59 | 3.90241 | 1.0 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

Errores estándar basados en el error puro con 2 gl.

Esta tabla muestra las estimaciones para cada uno ele los efectos estimados y las interacciones. También se muestra el error estándar de cada uno de estos efectos, el cual mide su error de muestreo.

### 5.7.1 ANÁLISIS

En la Tabla N° 5.1 se muestra los efectos de cada factor y las interacciones respectivas para la variable respuesta de dureza. Por ejemplo cuando la temperatura se varia del nivel inferior (820) al nivel superior (880) el efecto en la dureza se incrementara en +8.02 (efecto positivo) ídem para los demás factores.

Así por ejemplo cuando la interacción AB se varia del nivel inferior (820) al nivel superior (880) y se mantiene constante el tiempo en su promedio el efecto en la dureza se decrementará en -1.975 (efecto negativo).

### 5.7.2 GRÁFICO PARETO

Se grafica los estimados en orden decreciente de importancia, con la finalidad de probar la significancia estadística de los efectos, con un 95% de confianza o 5% de error. Los efectos de cada factor serán estadísticamente significativos si son menores que 0.05 (valor-p). Del gráfico se observa que la temperatura es el factor más importante, luego la interacción AC y la interacción AB tienen significancia estadística negativa.

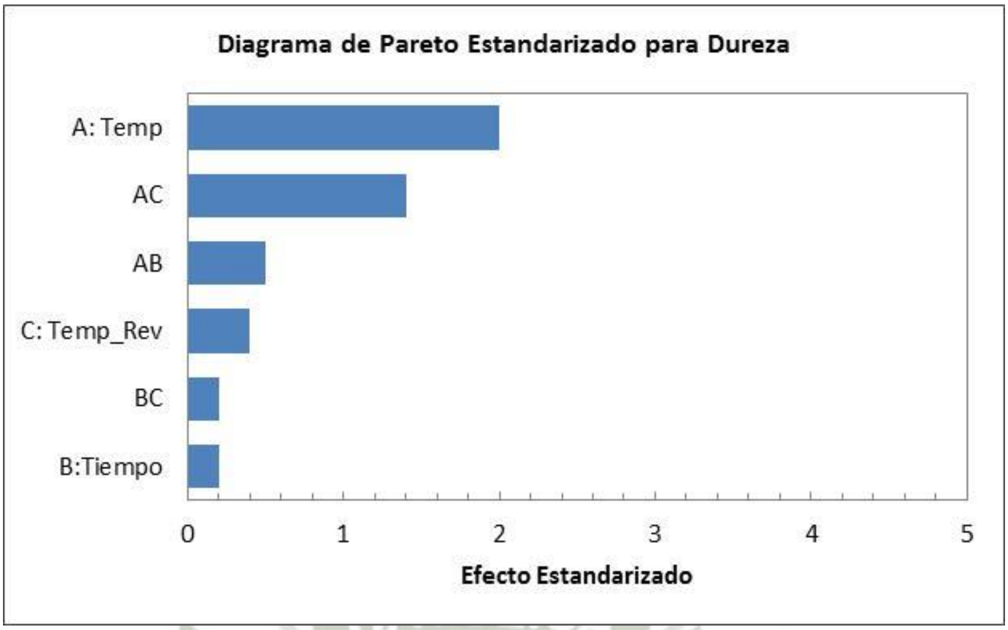


**Gráfico N° 5.7.**
**Diagrama de Pareto Estandarizada para Dureza**

**Tabla 5.2**

**Análisis de Varianza para Dureza ANOVA**

| Fuente | Suma de Cuadrados | Gl | Cuadrado Medio | Razón-F | Valor-P |
|---|---|---|---|---|---|
| A: Temp | 128.641 | 1 | 128.641 | 4.22 | 0.1762 |
| B:Tiempo | 0.66125 | 1 | 0.66125 | 0.02 | 0.8964 |
| C:Temp_Rev | 4.35125 | 1 | 4.35125 | 0.14 | 0.7418 |
| AB | 7.80125 | 1 | 7.80125 | 0.26 | 0.6631 |
| AC | 58.8613 | 1 | 58.8613 | 1.93 | 0.2990 |
| BC | 0.6962 | 1 | 0.6962 | 0.02 | 0.8937 |
| Falta de ajuste | 56.673 | 2 | 28.3365 | 0.93 | 0.5180 |
| Error puro | 60.9153 | 2 | 30.4576 | | |
| Total (corr.) | 318.6 | 10 | | | |

Fuente: Elaboración inédita del autor.-Arequipa 2014

R-cuadrada = porciento

R-cuadrada (ajustada por g.l.) = porciento

Error estándar del est. = 5.51884

Error absoluto medio = 2.35785

Estadístico Durbin-Watson = 2.68765 (P=0.7714)

Autocorrelación residual de Lag 1 = -0.358867

La Tabla ANOVA particiona la variabilidad de Dureza en piezas separadas para cada uno de los efectos. Entonces prueba la significancia estadística de cada efecto comparando su cuadrado medio contra un estimado del error experimental. En este caso, (no hay efectos) 0 efectos tienen una valor-P menor que 0.05, indicando que son significativamente diferentes de cero con un nivel de confianza del 95.0%.

La prueba de faifa de ajuste (la inclusión de los puntos centrales) está diseñada para determinar si el modelo seleccionado es adecuado para describir los datos observados o si se debería usar un modelo más complicado. La prueba se realiza comparando la variabilidad de los residuos del modelo actual con la variabilidad entre observaciones obtenidas en condiciones repetidas de los factores. Dado que el valor-P para la falta de ajuste en la tabla ANOVA es mayor que 0.05, el modelo parece ser adecuado para los datos observados al nivel de confianza del 95.0%.

El estadístico R-Cuadrada indica que el modelo, así ajustado, explica 83.0922% de la variabilidad en Dureza. El estadístico R-cuadrada ajustada, que es más -adecuado para comparar modelos con diferente número de variables independientes, es 7.73055%. El error estándar del estimado muestra que la desviación estándar de los residuos es 5.51884. El error medio absoluto (MAE) de 2.35785 es el valor promedio de los residuos. El estadístico de Durbin-Watson (DW) prueba los residuos para determinar si haya alguna correlación significativa basada en el orden en que se presentan los datos en el archivo. Puesto que el valor-P es mayor que 5.0%, no hay indicación de auto correlación serial en los residuos con un nivel de significancia del 5.0%.

La gráfica de efectos principales para la dureza confirma que la temperatura es el efecto principal luego la temperatura de revenido y casi no influye el tiempo. La intensidad del efecto del factor está determinado por la pendiente de la recta, a mayor pendiente mayor intensidad y viceversa.

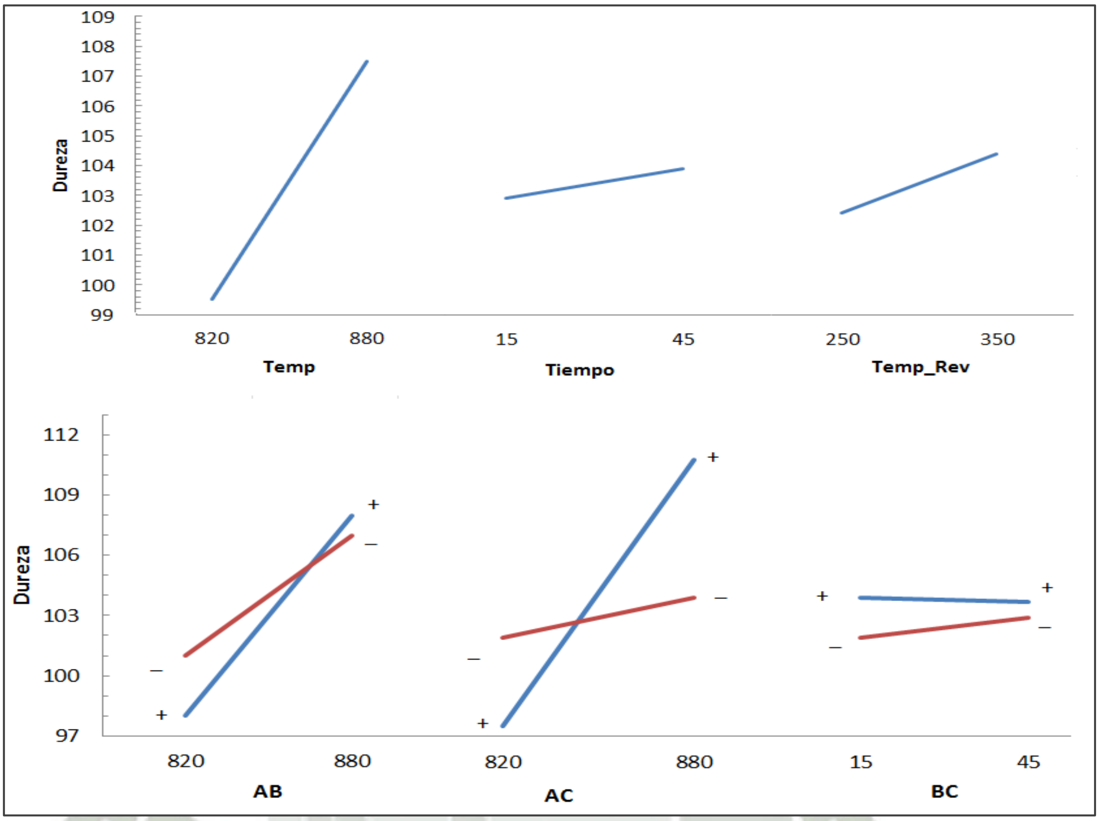


**Gráfico N° 5.8.**
**Gráficos de efectos principales de Dureza**

### Modelo Matemático

**Tabla 5.3. Coeficientes de regresión para Dureza**

| Coeficiente | Estimado |
|---|---|
| constante | 386.711 |
| A:Temp | -0.343 |
| B:Tiempo | 2.00244 |
| C:Temp_Rev | -1.51053 |
| AB | -0.00219444 |
| AC | 0.00180833 |
| BC | -0.000393333 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

La ecuación del modelo ajustado es

Dureza=386.711 - Q.343*Temp + 2.00244*Tiempo - 1.51053*Temp_Rev 0.00219444 *Temp *Tiempo + 0.00180833 *Temp *Temp_Rev - 0.000393333 * Tiempo *Temp_Rev

En donde los valores de las variables están especificados en sus unidades originales.

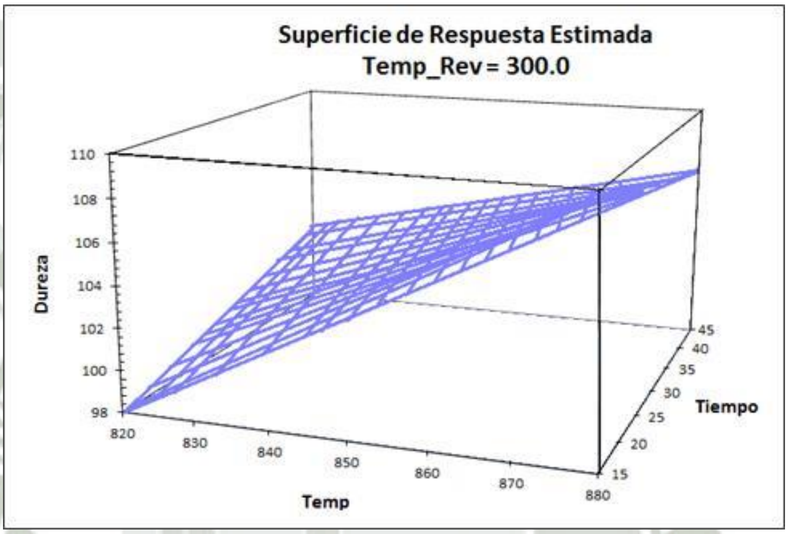


**Gráfico N° 5.9.**
**Gráfico de Regresión para Dureza**

**Tabla 5.4. Matriz de Correlación para los Efectos Estimados**

| | | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|---|
| (1) | promedio | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| (2) | A:Ternp | 0.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| (3) | B:Tiempo | 0.0000 | 0.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| (4) | C:Temp_Rev | 0.0000 | 0.0000 | 0.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 |
| (5) | AB | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 1.0000 | 0.0000 | 0.0000 |
| (6) | AC | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 1.0000 | 0.0000 |
| (7) | BC | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 1.0000 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

La matriz de correlación muestra el grado de confusión entre los efectos. Un diseño perfectamente ortogonal mostrará una matriz diagonal con 1's en la diagonal y 0's fuera de ella. Cualquier término distinto de cero implica que los estimados de los efectos correspondientes a esa fila y columna estarán correlacionados. En este caso, no hay correlación entre ninguno de los efectos. Esto significa que se obtendrán estimados 'limpios' para todos esos efectos.

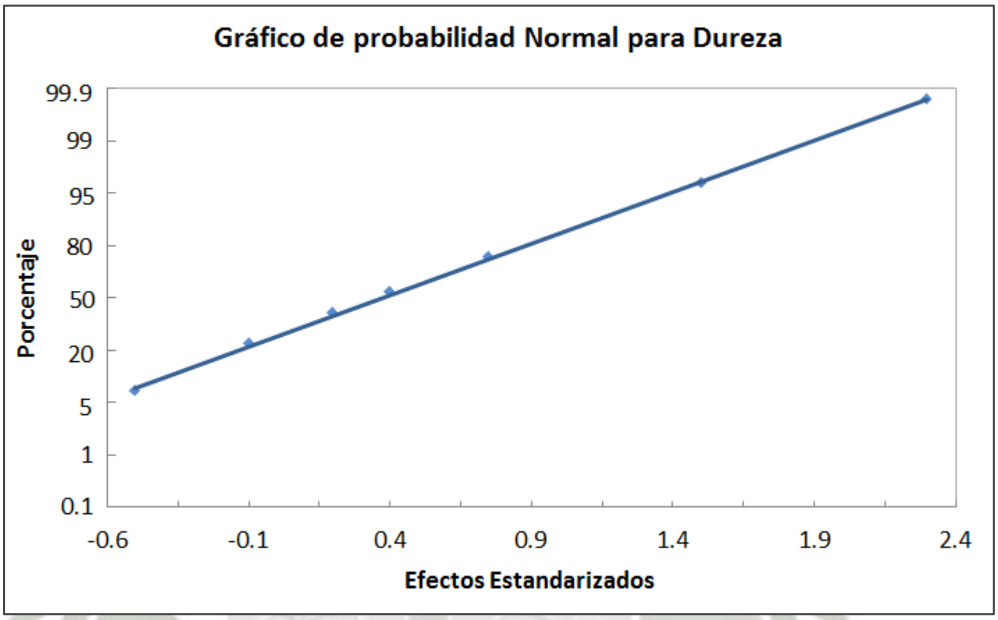


**Gráfico N° 5.10.**
**Gráfico de Correlación de Efectos Estimados**

**Tabla 5.5 Resultados Estimados para Dureza**

| Fuente | Suma de Cuadrados | Gl | Cuadrado Medio | Razón-F | Valor-P |
|---|---|---|---|---|---|
| A:Temp | 128.641 | 1 | 128.641 | 4.22 | 0.1762 |
| B:Tiempo | 0.66125 | 1 | 0.66125 | 0.02 | 0.8964 |
| C:Temp_Rev | 4.35125 | 1 | 4.35125 | 0.14 | 0.7418 |
| AB | 7.80125 | 1 | 7.80125 | 0.26 | 0.6631 |
| AC | 58.8613 | 1 | 58.8613 | 1.93 | 0.2990 |
| BC | 0.6962 | 1 | 0.6962 | 0.02 | 0.8937 |
| Falta de ajuste | 56.673 | 2 | 28.3365 | 0.93 | 0.5180 |
| Error puro | 60.9153 | 2 | 30.4576 | | |
| Total (corr.) | 318.6 | 10 | | | |

Fuente: Elaboración inédita del autor.-Arequipa 2014

Promedio de 3 puntos centrales = 107.023
Promedio de las predicciones del modelo al centro = 103.701

Esta tabla contiene información acerca de los valores de Dureza generados usando el modelo ajustado. La tabla incluye:

(1) Los valores observados de Dureza (los datos experimentales).
(2) El valor predicho de Dureza usando el modelo ajustado.
(3) Intervalos de confianza del 95.0% para la respuesta media.

**Tabla 5.6. Camino de Máximo Ascenso para Dureza**

| **Temp** | **Tiempo** | **Temp_Rev** | **Predicción para Dureza** |
|---|---|---|---|
| (Temperatura de temple °C) | (Tiempo de austenización min) | (Temperatura de revenido °C) | (Dureza HRB) |
| 850.0 | 30.0 | 300.0 | 103.701 |
| 851.0 | 30.0336 | 300.324 | 103.841 |
| 852.0 | 30.0628 | 300.685 | 103.982 |
| 853.0 | 30.0875 | 301.08 | 104.125 |
| 854.0 | 30.1077 | 301.51 | 104.27 |
| 855.0 | 30.1235 | 301.975 | 104.417 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

Esta ventana despliega el trayecto ele máximo ascenso (o descenso). Este es el trayecto, desde el centro de la región experimental actual, a través del cual la respuesta estimada cambia más rápidamente con un cambio menor en los factores experimentales. Indica buenas locaciones para correr experimentos adicionales si el objetivo es incrementar o decrementar Dureza. Actualmente, 8 puntos se han generado cambiando Temp en incrementos de 1.0 Temperatura de temple.

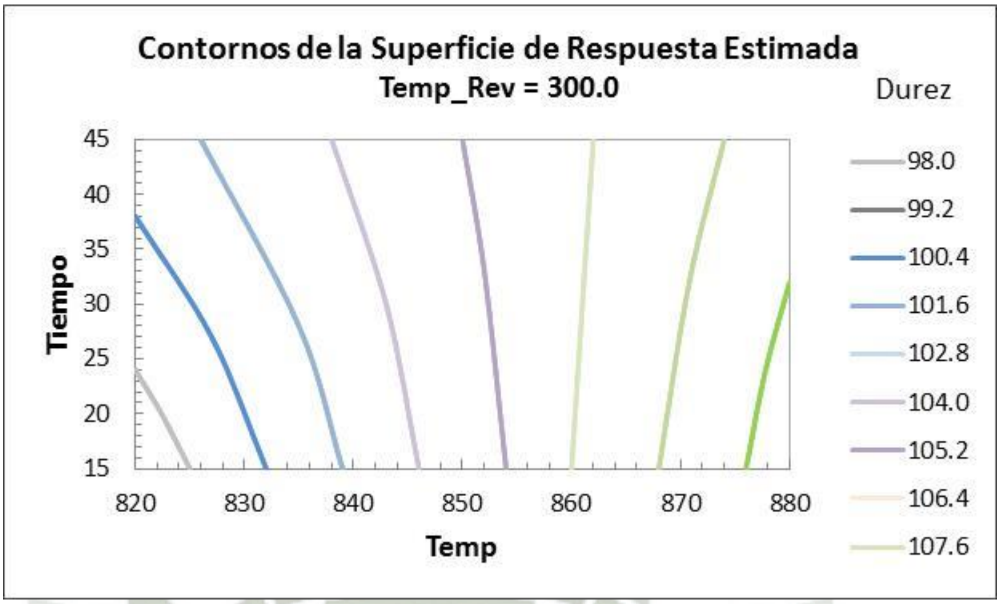


**Gráfico N° 5.11.**
**Gráfico de Máximo Ascenso para Dureza**

Optimizar Respuesta

Meta: maximizar Dureza

Valor óptimo - 112.156

**Tabla 5.7. Niveles de Factores**

| Factor | Bajo | Alto | Óptimo |
|---|---|---|---|
| Temp | 820.0 | 880.0 | 880.0 |
| Tiempo | 15.0 | 45.0 | 15.0 |
| Temp_Rev | 250.0 | 350.0 | 350.0 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

Esta tabla muestra la combinación de los niveles de los factores, la cual maximiza Dureza sobre la región indicada.

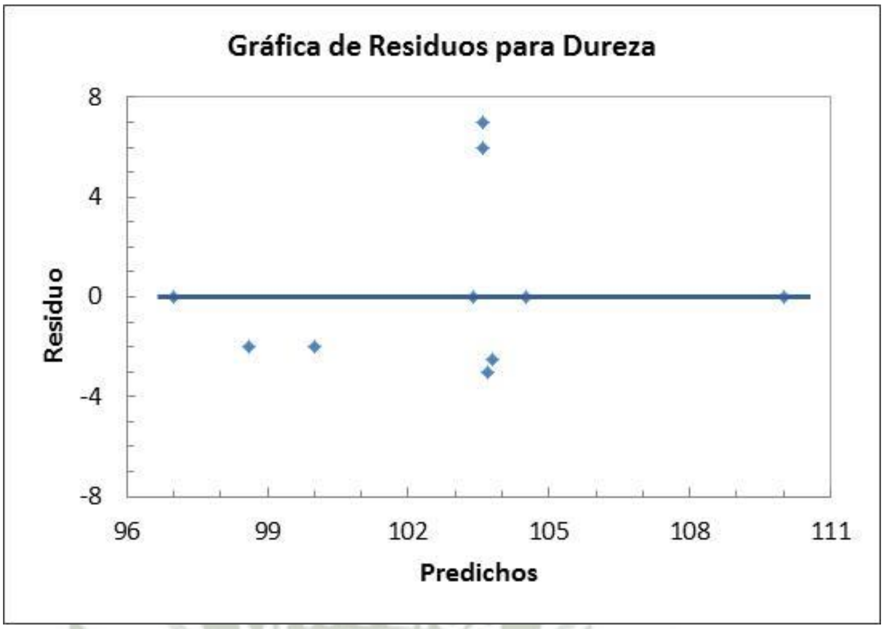


**Gráfico N° 5.12.**
**Gráfico de Correlación de Efectos Estimados**

## 5.8 ANÁLISIS DEL DISEÑO FACTORIAL SIN INTERACCIONES

**Tabla N°.5.8 Efectos estimados para Dureza (Dureza HRB)**

| Efecto | Estimado | Error Estd. | V.I.F. |
|---|---|---|---|
| promedio | 103.701 | 1.66399 | |
| A:Temp | 8.02 | 3.90241 | 1.0 |
| BTiempo : | 0.575 | 3.90241 | 1.0 |
| C:Temp_Rev | 1.475 | 3.90241 | 1.0 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

Errores estándar basados en el error puro con 2 g.l.

Esta tabla muestra las estimaciones para cada uno de los efectos estimados y las interacciones. También se muestra el error estándar de cada uno de estos efectos, el cual mide su error de muestreo.

### 5.8.1 ANÁLISIS

En la Tabla N° 5.7 se muestra los efectos de cada factor y las interacciones respectivas para la variable respuesta Dureza. Así por ejemplo cuando la temperatura se varia del nivel inferior (820) al nivel superior (880) el efecto en la dureza se incrementara en +8.02 (efecto positivo). ídem para los demás factores.

### 5.8.2 GRÁFICO PARETO

Se gráfica los estimados en orden decreciente de importancia, con la finalidad de probar la significancia estadística de tos efectos, con un 95% de confianza o 5% de error. Los efectos de cada factor serán estadísticamente significativos si son menores que 0.05 (valor-p). Del gráfico se observa que la temperatura es el factor más importante, luego Temperatura revenido y tiempo.

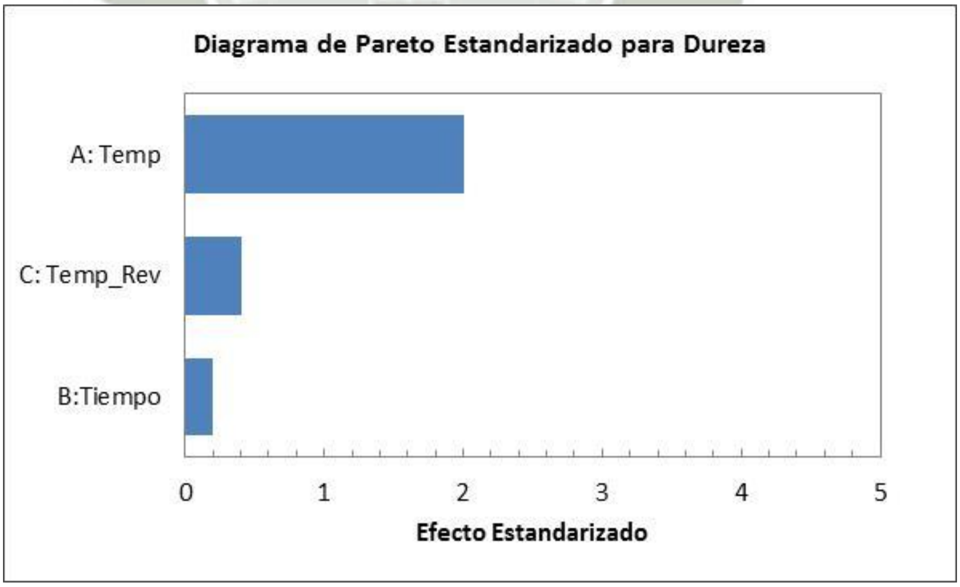


**Gráfico N° 5.13.**
**Gráfico Pareto**

### 5.8.3 ANÁLISIS DE VARIANZA PARA DUREZA

**Tabla 5.9. Resultados Estimados para Dureza**

| **Fuente** | **Suma de Cuadrados** | **Gl** | **Cuadrado Medio** | **Razón-F** | **Valor-P** |
|---|---|---|---|---|---|
| A:Temp | 128.641 | 1 | 128.641 | 4.22 | 0.1762 |
| B:Tiempo | 0.66125 | 1 | 0.66125 | 0.02 | 0.8964 |
| C:Temp_Rev | 4.35125 | 1 | 4.35125 | 0.14 | 0.7418 |
| Falta de ajuste | 124.032 | 5 | 24.8063 | 0.81 | 0.6317 |
| Error puro | 60.9153 | 2 | 30.4576 | | |
| Total (corr.) | 318.6 | 10 | | | |

Fuente: Elaboración inédita del autor.-Arequipa 2014

R-cuadrada = 41.9502 porciento
R-cuadrada (ajustada por g.l.) - 17.0716 porciento
Error estándar del est. - 5.51884
Error absoluto medio - 3.60554
Estadístico Durbin-Watson = 2.26231 (P-0.7198)
Autocorrelación residual de Lag 1 - -0.228104

La Tabla ANOVA particiona la variabilidad de Dureza en piezas separadas para cada uno de los efectos. Entonces prueba la significancia estadística de cada efecto comparando su cuadrado medio contra un estimado del error experimental. En este caso, (no hay efectos) 0 efectos tienen una valor-P menor que 0.05, indicando que son significativamente diferentes de cero con un nivel de confianza del 95.0%.

La prueba de falta de ajuste (la inclusión de los puntos centrales) está diseñada para determinar si el modelo seleccionado es adecuado para describir los datos observados o si se debería usar un modelo más complicado. La prueba se realiza comparando la variabilidad de los residuos del modelo actual con la variabilidad entre observaciones obtenidas en condiciones repetidas de los factores. Dado que el valor-P para la falta de ajuste en la tabla ANOVA es mayor que 0.05, el modelo parece ser adecuado para los datos observados al nivel de confianza del 95.0%.

El estadístico R-Cuadrada indica que el modelo, así ajustado, explica 41.9502% de la variabilidad en Dureza. El estadístico R-cuadrada ajustada, que es más adecuado para comparar modelos con diferente número de variables independientes, es 17.0716%. El error estándar del estimado muestra que la desviación estándar de los residuos es 5.51884. El error medio absoluto (MAE) de 8.60554 es el valor promedio de los residuos. El estadístico de Durbin-VVatson (DW) prueba los residuos para determinar si haya alguna correlación significativa basada en el orden en que se presentan los datos en el archivo. Puesto que el valor-P es mayor que 5.0%, no hay indicación de auto correlación serial en los residuos con un nivel de significancia del 5.0%.

La gráfica de efectos principales para la dureza confirma que la temperatura es el efecto principal luego la temperatura de revenido y casi no influye el tiempo. La intensidad del efecto del factor está determinado por la pendiente de la recta, a mayor pendiente mayor intensidad y viceversa.

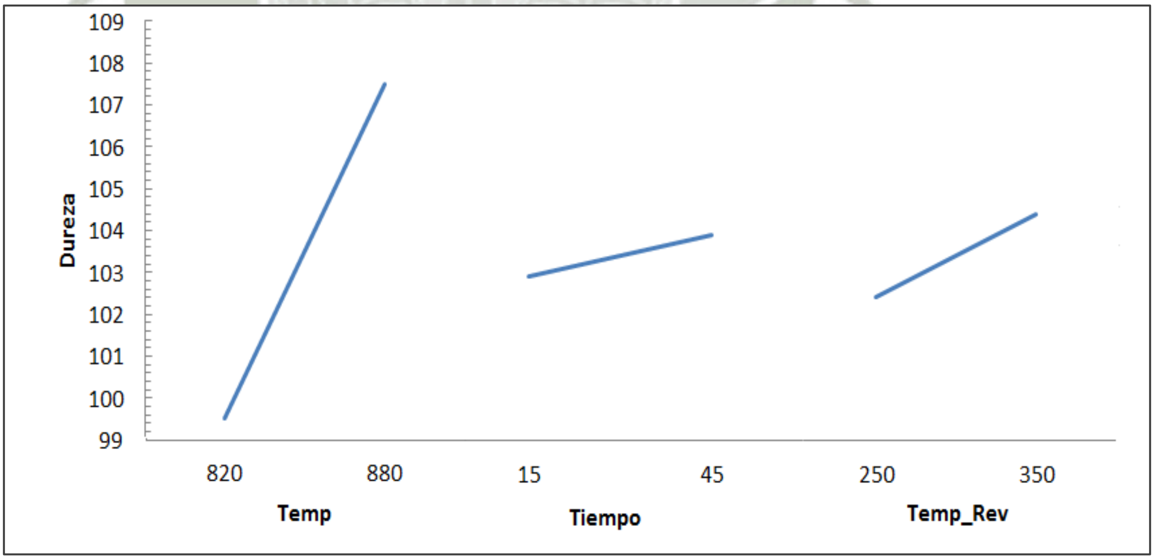


**Gráfico N° 5.14.**
**Gráfico ANOVA**

### 5.8.4 MODELO MATEMÁTICO

Coeficientes de regresión para Dureza

**Tabla 5.10. Coeficientes de regresión para Dureza**

| Coeficiente | Estimado |
|---|---|
| constante | -14.9158 |
| A:Temp | 0.133667 |
| B:Tiempo | 0.0191667 |
| C:Temp_Rev | 0.01475 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

La ecuación del modelo ajustado es:

Dureza=-14.9158+00.133667 *Temp+0.0191667
*TIempo + 0.01475 *Temp_Rev

En donde los valores de las variables están especificados en sus unidades originales.

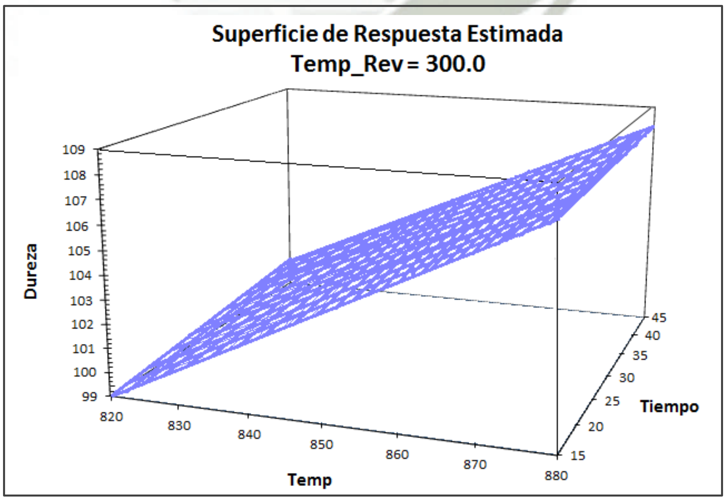


**Gráfico N° 5.15.**
**Gráfico Regresión de Dureza**

**Tabla N°.5.11. Matriz de Correlación para los Efectos Estimados**

| | | **(1)** | **(2)** | **(3)** | **(4)** |
|---|---|---|---|---|---|
| **(1)** | **promedio** | 1.0000 | 0.0000 | 0.0000 | 0.0000 |
| **(2)** | **A:Temp** | 0.0000 | 1.0000 | 0.0000 | 0.0000 |
| **(3)** | **B:Tiempo** | 0.0000 | 0.0000 | 1.0000 | 0.0000 |
| **(4)** | **C:Temp_Rev** | 0.0000 | 0.0000 | 0.0000 | 1.0000 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

La matriz de correlación muestra el grado de confusión entre los efectos. Un diseño perfectamente ortogonal mostrará una matriz diagonal con 1's en la diagonal y 0's fuera de ella. Cualquier término distinto de cero implica que los estimados de los efectos correspondientes a esa fila y columna estarán correlacionados. En este caso, no hay correlación entre ninguno de los efectos. Esto significa que se obtendrán estimados limpios para todos esos efectos.

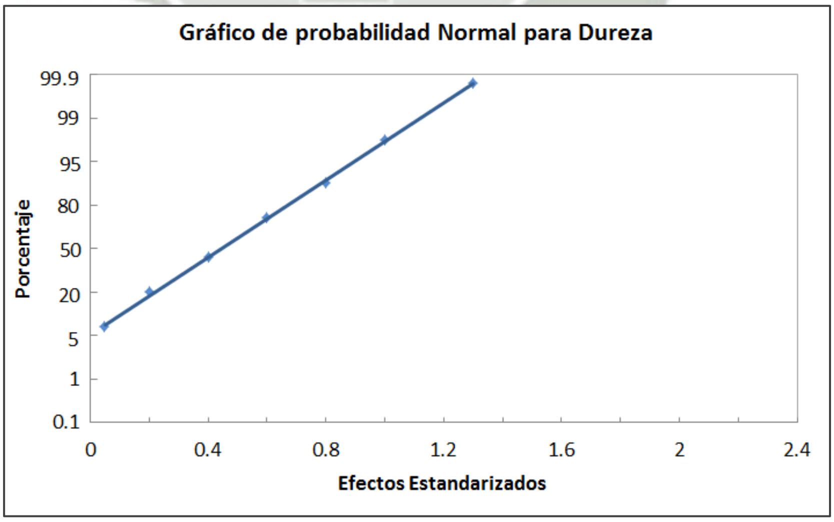


**Gráfico N° 5.16.**
**Gráfico Regresión de Dureza**

**Tabla N°.5.12. Resultados Estimados para Dureza (HRB)**

| | Observados | Ajustados | Inferior 95.0% | Superior 95.0% |
|---|---|---|---|---|
| **Fila** | **Valores** | **Valores** | **para Media** | **para Media** |
| **1** | 110.1 | 108.736 | 92.5277 | 124,944 |
| **2** | 109.73 | 108.161 | 91.9527 | 124.369 |
| **3** | 103.17 | 99.2409 | 83.0327 | 115.449 |
| **4** | 104.6 | 106.686 | 90.4777 | 122.894 |
| **5** | 97.67 | 98.6659 | 82.4577 | 114.874 |
| **6** | 109.5 | 103.701 | 96.5413 | 110.86 |
| **7** | 96.27 | 100.716 | 84.5077 | 116.924 |
| **8** | 100.7 | 103.701 | 96.5413 | 110.86 |
| **9** | 110.87 | 103.701 | 96.5413 | 110.86 |
| **10** | 96.67 | 100.141 | 83.9327 | 116.349 |
| **11** | 101.43 | 107.261 | 91.0527 | 123.469 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

Promedio de 3 puntos centrales = 107.023

Promedio de las predicciones del modelo al centro = 103.701

Esta tabla contiene información acerca de los valores de Dureza generados usando el modelo ajustado. La tabla incluye:

(1) los valores observados de Dureza (si alguno)

(2) el valor predicho de Dureza usando el modelo ajustado

(3) intervalos de confianza del 95.0% para la respuesta media

**Tabla N°.5.13. Camino de Máximo Ascenso para Dureza**

| Temp | Tiempo | Temp_RBV | Predicción para Dureza |
|---|---|---|---|
| (Temperatura de temple °C) | (Tiempo de austenización min) | (Temperatura de revenido °C) | (Dureza HRB) |
| 850.0 | 30.0 | 300.0 | 103.701 |
| 851.0 | 30.0358 | 300.307 | 103.84 |
| 852.0 | 30.0717 | 300.613 | 103.979 |
| 853.0 | 30.1075 | 300.92 | 104.118 |
| 854.0 | 30.1434 | 301.226 | 104.256 |
| 855.0 | 30.1792 | 301.533 | 104.395 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

Esta ventana despliega el trayecto de máximo ascenso (o descenso). Este es el trayecto, desde el centro de la región experimental actual, a través del cual la respuesta estimada cambia más rápidamente con un cambio menor en los factores experimentales. Indica buenas locaciones para correr experimentos adicionales si el objetivo es incrementar o decrementar Dureza. Actualmente, 6 puntos se han generado cambiando Temp en incrementos de 1.0 Temperatura de temple.

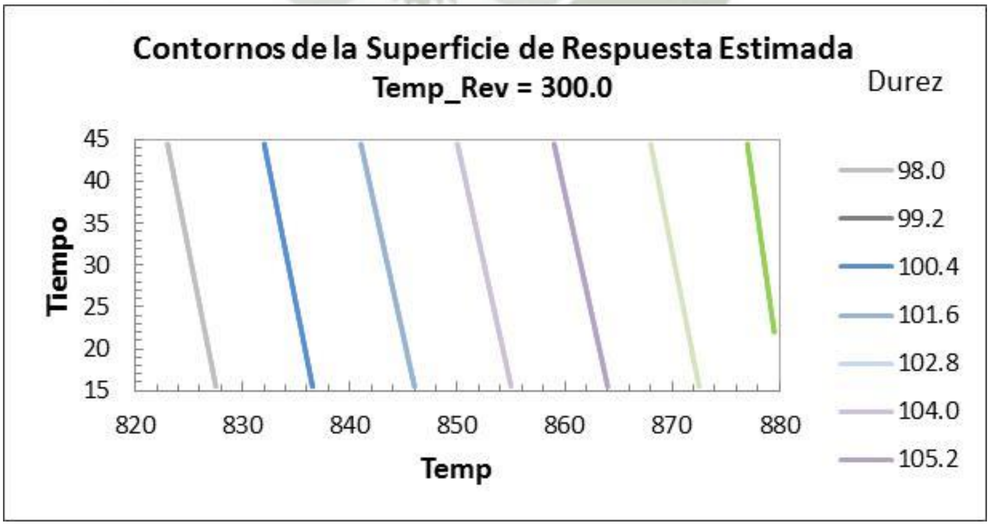


**Gráfico N° 5.17.**
**Trayecto de Máximo Ascenso**

**Optimizar Respuesta**

Meta: maximizar Dureza

Valor óptimo = 108.738

**Tabla N°.5.14. Niveles de Factores**

| Factor. | Bajo | Alto | Óptimo |
|---|---|---|---|
| **Temp** | 820.0 | 880.0 | 880.0 |
| **Tiempo** | 15.0 | 45.0 | 45.0 |
| **Temp_Rev** | 250.0 | 350.0 | 350.0 |

Fuente: Elaboración inédita del autor.-Arequipa 2014

Esta tabla muestra la combinación de los niveles de los factores, la cual maximiza Dureza sobre la región indicada.

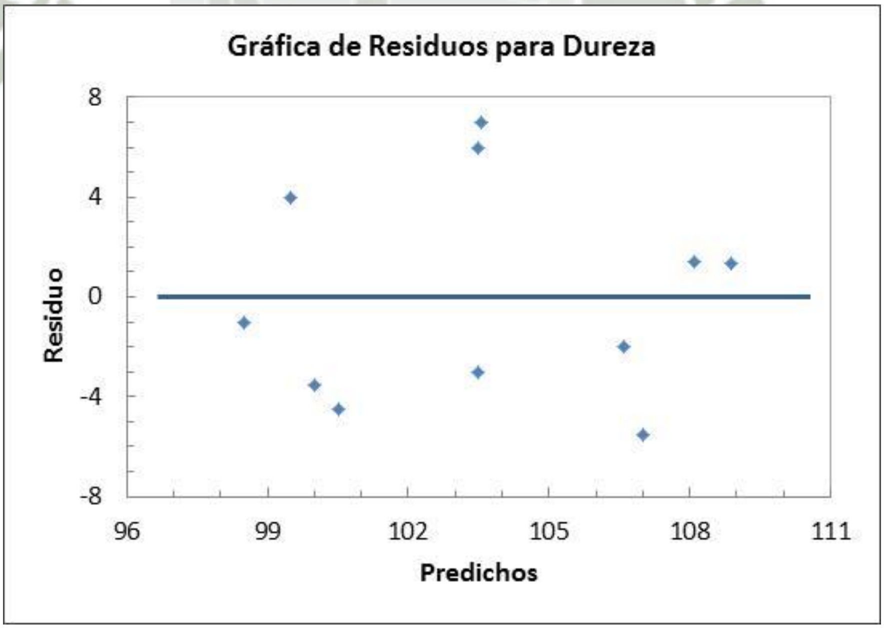


**Gráfico N° 5.18.**
**Niveles de Factores**

## 5.9 ANÁLISIS DE MICROESTRUCTURAS

### 5.9.1 ENSAYO CHARPY

El ensayo Charpy permite analizar la fragilidad o resiliencia de un material, al someter una muestra o probeta a un golpe o impacto súbito a gran velocidad.

Dicha probeta debe tener un entalle en V normalizado, la misma que se fija entre dos soportes de la máquina de ensayos de tal modo que la arista precursora del péndulo incida en el corte

### 5.9.2 PREPARACIÓN DE PROBETAS CHARPY

Para determinar la propiedad de tenacidad del acero C 45E-EN 10083 se maquinaron probetas cuadrangulares a partir de una barra cuadrada de 12 x12 x 60 mm con base en la norma INEN 130 (1973-03) con entalle en V, ver ANEXO E.

### 5.9.3 EQUIPO PARA EL ENSAYO CHARPY

Las probetas Charpy fueron ensayadas en la Máquina de Charpy, provisto por el Laboratorio de Ensayo de Materiales del Programa Profesional de Ingeniería Mecánica de la Universidad Católica de Santa María. En la tabla se muestra el equipo para el ensayo Charpy.

**Tabla N°.5.15. Especificaciones técnicas de la máquina universal de ensayos de impacto-LEM UCSM**

| | | |
|---|---|---|
|  | **Equipo** | Máquina universal de ensayos de impacto |
| | **Modelo** | Modelo JB-W300A |
| | **Ensayos** | Impacto |
| | **Display** | Digital |
| | **Energía máxima de impacto** | 300J/150J |
| | **Velocidad máxima de impacto** | 5,2m/s |

Fuente: Elaboración inédita del autor.-Arequipa 2013

### 5.9.4 PROCEDIMIENTO DEL ENSAYO DE IMPACTO

- Mecanizar las probetas según la norma INEN 130 (1973-03).
- Ubicar el péndulo en su posición inicial a la altura establecida por el equipo
- Colocar la probeta en la pinza porta probetas y posicionar sobre el yunque.
- Dejar caer el péndulo que contiene el martillo.
- Tomar lectura de los resultados.

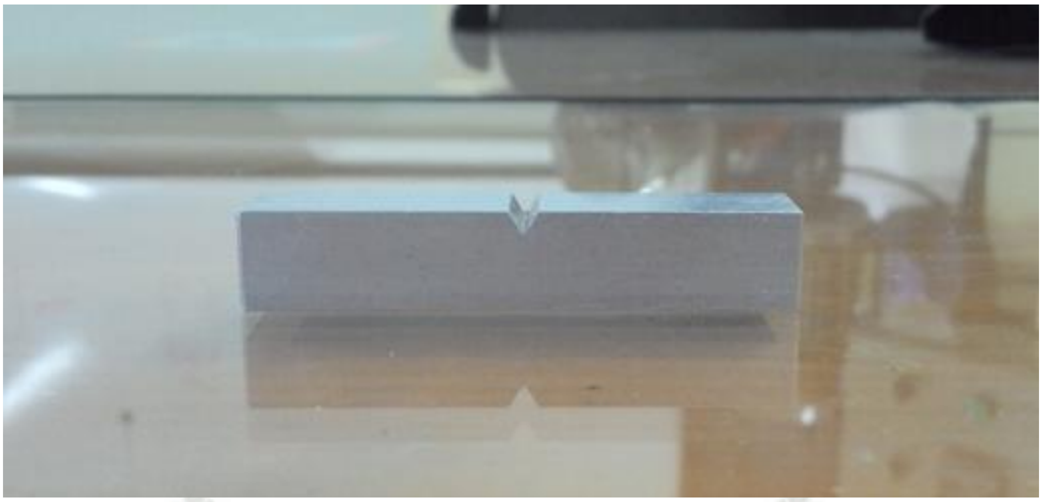


**Figura N° 5.1.**
**Probetas según Norma INEN 130 (1973-03)**

**Figura N° 5.2.**
**Péndulo en su posición inicial**

Figura N° 5.3.
Ubicación de la Probeta en el Yunque

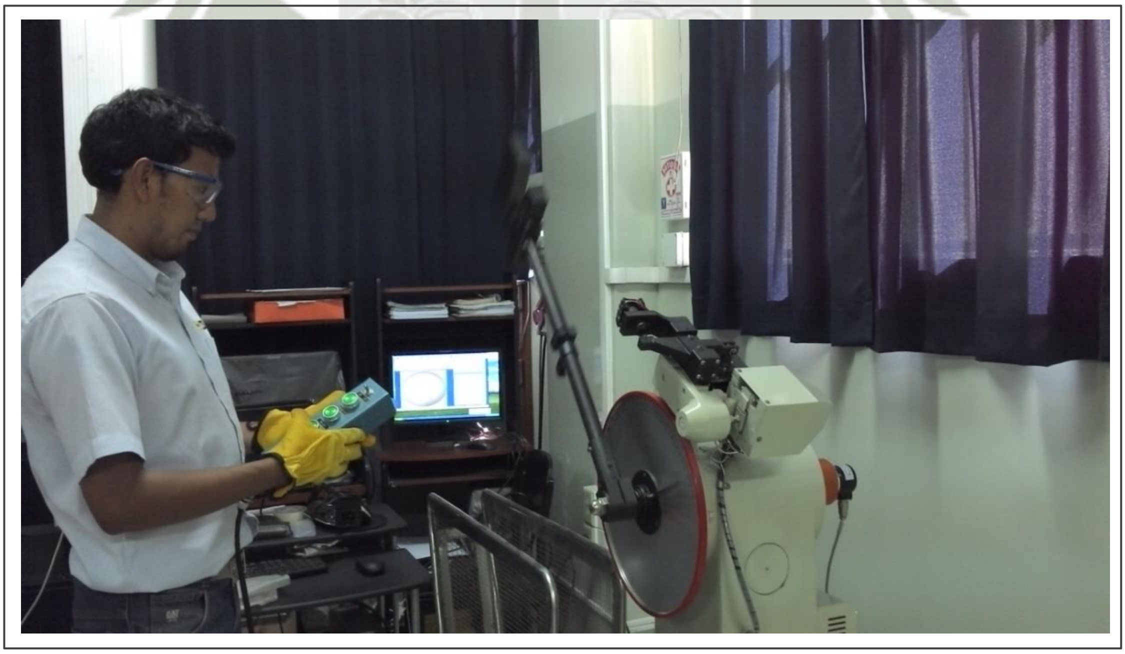
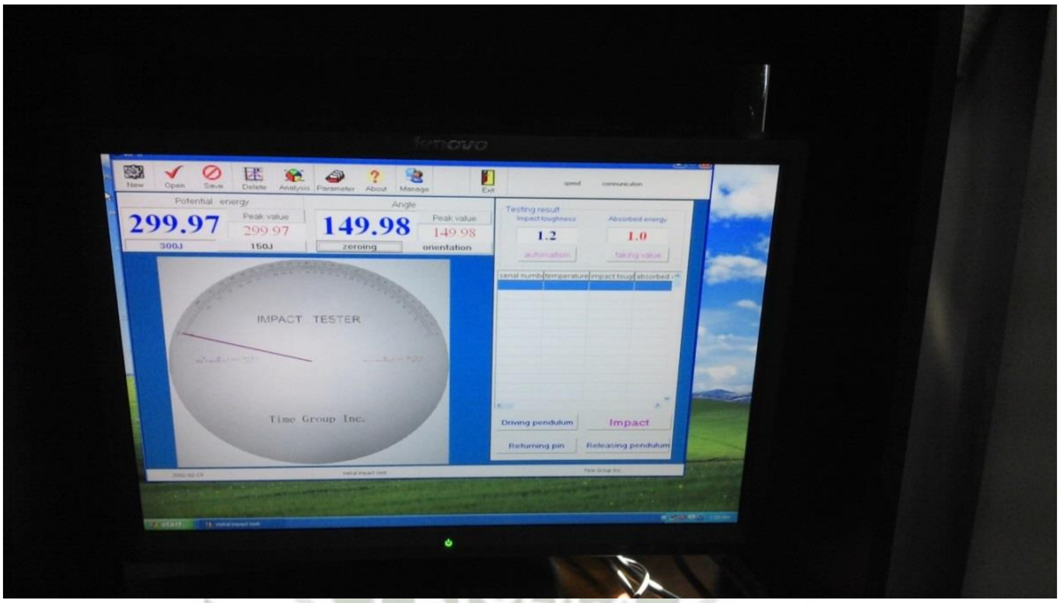


Figura N° 5.4.
Péndulo Liberado para la Prueba de Impacto



Potential energy 299.97
Peak value 299.97
Angle 149.98
Peak value 149.98
Testing result
Impact toughness 1.2
Absorbed energy 1.0

**Figura N° 5.5.**
**Resultados de la Prueba de Impacto**

### 5.9.5 RESULTADO DEL ENSAYO CHARPY DEL ACERO C 45E-EN 10083

**Tabla N°.5.15. Ensayo Charpy del Acero C 45E-EN 10083**

| **Muestra** | **Tenacidad** | |
|---|---|---|
| | **Lbf.pie** | **N.m** |
| 1.1 | 35 | 46 |
| 1.2 | 32 | 43 |
| 1.3 | 11 | 15 |
| 1.4 | 8 | 11 |
| 1.5 | 4 | 5 |
| 1.6 | 2 | 2,7 |
| 1.7 | 31 | 42 |

Fuente: Elaboración inédita del autor.-Arequipa 2013

### 5.9.6 RESULTADOS ANÁLISIS METALOGRÁFICO

Las micrografías de 100X fueron obtenidas en el Laboratorio de la UCSM, mientras que las fotografías con mayores aumentos (500X) en el Laboratorio de la Universidad Nacional de San Agustín.

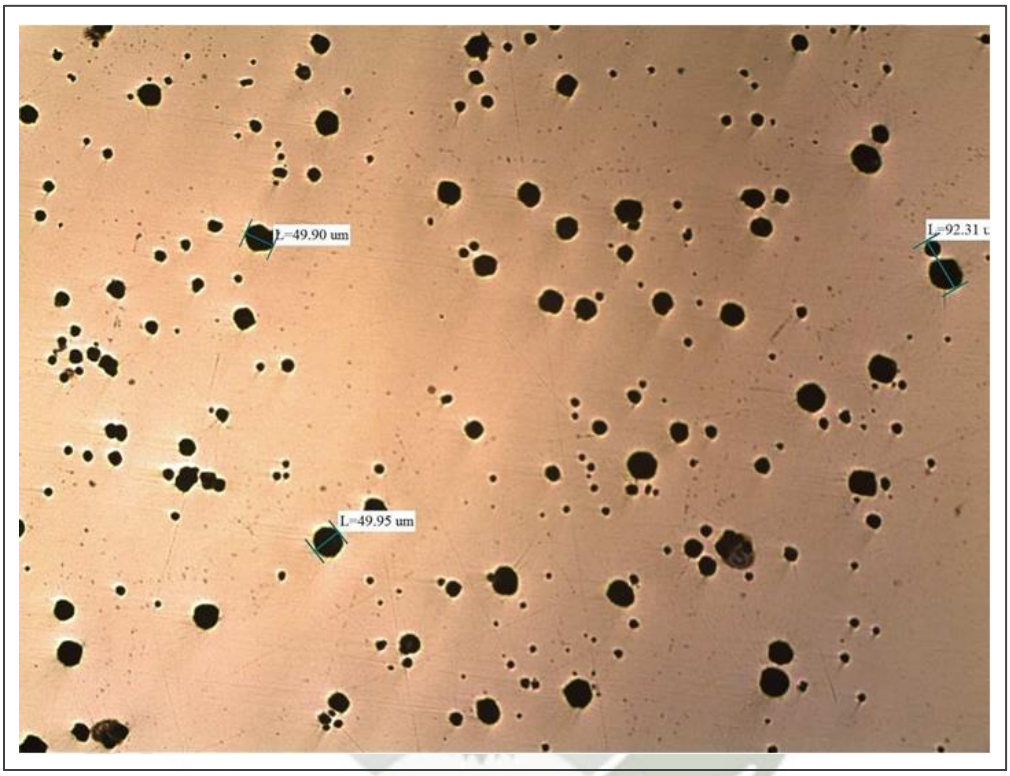


**Figura 5.6. Probeta 1 enfriada a 600 °C. Se muestra una gran cantidad de inclusiones tipo silicato, la mayor de ellas con una dimensión de 49,95 µm. 100X.**

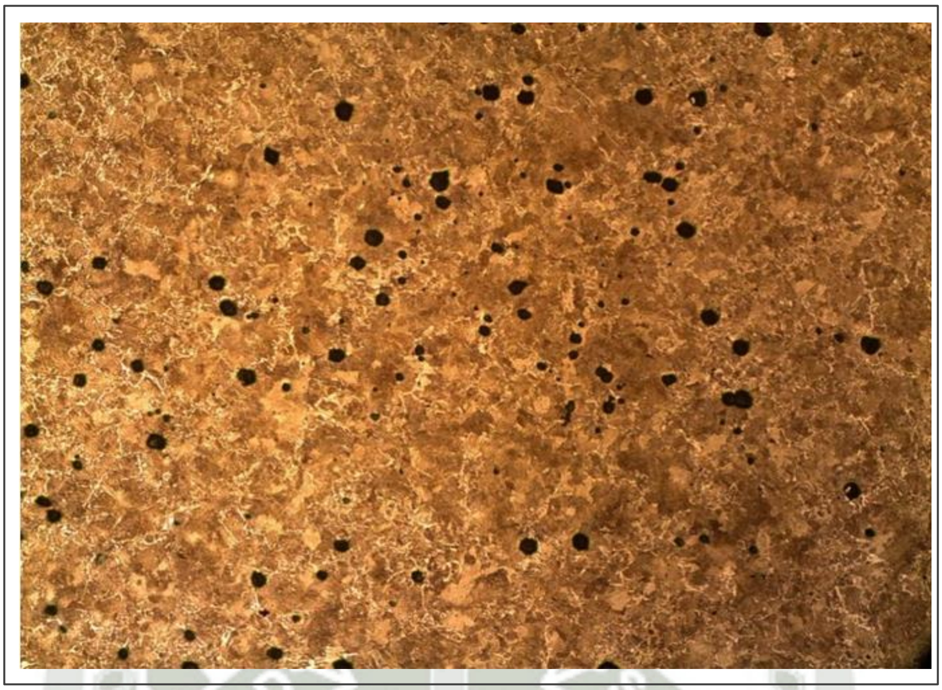


**Figura 5.7. Probeta 1 enfriada a 600 °C. Acero ferrítico-perlítico de contenido medio de Carbono, tratado térmicamente. Se observa gran cantidad de inclusiones tipo silicato. Tamaño de grano ASTM No 9.**

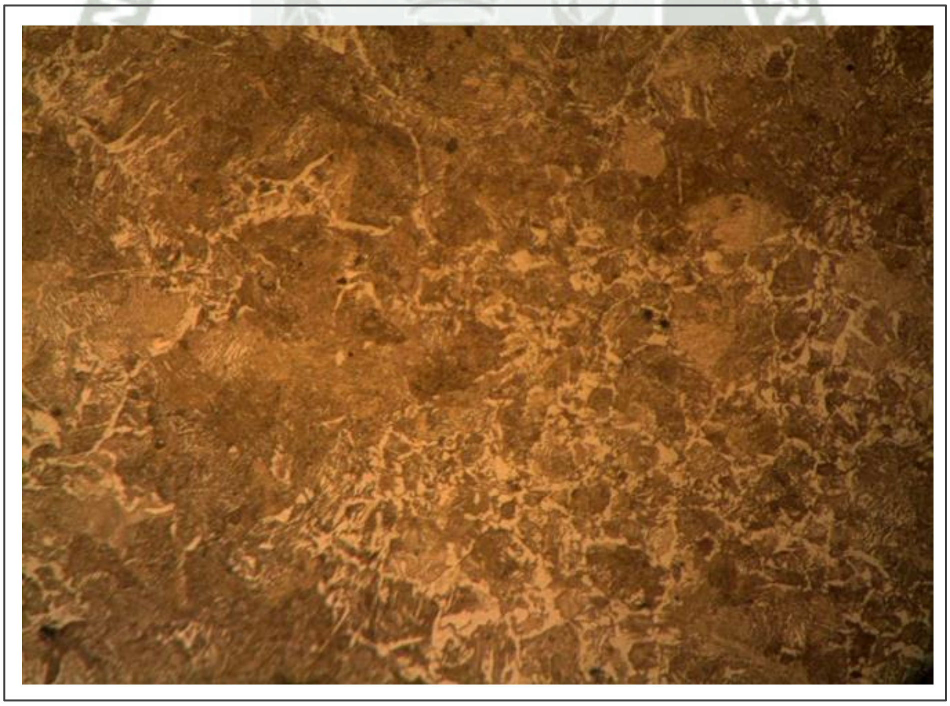


**Figura 5.8. Probeta 1 enfriada a 600 °C. Matriz metálica ferrítico-perlítica. Se observa la presencia de perlita fina y ferrita acicular precipitada al borde de grano, con zonas de perlita laminar. 500X (Laboratorio UNSA)**

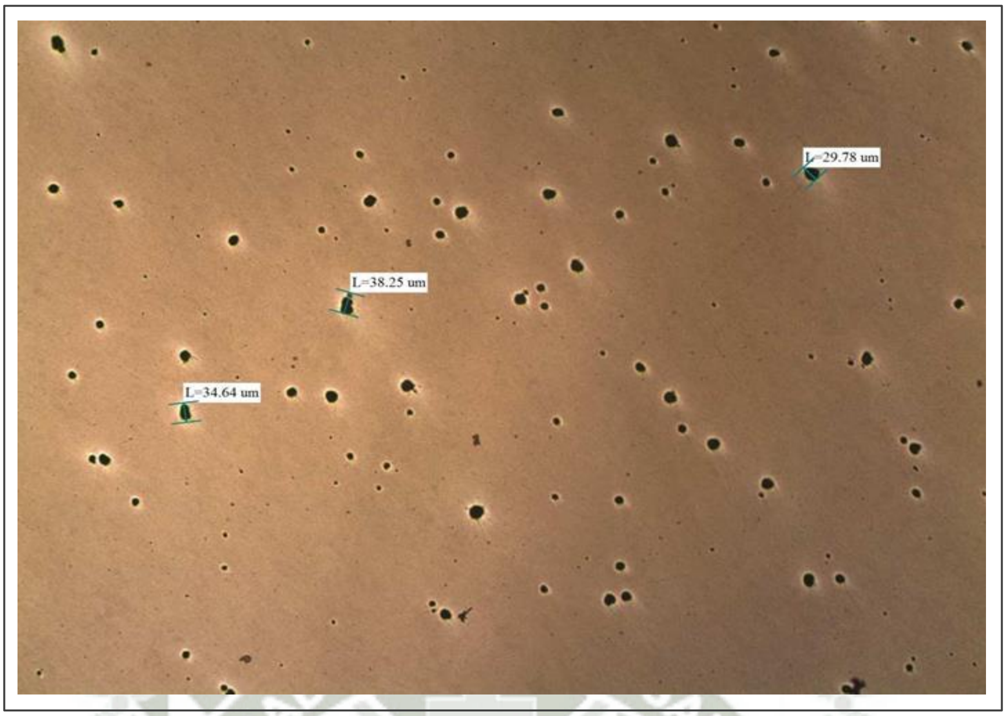


Figura 5.9. Probeta 2 enfriada a 500 °C. Se muestra una gran cantidad de inclusiones tipo silicato, la mayor de ellas con una dimensión de 38,25 µm. 100X

Figura 5.10. Probeta 2 enfriada a 500 °C. Acero ferrítico-perlítico de contenido medio de Carbono, tratado térmicamente. Se observan inclusiones tipo silicato. 100X

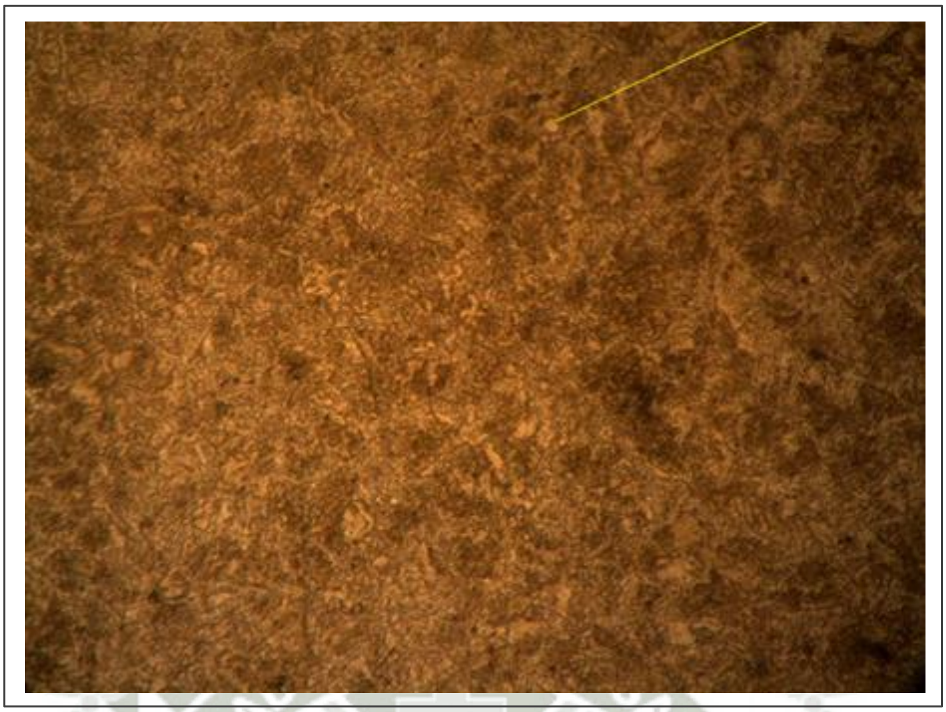


Figura 5.11. Probeta 2 enfriada a 500 °C. Matriz metálica ferrítico-perlítica. Se observa la presencia de perlita fina y sulfuros de Manganeso. 500X

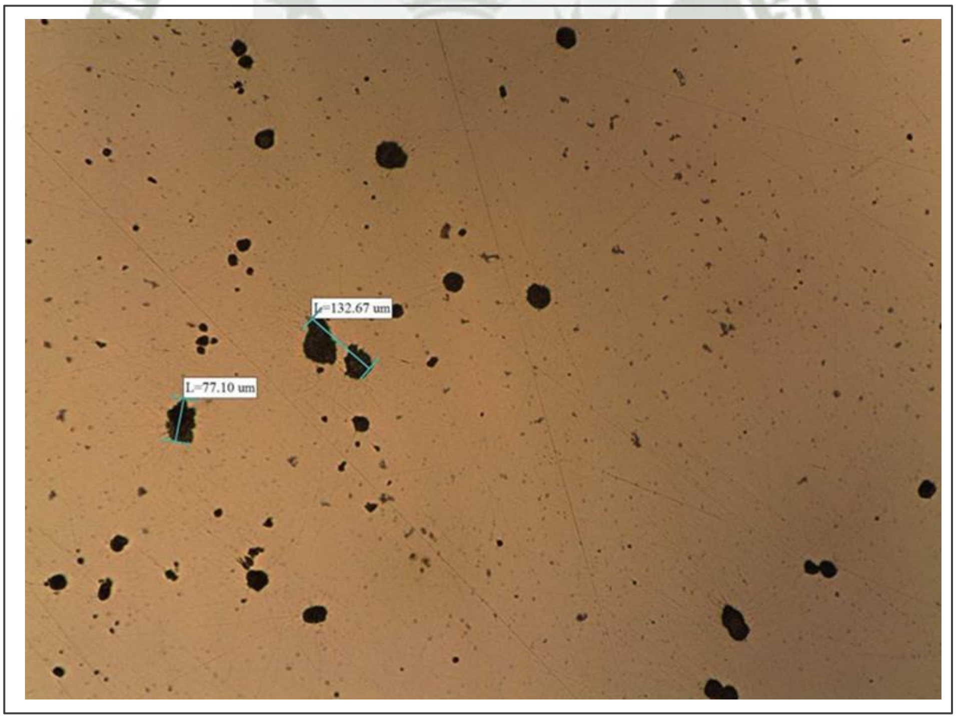


Figura 5.12. Probeta 3 enfriada a 380 °C. Se observan inclusiones tipo silicato, la mayor de ellas con una dimensión de 77,10 µm. 100X

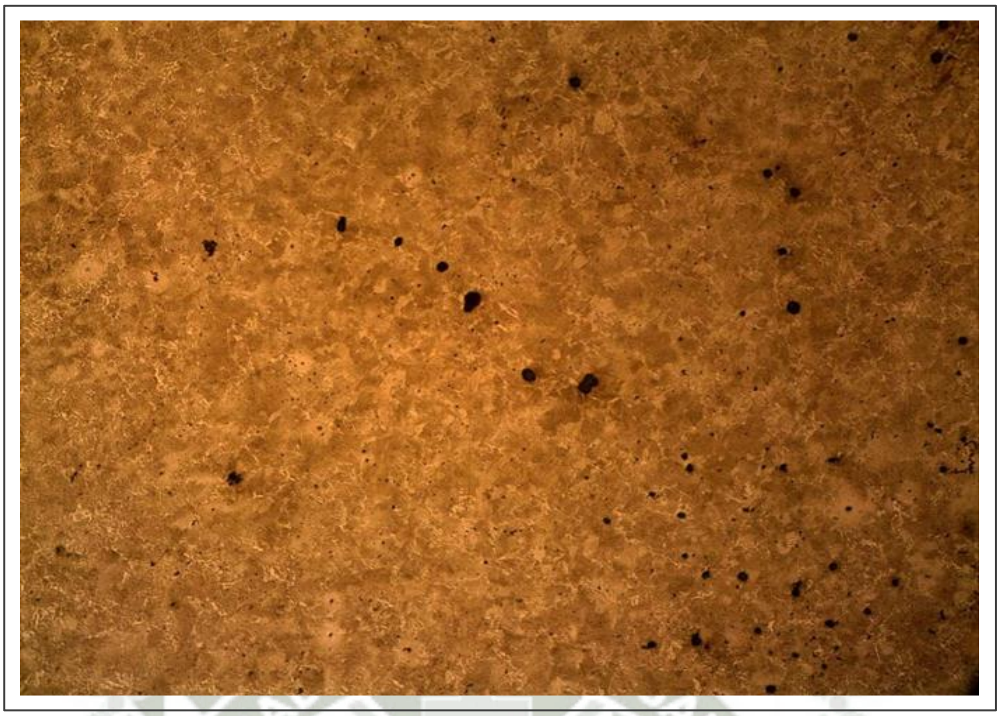


Figura 5.13. Probeta 3 enfriada a 380 °C. Acero ferrítico perlítico tratado térmicamente, de contenido medio de Carbono. Se observan inclusiones tipo silicato. 100X

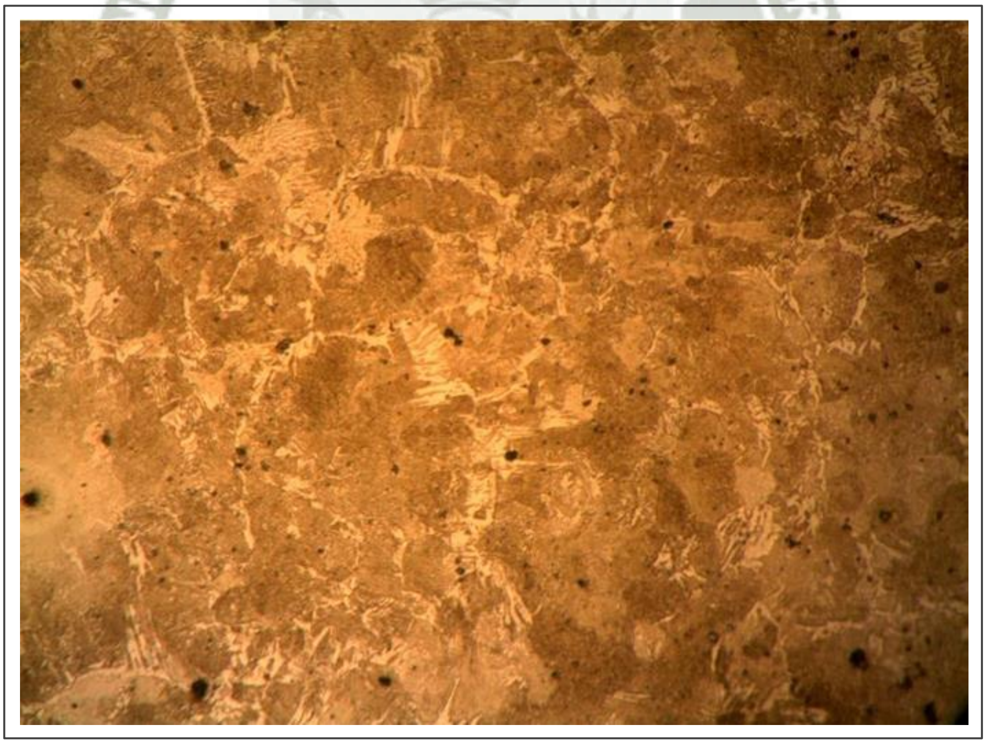


Figura 5.14. Probeta 3 enfriada a 380 °C. Matriz metálica ferrítico-perlítica. Se observa la presencia de perlita fina, ferrita acicular al borde de grano y bainita superior. 500X

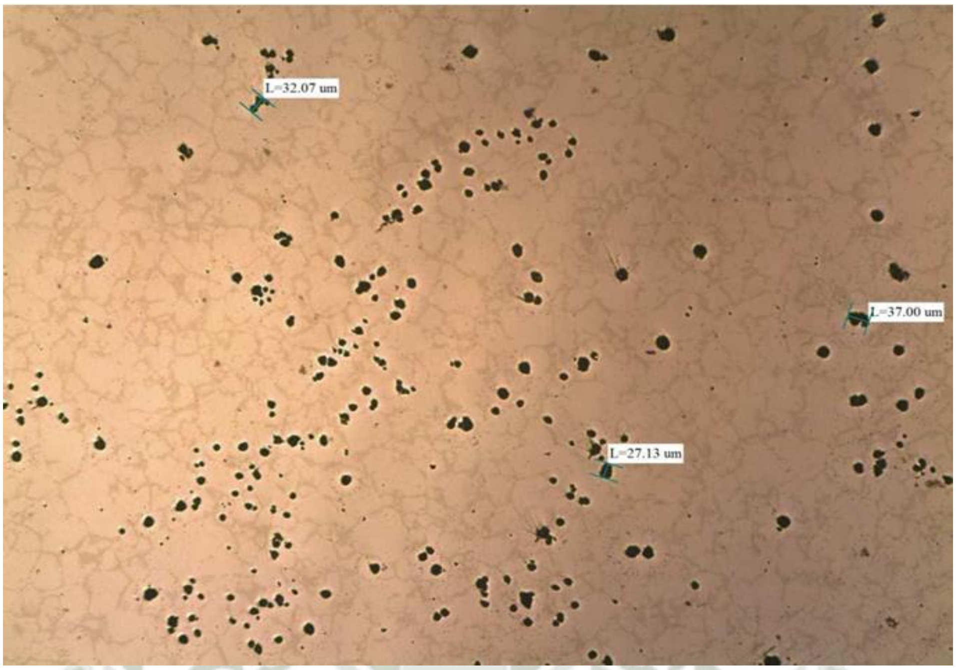


**Figura 5.15. Probeta 4 enfriada a 200 °C. Se observa gran cantidad de inclusiones tipo silicato, la mayor de ellas con una dimensión de 37,00 µm. 100X**

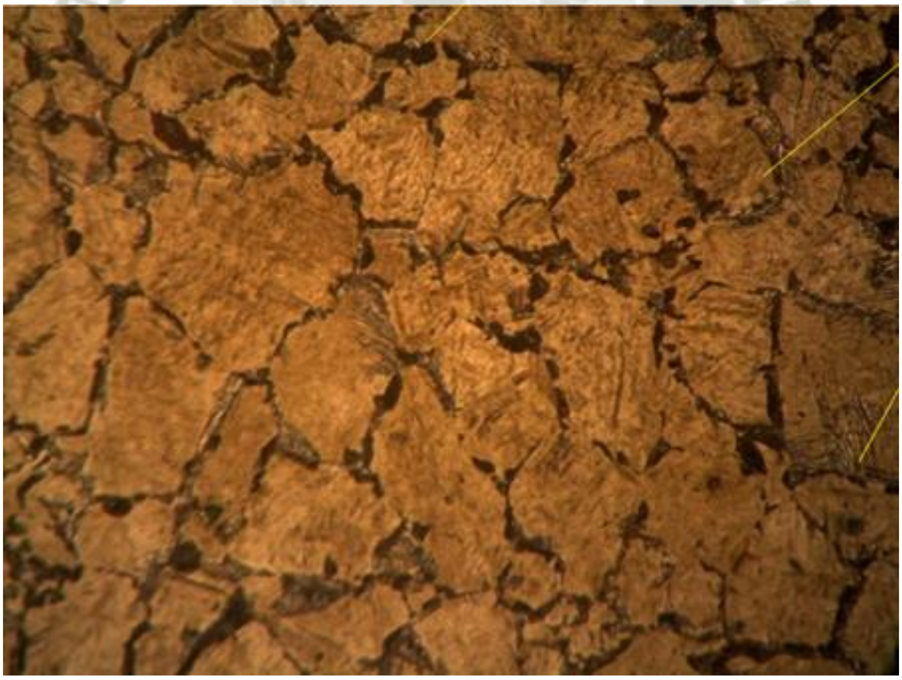


**Figura 5.16. Probeta 4 enfriada 200 °C. Matriz metálica bainítica con carburos de Cromo precipitados al borde de grano. La microestructura muestra también zonas con martensita. 500X**

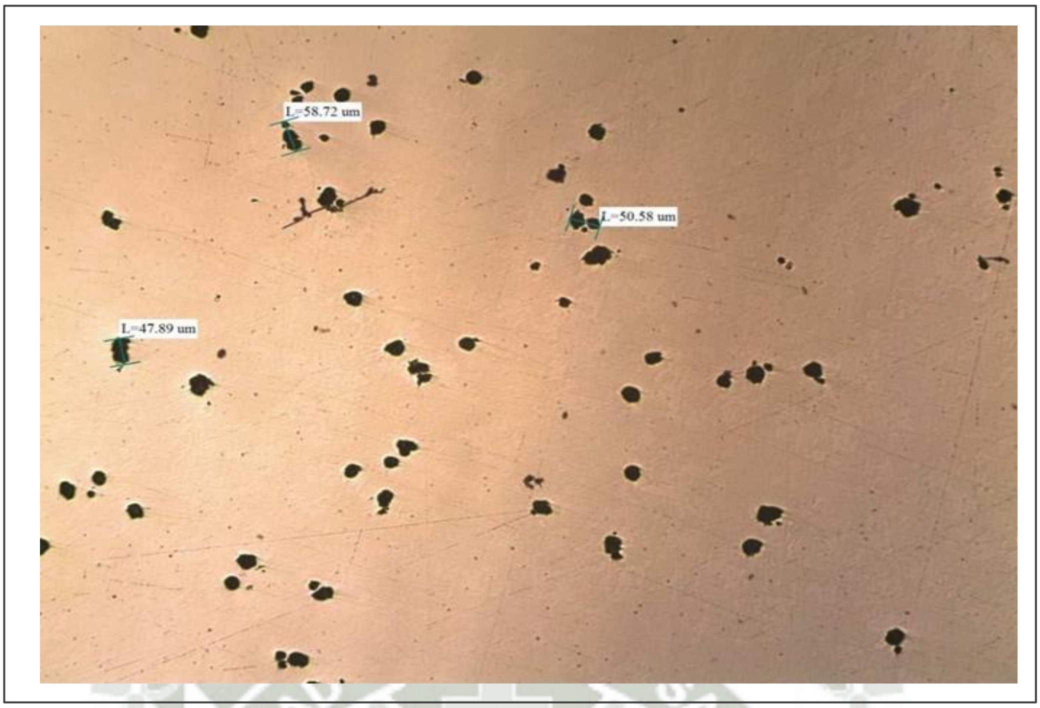


Figura 5.17. Probeta 5 enfriada en ACEITE. Se observan inclusiones tipo silicato, la mayor de ellas con una dimensión de 47,89 µm. 100X

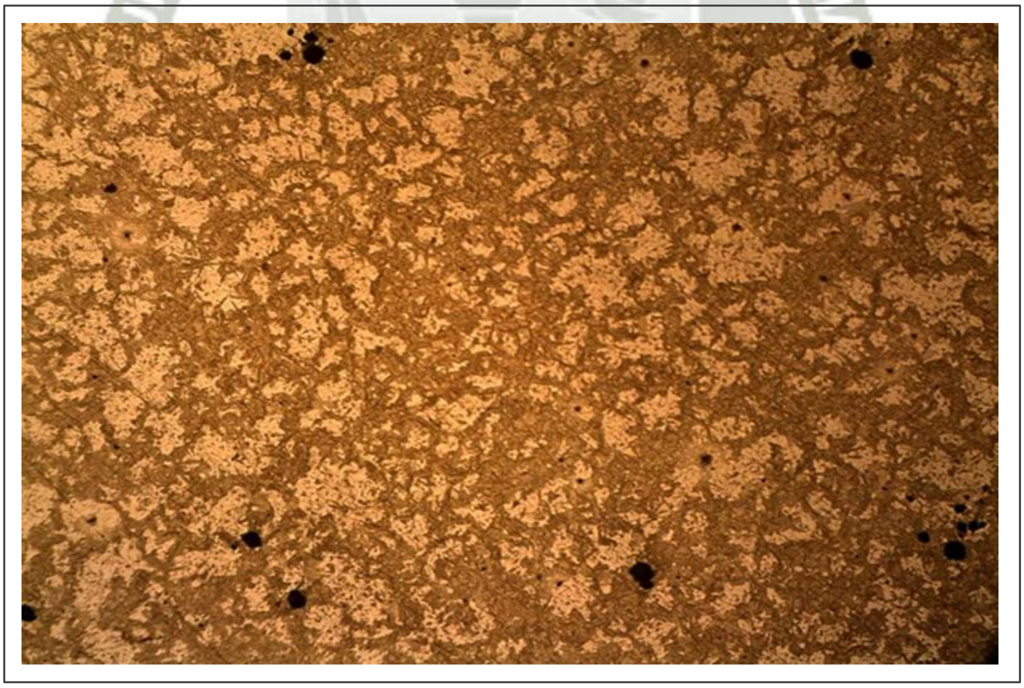


Figura 5.18. Probeta 5 enfriada en ACEITE. Acero ferrítico-perlítico tratado térmicamente. Se observan inclusiones tipo silicato. 100X

## 5.10 EQUIPOS UTILIZADOS EN EL EXPERIMENTO

Figura 5.19. Horno eléctrico

Figura 5.20. Durometro zwick/roell modelo: indentec

Figura 5.21. Microscopio metalográfico

Figura 5.22. Máquina de Charpy

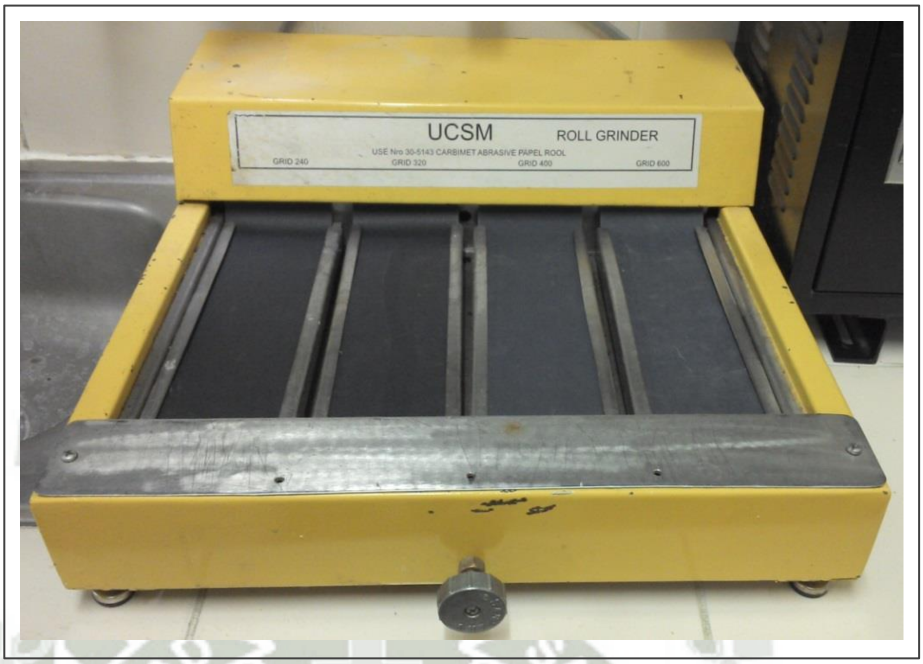


Figura 5.23. Equipo de Desbaste Fino

Figura 5.24. Equipo de Pulido Fino

Figura 5.25. Máquina de Ensayo de Tracción

Figura 5.26. Probetas ensayo tracción: acero C 45E-EN 1008

Figura 5.27. Ensayo de tracción

Máquina Universal de Ensayos Electrónica - Sistema de Medición y Control

Carga kN 90.36

Máximo 91.44

Deformación (mm) 25.976

Desplazamiento Transversal(mm) 25.977

Tiempo ensayo (s) 78.0

Figura 5.28. Resultados del Ensayo de Tracción

# VI. CONCLUSIONES

1. Después de haber efectuado una serie de pruebas experimentales del tratamiento térmico de bonificado con miras a verificar el efecto de las variables, temperatura, tiempo de austenización y temperatura de revenido, podemos establecer que la dureza se valora cuando realizamos el temple a 850°C con un tiempo de austenización de 30 minutos y 300°C como temperatura de revenido, obteniéndose una dureza promedio máximo de 110.86 HRB, lo que confirma que si es posible incrementar su dureza controlando adecuadamente las variables de temple y revenido.

2. El análisis de varianza nos permite afirmar que los parámetros evaluados, el que mayor significancia tiene en el proceso es la temperatura de temple y temperatura de revenido y más no el tiempo de austenización.

3. El análisis del diseño factorial que maximiza la dureza, confirma que los variables óptimos son la temperatura de temple a 880°C, tiempo de austenización 15 minutos y temperatura de revenido 350°C dando un valor óptimo de dureza de 112.156 HRB.

4. De los resultados que hemos obtenido como consecuencia de las pruebas experimentales, comparado con los resultados teóricos se concluye que eligiendo y realizando el tratamiento térmico adecuado se logra resultados óptimos requeridos de dureza, según posibles aplicaciones.

5. A partir del análisis de resultados y como consecuencia del diseño experimental, se han obtenido gráficas que muestran el efecto de revenido como tratamiento térmico complementario del temple a fin de obtener una dureza útil, lo cual demuestra que éste tratamiento térmico doble logra un equilibrio entre dureza y resistencia al acero.

6. Inicialmente el material presenta homogeneidad en sus propiedades físicas y mecánicas, esto indica que el material a trabajar, tiene las mismas propiedades elásticas en cualquier punto del cuerpo, pero a su vez existen mínimas diferencias.

7. El acero C 45E-EN 10083 después de haber sido sometido a un tratamiento térmico de temple, cambió de ser homogéneo a heterogéneo, esto implica que se incrementó su oxidación como una reacción a la corrosión, lo que produce también cambios en la estructura física y mecánica del material.

8. Luego de revenir el acero C 45E-EN 10083, este pasa de ser heterogéneo a homogéneo completamente en toda su estructura. El proceso térmico de revenido consigue, en aceros templados, disminuir tanto dureza como resistencia y a su vez elimina las tensiones que se crean en este tipo de material, optimizando de este modo su tenacidad y además deja al acero con la resistencia o dureza que se desea.

9. De las anteriores conclusiones se infiere que la primera etapa del bonificado, es decir el temple ayuda a aumentar tanto la dureza como la resistencia del acero C 45E-EN 10083. El acero luego del templado, se convierte en un material que si bien es mucho más duro que el mismo material sin templar, a su vez se vuelve mucho más frágil a temperatura ambiente, es por esto que con la segunda etapa del bonificado o sea el proceso térmico de revenido se evita que cuando al material se le aplique alguna tensión, este no se rompa o quiebre con relativa facilidad. En palabras sencillas, para obtener propiedades mecánicas superiores garantizadas en el acero C 45E-EN 10083 es indispensable aplicar un tratamiento de bonificado o mejorado.

# VII. RECOMENDACIONES

1. Las muestras deben entrar al horno completamente desengrasado y exento de óxidos, para evitar la formación de productos de combustión, ya que estos interactúan con la superficie calentada, esto produce la oxidación y descarburación de la capa superficial del acero, disminuyendo la dureza.

2. Una vez alcanzada la temperatura prefijada de calentamiento se expone la muestra a esta temperatura durante cierto tiempo para lograr su calentamiento total en toda la sección y homogenización de la austenita en todo su volumen.

3. Ampliar el estudio a piezas terminadas, para así tener una idea más clara de la importancia del proceso de tratamiento térmico y continuar con los estudios metalúrgicos y pruebas experimentales en otros aceros que actualmente se encuentra en el mercado, evaluando otros parámetros del proceso de bonificado.

4. Se recomienda hacer un análisis del proceso de bonificado mediante la aplicación de técnicas de difracción de rayos X para la obtención de difractogramas que muestren los parámetros de red del acero C 45E-EN 10083 luego del templado y luego del revenido para así comparar los cambios en la relación de parámetros c/a de la martensita (variaciones de su tetragonalidad) que va a tener un gran influencia en la fijación de un temperatura exacta de austenización, que finalmente influirá en una dureza satisfactoria del acero.

5. En futuros estudios se recomienda utilizar la técnica de elementos finitos a fin de simular las condiciones exactas de las pruebas y por otra parte permitiría validar los resultados obtenidos experimentalmente ya que esta técnica, reduce la necesidad de realizar pruebas de laboratorio, que generalmente son de un elevado costo y también permite ampliar el campo de investigación en el tema.

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# IX. ANEXOS

1. NORMA ASTM E8/E8M-09 Ensayo de Tracción (CD1).
2. NORMA ASTM E23 Ensayo Charpy (CD1).

Designation: E8/E8M – 09

American Association State
Highway and Transportation Officials Standard
AASHTO No.: T68
An American National Standard

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

This standard is issued under the fixed designation E8/E8M; 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.

1.2 The gage lengths for most round specimens are required to be 4D for E8 and 5D for E8M. The gage length is the most significant difference between E8 and E8M Test Specimens 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.

1.3 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 A370 and Test Methods B557, and B557M.

1.4 Room temperature shall be considered to be 10 to 38°C [50 to 100°F] unless otherwise specified.

1.5 The values stated in SI units are to be regarded as separate from inch/pound units. The values stated in each system are not exact equivalents; therefore each system must be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.6 *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:*[2]

A356/A356M Specification for Steel Castings, Carbon, Low Alloy, and Stainless Steel, Heavy-Walled for Steam Turbines
A370 Test Methods and Definitions for Mechanical Testing of Steel Products
B557 Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products
B557M Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products (Metric)
E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
E83 Practice for Verification and Classification of Extensometer Systems
E345 Test Methods of Tension Testing of Metallic Foil
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E1012 Practice for Verification of Test Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application
E1856 Guide for Evaluating Computerized Data Acquisition Systems Used to Acquire Data from Universal Testing Machines

## 3. Terminology

3.1 *Definitions*—The definitions of terms relating to tension testing appearing in Terminology E6 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—in a uniaxial test*, 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 *elongation at fracture*—the elongation measured just prior to the sudden decrease in force associated with fracture. For many 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.

3.1.3 *lower yield strength, LYS* $[FL^{-2}]$*—in a uniaxial test*, the minimum stress recorded during discontinuous yielding, ignoring transient effects.

3.1.4 *uniform elongation*, $El_u$, [%]—the elongation determined at the maximum force sustained by the test piece just prior to necking or fracture, or both.

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[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.

Current edition approved Dec. 1, 2009. Published December 2009. Originally approved in 1924. Last previous edition approved 2008 as E8/E8M – 08. DOI: 10.1520/E0008_E0008M-09.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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

3.1.4.1 *Discussion*—Uniform elongation includes both elastic and plastic elongation.

3.1.5 *upper yield strength, UYS [FL$^{-2}$]—in a uniaxial test*, the first stress maximum (stress at first zero slope) associated with discontinuous yielding at or near the onset of plastic deformation.

3.1.6 *yield point elongation, YPE—in a uniaxial test*, 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 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 E4. 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 E4.

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 1—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 [0.500-in.] diameter specimen, the stress increase is 1.5 percentage points for each 0.025 mm [0.001 in.] of eccentricity. This error increases to 2.5 percentage points/ 0.025 mm [0.001 in.] for a 9 mm [0.350-in.] diameter specimen and to 3.2 percentage points/ 0.025 mm [0.001 in.] for a 6-mm [0.250-in.] diameter specimen.

NOTE 2—Alignment methods are given in Practice E1012.

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 proven 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 Figs. 5 and 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.

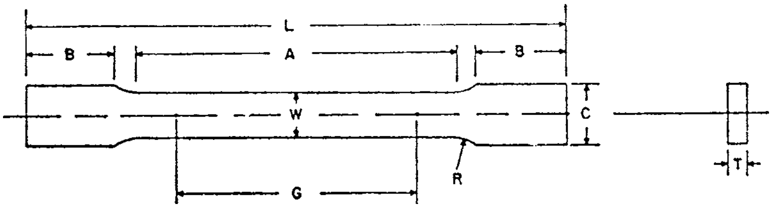
5.4 *Extensometers*—Extensometers used in tension testing shall conform to the requirements of Practice E83 for the classifications specified by the procedure section of this test method. Extensometers shall be used and verified to include the strains corresponding to the yield strength and elongation at fracture (if determined).

5.4.1 Extensometers with gage lengths equal to or shorter than the nominal gage length of the specimen (dimension 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.



| Dimensions | | | |
|---|---|---|---|
| | Standard Specimens | | Subsize Specimen |
| | Plate-Type, 40 mm [1.500 in.] Wide | Sheet-Type, 12.5 mm [0.500 in.] Wide | 6 mm [0.250 in.] Wide |
| | mm [in.] | mm [in.] | mm [in.] |
| *G*—Gage length (Note 1 and Note 2) | 200.0 ± 0.2<br>[8.00 ± 0.01] | 50.0 ± 0.1<br>[2.000 ± 0.005] | 25.0 ± 0.1<br>[1.000 ± 0.003] |
| *W*—Width (Note 3 and Note 4) | 40.0 ± 2.0<br>[1.500 ± 0.125, -0.250] | 12.5 ± 0.2<br>[0.500 ± 0.010] | 6.0 ± 0.1<br>[0.250 ± 0.005] |
| *T*—Thickness (Note 5) | | thickness of material | |
| *R*—Radius of fillet, min (Note 6) | 25 [1] | 12.5 [0.500] | 6 [0.250] |
| *L*—Overall length, min (Note 2, Note 7, and Note 8) | 450 [18] | 200 [8] | 100 [4] |
| *A*—Length of reduced section, min | 225 [9] | 57 [2.25] | 32 [1.25] |
| *B*—Length of grip section, min (Note 9) | 75 [3] | 50 [2] | 30 [1.25] |
| *C*—Width of grip section, approximate (Note 4 and Note 9) | 50 [2] | 20 [0.750] | 10 [0.375] |

NOTE 1—For the 40 mm [1.500 in.] 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 [1 in.] apart, or one or more pairs of punch marks 200 mm [8 in.] apart may be used.

NOTE 2—When elongation measurements of 40 mm [1.500 in.] wide specimens are not required, a minimum length of reduced section (*A*) of 75 mm [2.25 in.] may be used with all other dimensions similar to those of 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 [0.004, 0.002 or 0.001 in.], 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 [1.500 in.] wide specimens shall be 5 mm [0.188 in.]. Maximum thickness of 12.5 and 6 mm [0.500 and 0.250 in.] wide specimens shall be 19 and 6 mm [0.750 and 0.250 in.], respectively.

NOTE 6—For the 40 mm [1.500 in.] wide specimen, a 13 mm [0.500 in.] minimum radius at the ends of the reduced section is permitted for steel specimens under 690 MPa [100 000 psi] 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 [0.250-in.] wide specimens, the overall length should be as large as the material will permit, up to 200 mm [8.00 in.].

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 [0.500-in.] wide specimens is over 10 mm [0.375 in.], 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 [0.10, 0.01 and 0.005 in.], respectively. However, for referee testing and when required by product specifications, the ends of the 12.5 mm [0.500 in.] wide specimen shall be symmetrical within 0.2 mm [0.01 in.].

NOTE 11—For each specimen type, the radii of all fillets shall be equal to each other within a tolerance of 1.25 mm [0.05 in.], 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 0.2 mm [0.01 in.].

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**

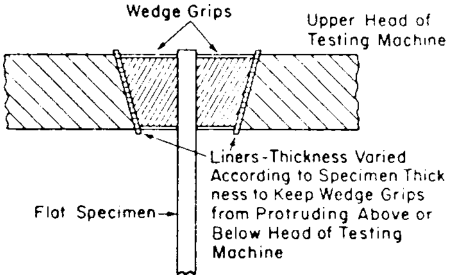


FIG. 2 Wedge Grips with Liners for Flat Specimens

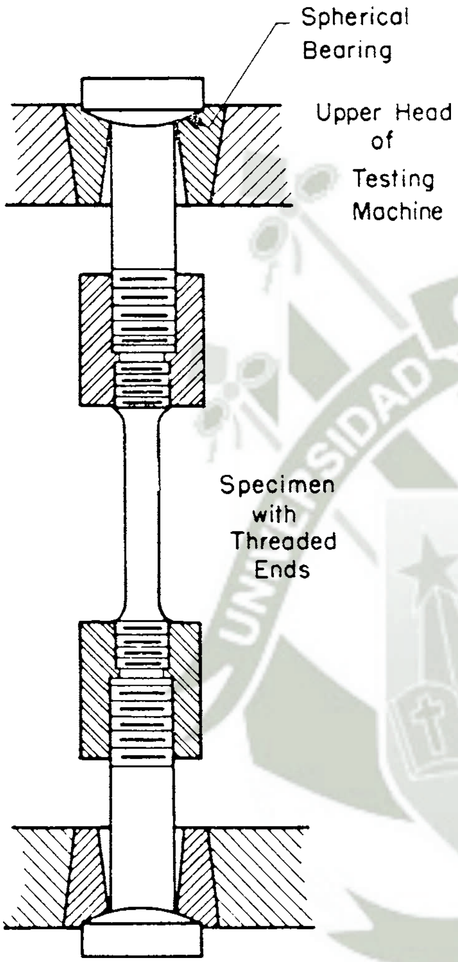


FIG. 3 Gripping Device for Threaded-End Specimens

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 [1.500 in.] 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 [1.500 in.] 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.

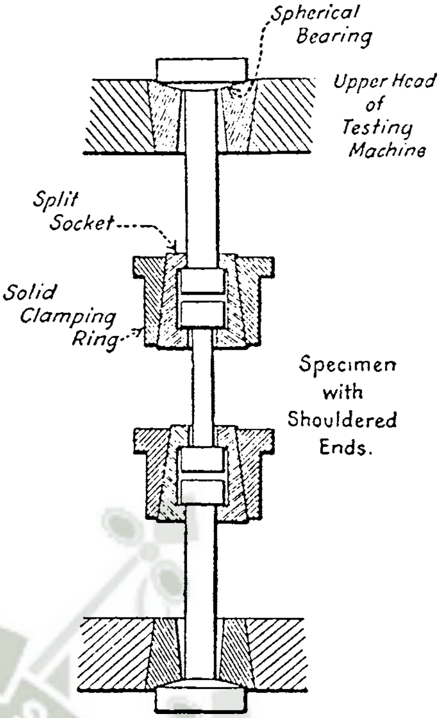


FIG. 4 Gripping Device for Shouldered-End Specimens

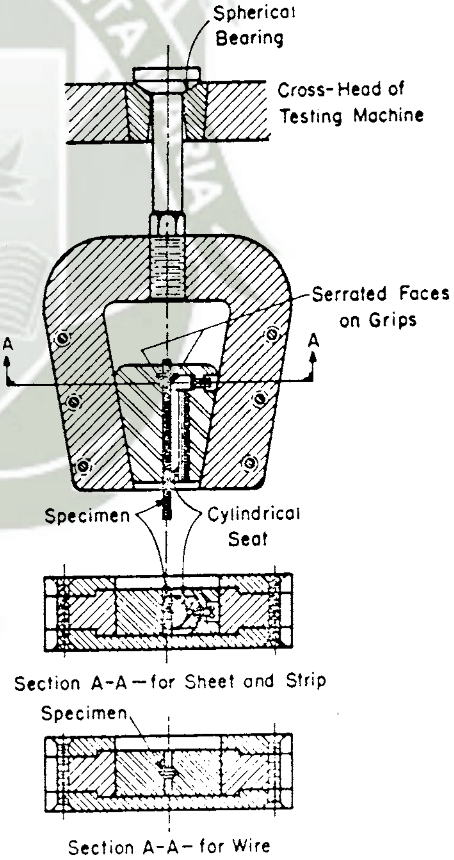


FIG. 5 Gripping Devices for Sheet and Wire Specimens

6.1.3.1 The reduced sections of prepared specimens should be free of cold work, notches, chatter marks, grooves, gouges,

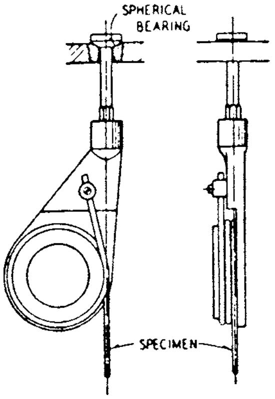


**FIG. 6 Snubbing Device for Testing Wire**

burrs, rough surfaces or edges, overheating, or any other condition which can deleteriously affect the properties to be measured.

NOTE 3—Punching or blanking of the 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 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 should be as provided in the applicable product specifications.

NOTE 4—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.

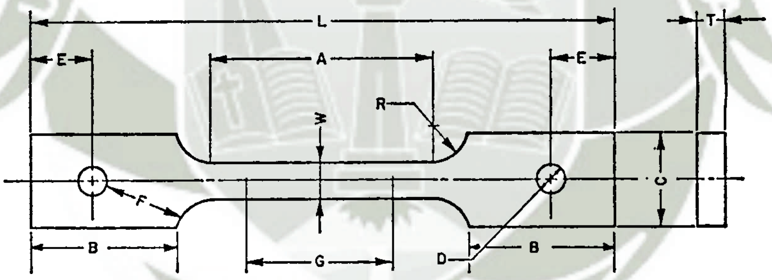
6.2 *Plate-Type Specimens*—The standard plate-type test specimen is shown in Fig. 1. This specimen is used for testing metallic materials in the form of plate, shapes, and flat material having a nominal thickness of 5 mm [0.188 in.] or over. When product specifications so permit, other types of specimens 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 [0.005 to 0.750 in.]. When product specifications so permit, other types of specimens may be used, as provided in 6.2, 6.4, and 6.5.

NOTE 5—Test Methods E345 may be used for tension testing of materials in thicknesses up to 0.15 mm [0.0059 in.].

6.3.2 Pin ends as shown in Fig. 7 may be used. In order to



| | Dimensions, mm [in.] |
|---|---|
| *G*—Gage length | 50.0 ± 0.1 [2.000 ± 0.005] |
| *W*—Width (Note 1) | 12.5 ± 0.2 [0.500 ± 0.010] |
| *T*—Thickness, max (Note 2) | 16 [0.625] |
| *R*—Radius of fillet, min (Note 3) | 13 [0.5] |
| *L*—Overall length, min | 200 [8] |
| *A*—Length of reduced section, min | 57 [2.25] |
| *B*—Length of grip section, min | 50 [2] |
| *C*—Width of grip section, approximate | 50 [2] |
| *D*—Diameter of hole for pin, min (Note 4) | 13 [0.5] |
| *E*—Edge distance from pin, approximate | 40 [1.5] |
| *F*—Distance from hole to fillet, min | 13 [0.5] |

NOTE 1—The ends of the reduced section shall differ in width by not more than 0.1 mm [0.002 in.]. 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 [0.500 in.] may be needed.

NOTE 4—Holes must be on center line of reduced section within ± 0.05mm [0.002 in].

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 [2-in.] Gage Length**

avoid buckling in tests of thin and high-strength materials, it may be necessary to use stiffening plates at the grip ends.

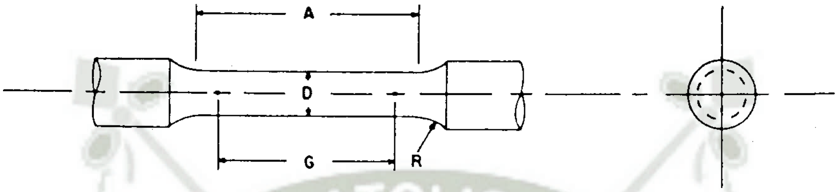
6.4 *Round Specimens*:

6.4.1 The standard 12.5-mm [0.500-in.] 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 four times the diameter of the specimen when following E8 and five times the diameter of the specimen when following E8M.

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, Strip, Flat Wire, and Plate*—In testing sheet, strip, flat wire, and plate, use a specimen type appropriate for the nominal thickness of the material, as described in the following:



Dimensions, mm [in.]
For Test Specimens with Gage Length Four times the Diameter [E8]

| | Standard Specimen | Small-Size Specimens Proportional to Standard | | | |
|---|---|---|---|---|---|
| | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 | Specimen 5 |
| *G*—Gage length | 50.0 ± 0.1<br>[2.000 ± 0.005] | 36.0 ± 0.1<br>[1.400 ± 0.005] | 24.0 ± 0.1<br>[1.000 ± 0.005] | 16.0 ± 0.1<br>[0.640 ± 0.005] | 10.0 ±0.1<br>[0.450 ± 0.005] |
| *D*—Diameter (Note 1) | 12.5 ± 0.2<br>[0.500 ± 0.010] | 9.0 ±0.1<br>[0.350 ± 0.007] | 6.0 ± 0.1<br>[0.250 ± 0.005] | 4.0 ± 0.1<br>[0.160 ± 0.003] | 2.5 ± 0.1<br>[0.113 ± 0.002] |
| *R*—Radius of fillet, min | 10 [0.375] | 8 [0.25] | 6 [0.188] | 4 [0.156] | 2 [0.094] |
| *A*—Length of reduced section, min (Note 2) | 56 [2.25] | 45 [1.75] | 30 [1.25] | 20 [0.75] | 16 [0.625] |

Dimensions, mm [in.]
For Test Specimens with Gage Length Five times the Diameter [E8M]

| | Standard Specimen | Small-Size Specimens Proportional to Standard | | | |
|---|---|---|---|---|---|
| | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 | Specimen 5 |
| *G*—Gage length | 62.5 ± 0.1<br>[2.500 ± 0.005] | 45.0 ± 0.1<br>[1.750 ± 0.005] | 30.0 ± 0.1<br>[1.250 ± 0.005] | 20.0 ± 0.1<br>[0.800 ± 0.005] | 12.5 ± 0.1<br>[0.565 ± 0.005] |
| *D*—Diameter (Note 1) | 12.5 ± 0.2<br>[0.500 ± 0.010] | 9.0 ± 0.1<br>[0.350 ± 0.007] | 6.0 ± 0.1<br>[0.250 ± 0.005] | 4.0 ± 0.1<br>[0.160 ± 0.003] | 2.5 ± 0.1<br>[0.113 ± 0.002] |
| *R*—Radius of fillet, min | 10 [0.375] | 8 [0.25] | 6 [0.188] | 4 [0.156] | 2 [0.094] |
| *A*—Length of reduced section, min (Note 2) | 75 [3.0] | 54 [2.0] | 36 [1.4] | 24 [1.0] | 20 [0.75] |

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.

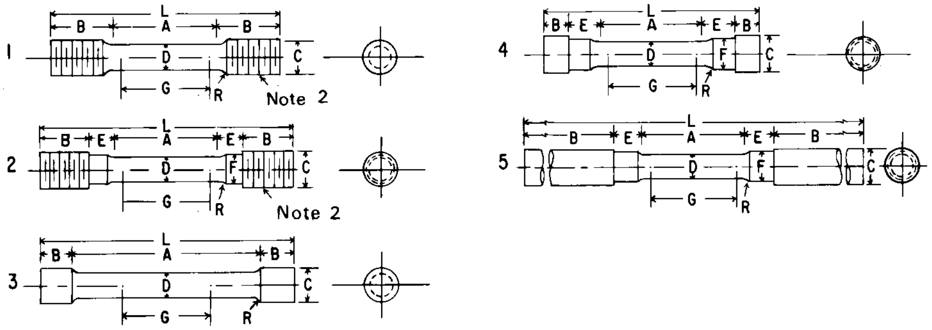
NOTE 3—The gage length and fillets may be as shown, but the ends may be of any form to fit the holders of the testing machine in such a way that the force shall be axial (see Fig. 9). If the ends are to be held in wedge grips it is desirable, if possible, to make the length of the grip section great 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 four [E8] or five times [E8M] the nominal diameter. In some product specifications other specimens may be provided for, but unless the 4-to-1 [E8] or 5-to-1 [E8M] 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 [0.250-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.

NOTE 6—For inch/pound units only: Five sizes of specimens often used have diameters of approximately 0.505, 0.357, 0.252, 0.160, and 0.113 in., the reason being to permit easy calculations of stress from loads, since the corresponding cross-sectional areas are equal or close to 0.200, 0.100, 0.0500, 0.0200, and 0.0100 in.$^2$, respectively. Thus, when the actual diameters agree with these values, the stresses (or strengths) may be computed using the simple multiplying factors 5, 10, 20, 50, and 100, respectively. (The metric equivalents of these five diameters do not result in correspondingly convenient cross-sectional areas and multiplying factors.)

**FIG. 8 Standard 12.5-mm [0.500-in.] Round Tension Test Specimen and Examples of Small-Size Specimens Proportional to the Standard Specimen**



Dimensions, mm [in.]
For Test Specimens with Gage Length Four times the Diameter [E8]

| | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 | Specimen 5 |
|---|---|---|---|---|---|
| *G*—Gage length | 50 ± 0.1<br>[2.000 ± 0.005] | 50 ± 0.1<br>[2.000 ± 0.005] | 50 ± 0.1<br>[2.000 ± 0.005] | 50 ± 0.1<br>[2.000 ± 0.005] | 50 ± 0.1<br>[2.000 ± 0.005] |
| *D*—Diameter (Note 1) | 12.5 ± 0.2<br>[0.500 ± 0.010] | 12.5 ± 0.2<br>[0.500 ± 0.010] | 12.5 ± 0.2<br>[0.500 ± 0.010] | 12.5 ± 0.2<br>[0.500 ± 0.010] | 12.5 ± 0.2<br>[0.500 ± 0.010] |
| *R*—Radius of fillet, min | 10 [0.375] | 10 [0.375] | 2 [0.0625] | 10 [0.375] | 10 [0.375] |
| *A*—Length of reduced section | 56 [2.25] min | 56 [2.25] min | 100 [4] approximate | 56 [2.25] min | 56 [2.25] min |
| *L*—Overall length, approximate | 145 [5] | 155 [5.5] | 155 [5.5] | 140 [4.75] | 255 [9.5] |
| *B*—Length of end section (Note 3) | 35 [1.375] approximate | 25 [1] approximate | 20 [0.75] approximate | 15 [0.5] approximate | 75 [3] min |
| *C*—Diameter of end section | 20 [0.75] | 20 [0.75] | 20 [0.75] | 22 [0.875] | 20 [0.75] |
| *E*—Length of shoulder and fillet section, approximate | | 15 [0.625] | | 20 [0.75] | 15 [0.625] |
| *F*—Diameter of shoulder | | 15 [0.625] | | 15 [0.625] | 15 [0.625] |

Dimensions, mm [in.]
For Test Specimens with Gage Length Five times the Diameter [E8M]

| | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 | Specimen 5 |
|---|---|---|---|---|---|
| *G*—Gage length | 62.5 ± 0.1<br>[2.500 ± 0.005] | 62.5 ± 0.1<br>[2.500 ± 0.005] | 62.5 ± 0.1<br>[2.500 ± 0.005] | 62.5 ± 0.1<br>[2.500 ± 0.005] | 62.5 ± 0.1<br>[2.500 ± 0.005] |
| *D*—Diameter (Note 1) | 12.5 ± 0.2<br>[0.500 ± 0.010] | 12.5 ± 0.2<br>[0.500 ± 0.010] | 12.5 ± 0.2<br>[0.500 ± 0.010] | 12.5 ± 0.2<br>[0.500 ± 0.010] | 12.5 ± 0.2<br>[0.500 ± 0.010] |
| *R*—Radius of fillet, min | 10 [0.375] | 10 [0.375] | 2 [0.0625] | 10 [0.375] | 10 [0.375] |
| *A*—Length of reduced section | 75 [3] min | 75 [3] min | 75 [3] approximate | 75 [3] min | 75 [3] min |
| *L*—Overall length, approximate | 145 [5] | 155 [5.5] | 155 [5.5] | 140 [4.75] | 255 [9.5] |
| *B*—Length of end section (Note 3) | 35 [1.375] approximate | 25 [1] approximate | 20 [0.75] approximate | 15 [0.5] approximate | 75 [3] min |
| *C*—Diameter of end section | 20 [0.75] | 20 [0.75] | 20 [0.75] | 22 [0.875] | 20 [0.75] |
| *E*—Length of shoulder and fillet section, approximate | | 15 [0.625] | | 20 [0.75] | 15 [0.625] |
| *F*—Diameter of shoulder | | 15 [0.625] | | 15 [0.625] | 15 [0.625] |

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.

NOTE 4—The values stated in SI units in the table for Fig. 9 are to be regarded as separate from the inch/pound units. The values stated in each system are not exact equivalents; therefore each system must be used independently of the other.

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

6.5.1 For material with a nominal thickness of 0.13 to 5 mm [0.005 to 0.1875 in.], use the sheet-type specimen described in 6.3.

6.5.2 For material with a nominal thickness of 5 to 12.5 mm [0.1875 to 0.500 in.], use either the sheet-type specimen of 6.3 or the plate-type specimen of 6.2.

6.5.3 For material with a nominal thickness of 12.5 to 19 mm [0.500 to 0.750 in.], use either the sheet-type specimen of 6.3, the plate-type specimen of 6.2, or the largest practical size of round specimen described in 6.4.

6.5.4 For material with a nominal thickness of 19 mm [0.750 in.], or greater, use the plate-type specimen of 6.2 or the largest practical size of round specimen described in 6.4.

6.5.4.1 If the product specifications permit, material of a thickness of 19 mm [ 0.750 in.], or greater may be tested using a modified sheet-type specimen conforming to the configuration shown by Fig. 1. The thickness of this modified specimen must be machined to 10 ± 0.5 mm [0.400 ± 0.020 in.], and must be uniform within 0.1 mm [0.004 in.] throughout the reduced section. In the event of disagreement, a round specimen shall be used as the referee (comparison) 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 [0.125 in.] in diameter shall be as prescribed in product specifications. When testing wire, rod, or bar having a diameter of 4-mm [0.125-in.] or larger diameter, a gage length equal to four times the diameter shall be used when following E8 and a gage length equal to five times the diameter shall be used when following E8M unless otherwise specified. 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 6)—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 [0.188 in.] 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 [0.188 in.] in diameter or distance between flats, the diameter or distance between flats may be reduced by not more than 0.25 mm [0.010 in.] without changing the shape of the cross section. Square, hexagonal, or octagonal wire or rod not exceeding 5 mm [0.188 in.] 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 [0.375 in.], but not less than 3 mm [0.125 in.], shall be used at the ends of the reduced sections. Square, hexagonal, or octagonal rod over 5 mm [0.188 in.] between flats may be turned to a round having a diameter no smaller than 0.25 mm [0.010 in.] less than the original distance between flats.

NOTE 6—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 [¾ in.] in length shall be parallel to each other and to the longitudinal axis of the specimen within 0.05 mm [0.002 in.]. Fillets, preferably with a radius of 10 mm [⅜ in.] but not less than 3 mm [⅛ in.] shall be used at the ends of the reduced sections.

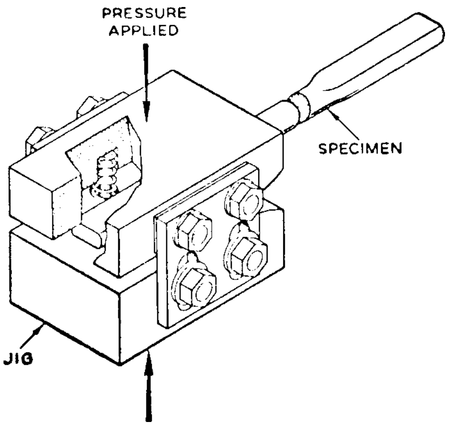


**FIG. 10 Squeezing Jig for Flattening Ends of Full-Size Tension Test Specimens**

6.7.2 Rectangular bar 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 not be 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.

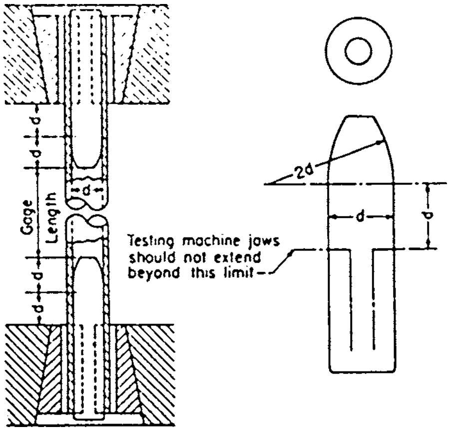
6.8 *Shapes, Structural and Other*—In testing shapes other than those covered by the preceding sections, one of the types of specimens described in 6.2, 6.3, and 6.4 shall be used.

6.9 *Specimens for Pipe and Tube* (Note 7):

6.9.1 For all small tube (Note 7), particularly sizes 25 mm [1 in.] and under in nominal outside diameter, and frequently for 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 four times the diameter when following E8 or five times the diameter when following E8M 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.

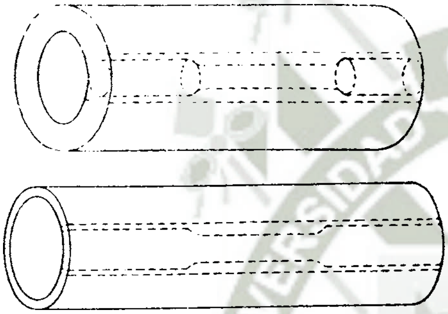
NOTE 7—The term "tube" is used to indicate tubular products in general, and includes pipe, tube, and tubing.

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 [0.750 in.], 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 [0.500-in.] specimen, as mentioned in 6.4.2 and shown in Fig. 8, shall be used. Specimens of the type shown in Fig. 13 may be tested



NOTE—The diameter of the plug shall have a slight taper from the line limiting the test 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**



NOTE—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**

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 [0.750 in.] or over, the standard specimen shown in Fig. 8 shall be used.

NOTE 8—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 [0.750 in.] 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 [0.750 in.] 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 Figs. 19 and 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

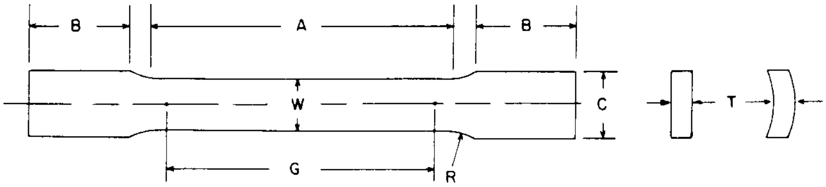
7.1 *Preparation of the Test Machine*—Upon startup, or following a prolonged period of machine inactivity, the test machine should be exercised or warmed up to normal operating temperatures to minimize errors that may result from transient conditions.

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 less than 5 mm [0.188 in.] 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 as follows:

*(1)* Specimen dimension ≥ 5 mm [0.200 in.] to the nearest 0.02 mm [0.001 in.].

*(2)* 2.5 mm [0.100 in.] ≤ Specimen dimension < 5 mm [0.200 in.] to the nearest 0.01 mm [0.0005 in.].



| Dimensions | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 | Specimen 5 | Specimen 6 | Specimen 7 |
| | mm [in.] | mm [in.] | mm [in.] | mm [in.] | mm [in.] | mm [in.] | mm [in.] |
| *G*—Gage length | 50.0 ± 0.1<br>[2.000 ± 0.005] | 50.0 ± 0.1<br>[2.000 ± 0.005] | 200.0 ± 0.2<br>[8.00 ± 0.01] | 50.0 ± 0.1<br>[2.000 ± 0.005] | 100.0 ± 0.1<br>[4.000 ± 0.005] | 50.0 ± 0.1<br>[2.000 ± 0.005] | 100.0 ± 0.1<br>[4.000 ± 0.005] |
| *W*—Width (Note 1) | 12.5 ± 0.2<br>[0.500 ± 0.010] | 40.0 ± 2.0<br>[1.5 ± 0.125-0.25] | 40.0 ± 0.2<br>[1.5 ± 0.125,-0.25] | 20.0 ± 0.7<br>[0.750 ± 0.031] | 20.0 ± 0.7<br>[0.750 ± 0.031] | 25.0 ± 1.5<br>[1.000 ± 0.062] | 25.0 ± 1.5<br>[1.000 ± 0.062] |
| *T*—Thickness | measured thickness of specimen | | | | | | |
| *R*—Radius of fillet, min | 12.5 [0.5] | 25 [1] | 25 [1] | 25 [1] | 25 [1] | 25 [1] | 25 [1] |
| *A*—Length of reduced section, min | 60 [2.25] | 60 [2.25] | 230 [9] | 60 [2.25] | 120 [4.5] | 60 [2.25] | 120 [4.5] |
| *B*—Length of grip section, min (Note 2) | 75 [3] | 75 [3] | 75 [3] | 75 [3] | 75 [3] | 75 [3] | 75 [3] |
| *C*—Width of grip section, approximate (Note 3) | 20 [0.75] | 50 [2] | 50 [2] | 25 [1] | 25 [1] | 40 [1.5] | 40 [1.5] |

NOTE 1—The ends of the reduced section shall differ from each other in width by not more than 0.5 %. 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 mm [0.05 in.] for specimens 1, 4, and 5, and 2.5 mm [0.10 in.] for specimens 2, 3, 6, and 7.

NOTE 4—For each specimen type, the radii of all fillets shall be equal to each other within a tolerance of 1.25 mm [ 0.05 in.], 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 [0.10 in.].

NOTE 5—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 1⁄6, the error in using this method to calculate the cross-sectional area may be appreciable. In this case, the exact equation (see 7.2.3) must be used to determine the area.

NOTE 6—Specimens with *G/W* less than 4 should not be used for determination of elongation.

NOTE 7—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. 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**

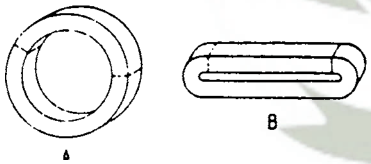


**FIG. 14 Location of Transverse Tension Test Specimen in Ring Cut from Tubular Products**

*(3)* 0.5 mm [0.020 in.] ≤ specimen dimension < 2.5 mm [0.100 in.] to the nearest 0.002 mm [0.0001 in.].

*(4)* Specimen dimensions < 0.5 mm [0.020 in.], to at least the nearest 1 % when practical but in all cases to at least the nearest 0.002 mm [0.0001 in.].

NOTE 9—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 10—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 test specimens with rough surfaces due to processing may be measured and recorded to the nearest 0.02 mm [0.001 in.]

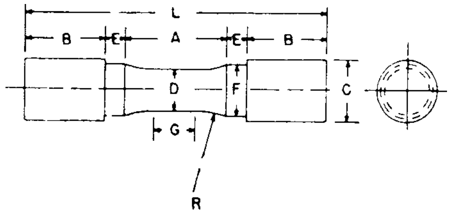
NOTE 11—See X2.9 for cautionary information on measurements taken from coated metal products.

7.2.2 Determine the cross-sectional area of a full-size test specimen of uniform but nonsymmetrical cross section by determining the mass of a length not less than 20 times longer than the largest cross-sectional dimension.

7.2.2.1 Determine the weight to the nearest 0.5 % or less.

7.2.2.2 The cross-sectional area is equal to the mass of the specimen divided by the length and divided by the density of the material.

7.2.3 When using specimens of the type shown in Fig. 13 taken from tubes, the cross-sectional area shall be determined as follows:



| | Dimensions | | |
|---|---|---|---|
| | Specimen 1 | Specimen 2 | Specimen 3 |
| | mm [in.] | mm [in.] | mm [in.] |
| *G*—Length of parallel section | Shall be equal to or greater than diameter *D* | | |
| *D*—Diameter | 12.5 ± 0.2<br>[0.500 ± 0.010] | 20 ± 0.4<br>[0.750 ± 0.015] | 36.0 ± 0.6<br>[1.25 ± 0.02] |
| *R*—Radius of fillet, min | 25 [1] | 25 [1] | 50 [2] |
| *A*—Length of reduced section, min | 32 [1.25] | 38 [1.5] | 60 [2.25] |
| *L*—Overall length, min | 95 [3.75] | 100 [4] | 160 [6.375] |
| *B*—Length of end section, approximate | 25 [1] | 25 [1] | 45 [1.75] |
| *C*—Diameter of end section, approximate | 20 [0.75] | 30 [1.125] | 48 [1.875] |
| *E*—Length of shoulder, min | 6 [0.25] | 6 [0.25] | 8 [0.312] |
| *F*—Diameter of shoulder | 16.0 ± 0.4<br>[0.625 ± 0.016] | 24.0 ± 0.4<br>[0.94 ± 0.016] | 36.5 ± 0.4<br>[1.438 ± 0.016] |

NOTE—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 can 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**

If $D/W \leq 6$:

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

where:

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

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$^2$ [in.$^2$],
$W$ = width of the specimen in the reduced section, mm [in.], and
$T$ = measured wall thickness of the specimen, mm [in.].

NOTE 12—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.

7.3.2 For materials where the specified elongation is 3 % or less, measure the original gage length to the nearest 0.05 mm [0.002 in.] prior to testing.

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 13) 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.

NOTE 13—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 14—It is the operator's responsibility to verify that an observed preload is acceptable and to ensure that grips operate in a smooth manner. 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)* crosshead speed, *(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 15—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 mm/mm/min [in./in./min]. Some testing machines are equipped with pacing or indicating 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.

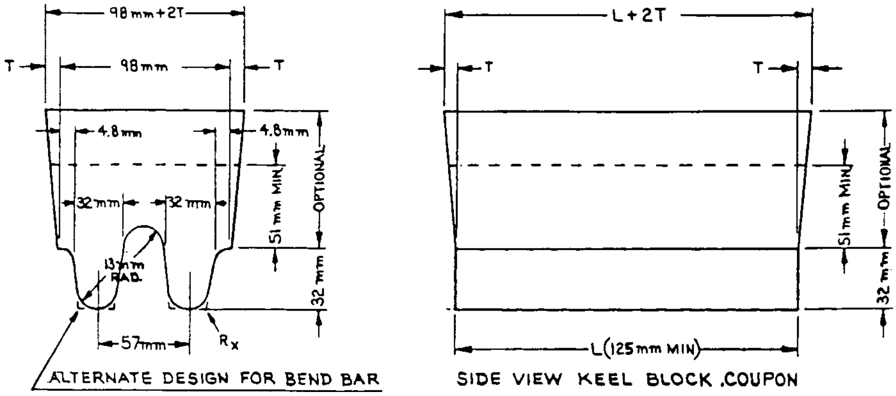
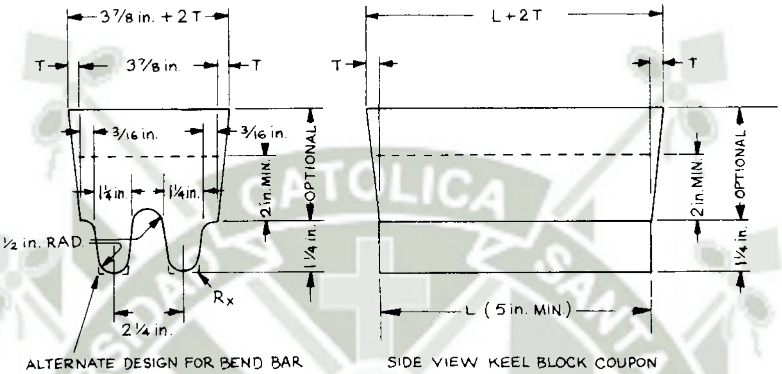
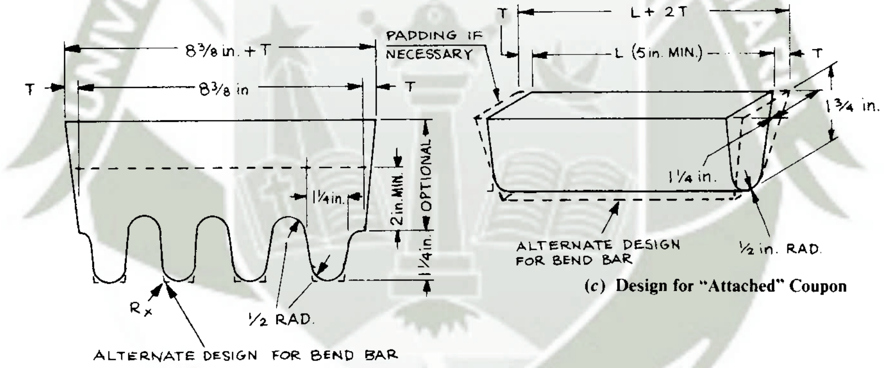


Fig. 16A Test Coupons for Castings (mm) (see Table 1 for Details of Design)



(*a*) Design for Double Keel Block Coupon



(*c*) Design for "Attached" Coupon

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

Fig. 16B Test Coupons for Castings (in.) (see Table 1 for Details of Design)

FIG. 16 Test Coupons for Castings

7.6.2.2 *Rate of Stressing*—The allowable limits for rate of stressing shall be specified in megapascals per second [pounds per square inch per minute]. 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.

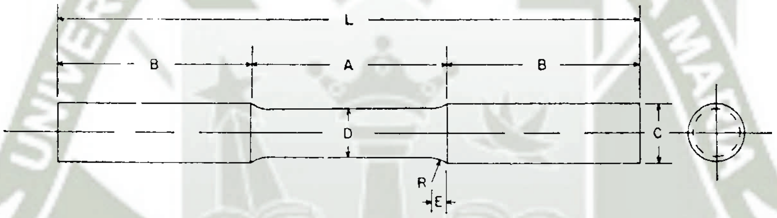
7.6.2.3 *Crosshead Speed*—The allowable limits for crosshead speed, during a test, may be specified in mm/min [in./min]; in this case, the limits for the crosshead speed should be further qualified by specifying different limits for various types and sizes of specimens. In cases where different length specimens may be used, it is often more practical to specify the crosshead speed in terms of mm [in.] per mm [in.] of length of the original reduced section of the specimen (or distance between grips for specimens not having reduced sections) per minute. Many testing machines are equipped with pacing or indicating devices for the measurement and control of the crosshead speed during a test, but in the absence of such

**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. 16A and B 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 A356/A356M.

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 [5 in.] | | Riser Design | |
|---|---|---|---|
| 1. *L* (length) | A125 mm [5-in.] 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 [*n* (2.25 in.) – 0.625 in.] 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 [1.25 in.] | | |
| 4. Width (at top) | 32 mm [1.25 in.] (see Note 1) | | |
| 5. Radius (at bottom) | 13 mm [0.5 in.] max | | |
| 6. Spacing between legs | A13 mm [0.5 in.] 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)<br>Height | Use of and size is at the option of the foundry.<br>The minimum height of the riser shall be 51 mm [2 in.]. 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 [0.062 in.] | | |



| Dimensions, mm [in.] | |
|---|---|
| *D*—Diameter | 16 [0.625] |
| *R*—Radius of fillet | 8 [0.312] |
| *A*—Length of reduced section | 64 [2.5] |
| *L*—Overall length | 190 [7.5] |
| *B*—Length of end section | 64 [2.5] |
| *C*—Diameter of end section | 20 [0.75] |
| *E*—Length of fillet | 5 [0.188] |

FIG. 17 Standard Tension Test Specimen for Malleable Iron

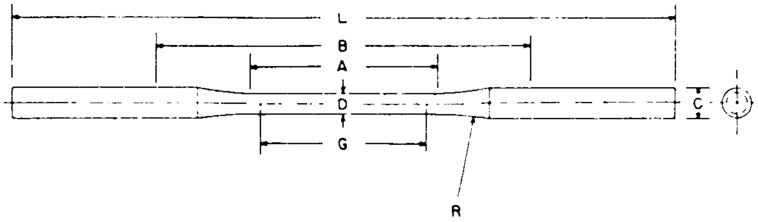
devices the average crosshead speed can be experimentally determined by using suitable length-measuring and timing devices.

NOTE 16—This method of specifying speed of testing, "Crosshead Speed", was previously called "Rate of Separation of Heads During Tests."

NOTE 17—For machines not having crossheads or having stationary crossheads, the phrase "crosshead speed" may be interpreted to mean the rate of grip separation.

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.

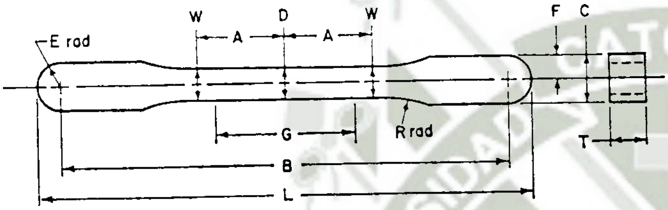
7.6.2.5 *Free-Running Crosshead Speed*—The allowable limits for the rate of movement of the crosshead of the testing machine, with no force applied by the testing machine, shall be specified in mm per mm [inches per inch] of length of reduced section (or distance between grips for specimens not having reduced sections) per second [minute]. The limits for the



| Dimensions, mm [in.] | |
|---|---|
| *G*—Gage length | 50 ± 0.1 [2.000 ± 0.005] |
| *D*—Diameter (see Note) | 6.4 ± 0.1 [0.250 ± 0.005] |
| *R*—Radius of fillet, min | 75 [3] |
| *A*—Length of reduced section, min | 60 [2.25] |
| *L*—Overall length, min | 230 [9] |
| *B*—Distance between grips, min | 115 [4.5] |
| *C*—Diameter of end section, approximate | 10 [0.375] |

NOTE—The reduced section may have a gradual taper from the end toward the center, with the ends not more than 0.1 mm [0.005 in.] larger in diameter than the center.

**FIG. 18 Standard Tension Test Specimens for Die Castings**



Pressing Area = 645 mm$^2$ [1.00 in.$^2$]

| Dimensions, mm [in.] | |
|---|---|
| *G*—Gage length | 25.4 ± 0.08 [1.000 ± 0.003] |
| *D*—Width at center | 5.72 ± 0.03 [0.225 ± 0.001] |
| *W*—Width at end of reduced section | 5.97 ± 0.03 [0.235 ± 0.001] |
| *T*—Compact to this thickness | 3.56 to 6.35 [0.140 to 0.250] |
| *R*—Radius of fillet | 25.4 [1] |
| *A*—Half-length of reduced section | 15.9 [0.625] |
| *B*—Grip length | 80.95 ± 0.03 [3.187 ± 0.001] |
| *L*—Overall length | 89.64 ± 0.03 [3.529 ± 0.001] |
| *C*—Width of grip section | 8.71 ± 0.03 [0.343 ± 0.001] |
| *F*—Half-width of grip section | 4.34 ± 0.03 [0.171 ± 0.001] |
| *E*—End radius | 4.34 ± 0.03 [0.171 ± 0.001] |

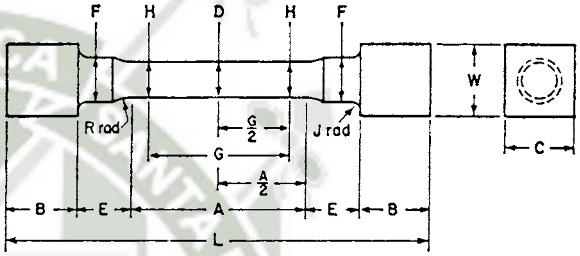
NOTE—Dimensions Specified, except *G* and *T*, are those of the die.

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

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 18—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 minimum yield strength or up to one quarter of the specified minimum tensile strength, whichever is smaller. The speed above this point shall be within the specified limits. If different speed limitations are required for use in determining yield strength,



Approximate Pressing Area of Unmachined Compact = 752 mm$^2$ [1.166 in.$^2$] Machining Recommendations

1. Rough machine reduced section to 6.35-mm [0.25-in.] diameter
2. Finish turn 4.75/4.85-mm [0.187/0.191-in.] diameter with radii and taper
3. Polish with 00 emery cloth
4. Lap with crocus cloth

| Dimensions, mm [in.] | |
|---|---|
| *G*—Gage length | 25.4 ± 0.08 [1.000 ± 0.003] |
| *D*—Diameter at center of reduced section | 4.75 ± 0.03 [0.187± 0.001] |
| *H*—Diameter at ends of gage length | 4.85 ± 0.03 [0.191 ± 0.001] |
| *R*—Radius of gage fillet | 6.35 ± 0.13 [0.250 ± 0.005] |
| *A*—Length of reduced section | 47.63 ± 0.13 [1.875 ± 0.003] |
| *L*—Overall length (die cavity length) | 75 [3], nominal |
| *B*—Length of end section | 7.88 ± 0.13 [0.310 ± 0.005] |
| *C*—Compact to this end thickness | 10.03 ± 0.13 [0.395 ± 0.005] |
| *W*—Die cavity width | 10.03 ± 0.08 [0.395 ± 0.003] |
| *E*—Length of shoulder | 6.35 ± 0.13 [0.250 ± 0.005] |
| *F*—Diameter of shoulder | 7.88 ± 0.03 [0.310 ± 0.001] |
| *J*—End fillet radius | 1.27 ± 0.13 [0.050 ± 0.005] |

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 [0.001 in.] 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**

yield point elongation, tensile strength, elongation, and reduction of area, they should be stated in the product specifications. In all cases, the speed of testing shall be such that the forces and strains used in obtaining the test results are accurately indicated. Determination of mechanical properties for comparison of product properties against a specification value should be run using the same control method and rate used to determine the specification value unless it can be shown that another method yields equivalent or conservative results. In the absence of any specified limitations, one of the following control methods shall be used. Appendix X4 provides additional guidance on selecting the control method.

NOTE 19—In the previous and following paragraphs, the yield properties referred to include yield strength, yield point, and yield point elongation.

7.6.3.1 *Control Method A—Rate of Stressing Method for Determining Yield Properties* - In this method, the testing machine shall be operated such that the rate of stress application in the linear elastic region is between 1.15 and 11.5 MPa/s [10 000 and 100 000 psi/min]. The speed of the testing machine shall not be increased in order to maintain a stressing rate when the specimen begins to yield. It is not recommended that the testing machine be operated in closed-loop control using the force signal through yield; however closed-loop control of the force signal can be used in the linear-elastic portion of the test.

NOTE 20—It is not the intent of this method to maintain constant stress rate or to control stress rate with closed loop force control while determining yield properties, but only to set the crosshead speed to achieve the target stress rate in the elastic region. 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 through the yielding process requires the testing machine to operate at extremely high speeds and, in most cases, this is neither practical nor desirable. In practice, it is simpler to use either a strain rate, crosshead speed, or a free-running crosshead speed that approximates the desired stressing rate in the linear-elastic portion of the test. As an example, use a strain rate that is between 1.15 and 11.5 MPa/s divided by the nominal Young's Modulus of the material being tested. As another example, find a crosshead speed through experimentation that approximates the desired stressing rate prior to the onset of yielding, and maintain that crosshead speed 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 are generally quite different in the region where yield properties are determined.

NOTE 21—This method has been the default method for many years for testing materials that exhibit low strain rate sensitivity such as some steels and aluminum.

7.6.3.2 *Control Method B - Rate of Straining Control Method for Determining Yield Properties* —In this method, the testing machine shall be operated in closed-loop control using the extensometer signal. The rate of straining shall be set and maintained at 0.015 ± 0.006 mm/mm/min [in./in./min].

NOTE 22—Proper precautions must be observed when operating a machine in closed-loop strain control because unexpected crosshead movement may occur if the control parameters are not set properly, if proper safety limits are not set, or if the extensometer slips.

NOTE 23—A Rate of Straining at 0.005 mm/mm/min [in./in./min] is often required for aerospace, high-temperature alloys, and titanium applications and when specified, must be followed rather than the requirement above.

7.6.3.3 *Control Method C—-Crosshead Speed Control Method for Determining Yield Properties*–The testing machine shall be set to a crosshead speed equal to 0.015 ± 0.003 mm/mm/min [in./in./min] of the original reduced section (dimension A in Fig. 1, Fig. 7, Fig. 8, Fig. 9, Fig. 13, Fig. 15, Fig. 17, Fig. 18, and Fig. 20, and 2 times dimension A in Fig. 19) or distance between grips for specimens without reduced sections.

NOTE 24—It is recommended that crosshead speed be used for control in regions of discontinuous yielding.

NOTE 25—Using different Control Methods may produce different yield results especially if the material being tested is strain-rate sensitive. To achieve the best reproducibility in cases where the material may be strain-rate sensitive, the same control method should be used. Methods described in 7.6.3.2 or 7.6.3.3 will tend to give similar results in the case of a strain-rate sensitive material. The control method described in 7.6.3.1 should be avoided for strain rate sensitive materials if it is desirable to reproduce similar test results on other testing machines or in other laboratories.

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 mm/mm [or in./in.] of the length of the reduced section (or distance between the grips for specimens not having a reduced section) per minute. Alternatively, an extensometer and strain rate indicator may be used to set the strain rate between 0.05 and 0.5 mm/mm/min [or in./in./min].

NOTE 26—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 27—Tensile strength and elongation are sensitive to test speed for many materials (see Appendix X1) 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 28—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 29—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 35). 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. Thus:

$$\text{Yield strength (offset} = 0.2\ \%) = 360\ \text{MPa}\ [52\ 000\ \text{psi}] \qquad (3)$$

In using this method, a Class B2 or better extensometer (see Practice E83) shall be used.

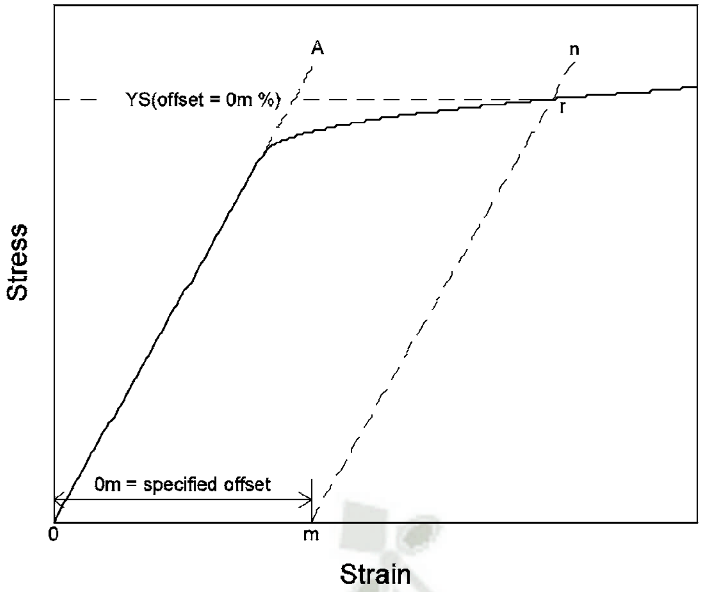


FIG. 21 Stress-Strain Diagram for Determination of Yield Strength by the Offset Method

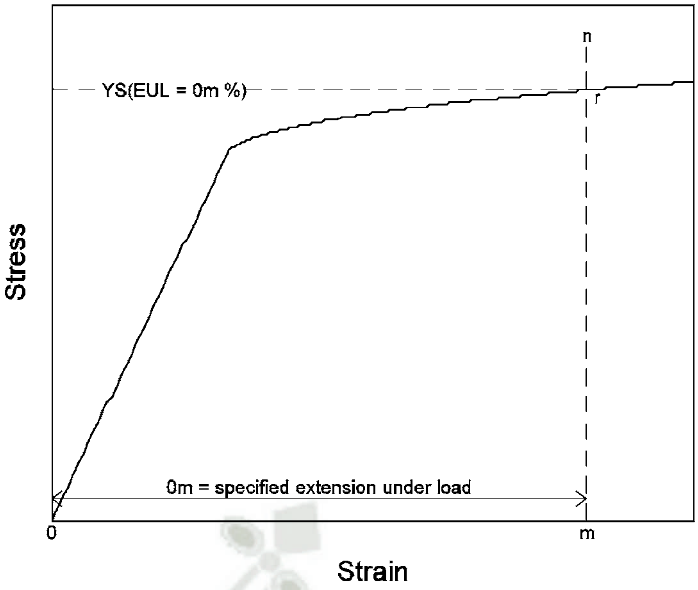


FIG. 22 Stress-Strain Diagram for Determination of Yield Strength by the Extension-Under-Load Method

NOTE 30—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 31—When there is a disagreement over yield properties, the offset method for determining yield strength is recommended as the referee method.

7.7.2 *Extension-Under-Load (EUL) 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 33). 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:

$$\text{Yield strength (EUL} = 0.5\ \%) = 52\ 000\ \text{psi} \quad (4)$$

Extensometers and other devices used in determination of the extension shall meet or exceed Class B2 requirements (see Practice E83) 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 32—The appropriate value of the total extension must be specified. For steels with nominal yield strengths of less than 550 MPa [80 000 psi], an appropriate value is 0.005 mm/mm [or in./in.] (0.5 %) of the gage length. For higher strength steels, a greater extension or the offset method should be used.

NOTE 33—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 [2 in.]. 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 force-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 Figs. 23 and 24.

NOTE 34—If multiple peaks are observed at the onset of discontinuous yielding, the first is considered the upper yield strength. (See Fig. 24.)

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.

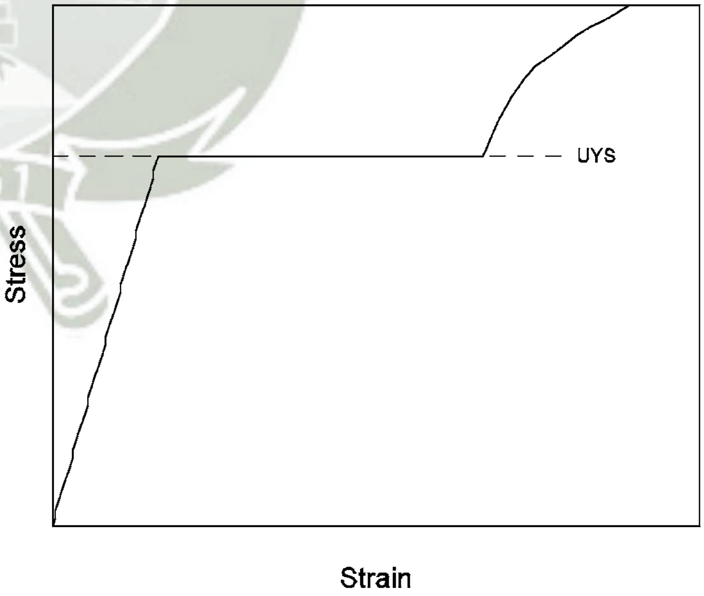


FIG. 23 Stress-Strain Diagram Showing Upper Yield Strength Corresponding with Top of Knee

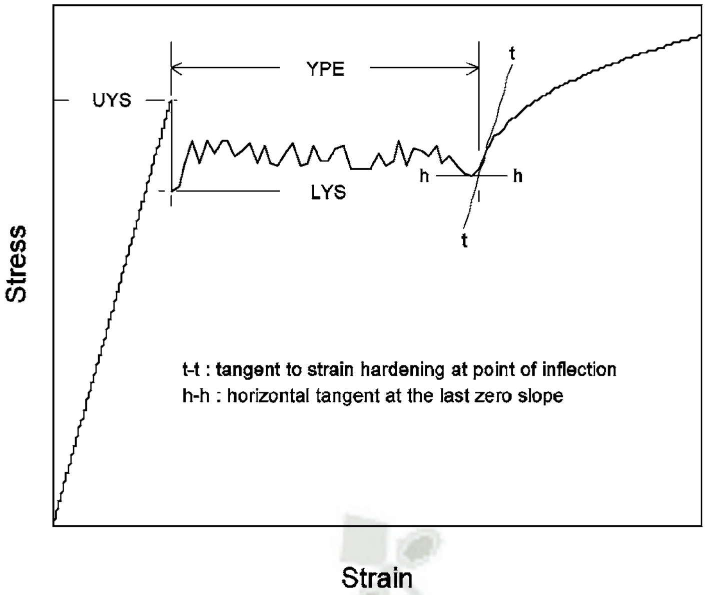


**FIG. 24 Stress-Strain Diagram Showing Yield Point Elongation (YPE) and Upper (UYS) and Lower (LYS) Yield Strengths**

NOTE 35—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 stress 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 36—Where low-magnification autographic recordings are needed to facilitate measurement of yield point elongation for materials which may exhibit 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 37—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 in Terminology E6 and Fig. 24).

NOTE 38—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 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 *Uniform Elongation (if required)*:

7.9.1 Uniform elongation shall include both plastic and elastic elongation.

7.9.2 Uniform elongation shall be determined using autographic methods with extensometers conforming to Practice E83. Use a class B2 or better extensometer for materials having a uniform elongation less than 5 %. Use a class C or better extensometer for materials having a uniform elongation greater than or equal to 5 % but less than 50 %. Use a class D or better extensometer for materials having a uniform elongation of 50 % or greater.

7.9.3 Determine the uniform elongation as the elongation at the point of maximum force from the force elongation data collected during a test.

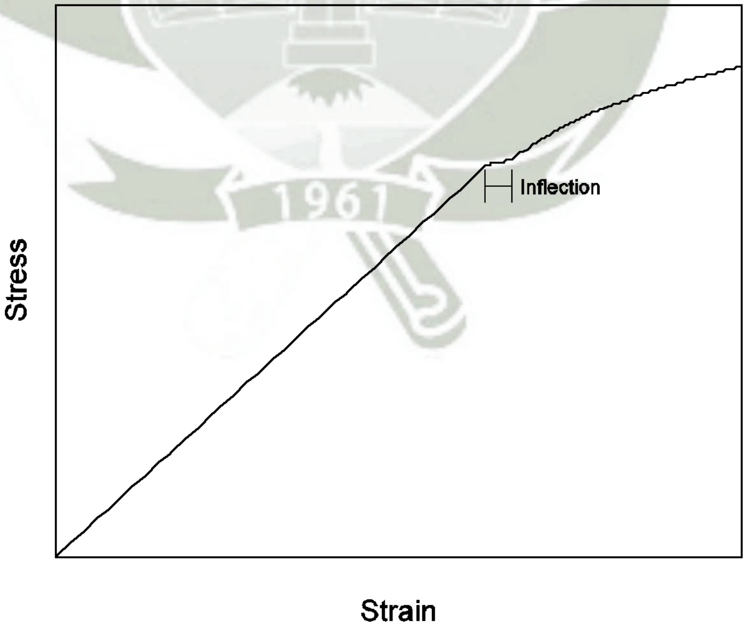


**FIG. 25 Stress-Strain Diagram With an Inflection, But No YPE**

7.9.3.1 Some materials exhibit a yield point followed by considerable elongation where the yield point is the maximum force achieved during the test. In this case, uniform elongation is not determined at the yield point, but instead at the highest force occurring just prior to necking (see Fig. 26).

7.9.3.2 Stress-strain curves for some materials exhibit a lengthy, plateau-like region in the vicinity of the maximum force. For such materials, determine the uniform elongation at the center of the plateau as indicated in Fig. 27 (see also Note 39 below).

Note 39—When uniform elongation is being determined digitally, noise in the stress-strain data generally causes many small, local peaks and valleys to be recorded in the plateau region. To accommodate this, the following procedure is recommended:

— Determine the maximum force recorded (after discontinuous yielding).

— Evaluate the sequence of force values recorded before and after the maximum force.

— Digitally define the "plateau" as consisting of all consecutive data points wherein the force value is within 0.5 % of the magnitude of the peak force value.

— Determine the uniform elongation as the strain at the mid-point of the "plateau."

7.9.3.3 *Discussion*—The 0.5 % value of Note 39 has been selected arbitrarily. In actual practice, the value should be selected so as to be the minimum figure that is large enough to effectively define the force plateau. This may require that the percentage be about 5 times the amplitude of the force fluctuations occurring due to noise. Values ranging from 0.1 % to 1.0 % may be found to work acceptably.

7.10 *Tensile Strength (also known as Ultimate 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 40—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.

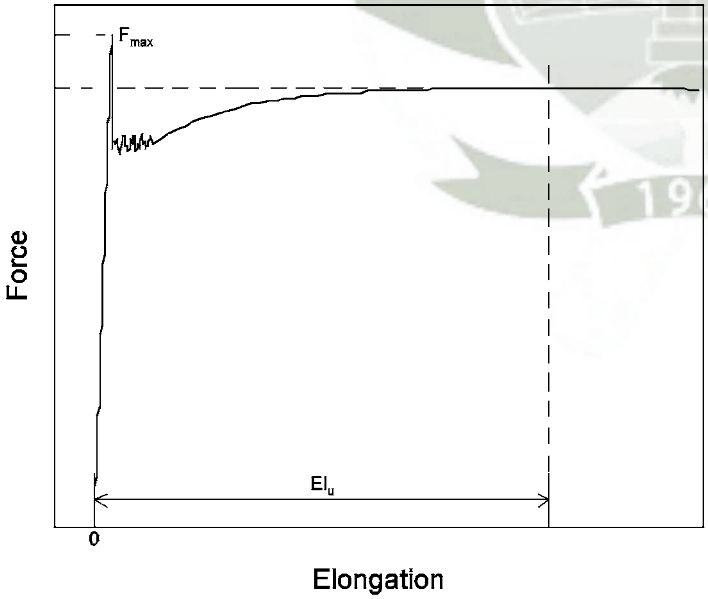


FIG. 26 Stress-Strain Diagram in Which the Upper Yield Strength is the Maximum Stress Recorded Method

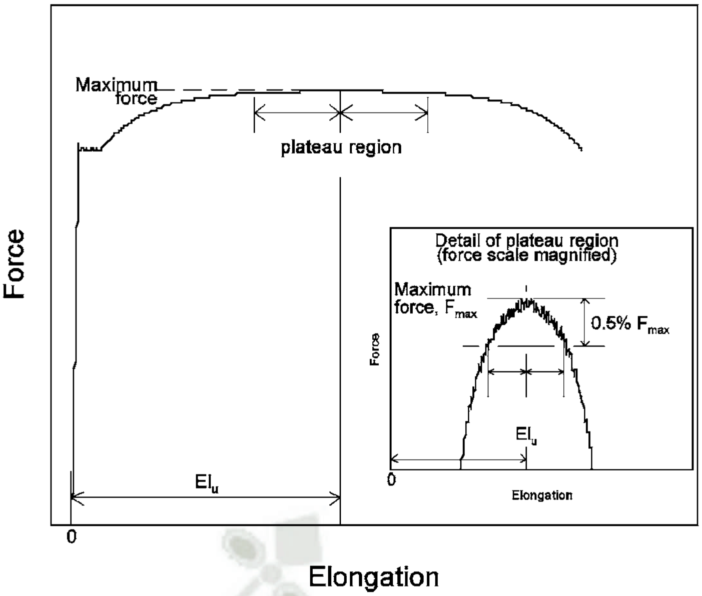


FIG. 27 Force-Elongation Diagram for Determination of Uniform Elongation of Steel Sheet Materials Exhibiting a Plateau at Maximum Force

7.11 *Elongation*:

7.11.1 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 also shall be noted.

$$\textit{Example}\text{: Elongation} = 30\ \%\ \text{ increase } (50-\text{mm } [2-\text{in.}] \text{ gage length}) \tag{5}$$

Note 41—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.

7.11.2 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 [0.01 in.] for gage lengths of 50 mm [2 in.] and under, and to at least the nearest 0.5 % of the gage length for gage lengths over 50 mm [2 in.]. A percentage scale reading to 0.5 % of the gage length may be used.

7.11.3 When the *specified* elongation is 3 % or less, determine the elongation of the specimen using the following procedure, except that the procedure given in 7.11.2 may be used instead when the *measured* elongation is greater than 3 %.

7.11.3.1 Prior to testing, measure the original gage length of the specimen to the nearest 0.05 mm [0.002 in.].

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

7.11.3.3 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 42—The use of a force generating a stress of approximately 15 MPa [2000 psi] has been found to give satisfactory results on test specimens of aluminum alloy.

7.11.3.4 Measure the final gage length to the nearest 0.05 mm [0.002 in.] and report the elongation to the nearest 0.2 %.

7.11.4 Elongation measured per paragraph 7.11.2 or 7.11.3 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.

7.11.5 *Elongation at Fracture*:

7.11.5.1 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.

7.11.5.2 Percent elongation at fracture may be calculated directly from elongation at fracture data and be reported instead of percent elongation as calculated in 7.11.2 to 7.11.3. However, these two parameters are not interchangeable. Use of the elongation at fracture method generally provides more repeatable results.

NOTE 43—When disagreements arise over the percent elongation results, agreement must be reached on which method to use to obtain the results.

7.12 *Reduction of Area*:

7.12.1 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.

7.12.2 *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 44—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.

7.12.3 *Specimens with Original 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 45—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, an effective thickness, $t_e$, may be calculated as follows: $(t_1 + 4t_2 + t_3)/6$, where $t_1$ and $t_3$ are the thicknesses at the corners, and $t_2$ is the thickness at mid-width. An effective width may be similarly calculated.

7.12.4 Calculate the reduced area based upon the dimensions determined in 7.12.2 or 7.12.3. 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.

7.12.5 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.

7.12.6 Results of measurements of reduction of area shall be rounded using the procedures of Practice E29 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 %.

7.13 *Rounding Reported Test Data for Yield Strength and Tensile Strength*—Test data should be rounded using the procedures of Practice E29 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.

7.13.1 For test values up to 500 MPa [50 000 psi], round to the nearest 1 MPa [100 psi]; for test values of 500 MPa [50 000 psi] and up to 1000 MPa [100 000 psi], round to the nearest 5 MPa [500 psi]; for test values of 1000 MPa [100 000 psi] and greater, round to the nearest 10 MPa [1000 psi].

NOTE 46—For steel products, see Test Methods and Definitions A370.

7.13.2 For all test values, round to the nearest 1 MPa [100 psi].

NOTE 47—For aluminum- and magnesium-alloy products, see Methods B557.

7.13.3 For all test values, round to the nearest 5 MPa [500 psi].

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

7.14.1 The original specimen had a poorly machined surface, 7.14.2 The original specimen had the wrong dimensions,

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

7.14.4 The test procedure was incorrect,

7.14.5 The fracture was outside the gage length,

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

7.14.7 There was a malfunction of the testing equipment.

NOTE 48—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 Reference to the standard used, i.e. E8 or E8M.

8.2.2 Material and sample identification.

8.2.3 Specimen type (see Section 6).

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

8.2.5 Yield point elongation (see 7.8).

8.2.6 Tensile Strength (also known as Ultimate Tensile Strength) (see 7.10).

8.2.7 Elongation (report original gage length, percentage increase, and method used to determine elongation; i.e. at fracture or after fracture) (see 7.11).

8.2.8 Uniform Elongation, if required (see 7.9).

8.2.9 Reduction of area, if required (see 7.12).

8.3 Test information to be available on request shall include:

8.3.1 Specimen test section dimension(s).

8.3.2 Equation used to calculate cross-sectional area of rectangular 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 7.13).

8.3.5 Reasons for replacement specimens (see 7.14).

## 9. Precision and Bias

9.1 *Precision*—An interlaboratory test program[3] 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 = 4 Diameter | Reduction of Area |
|---|---|---|---|---|---|
| CV $\%_r$ | 0.9 | 2.7 | 1.4 | 2.8 | 2.8 |
| CV $\%_R$ | 1.3 | 4.5 | 2.3 | 5.4 | 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 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 E8/E8Mfor measuring tensile properties have no bias because these properties can be defined only 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

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[3] Supporting data can be found in Appendix X1 and additional data are available from ASTM Headquarters. Request RR:E28-1004.

# 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 4) 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 10).

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:

$$L_o/(A_o)^{1/2} \quad \text{(X1.1)}$$

where:

$L_o$ = original gage length of specimen, and

$A_o$ = original cross-sectional area of specimen.

X1.4.4.1 Specimens with smaller $L_o/(A_o)^{1/2}$ 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 $L_o/(A_o)^{1/2}$ 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 nonuniformly, 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 40).

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 45).

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[3] was conducted in which six specimens each, of six different materials were prepared and tested by each of six different laboratories. Tables X1.1-X1.6 present the precision statistics, as defined in Practice E691, for: tensile strength, 0.02 % yield strength, 0.2 % yield strength, % elongation in 4D, % 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) 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 4D, % 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.

### TABLE X1.1 Precision Statistics—Tensile Strength, MPa [ksi]

NOTE—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) in MPa [ksi],
$s_r/X$ is the coefficient of variation in %,
$s_R$ is the reproducibility standard deviation (between-laboratory precision) in MPa [ksi],
$s_R/X$ is the coefficient of variation, %,
r is the 95 % repeatability limits in MPa [ksi],
R is the 95 % reproducibility limits in MPa [ksi].

| Material | X | $s_r$ | $s_r/X$, % | $s_R$ | $s_R/X$, % | r | R |
|---|---|---|---|---|---|---|---|
| EC-H19 | 176.9 [25.66] | 4.3 [0.63] | 2.45 | 4.3 [0.63] | 2.45 | 12.1 [1.76] | 12.1 [1.76] |
| 2024-T351 | 491.3 [71.26] | 6.1 [0.88] | 1.24 | 6.6 [0.96] | 1.34 | 17.0 [2.47] | 18.5 [2.68] |
| ASTM A105 | 596.9 [86.57] | 4.1 [0.60] | 0.69 | 8.7 [1.27] | 1.47 | 11.6 [1.68] | 24.5 [3.55] |
| AISI 316 | 694.6 [100.75] | 2.7 [0.39] | 0.39 | 8.4 [1.22] | 1.21 | 7.5 [1.09] | 23.4 [3.39] |
| Inconel 600 | 685.9 [99.48] | 2.9 [0.42] | 0.43 | 5.0 [0.72] | 0.72 | 8.2 [1.19] | 13.9 [2.02] |
| SAE 51410 | 1253.0 [181.73] | 0.25 [0.46] | 0.25 | 7.9 [1.14] | 0.63 | 8.9 [1.29] | 22.1 [3.20] |
| | | Averages: | 0.91 | | 1.30 | | |

### TABLE X1.2 Precision Statistics—0.02 % Yield Strength, MPa [ksi]

| Material | X | $s_r$ | $s_r/X$, % | $s_R$ | $s_R/X$, % | r | R |
|---|---|---|---|---|---|---|---|
| EC-H19 | 111.4 [16.16] | 4.5 [0.65] | 4.00 | 8.2 [1.19] | 7.37 | 12.5 [1.81] | 23.0 [3.33] |
| 2024-T351 | 354.2 [51.38] | 5.8 [0.84] | 1.64 | 6.1 [0.89] | 1.73 | 16.3 [2.36] | 17.2 [2.49] |
| ASTM A105 | 411.1 [59.66] | 8.3 [1.20] | 2.02 | 13.1 [1.90] | 3.18 | 23.2 [3.37] | 36.6 [5.31] |
| AISI 316 | 336.1 [48.75] | 16.7 [2.42] | 4.97 | 31.9 [4.63] | 9.49 | 46.1 [6.68] | 89.0 [12.91] |
| Inconel 600 | 267.1 [38.74] | 3.2 [0.46] | 1.18 | 5.2 [0.76] | 1.96 | 8.8 [1.28] | 14.7 [2.13] |
| SAE 51410 | 723.2 [104.90] | 16.6 [2.40] | 2.29 | 21.9 [3.17] | 3.02 | 46.4 [6.73] | 61.2 [8.88] |
| | | Averages: | 2.68 | | 4.46 | | |

### TABLE X1.3 Precision Statistics—0.2 % Yield Strength, MPa [ksi]

| Material | X | $s_r$ | $s_r/X$, % | $s_R$ | $s_R/X$, % | r | R |
|---|---|---|---|---|---|---|---|
| EC-H19 | 158.4 [22.98] | 3.3 [0.47] | 2.06 | 3.3 [0.48] | 2.07 | 9.2 [1.33] | 9.2 [1.33] |
| 2024-T351 | 362.9 [52.64] | 5.1 [0.74] | 1.41 | 5.4 [0.79] | 1.49 | 14.3 [2.08] | 15.2 [2.20] |
| ASTM A105 | 402.4 [58.36] | 5.7 [0.83] | 1.42 | 9.9 [1.44] | 2.47 | 15.9 [2.31] | 27.8 [4.03] |
| AISI 316 | 481.1 [69.78] | 6.6 [0.95] | 1.36 | 19.5 [2.83] | 4.06 | 18.1 [2.63] | 54.7 [7.93] |
| Inconel 600 | 268.3 [38.91] | 2.5 [0.36] | 0.93 | 5.8 [0.85] | 2.17 | 7.0 [1.01] | 16.3 [2.37] |
| SAE 51410 | 967.5 [140.33] | 8.9 [1.29] | 0.92 | 15.9 [2.30] | 1.64 | 24.8 [3.60] | 44.5 [6.45] |
| | | Averages: | 1.35 | | 2.32 | | |

### TABLE X1.4 Precision Statistics—% Elongation in 4D for E8 Specimens

NOTE—Length of reduced section = 6D.

| Material | X | $s_r$ | $s_r/X$, % | $s_R$ | $s_R/X$, % | r | R |
|---|---|---|---|---|---|---|---|
| EC-H19 | 17.42 | 0.64 | 3.69 | 0.92 | 5.30 | 1.80 | 2.59 |
| 2024-T351 | 19.76 | 0.58 | 2.94 | 1.58 | 7.99 | 1.65 | 4.43 |
| ASTM A105 | 29.10 | 0.76 | 2.62 | 0.98 | 3.38 | 2.13 | 2.76 |
| AISI 316 | 40.07 | 1.10 | 2.75 | 2.14 | 5.35 | 3.09 | 6.00 |
| Inconel 600 | 44.28 | 0.66 | 1.50 | 1.54 | 3.48 | 1.86 | 4.31 |
| SAE 51410 | 14.48 | 0.48 | 3.29 | 0.99 | 6.83 | 1.34 | 2.77 |
| | | Averages: | 2.80 | | 5.39 | | |

**TABLE X1.5 Precision Statistics—% Elongation in 5D for E8M Specimens**

NOTE—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 | 13.39 | 0.45 | 3.61 | 0.96 | 7.75 | 1.25 | 2.89 |
| | | Averages: | 2.96 | | 6.36 | | |

**TABLE X1.6 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 | | |

## 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 [0.003 in.]. 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 [0.003 in.] tolerance, a 10 % GR and R result (exceptionally good, even for digital hand-held micrometers reading to 0.001 mm [0.00005 in.]) indicates that the total variation due to repeatability and reproducibility is around 0.0075 [0.0003 in.]. This is less than or equal to 1 % only if all dimensions to be measured are greater than or equal to 0.75 mm [0.03 in.]. The relative error in using this device to measure thickness of a 0.25 mm [0.01 in.] flat tensile specimen would be 3 %—which is considerably more than that allowed for force 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 to 6.35 mm [0.018 to 0.25 in.] 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 technique, 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 7.2.3.)

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 [0.015 in.) 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 0.0025 mm [0.0001 in.] 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.

## X3. SUGGESTED ACCREDITATION CRITERIA FOR LABORATORIES PERFORMING TENSILE TESTS

### X3.1 Scope

X3.1.1 The following are specific features that an assessor may check to assess a laboratory's technical competence, if the laboratory is performing tests in accordance with Test Methods E8 and/or E8M.

### X3.2 Preparation

X3.2.1 The laboratory should follow documented procedures to ensure that machining or other preparation generates specimens conforming to applicable tolerances and requirements of Test Methods E8 or E8M. Particularly important are those requirements that pertain to the dimensions and finish of reduced sections, as found in the text and in applicable figures.

X3.2.2 Where gage marks are used, the laboratory should employ documented gage marking procedures to ensure that the marks and gage lengths comply with the tolerances and guidelines of Test Methods E8 or E8M.

X3.2.2.1 The gage marking procedure used should not deleteriously affect the test results.

NOTE X3.1—Frequent occurrence of fracturing at the gage marks may indicate that gage marks have excessive depth or sharpness and may be affecting test results.

### X3.3 Test Equipment

X3.3.1 As specified in the Apparatus sections of Test Methods E8 and E8M, the axis of the test specimen should coincide with the center line of the heads of the testing machine, in order to minimize bending stresses which could affect the results.

X3.3.2 Equipment verification requirements of Practices E4 and E83 shall be met. Documentation showing the verification work to have been thorough and technically correct should be available.

X3.3.2.1 Verification reports shall demonstrate that force and extension readings have been taken at the prescribed intervals and that the prescribed runs have been completed.

X3.3.3 Extensometers used shall meet all requirements of Test Methods E8 or E8M as to the classification of device to be used for the results determined. For example, an extensometer not meeting the Class B2 requirements of Practice E83 may not be used in determination of offset yield strengths.

X3.3.4 Before computerized or automated test equipment is put into routine service, or following a software revision, it is recommended that measures be taken to verify proper operation and result interpretation. Guide E1856 addresses this concern.

X3.3.5 Micrometers and other devices used in measurement of specimen dimensions should be selected, maintained and used in such a manner as to comply with the appendixes of Test Methods E8 and E8M on measurement. Traceability to national standards should be established for these devices, and reasonable effort should be employed to prevent errors greater than 1 % from being generated as a result of measurement error, resolution, and rounding practice.

### X3.4 Procedures

X3.4.1 The test machine shall be set up and zeroed in such a manner that zero force indication signifies a state of zero force on the specimen, as indicated in the Zeroing of the Test Machine sections of Test Methods E8 and E8M.

NOTE X3.2—Provisions should be made to ensure that zero readings are properly maintained, from test to test. These may include, for example, zeroing after a predetermined number of tests or each time, under zero force conditions, the indicator exceeds a predetermined value.

X3.4.2 Upon request, the laboratory should be capable of demonstrating (perhaps through time, force, displacement or extensometer measurements, or both) that the test speeds used conform to the requirements of Test Methods E8 or E8M, or other standards which take precedence.

X3.4.3 Upon request, the laboratory should be capable of demonstrating that the offsets and extensions used in determining yield strengths conform to the requirements of Test

Methods E8 or E8M and are constructed so as to indicate the forces corresponding to the desired offset strain or total strain.

NOTE X3.3—Use caution when performing calculations with extensometer magnification, because the manufacturer may report strain magnification, which relates the strain (not the elongation) to the x-axis displacement on the stress strain diagram. A user or assessor interested in an extensometer's magnification may use calibration equipment to determine the ratio between elongation and chart travel or may verify a reported magnification by calculating the Young's modulus from tests of specimens of a known nominal modulus.

X3.4.4 Measurement of elongation shall conform to requirements of Test Methods E8 or E8M.

NOTE X3.4—Test Methods E8 and E8M permit the measurement and reporting of elongation at fracture in place of elongation, as is often done in automated testing.

X3.4.5 Reduction of area, when required, shall be determined in accordance with the requirements of Test Methods E8 or E8M.

X3.4.6 Procedures for recording, calculating, and reporting data and test results shall conform to all applicable requirements of Test Methods E8 or E8M. In addition, wherever practical, the procedures should also be in accordance with widely accepted provisions of good laboratory practice, such as those detailed below.

X3.4.6.1 When recording data, personnel should record all figures that are definite, plus the best estimate of the first figure which is uncertain. (If a result is known to be approximately midway between 26 and 27, 26.5 should be the result recorded (not 26, 27, or 26.475).

X3.4.6.2 When performing calculations, personnel should avoid compounding of rounding errors. This may be accomplished by performing one large calculation, rather than several calculations using individual results. Alternatively, if multistep calculations are done, intermediate results should not be rounded before use in subsequent calculations.

X3.4.6.3 In rounding, no final result should retain more significant figures than the least-significant-figure measurement or data point used in the calculation.

### X3.5 Retention

X3.5.1 A retention program appropriate for the nature and frequency of testing done in the laboratory should be maintained. Items that may warrant retention for defined time periods include:

X3.5.1.1 Raw data and forms,

X3.5.1.2 Force-elongation or stress-strain charts,

X3.5.1.3 Computer printouts of curves and test results,

X3.5.1.4 Data and results stored on computer discs or hard drives,

X3.5.1.5 Broken specimens,

X3.5.1.6 Excess material,

X3.5.1.7 Test reports, and

X3.5.1.8 Verification reports and certifications.

### X3.6 Environment

X3.6.1 All test equipment should be located and connected to power sources in such a manner as to minimize the effects of vibrations and electrical disturbances on raw data collected, stress-strain charts, and operation of equipment.

### X3.7 Controls

X3.7.1 Controlled procedures and work instructions should cover all aspects of specimen preparation, tensile testing, and result reporting. These documents should be readily available to all involved in the documented tasks.

X3.7.2 Clear, concise, operating instructions should be maintained for equipment used in specimen preparation and tensile testing. These instructions should be readily available to all qualified operators.

X3.7.3 All applicable verification requirements shall be met, as detailed in X3.3.2.

X3.7.4 It is recommended that special studies and programs be employed to monitor and control tensile testing, because tensile test results are easily affected by operators, measuring devices, and test equipment. Examples of such programs include but are not limited to:

X3.7.4.1 Round-robin studies, proficiency tests, or other cross-checks,

X3.7.4.2 Repeatability and reproducibility (R and R) studies,

X3.7.4.3 Control charting, and

X3.7.4.4 Determination of typical lab uncertainties for each result typically reported.

NOTE X3.5—For nondestructive testing, repeatability and reproducibility are often measured by conducting gage R and R studies, as discussed in Appendix X2 of Test Methods E8 and E8M. These studies involve repeated determination of a test result, using a single part or specimen, so gage R and Rs are not directly applicable to mechanical properties, which are obtained through destructive testing. (True differences between even the best duplicate specimens manifest themselves in the form of poorer R and R results than would be obtained for perfect duplicates.) Nevertheless, quasi-R and R studies conducted with these limitations taken into consideration may be helpful in analyzing sources of error and improving reliability of test results.

## X4. ADDITIONAL INFORMATION ON SPEED OF TESTING AND EXAMPLES

X4.1 Many materials are strain-rate sensitive that is, the yield strength or tensile strength of the material is a function of the rate at which the material is being deformed. The yield strength of some materials can change by more than ten percent when tested with the slowest and then the highest speeds permitted by E8/E8M. In order to reproduce yield test results, for strain-rate sensitive materials, it is important that strain rates during the determination of yield are similar.

X4.2 The following paragraphs further explain the various Control Methods required to be used by E8/E8M when other guidance is not given. When other test speed requirements are specified, those speeds must be followed to comply with this test method. For example, aerospace specifications often require a test speed when determining yield strength to be a strain rate equal to 0.005 ± 0.002 mm/mm/min [in./in./min]; when specified, that speed must be followed in order to comply with this standard.

X4.2.1 *Control Method A - Rate of Stressing Method for Determining Yield Properties* – This method has been the default method of control in E 8/E 8M for many years. In this method, the crosshead speed of the machine is adjusted during the linear elastic portion of the curve to achieve the desired stress rate (or the speed is set to a predetermined value known to achieve the desired stress rate). The crosshead speed is not adjusted when the material begins to yield. The advantage of this control method is that it does not require any transducers other than the load indicator itself, although, load pacers and stress-rate indicators can be helpful. This method of control has a limitation in that the strain rate of the specimen at yield depends on the slope of the stress-strain curve (tangent modulus) and the testing machine stiffness. Because of this, the strain rate of the specimen when yield is determined can be different for different specimen sizes, different specimen configurations, different gripping configurations, and different testing machines. This difference in strain rate can affect the reproducibility of yield strength in strain-rate-sensitive materials.

X4.2.1.1 It is not the intent of this method to run the testing machine in closed-loop force control, because as the material begins to yield the testing machine will speed up, possibly to its maximum speed. However, using closed-loop force control during the elastic region of the test and switching to an equivalent crosshead speed prior to yield is an acceptable method.

X4.2.2 *Control Method B —Rate of Straining Control Method for Determining Yield Properties* - This method is usually performed with a testing machine that has a closed-loop control system that uses feedback from an extensometer to automatically adjust the speed of the testing machine. However, some skilled operators can monitor a strain rate indicator attached to the extensometer and adjust the speed of the testing machine manually to maintain the required strain rate test speed. To maintain constant strain rate control during a test, the crosshead speed of the testing machine must slow down drastically when the specimen begins to yield. This method has three advantages. *(1)* The time to achieve yield results is short (about 20 to 40 s). *(2)* The reproducibility of yield strength test results from machine to machine and laboratory to laboratory is good. *(3)* The agreement with the results of Control Method C is good, because the strain rates are similar when the specimen's yield strength is determined. This method has three disadvantages. *(1)* The testing equipment is generally more expensive. *(2)* Proper control and safety depend on the control parameters to be properly set and that the extensometer integrity be maintained (accidental slippage of the extensometer can result in unexpected movement of the crosshead). Proper safety limits must be set to ensure safety of personnel and equipment. *(3)* When materials have yield points or yield discontinuously, a machine under closed-loop strain-rate control can behave erratically. This control method is not recommended for materials that yield discontinuously.

X4.2.3 *Control Method C - Crosshead Speed Control Method for Determining Yield Properties*—This method can be performed on any testing machine that has reasonably good crosshead speed control. This method has three advantages. *(1)* The reproducibility from machine to machine and laboratory to laboratory is good. *(2)* The agreement with Control Method B is good, because the strain rates are similar when the specimen's yield strength is determined. *(3)* This method of controlling a testing machine is excellent for materials that yield discontinuously. The disadvantage of this method of control is that the test time to yield can be more than three minutes, depending on the material being tested and the compliance of the testing machine including its grip assemblies.

X4.2.3.1 *An example using SI metric units of how to apply Control Method C* to testing Specimen 1 in Fig. 13 is as follows. The length of the reduced section, that is, dimension A in Fig. 13, is equal to 60 mm. The crosshead speed is determined per Control Method C by multiplying 60 mm by 0.015 mm/mm/min to arrive at a crosshead speed of 0.9 mm/min.

X4.2.3.2 *An example using U.S. customary units of how to apply Control Method C* to testing Specimen 1 in Fig. 13 is as follows. The length of the reduced section, that is, dimension A in Fig. 13 is equal to 2.25 in. The crosshead speed is determined per Control Method C by multiplying 2.25 in. by 0.015 in./in./min to arrive at a crosshead speed of 0.034 in./min.

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## SUMMARY OF CHANGES

Committee E28 has identified the location of selected changes to this standard since the last issue (E8/E8M-08) that may impact the use of this standard. (Approved Dec. 1, 2009.)

(*1*) 7.6.2.3 was revised
(*2*) 7.6.3 was revised
(*3*) Appendix X4 was added.

Committee E28 has identified the location of selected changes to this standard since the last issue (E8 – 04 and E8M – 04) that may impact the use of this standard. (Approved Feb. 1, 2008)

(*1*) The two separate standards have been combined into one standard.
(*2*) Specimen drawing figures have been updated to include both the 4D and 5D elongation.
(*3*) Figs. 21-27 have been redrawn and updated.
(*4*) Definitions from E6 and from the body of the text have been brought in to the Terminology section.
(*5*) Notes 1-3 which previously contained mandatory information have been incorporated into the Scope section.

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# Standard Methods for
# NOTCHED BAR IMPACT TESTING OF METALLIC MATERIALS[1]

*These methods have been approved for use by agencies of the Department of Defense to replace method 221.1 of Federal Test Method Standard No. 151b and for listing in the DoD Index of Specifications and Standards.*

NOTE—Figures 2, 3, 4, 5, 6, 7, 11, 12, 13, 14, 15, and 16 were editorially corrected, and the designation date was changed March 5, 1982.

## 1. Scope

1.1 These methods describe notched-bar impact testing of metallic materials by the Charpy (simple-beam) apparatus and the Izod (cantilever-beam) apparatus. They give: (*a*) a description of apparatus, (*b*) requirements for inspection and calibration, (*c*) safety precautions, (*d*) sampling, (*e*) dimensions and preparation of specimens, (*f*) testing procedures, (*g*) precision and accuracy, and (*h*) appended notes on the significance of notched-bar impact testing. These methods will in most cases also apply to tests on unnotched specimens.

1.2 The values stated in SI units are to be regarded as the standard.

## 2. Summary of Methods

2.1 The essential features of an impact test are: (*a*) a suitable specimen (specimens of several different types are recognized), (*b*) an anvil or support on which the test specimen is placed to receive the blow of the moving mass, (*c*) a moving mass of known kinetic energy which must be great enough to break the test specimen placed in its path, and (*d*) a device for measuring the energy absorbed by the broken specimen.

## 3. Significance

3.1 These methods of impact testing relate specifically to the behavior of metal when subjected to a single application of a load resulting in multiaxial stresses associated with a notch, coupled with high rates of loading and in some cases with high or low temperatures. For some materials and temperatures, impact tests on notched specimens have been found to predict the likelihood of brittle fracture better than tension tests or other tests used in material specifications. Further information on significance appears in the Appendix.

## 4. Apparatus

4.1 *General Requirements:*

4.1.1 The testing machine shall be a pendulum type of rigid construction and of capacity more than sufficient to break the specimen in one blow.

4.1.2 The machine frame shall be equipped with a bubble level or a machined surface suitable for establishing levelness. The machine shall be level to within 3:1000 and securely bolted to a concrete floor not less than 150 mm (6 in.) thick or, when this is not practical, the machine shall be bolted to a foundation having a mass not less than 40 times that of the pendulum. The bolts shall be tightened as specified by the machine manufacturer.

4.1.3 The machine shall be furnished with scales graduated either in degrees or directly in energy on which readings can be estimated in increments of 0.25 % of the energy range or less. The scales may be compensated for wind-

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[1] These methods are under the jurisdiction of ASTM Committee E-28 on Mechanical Testing and are the direct responsibility of Subcommittee E28.07 on Impact Testing.

Current edition approved March 5, 1982. Published July 1982. Originally published as E 23 – 33 T. Last previous edition E 23 – 81.

age and pendulum friction. The error in the scale reading at any point shall not exceed 0.2 % of the range or 0.4 % of the reading, whichever is larger. (See 5.2.6.2 and 5.2.7.)

4.1.4 The total friction and windage losses of the machine during the swing in the striking direction shall not exceed 0.75 % of the scale range capacity, and pendulum energy loss from friction in the indicating mechanism shall not exceed 0.25 % of scale range capacity.

4.1.5 The dimensions of the pendulum shall be such that the center of percussion of the pendulum is at the center of strike within 1 % of the distance from the axis of rotation to the center of strike. When hanging free, the pendulum shall hang so that the striking edge is within 2.5 mm (0.10 in.) of the position where it would just touch the test specimen. When the indicator has been positioned to read zero energy in a free swing, it shall read within 0.2 % of scale range when the striking edge of the pendulum is held against the test specimen. The plane of swing of the pendulum shall be perpendicular to the transverse axis of the Charpy specimen anvils or Izod vise within 3:1000.

4.1.6 Transverse play of the pendulum at the striker shall not exceed 0.75 mm (0.030 in.) under a transverse force of 4 % of the effective weight of the pendulum applied at the center of strike. Radial play of the pendulum bearings shall not exceed 0.075 mm (0.003 in.). The tangential velocity (the impact velocity) of the pendulum at the center of the strike shall not be less than 3 nor more than 6 m/s (not less than 10 nor more than 20 ft/s).

4.1.7 Before release, the height of the center of strike above its free hanging position shall be within 0.4 % of the range capacity divided by the pendulum weight, measured as described in 5.2.3.3. If windage and friction are compensated for by increasing the height of drop, the height of drop may be increased by not more than 1 %.

4.1.8 The mechanism for releasing the pendulum from its initial position shall operate freely and permit release of the pendulum without initial impulse, retardation, or side vibration. If the same lever that is used to release the pendulum is also used to engage the brake, means shall be provided for preventing the brake from being accidentally engaged.

4.2 *Specimen Clearance*—To ensure satisfactory results when testing materials of different strengths and compositions, the test specimen shall be free to leave the machine with a minimum of interference and shall not rebound into the pendulum before the pendulum completes its swing. Pendulums used on Charpy machines are of two basic designs, as shown in Fig. 1. When using a C-type pendulum, the broken specimen will not rebound into the pendulum and slow it down if the clearance at the end of the specimen is at least 13 mm (0.5 in.) or if the specimen is deflected out of the machine by some arrangement as is shown in Fig. 1. When using the U-type pendulum, means shall be provided to prevent the broken specimen from rebounding against the pendulum (Fig. 1). In most U-type pendulum machines, the shrouds should be designed and installed to the following requirements: (*a*) have a thickness of approximately 1.5 mm (0.06 in.), (*b*) have a minimum hardness of 45 HRC, (*c*) have a radius of less than 1.5 mm (0.06 in.) at the underside corners, and (*d*) be so positioned that the clearance between them and the pendulum overhang (both top and sides) does not exceed 1.5 mm (0.06 in.).

NOTE 1—In machines where the opening within the pendulum permits clearance between the ends of a specimen (resting on the anvil supports) and the shrouds, and this clearance is at least 13 mm (0.5 in.) requirements (*a*) and (*d*) need not apply.

4.3 *Charpy Apparatus:*

4.3.1 Means shall be provided (Fig. 2) to locate and support the test specimen against two anvil blocks in such a position that the center of the notch can be located within 0.25 mm (0.010 in.) of the midpoint between the anvils (see 11.2.1.2).

4.3.2 The supports and striking edge shall be of the forms and dimensions shown in Fig. 2. Other dimensions of the pendulum and supports should be such as to minimize interference between the pendulum and broken specimens.

4.3.3 The center line of the striking edge shall advance in the plane that is within 0.40 mm (0.016 in.) of the midpoint between the supporting edges of the specimen anvils. The striking edge shall be perpendicular to the longitudinal axis of the specimen within 5:1000. The striking edge shall be parallel within 1:1000 to the face of a perfectly square test specimen held against the anvil.

4.3.4 Specimen supports shall be square with anvil faces within 2.5:1000. Specimen supports shall be coplanar within 0.125 mm (0.005 in.) and parallel within 2:1000.

4.4 *Izod Apparatus:*

4.4.1 Means shall be provided (Fig. 3) for clamping the specimen in such a position that the face of the specimen is parallel to the striking edge within 1:1000. The edges of the clamping surfaces shall be sharp angles of 90 ± 1° with radii less than 0.40 mm (0.016 in.). The clamping surfaces shall be smooth with a 2-μm (63-μin.) finish or better, and shall clamp the specimen firmly at the notch with the clamping force applied in the direction of impact. For rectangular specimens, the clamping surfaces shall be flat and parallel within 0.025 mm (0.001 in.). For cylindral specimens, the clamping surfaces shall be contoured to match the specimen and each surface shall contact a minimum of $\pi/2$ rad (90°) of the specimen circumference.

4.4.2 The dimensions of the striking edge and its position relative to the specimen clamps shall be as shown in Fig. 3.

4.5 *Energy Range*—Energy values above 80 % of the scale range are inaccurate and shall be reported as approximate. Ideally an impact test would be conducted at a constant impact velocity. In a pendulum-type test, the velocity decreases as the fracture progresses. For specimens that have impact energies approaching the capacity of the pendulum, the velocity of the pendulum decreases during fracture to the point that accurate impact energies are no longer obtained.

## 5. Inspection

5.1 *Critical Parts:*

5.1.1 *Specimen Anvils and Supports or Vise*—These shall conform to the dimensions shown in Fig. 2 or 3. To ensure a minimum of energy loss through absorption, bolts shall be tightened as specified by the machine manufacturer.

NOTE 2—The impact machine will be inaccurate to the extent that some energy is used in deformation or movement of its component parts or of the machine as a whole; this energy will be registered as used in fracturing the specimen.

5.1.2 *Pendulum Striking Edge*—The striking edge (tup) of the pendulum shall conform to the dimensions shown in Figs. 2 or 3. To ensure a minimum of energy loss through absorption, the striking edge bolts shall be tightened as specified by the machine manufacturer. The pendulum striking edge (tup) shall comply with 4.3.3 (for Charpy tests) or 4.4.1 (for Izod tests) by bringing it into contact with a standard Charpy or Izod specimen.

5.2 *Pendulum Operation:*

5.2.1 *Pendulum Release Mechanism*—The mechanism for releasing the pendulum from its initial position shall comply with 4.1.8.

5.2.2 *Pendulum Alignment*—The pendulum shall comply with 4.1.5 and 4.1.6. If the side play in the pendulum or the radial plays in the bearings exceeds the specified limits, adjust or replace the bearings.

5.2.3 *Potential Energy*—Determine the initial potential energy using the following procedure when the center of strike of the pendulum is coincident with the line from the center of rotation through the center of percussion. If the center of strike is more than 2.5 mm (0.1 in.) from this line, suitable corrections in elevation of the center of strike must be made in 5.2.3.2, 5.2.3.3, 5.2.6.1, and 5.2.7, so that elevations set or measured correspond to what they would be if the center of strike were on this line.

5.2.3.1 For Charpy machines place a half-width specimen (see Fig. 4) 10 by 5 mm (0.394 by 0.197 in.) in test position. With the striking edge in contact with the specimen, a line scribed from the top edge of the specimen to the striking edge will indicate the center of strike on the striking edge.

5.2.3.2 For Izod machines, the center of strike may be considered to be the contact line when the pendulum is brought into contact with a specimen in the normal testing position.

NOTE 3—A method of accurately determining the centers of strike of Izod machines is to place a specimen, so machined that the distance from the center of the notch to the top of the specimen is 22.66 mm (0.892 in.), in test position. With the striking edge in contact with the specimen, a line scribed from the top edge of the specimen to the striking edge will indicate the center of strike on the striking edge.

5.2.3.3 Support the pendulum horizontally to within 15:1000 with two supports, one at the bearings (or center of rotation) and the other at the center of strike on the striking edge (see Fig. 5). Arrange the support at the striking edge to react upon some suitable weighing device such as a platform scale or balance, and determine the weight to within 0.4 %. Take care to minimize friction at either point of support.

Make contact with the striking edge through a round rod crossing the edge at a 90° angle. The weight of the pendulum is the scale reading minus the weights of the supporting rod and any shims that may be used to maintain the pendulum in a horizontal position.

5.2.3.4 Measure the height of pendulum drop for compliance with the requirement of 4.1.7. On Charpy machines measure the height from the top edge of a half-width (or center of a full-width) specimen to the elevated position of the center of strike to 0.1 %. On Izod machines measure the height from a distance 22.66 mm (0.892 in.) above the vise to the release position of the center of strike to 0.1 %.

5.2.3.5 The potential energy of the system is equal to the height from which the pendulum falls, as determined in 5.2.3.4, times the weight of the pendulum, as determined in 5.2.3.3.

5.2.4 *Impact Velocity*—Determine the impact velocity, $v$, of the machine, neglecting friction, by means of the following equation:

$$v = \sqrt{2gh}$$

where:

$v$ = velocity, m/s (or ft/s),

$g$ = acceleration of gravity, m/s$^2$ (or ft/s$^2$), and

$h$ = initial elevation of the striking edge, m (or ft).

5.2.5 *Center of Percussion*—To ensure that minimum force is transmitted to the point of rotation, the center of percussion shall be at a point within 1 % of the distance from the axis of rotation to the center of strike in the specimen. Determine the location of the center of percussion as follows:

5.2.5.1 Using a stop watch or some other suitable time-measuring device, capable of measuring time to within 0.2 s, swing the pendulum through a total angle not greater than 15° and record the time for 100 complete cycles (to and fro).

5.2.5.2 Determine the center of percussion by means of the following equation:

$$l = 0.2484p^2, \text{ to determine } l \text{ in metres}$$

$$l = 0.815p^2, \text{ to determine } l \text{ in feet}$$

where:

$l$ = distance from the axis to the center of percussion, m (or ft), and

$p$ = time of a complete cycle (to and fro) of the pendulum, s.

5.2.6 *Friction*—The energy loss from friction and windage of the pendulum and friction in the recording mechanism, if not corrected, will be included in the energy loss attributed to breaking the specimen and can result in erroneously high impact values. In machines recording in degrees, normal frictional losses are usually not compensated for by the machine manufacturer, whereas they are usually compensated for in machines recording directly in energy by increasing the starting height of the pendulum. Determine energy losses from friction as follows:

5.2.6.1 Without a specimen in the machine, and with the indicator at the maximum energy reading, release the pendulum from its starting position and record the energy value indicated. This value should indicate zero energy if frictional losses have been corrected by the manufacturer. Raise the pendulum so it just contacts the pointer at the value obtained in the free swing. Secure the pendulum at this height and determine the vertical distance from the center of strike to the top of a half-width specimen positioned on the specimen rests (see 5.2.3.1). Determine the weight of the pendulum as in 5.2.3.2 and multiply by this distance. The difference in this value and the initial potential energy is the total energy loss in the pendulum and indicator combined. Without resetting the pointer, repeatedly release the pendulum from its initial position until the pointer shows no further movement. The energy loss determined by the final position of the pointer is that due to the pendulum alone. The frictional loss in the indicator alone is then the difference between the combined indicator and pendulum losses and those due to the pendulum alone.

5.2.6.2 To ensure that friction and windage losses are within tolerances allowed (see 4.1.4), a simple weekly procedure may be adopted for direct-reading machines. The following steps are recommended: (*a*) release the pendulum from its upright position without a specimen in the machine, and the energy reading should be 0 J (0 ft·lbf); (*b*) without resetting the pointer, again release the pendulum and permit it to swing 11 half cycles; and after the pendulum starts its 11th cycle, move the pointer to between 5 and 10 % of scale range capacity and record the value obtained. This value, divided by 11, shall not exceed 0.4 % of scale range capacity. If this value does exceed 0.4 %, the bearings should be cleaned or replaced.

5.2.7 *Indicating Mechanism*—To ensure that the scale is recording accurately over the entire range, check it at graduation marks corresponding to approximately 0, 10, 20, 30, 50, and 70 % of each range. With the striking edge of the pendulum scribed to indicate the center of strike, lift the pendulum and set it in a position where the indicator reads, for example, 13 J (10 ft·lbf). Determine the height of the pendulum to within 0.1 %. The height of the pendulum multiplied by its weight, as determined in 5.2.3.3, is the residual energy. Increase this value by friction and windage losses in accordance with 5.2.6 and subtract from the potential energy determined in 5.2.3. Make similar calculations at other points of the scale. The scale pointer shall not overshoot or drop back with the pendulum. Make test swings from various heights to check visually the operation of the pointer over several portions of the scale.

5.2.8 The impact value shall be taken as the energy absorbed in breaking the specimen and is equal to the difference between the energy in the striking member at the instant of impact with the specimen and the energy remaining after breaking the specimen.

## 6. Precaution in Operation of Machine

6.1 *Safety Precautions*—Precautions should be taken to protect personnel from the swinging pendulum, flying broken specimens, and hazards associated with specimen warming and cooling media.

## 7. Sampling

7.1 Specimens shall be taken from the material as specified by the applicable specification.

## 8. Test Specimens

8.1 *Material Dependence*—The choice of specimen depends to some extent upon the characteristics of the material to be tested. A given specimen may not be equally satisfactory for soft nonferrous metals and hardened steels; therefore, a number of types of specimens are recognized. In general, sharper and deeper notches are required to distinguish differences in the more ductile materials or with lower testing velocities.

8.1.1 The specimens shown in Figs. 6 and 7 are those most widely used and most generally satisfactory. They are particularly suitable for ferrous metals, excepting cast iron.[2]

8.1.2 The specimen commonly found suitable for die cast alloys is shown in Fig. 8.

8.1.3 The specimens commonly found suitable for powdered metals (P/M) are shown in Figs. 9 and 10. The specimen surface may be in the as-produced condition or smoothly machined, but polishing has proven generally unnecessary. Unnotched specimens are used with P/M materials. In P/M materials, the impact test results will be affected by specimen orientation. Therefore, unless otherwise specified, the position of the specimen in the machine shall be such that the pendulum will strike a surface that is parallel to the compacting direction.

8.2 *Sub-Size Specimen*—When the amount of material available does not permit making the standard impact test specimens shown in Figs. 6 and 7, smaller specimens may be used, but the results obtained on different sizes of specimens cannot be compared directly (X1.3). When Charpy specimens other than the standard are necessary or specified, it is recommended that they be selected from Fig. 4.

8.3 *Supplementary Specimens*—For economy in preparation of test specimens, special specimens of round or rectangular cross section are sometimes used for cantilever beam test. These are shown as Specimens X, Y, and Z in Figs. 11 and 12. Specimen Z is sometimes called the Philpot specimen after the name of the original designer. In the case of hard materials, the machining of the flat surface struck by the pendulum is sometimes omitted. Types Y and Z require a different vise from that shown in Fig. 3, each half of the vise having a semicylindrical recess that closely fits the clamped portion of the specimen. As previously stated, the results cannot be reliably compared to those obtained using specimens of other sizes or shapes.

8.4 *Specimen Machining:*

8.4.1 When heat-treated materials are being evaluated, the specimen shall be finish machined, including notching, after the final heat treatment, unless it can be demonstrated that

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[2] For testing cast iron, see 1933 Report of Subcommittee XV on Impact Testing of Committee A-3 on Cast Iron, *Proceedings*, Am. Soc. Testing Mats., Vol 33, Part 1, 1933.

there is no difference when machined prior to heat treatment.

8.4.2 Notches shall be smoothly machined but polishing has proven generally unnecessary. However, since variations in notch dimensions will seriously affect the results of the tests, it is necessary to adhere to the tolerances given in Fig. 6 (X1.2 illustrates the effects from varying notch dimensions on Type A specimens). In keyhole specimens, the round hole shall be carefully drilled with a slow feed. The slot may be cut by any feasible method. Care must be exercised in cutting the slot to see that the surface of the drilled hole opposite the slot is not marked.

8.4.3 Identification marks shall not be placed on any surface of the specimen that contacts the striking edge or specimen supports. All stamping shall be done in a way that avoids cold deforming of the specimen at the notch root or at any other portion of the specimen that is visibly deformed during fracture.

## 9. Preparation of Apparatus

9.1 *Daily Checking Procedure*—After the testing machine has been ascertained to comply with Sections 4 and 5, the routine daily checking procedures shall be as follows:

9.1.1 Prior to testing a group of specimens and before a specimen is placed in position to be tested, check the machine by a free swing of the pendulum. With the indicator at the maximum energy position, a free swing of the pendulum shall indicate zero energy on machines reading directly in energy, which are compensated for frictional losses. On machines recording in degrees, the indicated values when converted to energy shall be compensated for frictional losses that are assumed to be proportional to the arc of swing.

## 10. Verification of Charpy Machines

10.1 Verification consists of inspecting those parts subjected to wear to ensure that the requirements of Sections 4 and 5 are met and the testing of standardized specimens (Notes 4 to 6). It is not intended that parts not subjected to wear (such as pendulum and scale linearity) need to be remeasured during verification unless a problem is evident. The average value at each energy level determined for the standardized specimens shall correspond to the nominal values of the standardized specimens within 1.4 J (1.0 ft·lbf) or 5.0 %, whichever is greater.

NOTE 4—Standardized specimens are available for Charpy machines only.

NOTE 5—Information pertaining to the availability of standardized specimens may be obtained by addressing: Director, Army Materials and Mechanics Research Center, ATTN: DRXMR-MQ, Watertown, Mass. 02172.

NOTE 6—The Army Materials and Mechanics Research Center has for many years conducted a Charpy machine qualification program whereby standardized specimens are used to certify the machines of laboratories using the test as an inspection requirement on government contracts.[3] If the user desires, the results of tests with the standardized specimens will be evaluated. Participants desirous of the evaluation should complete the questionnaire provided with the standardized specimens. The questionnaire provides for information such as testing temperature, the dimensions of certain critical parts, the cooling and testing techniques, and the results of the test. The broken standardized specimens are to be returned along with the completed questionnaire for evaluation (see Note 5 for address). Upon completion of the evaluation, the Army Materials and Mechanics Research Center will return a report. If a machine is producing values outside the standardized specimen tolerances, the report may suggest changes in machine design, repair or replacement of certain machine parts, a change in testing techniques, etc.

10.2 *Frequency of Verification*—Charpy machines shall be verified within one year prior to the time of testing. Charpy machines shall, however, be verified immediately after replacing parts, making repairs or adjustments, after they have been moved, or whenever there is reason to doubt the accuracy of the results, without regard to the time interval.

## 11. Procedure

11.1 The Daily Checking Procedure (Section 9) shall be performed at the beginning of each day or each shift.

11.2 *Charpy Test Procedure*—The Charpy test procedure may be summarized as follows: the test specimen is removed from its cooling (or heating) medium, if used, and positioned on the specimen supports; the pendulum is released without vibration, and the specimen is broken within 5 s after removal from the medium. Information is obtained from the machine and from the broken specimen. The details are described as follows:

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[3] Driscoll, D. E., "Reproducibility of Charpy Impact Test," *Symposium on Impact Testing, ASTM STP 176*, Am. Soc. Testing Mats., 1955, p. 170.

11.2.1 *Temperature of Testing*—In most materials, impact values vary with temperature. Unless otherwise specified, tests shall be made at 15 to 32°C (60 to 90°F). Accuracy of results when testing at other temperatures requires the following procedure: For liquid cooling or heating fill a suitable container, which has a grid raised at least 25 mm (1 in.) from the bottom, with liquid so that the specimen when immersed will be covered with at least 25 mm (1 in.) of the liquid. Bring the liquid to the desired temperature by any convenient method. The device used to measure the temperature of the bath should be placed in the center of a group of the specimens. Verify all temperature-measuring equipment at least twice annually. When using a liquid medium, hold the specimens in an agitated bath at the desired temperature within ±1°C (±2°F) for at least 5 min. When using a gas medium, position the specimens so that the gas circulates around them and hold the gas at the desired temperature within ±1°C (±2°F) for at least 30 min. Leave the mechanism used to remove the specimen from the medium in the medium except when handling the specimens.

NOTE 7—Temperatures up to +260°C (+500°F) may be obtained with certain oils, but "flash-point" temperatures must be carefully observed.

11.2.2 *Placement of Test Specimen in Machine*—It is recommended that self-centering tongs similar to those shown in Fig. 13 be used in placing the specimen in the machine (see 4.3.1). The tongs illustrated in Fig. 13 are for centering V-notch specimens. If keyhole specimens are used, modification of the tong design may be necessary. If an end-centering device is used, caution must be taken to ensure that low-energy high-strength specimens will not rebound off this device into the pendulum and cause erroneously high recorded values. Many such devices are permanent fixtures of machines, and if the clearance between the end of a specimen in test position and the centering device is not approximately 13 mm (0.5 in.), the broken specimens may rebound into the pendulum.

11.2.3 *Operation of the Machine:*

11.2.3.1 Set the energy indicator at the maximum scale reading; take the test specimen from its cooling (or heating) medium, if used; place it in proper position on the specimen anvils; and release the pendulum smoothly. This entire sequence shall take less than 5 s if a cooling or heating medium is used.

11.2.3.2 If any specimen fails to break, do not repeat the blow but record the fact, indicating whether the failure to break occurred through extreme ductility or lack of sufficient energy in the blow. Such results of such tests shall not be included in the average.

11.2.3.3 If any specimen jams in the machine, disregard the results and check the machine thoroughly for damage or maladjustment, which would affect its calibration.

11.2.3.4 To prevent recording an erroneous value caused by jarring the indicator when locking the pendulum in its upright position, read the value from the indicator prior to locking the pendulum for the next test.

11.2.4 *Information Obtainable from the Test*:

11.2.4.1 *Impact Energy*—The amount of energy required to fracture the specimen is determined from the machine reading.

11.2.4.2 *Lateral Expansion*—The method for measuring lateral expansion must take into account the fact that the fracture path seldom bisects the point of maximum expansion on both sides of a specimen. One half of a broken specimen may include the maximum expansion for both sides, one side only, on neither. The technique used must therefore provide an expansion value equal to the sum of the higher of the two values obtained for each side by measuring the two halves separately. The amount of expansion on each side of each half must be measured relative to the plane defined by the undeformed portion of the side of the specimen, Fig. 16. Expansion may be measured by using a gage similar to that shown in Figs. 17 and 18. Measure the two broken halves individually. First, though, check the sides perpendicular to the notch to ensure that no burrs were formed on these sides during impact testing; if such burrs exist, they must be removed, for example, by rubbing on emery cloth, making sure that the protrusions to be measured are not rubbed during the removal of the burr. Next, place the halves together so that the compression sides are facing one another. Take one half and press it firmly against the reference supports, with the protrusion against the gage anvil. Note the reading, then repeat this step with the other broken half, ensuring that the same side of the specimen is measured. The larger of the two values is the expansion of that side of the specimen. Next, repeat this procedure to measure the protrusions on the opposite side, then add the larger values obtained for each side. Measure each specimen.

NOTE 8—Examine each fracture surface to ascertain that the protrusions have not been damaged by contacting the anvil, machine mounting surface, etc. Such specimens should be discarded since this may cause erroneous readings.

11.2.4.3 *Fracture Appearance*—The percentage of shear fracture may be determined by any of the following methods: (*1*) measure the length and width of the cleavage portion of the fracture surface, as shown in Fig. 14, and determine the percent shear from either Table 1 or Table 2 depending on the units of measurement; (*2*) compare the appearance of the fracture of the specimen with a fracture appearance chart such as that shown in Fig. 15; (*3*) magnify the fracture surface and compare it to a precalibrated overlay chart or measure the percent shear fracture by means of a planimeter; or (*4*) photograph the fracture surface at a suitable magnification and measure the percent shear fracture by means of a planimeter.

NOTE 9—Because of the subjective nature of the evaluation of fracture appearance, it is not recommended that it be used in specifications.

11.3 *Izod Test Procedure*—The Izod test procedure may be summarized as follows: the test specimen is positioned in the specimen-holding fixture and the pendulum is released without vibration. Information is obtained from the machine and from the broken specimen. The details are described as follows:

11.3.1 *Temperature of Testing*—The specimen-holding fixture for Izod specimens is in most cases part of the base of the machine and cannot be readily cooled (or heated). For this reason, Izod testing is not recommended at other than room temperature.

11.3.2 Clamp the specimen firmly in the support vise so that the centerline of the notch is in the plane of the top of the vise within 0.125 mm (0.005 in.). Set the energy indicator at the maximum scale reading, and release the pendulum smoothly. Sections 11.2.3.2 to 11.2.3.4 inclusively, also apply when testing Izod specimens.

11.3.3 *Information Obtainable from the Test*—The impact energy, lateral expansion, and fracture appearance, may be determined as described in 11.2.4.

## 12. Report

12.1 For commercial acceptance testing, the following is considered sufficient:

12.1.1 Type of specimen used (and size if not the standard size).

12.1.2 Temperature of the specimen.

12.1.3 When required any or all of the following shall be reported:

12.1.3.1 Energy absorbed,

12.1.3.2 Lateral expansion, and

12.1.3.3 Fracture appearance (see Note 9).

## 13. Precision and Accuracy

13.1 The precision and accuracy of these methods are being established.

**TABLE 1 Percent Shear for Measurements Made in Millimetres**

NOTE—100 % shear is to be reported when either *A* or *B* is zero.

| Dimension *B*, mm | Dimension *A*, mm | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.0 | 9.5 | 10 |
| 1.0 | 99 | 98 | 98 | 97 | 96 | 96 | 95 | 94 | 94 | 93 | 92 | 92 | 91 | 91 | 90 | 89 | 89 | 88 | 88 |
| 1.5 | 98 | 97 | 96 | 95 | 94 | 93 | 92 | 92 | 91 | 90 | 89 | 88 | 87 | 86 | 85 | 84 | 83 | 82 | 81 |
| 2.0 | 98 | 96 | 95 | 94 | 92 | 91 | 90 | 89 | 88 | 86 | 85 | 84 | 82 | 81 | 80 | 79 | 77 | 76 | 75 |
| 2.5 | 97 | 95 | 94 | 92 | 91 | 89 | 88 | 86 | 84 | 83 | 81 | 80 | 78 | 77 | 75 | 73 | 72 | 70 | 69 |
| 3.0 | 96 | 94 | 92 | 91 | 89 | 87 | 85 | 83 | 81 | 79 | 77 | 76 | 74 | 72 | 70 | 68 | 66 | 64 | 62 |
| 3.5 | 96 | 93 | 91 | 89 | 87 | 85 | 82 | 80 | 78 | 76 | 74 | 72 | 69 | 67 | 65 | 63 | 61 | 58 | 56 |
| 4.0 | 95 | 92 | 90 | 88 | 85 | 82 | 80 | 77 | 75 | 72 | 70 | 67 | 65 | 62 | 60 | 57 | 55 | 52 | 50 |
| 4.5 | 94 | 92 | 89 | 86 | 83 | 80 | 77 | 75 | 72 | 69 | 66 | 63 | 61 | 58 | 55 | 52 | 49 | 46 | 44 |
| 5.0 | 94 | 91 | 88 | 85 | 81 | 78 | 75 | 72 | 69 | 66 | 62 | 59 | 56 | 53 | 50 | 47 | 44 | 41 | 37 |
| 5.5 | 93 | 90 | 96 | 83 | 79 | 76 | 72 | 69 | 66 | 62 | 59 | 55 | 52 | 48 | 45 | 42 | 38 | 35 | 31 |
| 6.0 | 92 | 89 | 85 | 81 | 77 | 74 | 70 | 66 | 62 | 59 | 55 | 51 | 47 | 44 | 40 | 36 | 33 | 29 | 25 |
| 6.5 | 92 | 88 | 84 | 80 | 76 | 72 | 67 | 63 | 59 | 55 | 51 | 47 | 43 | 39 | 35 | 31 | 27 | 23 | 19 |
| 7.0 | 91 | 87 | 82 | 78 | 74 | 69 | 65 | 61 | 56 | 52 | 47 | 43 | 39 | 34 | 30 | 26 | 21 | 17 | 12 |
| 7.5 | 91 | 86 | 81 | 77 | 72 | 67 | 62 | 58 | 53 | 48 | 44 | 39 | 34 | 30 | 25 | 20 | 16 | 11 | 6 |
| 8.0 | 90 | 85 | 80 | 75 | 70 | 65 | 60 | 55 | 50 | 45 | 40 | 35 | 30 | 25 | 20 | 15 | 10 | 5 | 0 |

TABLE 2 Percent Shear for Measurements Made in Inches

NOTE—100 % shear is to be reported when either *A* or *B* is zero.

| Dimension *B*, in. | Dimension *A*, in. | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.05 | 0.10 | 0.12 | 0.14 | 0.16 | 0.18 | 0.20 | 0.22 | 0.24 | 0.26 | 0.28 | 0.30 | 0.32 | 0.34 | 0.36 | 0.38 | 0.40 |
| 0.05 | 98 | 96 | 95 | 94 | 94 | 93 | 92 | 91 | 90 | 90 | 89 | 88 | 87 | 86 | 85 | 85 | 84 |
| 0.10 | 96 | 92 | 90 | 89 | 87 | 85 | 84 | 82 | 81 | 79 | 77 | 76 | 74 | 73 | 71 | 69 | 68 |
| 0.12 | 95 | 90 | 88 | 86 | 85 | 83 | 81 | 79 | 77 | 75 | 73 | 71 | 69 | 67 | 65 | 63 | 61 |
| 0.14 | 94 | 89 | 86 | 84 | 82 | 80 | 77 | 75 | 73 | 71 | 68 | 66 | 64 | 62 | 59 | 57 | 55 |
| 0.16 | 94 | 87 | 85 | 82 | 79 | 77 | 74 | 72 | 69 | 67 | 64 | 61 | 59 | 56 | 53 | 51 | 48 |
| 0.18 | 93 | 85 | 83 | 80 | 77 | 74 | 72 | 68 | 65 | 62 | 59 | 56 | 54 | 51 | 48 | 45 | 42 |
| 0.20 | 92 | 84 | 81 | 77 | 74 | 72 | 68 | 65 | 61 | 58 | 55 | 52 | 48 | 45 | 42 | 39 | 36 |
| 0.22 | 91 | 82 | 79 | 75 | 72 | 68 | 65 | 61 | 57 | 54 | 50 | 47 | 43 | 40 | 36 | 33 | 29 |
| 0.24 | 90 | 81 | 77 | 73 | 69 | 65 | 61 | 57 | 54 | 50 | 46 | 42 | 38 | 34 | 30 | 27 | 23 |
| 0.26 | 90 | 79 | 75 | 71 | 67 | 62 | 58 | 54 | 50 | 46 | 41 | 37 | 33 | 29 | 25 | 20 | 16 |
| 0.28 | 89 | 77 | 73 | 68 | 64 | 59 | 55 | 50 | 46 | 41 | 37 | 32 | 28 | 23 | 18 | 14 | 10 |
| 0.30 | 88 | 76 | 71 | 66 | 61 | 56 | 52 | 47 | 42 | 37 | 32 | 27 | 23 | 18 | 13 | 9 | 3 |
| 0.31 | 88 | 75 | 70 | 65 | 60 | 55 | 50 | 45 | 40 | 35 | 30 | 25 | 20 | 18 | 10 | 5 | 0 |

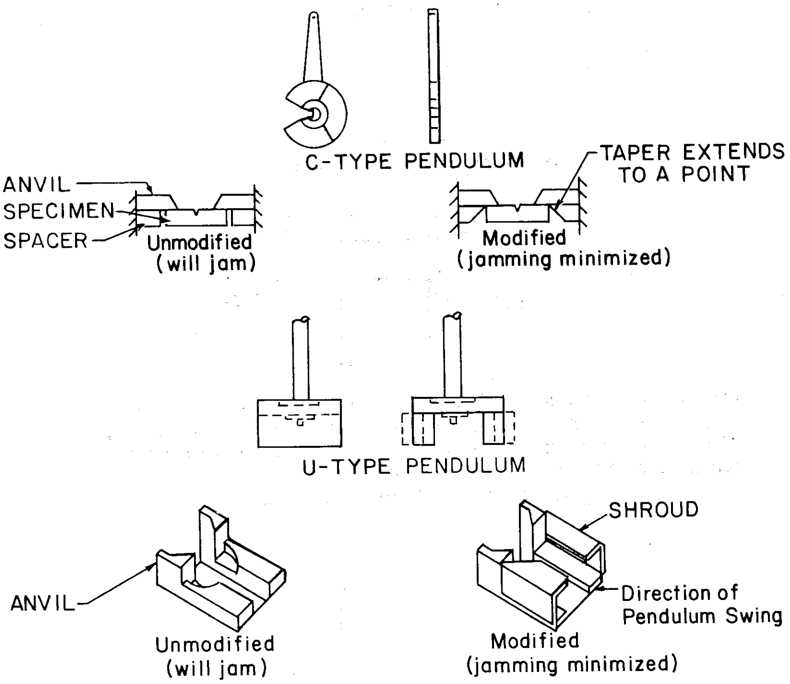
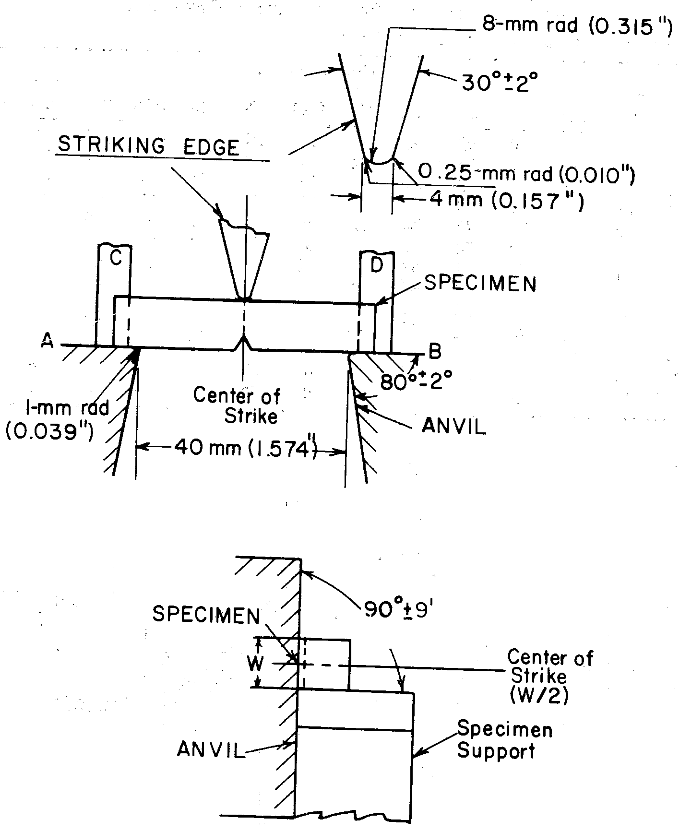


FIG. 1 Typical Pendulums and Anvils for Charpy Machines, Shown with Modifications to Minimize Jamming



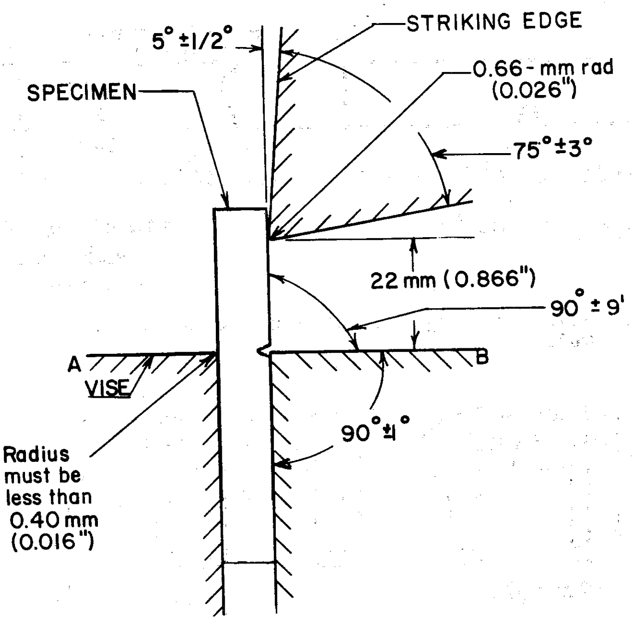
All dimensional tolerances shall be ±0.05 mm (0.002 in.) unless otherwise specified.

NOTE 1—A shall be parallel to B within 2:1000 and coplanar with B within 0.05 mm (0.002 in.).

NOTE 2—C shall be parallel to D within 2.0:1000 and coplanar with D within 0.125 mm (0.005 in.).

NOTE 3—Finish on unmarked parts shall be 4 μm (125 μin.).

**FIG. 2 Charpy (Simple-Beam) Impact Test**



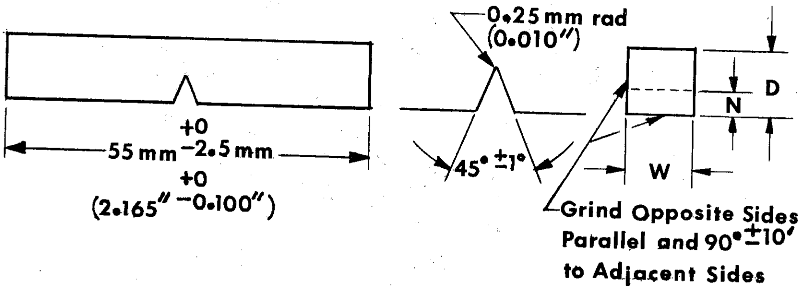
All dimensional tolerances shall be ±0.05 mm (0.002 in.) unless otherwise specified.

NOTE 1—The clamping surfaces of A and B shall be flat and parallel within 0.025 mm (0.001 in.).

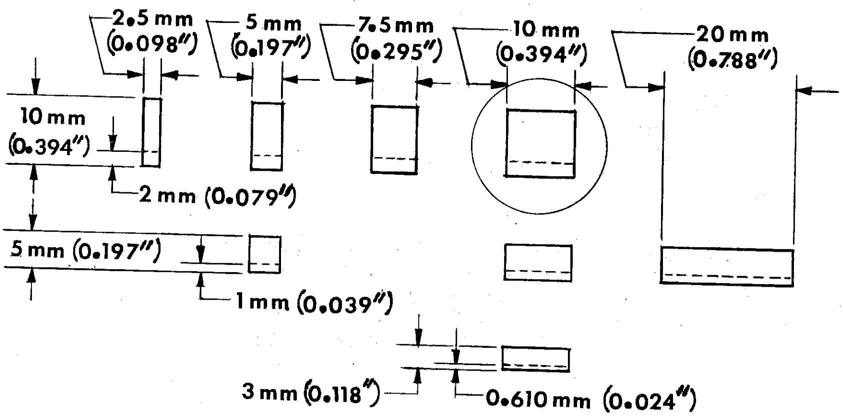
NOTE 2—Finish on unmarked parts shall be 2 μm (63 μin.).

NOTE 3—Striker width must be greater than that of the specimen being tested.

**FIG. 3 Izod (Cantilever-Beam) Impact Test**



On subsize specimens the length, notch angle, and notch radius are constant (see Fig. 6); depth (*D*), notch depth (*N*), and width (*W*) vary as indicated below.



NOTE 1—Circled specimen is the standard specimen (see Fig. 6).

NOTE 2—Permissible variations shall be as follows:

| | |
|---|---|
| Cross-section dimensions | ±1% or ±0.075 mm (0.003 in.), whichever is smaller |
| Radius of notch | ±0.025 mm (0.001 in.) |
| Depth of notch | ±0.025 mm (0.001 in.) |
| Finish requirements | 2 μm (63 μin.) on notched surface and opposite face; 4 μm (125 μin.) on other two surfaces |

FIG. 4 Charpy (Simple-Beam) Subsize (Type A) Impact Test Specimens

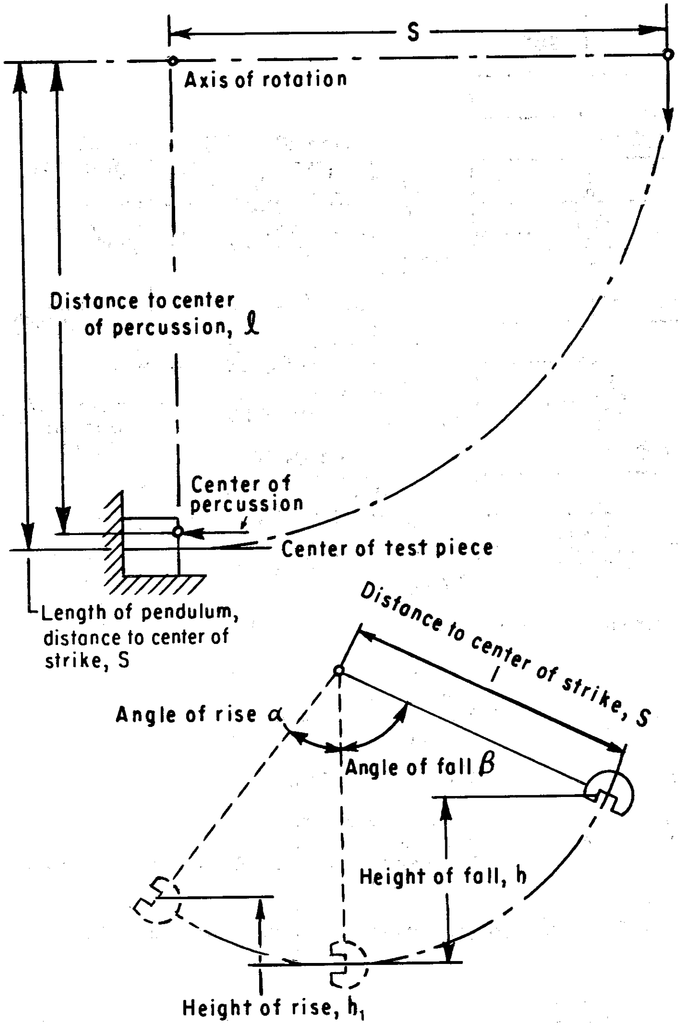
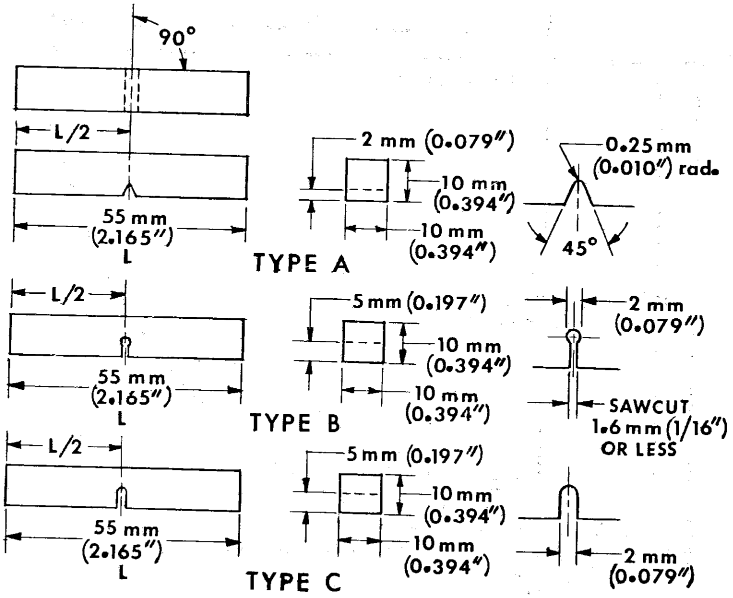


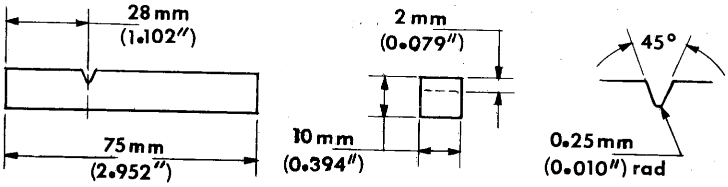
FIG. 5 Dimensions for Calculations



NOTE—Permissible variations shall be as follows:

| | |
|---|---|
| Notch length to edge | ±2° |
| Adjacent sides shall be at | 90° ±10 min |
| Cross-section dimensions | ±0.075 mm (±0.003 in.) |
| Length of specimen (*L*) | +0, −2.5 mm (+0, −0.100 in.) |
| Centering of notch (*L*/2) | ±1 mm (±0.039 in.) |
| Angle of notch | ±1° |
| Radius of notch | ±0.025 mm (±0.001 in.) |
| Notch depth: | |
| Type A specimen | ±0.025 mm (±0.001 in.) |
| Types B and C specimen | ±0.075 mm (±0.003 in.) |
| Finish requirements | 2 µm (63 µin.) on notched surface and opposite face; 4 µm (125 µin.) on other two surfaces |

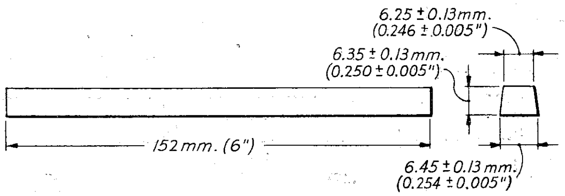
FIG. 6 Charpy (Simple-Beam) Impact Test Specimens, Types A, B, and C



NOTE—Permissible variations shall be as follows:

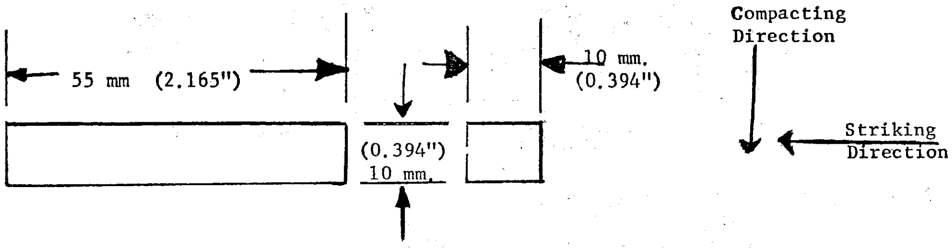
| | |
|---|---|
| Notch length to edge | 90 ±2° |
| Cross-section dimensions | ±0.025 mm (±0.001 in.) |
| Length of specimen | +0, −2.5 mm (±0, −0.100 in.) |
| Angle of notch | ±1° |
| Radius of notch | ±0.025 mm (±0.001 in.) |
| Notch depth | ±0.025 mm (±0.001 in.) |
| Adjacent sides shall be at | 90° ± 10 min |
| Finish requirements | 2 µm (63 µin.) on notched surface and opposite face; 4 µm (125 µin.) on other two surfaces |

FIG. 7 Izod (Cantilever-Beam) Impact Test Specimen, Type D



NOTE 1—Two test specimens may be cut from this bar.
NOTE 2—Blow shall be struck on narrowest face.

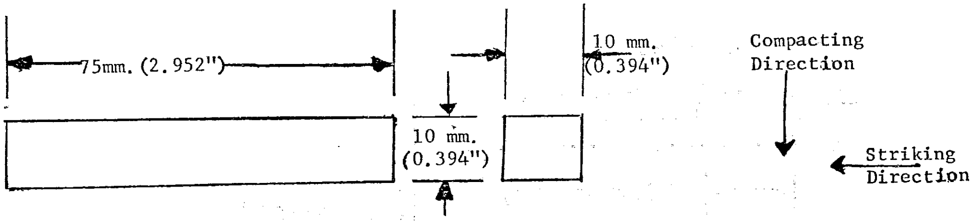
**FIG. 8 Simple Beam Impact Test Bar for Die Castings Alloys**



NOTE—Permissible variations shall be as follows:

| | |
|---|---|
| Adjacent sides shall be at | 90° ± 10 min |
| Cross section dimensions | ±0.125 mm (0.005 in.) |
| Length of specimen | ±0, −2.5 mm (0.100 in.) |

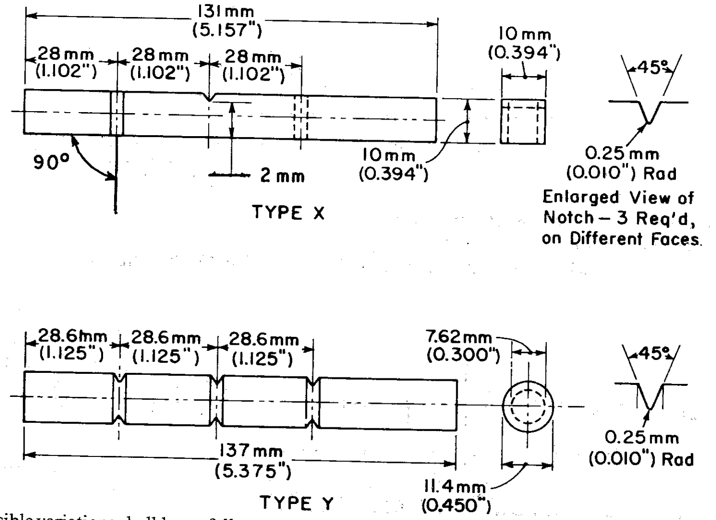
**FIG. 9 Charpy (Simple Beam) Impact Test Specimens for Metal Powder Structural Parts**



NOTE—Permissible variations shall be as follows:

| | |
|---|---|
| Adjacent sides shall be at | 90° ± 10 min. |
| Cross section dimensions | ±0.125 mm (0.005 in.) |
| Length of specimens | +0, −2.5 mm (0.100 in.) |

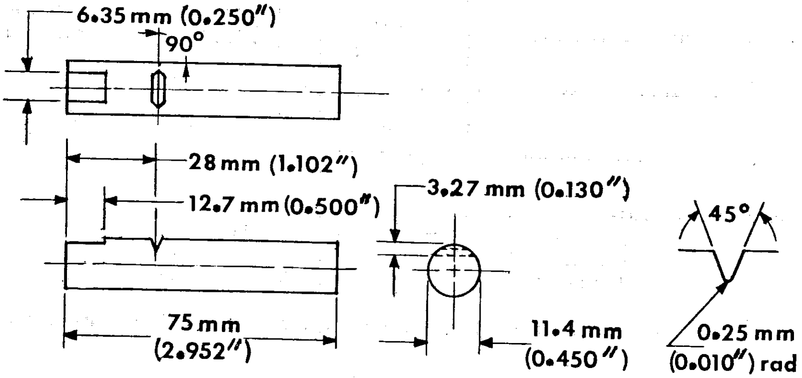
**FIG. 10 Izod (Cantilever-Beam) Impact Test Specimen for Metal Powder Structural Parts**



NOTE—Permissible variations shall be as follows:

| | |
|---|---|
| Notch length to edge | ±2 mm |
| Adjacent sides shall be at | 90° ±10 min |
| Cross-section dimensions | ±0.025 mm (±0.001 in.) |
| Lengthwise dimensions | +0, −2.5 mm (±0.100 in.) |
| Angle of notch | ±1° |
| Radius of notch | ±0.025 mm (±0.001 in.) |
| Notch depth of Type X specimen | ±0.025 mm (±0.001 in.) |
| Notch diameter of Type Y specimen | ±0.025 mm (±0.001 in.) |

FIG. 11 Izod (Cantilever-Beam) Impact Test Specimens, Types X and Y

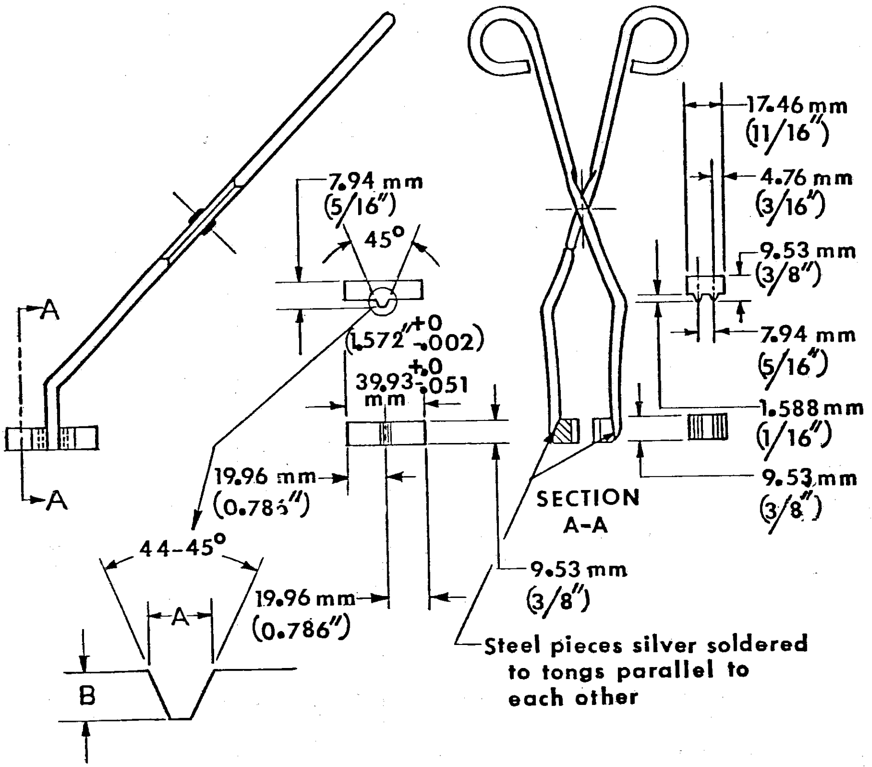


The flat shall be parallel to the longitudinal centerline of the specimen and shall be parallel to the bottom of the notch within 2:1000.

NOTE—Permissible variations shall be as follows:

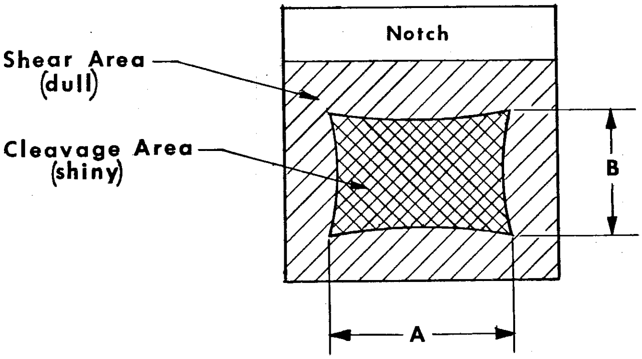
| | |
|---|---|
| Notch length to longitudinal centerline | ±2° |
| Cross-section dimensions | ±0.025 mm (−0.001 in.) |
| Length of specimen | +0, −2.5 mm (+0 −0.100 in.) |
| Angle of notch | ±1° |
| Radius of notch | ±0.025 mm (±0.001 in.) |
| Notch depth | ±0.025 mm (.130 ±0.001 in.) |

FIG. 12 Izod (Cantilever-Beam) Impact Test Specimen (Philpot), Type Z



| Specimen Depth, mm (in.) | Base Width (A), mm (in.) | Height (B), mm (in.) |
|---|---|---|
| 10 (0.394) | 1.60 to 1.70 (0.063 to 0.067) | 1.52 to 1.65 (0.060 to 0.065) |
| 5 (0.197) | 0.74 to 0.80 (0.029 to 0.033) | 0.69 to 0.81 (0.027 to 0.032) |
| 3 (0.118) | 0.45 to 0.51 (0.016 to 0.020) | 0.36 to 0.48 (0.014 to 0.019) |

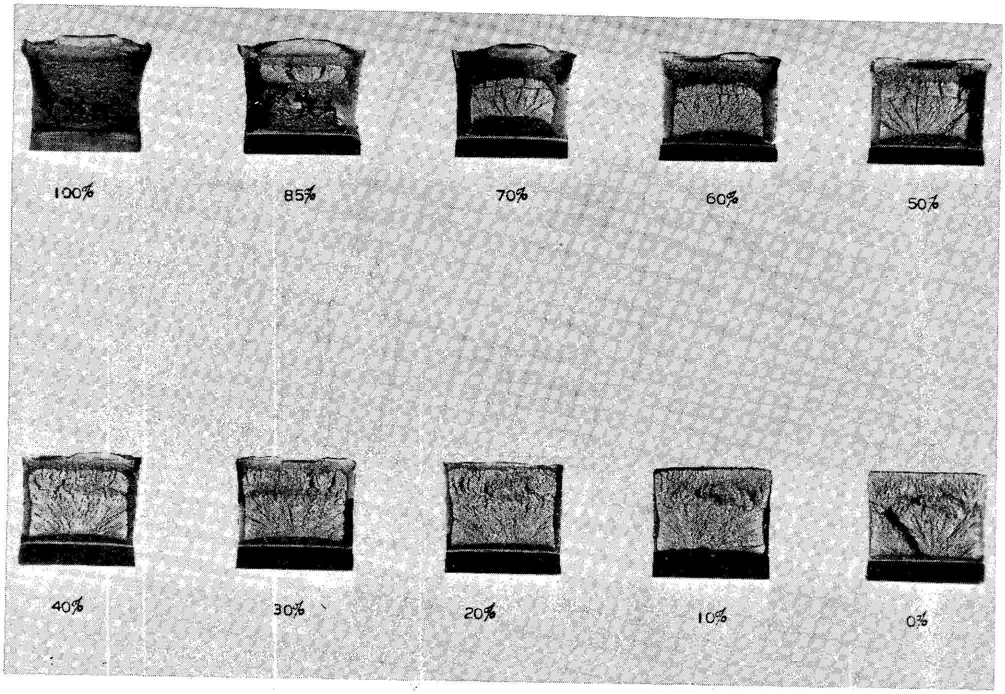
**FIG. 13 Centering Tongs for V-Notch Charpy Specimens**



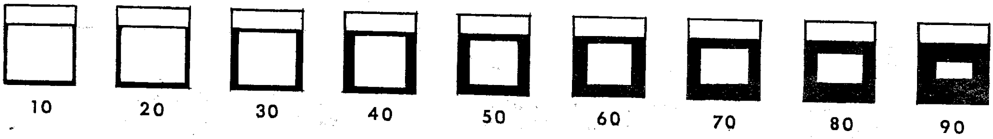
NOTE 1—Measure average dimensions *A* and *B* to the nearest 0.5 mm or 0.02 in.

NOTE 2—Determine the percent shear fracture using Table 1 or Table 2.

**FIG. 14 Determination of Percent Shear Fracture**



(*a*) Fracture Appearance Charts and Percent Shear Fracture Comparator



(*b*) Guide for Estimating Fracture Appearance Using SulAG Method

**FIG. 15 Fracture Appearance**

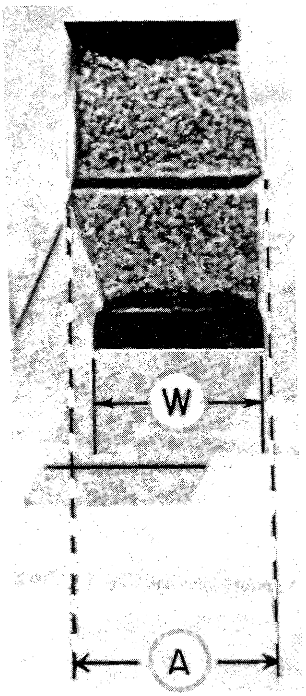


FIG. 16 Halves of Broken Charpy V-Notch Impact Specimen Positioned to Illustrate the Measurement of Lateral Expansion, Dimension *A* and Original Width, Dimension *W*

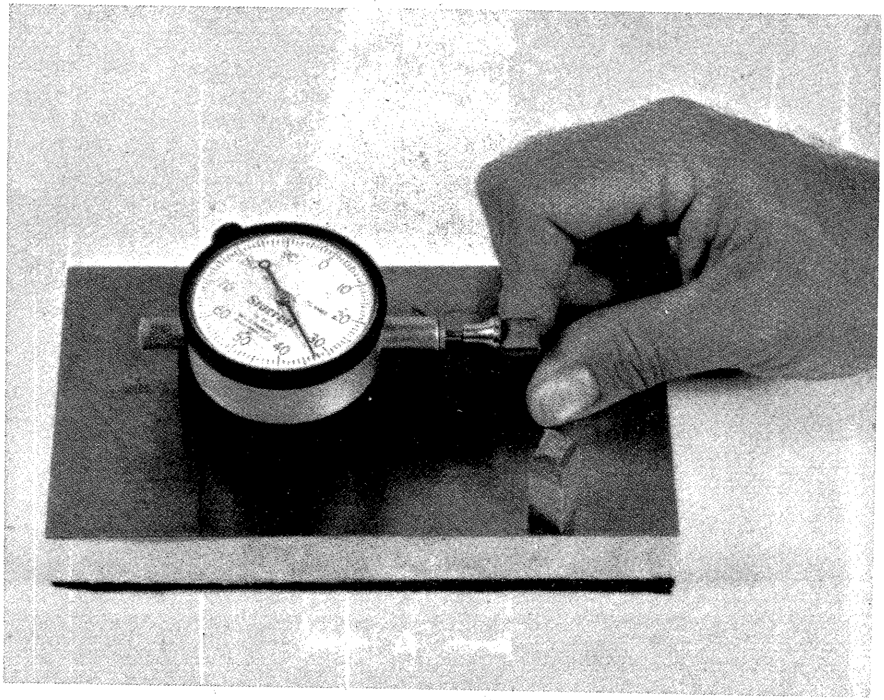
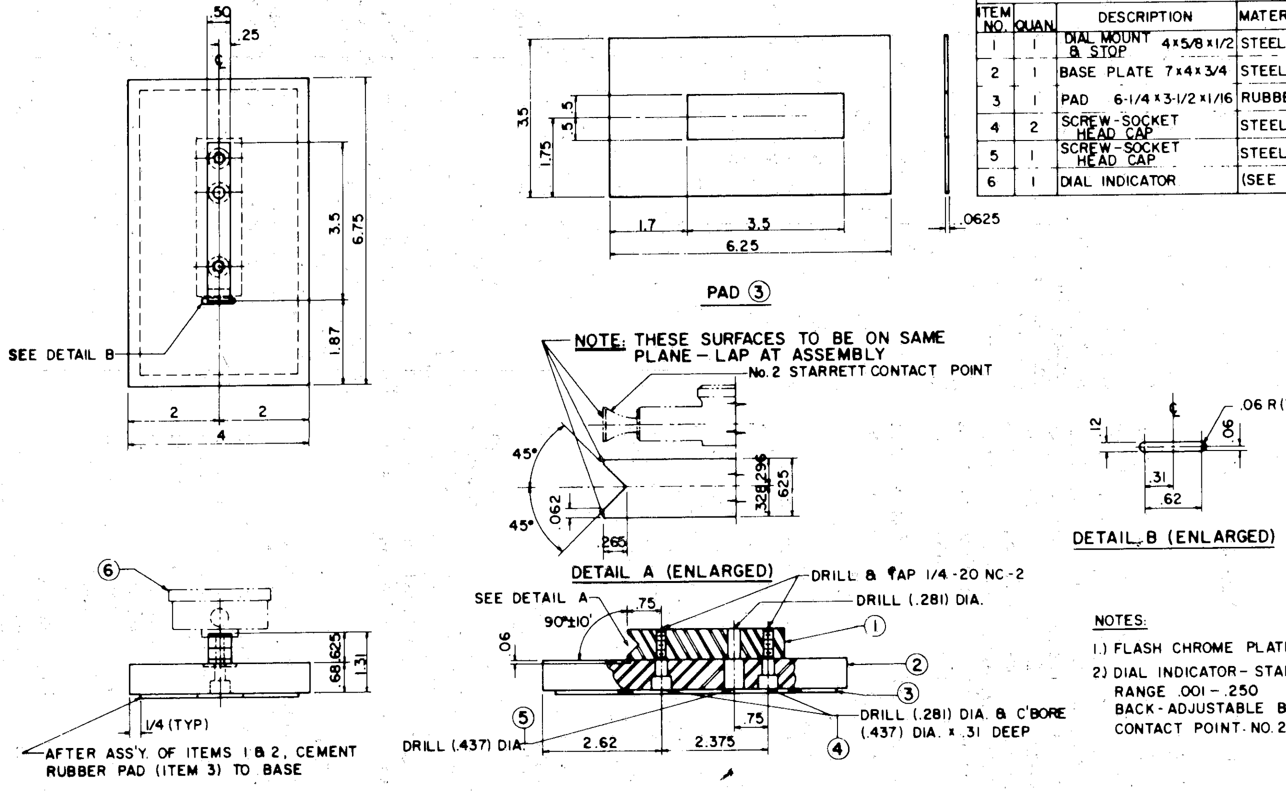


FIG. 17 Lateral Expansion Gage for Charpy Impact Specimens



| BILL OF MATERIAL | | | |
|---|---|---|---|
| ITEM NO. | QUAN. | DESCRIPTION | MATERIAL AND SIZE |
| 1 | 1 | DIAL MOUNT & STOP 4×5/8×1/2 | STEEL SAE 1015-1020 |
| 2 | 1 | BASE PLATE 7×4×3/4 | STEEL SAE 1015-1020 |
| 3 | 1 | PAD 6-1/4×3-1/2×1/16 | RUBBER |
| 4 | 2 | SCREW-SOCKET HEAD CAP | STEEL 1/4-20×1" LG. |
| 5 | 1 | SCREW-SOCKET HEAD CAP | STEEL 1/4-20×3/4" LG. |
| 6 | 1 | DIAL INDICATOR | (SEE NOTE 2) |

NOTES:

1.) FLASH CHROME PLATE ITEMS 1 & 2

2.) DIAL INDICATOR – STARRETT NO. 25-241
RANGE .001 – .250
BACK-ADJUSTABLE BRACKET
CONTACT POINT. NO. 2

FIG. 18 Assembly and Details for Lateral Expansion Gage

# APPENDIX

## X1. NOTES ON SIGNIFICANCE OF NOTCHED-BAR IMPACT TESTING

### X1.1 Notch Behavior

X1.1.1 The Charpy and Izod type tests bring out notch behavior (brittleness versus ductility) by applying a single overload of stress. The energy values determined are quantitative comparisons on a selected specimen but cannot be converted into energy values that would serve for engineering desgin calculations. The notch behavior indicated in an individual test applies only to the specimen size, notch geometry, and testing conditions involved and cannot be generalized to other sizes of specimens and conditions.

X1.1.2 The notch behavior of the face-centered cubic metals and alloys, a large group of nonferrous materials and the austenitic steels can be judged from their common tensile properties. If they are brittle in tension they will be brittle when notched, while if they are ductile in tension they will be ductile when notched, except for unusually sharp or deep notches (much more severe than the standard Charpy or Izod specimens). Even low temperatures do not alter this characteristic of these materials. In contrast, the behavior of the ferritic steels under notch conditions cannot be predicted from their properties as revealed by the tension test. For the study of these materials the Charpy and Izod type tests are accordingly very useful. Some metals that display normal ductility in the tension test may nevertheless break in brittle fashion when tested or when used in the notched condition. Notched conditions include restraints to deformation in directions perpendicular to the major stress, or multiaxial stresses, and stress concentrations. It is in this field that the Charpy and Izod tests prove useful for determining the susceptibility of a steel to notch-brittle behavior though they cannot be directly used to appraise the serviceability of a structure.

### X1.2 Notch Effect

X1.2.1 The notch results in a combination of multiaxial stresses associated with restraints to deformation in directions perpendicular to the major stress, and a stress concentration at the base of the notch. A severely notched condition is generally not desirable, and it becomes of real concern in those cases in which it initiates a sudden and complete failure of the brittle type. Some metals can be deformed in a ductile manner even down to the low temperatures of liquid air, while others may crack. This difference in behavior can be best understood by considering the cohesive strength of a material (or the property that holds it together) and its relation to the yield point. In cases of brittle fracture, the cohesive strength is exceeded before significant plastic deformation occurs and the fracture appears crystalline. In cases of the ductile or shear type of failure, considerable deformation precedes the final fracture and the broken surface appears fibrous instead of crytalline. In intermediate cases the fracture comes after a moderate amount of deformation and is part crystalline and part fibrous in appearance.

X1.2.2 When a notched bar is loaded, there is a normal stress across the base of the notch which tends to initiate fracture. The property that keeps it from cleaving, or holds it together, is the "cohesive strength." The bar fractures when the normal stress exceeds the cohesive strength. When this occurs without the bar deforming it is the condition for brittle fracture.

X1.2.3 In testing, though not in service because of side effects, it happens more commonly that plastic deformation precedes fracture. In addition to the normal stress, the applied load also sets up shear stresses which are about 45° to the normal stress. The elastic behavior terminates as soon as the shear stress exceeds the shear strength of the material and deformation or plastic yielding sets in. This is the condition for ductile failure.

X.1.2.4 This behavior, whether brittle or ductile, depends on whether the normal stress exceeds the cohesive strength before the shear stress exceeds the shear strength. Several important facts of notch behavior follow from this. If the notch is made sharper or more drastic, the normal stress at the root of the notch will be increased in relation to the shear stress and the bar will be more prone to brittle fracture (see Table X1.1). Also, as the speed of deformation increases, the shear strength increases and the likelihood of brittle fracture increases. On the other hand, by raising the temperature, leaving the notch and the speed of deformation the same, the shear strength is lowered and ductile behavior is promoted, leading to shear failure.

X1.2.5 Variations in notch dimensions will seriously affect the results of the tests. Tests on E 4340 steel specimens[4] have shown the effect of dimensional variations on Charpy results (see Table X1.1).

### X1.3 Size Effect

X1.3.1 Increasing either the width or the depth of the specimen tends to increase the volume of metal subject to distortion, and by this factor tends to

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[4] N. H. Fahey, "Effects of Variables in Charpy Impact Testing," *Materials Research & Standards*, Vol 1, No. 11, November 1961, p. 872.

increase the energy absorption when breaking the specimen. However, any increase in size, particularly in width, also tends to increase the degree of restraint and by tending to induce brittle fracture, may decrease the amount of energy absorbed. Where a standard-size specimen is on the verge of brittle fracture, this is particularly true, and a doublewidth specimen may actually require less energy for rupture than one of standard width.

X1.3.2 In studies of such effects where the size of the material precludes the use of the standard specimen, as for example when the material is 6.35 mm (0.25-in.) plate, subsize specimens are necessarily used. Such specimens (Fig. 4) are based on the Type A specimen of Fig. 6.

X1.3.3 General correlation between the energy values obtained with specimens of different size or shape is not feasible, but limited correlations may be established for specification purposes on the basis of special studies of particular materials and particular specimens. On the other hand, in a study of the relative effect of process variations, evaluation by use of some arbitrarily selected specimen with some chosen notch will in most instances place the methods in their proper order.

## X1.4 Temperature Effect

X1.4.1 The testing conditions also affect the notch behavior. So pronounced is the effect of temperature on the behavior of steel when notched that comparisons are frequently made by examining specimen fractures and by plotting energy value and fracture appearance versus temperature from tests of notched bars at a series of temperatures. When the test temperature has been carried low enough to start cleavage fracture, there may be an extremely sharp drop in impact value or there may be a relatively gradual falling off toward the lower temperatures. This drop in energy value starts when a specimen begins to exhibit some crystalline appearance in the fracture. The transition temperature at which this embrittling effect takes place varies considerably with the size of the part or test specimen and with the notch geometry.

## X1.5 Testing Machine

X1.5.1 The testing machine itself must be sufficiently rigid or tests on high-strength low-energy materials will result in excessive elastic energy losses either upward through the pendulum shaft or downward through the base of the machine. If the anvil supports, the pendulum striking edge, or the machine foundation bolts are not securely fastened, tests on ductile materials in the range from 108 J (80 ft·lbf) may actually indicate values in excess of 122 to 136 J (90 to 100 ft·lbf)

X1.5.2 A problem peculiar to Charpy-type tests occurs when high-strength, low-energy specimens are tested at low temperatures. These specimens may not leave the machine in the direction of the pendulum swing but rather in a sidewise direction. To ensure that the broken halves of the specimens do not rebound off some component of the machine and contact the pendulum before it completes its swing, modifications may be necessary in older model machines. These modifications differ with machine design. Nevertheless the basic problem is the same in that provisions must be made to prevent rebounding of the fractured specimens into any part of the swinging pendulum. Where design permits, the broken specimens may be deflected out of the sides of the machine and yet in other designs it may be necessary to contain the broken specimens within a certain area until the pendulum passes through the anvils. Some low-energy high-strength steel specimens leave impact machines at speeds in excess of 15.2 m/s (50 ft/s) although they were struck by a pendulum traveling at speeds approximately 5.2 m/s (17 ft/s). If the force exerted on the pendulum by the broken specimens is sufficient, the pendulum will slow down and erroneously high energy values will be recorded. This problem accounts for many of the inconsistencies in Charpy results reported by various investigators within the 14 to 34-J (10 to 25-ft·lb) range. Figure 1 illustrates a modification found to be satisfactory in minimizing jamming.

## X1.6 Velocity of Straining

X1.6.1 Velocity of straining is likewise a variable that affects the notch behavior of steel. The impact test shows somewhat higher energy absorption values than the static tests above the transition temperature and yet, in some instances, the reverse is true below the transition temperature.

## X1.7 Correlation with Service

X1.7.1 While Charpy or Izod tests may not directly predict the ductile or brittle behavior of steel as commonly used in large masses or as components of large structures, these tests can be used as acceptance tests or tests of identity for different lots of the same steel or in choosing between different steels, when correlation with reliable service behavior has been established. It may be necessary to make the tests at properly chosen temperatures other than room temperature. In this, the service temperature or the transition temperature of full-scale specimens does not give the desired transition temperatures for Charpy or Izod tests since the size and notch geometry may be so different. Chemical analysis, tension, and hardness tests may not indicate the influence of some of the important processing factors that affect susceptibility to brittle fracture nor do they comprehend the effect of low temperatures in inducing brittle behavior.

**TABLE X1.1 Effect of Varying Notch Dimensions on Standard Specimens**

| | High-Energy Specimens, J (ft·lbf) | High-Energy Specimens, J (ft·lbf) | Low-Energy Specimens, J (ft·lbf) |
|---|---|---|---|
| Specimen with standard dimensions | 103.0 ± 5.2 (76.0 ± 3.8) | 60.3 ± 3.0 (44.5 ± 2.2) | 16.9 ± 1.4 (12.5 ± 1.0) |
| Depth of notch, 2.13 mm (0.084 in.)[A] | 97.9 (72.2) | 56.0 (41.3) | 15.5 (11.4) |
| Depth of notch, 2.04 mm (0.0805 in.)[A] | 101.8 (75.1) | 57.2 (42.2) | 16.8 (12.4) |
| Depth of notch, 1.97 mm (0.0775 in.)[A] | 104.1 (76.8) | 61.4 (45.3) | 17.2 (12.7) |
| Depth of notch, 1.88 mm (0.074 in.)[A] | 107.9 (79.6) | 62.4 (46.0) | 17.4 (12.8) |
| Radius at base of notch 0.13 mm (0.005 in.)[B] | 98.0 (72.3) | 56.5 (41.7) | 14.6 (10.8) |
| Radius at base of notch 0.38 mm (0.015 in.)[B] | 108.5 (80.0) | 64.3 (47.4) | 21.4 (15.8) |

[A] Standard 2.0 ± 0.025 mm (0.079 ± 0.001 in.).

[B] Standard 0.25 ± 0.025 mm (0.010 ± 0.001 in.).