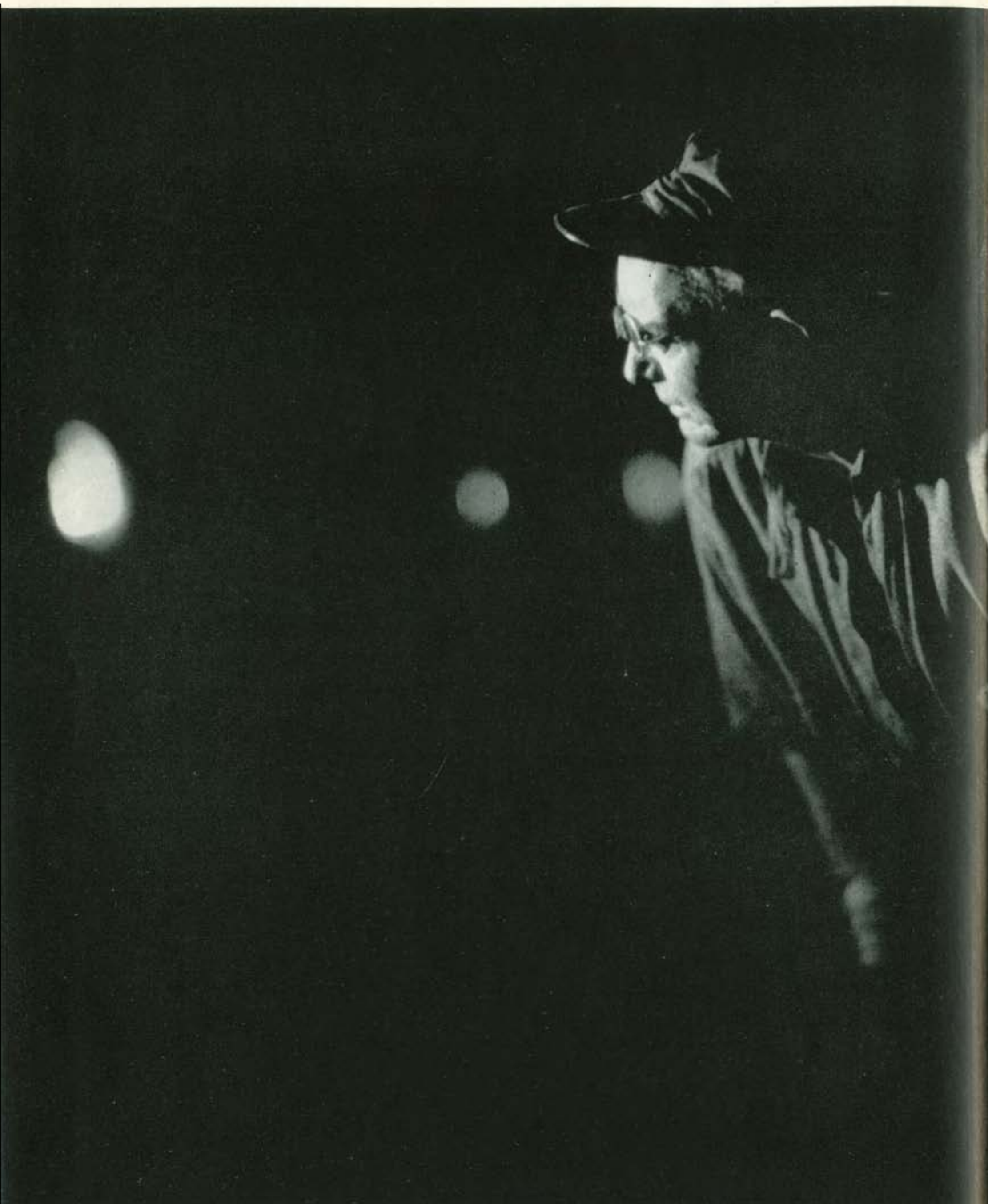
U·S·S CARILLOY STEELS

CARNEGIE - ILLINOIS STEEL CORPORATION

UNITED STATES STEEL

U·S·S
CARILLOY STEELS



An experienced workman checks up on temperature visually. Control of temperature with pyrometers and other equipment is essential in making steel of high quality

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U·S·S CARILLOY STEELS

CARNEGIE-ILLINOIS STEEL CORPORATION

Columbia Steel Company, San Francisco, *Pacific Coast Distributors*
United States Steel Products Company, New York, *Export Distributors*

UNITED STATES STEEL

G15190XM738

Printed in U. S. A.

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Ingot of steel being lifted from soaking pit after it has been heated
to the temperature necessary for subsequent rolling operations

FOREWORD

Alloy Steels produced by Carnegie-Illinois Steel Corporation are identified by the trade name "U·S·S Carilloy." This relatively new name does not signify a single grade of alloy steel, but rather serves as a name and a mark of established quality for ***all*** Carnegie-Illinois Alloy Steels.

While the name "U·S·S Carilloy" is of recent adoption, the products it identifies are far from being new or untried. Alloy steels have been produced for many years by United States Steel Corporation Subsidiaries, including the former Carnegie Steel Company and the former Illinois Steel Company (now combined in Carnegie-Illinois Steel Corporation). The Carnegie Steel Company indeed was one of the pioneer producers of alloy steels in this country.

Under the quality trade name "U·S·S Carilloy," the alloy steels of Carnegie-Illinois Steel Corporation are produced on a "control" basis. Each order, made to rigid specifications, demands—and receives—individual care. The steel craftsmen who produce "U·S·S Carilloy" steels are trained to this precise production practice. They are drilled to think first and always of ***quality.***

Because the making of "U·S·S Carilloy" is a precise and exacting process, Carnegie-Illinois Steel Corporation has established separate facilities devoted exclusively to the production and handling of alloy steels. These equipment facilities are matched in caliber by the skill of mill and metallurgical personnel.

In "U·S·S Carilloy" production, temperatures are rigidly controlled through each process. Special roll pass formations help to eliminate possible mechanical defects. Constant chemical and metallurgical checks are maintained. In melting, rolling, finishing, heat-treating, annealing, testing—in each step from furnace to final inspection—Carnegie-Illinois alloy steel production is on a ***controlled quality*** basis.

"U·S·S Carilloy" steels produced under these rigid methods are alloy steels that assure you consistently economical fabrication and promote the dependable performance of ***your*** products.

There are four reasons why it pays to specify "U·S·S" when you select alloy steels. They are four emblems of leadership.

First: Modern mills with the most advanced equipment for making alloy steels.

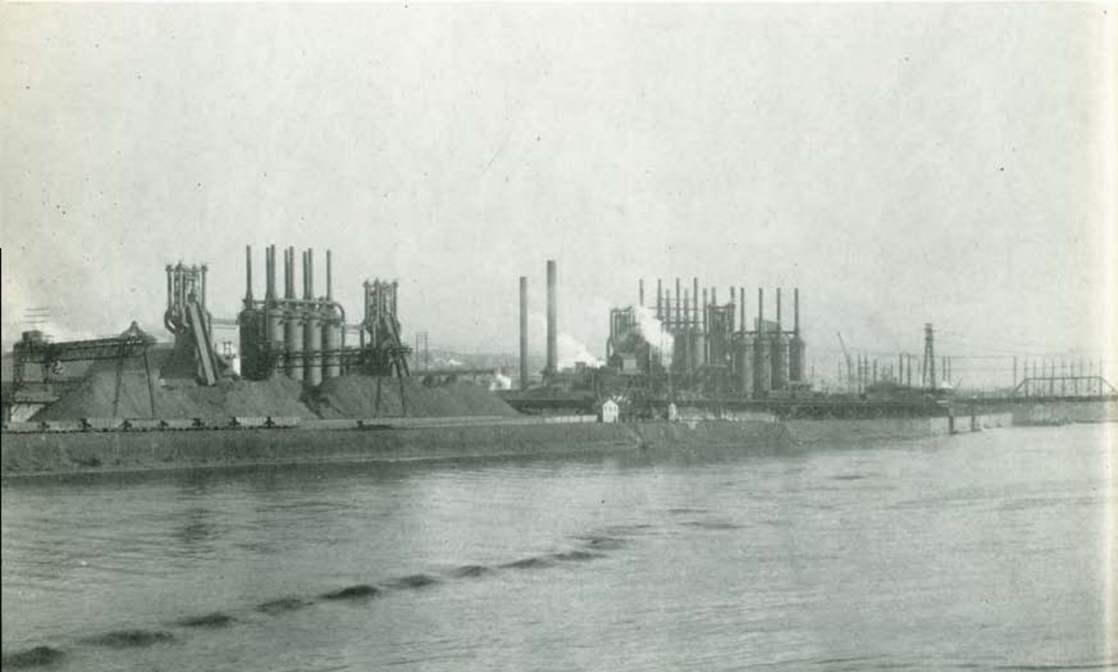
Second: Unexcelled research facilities for improving existing practices and products, and for developing new, better steels.

Third: Efficient distribution of U·S·S Carilloy Alloy Steels. Our mills and warehouses are near you in miles and hours.

Fourth: A consulting service offered to you at no obligation. Bring your problems in alloy steels to us.

We wish this book to serve as a useful guide in your use of alloy and other special steels. We strongly recommend, however, that on each specific problem involving alloy steels you take advantage of our trained consultants. With your knowledge of steel processing and our knowledge of steel making combined, questions are easy to answer, and difficulties disappear.

To indicate what we mean by "unexcelled research facilities," we invite you to take a brief trip through our laboratories. To make this visit possible, the next few pages are devoted to illustrations showing some of our research men at work.



Across the river are the stacks of giant blast furnaces where ore is converted into molten pig iron

A

Pictorial Visit

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To the

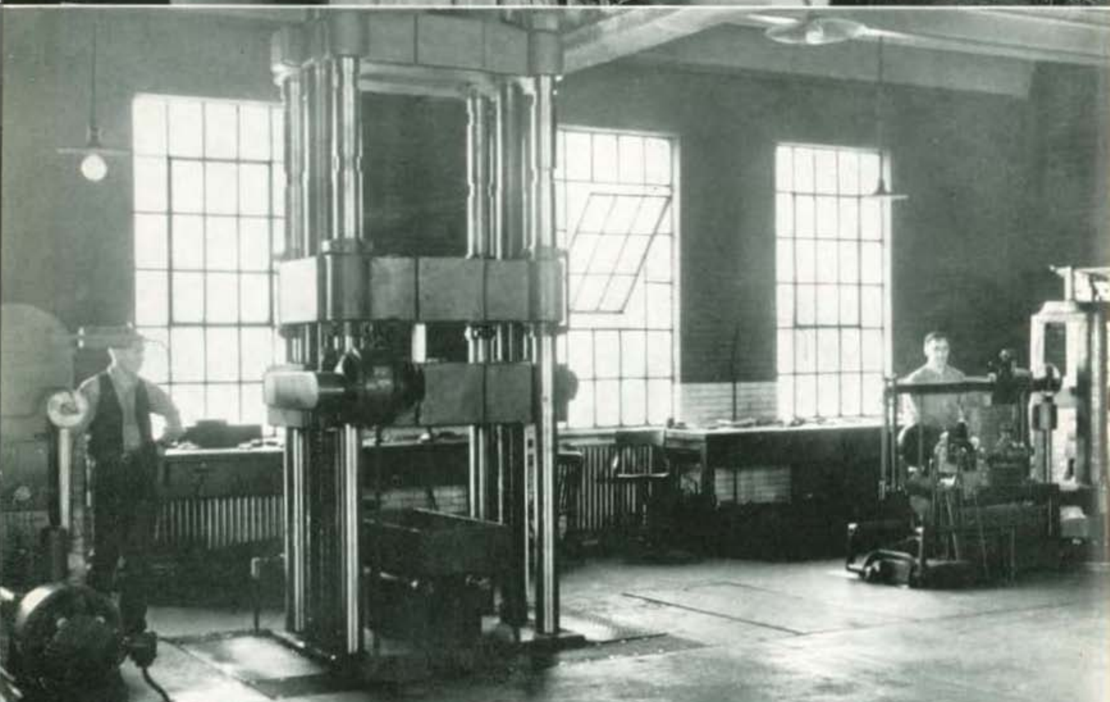
Carnegie-Illinois Steel Corporation's

Metallurgical Laboratories

and the

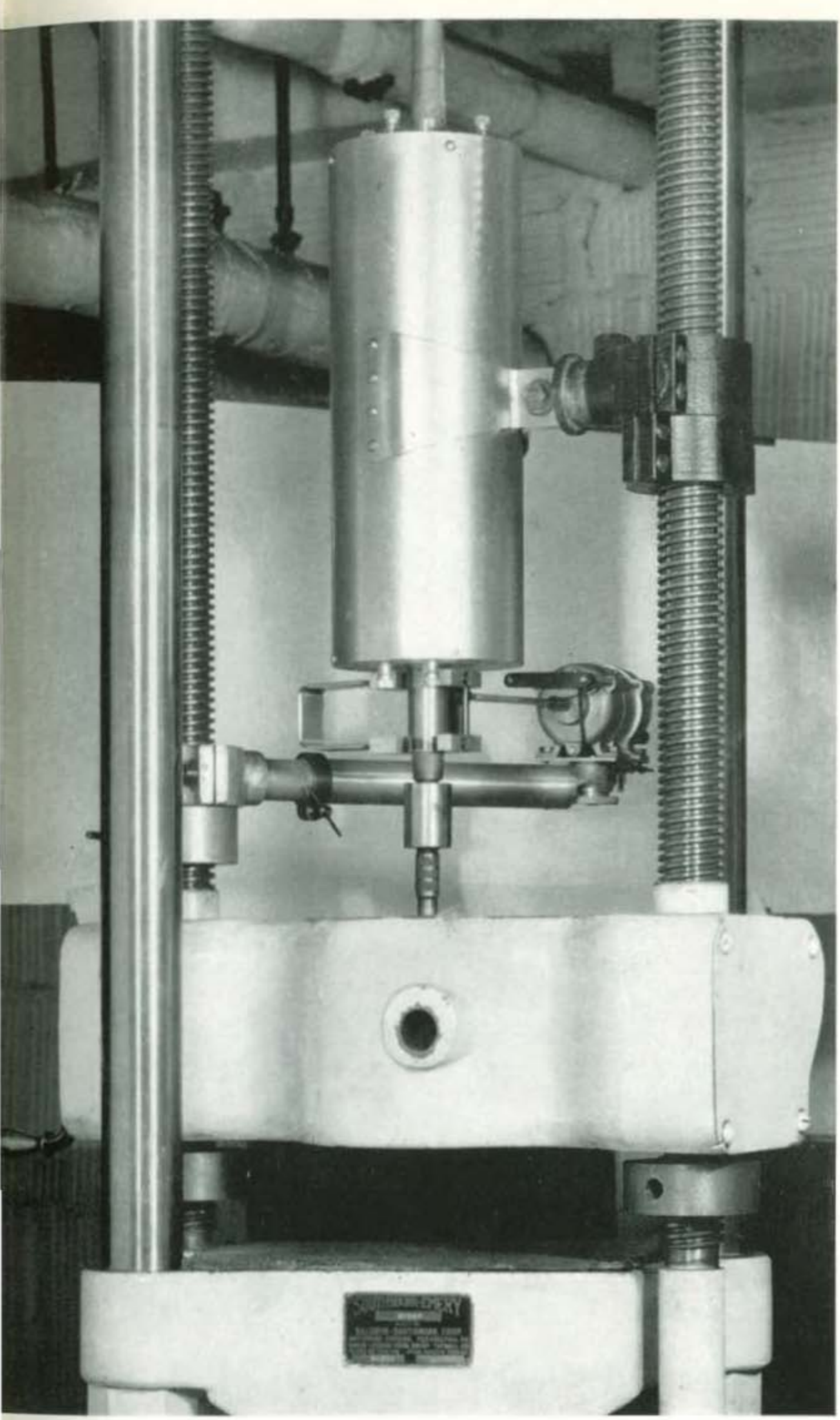
United States Steel Corporation's

Research Laboratory

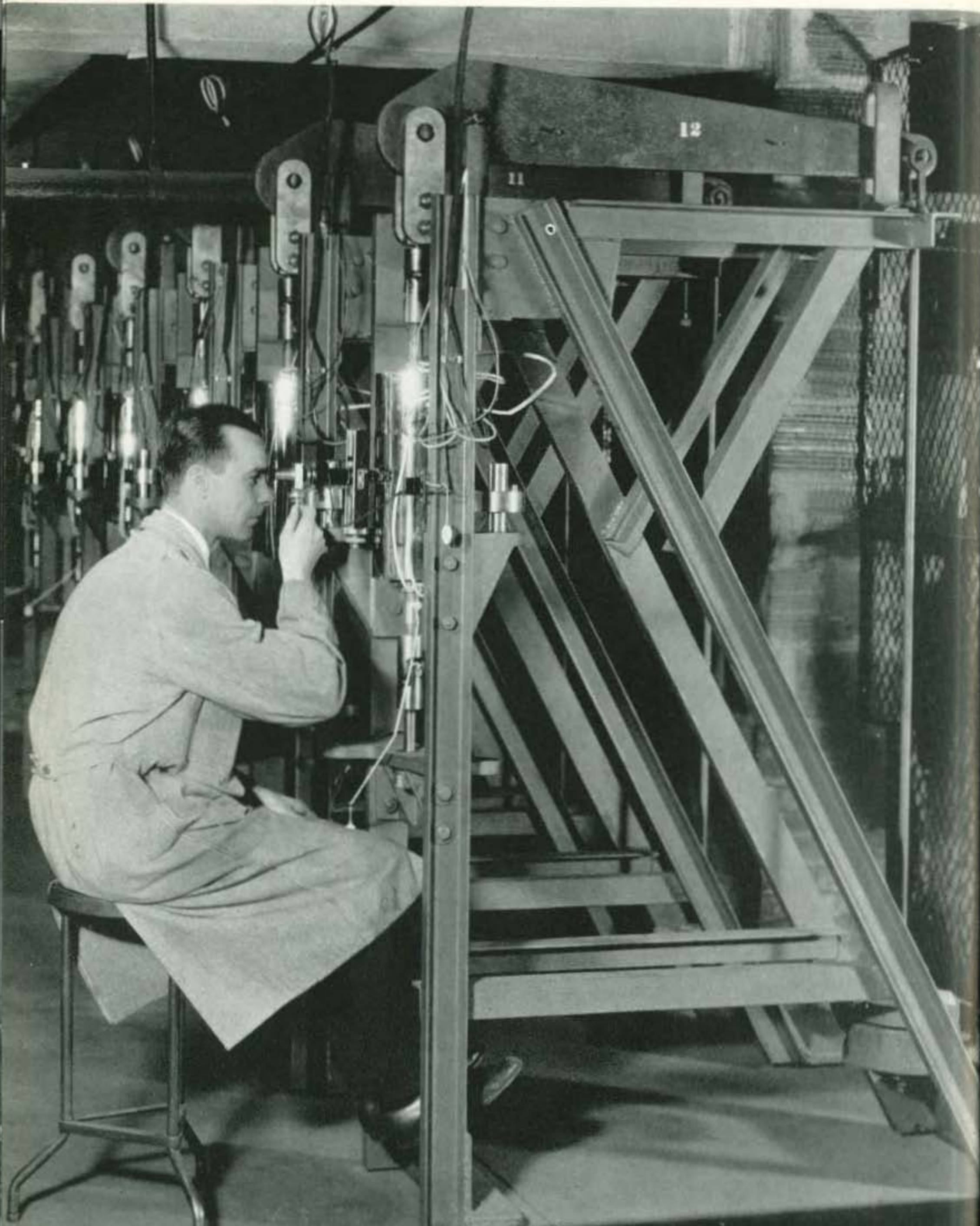


Above: Taking exact measurements of strength and elastic properties of steel in a tensile testing machine

Below: Large tensile testing machines. The one on the left will exert a stress up to 600,000 lbs.



Making tensile tests at high temperatures



Measuring "creep," in tests for slow yielding under stress at high temperature. A battery of twelve such machines is in use continuously

Etching a specimen of steel
for subsequent examination
under the microscope

Examining a steel specimen with a microscope

Heat treating steel under accurately controlled conditions in the laboratory

Making a Brinell hardness test

Testing the toughness of steel by breaking it in an impact testing machine

Ascertaining hardenability by examining fractured pieces and etched sections

Setting up X-ray equipment for ascertaining the crystal structure of metal

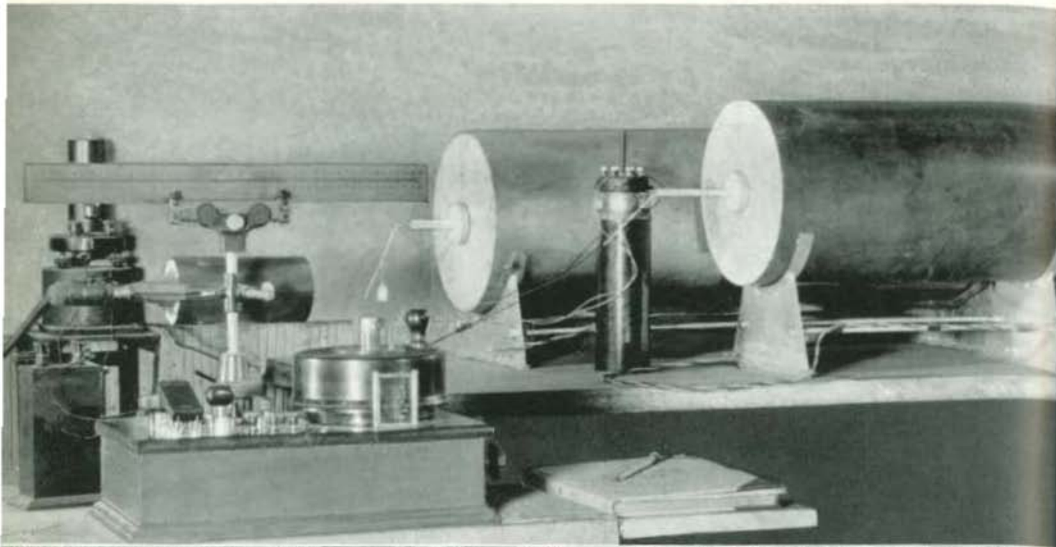
Above: Fatigue machine for testing the behavior of steel under repeated alternating stress

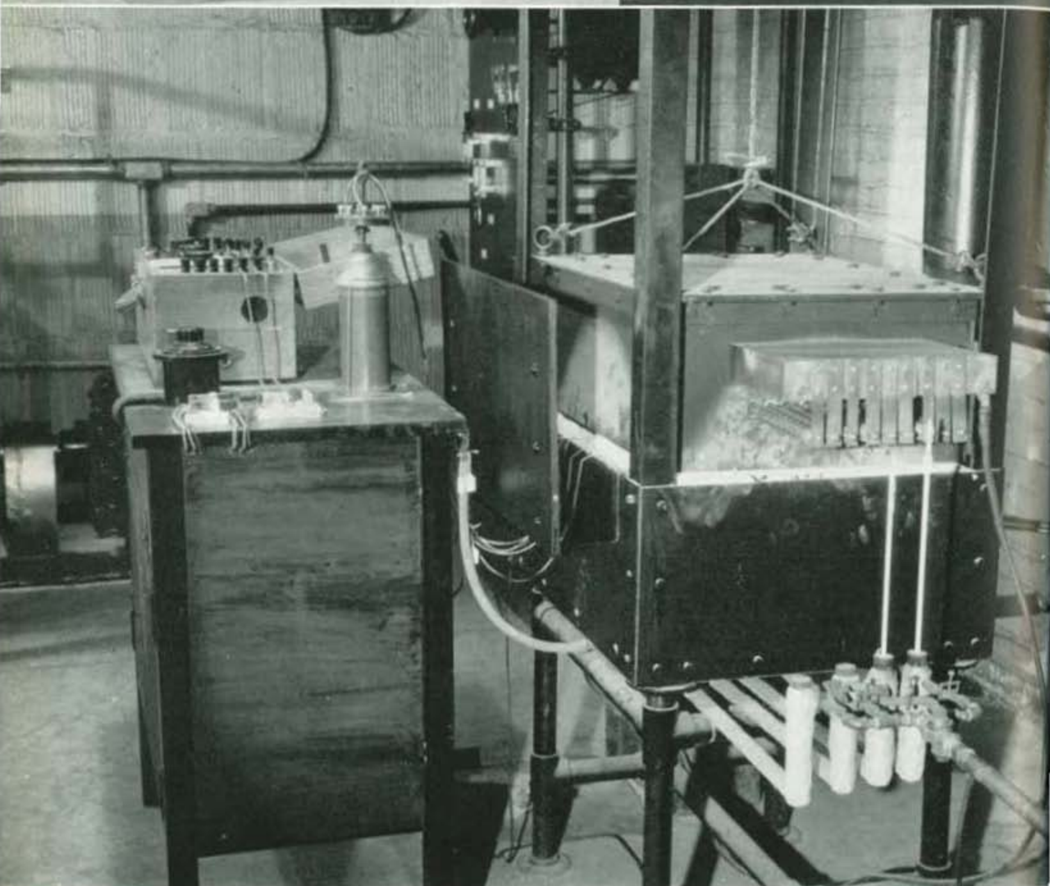
Below: Band saws and other laboratory equipment for the preparation of test pieces

Above: Rolling experimental pieces in the 6-inch experimental rolling mill

Below: Calibration of optical pyrometers to be used in the measuring of temperature of liquid steel from furnaces or solid steel in rolling mills

Determining the thermal expansion of metals and refractories in vacuum, air or other gases

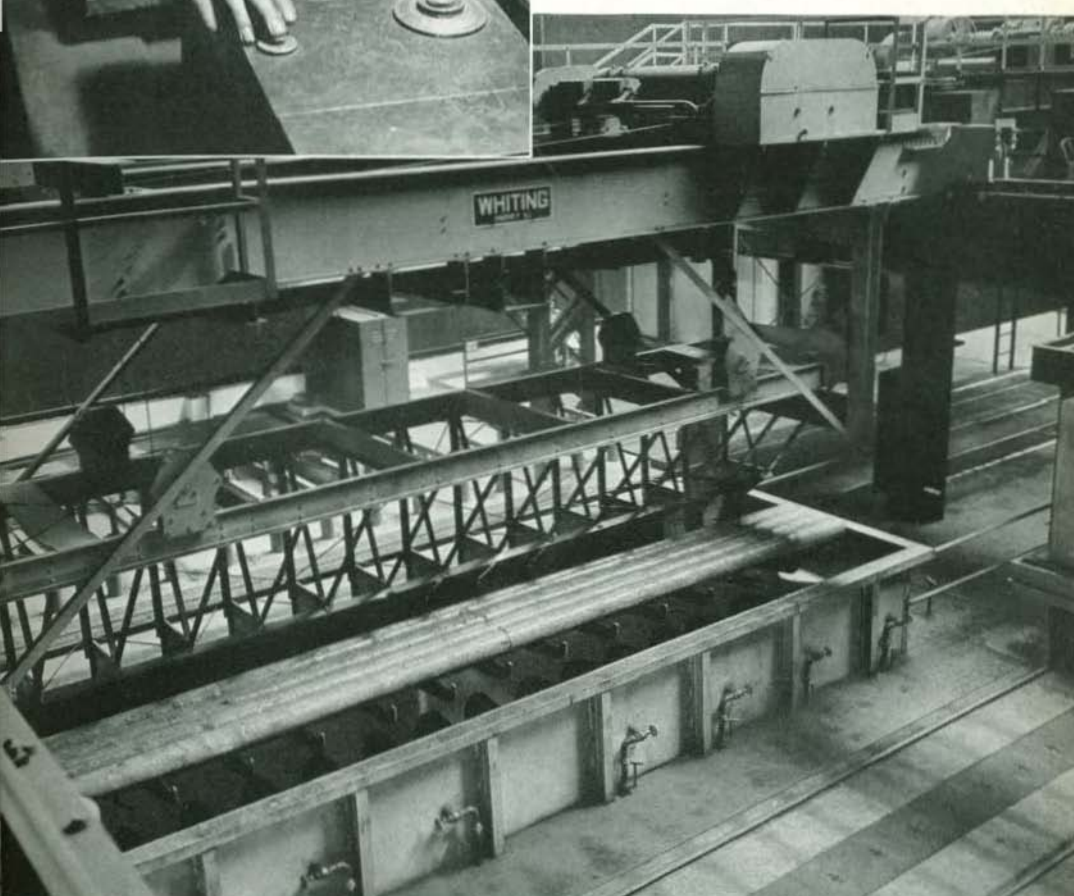




Above: Apparatus for the calibration of thermocouples for measurement of temperature

Below: Apparatus for measuring the thermal conductivity of refractories

An open hearth melter making a rapid and accurate determination of the carbon content of the steel he is melting



Large-scale equipment for the automatic heat treatment of steel bars

Tapping an Electric Furnace Heat

PURPOSE AND SCOPE OF THIS BOOK

It is the purpose of this booklet to describe the mechanical properties of the various alloy and special steels, the factors which influence them and the manner in which changes in properties are brought about.

The interest of a buyer of steel is in purchasing certain mechanical properties. It is true that in an attempt to do so he may specify chemical compositions, but these are not his primary concern. A buyer of alloy and special steels, furthermore, is often interested in purchasing two sets of properties in the same steel; namely, a soft condition, in which the steel may be machined, and then adequate strength after the steel has been hardened.

The great value of heat treatable steel lies in its affording this combination of properties at low cost. Structurally, this is due to the fact that iron and steel may exist in two different crystal forms, and that the change from one to the other takes place slowly enough to be controllable. When alloys are added, the change takes place still more slowly, thus making it possible to treat large sections and to secure special properties. The change can be controlled to a high degree of precision. Hardening, tempering and annealing operations may today be carried out with a regularity and precision that are quite adequate for even the most exacting requirements in industry, and it is the role of the steel-maker to provide suitable steels for the various specific uses.

For the present discussion, steel may be considered to be an alloy of iron and carbon. Commercial steels contain small amounts of other elements, for example manganese to counteract the effect of sulphur, and silicon to lessen the amount of oxygen. But the reactions which take place in heat treatment are governed largely by the behavior of the carbon, and the behavior of the carbon is in turn influenced by alloys when these are present.

Carbon is present in steel as a compound with iron, Fe_3C, called carbide of iron or cementite. When the steel is in its soft condition, this iron carbide is present as fairly coarse particles, readily discernible under the microscope. If the steel is to be hardened, it must be heated to a high temperature and then cooled rapidly (quenched). In the heating to the high temperature, the carbide goes into solution in the iron. For a discussion of this dissolving of the iron carbide, see the section entitled "Iron-Carbon Diagram." For a discussion of commercial practice in this operation, see the section entitled "Heating Practice for Hardening."

If the heated steel is to be hardened, it must be cooled rapidly, usually by being quenched in water or oil. For a discussion of the behavior of the steel during different rates of cooling, see the section entitled "S-Curve of Hardening." For a discussion of commercial practice in quenching, see the section entitled "Quenching Practice."

As stated above, the hardening of steel is due primarily to the effect of the carbon. When a steel has been heated so that the carbide is in solution, and when it is then cooled rapidly by immersing in water, the carbon does not have time to separate from the iron and coagulate into large particles. That is to say, the carbon remains in a highly dispersed state, and the resulting steel is hard. In plain carbon steels, the quenching must be carried out very rapidly in order to secure this hard condition. This means that in large sections there is no possibility of hardening plain carbon steel, because even when quenching in water the cooling is not rapid enough. Most alloys cause the carbon reactions in steel to take place more slowly (although some alloys have the opposite effect). A judicious selection of alloys therefore makes it possible to harden larger sections by quenching than can be done with plain carbon steels. Plain carbon steels are said to have "low hardenability," and alloy steels higher hardenability. For a discussion of these effects, see the section entitled "Hardenability." The hardnesses actually obtained in quenching various steels in different sizes are shown in a separate chart at the back of the book.

The present booklet is primarily concerned with a discussion of the mechanical properties of carbon and alloy steels, as applied in the automotive, petroleum, aircraft, railroad, and machine and tool industries. Stainless and certain other grades are discussed in separate publications.

THE STEEL-MAKING ELEMENTS

CARBON

DISCOVERY

Known to the ancients.

OCCURRENCE IN NATURE

Wood, coal, graphite, diamond, and a constituent of all plant life and all animal bodies.

COMMERCIAL USES

In all organic chemical compounds, dyes, flavors, gasoline, etc.

Coal for heating; natural and manufactured gas, gasoline, acetylene.

Coke for heating, smelting, etc.

Diamonds for industrial cutting and for gems.

Cast iron.

Steel.

EFFECT IN STEEL

The principal hardening element.

TYPES OF STEEL

Low carbon, carburizing grades, structural steels, stainless, sheets.

Medium carbon, water-hardening and (with alloys) oil-hardening.

High carbon, spring steels, tool steels.

PHYSICAL CONSTANTS

Symbol:	C
Atomic weight:	12.005
Boiling point:	6500° F.
Density: Diamond:	3.52
Density: Graphite:	2.25

Type of crystal lattice and unit cell edge:

Diamond, tetrahedral cubic	a=3.56 Å
Graphite, hexagonal	a=2.46 Å
	c=6.79 Å

MANGANESE

DISCOVERY

Discovered by Gahn (in Sweden) in 1774.

OCCURRENCE IN NATURE

Manganese ores, manganiferous iron ores.

COMMERCIAL USES

Glass-making.

Steel.

EFFECT IN STEEL

Strong hardening element, deoxidizer, desulphurizer.

TYPES OF STEEL

Low Manganese, deoxidizer, desulphurizer.

Medium Manganese, for strength and response to quenching. Abrasion.

High Manganese, Hadfield steel, toughness and wear resistance.

PHYSICAL CONSTANTS

Symbol:	Mn
Atomic weight:	54.93
Melting point:	2240° F.
Boiling point:	3450° F.
Density:	7.42

Type of crystal lattice and unit cell edge:

α: Cubic	a = 8.903 Å
β: Cubic	a = 6.289 Å
γ: Face-centered tetragonal	a = 3.744 Å
	c = 3.533 Å

PHOSPHORUS

DISCOVERY

Discovered by Brand (in Germany) in 1669.

OCCURRENCE IN NATURE

An important constituent of bones.

Commercial source: "phosphate rock" (calcium phosphate).

COMMERCIAL USES

Fertilizer.

Free-cutting steels.

EFFECT IN STEEL

Contributes weathering resistance in presence of copper.

Raises tensile strength.

In large amounts lessens ductility, often considered an impurity.

TYPES OF STEEL

0.1% in free-cutting steels.

Up to 0.2% in rust-resisting steels.

PHYSICAL CONSTANTS

Symbol:	P	
Atomic weight:	31.04	
Melting point:	111° F. (yellow)	
Boiling point:	554° F. (yellow)	
Density:	1.83 (yellow)	2.70 (black)

Types of crystal lattice and unit cell edge:

(black) Orthorhombic a = 3.31 Å
b = 4.38 Å
c = 10.50 Å

(yellow) Evidence inconclusive.

(red) Evidence inconclusive.

SULPHUR

DISCOVERY

Known to the ancients.

OCCURRENCE IN NATURE

Occurs as sulphur, also with iron (pyrite) and in other minerals.

COMMERCIAL USES

In rubber, lubricants, acid-proof cement.

In gunpowder.

In "sulphur matches."

In bleaching compounds.

In sulphuric acid.

In free-cutting steels.

EFFECT IN STEEL

Enhanced machinability; causes hot-shortness which may be overcome by manganese; generally an impurity.

TYPES OF STEEL

0.05 to 0.30%, free-cutting steels.

PHYSICAL CONSTANTS

Symbol:	S	
Atomic weight:	32.06	
Melting point:	235° F. (R).	247° F. (M)
Boiling point:	832° F.	
Density:	2.07 (R).	1.96 (M)

Types of crystal lattice and unit cell edge:

Rhombic (stable below 96°C.)	a=10.48 Å
	b=12.92 Å
	c=24.55 Å
Monoclinic	a=26.4 Å
	c=12.32 Å

SILICON

DISCOVERY

Isolated by Berzelius (in Sweden) in 1823.

OCCURRENCE IN NATURE

Sand, quartzite (7% of earth's crust).

COMMERCIAL USES

Glass, portland cement, carborundum, brick, as compounds.
Cast iron, steel, as dissolved element.

EFFECT IN STEEL

Deoxidizer and special properties.

TYPES OF STEEL

Low silicon in all alloy and special steels as deoxidizer.
.5 to 2%, spring steels, structural steels.
1 to 4%, transformer steel.
2 to 3%, in heat-resisting stainless steels.
10%, acid-resisting iron.

PHYSICAL CONSTANTS

Symbol:	Si
Atomic weight:	28.1
Melting point:	2590° F.
Density:	2.42

Type of crystal lattice and unit cell edge:
Tetrahedral cubic $a = 5.42$ Å

CHROMIUM

DISCOVERY

Discovered by Vauquelin (in France) in 1798.

OCCURRENCE IN NATURE

Chromite, etc. All chromium ores are oxides.

COMMERCIAL USES

Color and paint pigments (chrome yellow, etc.).

Water treatment against corrosion (potassium dichromate).

Chromium plating.

Tanning.

Electrical resistor and pyrometer wires (with nickel).

Cast iron.

Steel.

EFFECT IN STEEL

Hardenability, abrasion-resistance, stainless properties, heat-resistance.

TYPES OF STEEL

0 to 1%, automotive and farm implement steels, gears, springs, tool steels.

1 to 2%, ball bearing and roller bearing steels.

2 to 4%, wear and heat-resisting steels, magnet steels, high speed tool steels (with tungsten).

4 to 6%, heat-resisting steels.

12 to 16%, high-carbon, tool steels.

12 to 14%, medium-carbon, cutlery.

12 to 30%, low-carbon, stainless and heat-resisting steels.

PHYSICAL CONSTANTS

Symbol:	Cr
Atomic weight:	52.0
Melting point:	2940° F.
Boiling point:	4000° F.
Density:	6.92

Type of crystal lattice and unit cell edge:

α: Body-centered cubic, usual	a = 2.879 Å
β: Close-packed hexagonal, possible modification	a = 2.72 Å c = 4.42 Å

NICKEL

DISCOVERY

Discovered by Cronstedt (in Sweden) in 1754.

OCCURRENCE IN NATURE

Sulphide ores. As metal in meteors (rare).

COMMERCIAL USES

Coinage.
Magnetic alloys.
Metallic nickel.
Nickel-copper alloys.
Electrical resistor and pyrometer wires (with chromium).
Cast iron.
Steel.

EFFECT IN STEEL

Toughness, hardenability, corrosion-resistance.

TYPES OF STEEL

0 to 4%, automotive, farm implement and railroad steels.
5%, special carburizing steels.
6 to 20%, stainless and heat-resisting steels.

PHYSICAL CONSTANTS

Symbol:	Ni
Atomic weight:	58.68
Melting point:	2650° F.
Density	8.9

Type of crystal lattice and unit cell edge:

α: Close-packed hexagonal	a = 2.49 Å
	c = 4.08 Å
β: Face-centered cubic	a = 3.517 Å

MOLYBDENUM

DISCOVERY

Discovered by Hjelm (in Sweden) at the suggestion of Scheele, in 1780.

OCCURRENCE IN NATURE

Molybdenum sulphide (molybdenite).

Calcium molybdate.

COMMERCIAL USES

Plates and grids for vacuum tubes.

Paint pigment.

Cast iron.

Steel.

EFFECT IN STEEL

Hardenability, occasional free-cutting agent.

High temperature hardness.

TYPES OF STEEL

0 to .3%, automotive and allied steels.

0 to .6%, die steels, heat-resisting steels.

0 to 4%, special corrosion-resisting applications (in stainless steels).

2 to 8%, high-speed steels.

PHYSICAL CONSTANTS

Symbol:	Mo
Atomic weight:	96.0
Melting point:	4760° F.
Boiling point:	6500° F.
Density:	10.3

Type of crystal lattice and unit cell edge:

Body-centered cubic $a = 3.14$ Å

VANADIUM

DISCOVERY

Discovered by del Rio (in Mexico) in 1801.

OCCURRENCE IN NATURE

Various oxide and sulphide ores.

COMMERCIAL USES

Steel.

EFFECT IN STEEL

Toughening agent by grain refinement, and in larger percentages a hardener.

TYPES OF STEEL

0 to .25%, automotive and tool steels.

1 to 2%, high-speed tool steels.

PHYSICAL CONSTANTS

Symbol:	V
Atomic weight:	51.0
Melting point:	3130° F.
Density:	6.0

Type of crystal lattice and unit cell edge:

Body-centered cubic $a = 3.01$ Å

COPPER

DISCOVERY

Known to the ancients.

OCCURRENCE IN NATURE

As oxides, as sulphides and as metallic copper.

COMMERCIAL USES

Is one of the metals most widely used in pure form.
Wire for electrical purposes.
Coinage.
Major constituent of bronze and brass.
Household and industrial uses.
Copper plating.
Steel.

EFFECT IN STEEL

Corrosion resistance. Occasionally for hardening.

TYPES OF STEEL

0.2 to 0.8%, weather-resisting steels.
Up to 4%, hardening effects.

PHYSICAL CONSTANTS

Symbol:	Cu
Atomic weight:	63.57
Melting point:	1980° F.
Boiling point:	4190° F.
Density:	8.93

Type of crystal lattice and unit cell edge:
Face-centered cubic $a = 3.608$ Å

TITANIUM

DISCOVERY

Discovered by Gregor (in England) in 1791.

OCCURRENCE IN NATURE

As oxide compound. Rutile. Ilmenite.

COMMERCIAL USES

White paint pigment.
Steel deoxidizer.

EFFECT IN STEEL

Deoxidizer. Denitrider.

TYPES OF STEEL

Low-carbon steels, deoxidizer.
Stainless steels, to "fix" carbon.

PHYSICAL CONSTANTS

Symbol:	Ti
Atomic weight:	48.0
Melting point:	3270° F.
Density:	4.55

Type of crystal lattice and unit cell edge:

Close-packed hexagonal $a = 2.95$ Å
$c = 4.73$ Å

COLUMBIUM

DISCOVERY

Discovered by Hatchett (in England) in 1801.

OCCURRENCE IN NATURE

The mineral columbite (oxide).

COMMERCIAL USES

As metal and in steel.

EFFECT IN STEEL

Combines with carbon.

TYPES OF STEEL

In stainless steel, to "fix" carbon.

PHYSICAL CONSTANTS

Symbol:	Cb
Atomic weight:	92.9
Melting point:	3540° F.
Density:	8.4

Type of crystal lattice and unit cell edge:

Body-centered cubic $a = 3.294$ Å

ZIRCONIUM

DISCOVERY

Discovered by Klaproth (in Germany) in 1789. Reduced to metal by Berzelius (in Sweden) in 1824.

OCCURRENCE IN NATURE

Widespread occurrence as oxide, silicate, etc.

COMMERCIAL USES

Opacifier in enamels.

The oxide is used as a refractory.

The metal as a steel deoxidizer.

EFFECT IN STEEL

Deoxidizer; denitrider.

TYPES OF STEEL

Small amounts used for deoxidation.

PHYSICAL CONSTANTS

Symbol:	Zr
Atomic weight:	90.6
Melting point:	3090° F.
Density:	6.4

Type of crystal lattice and unit cell edge:

α: Close-packed Hexagonal	a = 3.22 Å
	c = 5.12 Å
β: Body-centered cubic	a = 3.61 Å

ALUMINUM

DISCOVERY

Prepared by Oersted (in Denmark) in 1825, and Wöhler (in Germany) in 1827.

OCCURRENCE IN NATURE

Very widespread in clays and rocks.

Commercial source for metal is the mineral bauxite.

COMMERCIAL USES

The oxide as abrasive and as refractory.

The metal as such in industrial and household uses.

Alloyed with copper.

Steel.

EFFECT IN STEEL

Deoxidizer, grain refiner.

TYPES OF STEEL

Wide use in small amounts in many grades.

Up to 1.5%, a steel alloy for surface hardening by nitrogen.

PHYSICAL CONSTANTS

Symbol:	Al
Atomic weight:	27.0
Melting point:	1220° F.
Boiling point:	3270° F.
Density:	2.70

Type of crystal lattice and unit cell edge:

Face-centered cubic $a = 4.04$ Å

TUNGSTEN

DISCOVERY

Discovered by Scheele (in Sweden) in 1781.

Reduced to metal by the d'Elhuyar Brothers (in Spain) in 1783.

OCCURRENCE IN NATURE

Largely as oxide compounds. Calcium tungstate (scheelite).

COMMERCIAL USES

Lamp filaments (the pure metal), sintered tools and dies (carbide).

High-speed tool steel.

Heat-resisting steels.

Magnet steels.

EFFECT IN STEEL

Provides stability at high temperature.

Also special uses.

TYPES OF STEEL

5%, magnet steels.

12 to 25%, high-speed tool steels.

1 to 5% in chromium nickel heat-resisting steels.

PHYSICAL CONSTANTS

Symbol:	W
Atomic weight:	184.0
Melting point:	6150° F.
Density:	19.3

Type of crystal lattice and unit cell edge:

Body-centered cubic $a = 3.159$ Å

COBALT

DISCOVERY

Discovered by Brandt (in Sweden) in 1735.

OCCURRENCE IN NATURE

As oxide and sulphide ores.

COMMERCIAL USES

For coloring glass blue, also artificial gems.
Steel.

EFFECT IN STEEL

High-temperature stability.
Magnetic properties.

TYPES OF STEEL

2 to 5% in high-speed tool steel.
5 to 30% in magnet steels.

PHYSICAL CONSTANTS

Symbol:	Co
Atomic weight:	58.97
Melting point:	2630° F.
Density:	8.71

Type of crystal lattice and unit cell edge:

α: Close-packed hexagonal unit cell edge	a = 2.51 Å
	c = 4.07 Å
β: Face-centered cubic unit cell edge	a = 3.545 Å

IRON

DISCOVERY

Known to the ancients (Biblical, Egyptian, etc.).

OCCURRENCE IN NATURE

Occurs as iron ores (hematite, magnetite, limonite, siderite, etc.) and as impurity in many other ores. As metal in meteors. Constitutes 4½% of the earth's crust.

PHYSICAL CONSTANTS

Symbol:	Fe
Atomic weight:	55.84
Melting point:	2780° F.
Boiling point:	4440° F.
Density:	7.88

Type of crystal lattice and unit cell edge:

α:	Body-centered cubic	2.861 Å
γ:	Face-centered cubic	3.564 Å*

*extrapolated to room temperature.

For brief chronology, see following pages.

CHRONOLOGY OF IRON

The name of iron in ancient Egyptian was  meaning Stone of Heaven, and in ancient Babylonian was Ana-bar, also said to mean Stone of Heaven. There seems to be an obvious relation to meteorites.

Prior to 1300 B.C. Only six iron articles are known which can definitely be shown to belong prior to this date. Two of these are of meteoric iron.

1000 B.C. By this time iron was being made regularly for weapons and instruments.

300 B.C. to 200 A.D. Very extensive iron arms factories established by the Romans.

1000 A.D. to 1700 A.D. Skilled development of the charcoal hearth process for making iron, later carburizing it (in charcoal) to make steel.

1556 Agricola published "De Re Metallica."

1643 Iron works established at Lynn, Mass., the first in what is now the United States.

1740 Huntsman invented the crucible melting process for steel (England).

1796 Clouet in France proved that steel is iron and carbon, by making steel from pure iron and a diamond.

In 1815, the first pipe line for coal gas distribution, for lighting purposes, was made by assembling old musket barrels. (England.)

1831 First all-iron rails used. Camden and South Amboy Railroad near Philadelphia.

1832 a committee of the Franklin Institute designed and built a tensile testing machine.

About 1850 the first all-iron ship built.

About 1850 to 1856. Kelly in U. S. and Bessemer in England invented the "Bessemer" process.

About 1860. Mushet developed a tungsten air-hardening tool steel, the first commercial alloy steel.

About 1862. Siemens invented the open hearth furnace.

About 1878. Thomas and Gilchrist invented the basic Bessemer.

About 1880. Ni and Cr used in armor plate.

About 1883. Osmond first announced transformation points in iron and steel.

About 1885. The first steel skyscraper (10 stories) built in Chicago.

About 1886. Sorby described microstructure of steel.

About 1890. Heroult invented his electric furnace.

About 1893. 12% manganese steel invented by Hadfield.

About 1890 to 1900. Ni and Cr steels used more generally, as in guns bicycles, shafts, etc.

About 1900. Brinell invented his hardness test.

1906. First tonnage production of alloy steel (chrome-vanadium) for automobiles.

1914-1918. World War responsible for tremendous industrial development in alloy steels. Automobile industry prime factor in subsequent years.

TABLE OF FUNCTIONS OF THE ELEMENTS

Principal Effects in Medium or High Carbon Steel

Alloy Element	To Increase Harden-ability	To Strengthen Ferrite	To Form Carbides; Decreasing Creep, Restraining Grain Growth	To Form Oxide Particles to Restrain Grain Growth
Mn	Strong	Strong	Mild	Weak
Si	Moderate	Strong	No	Moderate
Cr	Strong	Moderate	Moderate	Weak
Ni	Moderate	Strong	No	No
Mo	Moderate*	Weak	Strong	Weak if any
W	Moderate*	Weak	Strong	Weak if any
V	Mild*	Weak	V. strong	Prob. strong
Ti	Weak	Weak	V. strong	Prob. strong
Co	Weak	Strong	V. weak	No
Al	Moderate	Strong	No	Strong
Zr	Prob. weak	Weak	Moderate	Strong
Cu	Mild	Moderate	No	No

*These designations refer to the behavior in steels as usually heat-treated. It should be noted that Mo, W and V *when actually dissolved in Austenite* greatly increase hardenability.

DEFINITIONS OF TERMS RELATING TO STEEL and ITS HEAT TREATMENT

(Taken from the 1936 edition of the Metals Handbook of the American Society for Metals.)

Acid Steel—Steel melted under a slag which has an acid reaction and in a furnace with an acid bottom and lining.

Aging—The term originally applied to the process or sometimes to the effects of allowing a metal to remain at ordinary temperatures. Heat treatment at temperatures above normal for the purpose of accelerating changes of the type that might take place on aging at ordinary temperature is called "artificial aging," and sometimes merely "aging." When the changes taking place during artificial aging are due to the precipitation of some substance from solid solution the heat treatment may be called "precipitation treatment."

Alloy Elements—Elements added for the purpose of improving properties.

Alpha Iron—The crystalline form in which pure iron exists at relatively low temperature. The structure is "body-centered cubic." See ferrite.

Amorphous—Non-crystalline.

Annealing—A heating and cooling operation of a material in the solid state. Annealing usually implies a relatively slow cooling.

Note—Annealing is a comprehensive term. The purpose of such a heat treatment may be:

(a) To remove stresses.
(b) To induce softness.
(c) To alter ductility, toughness, electrical, magnetic or other physical properties.
(d) To refine the crystalline structure.
(e) To remove gases.
(f) To produce a definite microstructure.

In annealing, the temperature of the operation and the rate of cooling depend upon the material being heat treated and the PURPOSE of the treatment.

Certain specific heat treatments coming under the comprehensive term "annealing" are:

A. Full Annealing—Heating iron base alloys above the critical temperature range, holding above that range for a proper period of time, followed by slow cooling through the range.

Note—The annealing temperature is generally about 100° F. above the upper limit of the critical temperature range, and the time of holding is usually not less than 1 hr. for each inch of section of the heaviest objects being treated. The objects being treated are ordinarily allowed to cool slowly in the furnace. They may, however, be removed from the furnace, and cooled in some medium which will prolong the time of cooling as compared to unrestricted cooling in the air.

B. Process Annealing—Heating iron base alloys to a temperature below or close to the lower limit of the critical temperature range followed by cooling as desired.

Note—This heat treatment is commonly applied in the sheet and wire industries and the temperatures generally used are from 1020-1200° F.

C. Normalizing—Heating iron base alloys to approximately 100° F. above the critical temperature range followed by cooling to below that range in still air at ordinary temperature.

Note—Normalizing is rarely practiced with hypereutectoid steels because of the coarsening of the grain and the tendency to crystallize cementite at grain boundaries or in needles. However, it may sometimes be necessary to normalize these steels by heating them above the Ac_{cm} line of the iron-carbon diagram.

D. Patenting—Heating iron base alloys above the critical temperature range, followed by cooling to below that range in air or in molten lead maintained at a temperature of about 700° F.

Note—This treatment is applied in the wire industry as a finishing treatment or especially in the case of eutectoid steel, as a treatment previous to further wire drawing. Its purpose is to produce a fine pearlitic structure.

E. Spheroidizing—Prolonged heating of iron base alloys at a temperature in the neighborhood of, but generally slightly below, the critical temperature range, usually followed by relatively slow cooling.

Note—(a) In the case of small objects of high carbon steels, the spheroidizing result is achieved more rapidly by prolonged heating to temperature alternately within and slightly below the critical temperature range.

(b) The object of this heat treatment is to produce a globular condition of the carbide.

F. Tempering—(also termed Drawing)—Reheating iron base alloys, after hardening, to some temperature below the critical temperature range, followed by any desired rate of cooling.

Note—(a) Although the terms "tempering" and "drawing" are practically synonymous as used in commercial practice, the term "tempering" is preferred.

(b) Tempering, meaning the operation of hardening followed by reheating, is a usage which is illogical and confusing in the present state of the art of heat treating and should be discouraged.

G. Malleableizing—Malleableizing is a type of annealing operation with slow cooling whereby the combined carbon in white cast iron is partially or wholly transformed to temper carbon and in some cases the carbon is entirely removed from the iron.

Note—Temper carbon is free carbon in the form of rounded nodules made up of an aggregate of minute crystals.

H. Graphitizing—Graphitizing is a type of annealing for gray cast iron whereby some or all of the combined carbon is transformed to free or uncombined carbon.

Austenite—Gamma iron containing any other element in solution. See gamma iron.

Basic Steel—Steel melted under a slag having a basic reaction and in a furnace with a basic bottom and lining.

Bessemer Process—A process for making steel by blowing air through molten pig iron contained in a suitable vessel, thus removing the impurities by oxidation.

Billet—A semi-finished rolled ingot of rectangular cross section or nearly so. In general the term "billet" is used when the cross section ranges from 4 up to 36 sq. in., the width always being less than twice the thickness. Small sizes are usually classed as bars or "small billets." The term "bloom" is properly used when the cross section is greater than about 36 sq. in., but this distinction is not universally observed.

Blister—A defect in metal produced by gas bubbles either on the surface or formed beneath the surface while the metal is hot or plastic. Very fine blisters are called pinhead or pepper blisters.

Blister Bar—Wrought iron bars impregnated with carbon and used in the manufacture of crucible steel. Also called blister steel.

Bloom—See billet.

Blue Brittleness—Brittleness occurring in steel when in the temperature range of 400-700° F., or when cold after being worked within this temperature range.

Burning—The heating of a metal to a temperature sufficiently close to the melting point to cause permanent injury. Such injury may be caused by the melting of the more fusible constituents, by the penetration of gases such as oxygen into the metal with consequent reactions, or perhaps by the segregation of elements already present in the metal.

Carbon Steel—Steel which owes its properties chiefly to various percentages of carbon without substantial amounts of other alloying elements; also known as ordinary steel or straight carbon steel.

Carbonization—Coking or driving off the volatile matter from fuels such as coal and wood. (Carbonizing should not be confused with "carburizing" q. v.)

Carburizing (Cementation)—Adding carbon to iron base alloys by heating the metal below its melting point in contact with carbonaceous solids, liquids or gases.

Note—The term "carbonizing" used in this sense is incorrect so its use should be discouraged.

Cementite—A compound of iron and carbon, Fe_3C, which is the form in which carbon occurs in unhardened steels.

Cleavage Plane—Crystals possess the property of breaking more readily in one or more directions than in others. The planes of easy rupture are called cleavage planes.

Cold Working—Permanent deformation of a metal below its recrystallization temperature.

Critical Points—See the article "Iron-Carbon Diagram" in this booklet.

Critical Range—See critical points.

Critical Temperature—See critical points.

Cup Fracture—The form of fracture of a tensile test specimen when the exterior portion is extended and the interior relatively depressed, so that it looks like a cup, as the name implies. When only a portion of the exterior is extended the terms "half cupped" and "quarter cupped" are used, as the case may be.

Cyaniding—Surface hardening of an iron base alloy article or portion of it by heating at a suitable temperature in contact with a cyanide salt, followed by quenching.

Decarburization—The removal of carbon (usually refers to the surface of solid steel).

Dendrite—A crystal formed during solidification having many branches and a tree-like pattern; also termed "pine tree" and "fir tree" crystals.

Divorced Cementite—See spheroidal cementite.

Elongation—The amount of permanent stretch, before rupture; usually expressed as a percentage of the original length, such as 25% in 2 in.

Endurance Limit—The maximum stress to which material may be subjected an indefinitely large number of times without causing failure.

Eutectic—An alloy having the lowest melting point possible with the given components.

Eutectoid Steel—A steel of the eutectoid composition. In plain carbon steel this composition is considered to be between 0.85 and 0.90% carbon. Composition S on the iron-carbon diagram. In alloy steels the carbon content may be considerably lower.

Ferrite—Alpha iron containing any other element in solution. See alpha iron.

Ferroalloys—An alloy of iron with a sufficient amount of some element or elements, such as manganese, chromium or vanadium, used as a means of introducing these elements into steel.

Fiber Stress—Local unit stress at a point or line on a section over which stress is not uniform, such as the cross section of a beam under a bending load.

Finishing Temperature—The temperature at which hot mechanical working of metal is completed.

Flakes—Portions of a steel fracture with a bright, scaly appearance.

Free Ferrite—Ferrite which is structurally separate and distinct.

Gamma Iron—The crystalline form in which pure iron exists at relatively high temperature (between the A_3 and A_4 critical points). The structure is face-centered cubic. See austenite.

Globular Cementite—See spheroidal cementite.

Grain Growth—An increase in the grain size of metal.

Hot Shortness—Brittleness in metal when hot.

Hypereutectoid Steel—A steel containing more than the eutectoid percentage of carbon. See eutectoid.

Hypoeutectoid Steel—A steel containing less than the eutectoid percentage of carbon. See eutectoid.

Impact Test—A test in which one or more blows are suddenly applied to a specimen. The results are usually expressed in terms of energy absorbed or number of blows (of a given intensity) required to break the specimen.

Killed Steel—Steel treated with aluminum, silicon or equivalent "killing agent" so that no gas is evolved during solidification.

Ledeburite—The carbide-austenite eutectic forming at point C on the iron-carbon diagram. During cooling the austenite in ledeburite transforms to ferrite and carbide. It is found in cast iron and high alloy steels such as high speed steel.

Macroscopic—Visible either with the naked eye or under low magnifications (up to about 10 diameters).

Macrostructure—The structure and internal condition of metals as revealed on a ground or polished (and sometimes etched) sample, by either the naked eye or under low magnifications (up to about 10 diameters).

Martensite—A microconstituent or structure in quenched steel characterized by an acicular or needle-like pattern. It has the maximum hardness of any of the decomposition products of austenite.

Note—Latest researches indicate that martensite is a super-saturated solid solution of carbon in iron. When the steel contains less than 0.60% carbon, the X-ray diffraction lines indicating tetragonal crystalline lattice do not appear; the axial ratio of the tetragonal crystal increases with carbon content, being c:a = 1.03 for an 0.80% carbon steel and 1.07 for a 1.60% carbon steel. The dominant orientation of martensite depends upon that of the parent austenite grain.

Modulus of Elasticity—The ratio, within the limits of elasticity, of the stress to the corresponding strain. The stress in pounds per square inch is divided by the elongation in fractions of an inch for each inch of the original gage length of the specimen.

Neumann Bands—Parallel lines or narrow bands running across crystalline grains of metal. The lines or bands undoubtedly indicate mechanical twins. Neumann bands are generally produced by a sudden deformation of the metal such as would result from shock, impact or explosion.

Normalizing—See annealing.

Overheating—Heating to such high temperatures that the grains have become coarse, thus impairing the properties of the steel.

Patenting—See Annealing.

Pearlite—The lamellar aggregate of ferrite and carbide resulting from the direct transformation of austenite at Ar_1.

Note—It is recommended that this word be reserved for microstructures consisting of thin plates or lamellae—that is, those that may have a pearly luster in white light. The lamellae can be very thin and resolvable only with the best microscopic equipment and technique, which fact has caused many fine pearlites to be erroneously called "troosite" or "sorbite."

Pine Tree Crystals—See Dendrite.

Quenching—Rapid cooling by immersion.

Note—Immersion may be in liquids, gases or solids.

Red Shortness—Brittleness in steel when it is red hot.

Reduction of Area—The difference between the original cross sectional area and that of the smallest area at the point of rupture. It is usually stated as a percentage of the original area; also called "contraction of area."

Rimmed Steel—A low carbon steel which (a) is effervescent when cast and during a considerable part of its solidification; (b) neither rises nor falls in the mold to any marked extent; (c) when completely solidified has no pipe but blow holes both centrally located and deep seated below the surface; (d) has been cleansed from some of the impurities and dirt because of their rising to the top during the agitation of the molten metal by the escaping gases; and (e) has a cross section divided into three fairly well defined zones: (1) a very clean thin outer layer of nearly the same chemical composition as when poured; (2) a central portion; and (3) an intermediate portion. The three zones are positively and negatively segregated with respect to metalloids.

Note—The term "rimmed" comes from the fact that during the gradual freezing inwards from the sides the molten portion at the top of the ingot becomes smaller and smaller and is said to "rim in" until finally the whole top is solidified.

Secondary Hardening—Hardness developed by tempering high alloy steels.

Self Hardening Steel—Alloy tool steel that becomes sufficiently hard by cooling in air (sometimes an air blast is employed) and whose cutting edges remain practically intact at temperatures approaching a visible red.

Slip Bands—A series of parallel lines running across a crystalline grain. Slip bands are formed when the elastic limit is passed by one layer or portion of the crystal slipping over another portion along a plane, known as the slip plane.

Slip Plane—See slip bands.

Sonims—Solid non-metallic inclusions in metal.

Sorbite—A late stage in the tempering of martensite, when the carbide particles have grown so that the structure has a distinctly granular appearance. Further and higher tempering causes globular carbides to appear clearly.

Note—Many times the term sorbite is erroneously given to an imperfectly developed pearlite or mixed structure in steel.

Spheroidal or Spheroidized Cementite—The product of long annealing of unhardened steel (spheroidizing anneal) near but below its transformation range, whereby the carbide lamellae in pearlitic areas ball up into small globules in the ferrite matrix. The same structure is achieved by long, high tempering of hardened steel.

Note—The term "spheroidized pearlite" should be avoided, when the structure is undoubtedly the result of spheroidizing anneal of a pearlitic steel. The term "spheroidite" has been proposed.

Spheroidizing—See annealing.

Tempering—See annealing.

Troostite—A microconstituent of hardened or hardened and tempered steel which etches rapidly and therefore usually appears dark. It consists of a very fine aggregate of ferrite and cementite and is not resolved.

Note—Two entirely different structures are frequently confused and called troostite. Since the nodular, quick etching micro-constituent found in steels cooled slightly too slowly to be fully martensitic can be resolved into very fine pearlite, it is recommended that the use of the term troostite or "quenching or nodular troostite" to denote this structure be avoided. "Temper troostite" is the first product of the tempering of martensite and consists of submicroscopic particles of carbide in ferrite, and is frequently indistinguishable in general appearance from a quickly etching martensite. If the word troostite is to be retained it should be reserved for this. It changes on higher tempering by indistinguishable degrees into sorbite.

Widmanstätten Structure—When the austenite in low carbon steel transforms to ferrite and pearlite in such a manner as to produce marked precipitation of the ferrite at the crystallographic planes so that the ferrite appears as long continuous plates which occur in definite directions in each grain, the structure is referred to as the Widmanstätten structure. The term is sometimes applied to similar structures in other alloys.

Yield Point—The load per unit of original cross section at which, in soft steel, a marked increase in deformation occurs without increase in load. In other steels and in non-ferrous metals, "yield point" is the stress corresponding to some definite and arbitrary total deformation, permanent deformation or slope of the stress deformation curve; commonly, the stress corresponding to a unit deformation of about 0.5%.

Young's Modulus—See modulus of elasticity.

The above definitions are quoted by permission of the American Society for Metals from the 1936 Metals Handbook.

Tapping an open hearth. As the molten metal flows into the ladle in the foreground, the observer at the right is taking its temperature with an optical pyrometer

A close-up of a blast furnace in which ore, limestone and coke are heated to produce molten iron

IRON-CARBON DIAGRAM

The iron-carbon diagram is in essence a concise statement of the temperatures at which transformations take place in carbon steels when they are heated.

An iron-carbon diagram is shown in the accompanying figure, Fig. 1, and its significance may be illustrated with a simple example. A piece of steel containing 0.43% carbon consists in its annealed or unhardened condition of regions of relatively pure iron, called ferrite, and regions of pearlite which is the carbon-containing constituent of steel. This structure is illustrated in the accompanying photomicrograph, Fig. 2. The light regions are ferrite and the dark (mottled or laminated) regions are pearlite. If a piece of steel which is constituted of these structures is heated, these structures remain as they are over a certain range of temperature. Thus, no change occurs as the steel is heated up to a temperature of about 1320° F. When this temperature is reached, however, a change in the structure sets in, and this temperature is therefore called the lower critical temperature. The change is that some of the pearlite transforms to the high-temperature form of steel; the iron in the pearlite transforms and at the same time takes the carbide into solution, thus forming the high-temperature solution of carbon in iron called austenite. The structure is shown in Fig. 3. Actually, the sample was quenched in water (from this

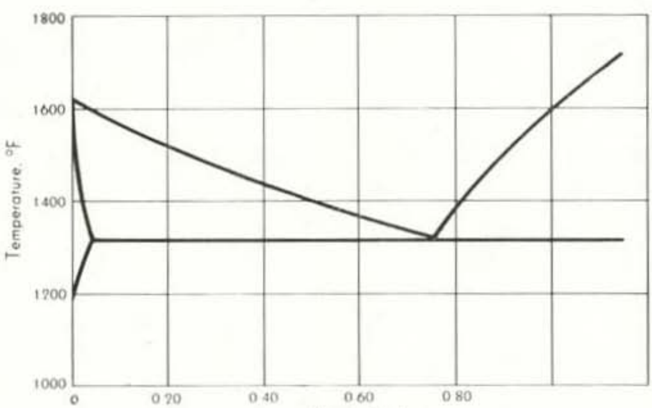


Fig. 1. Iron-carbon diagram

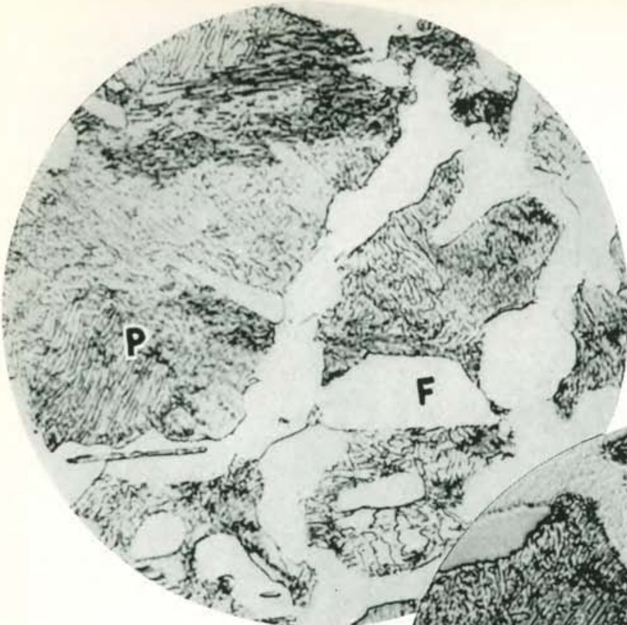


Fig. 2. Unhardened 0.43% carbon steel. (X1000)
P—pearlite
F—ferrite

Fig. 3. 0.43% carbon steel quenched from 1320°F.
M—martensite

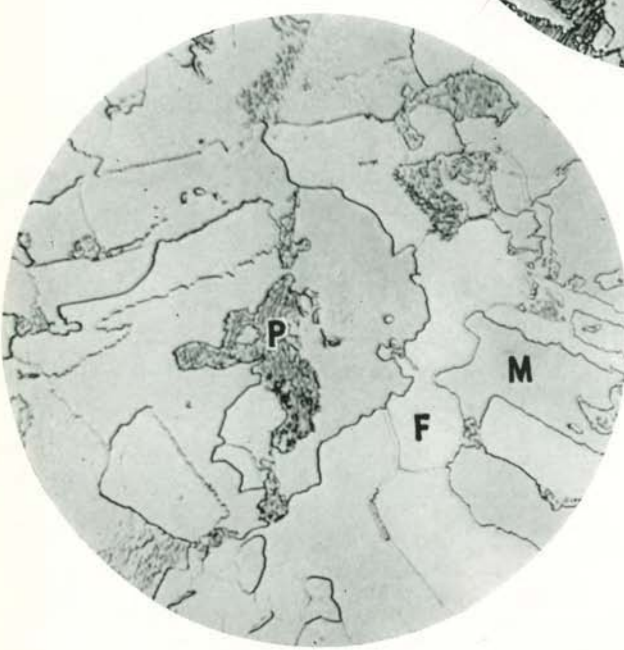


Fig. 4. 0.43% carbon steel quenched from 1340° F.

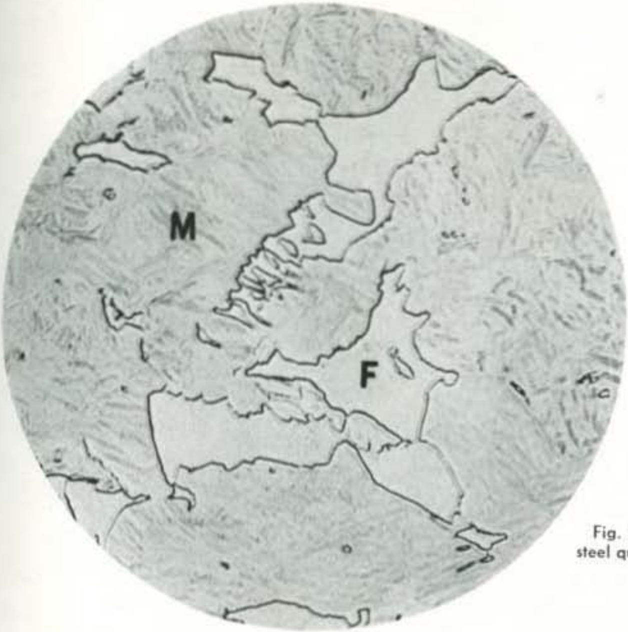
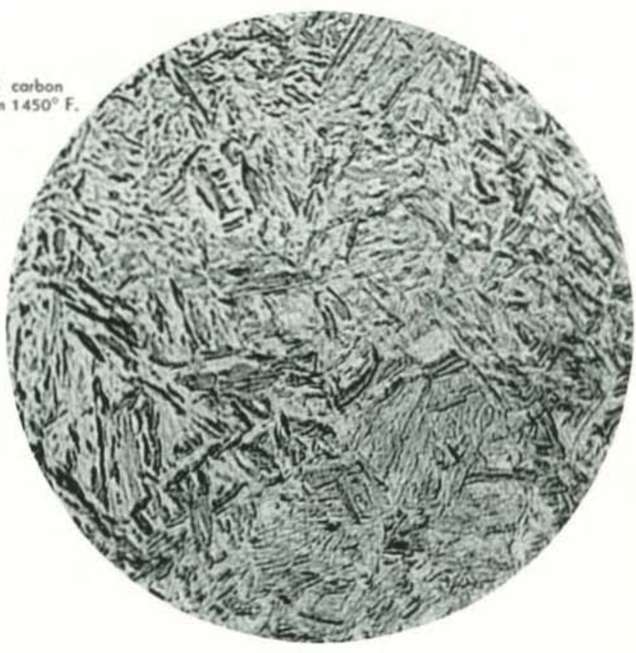


Fig. 5. 0.43% carbon steel quenched from 1380° F.

Fig. 6. 0.43% carbon steel quenched from 1450° F.



temperature of 1320° F.), so that the regions which were austenite at the high temperature are now the hard constituent martensite. With a further small rise in heating temperature, the pearlite is soon transformed entirely to austenite. Thus at a temperature of 1340° the pearlite is practically entirely thus transformed, only small regions of it remaining as shown in Fig. 4. The structure of Fig. 4 is mostly martensite (prior austenite) and ferrite. At this temperature most of the original ferrite is still present, but as the heating temperature is raised further the austenite begins to encroach into the ferrite and absorb it. Thus at 1380° F., as shown in Fig. 5, the pearlite has entirely transformed and the austenite has absorbed a certain amount of the ferrite. As the temperature is raised still further, the austenite spreads more and more, until at a temperature of about 1450° F. the steel consists entirely of austenite and upon quenching is therefore wholly martensite, as in Fig. 6.

It is noted that the first change in structure occurred at about 1320° F. and that the change was completed at about 1450° F. These two points are called the lower and upper critical points on heating. Referring now to the iron-carbon diagram, Fig. 1, it will be observed that the diagram shows temperature plotted vertically and carbon content plotted horizontally. If a vertical line is erected at the position of 0.43% carbon, it will be found to intersect the lines on the diagram at about 1320° F. and at about 1450° F. The diagram thus indicates the temperatures of the two critical points for this steel.

In the same way, it indicates the critical temperatures for other carbon contents. Thus, if a line is erected at 0.15% carbon, it is found that the lower critical point is at about 1320° F. and the upper critical point is at about 1550° F.; at 0.65% carbon the respective critical points are at about 1320° F. and about 1370° F., and at 0.75% carbon the two critical points merge at about 1320° F.

It is important to note that the iron-carbon diagram of Fig. 1 represents some plain-carbon commercial steels. Such steels contain appreciable amounts of manganese and silicon, which change the iron-carbon diagram, as shown in Fig. 7. Thus in the frequently cited diagram for pure iron-carbon alloys, the lower critical temperature is about 1340° F. (instead of 1320° F. as in Fig. 1) and the "eutectoid" point is at 0.85% carbon (instead of at 0.75% as in Fig. 1). The iron-carbon diagram should therefore be used only as a rough approximation to the exact critical points of commercial steels, since alloys other than carbon affect it.

USE OF THE IRON-CARBON DIAGRAM FOR HARDENING OPERATIONS

To secure the fullest possible hardening, it is necessary to exceed the upper critical temperature, in order that all ferrite may be dissolved. Fig. 5, which represents a temperature between the lower and upper critical temperatures of the 0.43% carbon steel shown there, indicates that a large portion of the ferrite is still untransformed. A piece quenched from this temperature has a Rockwell-C hardness of only 51. Fig. 6 on the other hand shows the same steel quenched from above the upper critical temperature, that is to say when the ferrite had all been transformed and the structure was entirely austenite. A piece quenched from this temperature had a Rockwell-C hardness of 60, and was fully hardened.

It should be noted however that the mere fact that the indicated upper critical temperature has been passed, does not always insure that the steel is in a condition for full hardening. The difficulty is in the rate of solution of carbides. Some carbides are particularly sluggish in going into solution. Therefore, although in the case of plain-carbon steels the carbides are usually all in solution very shortly after the upper critical point is exceeded, nevertheless alloy steels should be examined to make sure of complete, or desired degree of, solution. Microscopic examination and mechanical tests are both useful in determining this point.

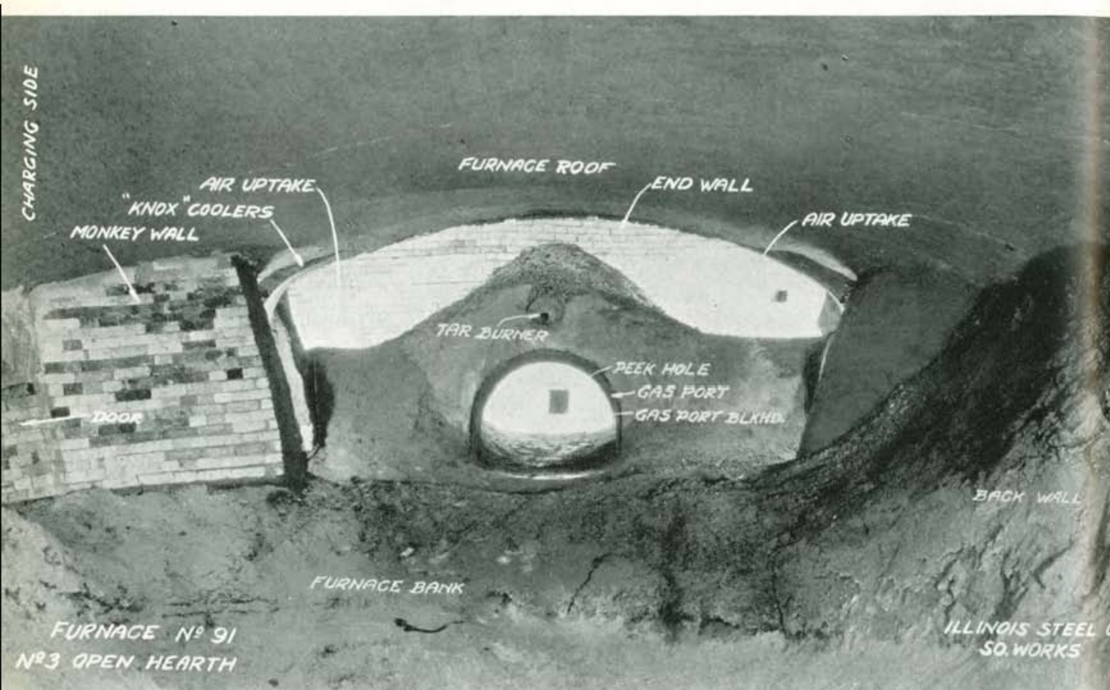
USE OF THE IRON-CARBON DIAGRAM FOR ANNEALING

Full annealing is the term applied to an annealing (softening) operation, in which the steel is heated to above the upper critical temperature and then cooled slowly. It is therefore apparent that in using the iron-carbon diagram as a guide for annealing, the same reasoning is employed as in the case of heating for hardening as described above.

Sub-critical annealing is the process of re-heating at a temperature just below the lower critical point. The iron-carbon diagram shows that the lower critical temperature does not change with variations in the carbon content, at least in the plain-carbon steels of Fig. 1. The addition of alloys does however change this point, and sub-critical annealing temperatures must therefore be varied accordingly.

RELATIONSHIP OF THE IRON-CARBON DIAGRAM TO THE STRUCTURES FOUND AFTER COOLING

The iron-carbon diagram thus indicates the structures present in steel when heated to the temperatures shown in the diagram. It may therefore be used as a guide in preparing pieces for subsequent cooling. It does not however show what is to be expected with various ***rates*** of cooling from these high temperatures. The structures obtained after cooling may only be deduced after a study of the transformation rates. That is to say, the iron-carbon diagram shows the temperatures at which steel may be expected to become austenitic. The structures to be expected when this austenite is cooled at rapid or intermediate or slow rates is to be deduced from the transformation rate curves (discussed in the following section).



A diagram of the typical construction of an open hearth furnace showing the port end in detail

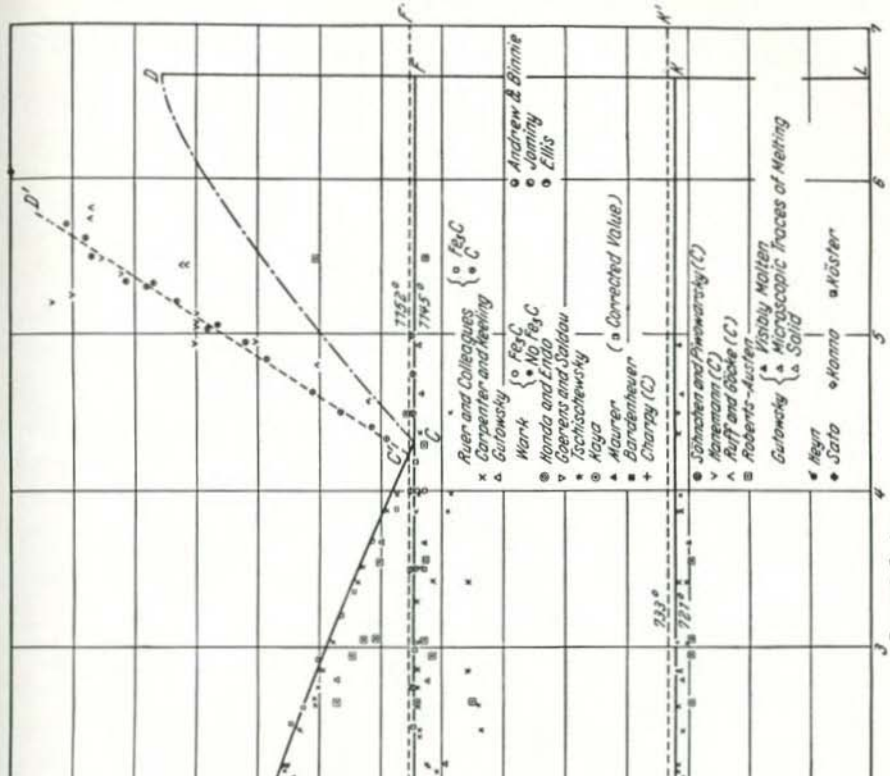


Fig. 7. Summary of Available Data on the Iron-carbon Diagram

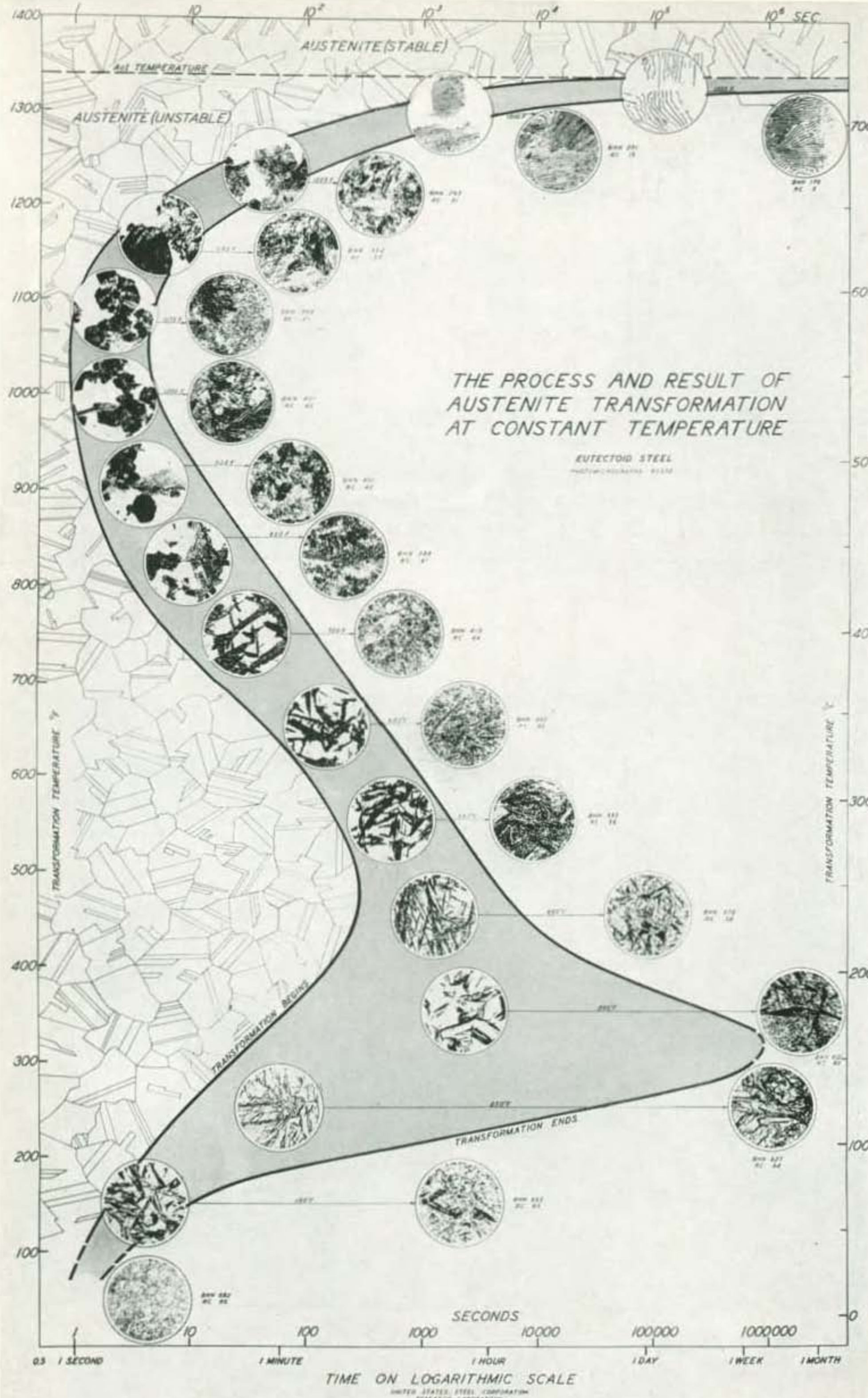

THE PROCESS AND RESULT OF AUSTENITE TRANSFORMATION AT CONSTANT TEMPERATURE
EUTECTOID STEEL
AUSTENITE (STABLE)
AUSTENITE (UNSTABLE)
TRANSFORMATION BEGINS
TRANSFORMATION ENDS
TRANSFORMATION TEMPERATURE °F
TRANSFORMATION TEMPERATURE °C
SECONDS
TIME ON LOGARITHMIC SCALE
UNITED STATES STEEL CORPORATION
RESEARCH LABORATORY
1 SECOND
1 MINUTE
1 HOUR
1 DAY
1 WEEK
1 MONTH

Fig. 8

S-CURVE OF AUSTENITE DECOMPOSITION

THE PROCESS AND RESULT OF AUSTENITE TRANSFORMATION AT CONSTANT TEMPERATURE

General Statement

In the previous section, it was pointed out that the iron-carbon diagram indicates the temperatures at which a steel may be expected to become wholly austenitic, in which condition it is ready for hardening or for full annealing. There was however no detailed discussion of the effect of rate of cooling. The iron-carbon diagram tells nothing of ***rates*** of transformation.

In order to understand the effect of different rates of cooling, it is necessary to study the time required for decomposition of austenite, when it is caused to decompose at different temperatures. Just as the temperatures of formation of austenite are important in heating, so the temperatures of decomposition of that austenite are important in cooling.

The reactions during cooling may be summarized in a diagram. A large copy of this diagram is inserted in the envelope accompanying this book, and Fig. 8 herewith is a reproduction of it on a small scale. The phenomena summarized on this diagram are of fundamental significance to the whole subject of heat-treatment of steels, whether plain-carbon or ordinary alloy steels; for the general pattern of transformation behavior of all is substantially the same, except for differences in the time scale. The diagram illustrates, for a typical carbon steel, how change of the actual transformation temperature influences

(a) the time interval required for the onset and completion of the transformation of austenite at constant temperature, and

(b) the structure and hardness of the product resulting from this type of heat-treatment.

The ordinary alloying elements retard the transformation process under comparable conditions; indeed this appears to be the main way by which they affect the mechanical properties of a steel, for in general the presence of a dissolved alloying element results in a lower actual transformation temperature during quenching, hence in a harder and stronger final product.

It is to be emphasized that the behavior represented on the diagram is an inherent property of the heated piece of steel itself, as observed in specimens small enough to be brought immediately to temperature throughout. When the mass is large so that there is appreciable thermal lag, its effect is taken into account, and serves to explain the various structures encountered, as explained in connection with Fig. 9.

A selected list of reports and publications on this topic is appended.

DESCRIPTION OF THE DIAGRAM FOR A TYPICAL STEEL

(Eutectoid Steel 0.85% Carbon)

For steel of eutectoid composition there is a characteristic equilibrium temperature (the so-called Ae_1 point in pure iron-carbon alloys) above which the steel will remain for an indefinite time in the austenitic condition, in which the carbon and alloying elements are in solution in the high-temperature, or "gamma," form of iron. The corresponding field on the diagram (see Fig. 8) is labelled "austenite (stable)." When the steel has been heated so that it is austenitic, and is then cooled and held at a constant temperature below the Ae_1 point, it remains austenitic for a definite interval before beginning to transform; the transformation is not instantaneous, as has commonly been presumed erroneously, but requires for its completion a period which is characteristic of the temperature at which it is held during this period. On a temperature-time diagram therefore, such as this is, there are, at temperatures below the characteristic Ae_1 point, three regions: (1) that in which the austenite has not yet begun to transform, which lies to the left of the left-hand curve, and is labelled "austenite (unstable)," (2) that in which the transformation proceeds, at constant temperature, to completion—the region (shaded on the large chart) between the pair of S-shaped curves, (3) that in which transformation is complete, with the structure and properties of the treated steel substantially fixed, which lies to the right of the right-hand curve.

The region on this diagram within which austenite can exist—that is, above and to the left of the left-hand curve—is shown by the idealized austenite structure, as a means of emphasizing the fact that the steel within this region has a quite different structure from that encountered elsewhere in the diagram. The photomicrographs between the pair of curves show the structure of the transformed material when the austenite is one-half transformed at that temperature; those to the right of the pair of curves show the structure, corresponding to that temperature, when the transformation is complete. The hardness number, both in Brinell and in Rockwell "C" units, of the finished product is given alongside the photomicrograph.

Coordinates. The vertical coordinate is the temperature at which the constant temperature transformation is caused to take place; the horizontal coordinate is the time interval expressed on a logarithmic scale. This scale is employed for convenience because the range of time at the several constant temperatures is so large; on a linear scale these long periods would necessitate either an unmanageably large diagram or a scale too compressed for detail in the shorter intervals. For convenience, the chart shows time in seconds, as well as in minutes, hours, days, weeks and months.

Rate of Transformation—When the austenitic solid solution becomes unstable, hence tends to transform and break down, the process may be represented

austenite (gamma) $\longrightarrow$ ferrite (alpha) + carbide.

In this process there are two changes, in general more or less simultaneous: (a) the gamma form of iron changes to the low-temperature or "alpha" form, (b) the carbon is thrown out of solution, in the form of carbide. These processes are not instantaneous. The time involved depends upon the temperature at which the process is made to take place, and it is this dependence which is brought out by the pair of S-shaped curves. The left-hand curve represents the time required for the transformation to begin, when the steel is held at any constant temperature level within the range; the right-hand curve the total time to completion of the transformation, at that same constant temperature level.

It will be noted that there are two temperature ranges of relatively rapid transformation, one in the vicinity of 1000-1100° F. and another much lower, at about room temperature; it is also evident that there are two regions of relatively slow transformation, one at high temperatures just under the equilibrium temperature (Ae_1 line) and another in the range 900-300° F. In other words, when properly manipulated, the steel transforms very rapidly or quite slowly depending upon the temperature at which the transformation is caused to take place. These temperature ranges of high and low transformation will be referred to again later.

Structure of Transformation Products. In addition to the effect of temperature on the ***rate*** of transformation, there is a marked effect of temperature on the ***structure***, that is the mode of dispersion and distribution of the products of transformation (ferrite and carbide). At high transformation temperature, just under the Ae_1 line, the product consists of ferrite and carbide arranged in the coarsely lamellar condition known as "pearlite"; as the transformation temperature is lowered, the pearlite becomes finer and finer until at temperatures in the vicinity of 1000° F. it is practically unresolvable even with the highest power lens. At still lower transformation temperatures the ferrite—carbide product assumes a needle-like or acicular form as contrasted to the rosette-like or nodular form characteristic of temperatures above about 950° F. At the very lowest temperatures shown in the diagram the carbide is not precipitated at all during transformation, but is retained in the unstable solid solution known as "martensite," the chief constituent of quench-hardened steel.

The photomicrographs (all at an original magnification of 2500, reduced to 800X in printing) illustrate the typical microstructure of the product of austenite transformation at various arbitrarily chosen constant temperature levels, namely 1325, 1300, 1225, 1150, 1075, 1000, 925, 850, 750, 650, 550, 450, 350, 250, 150 and 70° F. These temperatures were selected merely to give a uniform distribution of photomicrographs along the curve. The photomicrographs ***between*** the two S-shaped curves, i.e., within the zone of transformation, show the structure when the transformation is about 50% completed; the dark portions of these photomicrographs represent the products of this transformation, while the white matrix or background corresponds to the untransformed austenite* out of which the products are forming. The photomicrographs to the ***right*** of the curves represent the structure of the fully-transformed steel when the process of transformation has been completed at each of the several temperature levels. No further changes occur in the steel with increased time at temperature except those associated with carbide diffusion and coalescence in the ferrite; these changes proceed relatively slowly and result only in the very gradual softening of the material as in subcritical spheroidizing treatments.

Hardness of Transformation Products. In addition to the photomicrographs the hardness of the products of transformation at the various temperatures is

*Actually the background is not austenite, but martensite resulting from a water quench applied to halt the reaction at any desired stage of its progress.

shown on the chart in both Brinell (BHN) and Rockwell "C" (RC) units. It will be noted that at high transformation temperature the low hardness, characteristic of coarse pearlite in well-annealed steel, is obtained; as the temperature of transformation is lowered the hardness of the product, in general, gradually increases until at the lowest transformation temperature shown (70° F.) full martensitic hardness (RC 66) is developed.

Summary. The diagram shows the following items for a carbon steel of eutectoid composition (0.85% carbon):

(a) Time required at constant temperature for the earliest detectable beginning of the transformation at all temperatures between 1325° F. and 70° F.

(b) Time required for the ***completion*** of the constant temperature transformation at all temperatures between 1325° F. and 70° F.

(c) Microstructure of the products of transformation at fifteen temperature levels when the reaction is about 50% completed.

(d) Microstructure of the products of complete transformation at sixteen temperature levels.

(e) Hardness of the products of complete transformation at sixteen temperature levels in both Brinell and Rockwell "C" units.

RELATION OF CONSTANT TEMPERATURE TRANSFORMATION RATES TO COOLING RATES ENCOUNTERED IN ORDINARY PRACTICE

In ordinary practice, steels are not caused to transform uniformly by thus holding at a constant temperature. Rather, the transformation takes place while the piece is cooling at some desired rate. But the transformation rate curves indicate also what takes place under the latter circumstances. For example, in Fig. 9 curve B shows a very slow rate of cooling, as in annealing. When the bar of steel reaches the temperature B_1, the transformation to pearlite begins. As it proceeds, a certain amount of heat is liberated due to the transformation, as indicated by the flat part of the curve, so prolonging the time in this temperature range. As the temperature drops, the rate at which the pearlite forms becomes more rapid, and when the cooling curve reaches the point B_2 the transformation to pearlite is complete. Incidentally, the

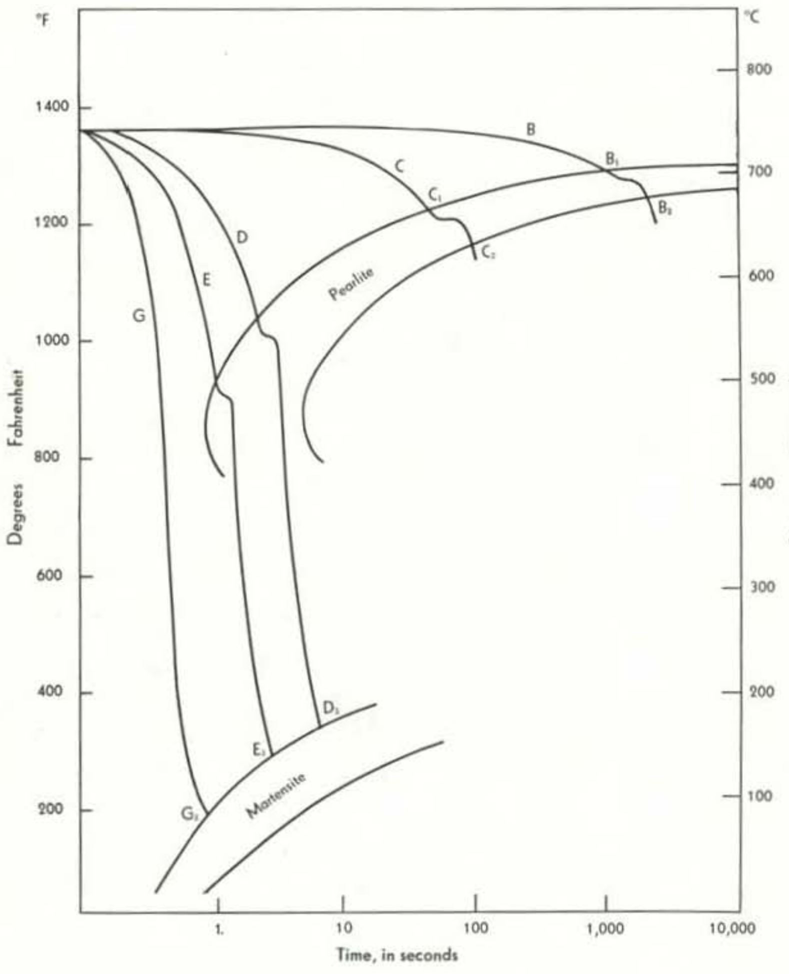

°F
1400
1200
1000
800
600
400
200
Degrees Fahrenheit
°C
800
700
600
500
400
300
200
100
Degrees Centigrade
B
B1
B2
C
C1
C2
D
D1
E
E1
G
G1
Pearlite
Martensite
1.
10
100
1,000
10,000
Time, in seconds

Fig. 9.

pearlite formed first, namely at point B_1, will be somewhat coarser, and therefore softer, than the last pearlite to form, namely that at point B_2.*

A somewhat more rapid rate of cooling, as in air cooling or normalizing, is indicated in curve C. Here the development of pearlite is quite analogous to that in curve B, but the pearlite formed at C_1 will be somewhat finer, and therefore harder, than that first formed in the other product, namely in B_1. Likewise, the pearlite formed at C_2 will be still finer, and therefore still harder, since it was formed at the lowest temperature discussed thus far.

Supposing however that a piece is cooled so rapidly, as in curve G, that it fails to form any pearlite at all. It will then be cooled without any transformation taking place until it reaches the temperature G_3, at which point it will form martensite. This curve G represents then a steel being hardened fully to martensite. With rates of cooling intermediate between C and G, such as curves D and E, the final structures will be intermediate between those previously described. That is to say, pieces cooled at these intermediate rates will form a certain proportion of pearlite, but since the time at the high temperature is not sufficient to allow the transformation to pearlite to be completed, the steel with its partially pearlitic structure cools to low temperatures where the remaining austenite transforms to martensite, as at points D_3 and E_3. The resultant structure is therefore a mixture of pearlite and martensite.

In any ordinary cooling schedule the conditions giving rise to the products of constant temperature transformation within the range 950-300° F. will not be encountered. In order to make these products the steel must be rapidly cooled to within this temperature range, and ***then held at the desired temperature long enough for the transformation to complete itself.*** Carbon steel heat-treated in this manner possesses some rather unusual combinations of ductility, strength and hardness; this method of heat-treatment has been discussed in several reports and papers; some patent applications on it have been granted (Bain and Davenport, U.S. Patent No. 1,924,099—1933: British Patent).

Effect of Alloying Elements. With one or two possible exceptions, the effect of any alloying element which can be put into solution in austenite is to retard the transformation rate; that is, alloying elements make the austenite sluggish and more reluctant to transform, and the pair of rate curves is moved to the

*Actually, the temperature of completion of transformation under these conditions would be slightly lower than the intersection with the constant-temperature curves.

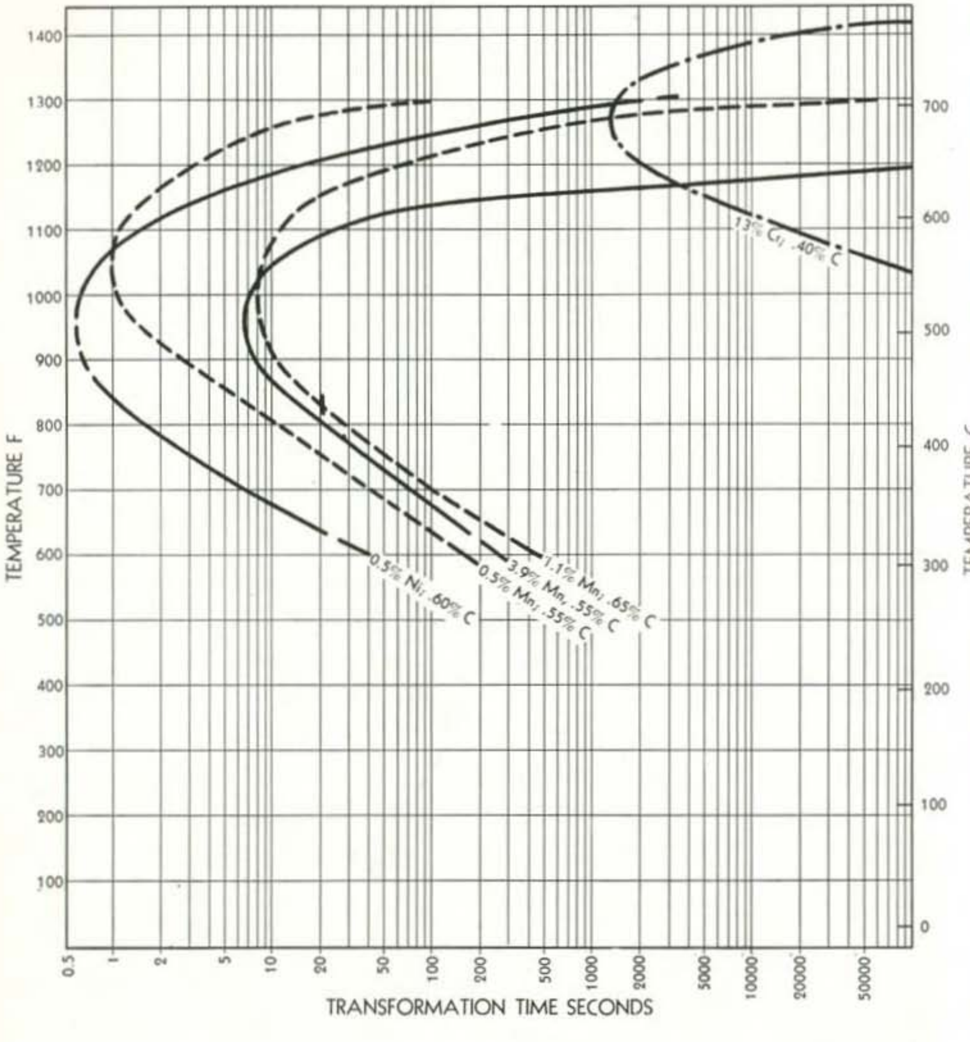


Fig. 10. Comparative Time Intervals for 50% Transformation in Steels Containing Different Amount of Nickel Manganese and Chromium.

right. Consequently, for a given cooling schedule relative to the appropriate Ae_1 point, an alloy steel actually transforms at a lower temperature than a carbon steel, and therefore has the properties corresponding to that lower transformation temperature. Indeed we may say that if a series of low-alloy steels of constant carbon content are all made to transform completely at the same relative temperature, the resultant structures will all be very similar and the properties of the products will differ comparatively little.

Elements retard differently the rate of transformation, just as analogously they affect differently the equilibrium temperature (Ae_1). The influence of various amounts of a few common alloying elements is illustrated in Fig. 10, comprising, to obviate confusion, only the upper portion of the curve corresponding to 50% transformation in each case. The precise temperature position of the upper region of most rapid transformation (in the vicinity of 1000° F.) of alloy steels appears to follow that of the equilibrium temperature; for instance, compare in Fig. 10 the curve for the chromium steel with those for the nickel and manganese steels.

It becomes clear at once, from a study of Fig. 10, why the alloy-bearing steels possess higher hardenability than carbon steels, that is, why they are deeper-hardening. The relative retardation of the transformation rate, particularly in the vicinity of 1000° F., permits a rate of cooling of the alloy steels which, if used on carbon steels, would bring about transformation to the softer pearlitic products; stated in another way, the alloy steels will harden more deeply, i.e., they can at a given cooling rate be hardened throughout heavier sections than carbon steels, due to the increased sluggishness of the alloy-bearing materials. Thus the study of transformation rates at constant temperature has thrown considerable light on at least one of the basic reasons for adding alloying elements to steel, particularly the low-alloy structural and automotive steels.

Effect of Austenite Grain Size. Increasing the austenite grain size by heating to higher and higher temperatures in the austenitic field has the same general effect on transformation rate as increasing the alloy content of the steel; that is, it causes the steel to be more sluggish and reluctant to transform and results in increased hardenability or depth of hardening on quenching. In other words, the transformation rate curves are moved toward the right of the diagram either by increasing alloy content or by increasing austenite grain size, or, of course, both. Fig. 11, which presents a group of curves correspond-

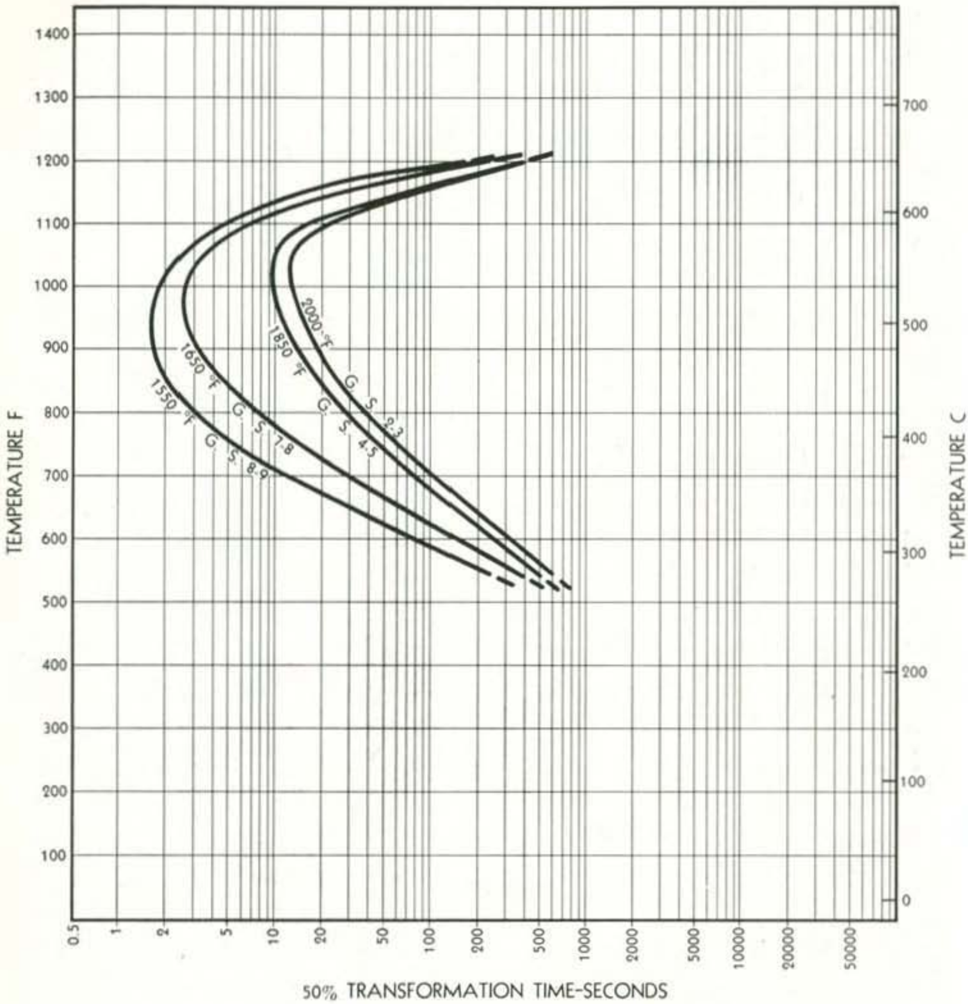


Fig. 11. Comparative Time Intervals for 50% Transformation in a Single Steel as Heated to Four Different Temperatures in the Austenite Range Prior to Transformation, with Corresponding Difference in Austenite Grain Size (G.S.)

ing to 50% transformation within the temperature region of practical interest, illustrates the effect of increasing grain size on the transformation rate of low-alloy steel as heated to one of four temperatures (1550°, 1650°, 1850°, 2000° F.) in the "austenite (stable)" field before transfer to the several constant temperature transformation levels; and it shows the grain size established at each of the four high temperatures at which the austenite was established prior to bringing to the constant temperature for transformation.

The investigations, the results of which are summarized in the main diagram, are the work of members of the staff of the United States Steel Corporation Research Laboratory.

SELECTED LIST OF UNITED STATES STEEL CORPORATION RESEARCH LABORATORY REPORTS AND PUBLICATIONS DEALING WITH THIS TOPIC

Transformation of Austenite at Constant Subcritical Temperatures. E. S. Davenport and E. C. Bain, Report No. 66 (1930); publication No. 6—*Trans. Am. Inst. Min. and Met. Engrs.,* Iron and Steel Div., Vol. 3, pp. 117-154, 1930.

On the Rates of Reactions in Solid Steel. E. C. Bain (Henry Marion Howe Memorial Lecture for 1932), Publication No. 22—*Trans. Am. Inst. Min. and Met. Engrs.,* Vol. 100, pp. 13-46, 1932.

Factors Affecting the Inherent Hardenability of Steel. E. C. Bain (Edward DeMille Campbell Memorial Lecture for 1932), Publication No. 29—*Trans. Am. Soc. for Steel Treating,* pp. 385-428, 1932.

Microscopic Cracks in Hardened Steel, their Effects and Elimination. E. S. Davenport, E. L. Roff, and E. C. Bain, Report No. 195 (133); Publication No. 44—*Trans. Am. Soc. for Metals,* Vol. 22, pp. 289-310, 1934.

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The Estimation, and Significance, of the Austenitic Grain Size of Steel. E. C. Bain and E. S. Davenport, Publication (1934).

Some Characteristics Common to Carbon and Alloy Steels. E. C. Bain, Publication No. 46. *Am. Iron and Steel Inst. Yearbook,* pp. 86-119, 1934.

Tapping a Heat from an Electric Furnace

CRITICAL COOLING RATES OF THE BUREAU OF STANDARDS

Some years ago the Bureau of Standards undertook a detailed investigation of the rate of cooling of steels when quenched in different media. A comprehensive report of this work is given in the article by H. J. French (under whose direction the work was done) in the Transactions of the American Society for Steel Treating, May and June, 1930.

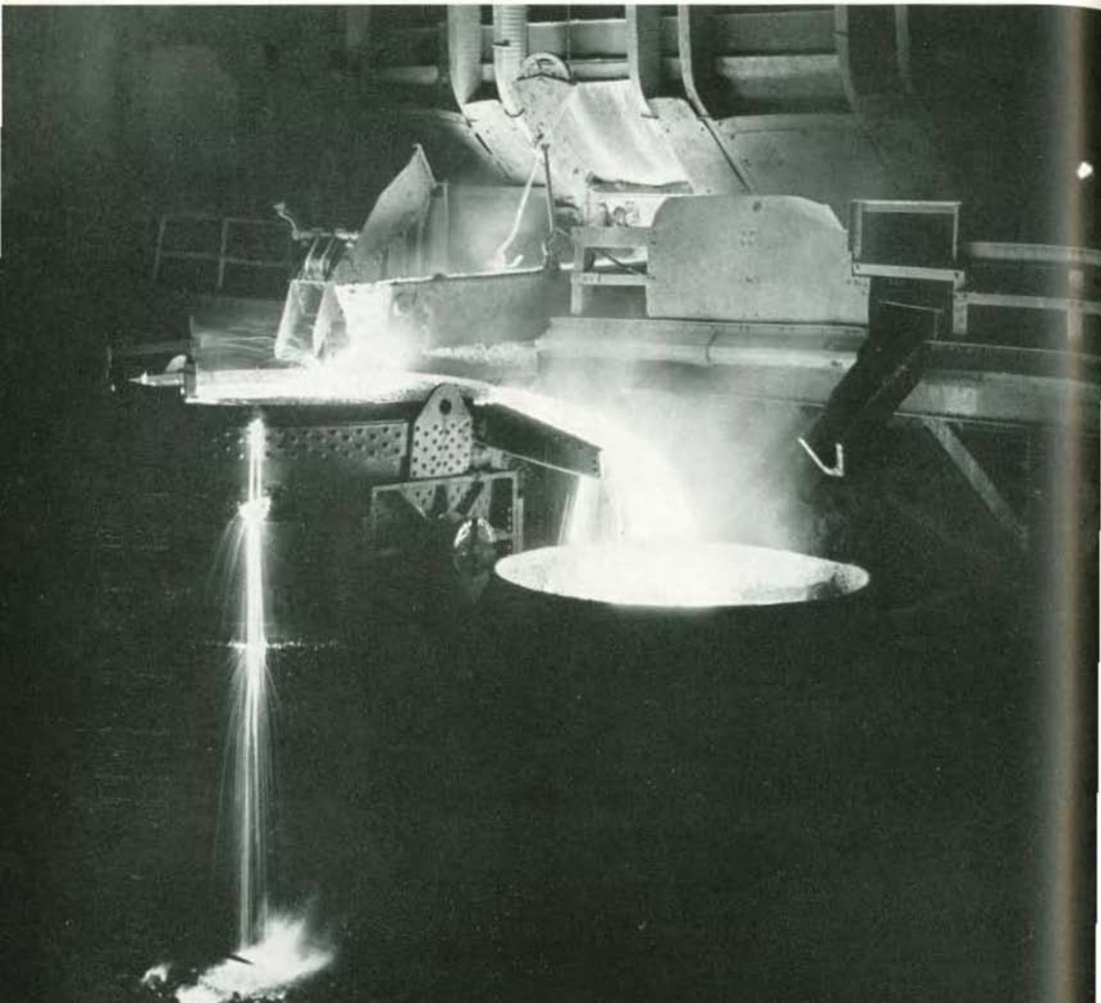
The work comprised largely a study of the rates at which samples cooled when quenched, the cooling curves being recorded on a string galvanometer. For the most part, the cooling rate was recorded for the surface of the piece and for the center of the piece. The pieces tested were spheres, rounds and plates, and the dimensions ranged from 1/4" to 11 1/4". The tests included the quenching speeds in water, in a quenching oil, in sodium hydroxide solution and in still air.

The great value of this work rests in its furnishing actual data on the rate of cooling of a wide range of sizes when immersed in cooling media having a wide range of quenching powers. This assumes special significance when considered in connection with the discussion of the S-curve, as illustrated for example in Fig. 10 of that discussion. It was pointed out there that if the cooling of a piece is sufficiently rapid, so that it cools past the nose of the curve without forming pearlite at that temperature, then the piece will form martensite and will be hardened. The nose of the curve is usually in the range 900 to 1100° F. (500 to 600° C.). If the inherent hardenability characteristics are known for a particular steel, then the behavior of that steel in quenching may be judged from the time-temperature cooling curves of various sizes and in various quenching media given in the data reported by French. Further, if the hardening behavior of a steel in a particular quenching medium is known, then its behavior in other quenching media or in other sizes may again be judged by reference to the various time-temperature cooling curves.

It is perhaps worth pointing out that the maximum cooling rate, as shown in the Bureau of Standards curves, is in general in the neighborhood of 720° C. (1325° F.), and that this is not the decisive temperature as regards the hardening of the steel. The decisive temperature, as already stated, is at the nose of the curve, which varies with different steels but is usually in the range from

900 to 1100° F. A correlation between the S-curve and the cooling rates is therefore made more readily if the cooling rates are represented by the total time from entering the "critical" range until the sample passes 900° F. (500° C.). This should indicate whether the sample has formed any pearlite in quenching, and any portion of the steel which has not formed pearlite in this temperature range will ultimately form martensite when the lower temperature is reached at which martensite forms.

Such data furnish some indications of the probable hardening of a bar of steel in quenching.



Tapping 160-ton-heat of steel from an open hearth. In the foreground the slag which floats on top of the molten steel is overflowing into the slag ladle

HARDENABILITY

It is generally stated that the reason for the use of alloy steels in the construction of automobiles, farm implements, railroad equipment and the like, is that they possess greater strength. While this is correct, it is important to observe that the greater strength is due to the ability of alloy steels to be quench-hardened in greater thicknesses. That is to say, in thin sections such as $^3/_{16}$", carbon steel may be quenched to fully as great a strength and hardness as any alloy steels in the same size. But in larger sections, such as 1" diameter, carbon steels cannot be hardened below a depth of perhaps $^3/_{16}$", so that the core remains unhardened and therefore not very strong. On the other hand, many alloy steels can be hardened in 1-inch sections, and some of them very much more. It is thus not any higher degree of hardness but rather the greater depth of hardening which accounts for the greater strength of pieces of substantial size made of alloy steel.

It therefore becomes important, in selecting alloy steels for construction purposes, to consider the depth to which they will harden in quenching. This extent of hardening is often spoken of as the hardenability.

METHODS OF MEASURING HARDENABILITY

Since the hardenability of a piece of steel is so important a property, it is clearly desirable to establish a means of measuring it—to ascertain a value which would designate the degree of hardenability.

This need has been widely recognized, with the result that a number of methods have been employed:—

(1) Fundamental hardenability (transformation rates at constant temperature)

(2) Hardness gradient (hardness distribution curves)

(3) Fracture and etch test (Shepherd standard)

(4) Microstructure

(5) Ar point in a cooling curve

Since the methods all refer to hardenability, the results will of course be related to one another, and this inter-relationship may be shown with proper examples. The following discussion points in this direction.

1. FUNDAMENTAL HARDENABILITY

The study of transformation rates gives the most complete information regarding the hardenability of a steel. It is discussed in detail in a previous section (which see) and is therefore not described further here. Its limitation is the time required to accumulate the data. Complete correlations are not yet available to show the depth to which a given size section will harden in a particular quenching medium, when the fundamental hardenability of the steel is known.

2. HARDNESS GRADIENT

Many investigators of the hardening of steel have illustrated hardenability by showing the hardening across a quenched cross section. This is an extremely useful method of showing hardening, and will be discussed here in some detail. Further, if instead of the customary single size, a series of sizes of the same steel is employed, the result, as shown in Fig. 12, gives a rather complete idea of the hardening behavior of the steel. The example given in Fig. 12 is a 1045 steel, and shows the hardnesses obtained when various sizes from ½″ round to 5″ round are quenched in water. It is obvious that the surfaces of the ½″ round and 1″ round hardened fully (to martensite), and it is also apparent that the centers of the 4″ round and 5″ round failed to harden at all (they formed pearlite).

It is evident that such a series of hardness curves, taken on any steel, carbon or alloy, would result in a clear picture of the hardening behavior of that steel. Further, if this method is extended to include oil quenching, then the behaviors both in water quenching and in oil quenching will be manifest. A large chart will be found in the envelope accompanying this book, showing the hardening behaviors of S.A.E. 1045, 6140, 4140, 3240 and 3340, quenched both in water and in oil, in sizes up to 5″ round. These charts bring out quite clearly a wide range of hardening behavior, from the relatively low hardenability of S.A.E. 1045 to the very high hardenability of S.A.E. 3340. These curves are also reproduced individually in the succeeding pages of this section.

A Sensitive Criterion of Hardenability. The above mentioned chart gives a good general idea of the hardening of such steels. There are also further details of hardening which appear upon closer examination. Fig. 22 shows a similar series of hardness curves obtained upon oil-quenching a carbon-molybdenum steel, but the successive sizes are here graduated closely (rather than over a wide range as in Fig. 12). Further, the range of sizes includes only sections which harden fully at the surface of the piece but fail to harden entirely at the center. Attention is now called to the following circumstance. In the range of sizes from 5/8" diameter to 15/16" diameter, the change in hardness at the center (as the size is increased) is only slight, namely from 63 down to 61. In the range from 15/16" diameter to 1 1/8" diameter, the change in center hardness is relatively very great, namely from 61 down to 45. In the range from 1 1/8" diameter to 1 1/2" diameter, the change in center hardness is again relatively slight for such a large increase in size, namely from 45 down to about 38. Hardness is a function of the proportion of martensite in the structure. That is to say, if this steel has hardened fully, so that its structure is entirely martensite, it has a Rockwell-C hardness of about 63. If however it has not hardened fully, that is if the structure is partially pearlite, then the hardness is less than 63. In these steels, the relationship is shown in Fig. 23. This diagram was derived by examining a large number of samples and points within the samples, taking the hardness readings at the respective points and estimating under the microscope the proportion of martensite at these points. It is apparent that the hardness varies regularly with the proportion of martensite. Therefore if there is a rapid change in hardness in a narrow range of sizes we know that there is a corresponding rapid change in the proportion of pearlite. In Fig. 24 are plotted the center hardnesses (from Fig. 22) against the diameters of the respective bars. At some other location between surface and center the hardness change would have been most rapid at other diameters, i.e. in rounds of some other range of sizes.

In Fig. 26 are shown the hardness curves of two steels, over a closely graduated series of sizes as in Fig. 22. At 3/4" round, the difference between the two hardness curves is not very great. At 15/16" diameter, and at 1" diameter, the difference is still not very great. However, at 1 1/16" diameter, it will be observed that the difference between the two steels is very pronounced. The shallower hardening steel has now formed more than 50% pearlite at the center, whereas the deeper hardening steel has not yet reached nearly that amount. The same relationship is still evident at 1 1/8" diameter. However, at 1 3/8" diameter, the difference is appreciably less, and at 1 1/2", diameter the apparent difference is no longer very great. It thus becomes clear that in order to distinguish slight differences in hardenability, it is desirable to use a section of suitable size.

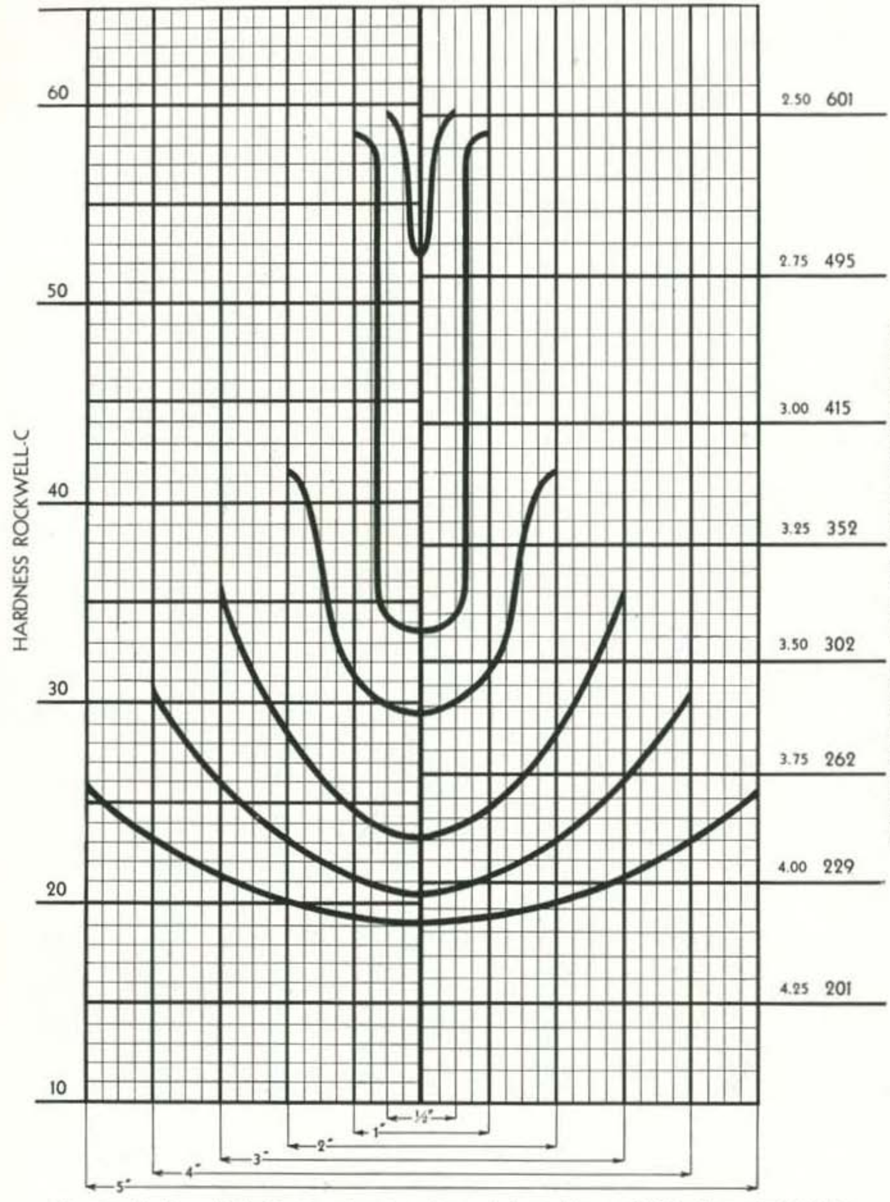


Fig. 12. Hardness distribution in various sizes of quenched round bars. ***1045*** Steel quenched in ***Water***

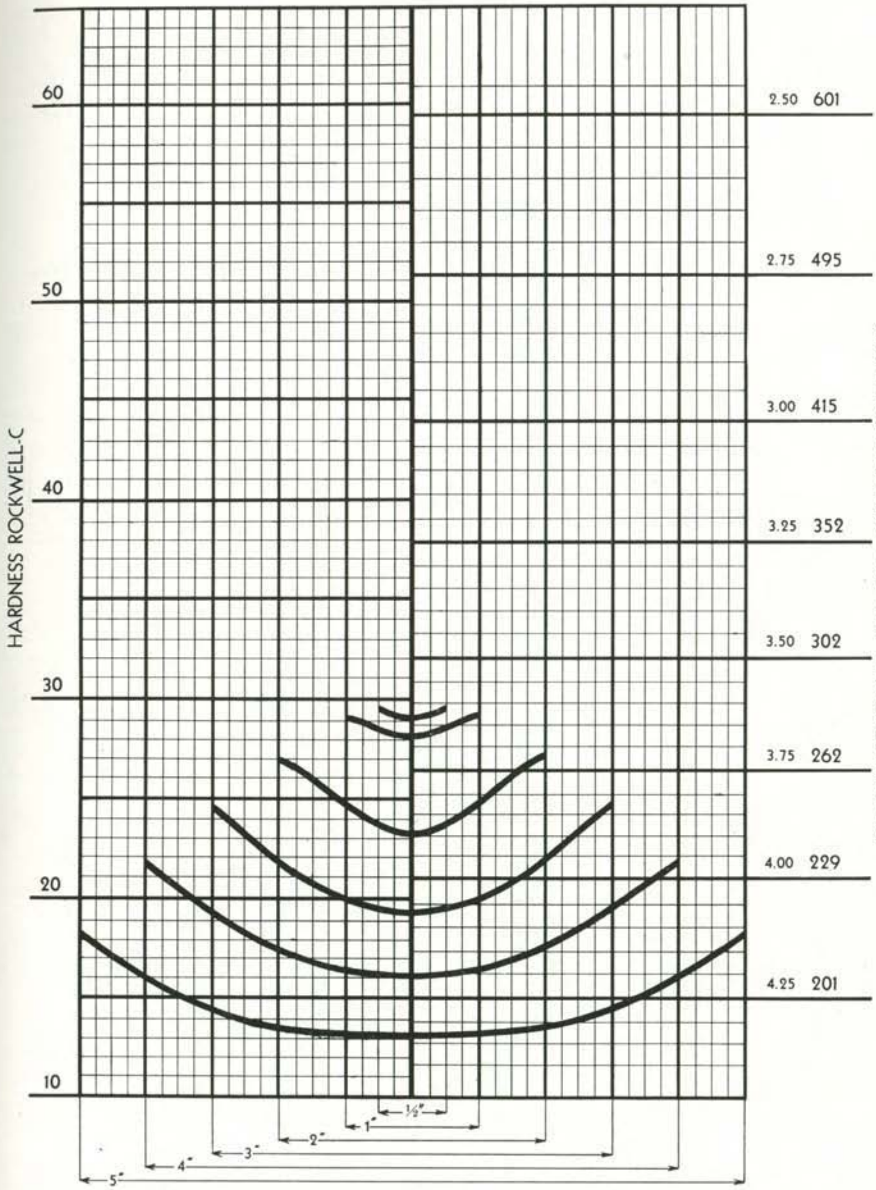


Fig. 13. Hardness distribution in various sizes of quenched round bars. ***1045*** Steel quenched in ***Oil***

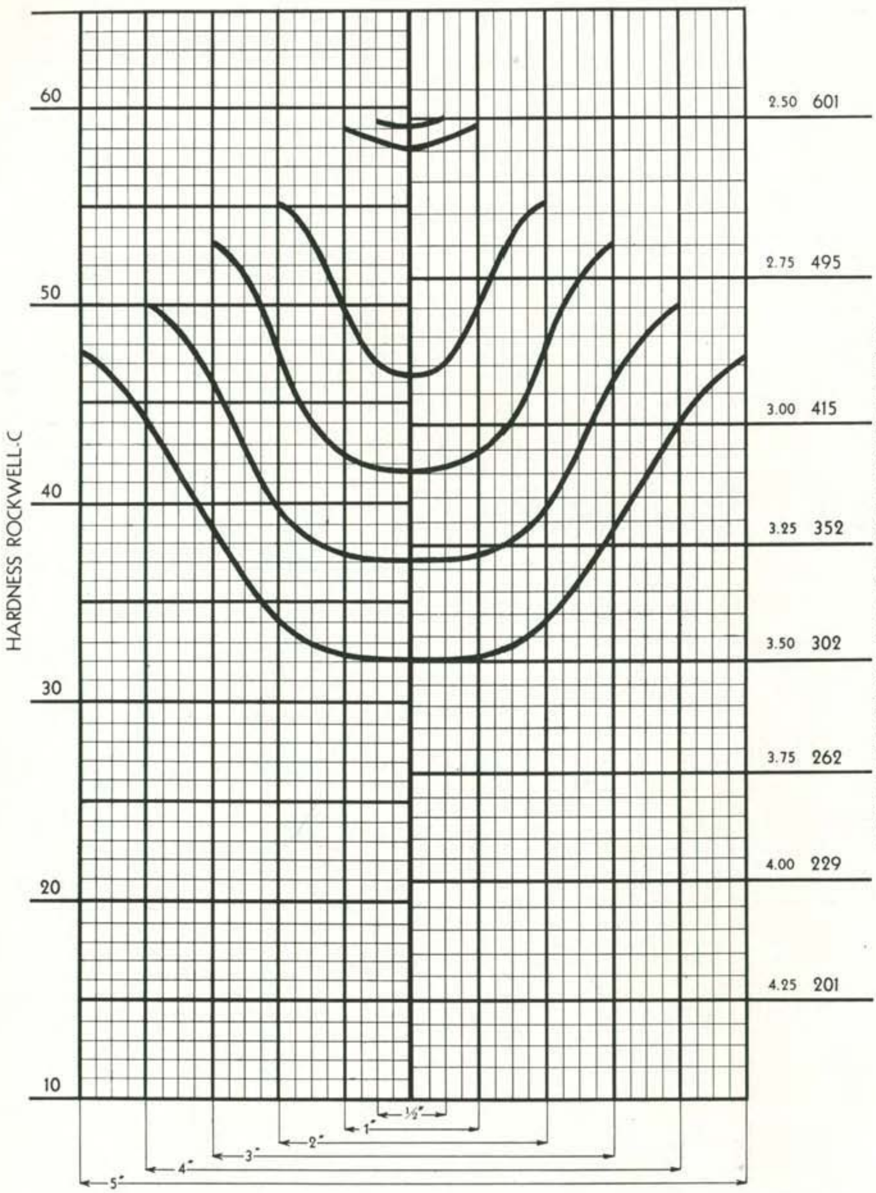


Fig. 14. Hardness distribution in various sizes of quenched round bars. *6140* Steel quenched in *Water*

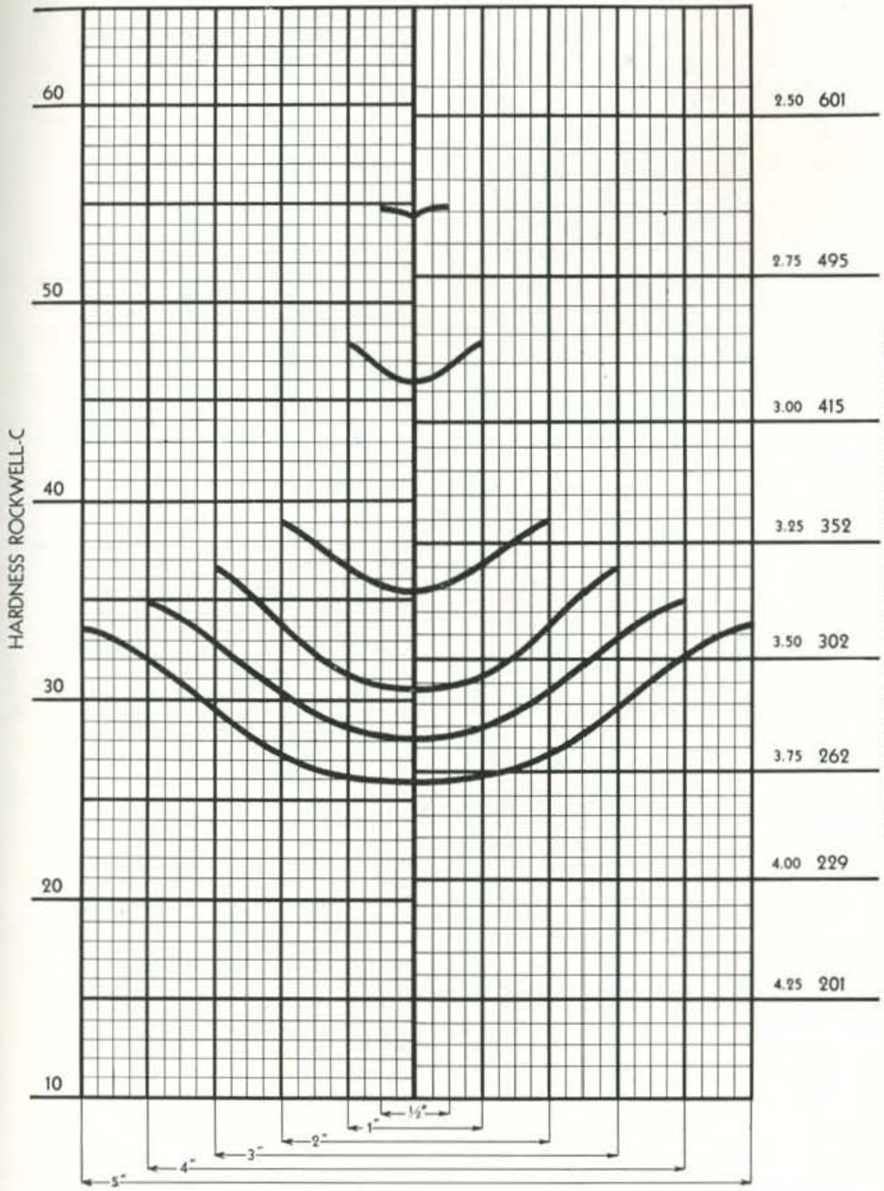


Fig. 15. Hardness distribution in various sizes of quenched round bars. *6140* Steel quenched in *Oil*

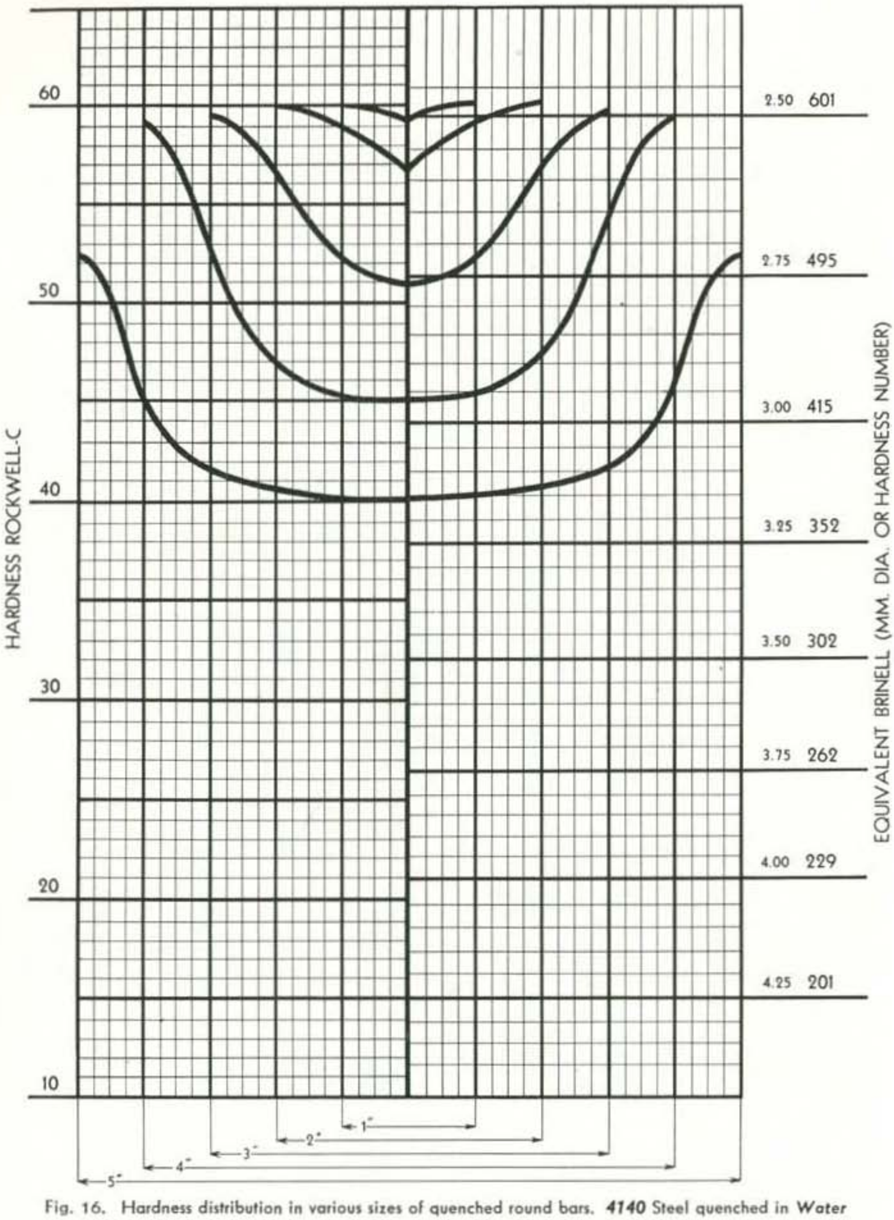


Fig. 16. Hardness distribution in various sizes of quenched round bars. **4140** Steel quenched in *Water*

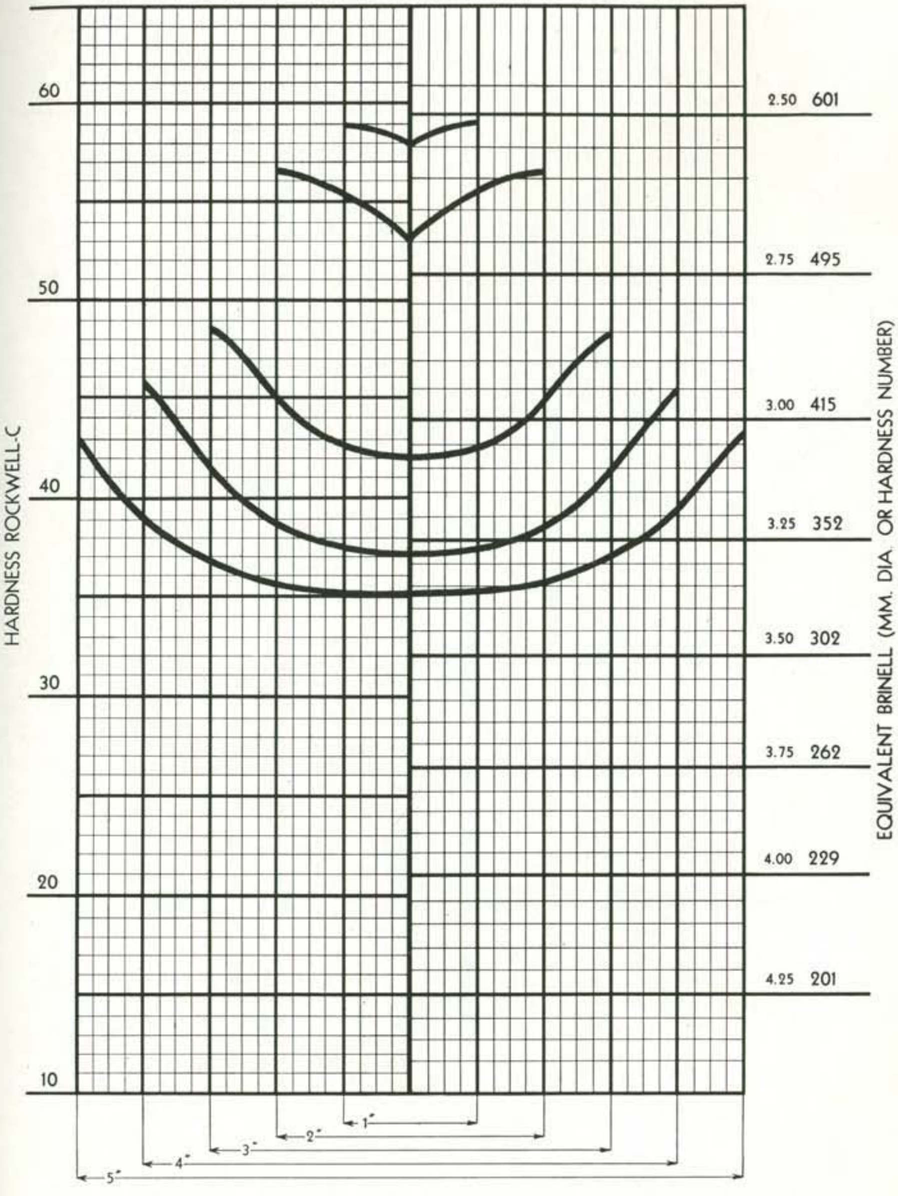


Fig. 17. Hardness distribution in various sizes of quenched round bars. ***4140*** Steel quenched in *Oil*

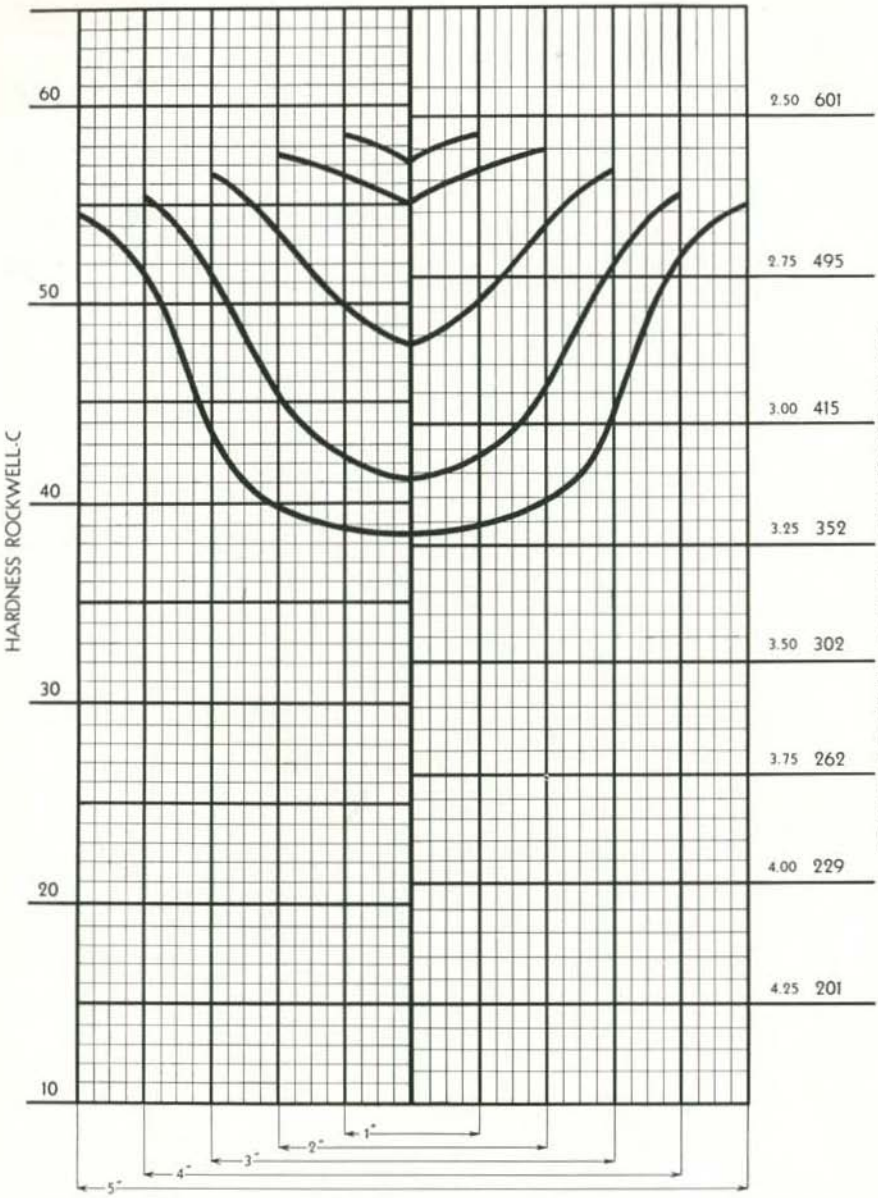


Fig. 18. Hardness distribution in various sizes of quenched round bars. ***3240*** Steel quenched in ***Water***

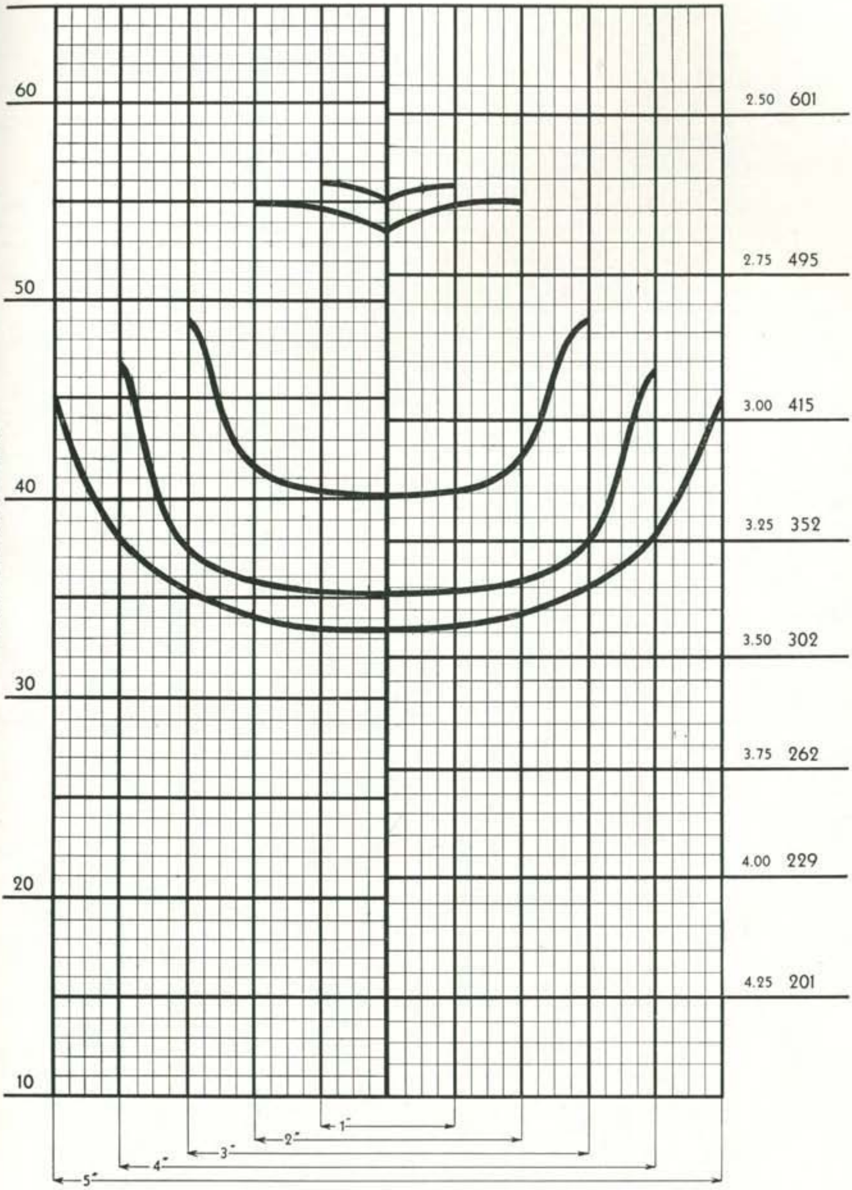


Fig. 19. Hardness distribution in various sizes of quenched round bars. **3240** Steel quenched in *Oil*

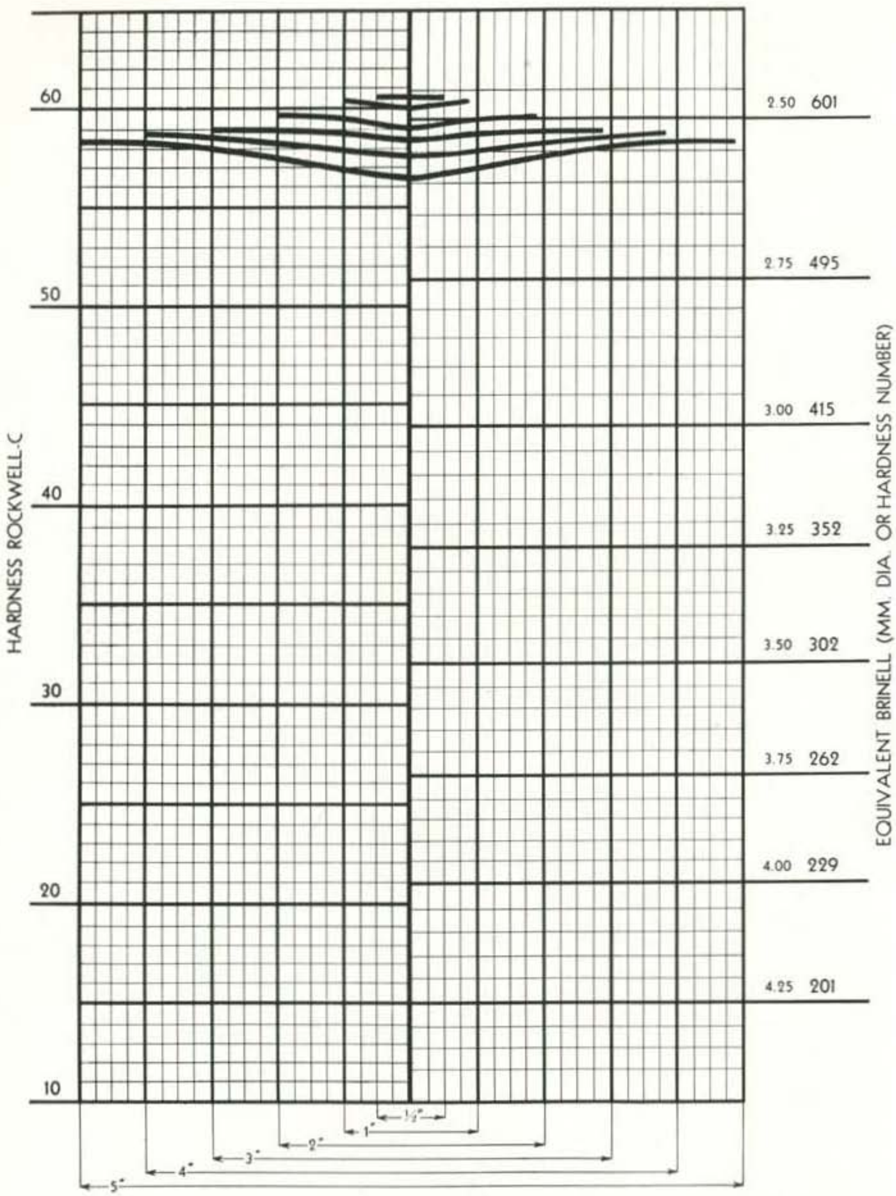


Fig. 20. Hardness distribution in various sizes of quenched round bars. **3340** Steel quenched in ***Water***

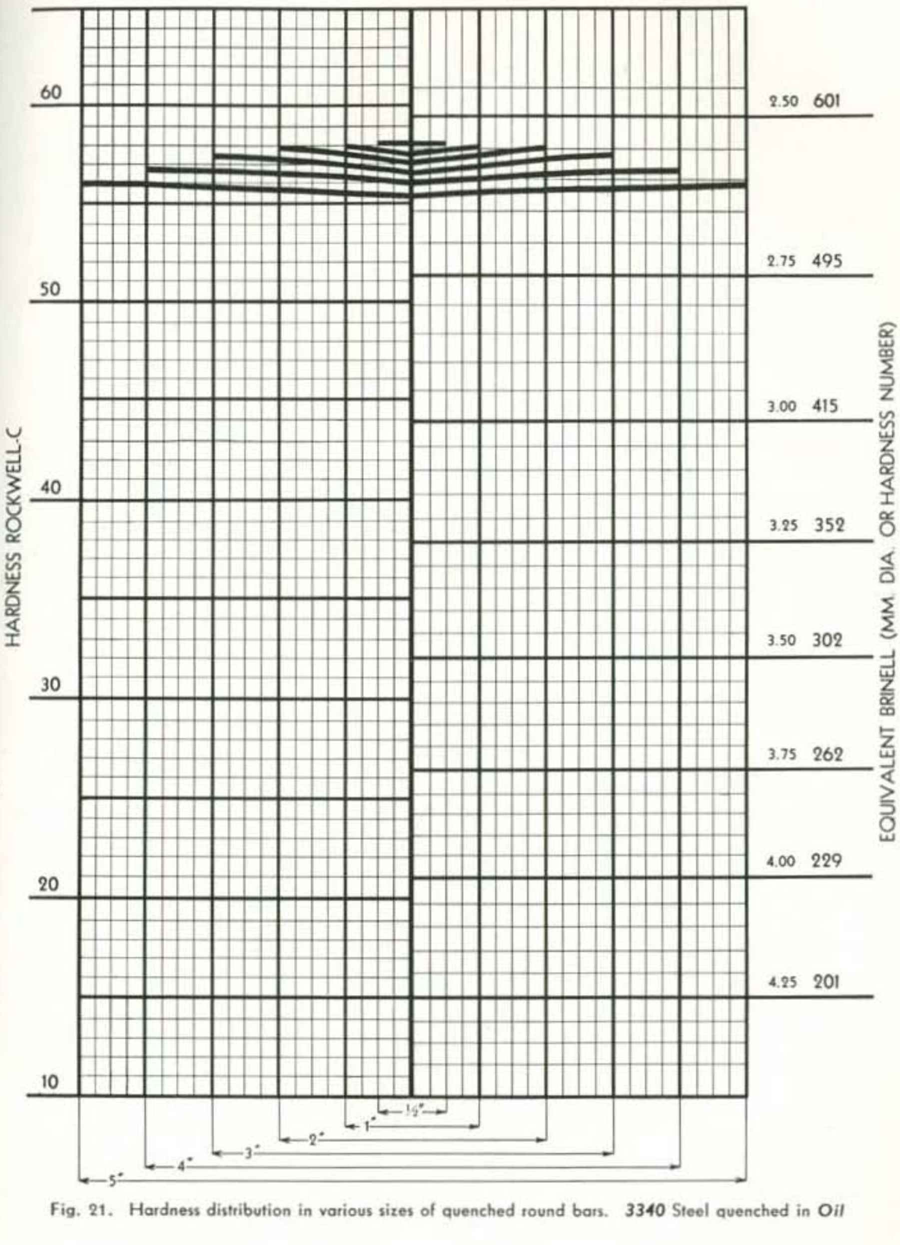


Fig. 21. Hardness distribution in various sizes of quenched round bars. ***3340*** Steel quenched in ***Oil***

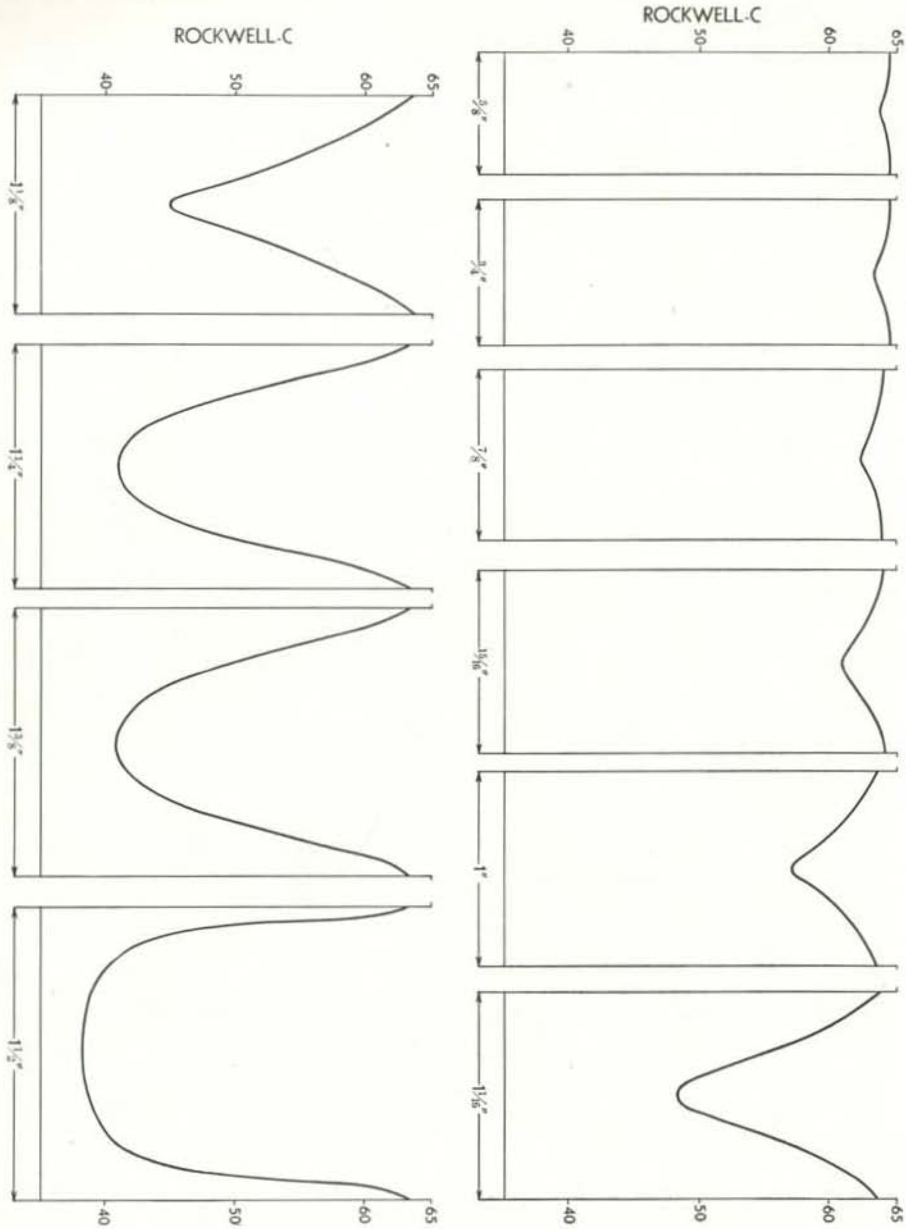

ROCKWELL-C
40
50
60
65
1⅛"
1¼"
1⅜"
1½"
⅝"
¾"
⅞"
15/16"
1"
1 1/16"
ROCKWELL-C
ROCKWELL-C
ROCKWELL-C

Fig. 22.

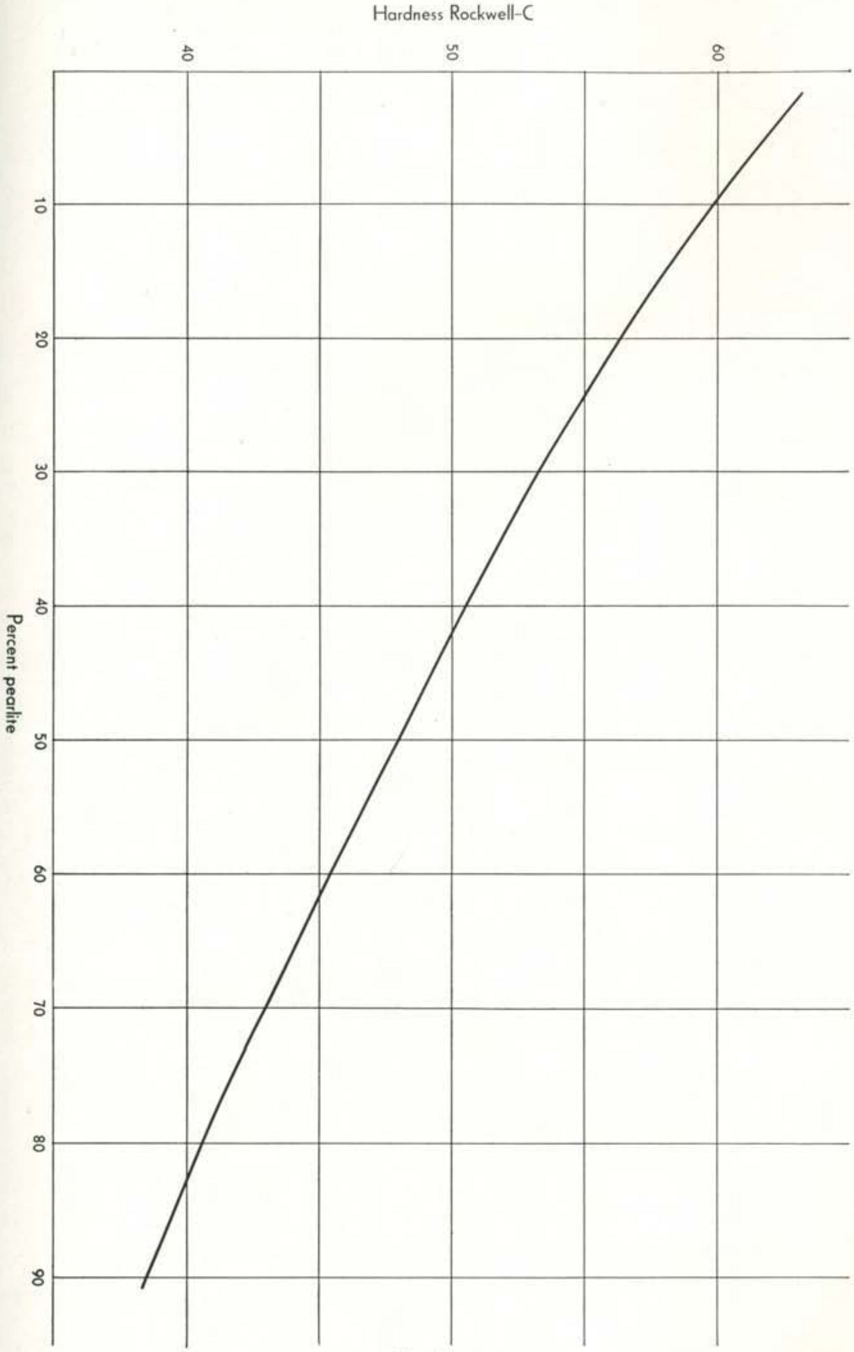

Hardness Rockwell-C
40
50
60
Percent pearlite
10
20
30
40
50
60
70
80
90

Fig. 23.

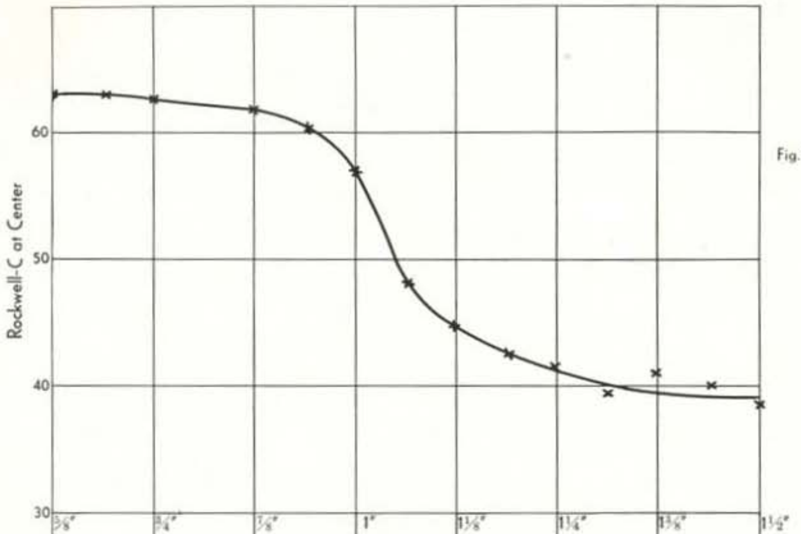

Rockwell-C at Center
60
50
40
30
5/8"
3/4"
7/8"
1"
1 1/8"
1 1/4"
1 3/8"
1 1/2"

Fig. 24

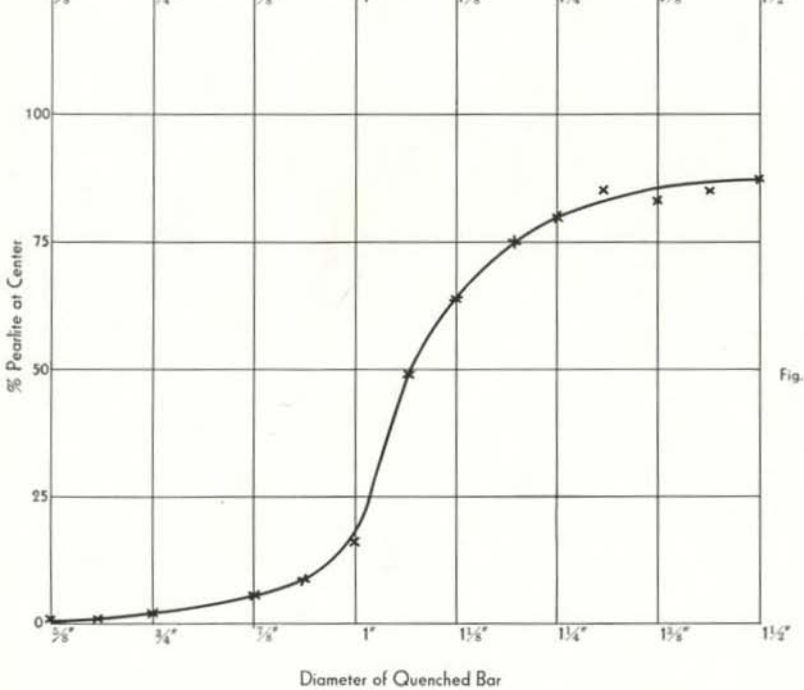

% Pearlite at Center
100
75
50
25
0
5/8"
3/4"
7/8"
1"
1 1/8"
1 1/4"
1 3/8"
1 1/2"
Diameter of Quenched Bar

Fig. 25

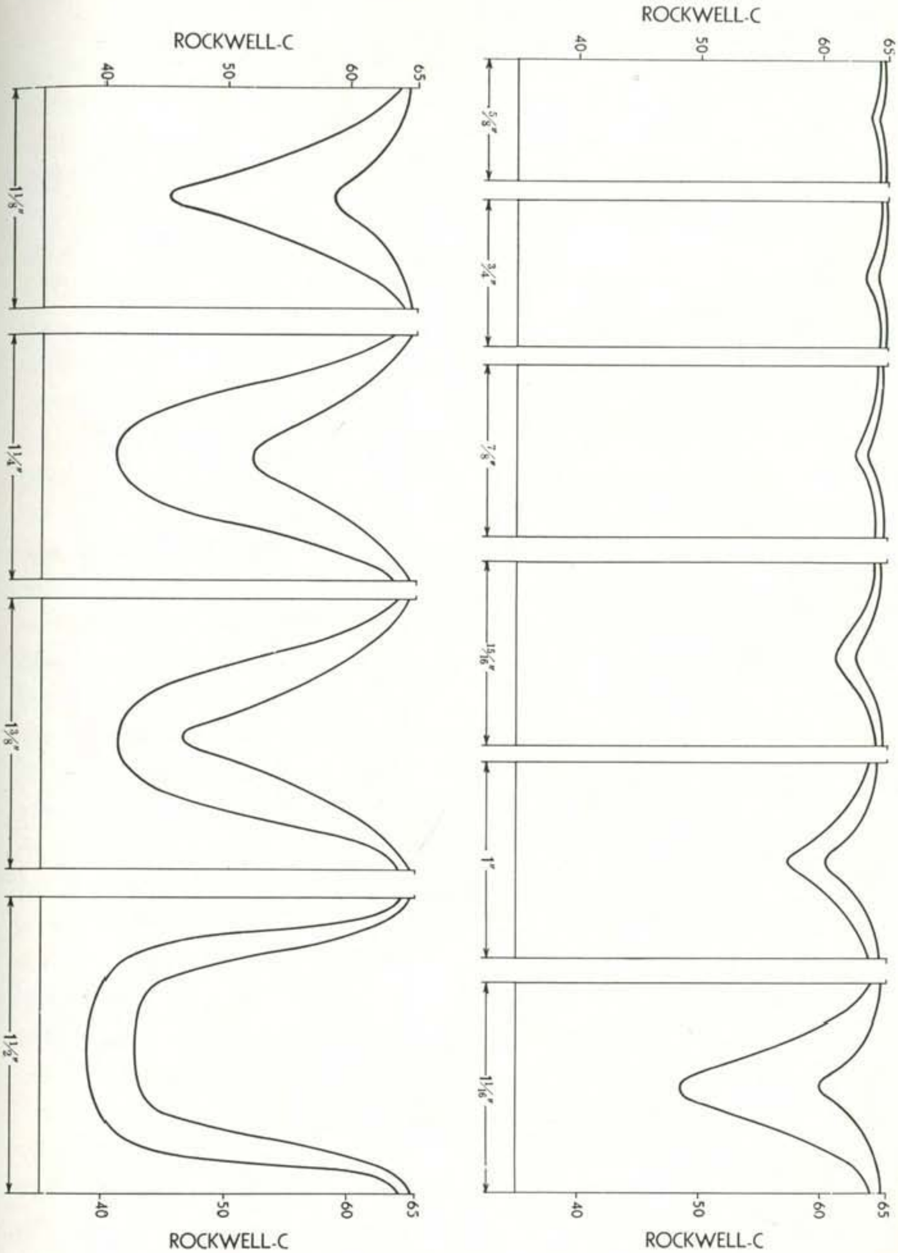

ROCKWELL-C
40
50
60
65
1⅛"
1¼"
1⅜"
1½"
ROCKWELL-C
ROCKWELL-C
⅝"
¾"
⅞"
15/16"
1"
1 1/16"
ROCKWELL-C

Fig. 26.

3. FRACTURE TEST

One widely practiced method of determining hardenability consists in fracturing a hardened piece and observing the "depth of hardening" in relation to the unhardened core. A carefully prepared program based on this system has been used by Shepherd (*), particularly for judging the hardenability of carbon tool steels.

That quenched steels show a "depth of hardening" is due to the following circumstances. When a bar of steel is hardened in such a manner that the outside of the bar is wholly or predominantly martensite, whereas the center of the bar is predominantly pearlite, then the fracture of the piece when broken reveals this condition. The outside of the piece, where the structure is largely martensite, breaks with a brittle fracture around the martensite grains (the facets of the martensite grains indeed show the grain size because of this brittle breaking around the individual grains). The inside of the bar, the unhardened portion, breaks in a more or less ductile manner, so that its appearance contrasts strongly with the brittle break at the outside of the bar. The transition from the hardened rim to the unhardened core is fairly sharp, thus making it possible to read the "depth of hardening." The reason for this sharp transition may be deduced from our previous discussion. It has been pointed out that the change in hardening in the neighborhood of 50% pearlite is very abrupt,—in other words, the change from predominantly martensitic to predominantly pearlitic structure is very marked. ***It is this sudden change from predominantly martensitic to predominantly pearlitic structure which determines the so-called "depth of hardening" in a fracture test,*** because of the change from brittle breaking to ductile breaking. This is illustrated in Fig. 27, which shows the fractures of two pieces of steel, and beneath each fracture photograph is shown the hardness curve taken at the fracture position. It will be seen that the "depth of hardening" corresponds to that depth below the surface where the steel is still predominantly martensite. The inside or unhardened core is relatively soft and is predominantly pearlite.

It is important to note that the hardened rim is not by any means wholly martensite. It ranges from a wholly martensitic structure on the outside to one containing perhaps 30 to 40% pearlite at the inside of the hardened rim.

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*The P-F Characteristic of Steel, by B. F. Shepherd, Trans. of American Society for Metals, pp. 979-1001, December 1934.

Obviously then, a quenched piece may contain 30 to 40% pearlite at the center and still in a fracture will disclose no unhardened core. A fractured piece therefore, in which the fracture indicates that the piece "hardened throughout," discloses only that the piece contained more than 50% martensite. A hardness test or microscopic investigation would be needed to find out whether the piece hardened fully to martensite or was partly pearlite. Thus Fig. 28 shows a fracture which is "hardened throughout," yet the accompanying hardness diagram shows that the piece is not by any means fully hardened.

On this basis then we may discuss the sensitiveness of the fracture test in determining hardenability, on the same basis as we discussed the sensitiveness of the hardness curves. In discussing Fig. 22, it was pointed out that the hardness curves were very sensitive to certain changes in section, but that this specially high sensitiveness occurred only at the sizes where the structures near the center of the quenched bar were in the neighborhood of 50% pearlite. In the same way, and for the same reasons, the "depth of hardening" will vary rapidly as the section is changed in the neighborhood of the same critical size. Likewise it will be less sensitive with change of section in larger sizes.

Furthermore, if hardenability is measured by the "depth of hardening," then differences in hardenability between two heats will be very apparent in the neighborhood of the critical sizes, where the unhardened core is small, but will not be so clear in the fracture test in larger sizes, where the unhardened core is large.

These phenomena explain another behavior which has been encountered frequently in fracture tests of deeper hardening steels. The deeper hardening steels must of course be quenched in rather larger sections to show an unhardened core. In such large sections the hardness penetration curve is not so steep as in shallow-hardening steels, ***particularly when the unhardened core is small.*** That is to say, the gradation from predominantly martensitic to predominantly pearlitic structure is more gradual. As a result, the boundary of the unhardened core is difficult to judge,—it is difficult to read the depth of hardening. The depth of hardening will be rather easier to read if the size of section is increased slightly, as this will result in a somewhat steeper hardness gradient (a sharper transition from predominantly martensitic to predominantly pearlitic).

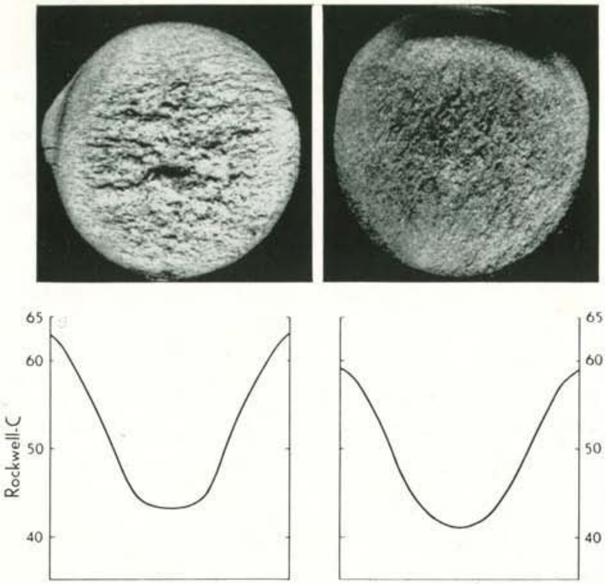


Fig. 27.
Hardness gradients on pieces showing unhardened cores.

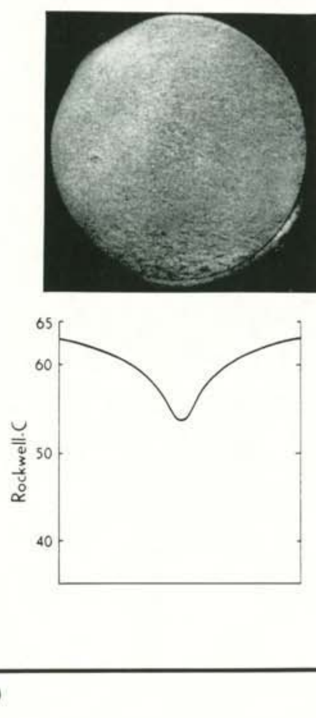


Fig. 28.
Hardness gradient showing that even when a fracture is free of any unhardened core, the piece may still be incompletely hardened.

4. MICROSTRUCTURE

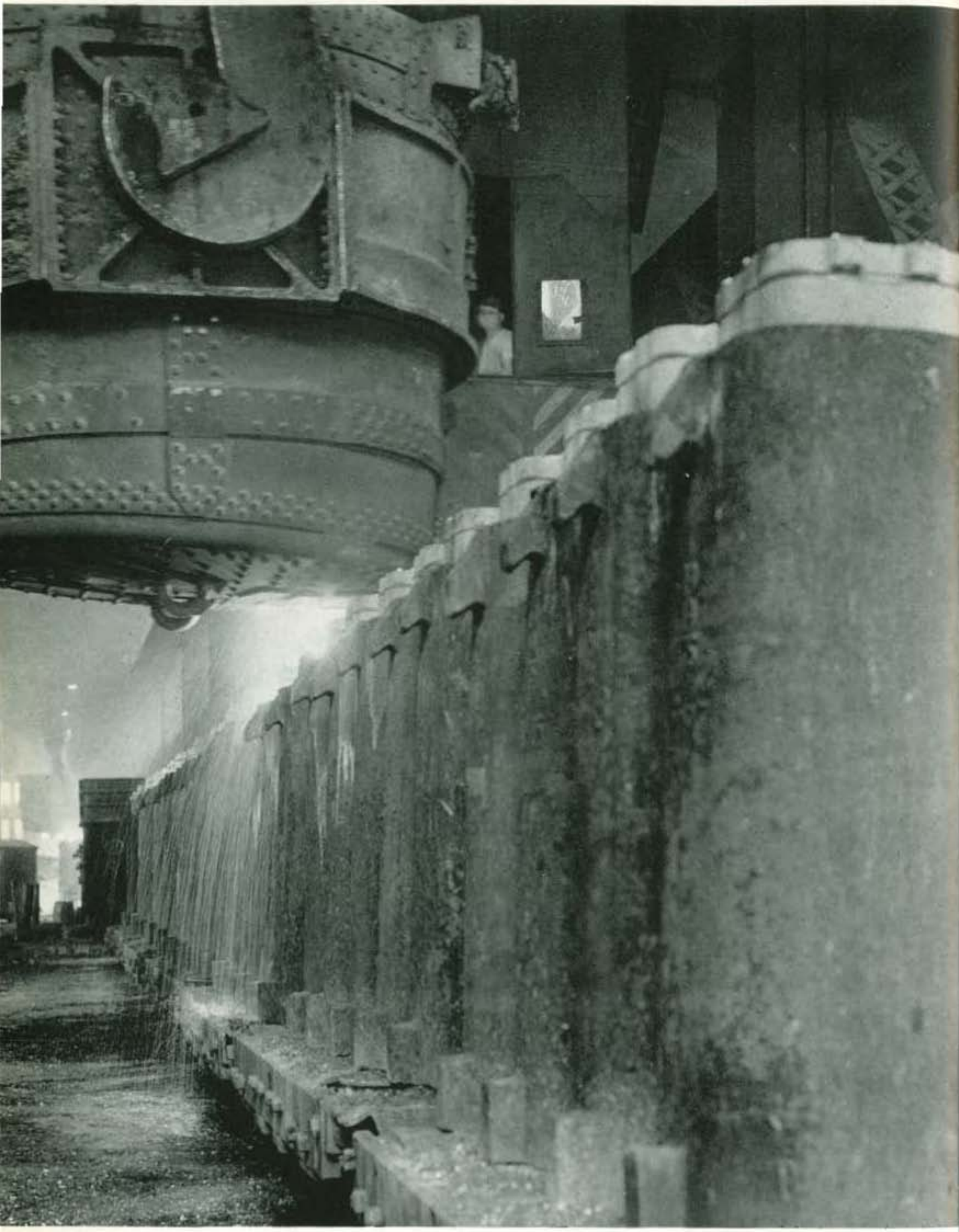
Another common test for judging the hardening of a piece of steel is to examine its microstructure. As discussed previously, the hardness of pieces which are almost fully hardened is influenced in a regular manner by the proportion of pearlite present. The relationship is illustrated in Fig. 23. The previous discussion of the hardness gradient is valid whether the hardening be judged by the Rockwell hardness or by the proportion of pearlite which is present, see Figs. 24 and 25.

5. Ar POINT IN A COOLING CURVE

The hardenability of steel has on occasion been judged by observing the temperature of the Ar_1 point when a sample of the steel is cooled in air. It will be evident from the discussion under the "S-curve" (which see) that this is a perfectly valid method of judging hardenability provided the steels are of the same general composition, and provided further that the samples are of such size and the steel of such hardenability that the sample transforms completely to pearlite in the test.

This may be illustrated by referring to Fig. 11, which shows a single steel, which is caused to have different hardenabilities by introducing differences in austenite grain size. The samples having higher hardenability are toward the right of Fig. 11, and it is evident that any particular cooling curve would meet the hardenability curve at a lower temperature in the curves at the right than in the curves toward the left. Tests have shown that differences in hardenability may be judged quite accurately by this method, the hardenability being greater as the Ar_1 point is lower.

The necessity for restricting such comparisons to a single grade of steel arises from the fact that different alloys may cause the S-curve to shift vertically (that is, in temperature) as well as horizontally (that is, in time). The Ar_1 method would obviously lead to confusion if used to compare different grades of steel having different true critical temperatures, whose temperatures of transformation might therefore be different without differences in hardenability.



Pouring

GRAIN SIZE IN STEEL

The study of grain size in hardened steels has extended over many years, beginning with tool steels and extending in recent years to almost all other grades.

The tool steels were the first hardened steels where quality was studied carefully, and it is not surprising to find that it was in this field that studies of grain size began. The observation must have been made very long ago that coarse-grained fractures in tool steels were more brittle than fine-grained ones. In the early days, it is true, it was not recognized that grain size itself was a determining factor. When a piece of tool steel had been hardened properly so that it gave good performance in service, the early metal workers found that the tool, if broken, gave a fracture appearance which they described as "tough" (it would today be called "fine-grained," or perhaps "silky"). When it had been overheated so as to be brittle, the fracture appearance was generally called "dry" (today called "coarse"). It must have been observations such as these which led to avoidance of overheating in heat treatment. Such observations must be at least half a century old, and perhaps many centuries.

The knowledge is, however, not so old that the fracture grain size of the hardened piece is subject to control because it reflects quite accurately the prior austenite grain size (the size of the austenite grains which composed the piece at the moment of quenching). This relationship first became known in the case of high speed steels, probably because it was easy to observe the prior austenite grain size in these steels in the microscope after the quenching operation (in the hardened state). That the prior austenite grain size governs the fracture grain size of other hardened steels has been proven only recently.

In 1922[1] attention was called to the importance of grain size in connection with an entirely different property of steel—not toughness but hardenability. McQuaid and Ehn showed that when pieces of low-carbon steel were carburized and quenched, their hardening behavior upon quenching correlated well with certain characteristics seen in the microscope. More specifically, if two pieces of the same steel were carburized, and one of these pieces was cooled slowly from the carburizing and then observed in the microscope, while the

[1] H. W. McQuaid and E. W. Ehn, Trans., American Institute Mining and Metallurgical Engineers, Vol. 67, 1922, p. 341-391.

companion carburized piece was quenched, the following correlation was observed. If the microstructure of the slowly-cooled piece showed coarse (and "normal") grains, then the quenched piece was likely to be hard, free of soft spots. If on the other hand the slowly-cooled piece showed a fine-grained (and "abnormal") structure, then the quenched piece was likely to show some unhardened areas. Since then ([2]) it has been shown that the grain size is the important factor in the hardenability, and further that the grain size itself influences the abnormality; that is, steels of the same composition tend to be more abnormal the finer the grain size. Through the above correlation of coarse grain size and hardenability, it has come about that coarse-grained steels are employed where the hardenability which they supply is needed.

The McQuaid-Ehn carburizing test achieved prominence quickly, and in a few years standard grain size charts were developed. These charts were subsequently made the subject of a standard issued by the American Society for Testing Materials, listing a series of grain sizes from No. 1, coarse, to No. 8, fine. The range of sizes in the A. S. T. M. chart has found wide application, since it covers in a convenient manner practically all the grain sizes commonly encountered in practice. This same range of sizes is therefore employed in the Grain Size Chart which will be found in the envelope accompanying this book and which is described later on in this article. (The new Chart shows grain ***outlines only***, since the sizes may be used not only for carburized structures but for other methods of determining grain size as well.)

Presently this same carburizing test came to be applied to steels that were not to be carburized, but were to be hardened directly by quenching. It was also found that other properties (in addition to hardenability) showed some correlation with the McQuaid-Ehn grain size. During the past few years however, it has come to be recognized that the determination of austenitic grain size is not by any means restricted to the carburizing procedure, and that it is often advantageous to use other methods. These will be discussed here, after the following discussion of some of the fundamentals of grain coarsening.

1. THE COARSENING TEMPERATURE

To arrive at an understanding of a grain size test, one may follow the

[2] E. C. Bain, "Factors Affecting the Inherent Hardenability of Steel," Trans., American Society for Steel Treating, Vol. XX, No. 5, 1932, p. 385.

changes in a piece of steel while it is being heated. The steel chosen here is a plain-carbon steel of the following composition:

C.	Mn.	P.	S.	Si.
.15	.44	.015	.019	.22

Before heating, it has the structure shown at 100 diameters in Fig. 29. As its temperature rises, its structure remains the same until it reaches its lower critical or Ac_1 temperature, at which moment it begins to transform to austenite. The transformation process continues through the critical temperature range, to the Ac_3 or upper critical temperature. Fig. 30 shows the grain size just beyond the Ac_3 point when the steel has entirely transformed to austenite. It is seen that the austenite grains have an appreciable and measurable size, in this case about No. 6 on the A. S. T. M. grain size chart.

The sample of Fig. 30 was quenched from the heating temperature, so that what were austenite regions at high temperature are now martensite. A small amount of ferrite is precipitated in the original austenite grain boundaries, thus outlining the original austenite grains. Ample proof is available that the austenite grain size is as indicated.

It is also possible to use the carburizing method, as in the McQuaid-Ehn test, where sufficient carbon is introduced (usually about 1.20% at the surface) so that when the steel is cooled slowly the austenite grains will be outlined by the carbide which precipitates in the grain boundaries in cooling. In the remaining tests of this particular series, the grain size is tested by the carburizing method.

There are many steels in which the carburized grain size differs from that of the uncarburized material. The carburized case is often finer than the uncarburized core, and in some instances it is coarser than the core.

The Ac_3 temperature, at which the steel has just transformed to austenite, is in the present steel about 1575° F. If the steel is now heated further, it is found that coarsening does not begin immediately. There is a small temperature range in which the grain size remains substantially constant.

The steel remains at No. 6 grain size from the moment it transformed to austenite at 1575°, through its heating to 1600° and slightly higher. But if the steel is now carburized at a higher temperature, namely 1675° F., we find that it begins to coarsen in certain isolated regions, with the appearance shown in Fig. 31. A certain amount of the area has coarsened, although the majority of the grains are still at their original grain size of No. 6, giving the "duplex" appearance shown. At a still higher temperature, in this case 1700°, the grains have coarsened almost entirely, and we find in Fig. 32 a grain size consisting of about 85% No. 1 (or No. 0, extending the grain size numbers)

Fig. 29. Grain size test showing structure before heating

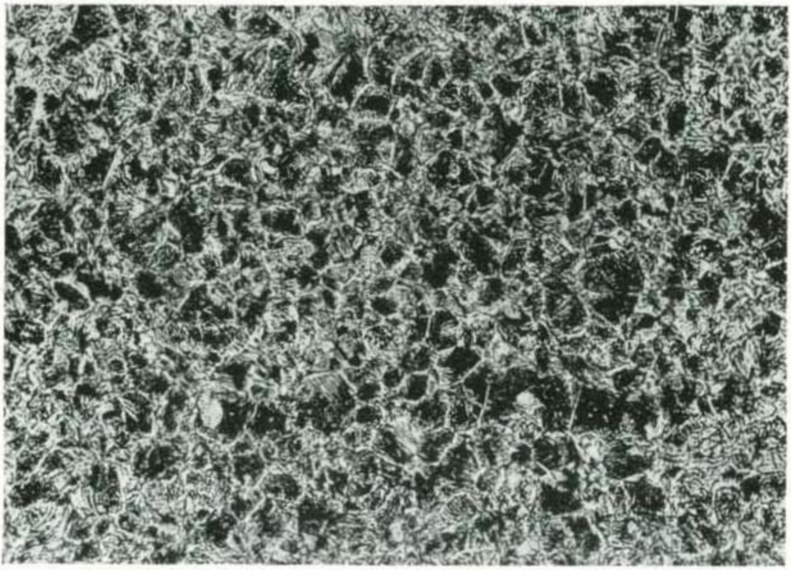


Fig. 30. Grain size test showing grain size just above upper critical temperature

and about 15% No. 6. At still higher carburizing temperatures the last of the No. 6 grains will disappear and the steel will be coarsened entirely. The "coarsening temperature" may in this case be considered to be around 1650°, and is the temperature at which coarsening just began. The grain size prior to coarsening—that is, the size of the austenite grains formed when the steel first transformed to austenite—may for convenience be called the "initial austenite grain size."

If we now consider the results of the carburizing at 1700°, and realize that this constitutes the McQuaid-Ehn test, we obtain a clear picture of what the McQuaid-Ehn test disclosed about this steel; namely that the initial austenite grains coarsened, and that the coarsening temperature was comparatively low, so that when the steel had been heated for 8 hours at 1700° F., the grains had coarsened almost completely.

That the initial austenite grains, as just shown, could remain stable over the small temperature range 1575° to 1650° is perhaps readily conceivable, but there are many steels in which the initial austenite grains remain at constant size to very much higher temperatures. Thus, there are many steels which, after they have attained their "initial austenite grain size" at say 1575° F., remain at this same grain size up to temperatures of 1800° F. and sometimes even 1900° F. and higher. Such steels will of course, when subjected to a McQuaid-Ehn test at 1700° F., exhibit their relatively fine initial austenite grain size. However, the 1700° test obviously affords no information as to the temperature at which coarsening will ultimately set in.

Thus we may summarize what is disclosed about grain size in a McQuaid-Ehn test. ***The McQuaid-Ehn carburizing test shows whether the temperature of 1700° F. is above or below the coarsening temperature of the grains in the carburized case.***

It should be mentioned that the sudden or "exaggerated" coarsening described here is characteristic of the relatively low-carbon steels (say under 0.50% carbon) and is also found often in the higher carbon steels. However, some steels appear to coarsen more gradually. Also, in conducting coarsening tests, a short heating time such as 30 minutes may be insufficient for the development of exaggerated coarsening which might take place, with prolonged heating, at that temperature if the steel is just entering the coarsening range.

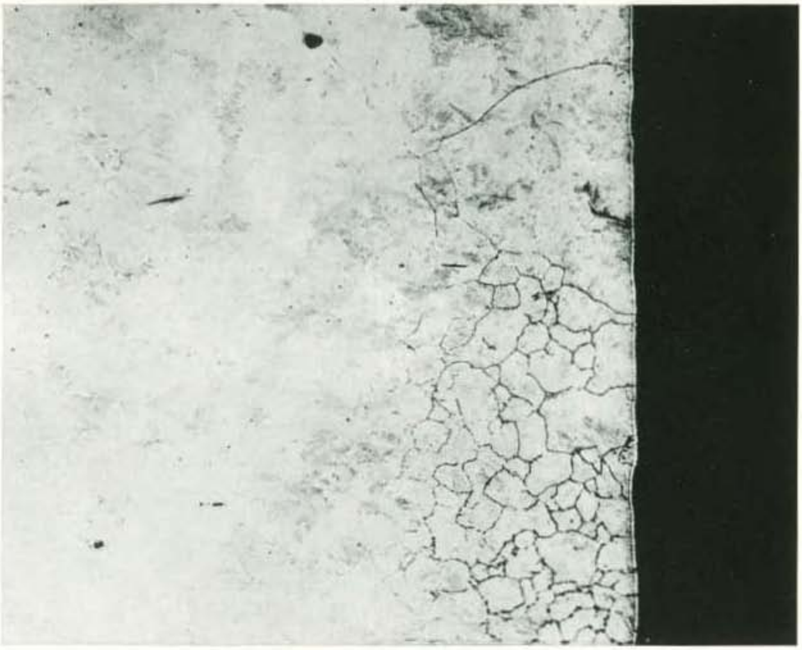


Fig. 31. Structure of the steel of Figs. 29 and 30 after carburizing for 8 hours at 1675° F. Sodium picrate etch. X100

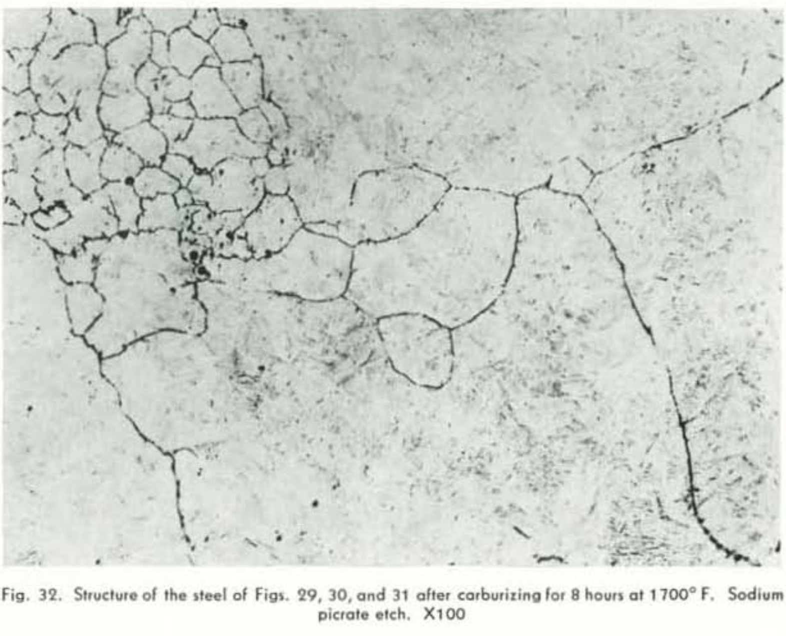


Fig. 32. Structure of the steel of Figs. 29, 30, and 31 after carburizing for 8 hours at 1700° F. Sodium picrate etch. X100

2. LOWERING THE COARSENING TEMPERATURE BY NORMALIZING

A study of the coarsening temperature assumes further importance when it is found that this coarsening temperature may be changed by heat treatment, and also by hot-working or by cold-working.

It is true that the effects of the melting process in establishing a coarsening temperature are much more far-reaching than any subsequent changes of it induced by treatment. Thus it is well known that the addition of aluminum to molten steel affects austenite "grain sizes." Depending upon the amount added, and the condition of the molten steel, the coarsening temperature may be raised from below 1600° F. to well above 1750° F. by the judicious use of aluminum. At the same time, once the general behavior has been set by the melting process, then the subsequent treatment of the solid steel may change the coarsening temperature by as much as 100° or even up to 200° F.

A striking example of such behavior is shown in Figs. 33 and 34. A carburizing grade of steel was subjected to a McQuaid-Ehn test, and its grain size was as shown in Fig. 33. A piece of the same steel was normalized and was then subjected to a McQuaid-Ehn test (after the normalizing). Its structure after this second treatment is shown in Fig. 34. It is clear that the specimen of Fig. 33 retained its initial austenite grain size when carburized at 1700° F. for 8 hours, but when normalized the initial austenite grain size coarsened when subjected to a similar treatment. In other words, in the case of Fig. 33, the specimen at 1700° had not yet reached its coarsening temperature, whereas the specimen in Fig. 34 had exceeded its coarsening temperature so that the grains became coarse. In still other words, the normalizing had lowered the coarsening temperature from somewhere above 1700° to somewhere below 1700°.

It will of course be realized that a 1700° (McQuaid-Ehn) test does not always reveal whether the coarsening temperature has been lowered, as it did in Figs. 33 and 34. If the coarsening temperature had been lowered for example from 1800° to 1725°, then a test at 1700° would obviously not have disclosed it. Neither would a 1700° test have disclosed a lowering of the coarsening temperature from 1650° to 1600°.

It is common to find that a normalizing will lower the coarsening temperature by 75° to 100° F. The amount of lowering varies with different steels.

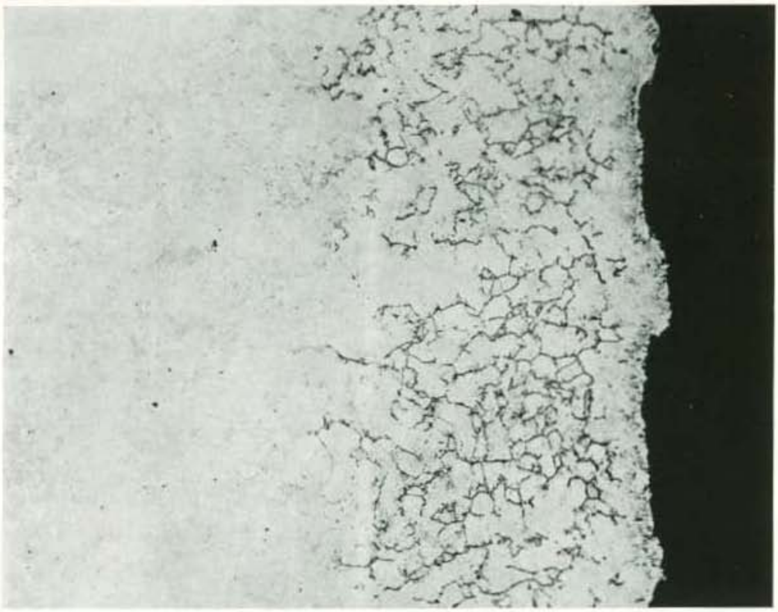


Fig. 33. McQuaid-Ehn test on a steel before normalizing. See Fig. 34. X100

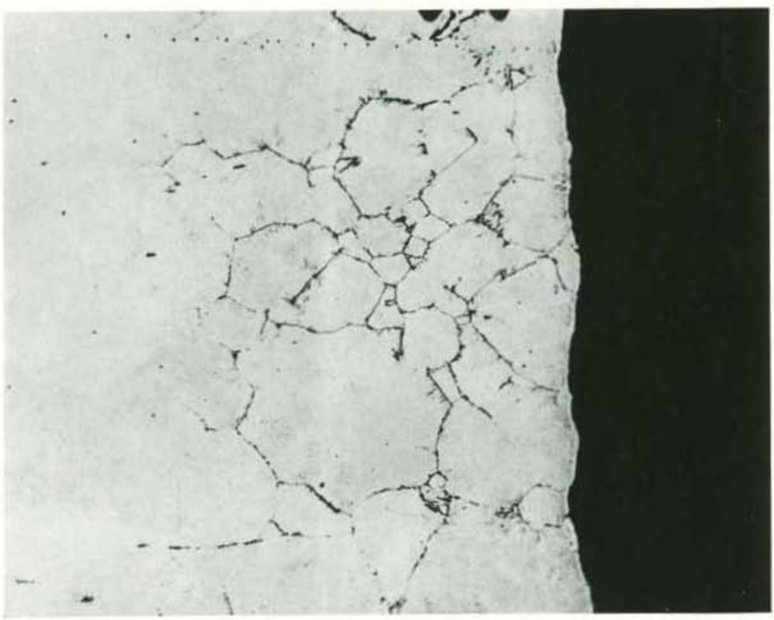


Fig. 34. McQuaid-Ehn test on the same steel as Fig. 33, but after normalizing. X100

3. DIFFERENT NORMALIZING TEMPERATURES AFFECT THE COARSENING TEMPERATURE DIFFERENTLY

It is found that different normalizing temperatures affect the coarsening temperature differently, but that the normalizing temperature must be changed markedly to cause appreciable differences. Data are scarcely available to give very precise figures for all steels and over a wide range of temperatures, but the following general statement may be made.

In fine-grained steels, that is to say in steels in which the coarsening temperature is high, normalizing will usually lower the coarsening temperature 75° or 100°. This refers to normalizing at customary normalizing temperatures, say in the range 1600° to 1700°. As the normalizing temperature is raised, the subsequent coarsening temperature will not be lowered so much. After a normalizing from perhaps 1800°, the coarsening temperature may only be lowered 50°. If the normalizing temperature is around 1900° to 2000°, the subsequent coarsening temperature is not likely to be lowered much, if at all. Indeed, steels vary in their response to normalizing in this particular range of temperatures, so that some will have their coarsening temperatures lowered while others will have theirs raised. With extremely high normalizing temperatures, such as 2100 to 2300° F., the coarsening temperature is apt to be raised slightly.

4. LOWERING THE COARSENING TEMPERATURE BY HEAT TREATMENTS OTHER THAN THE NORMALIZING

Since heating to 1600° F. and cooling in ***air*** will lower the coarsening temperature, a question arises as to the effect of ***other*** rates of cooling. It has been found that all of the common rates of cooling cause the coarsening temperature to be lowered, though not precisely in the same manner nor to the same degree. Slow cooling, namely heating to 1600° and cooling in the furnace, lowers the coarsening temperature a little, but not nearly so much as when the piece is cooled in air. When the piece is cooled in air there may be variations even here, if the size of the piece is varied. That is to say, if the piece is large and therefore cools slowly in air, the coarsening temperature will indeed be lowered, but if the piece is quite small, so that it cools more rapidly, then the coarsening temperature is lowered even more.

With still more rapid cooling, as when being quenched in oil, the coarsening temperature is likewise lowered, but there may be anomalies here, since cases have been observed where a cooling in oil caused a lesser lowering of the coarsening temperature than when the piece was cooled in air.

If the piece is cooled still more rapidly, as by being quenched in water, the coarsening temperature is likewise lowered. Here however there may be still further anomalies. In some cases it is found that the coarsening temperature is lowered in a manner quite analogous to the effect of normalizing. In other cases, and these have been observed not infrequently, an additional effect is observed. Not only is the coarsening temperature lowered, but the manner of coarsening may change from the mechanism of sudden coarsening to the other mechanism of rather uniform coarsening.

The effects of various rates of cooling, just described, apply when the temperature of heating was in the neighborhood of 1600° F. When the heating temperature is higher, in the range 1700 to 2300°, it will be understood that the effects will be different, in accordance with the previous description of effect of heating temperature before normalizing.

5. ESTIMATION OF GRAIN SIZE BY A VARIETY OF METHODS

(1) Microscopic examination. Austenite grain size is revealed under the microscope if a constituent precipitates in the grain boundaries of the austenite. This principle governs most of the methods for microscopic examination of austenite grain size. Thus high-carbon steels, for example over 1.10% carbon, when cooled from the austenitic state, precipitate carbide in the grain boundaries. This principle was the one applied by McQuaid and Ehn, when in 1922 they introduced the carburizing test, since the carbon content of their steels was raised sufficiently so that carbide precipitated in the austenite grain boundaries upon slow cooling. In lower carbon steels, the austenite grains may be outlined by ferrite. Thus steels in the range .45 to .65% carbon will, when cooled slowly from the austenite range, have ferrite precipitated in the former austenite grain boundaries and will thus show the size of the austenite grains. In 1933[3] the precipitation of ferrite was applied to still lower carbon

[3] M. A. Grossmann, "On Grain-Size and Grain-Growth," Trans., American Society for Steel Treating, Vol. XXI, No. 12, 1933, p. 1079.

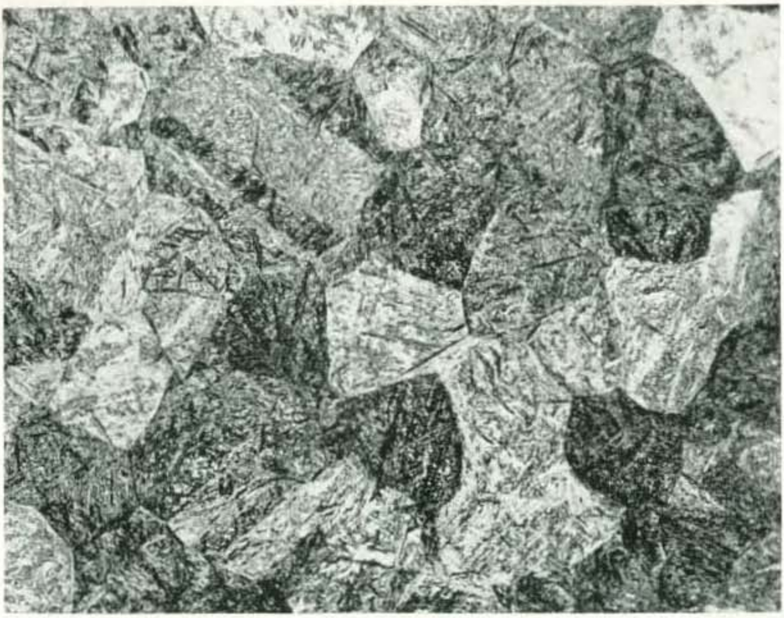
steels, by employing interrupted cooling. In 1934, Davenport and Bain[4] described an additional method, based on the fact that when steels are not quite hardened, the first precipitation of fine pearlite will be found in the martensite (prior austenite) grain boundaries. Still more recently, Vilella and Bain[5] have described an etching reagent for revealing the grain size of steels fully hardened to martensite, as illustrated in Figs. 35 and 36.

It thus becomes apparent that a variety of techniques may be employed for ascertaining austenite grain size microscopically. Whether it be a carburizing procedure, a simple heating and cooling, or a quenching, the structure will show the size of the austenite grains which existed at the high temperature and after the time employed. The chart at the back of this book shows a series of grain sizes which may serve as a standard for any of the microscopic methods of studying austenite grain size. For facility in comparison, the chart shows both light grains with dark borders and dark grains with light borders. The sizes are numbered to correspond with the standard grain sizes of the American Society for Testing Materials. The large chart is also reproduced in sections on individual pages herewith.

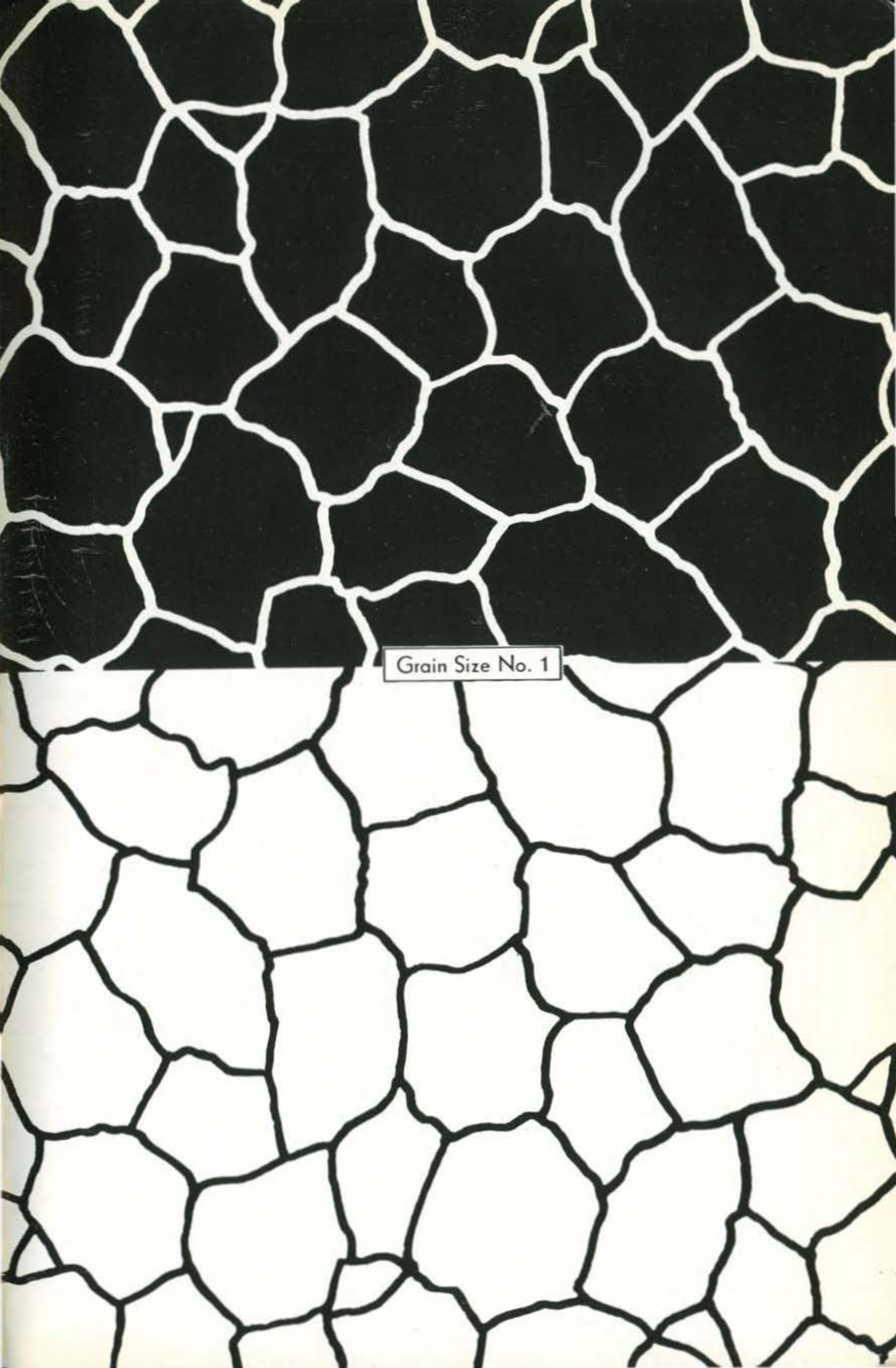
(2) Fracture Method. Mention has already been made of the early examination of tool steels for their fracture appearance. The fractures were rated on the basis of an appearance which depended on grain size (although the relation to prior austenite grain size was not at first appreciated). Fracture grain sizes have more recently been carefully standardized and sets of reference standards prepared, to afford ready comparison with fractured bars. B. F. Shepherd has prepared and issued such sets of standards. The fracture grain sizes have been described in a number of articles by Shepherd[6] and have been used regularly by him and others in determining the fracture characteristics of steels.

The relation between austenite grain size and fracture grain size was recognized in high speed steel many years ago. It is only quite recently however that this relationship was recognized and demonstrated by Vilella and Bain[5] for plain-carbon and low-alloy steels. Their work shows that over the range of grain sizes determined by fracture, the Shepherd standards coincide substantially with the grain sizes judged microscopically and rated by the A. S. T. M. chart.

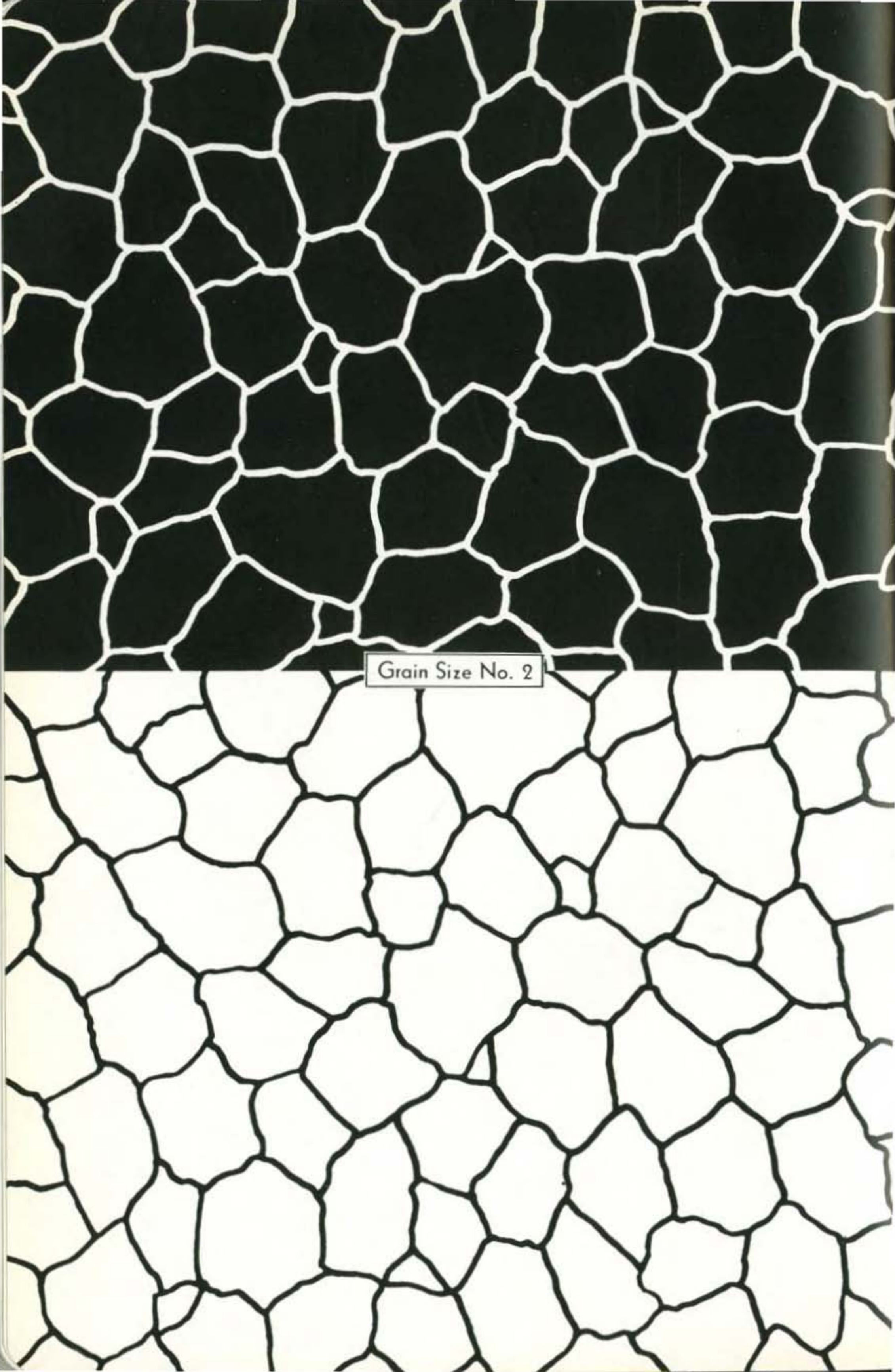
[4] E. S. Davenport and E. C. Bain, "General Relations Between Grain-Size and Hardenability and the Normality of Steels," Trans., American Society for Metals, Vol. XXII, No. 10, 1934, p. 879.
[5] J. R. Vilella and E. C. Bain, "Methods of Revealing Austenite Grain-Size," Metal Progress, Sept. 1936, p. 39.
[6] B. F. Shepherd, "The P-F Characteristic of Steel," Trans., American Society for Metals, Vol. 22, 1934, p. 979



Grain size by etching of fully hardened martensite
Fig. 35, Above. Grain size No. 2
Fig. 36, Below. Grain size No. 4



Grain Size No. 1



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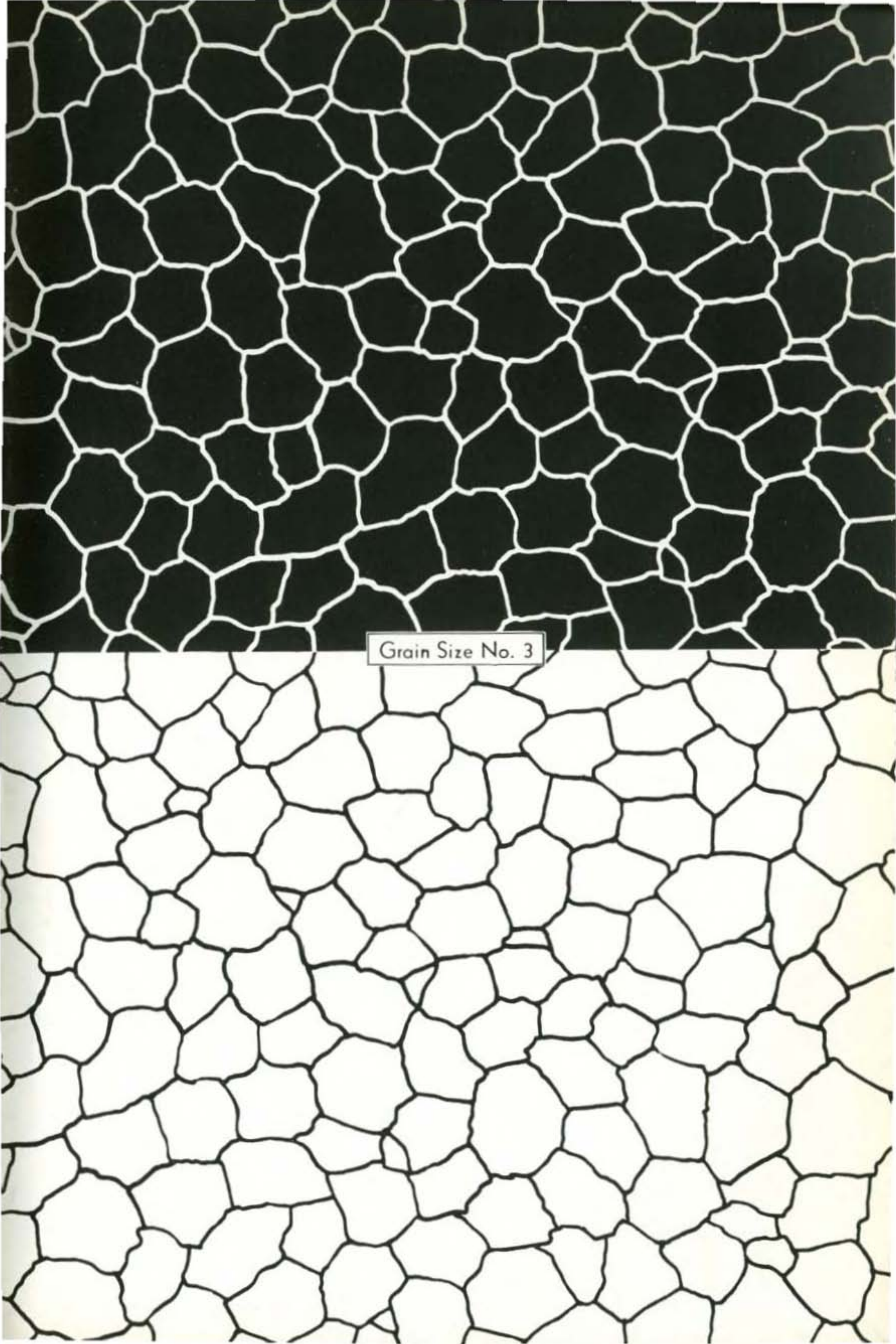
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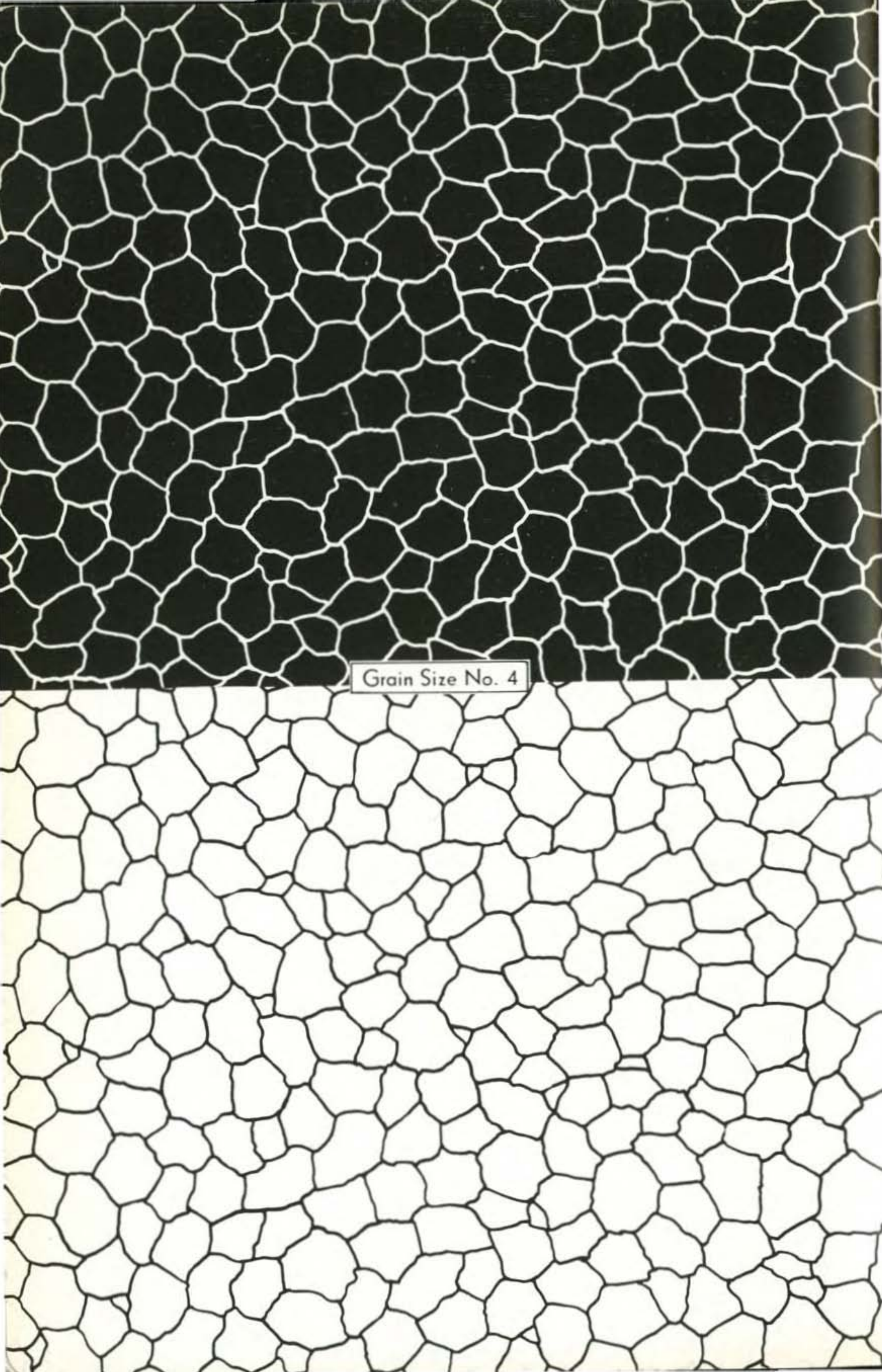
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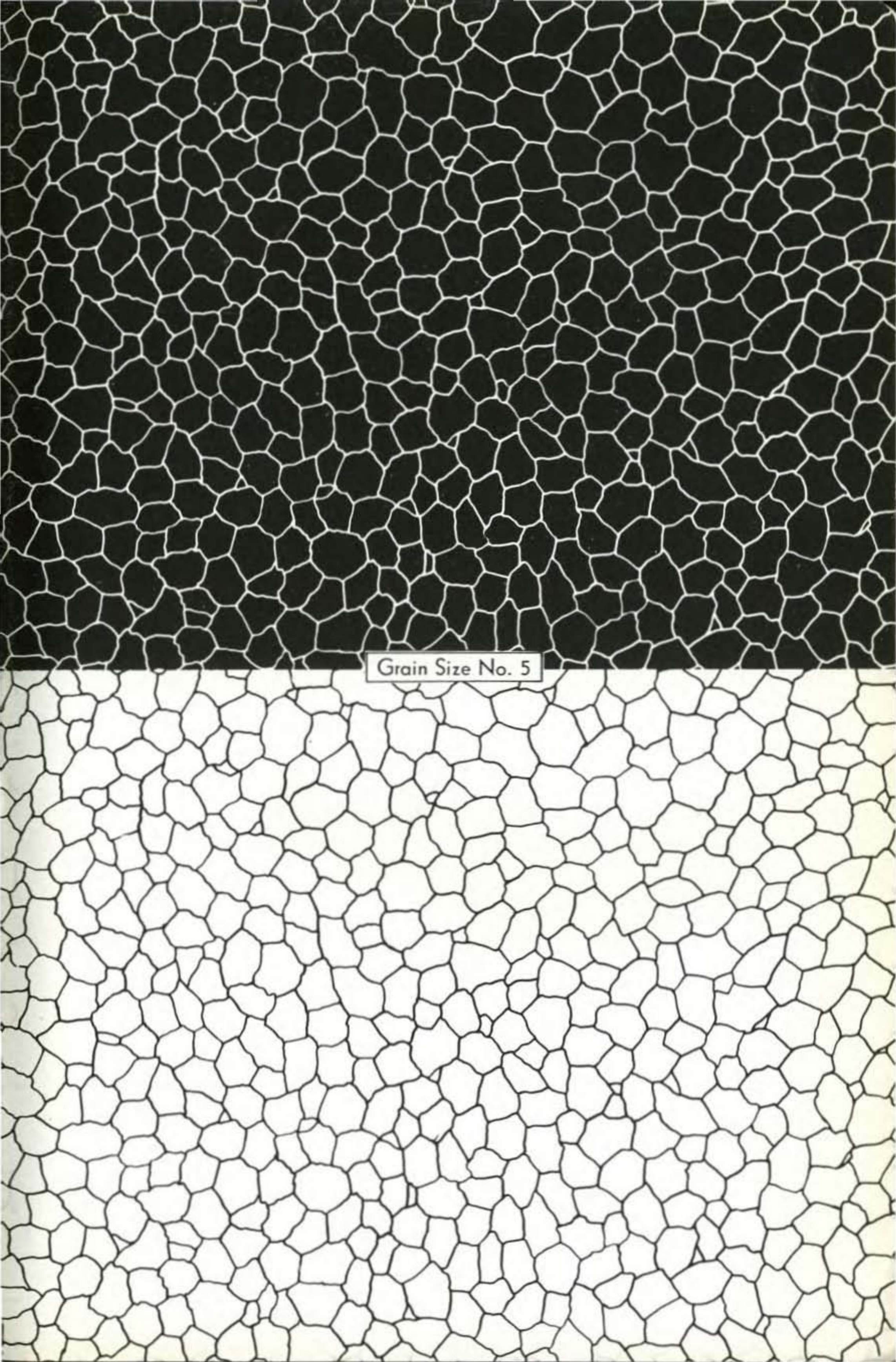

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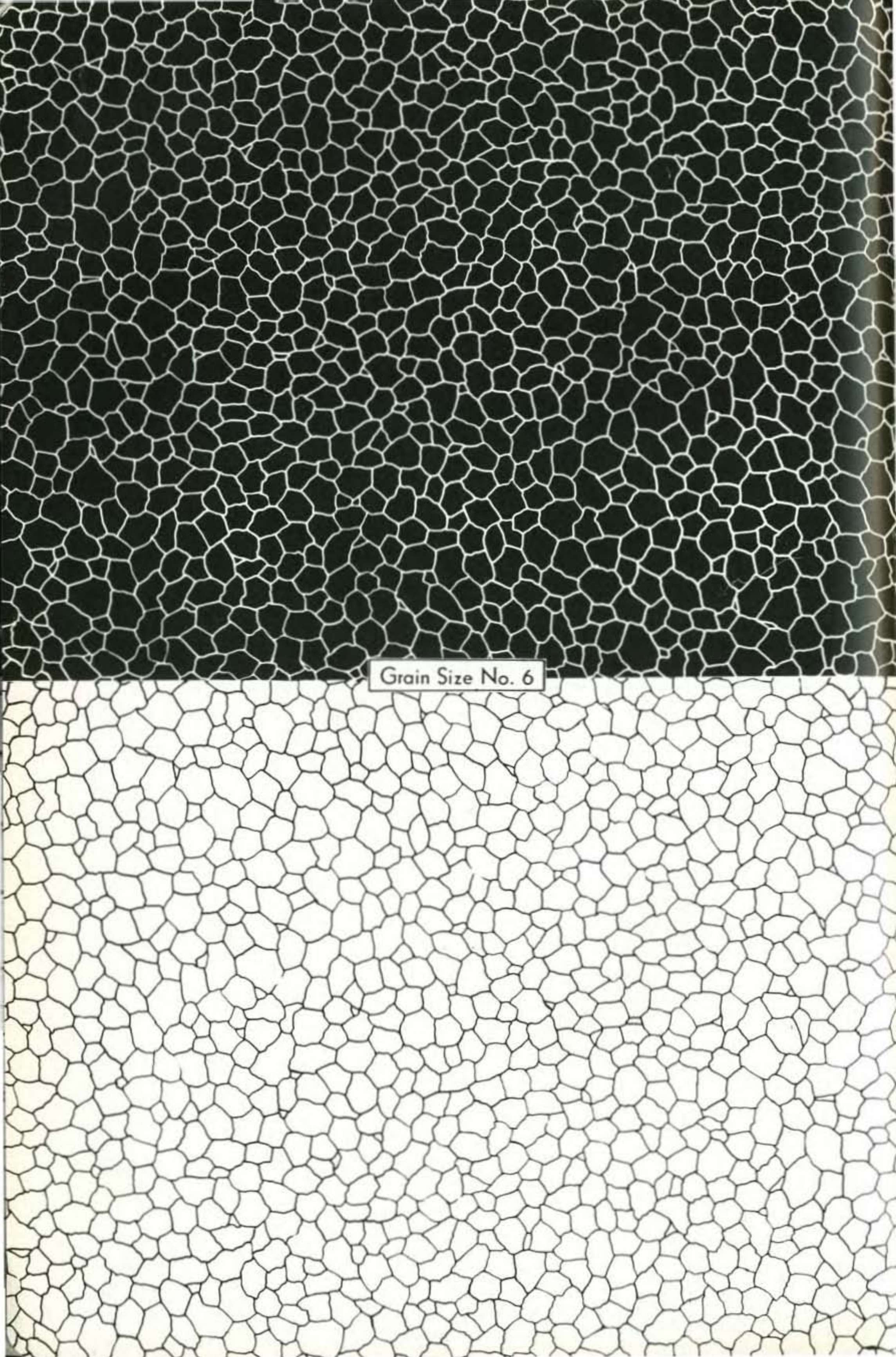

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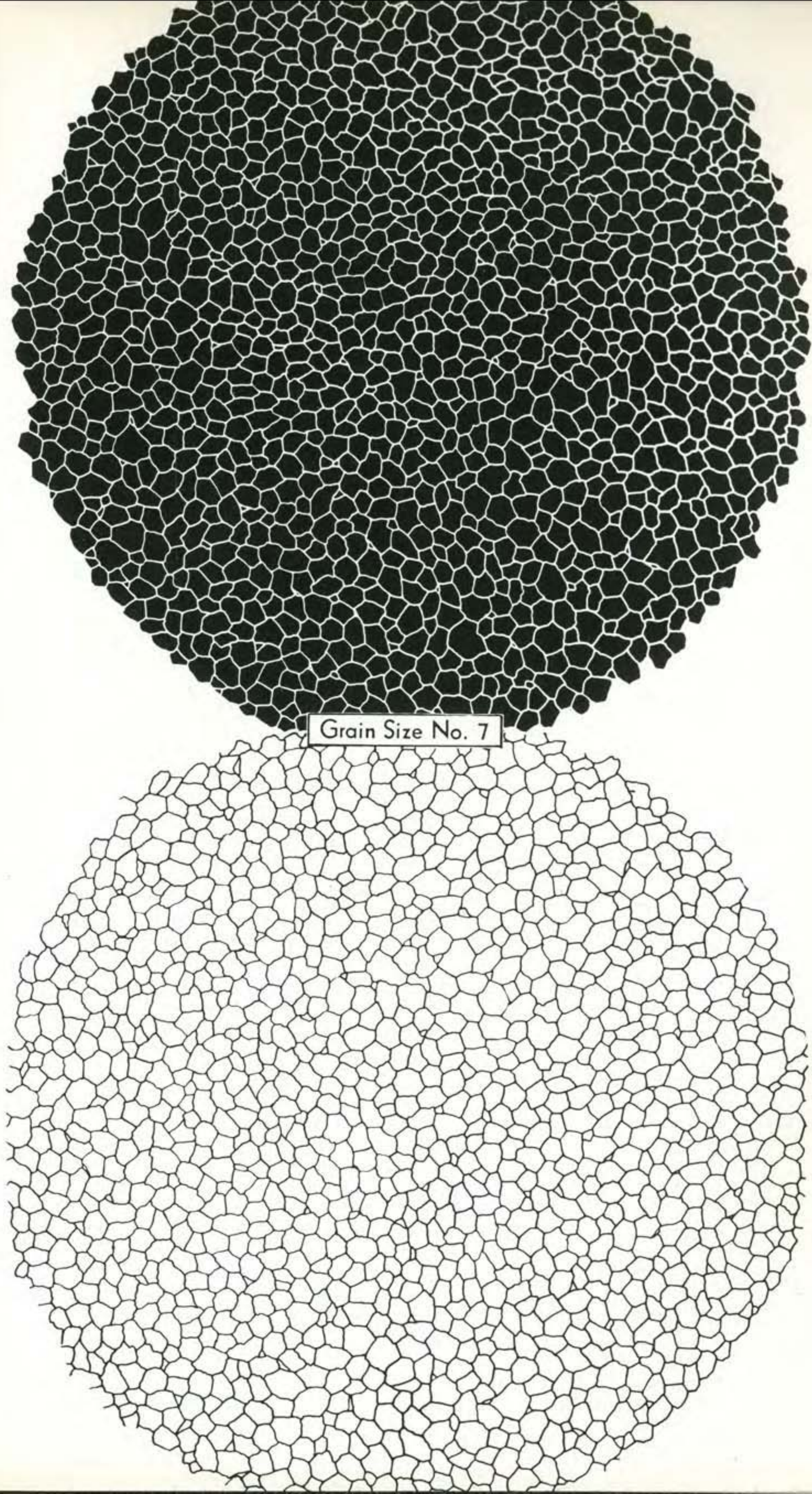
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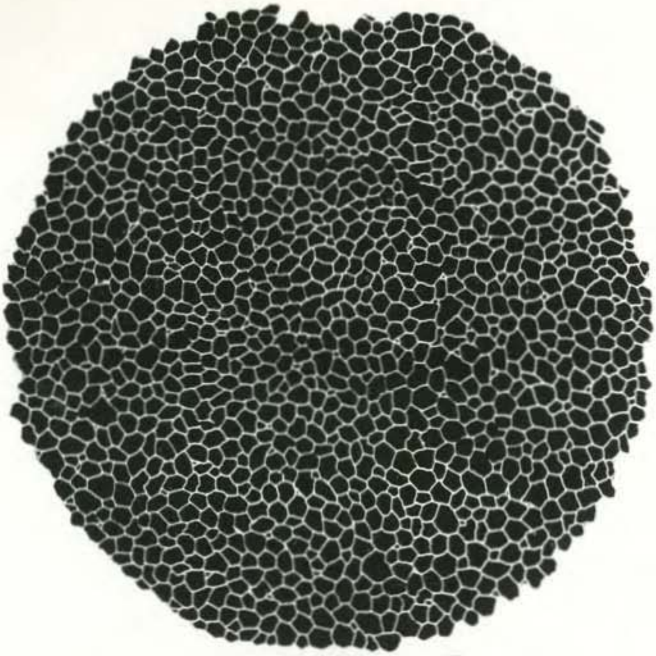

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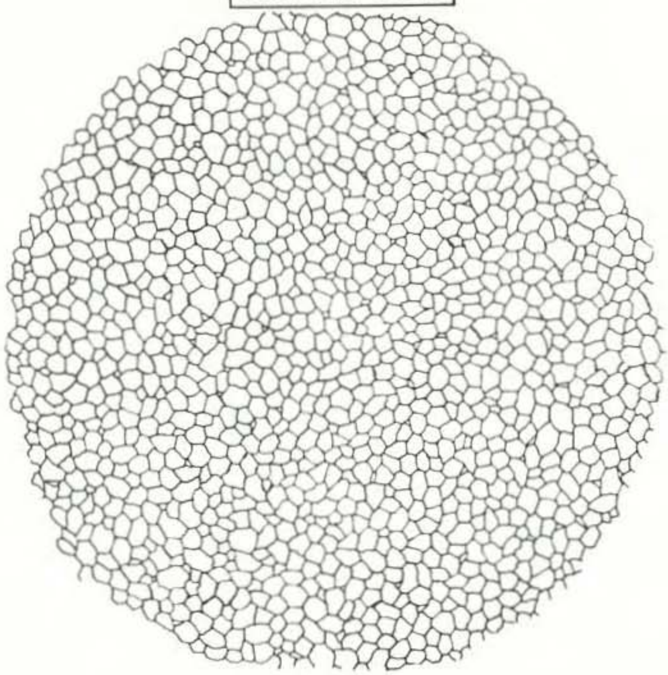


HEATING PRACTICE AND HEATING FURNACES FOR HARDENING OR ANNEALING

An improved order of mechanical properties in steels over that present in the rolled or forged condition may readily be attained by heat treatment. This process comprises heating at a suitable temperature for a proper length of time, followed by cooling at a determined rate and, in most cases, reheating at moderately low temperature for tempering. A most significant feature of good quality steel is recognized by the consistently uniform results which may be obtained if the heating and cooling conditions are properly controlled. Because of the narrow range of acceptable physical properties now expected in heat treated products, the equipment used and practices employed require careful attention and precision of handling.

HEATING FOR HARDENING

Since it is important that each piece of steel, in a group of pieces, be heat treated uniformly, furnaces must be employed which are capable of controlled heating. Such furnaces may be fired by gas, oil or electricity, the choice depending upon relative costs and the suitability of each for the type of work. Obviously each has certain advantages and disadvantages but under proper conditions any of them may be entirely satisfactory. The requisites of a good furnace for heat treating are uniform temperature distribution, close temperature control, and adequate provision for control of the furnace atmosphere. All of these are essential for successful heat treating. The first two have been studied for a number of years, and the last-named is now receiving much attention in order to prevent excessive scaling or decarburization.

Consideration must be given to the location of the furnace load in order to permit a uniform rate of heating of the load. This is readily accomplished in continuous furnaces, in which the work is carried on conveyors or other means, by a close control of the temperatures in the successive heating zones. In batch furnaces, however, the work should be arranged in such a manner as to permit free transfer of heat to all pieces of the charge; in case radiant furnaces are used the work should be so placed that a maximum amount of the surface is exposed to the radiating furnace surfaces. This may usually be accomplished by providing some means of elevating the material above the hearth, even in large furnaces. Where this is not feasible, overheating of the outside of the mass before the interior reaches the desired temperatures must be prevented through control of heating rate.

A controlled rate of heating is always desirable since rapid heating, particularly in certain sections, may cause considerable distortion or even rupture. These rates of heating must, of course, depend upon the character of the product and must be established on the basis of the shape, composition and size of the product. The rate of heating may be readily controlled but it should be recognized that it is directly influenced by several factors. The rate of heat transfer follows certain definite physical laws. Thus for a 100 degree difference in temperature between the furnace wall at 1700° F. and the furnace load, at 1600° F., the heat transfer would be at a higher rate than for the same temperature difference at lower temperatures.

The relation of the transformation temperature (critical temperature) of the steel to the furnace temperature is likewise of importance. If the selected temperature is but slightly above the critical range, then the heat absorbed by the steel in going through the transformation must be considered. If the furnace is heated at a temperature considerably above the critical range, the influence of the transformation effect is much less pronounced on the rate of heating. So many other conditions, e.g. mass, chemical composition and structure, may influence the results that each heating condition must be considered specifically and must be controlled in order to avoid inferior results.

The length of time which various steels should be held at the required temperature is of utmost importance. The usual rules are expressed in terms of total heating time and are dependent upon section size and the temperature at which the furnace load is to be heated. The most common of these is given as one hour per inch of thickness or diameter. This is obviously only approximate and can apply directly only to a limited range of sizes and temperatures. In heating for quenching, the essential feature is the time at temperature during which carbide solution and diffusion progresses. The aim is to obtain uniform distribution of the carbon throughout the structure (i.e., a homogeneous austenite), so that prior to cooling an essentially uniform condition exists. Thus holding time even at correct furnace temperature may vary from five minutes to an hour or more as influenced by the composition and section of the material.

QUENCHING PRACTICE

The manner and means of quenching are just as important as heating for hardening. The selection of a proper quenching medium depends entirely upon the hardenability of the steel and the shape of the part. In other words, each steel has a critical quenching rate which will harden the surface as well as part of the interior to a definite depth when a piece of a specific size is quenched. If the piece is larger or smaller, a lesser or greater depth of hardness penetration will be obtained after a given type of quench. A small piece may harden entirely through its section while a large piece may not harden at all. Both of these results may be objectionable since the smaller piece may be too brittle and the larger may be unsuitable because of the lack of sufficient increase in hardness. Under these conditions, it is necessary to choose a quenching medium which will provide a slower rate of cooling for the smaller piece, while the larger piece will require means for more rapid cooling, unless different steels are selected.

The means available for covering such a range of cooling rates are somewhat limited but the use of oil, water or aqueous solutions of brine or caustic serves well enough. The rates afforded by oil and water are rather widely separated; the brine or caustic solutions are generally more effective than water. Cold water is more effective than warm water, because the cold water largely condenses the steam jacket which tends to form around a steel piece in quenching. On the other hand, warm oil is often more effective than cold oil, because the warm oil is more fluid (lower viscosity) and therefore flows around the piece more readily and so cools it more rapidly.

Parts of simple shape and reasonable size may be quenched directly in the desired medium, using moderate agitation. On a production basis or with large parts, it is frequently necessary to provide sprays or pumps to flush the water or oil around the part. This may be provided by manifolds in the quenching tank with outlets so placed that a substantial flow is continually directed against the piece being quenched.

Frequently it is necessary to quench large pieces of steel of high hardenability, e.g., alloy steels, in water since the oils do not provide a sufficiently rapid quench to harden the materials in these sections. In such cases the parts, if allowed to remain too long in the water or brine, may acquire internal stresses so high that rupture follows. For such parts the expedient of a "time-quench" may be used, in which the steel part is held in the water or brine for a definite period of time and the quench then immediately completed in oil. In many classes of work the period of time in the first quenching medium is extremely critical, if rupture is to be avoided, and unless done mechanically, the operator must time each quench in seconds. Often only a careful control of quenching conditions permits the hardening of some sections of certain compositions. Under any condition steels which are fully hardened should be removed from the quench while still warm and then promptly tempered.

The volume of the quenching bath is of particular importance and must be great enough to admit continued frequent quenching without an appreciable rise in the bath temperature. In addition, the relation of size of the quenching tank to the piece should be such that the steel part may be moved freely during cooling, to assure uniform extraction of heat. Constant bath temperature is accomplished by the use of a sufficiently large volume of coolant and a circulating system for the quenching medium which frequently includes a refrigerating unit and automatic temperature control. High velocity of flow of the quenching medium exerts a pronounced influence in promoting more rapid quenching. When we consider that the "critical quenching rates" are dependent on the rate of the transformation of the austenite in the range of 800 to 1000° F., the importance of a thoroughly effective quench in the early cooling stages may be realized.

The problem of distortion is frequently of paramount importance and within certain limits is controlled by the manner of quenching and by the characteristics of the steels. Many shapes such as rings, long rods and gears must be heat treated to very close tolerances since machining allowances are at a minimum. For such cases, the usual practice is to provide a jig or fixture which is sufficiently rigid to prevent any appreciable distortion during the quench. Many such devices are in common use, some simple and others more intricate, but in general the part is, upon removal from the heating furnace, quickly clamped to the jig or fixture, and the whole promptly quenched in a flow of oil or water.

TEMPERING

Pieces which have merely been hardened are generally too brittle to be put into service. They are therefore given a tempering (drawing) treatment, which consists in reheating the quenched piece at a relatively low temperature, which may be anywhere in the range from 300 to 1200° F. depending on the ultimate service. Steels which must be very hard, such as ball bearing steels, gear steels and the like, are usually tempered in the range from 300 to 450° F. Steels which must be very tough, such as spring steels, shafts, steering knuckles, axles and the like, are tempered at higher temperatures, say in the range from 700 to 1200° F. It is to be noted that the range from 450 to 650° F. is often avoided, particularly if the steel is to be subjected to impact, since some brittleness frequently develops after such a tempering temperature.

As pointed out above in the discussion of heating for hardening, the rate of heat transfer from the furnace to the work becomes less as the temperature becomes lower. Circulation of the furnace gases or of the air in a furnace is very helpful in securing more rapid and uniform heating. For the same reason, liquid baths are often used in tempering operations, particularly oil baths at low temperatures and salt baths or lead baths at intermediate temperatures.

ANNEALING

The softening of steel always requires some kind of controlled heating and cooling. In the case of "full annealing," the steel is heated to above its critical range and is thereupon cooled slowly through the critical range. In the case of "sub-critical annealing," the steel is heated to some temperature near to but below the critical range, whereupon it may be cooled at any convenient rate.

For the heating operations in annealing the same precautions apply as are described above for heating for hardening.

Tapping heat of alloy steel from an electric furnace

TEMPERING, DUCTILITY AND IMPACT

When a piece has been hardened by quenching, it is usually quite brittle, and must therefore be tempered before being put into service. The martensite of which it is composed has little ductility, but the tempering operation effectively increases its ductility and toughness, while at the same time decreasing the hardness.

The decrease in hardness may be illustrated by the following figures, which refer to a .43% carbon steel which had been hardened fully to martensite by being quenched in water. Upon tempering, that is by reheating to successively higher temperatures, the following hardness values resulted.

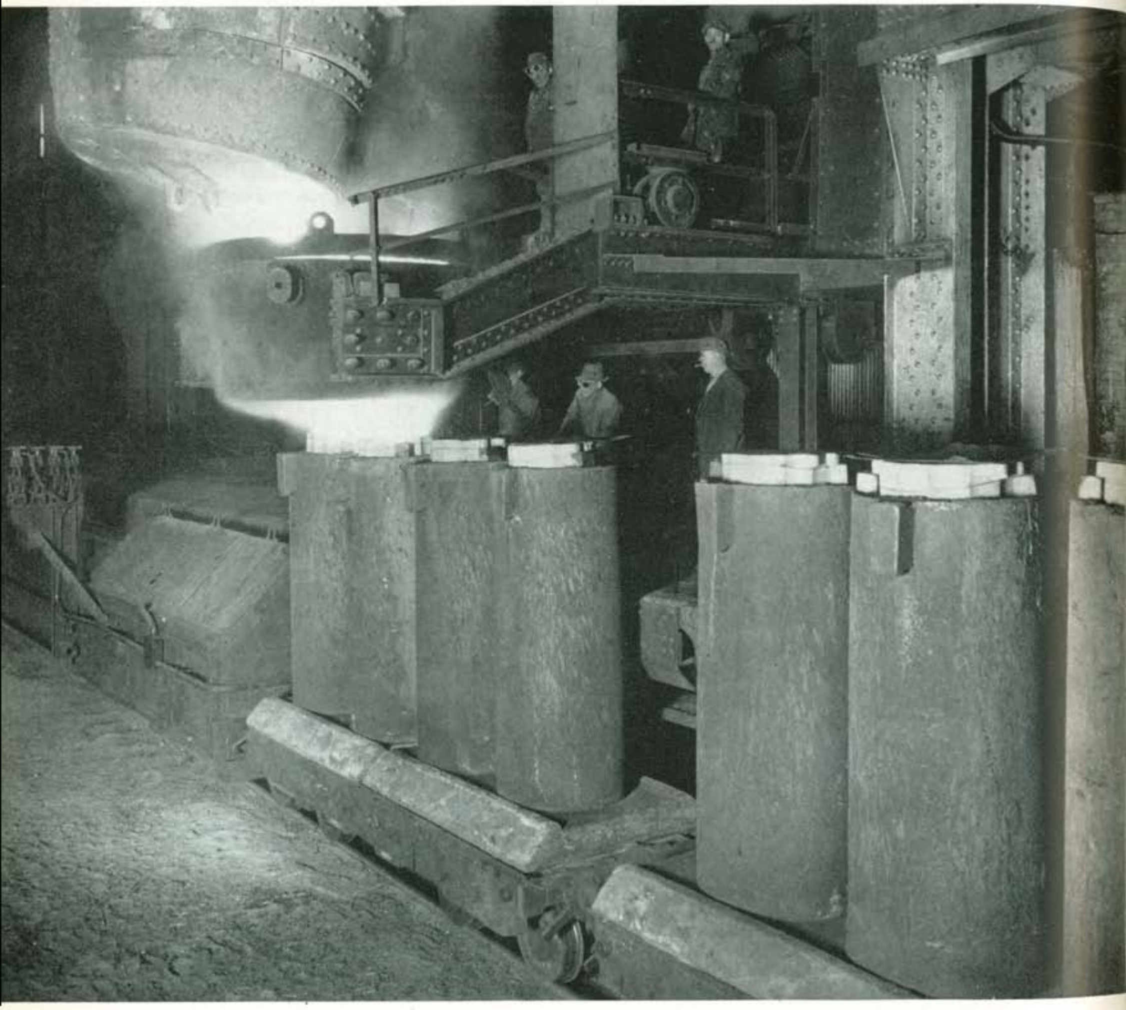
As quenched	60 Rockwell-C
Tempered at 400° F.	56 Rockwell-C
Tempered at 650° F.	49 Rockwell-C
Tempered at 900° F.	39 Rockwell-C
Tempered at 1200° F.	24 Rockwell-C
Tempered at 1250° F.	20 Rockwell-C

Accompanying this decrease in the hardness, there is a decrease in the yield strength and the tensile strength and also an increase in the ductility as measured by elongation and reduction of area. The changes in the tensile properties follow quite regularly the decrease in the hardness. Typical changes in tensile strength, yield strength, elongation, reduction of area and hardness will be found in the charts of physical properties, which are reproduced elsewhere in this booklet.

Associated with the increase in tensile elongation and reduction of area is an increase in impact toughness upon tempering. As the tempering temperature is raised, the impact toughness gradually increases, particularly beyond a tempering temperature of about 800° F.

The impact toughness is commonly measured on standard Charpy or Izod impact test pieces. When using this form of impact test for measuring toughness, it is important to note that there is a region of decreased toughness upon tempering. When fully hardened steels are tempered at successively higher temperatures, there is a gradual increase in the impact toughness up to a tempering temperature of about 400 to 450° F. As the tempering temperature is raised further, the impact toughness then falls off, until at about 650° F. the impact toughness may again be decidedly low. As the tempering temperature is raised beyond 650° F., there is then a very rapid increase in toughness, until at tempering temperatures of 1200 to 1250° F. the impact toughness is likely to be very high.

The decrease in toughness in the tempering range 400 to 650° F. probably attends the decomposition of retained austenite. The quenched structure, martensite, retains with it a certain small proportion of austenite from the quench.



Teeming ingots of alloy steel

This austenite is not decomposed upon tempering until a temperature of about 400 or 450° F. is reached. In the range 450 to 650° F. the austenite is gradually decomposed to alpha iron and carbide, its decomposition being complete at about 650° F.; internal stress may be set up.

A form of brittleness, encountered particularly in nickel-chromium steel, is found when these steels are tempered in the range 1000 to 1200° F. Such tempered pieces are liable to be less tough than expected when cooled merely in air from the tempering heat. Full toughness is obtained however if such pieces are quenched in water from the tempering heat. This phenomenon, for which no adequate explanation is yet available, is known as "temper brittleness," and different lots of such steel are liable to vary in the degree to which they exhibit it. Molybdenum tends to counteract this behavior, or shift the active range to higher temperatures.

As pointed out above, the hardness of martensite is lessened markedly by tempering. The hardness of pearlite is however influenced much less markedly by a similar tempering on pieces which are not hardened throughout their section. The structure of incompletely hardened pieces is a mixture of martensite and pearlite. When such a mixture of structures is tempered, the martensitic portion is softened markedly by the tempering, whereas the pearlitic portion is softened much less. As a result, if one tempers a piece which after quenching consisted largely of martensite on the outside of the piece and largely of pearlite at the center of the piece, the tempering operation will cause much more pronounced softening of the outside than of the inside. In such circumstances, differences in hardness between the outside and the inside of a quenched piece are lessened upon tempering. The difference in hardness between the outside and the center might for example be 25 points Rockwell-C in a quenched bar and only 10 points after tempering. This is illustrated in Figs. 37, 38, 39, 40 and 41, for a carbon-manganese steel containing about .45% carbon and about .90% manganese. The steel was hardened by quenching in water, in sizes ½", 2" and 5" round, and the charts show the effect of tempering at 400, 600, 800 and 1000° F.

HARDNESS DISTRIBUTION IN THREE SIZES OF QUENCHED ROUNDS OF CARBON-MANGANESE STEEL

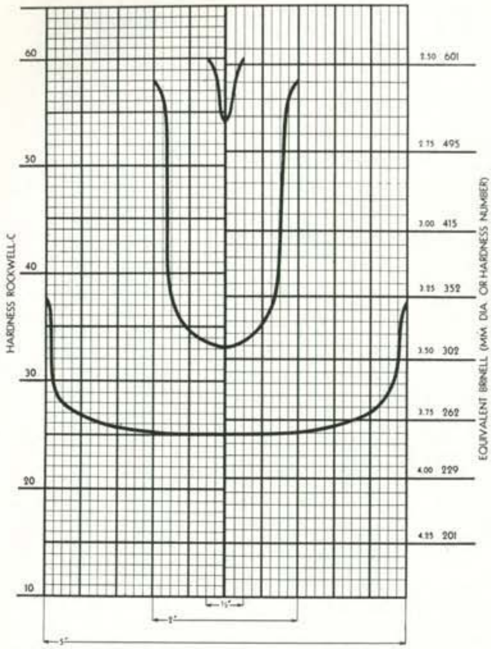


Fig. 37. As quenched

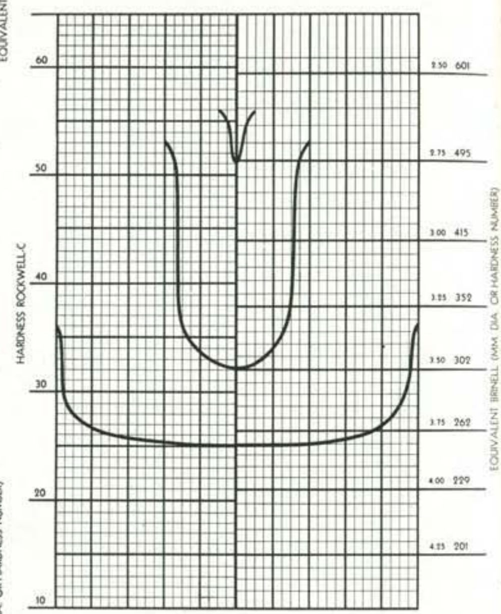


Fig. 38. Tempered at 400° F.

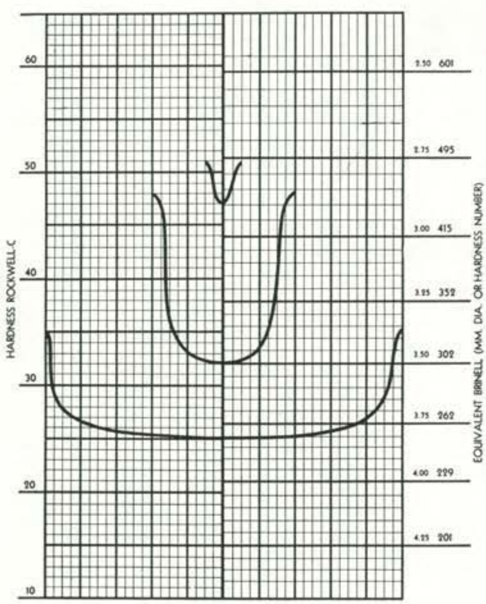


Fig. 39. Tempered at 600° F.

HARDNESS DISTRIBUTION IN THREE SIZES OF QUENCHED ROUNDS OF CARBON-MANGANESE STEEL

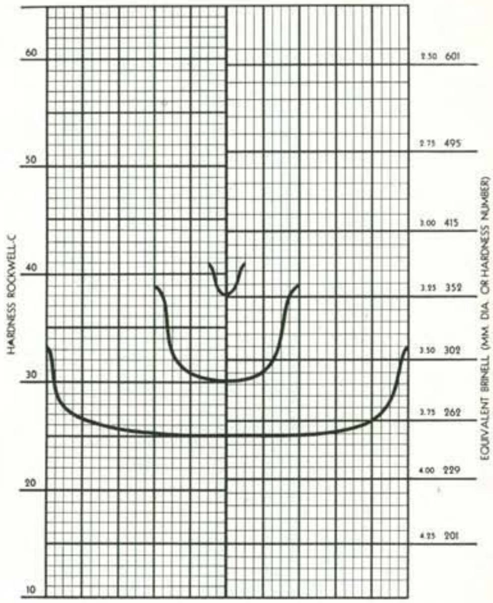


Fig. 40. Tempered at 800° F.

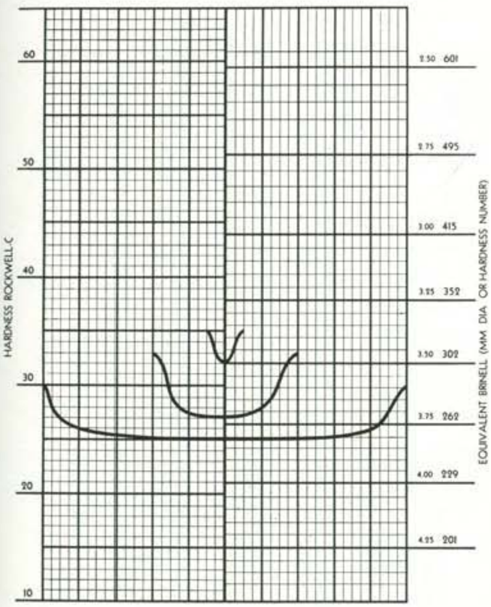


Fig. 41. Tempered at 1000° F.

At the right a workman is checking the temperature with an optical pyrometer as this heat is tapped

ABRASION RESISTING STEEL

Replacement of worn parts is a serious economic factor in many industries, both on account of the cost of renewals and the losses incident to interruption of operations while making repairs. Various materials or methods of treatment have been tried where abrasion is severe—some proving a success under certain conditions, but a failure in others.

Special alloy steels, with or without heat treatment, have solved some of the problems of abrasion. Hard facing, nitriding and case-hardening also have their special applications, particularly wherein initial cost is not the determining factor, but often they are either too expensive or their use is impracticable.

There has been a demand for a durable, yet low priced steel, for general applications where the material is subjected to abrasion. After a thorough study of the requirements, the Carnegie-Illinois Steel Corporation developed an abrasion resisting steel, which has been designated by the trade-name A-R Steel.

This steel is a medium manganese steel of 0.35 to 0.50% carbon, 1.50 to 2.00% manganese, maximum of 0.050% phosphorus and 0.055% sulphur and with 0.15 to 0.30% silicon. It is also supplied with a minimum of 0.20% copper for use where atmospheric corrosion is a problem. It is available in standard bar sections, structural shapes, universal and sheared plates, sheets and strip.

In the as-rolled condition, A-R Steel has a tensile strength of approximately 100,000 to 125,000 p.s.i. and a Brinell hardness of 200 to 250, depending upon the gage. While this steel is primarily designed for use in the untreated condition, it may be heat-treated to give tensile strengths up to 150,000 p.s.i. with good ductility.

One of the requirements of abrasion resisting steel for general application is that the steel must be capable of being fabricated by the usual shop equipment and practices. A-R Steel has now been on the market for approximately six years, and the numerous repeat orders have demonstrated that it can be fabricated by only slight modifications of the regular methods. As it is a steel of higher tensile strength than the plain-carbon steels familiar to fabricating shops, more power is required for shearing, punching and cold forming; and special precautions must be taken with the heavier gages, such as preheating before shearing to short lengths or before flame cutting.

A-R Steel can be cold punched in gages of $\frac{3}{8}$ inches and under. Drilling and machining can be done with standard equipment with speeds and feeds reduced, as is necessary with any high-tensile steel. It can be welded satisfactorily with proper welding technique as has been demonstrated by many shop experiences.

A-R Steel has been used successfully in coke handling equipment, chutes for handling coal, ore, rock, gravel and sand, for screens, concrete mixer parts, pug mill liner plates, furnace skips and hoppers, dredge and pontoon pipe, conveyor parts and in road machinery. The satisfactory results reported by customers regarding the increased life of parts fully justifies the use of A-R Steel for purposes such as cited.

This giant bucket is charging an open hearth furnace with molten metal from the blast furnace

ALLOY STEELS IN THE AIRCRAFT INDUSTRY

The aircraft industry requires fine steel of the highest strength obtainable due to the constant efforts being made to increase the ratio of horsepower to weight. Constant rigorous study is made of the strength, ductility, fatigue resistance, corrosion resistance and wear resistance, all of which are directly related to expert steel manufacture and careful efficient heat treatment.

In building this flying fortress, alloy steels such as S.A.E. X-4130 play an important part

The choice of a steel to be used in any part for aircraft purposes is always based upon an intimate knowledge of its various properties. All preliminary testing imaginable is carried out on raw materials; and likewise various forms of testing to destruction on the finished parts are practiced in an endeavor to determine the suitability of such a steel for a particular application. That the reader may know the opportunity for steel selection, the principal grades commonly used for engine parts are indicated.

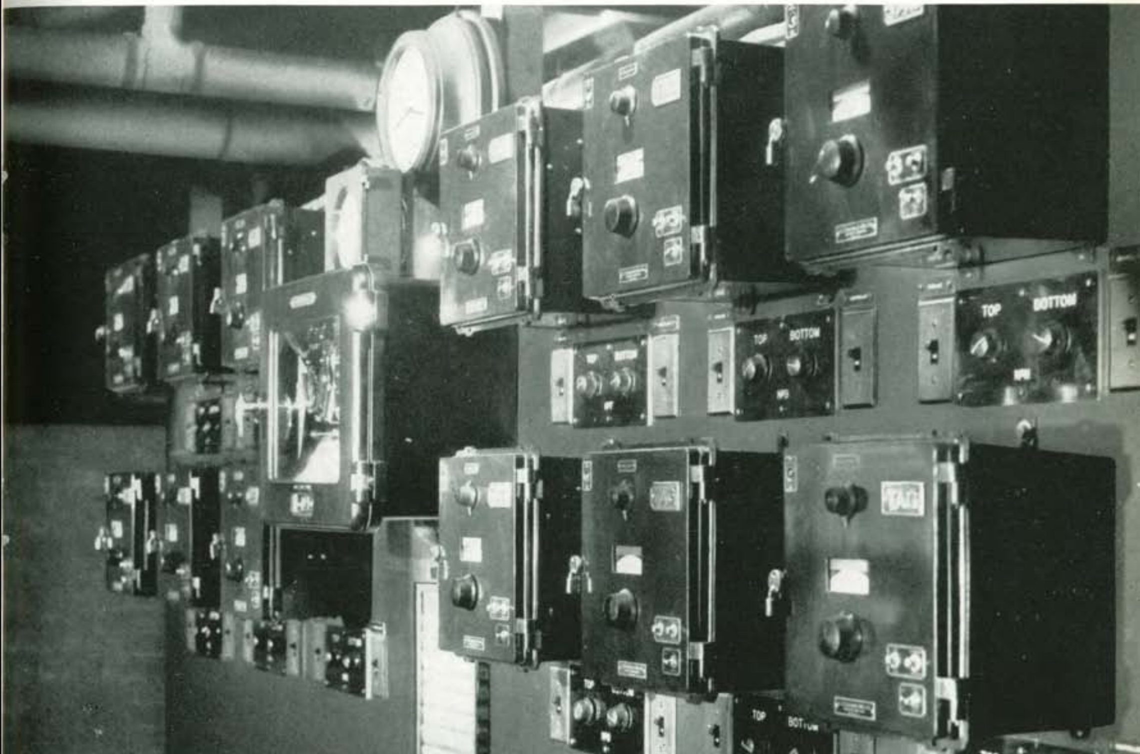
Crankshafts	SAE 3150, 3250, 4340, 2520, 2335
Connecting Rods	SAE 2335, 4145, 4340, 3150
Cam Shafts	SAE 3115, 2315, 2340, 2520
Pins	SAE 2315, 2340, 3250, 4620, 52100
Bolts and Studs	SAE 2335, X-3140
Bearings	SAE 4620, 52100
Structural Shapes and Tubing	SAE X-4130, 4140, U·S·S 18-8
Propeller Hubs	SAE 3150, 4140, 6140, 4340
Propeller Blades	SAE 4140, 4340
Gears	SAE 3115, 3315, 4620, 3250, 6150
Springs	SAE 6150, 9260

Only the electric furnace is employed in melting these numerous steels, for it possesses certain advantages in meeting the exacting requirements for each application.

Leading aviation authorities have found that heat treatable alloy steels, such as chrome-nickel, chrome-vanadium, and chrome-molybdenum (S.A.E. X-4130) alloys, have several marked advantages for aircraft construction. Properly chosen alloy steel structural materials have the highest strength-to-weight ratio now commercially practicable. S.A.E. X-4130, for example, a chrome-molybdenum steel, has become virtually the standard alloy in aircraft construction because of its remarkable combination of desirable properties.

The advantages of welding often include a decrease in difficulty and cost of fabricating aircraft structures. The heat treatable alloy steels are usually fabricated in the annealed state and then heat treated. For instance, steel structures assembled by welding tubing into units of convenient size such as wing spars, landing gears, and fuselage sections, are regularly heat treated without harmful distortion by quenching in oil and tempering to strength values as high as 200,000 p.s.i. Heat treatment greatly improves the strength, toughness and durability of the welded joints.

Similar to the very rigid requirements mentioned above in reference to steel manufacture, exceptional care and supervision is exercised over each step in the handling, forging and heat treatment of all parts destined for aircraft purposes, each step in the fabricating process from raw material to finished part being subjected to the most exacting control known to metallurgical science. The combined efforts of steel manufacturer and aircraft metallurgist have thus placed before the designer an array of alloy steels, with their attendant high physical properties, which has contributed in no small measure to the advance of modern air travel.



Temperature Control

ALLOY STEELS IN THE PETROLEUM INDUSTRY

Of the several hundred different compositions of various alloys that have been used in the petroleum industry, there are a group of approximately two dozen alloy steels which cover the majority of applications. The alloy steels discussed under what follows can be used with reasonable assurance that these steels provide a good starting point for a more refined selection, which may ultimately be governed by peculiarities of design, economic conditions or other factors. Under the following classifications several alloy steels are indicated which are widely used for the specific purposes.

OIL WELL DRILLING EQUIPMENT

Drilling tools must be of sufficient hardness to resist wear and yet possess sufficient shock resistance to withstand the impacts encountered in drilling operations.

Bits, core drills and reamer bodies are made of forged S. A. E. 3140, X-3140 and 4140, heat treated to 269-321 Brinell.

Rock bit cutters are made from forged S. A. E. 2315, 3115, 4615 and 4815, hard faced and carburized to impart the necessary resistance to wear. The pins or bearings on which these cutters are mounted in the body of the bit are usually made from oil quenched S. A. E. 3250, 3340 and 4650.

Drill collars and tool joints are made from either S. A. E. 3140, X-3140 or 4140, the drill collars being normalized and tempered to produce the desired properties, while the tool joints are oil quenched and tempered to a Brinell hardness of approximately 287-321 Brinell.

Sucker rods and accessories for sour oils are commonly made of low-carbon, low-metalloid 3.5% nickel-molybdenum steel, S.A.E. 4615 and 4815. For less corrosive service, S.A.E. T-1335 is commonly used. Sucker rod couplings are made of carburized S.A.E. 2315, 4120 and 4615.

DRILL PIPE AND CASING

Drill pipe and casing must have exceedingly high strength, resistance to abrasion and at least moderate ductility. For this purpose the manganese-molybdenum or Simancro or Cromansil types are usually used.

PUMPS

Pumps used in the oil industry may be grouped roughly as follows:

(a) Pumps for low and moderate temperatures,

(b) Pumps for service up to 900° F.

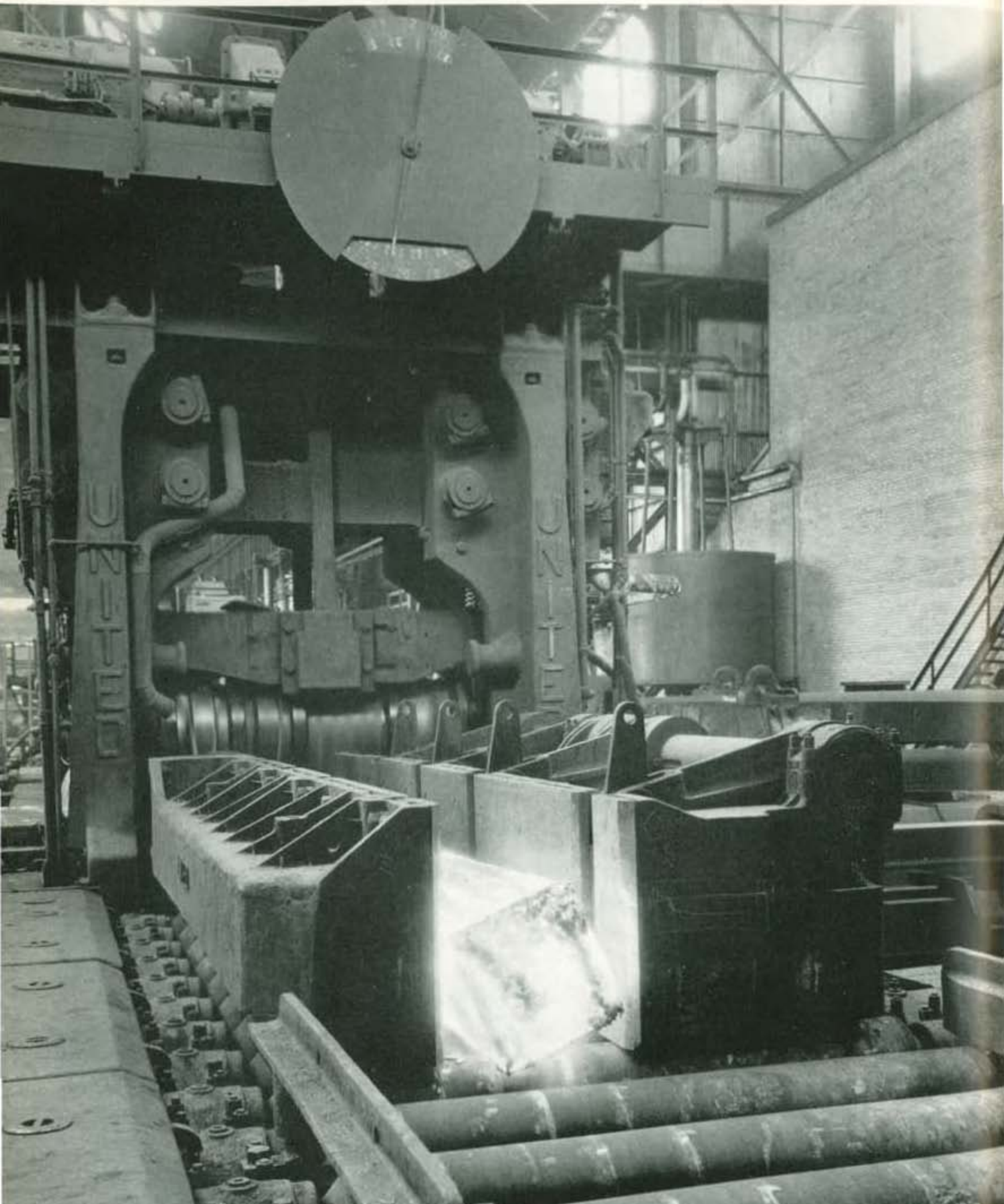
The choice of steel for pumps within either group depends upon the type of pump, the corrosiveness of the liquids being handled and upon the probable abrasiveness of suspended solids.

Pumps for Low and Moderate Temperatures. Piston rods for reciprocating pumps, sleeves for centrifugal pumps and miscellaneous shafts and rotors are made of S.A.E. 2335, 3140, 4140 and 6150, heat treated to approximately 300 Brinell. Carburized S.A.E. 2320 and 4815 are also used for piston rods where high resistance to abrasion is desirable. For most severe types of service 12% chromium steel is used at approximately 300 Brinell, while impellers for this type of service are made from 4–6% chromium steel containing .20/.30 carbon.

Pumps for Service up to 900° F. For high temperature and pressure service the casings for all types of pumps are made almost exclusively of forged steel. Piston rods and plungers are made of S.A.E. 6150 or 12% chromium steel hardened to about 300 Brinell. Valve bodies are made of S.A.E. 3140 and 4140, while the seats and discs are made of 12% chromium steel hardened to approximately 400 Brinell. Inner casings on centrifugal pumps are usually made of 4–6% chromium steel. Because of the large joints involved in this type of pump, case stud bolts are made of high strength steel, usually S.A.E. 3140 or 4140, heat treated, and sometimes even 4–6% chromium steel with tungsten or molybdenum additions. Impellers for exceptionally severe corrosive conditions are made of 25% chromium, 12% nickel steel and perform satisfactorily with practically no corrosion, even after several years of service. Shaft sleeves on centrifugal pumps are made either of 4–6% or 12% chromium steels which are hard faced on the working surface.

HIGH TEMPERATURE FURNACE, STILL AND HEAT EXCHANGER TUBES

Present day equipment such as stills and cracking units are operated at temperatures and pressures considerably in excess of those used as recently as



Turning a bloom over,
Between passes in rolling

eight to ten years ago. High pressures naturally increase the working stresses, while higher temperatures decrease the permissible working stresses that can be maintained on any particular steel. Furthermore, high temperatures intensify the corrosion and scaling of steels. These factors all indicate many places where substitution of alloy steel should be considered if the substitution will increase the life of the unit three or four times, provided of course that the obsolescence period of the particular design is not exceeded.

The safe load which can be maintained is usually expressed as that load which will cause elongation (known as creep) of not more than 1% in 10,000 hours. Broadly speaking, experience indicates that the creep strength of carbon steel is such that alloy steel is preferable at temperatures higher than 1000° F. However, because of the low corrosion and scaling resistances of this steel, it is seldom used above 800° F. 4–6% chromium steel has good creep strength up to 1100° F. and the same type of steel with ½% molybdenum may be used up to 1200° F. The corrosion and scaling resistance of these 4–6% chromium steels is further enhanced by the use of titanium or columbium in addition to molybdenum. Although the creep strengths of the 12% and 17% chromium steels are nearly the same as that of the 4–6% chromium steel with molybdenum at 1200° F., the advantage of the higher chromium steels is due to their greater resistance to corrosion and scaling. For the highest temperatures in the neighborhood of 1350° F., the 18% chromium, 8% nickel steels have proven very satisfactory because of their high creep strength combined with scaling and corrosion resistance.

Aside from the better creep properties of the 4–6% chromium steel with molybdenum, as compared to the same type without molybdenum, the former have the advantage of retaining low temperature ductility after prolonged use at elevated temperatures. This is an important consideration where tubes are cooled down for coke removal.

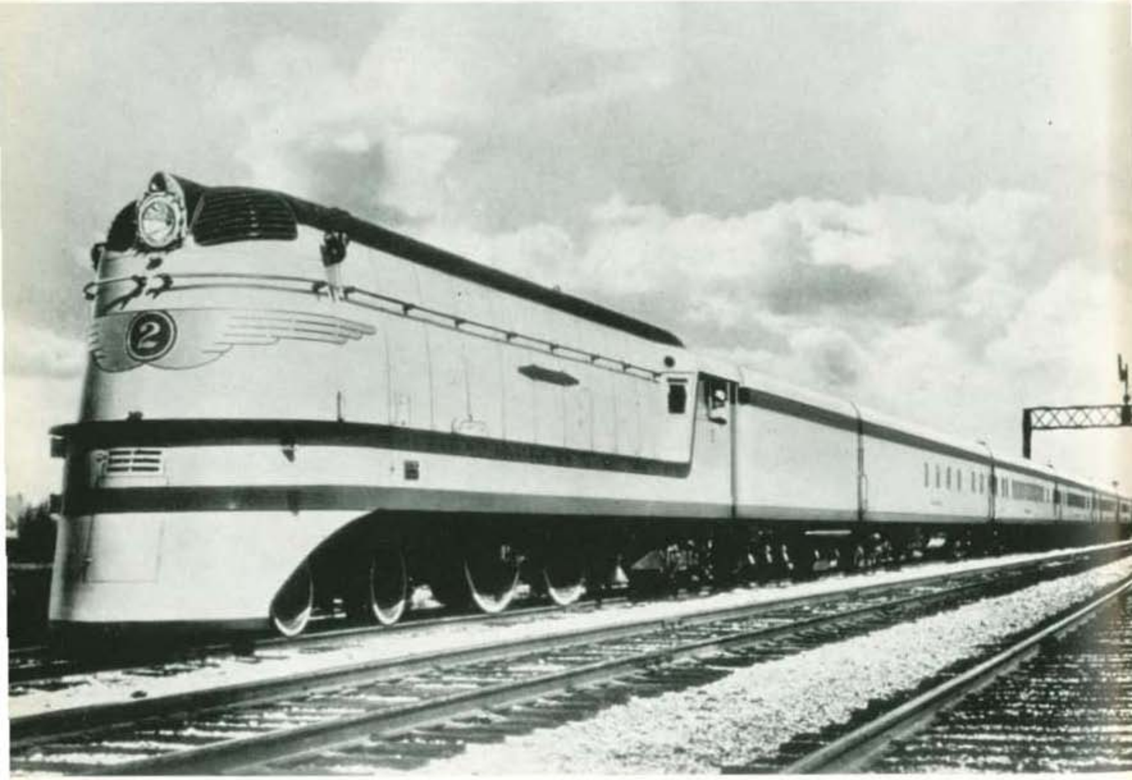
PRESSURE VESSELS FOR DEWAXING

In the manufacture of lubricating oils it is customary to remove the paraffin by cooling the oils to low temperatures, in the neighborhood of -75° F. For this purpose 2½% nickel steels containing up to about .25% carbon have been widely used because of their satisfactory impact strength at these low temperatures. The 4–6% chromium steels with additions of molybdenum, titanium or columbium have also proven satisfactory for this type of service.

THE APPLICATION OF ALLOY STEELS ON AMERICAN RAILROADS

The relatively recent adoption of light-weight high-speed equipment has been facilitated by the development of special steels and has had a very stimulating effect on the use of alloy steels by the entire country's railroad systems.

The first alloy steels used in railroad applications consisted of steels of the carbon-vanadium type, the chromium-vanadium type, the manganese-vanadium type, and the 2 ¾% nickel type used principally on reciprocating parts and main axles. More recently for reciprocating parts, we have witnessed the introduction of the chromium-nickel-molybdenum steels, originally used on light-weight locomotives only, but now gradually being adopted for a wide variety of uses.


Modern trains are built lighter and stronger for faster, more economical service, by using alloy steels

The stainless steels, particularly U·S·S 18-8, also belong in the classification of the more recent developments, which are being used in light gages as sheathing and trim for both passenger car equipment and locomotives, for fittings and in many cases even for complete train structures, including framing members. Surprising as it may seem, while the first cost of these stainless steels is relatively high, the final cost of completed trains, partly due to high percentage of weight reductions, compares very favorably with that of equipment made from lower priced steels. Along the same lines, the high tensile steels are gaining considerable favor, particularly Cor-Ten and Man-Ten which, because of their higher strength and corrosion resistance, are being used for siding and structural members, as a means of reducing weight.

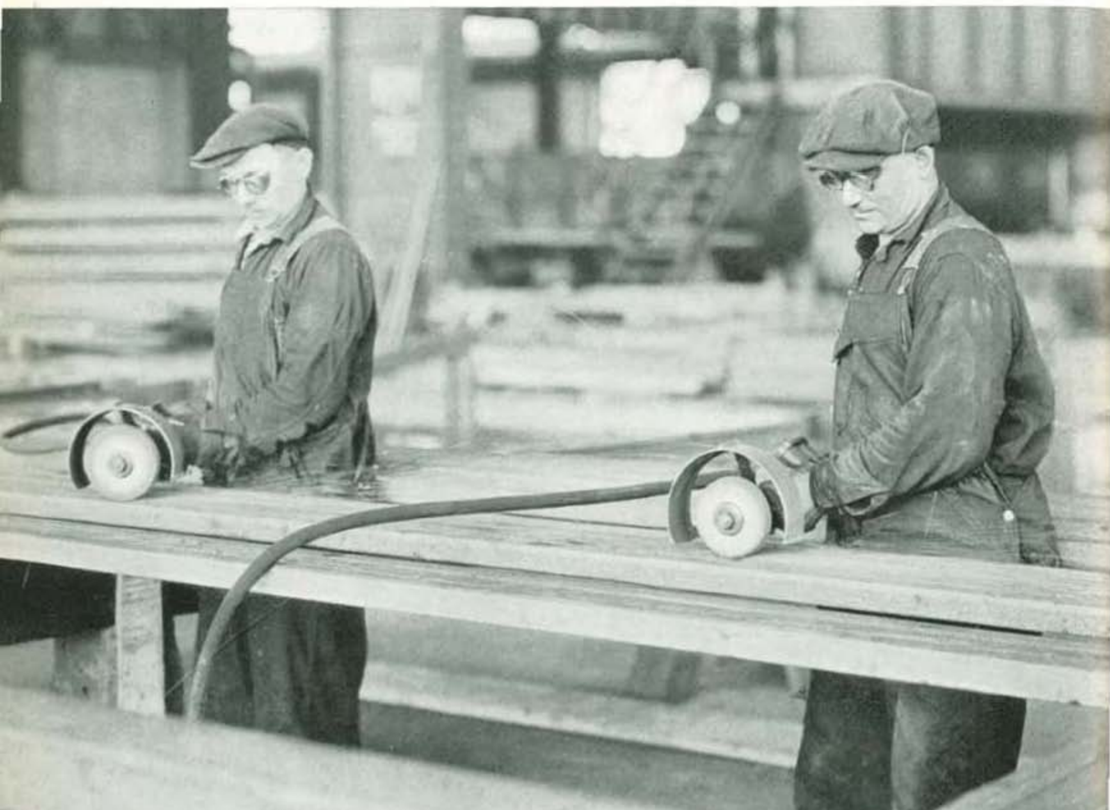
A few typical examples of the alloy steels now being used may be outlined as follows. 2¼% nickel, medium-carbon, boiler plate material permitting boiler pressures of 300 pounds per square inch with no increase of plate thicknesses. We find numerous applications of low-carbon 2% nickel steel in staybolts due to its high fatigue properties and in certain cases to its corrosion resistance. There are wide uses of S.A.E. 2115 and S.A.E. 3120 steels for engine bolts. Piston rods, crank pins, main rods, side rods and main axles are made up of the carbon-vanadium and nickel-manganese types, and where sections are being reduced, the chromium-nickel-molybdenum type.

Alloy parts, particularly when used in reciprocating motion, are heat-treated to the required physical properties depending upon the strength and ductility required to do the job.

Molybdenum, in addition to being used with the nickel-chromium combinations, is being used in low-carbon combinations for framing members of some of the new Diesel locomotive super-structures. A recent development in steels for high-speed trains is the production of wheels from a .45/.55% carbon, .50/.80% manganese and .40/.50% molybdenum steel.

Included among the most recent adoptions of alloy steels in American railroad practice, we find S.A.E. 52100, S.A.E. 4615 and S.A.E. 3312 in use in the roller bearings which are rapidly gaining favor for use on high-speed passenger trains. There is likewise a trend toward S.A.E. 6150 and S.A.E. 9260 for springs in both locomotive and passenger equipment.

No discussion of the use of alloy steels in present day railroad practice would be complete without mention of the numerous applications in the many auxiliaries constituting the make-up of present day locomotives and high-speed passenger equipment. They are found in the form of shafts in air conditioning accessories, such as motors, blowers and pumps, both centrifugal and reciprocating, as well as in the roller bearings supporting them. The same is true of bearings, gears and shafts of the axle generators mounted on passenger car axles to supply electric current for lighting and other requirements. Among the locomotive auxiliaries using alloy steels are boosters, feed pumps, headlight generators and automatic stokers. While specifications for these many auxiliary parts are not generally controlled by the purchasing railroad, the efficacy of alloy steels, where long life under repeated high stresses is imperative, has been indisputably proven.



Grinding surface defects from round cornered square billets in the alloy bar mill

U·S·S CARILLOY ALLOY GEAR STEELS

In making gears so many difficulties have arisen that metallurgists have been inspired, by the problems of gears alone, to develop many improved alloy steels.

Gear steels suitable for use in the automotive industry, in agricultural implements and machinery, in oil well equipment, in machine tools and many other fields must meet rigid requirements. These gear steels must have superior physical characteristics. They must be uniform in chemical composition and in grain size characteristics.

The superior physical characteristics which are required of gear steels include the following:

(1) The steel must forge successfully.

(2) The steel must respond to the annealing cycle so that the proper structure for machinability is readily established.

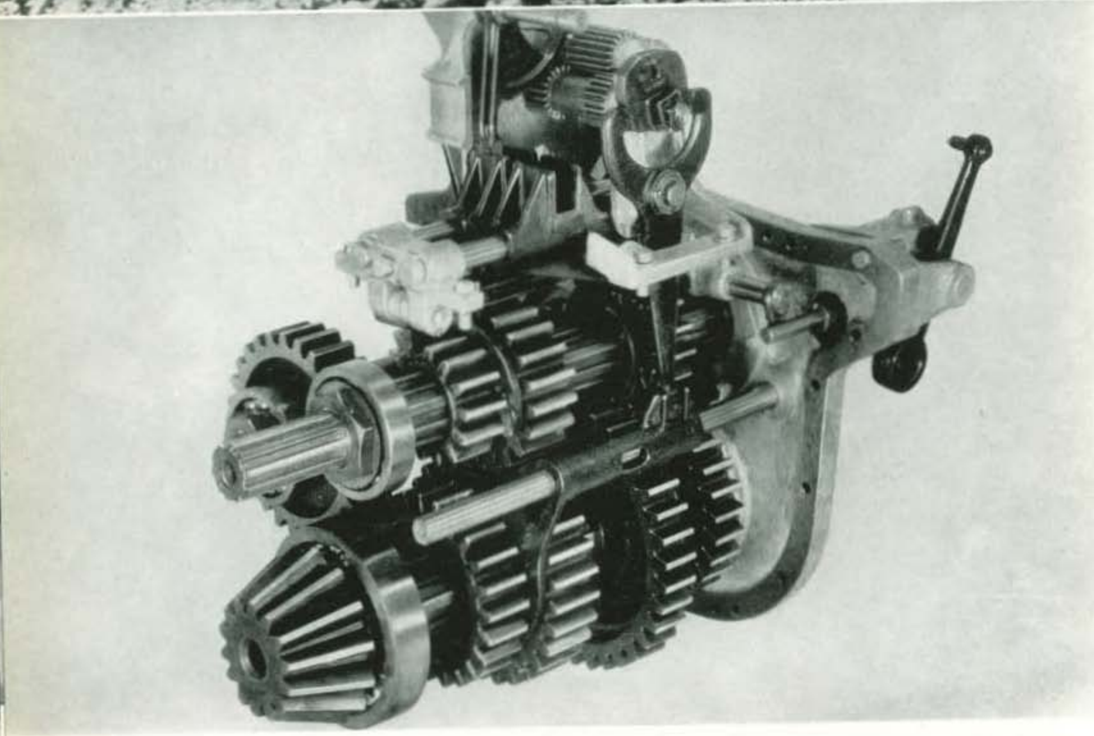
(3) The steel must react properly to standard heat-treating methods, whether the treatment consists of a direct quenching or a reheating, or a thorough hardening cyanide treatment.

(4) The results of heat-treating the steel must be such that minimum distortion and the maximum uniformity is regularly achieved from gear to gear.

(5) The steel must be wear and fatigue resisting, to last the life of the equipment in which it is used.

Steels which do not conform to these requirements increase production costs in making gears. For instance, steels which do not respond to annealing increase cutter costs. Steels which do not respond to heat-treating must be scrapped or require expensive re-treatment undesirable from the point of view of distortion.

Steels which distort non-uniformly are troublesome because of excessive helix angle changes, excessive spiral angle changes, bore changes, involute changes, spacing changes, pitch line changes, lack of back flatness, stem distortion, and other numerous volume or dimensional changes reflecting in mismatched contacts, run-out, noisy gears, and excessive lapping and rematching costs.



Above: This new Diesel tractor includes parts made of U·S·S Carilloy Alloy Steels in the form of shapes, plates and bars

Below: These tractor gears are lighter and sturdier because they are made in part of U·S·S Carilloy Alloy Steels

In the array of chemical compositions used for gears, we have the following types:

In the carburizing grades

*Amola	
S.A.E. 2315	*S.A.E. 4120
*S.A.E. 2512	S.A.E. 4620
*S.A.E. 3020	*S.A.E. 4620 with .30/.60% Cr.
S.A.E. 3120	S.A.E. 4815
*S.A.E. 3120 with .10/.20% Mo.	S.A.E. 5120
S.A.E. 3312	S.A.E. 6120

In the full hardening types

*Amola	
S.A.E. 2345	*S.A.E. 4645
S.A.E. 3130	S.A.E. 5140
S.A.E. 3145	S.A.E. 5145
S.A.E. 3250	S.A.E. 6130
S.A.E. 4640	S.A.E. 6150

(*) Not standard S.A.E. types.

Treatments used on the carburizing grades consist of either direct quenching or a pot cool and single reheat in the majority of cases. However, some types for certain applications are double treated.

Treatments used on the thorough hardening types consist, in the majority of cases, of cyanide heatings, next the cyanide dip, and last open furnace treatment. In some instances, the thorough hardening types are carburized lightly to produce wear resistance comparable to cyaniding. This has been found to be very desirable, particularly from the standpoint of cleanliness and distortion.

Because these requirements for gear steels are so exacting, both as to the manufacturer's processing and for the ultimate product, these steels must truly be controlled in every step of their making. Each minute detail must be uniform from one heat to the next. U·S·S Carilloy Alloy Steels are made with this precision, to meet exactly these stringent requirements.

The perfect mirror finish of this giant rollneck bearing made of U·S·S Carilloy Alloy Steel is remarkable because it is merely ground, not polished

ALLOY STEELS APPLIED TO BEARINGS

Bearings occupy a dominating place in modern mechanical progress and from their vital position they have had a profound influence on the perfection of transportation, the degree of accuracy with which it is now possible to produce rolled steel, and in general the precision with which our machine tools now operate.

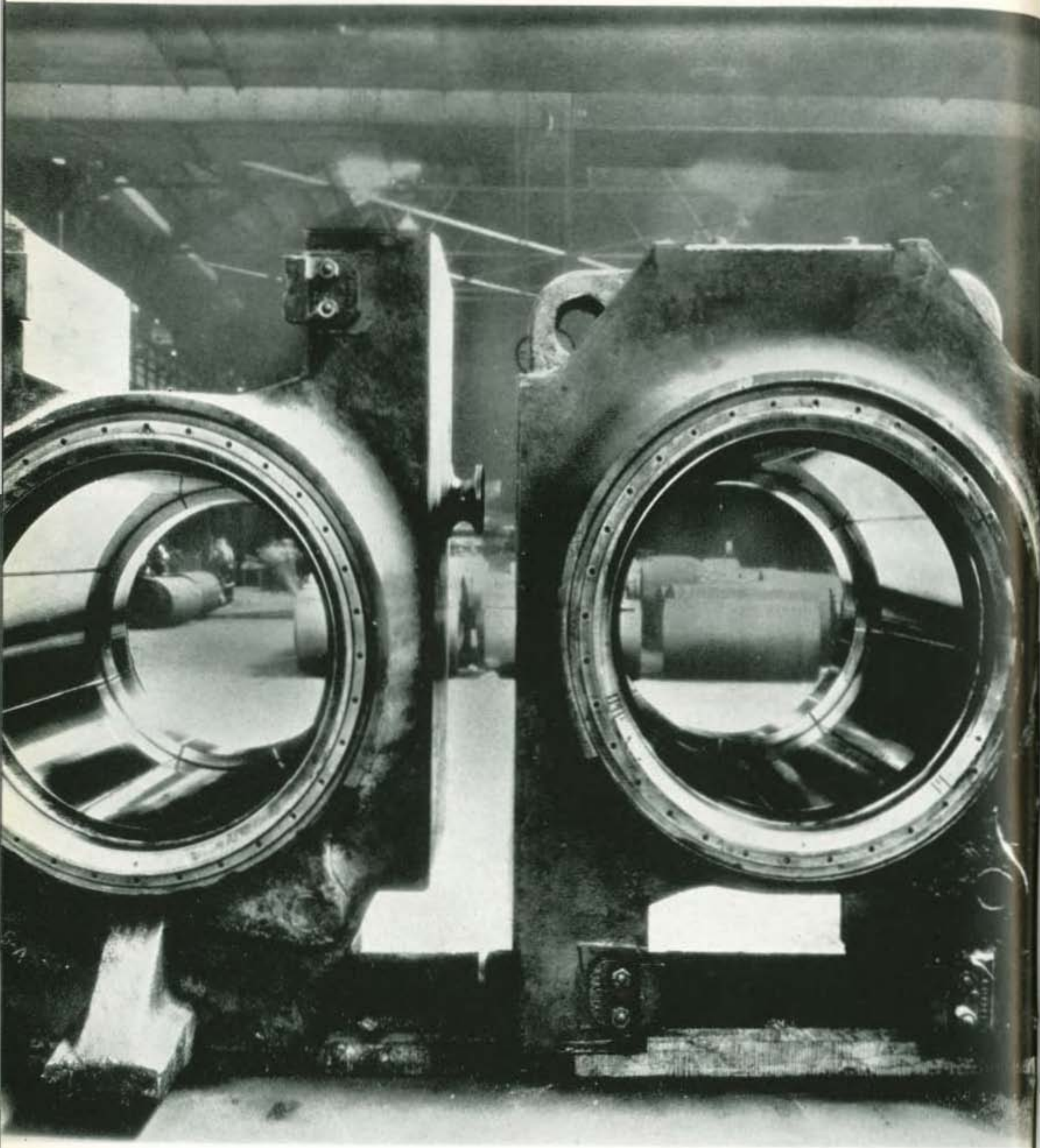
Steel used for the manufacture of bearings must be of the very highest quality as regards cleanliness, hardenability and inherent uniformity. The handling of the material, from the selected scrap charge in the melting furnace to the finished assembled bearing, must be such that the resulting product meets the very exacting requirements of field service.

Bearings have a multitude of applications from the small needle or quill bearings to the large bearings used in steel mills, bridges and hydro-electric plants. The increased speeds of rail and automotive travel as reflected in the increased use of anti-friction devices has, in turn, emphasized precision control of the raw material involved in bearing manufacture, its heat treatment and the limits of dimensional tolerances of the bearings themselves. Due to recent trends toward streamlining in transportation equipment, and the consequent requirement of wider flat steel products to make these parts, anti-friction bearings have become a necessary adjunct to the steel industry. They have played no small part in the solution of the problems involved in precision rolling for width and gage of wide strip and plate on our modern continuous mills.

The types of steel most commonly used for bearing application fall into two classes; first, the direct hardening and, second, the carburizing grades.

	Direct Hardening	*Carburizing Types*
	S.A.E. 52100	S.A.E. 4620
	S.A.E. 5150	*S.A.E. 4120
	*S.A.E. 6190	S.A.E. 3120
Modifications of	S.A.E. 52100	S.A.E. 3312
		S.A.E. 5120
		S.A.E. 6120

(*) Not standard S.A.E. types.



This is the world's largest capacity rollneck bearing designed to carry a radial load of 5,247,000 lbs. and made of U·S·S Carilloy Alloy Steels

Care matching that of steel making should be exercised in the forging, normalizing, annealing and final heat treatment of bearing parts, particularly those involving complicated cross sectional shapes. To obtain the best results in forging, the parts must be preheated and raised to the forging temperature very slowly; likewise, suitably slow cooling to prevent internal ruptures is requisite. A normalizing treatment is used on the forgings followed by an annealing treatment. On the thorough hardening types the annealing treatment is adjusted to produce a well distributed spheroidized structure.

In the heating for quenching, after machining, in order to avoid distortion and undue thermal stresses, preheating is most effective. The rate at which the temperature is raised should be controlled so as to minimize temperature differences throughout the cross section being treated. In quenching the following factors must receive particular attention.

Temperature of the quenching medium.

The time the section is left in the quenching bath.

The temperature at which the section is removed from the quenching bath.

The time interval between quenching and drawing operation.

The proper drawing temperature and proper time in draw.

Since the possibility for now destructively testing the very large bearings is limited, no pains are spared in the manufacture of each individual small part which goes to make up the large bearing because the success of the bearing as a whole lies in the excellence of the performance of each component part.

The remarkable duties being performed by bearings of present day design were practically unheard of as recently as five years ago. This exceptional record of performance has been made possible by the constant endeavors of those engaged in the bearing industry, in co-operation with the steel manufacturer and the forging sources; this co-operation has resulted in the production of the optimum structures with properties necessary to resist wear, shock and fatigue.

THE USE OF STEELS AT ELEVATED TEMPERATURES

The development of the chemical, petroleum and power industries to a greater efficiency and economy depends to a considerable extent on the use of higher and higher operating pressures and temperatures; higher stresses at higher temperature for the steel involved. Representative installations requiring steels for service at high temperatures and pressures include oil stills, cracking units, pumps, valves, pressure tanks, steam turbines, boilers, superheaters and high temperature steam piping.

In view of the requirements and possible safety hazards involved in this type of service, it has been recognized that the materials should have the following qualities:

(a) adequate strength at elevated temperature,
(b) maximum resistance to oxidation and attack in the corroding media to which it may be exposed in service,
(c) good ductility and toughness during its period of service,
(d) weldability, if application involves welding,
(e) generally satisfactory fabrication characteristics, i.e., it should be suitable for rolling, forging or tube piercing.

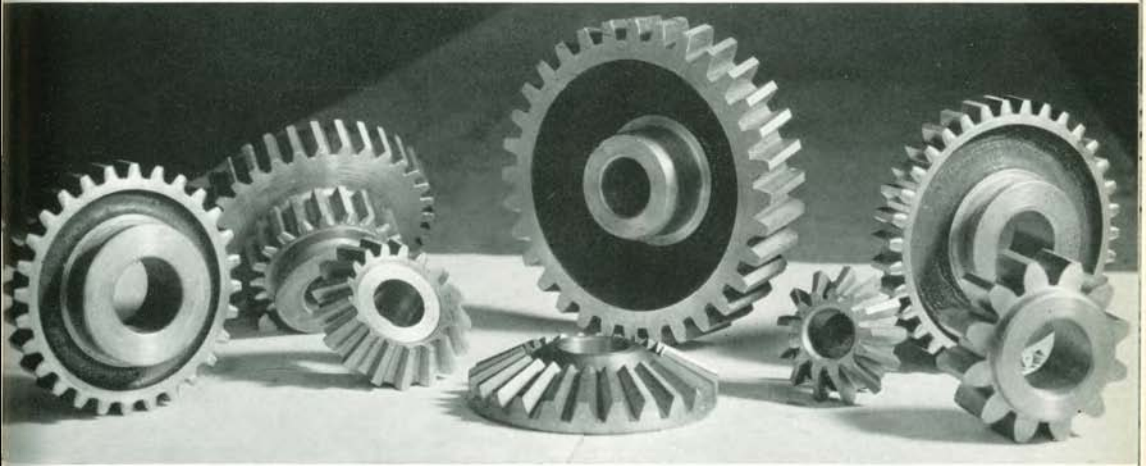
The relative importance of these characteristics depends upon the application, but creep strength and corrosion resistance are of prime importance. With regard to creep, it has been found that the determinations of tensile strength, yield strength and elastic limit, when measured in a short time test at high temperatures, are inadequate. When materials are maintained at high temperatures even under a relatively low stress, a gradual yield or extension occurs. This gradual yield, because of its small magnitude, has been termed creep and is customarily expressed in terms of rate, based on time, temperature and percentage of elongation. For example, the stress which causes elongation at a rate of 1% per 100,000 hours at 1000° F., or of 0.1% elongation per 10,000 hours at 1100° F. is termed the creep stress for the material at the particular temperature. For certain applications, such as steam turbines, total elongation rather than the rate is of greatest importance, since the construction tolerances are very small; furthermore materials under stress at high temperatures do not necessarily elongate most rapidly during the early period of service.

Factors influencing the creep characteristics are primarily the presence of effective alloys and the microstructure which has been induced by suitable heat treatment. Study of this problem has been very extensive and, although it is believed that the alloys which have low diffusion rates and which form carbides, such as molybdenum, chromium, tungsten, vanadium and titanium, are most effective in producing a steel of high creep strength, other alloys are frequently used either to assist in obtaining this quality or for oxidation and corrosion resistance. The classes of steels used may range from the austenitic high chromium-nickel stainless alloys to pearlitic steels of moderate alloy content or simple carbon steels, the selection of which must depend on the conditions of service.

Scaling and corrosion are of course very important problems since these reactions result in loss of metal with a consequent loss in strength, or under certain conditions, cause embrittlement because of intergranular attack.

The advantages of welding are so well established that many steels for high temperature service are designed to be weldable and do not seriously air-harden in the vicinity of the weld.

The ease of fabrication of steels for this purpose is important not only for economical production, but also to avoid difficulties in construction. This is particularly true for tubing which must be pierced satisfactorily and in many cases subsequently be shaped to conform with a required design.



Each steel is suited to its job

PROPERTIES and USES OF U·S·S COR-TEN, MAN-TEN AND SIL-TEN STEELS

COR-TEN

U·S·S Cor-Ten is a low-alloy open hearth steel with the elements adjusted primarily to give good corrosion resistance with high physical properties. Cor-Ten is a ductile low carbon-chromium-copper-silicon-phosphorus steel. The proportion of elements is such as to produce a steel which, in gages up to ¾-inch thickness, has a minimum yield point of 50,000 pounds per square inch, and a minimum tensile strength of 70,000 pounds per square inch in combination with excellent ductility. Endurance limits of this steel are high, being at least 65% of the tensile strength. Its ideal combination of phosphorus and copper for corrosion resistance and of silicon and chromium for high strength makes this steel suitable for a variety of applications, particularly in the railroad, automobile, bus and truck transportation

Hot pressing a longitudinal hood for a hopper car made of U·S·S Cor-Ten is an operation where the excellent forming qualities of Cor-Ten are proven industries. No difficulty is experienced in welding this steel with shielded metal arc, flash or spot welding equipment.

The reduction in weight, through the use of thinner members, in a structure which must remain serviceable for many years depends not only on the strength of the material used in the structure, but also on the resistance of the material to corrosion; otherwise the strength of the structure might be markedly reduced in a short time by corrosion and, as a result, defeat the purpose for which the thinner members are used. It is obvious, therefore, that high tensile steels designed for weight reduction must be resistant to severely corrosive conditions, and Cor-Ten has four to six times the life of plain steel in industrial atmosphere. U·S·S Cor-Ten is twice as resistant to sea water and intermittent brine conditions as copper steel. Its resistance to corrosion, combined with high physical properties, favors its use in the economical construction of ships, boats and barges of many kinds.

Cor-Ten is also more resistant to abrasion than standard structural steel, tests showing 33% greater durability than for mild steel when subjected to the abrasive action of coke. There are definite indications that Cor-Ten may be classed as a mildly heat-resistant steel for moderately high temperatures. The material oxidizes or scales less rapidly than mild steel.

Cor-Ten is now in use in railroad passenger and freight cars of all kinds, automotive trucks and buses, trolley buses, street railway cars, river dam structures, bridge members, tanks of various kinds, mine cars, industrial building roofing and siding, highway construction and farm implements. In short, Cor-Ten may be used where any of the following features are required,

(1) Greater structural strength.

(2) Increased corrosion resistance.

(3) Weight reduction.

(4) Greater durability, or

(5) Some combination of moderate weight reduction and greater durability.

MAN-TEN

Man-Ten takes its name from its manganese content and its high tensile strength. Its composition of manganese 1.25/1.70, carbon .30 maximum, and silicon .30 maximum was adjusted to produce a type of steel intended as a substitute for more costly alloy structural steel. The yield point and tensile strength of Man-Ten in gages up to ¾ inch are 50,000 and 80,000 lbs. p. sq. in. minimum, respectively. Man-Ten is slightly less ductile than Cor-Ten and its resistance to atmospheric corrosion is only commensurate with other plain steels containing .20 minimum copper. Its resistance to abrasion is about 33% greater than that of mild steel.

Man-Ten can be welded with the shielded metal arc or flash welding equipment by taking the usual precautions necessary to weld any high tensile steel. It is successfully used in ore bridges, cranes, dipper sticks, walking beams, vibrating screens, booms for ditch diggers and other purposes where a rugged durable service is necessary. It is advantageously used for applications where resistance to wear and vibration are factors, such as in light-weight welded construction of dredge buckets, hummer screen frames and similar applications.

SIL-TEN

Sil-Ten is a high strength structural steel and is used in bridges, buildings, oil well derricks, walking beams, transmission towers, and for similar purposes where a steel is desired having higher physical properties than required in standard structural steel. At the present time, Sil-Ten is not generally used in welded construction. This steel is equivalent in every respect to the standard structural silicon steel of the American Society for Testing Materials, Specification A-94. As its name suggests, its principal alloying element is silicon.

Uniformity of Product

INDUSTRIAL APPLICATIONS OF U·S·S CARILLOY ALLOY STEELS

The following tabulation shows how various grades of alloy steels are utilized in industry. The listings under the several applications shown are not in any case to be taken as representing the only grades for a particular purpose, but rather the grades most commonly used. It can readily be appreciated that questions of design, economics, machining facilities, availability of heat-treating equipment and other factors enter into a definite selection of a particular grade for a particular purpose. Limitations of space preclude listing all of the alloy grades which can be used for any one application.

To assist users of Carilloy Alloy Steels in selecting the proper grades most suitable for their needs, a staff of consulting metallurgists are employed who are at your service at all times to study your particular problems, and to assist you with their knowledge of steel-making, treating and fabrication. This service is available to all industries using alloy steels for any purpose whatsoever, at no obligation. We are justly proud of the strides made in applying the results of quality steel manufacture to the needs of the consuming industries in our modern era of alloy steels.

APPLICATION	STEEL
AIRCRAFT	
Blades	S.A.E. X-4130—*4345—6130
Bolts, Nuts and Studs	S.A.E. 2330—3140—4140
Cams	S.A.E. 2515—3312
Coil Springs	S.A.E. 6150—9255
Collector Rings	U·S·S 18-8 Cb
Connecting Rods	S.A.E. 2330—3130—*X-4135
Crankshafts	S.A.E. *2512—3140—4140—4340
Cylinder Liners	S.A.E. 4140—Nitralloy
Drive Shafts	S.A.E. 2330
Exhaust Manifold	U·S·S 18-8 Ti
Gears	S.A.E. *2512—3240—Nitralloy
Instrument Boards	Non-magnetic stainless steels, U·S·S 18-8—U·S·S 25-12

(*) Not standard S.A.E. types.

"These gears made of a special grade of U·S·S Carilloy Alloy Steel will scuff less, run more quietly, and cost 12½c less per set"

APPLICATION	STEEL
AIRCRAFT—*Continued*	
Magneto, Distributor and Generator Shafts	S.A.E. 2340—3250
Pistons and Knuckle Pins	S.A.E. 3312—6150—Nitralloy
Propeller Hubs	S.A.E. 4340—6135
Pump Shafts	S.A.E. 2315—2330—Nitralloy
Rocker Arms	S.A.E. 2330—3140
Structural Shapes	S.A.E. X-4130—U·S·S 18-8
Tubing	S.A.E. X-4130
Valves	
Exhaust	Special high temperature alloy steels with numerous combinations of various elements as Cr, Ni, Si, Mo, Va, W, Al, Co.
Intake	S.A.E. 3140
Wing Covering	U·S·S 18-8
AUTOMOTIVE PASSENGER AND TRUCK PARTS	
Arms	S.A.E. T-1340—*3045—3135—3140—3240—4130—4140
Bearings	See BEARINGS
Body Construction	Cor-Ten and Man-Ten
Body Trim	U·S·S 17—U·S·S 17-7—U.S.S 18-8
Bolts	S.A.E. T-1335—3135—Amola .40/.45C
Connecting Rods	S.A.E. 4130—4140
Crankshafts (Trucks and Busses)	S.A.E. 3140—3240—4140—4340
Differential Pinions	S.A.E. 3115—*4115—4615—6130—Amola .20/.25 C
Differential Drive Pinions	S.A.E. *2512—3115—4115—4620—4815—Amola .25/.30 C
Differential Pinion Shafts	S.A.E. 3115—4615—Amola .20/.25C
Differential Ring Gears	S.A.E. 2320—3115—4115—4620—Amola .25/.30 C
Exhaust Valves	Si-Cr and various high temperature resisting combinations of Ni-Cr-V-W-Si-Al
Frame Parts	Cor-Ten and Man-Ten

(*) Not standard S.A.E. types.

APPLICATION	STEEL
AUTOMOTIVE PASSENGER AND TRUCK PARTS—*Continued*	
Front Axles	S.A.E. 4140—Amola .45/.50 C
Gears—Differential Side Gears	S.A.E. 2315—3115—4115—4615—6130—Amola (.35/.40 C)
Intake Valves	S.A.E. 3140
Knuckles	S.A.E. T-1340—3135—3140—3335—4140
Knuckle Pins	S.A.E. 2315—3115—4615
Piston Pins	S.A.E. *4120—4615—5120
Propeller Shafts . . .	S.A.E. 3140
Pump Shafts	S.A.E. 4615—U·S·S 12—Nitralloy
Radiator Grills . . .	U·S·S 18-8
Rear Axles	S.A.E. 1330—X-3140—3240—4140—4150—4340—Amola .60/.70 C
Springs—Leaf and Coil . .	S.A.E. 5150—6150—9255-60—Amola .60/.70 C
Steering Worm . . .	S.A.E. 4120—*5130—*5135—3115+.10/.20 Mo
Trailer Axles . . .	S.A.E. T-1345—2340—3140—4140
Transmission Gears . .	S.A.E. 2315—3120—3145—3312—*4115—4620—4620(½% Cr)—4640 5140—*5145—Amola (.30/.35 C)
Transmission Spline Shafts .	S.A.E. T-1345—3115—4140—4620—*5145—Amola (.20/.25 C)
Valve Springs . . .	S.A.E. 6150
BEARING STEELS	
Balls	S.A.E. 52100 and modifications, viz.: *(a) 1% C—1% Cr—1% Mn *(b) 1% C—1% Cr *(c) 1% C—½% Cr *(d) 1% C—1% Mn—½% Cr *(e) 1% C—18% Cr
Cups, Cones (Outer and Inner Races)	S.A.E. 3120—3312—4120—4615—4815—5120—6120—52100—*a—b—c—d—e

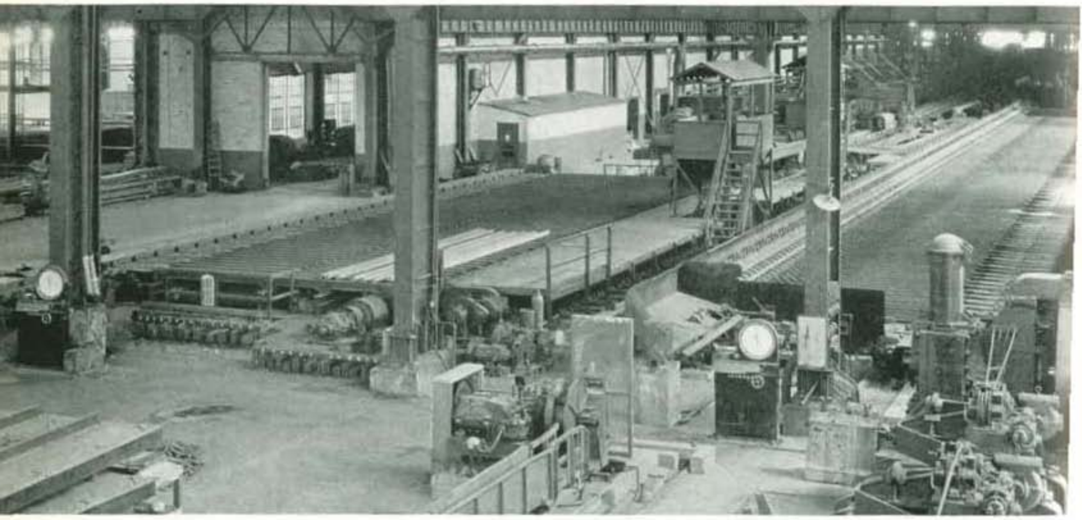
(*) Not standard S.A.E. types.

APPLICATION	STEEL
BEARING STEELS—*Continued*	
Rollers	S.A.E. 3312—4615—4815—6120—1% C—18% Cr
BRIDGES—DAMS AND LOCKS (CONTROLLED WATERWAYS)	
Bearing Plates	U·S·S 18-8
Blast & Cover Plates . .	Cor-Ten
Bulkheads	Cor-Ten and Man-Ten
Bumper Plates . . .	Cor-Ten
Cables	.35 C + ½% Ni
Cantilever Pins . . .	S.A.E. 3130—X-4130—Normalloy
Controller Boxes . . .	Cor-Ten
Crest Plates	Cor-Ten
Eye Bars	S.A.E. 2335—*X-4135
Nappe (side) Shields . .	Cor-Ten
Reinforcing Bars (High Strength)	4 to 6% Cr
Roller Gates	Cor-Ten and Man-Ten—U·S·S 12
Seal Plates	Cor-Ten and A-R Steel
Tainter Gates . . .	Cor-Ten
Tie Plates and Trusses . .	S.A.E. 2330—Cor-Ten
Tracks	Cor-Ten and A-R Steel
BUILDING TRADES	
For architectural applications	U·S·S· 18-8—U·S·S 18-8 S—U·S·S 17—Cor-Ten
CHEMICAL INDUSTRY	
Heat Exchanger Tubes . .	S.A.E. 2315—2515—U·S·S 18-8—U·S·S 16-13-3—U·S·S 17
Jordan Bars (paper industry) .	S.A.E. 3140—4140—U·S·S-12
Low Temperature Processing Equipment . . .	S.A.E. 2315 *(2½% Ni—.25 C max.)
Reaction Vessels—Vacuum, Atmospheric and high pressure . . .	U·S·S 27—25-20—25-12—U·S·S 12—U·S·S 18-8s—U·S·S 18-8s-Mo—U·S·S 17

(*) Not standard S.A.E. types.

APPLICATION	STEEL
CHEMICAL INDUSTRY—*Continued*	
Shafting	S.A.E. 2335—U·S·S 18-8
Tubes for Conveying Purposes	U·S·S 18-8s—U·S·S 17—U·S·S 16-13-3
Tube Sheets for Evaporators	S.A.E. 2315—U·S·S 18-8s—U·S·S 17—U·S·S 16-13-3
ERECTION AND CONSTRUCTION MACHINERY	
Booms	S.A.E. 2335—Cor-Ten and Man-Ten
Buckets	Cor-Ten, Man-Ten and A-R Steel
Bucket Teeth	S.A.E. X-3140—5150—9260—*Cr-Ni-Mo (4355)—12% Mn Steel
Chain Links	S.A.E. T-1345—3135—3145—3250—4140 (.25/.40 Mo)—*5130
Chain Pins	S.A.E. 2315—3250—4150—4620—Amola .60/.70 C
Chutes	Cor-Ten, Man-Ten and A-R Steel—U·S·S 12
Conveyors	Cor-Ten, Man-Ten and A-R Steel—U·S·S 12
Conveyor Links	Cor-Ten, Man-Ten and A-R Steel
Dredging Cutters	S.A.E. 2315—4615—4815
Gears	S.A.E. 2320—3115—3140—4620

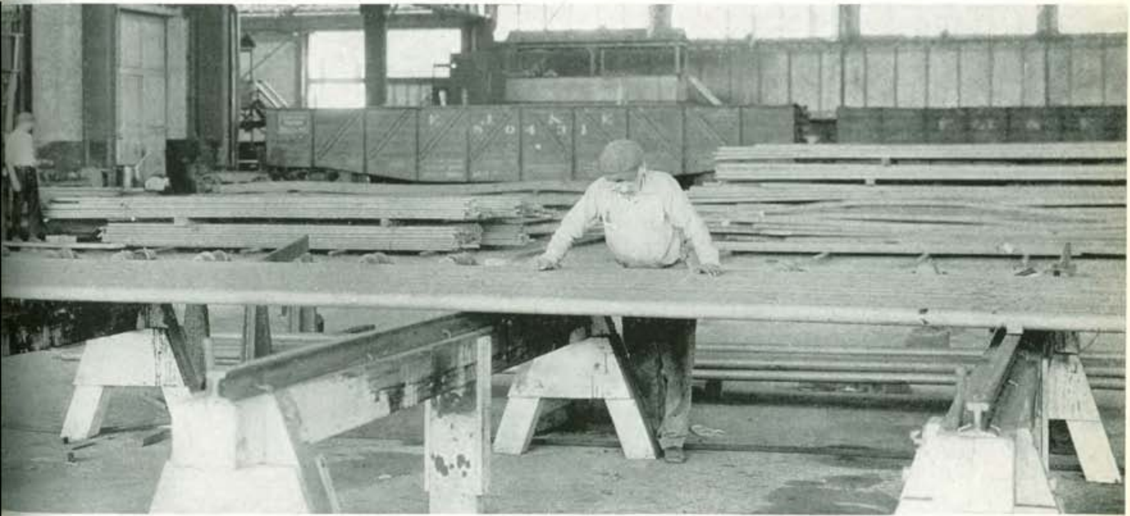
(*) Not standard S.A.E. types.



In this section of the mill alloy bars are accurately sheared to length

APPLICATION	STEEL
ERECTION AND CONSTRUCTION MACHINERY—*Continued*	
Hoppers	Cor-Ten, Man-Ten and A-R Steel
Scarifier Teeth . . .	S.A.E. *3160—5150—6150—9260—A-R Steel
Scraper Blades . . .	S.A.E.*3160—Amola(.60/.70C)—A-R Steel
Skips and Cages . . .	S.A.E. 2320—2330—Cor-Ten, Man-Ten and A-R Steel
Sprockets	S.A.E. T-1345—3115—3140—4140—4620
Track Pins . . .	S.A.E. 2320—4620
Winch Shafts . . .	S.A.E. 2340—3140—4145—6140
FOOD INDUSTRIES	
Cooking Utensils . . .	U·S·S 18-8s—U·S·S 17—U·S·S 18-8s Mo
Milk Cans	U·S·S 18-8s—U·S·S 17—U·S·S 18-8s Mo
Pasteurizing Equipment . .	U·S·S 18-8s—U·S·S 17—U·S·S 18-8s Mo
Processing Equipment . .	U·S·S 18-8s—U·S·S 17—U·S·S 18-8s Mo
Storing Equipment . .	U·S·S 18-8s—U·S·S 17—U·S·S 18-8s Mo
Tanks, Vats, Fermentation Vessels	U·S·S 18-8s—U·S·S 17—U·S·S 18-8s Mo
Trays	U·S·S 18-8s—U·S·S 17—U·S·S 18-8s Mo
Tubing	U·S·S 18-8s—U·S·S 17—U·S·S 18-8s Mo

(*) Not standard S.A.E. types.



A trained workman is examining 3½% nickel alloy 3" rounds for possible surface defects

APPLICATION	STEEL
FORMING DIES AND HAMMER SHOP EQUIPMENT	
Blanking Dies . . .	S.A.E. *3440—*4345—Cr-Va (.45 C)—C-Va (.90 C)
Cold Heading Dies . .	S.A.E. *4345
Crankshafts (Heavy Duty) .	Cr-Ni-Mo (.40C)
Die Blocks—hot work . .	S.A.E. *3160—*4155—6150 Cr-Ni-Mo (.50/.60 C-.30 Mo) Cr-Ni-Mo (.50/.60 C-.75 Mo)
Die Casting Dies . . .	S.A.E. 3140—*4345
Piston Rods	Cr-Ni-Mo (.30/.35 C-.25 Mo)
Plastic Molding Dies . .	S.A.E. *3110—4610
Rams	Cr-Ni-Mo (.40 C)
Saw Blocks	Cr-Ni-Mo (.55 C)
Trimmer Dies . . .	Cr-Ni-Mo (.65 C) Cr-Mo (.85 C)
HYDRAULIC MACHINERY	
Impellers	S.A.E. 3140—4140—4145
Piston Rods	S.A.E. 2335—4140—6145—Normalloy
Rams	S.A.E. 2335—4140
Shafts	S.A.E. 2335—3140—4145—4345—6145
Valves, Fittings . . .	S.A.E. 2320—Nitralloy
MACHINE TOOLS	
Chuck Jaws	S.A.E. 4615—6150
Collets—Feed Fingers . .	S.A.E. 2350
Gears	S.A.E. 2315—2350—3115—4615—*4650—*5145—*6145
Lead Screws (Precision) .	S.A.E. 3140—4140—6140
Shafts	S.A.E. 2340—3140—3150—3250—*4650
Spindles	S.A.E. 2315—2340—3140—4145—4615—6145
Tool Holders . . .	S.A.E. 2315—3115—3245—4150—4620—6150

(*) Not standard S.A.E. types.

APPLICATION	STEEL
MARINE APPLICATIONS	
Barges	Cor-Ten and Man-Ten
Camshafts	S.A.E. 2335
Crankshafts	S.A.E. 3140—*4145—*4345—6140
Dredges	Cor-Ten, Man-Ten and A-R Steel
Engine Bolts	S.A.E. 3140—4140
Propeller Shafts	S.A.E. 2335—3240—4340—18-8
River Boats	Cor-Ten and Man-Ten
Steamer Parts	Cor-Ten, Man-Ten and A-R Steel
Tankers	Cor-Ten
See also Power Plants for high pressure steam parts	
MILL EQUIPMENT	
Textile, Printing and Laundry Equipment—	
Bearings	See BEARING STEEL
Chain Links	S.A.E. 4140—*5135
Connecting Rods	S.A.E. 3140—4140
Gears	S.A.E. 2315—3115—4620—5150
Rollers	S.A.E. 2335—2340
Shafts	S.A.E. 3140—4140—6140
Spindles	S.A.E. 3140—4140
See also Chemical Industry for Vats, Tubs, etc.	
MINING AND MILLING MACHINERY	
Drilling and Digging Machinery—	
Bits	S.A.E. 9260—Si-Mn-Mo (.50/.60% C)
See also Pneumatic Machinery	
Crusher Jaws	S.A.E. 5150—9260—12-14% Mn
Crusher Shafts	S.A.E. 3140—4145—4340
Cutters for Undercutting Machines	S.A.E. 9260—Si-Mn-Mo(.50/.60% C)
Mill Balls	S.A.E. 9260—52100
Screens	S.A.E. 6150—A-R Steel—U·S·S 12

(*) Not standard S.A.E. types.

APPLICATION	STEEL
MINING AND MILLING MACHINERY—*Continued*	
Handling Equipment—	
Conveyor Parts and Chains	Cor-Ten, Man-Ten and A-R Steel
See also ERECTION AND CONSTRUCTION	
Hoist Cables	1½% Ni
Quarry and Mine Cars	Cor-Ten and Man-Ten
Skips and Cages	Cor-Ten, Man-Ten and A-R Steel
OIL INDUSTRY	
Oilwell Drilling and Pumping Equipment—	
Bolts	S.A.E. 3140—3245—4140
Crown and Travel Block Pins	S.A.E. 3115—4615
Bearings	S.A.E. 3115—4615—52100
Couplings	S.A.E. 3140—4140
Derricks	Sil-Ten
Draw Works Chain—	
Bushings	S.A.E. 2320
Pins	S.A.E. 2515—3240—Amola(.60/.70C)
Side Bars	S.A.E. 3135—4140
Draw Works Shafting	S.A.E. 3140—X-3140—3245—*4145
Drill Collars	S.A.E. 3140—X-3140—4140
Drill Pipe	Mn-Mo—Si-Mn-Cr
Jars	S.A.E. 3140—4140
Kelly Bars	S.A.E. 3140—X-3140—4140
Reamer Bodies	S.A.E. 3140—4140
Reamer Cutters	S.A.E. 3115
Rods—Polished	S.A.E. T-1340—4130—U·S·S 18-8
Pony	S.A.E. T-1340—4130
Pull	S.A.E. T-1330—T-1340—4130
Rods—Sucker, Sub Rods	S.A.E. T-1340—*2310—3135—4615—4815—3½% Ni-Mo (low C)
Rotary Cutters	S.A.E. 3115—4815
Rotary Table—Gears	S.A.E. 2315—2515—3245
Shafting	S.A.E. X-3140—3240—4140
Slips	S.A.E. 2315—3115—4615

(*) Not standard S.A.E. types.

APPLICATION	STEEL
OIL INDUSTRY—*Continued*	
Oilwell Drilling and Pumping Equipment—*Continued*	
Slush Pump Liners	S.A.E. 4615—*4120
Rods	S.A.E. 3140—4140—4815—U·S·S 18-8
Swivels and Bearings	S.A.E. 3312—52100
Tool Joints	S.A.E. 3135—3140—X-3140—4140
Walking Beams	Man-Ten and Sil-Ten
PNEUMATIC MACHINERY	
Air Compressors—	
Crankshafts—Small	S.A.E. 3140—4140—6140
Large	S.A.E. 2340—3240—*4145
Pneumatic Tools—	
Barrels	S.A.E. 2315—4615
Bits	S.A.E. 5150—6150—9260—Amola .60/.70 C—Si-Mn-Mo (.50/.60 C)
Chucks	S.A.E. 3120—4620
Pistons	S.A.E. 2345—3140
Valves and Valve Seats	S.A.E. 3140—6140
POWER HOUSE EQUIPMENT	
Auxiliary Equipment—	
Coal Crusher Jaws	S.A.E. 5150—9260
Flanges	2½% Ni
Pins	S.A.E. 3140
Studs	S.A.E. 4140—U·S·S 12
Valve Bodies	S.A.E. 3140—4140
Valve Seats	S.A.E. 6140—U·S·S 12
High Temperature Applications—	
Boiler Staybolts	2% Ni (low C)
Prime Movers—	
Rotors	S.A.E. 2335—3140—4130—Cr-Ni-Mo .35 C
Shafts	S.A.E. 2340—3140—4140
Turbine Blades	S.A.E. *2512—U·S·S 12—U·S·S 12 with .50 Mo

(*) Not standard S.A.E. types.

APPLICATION	STEEL
RAILWAY APPLICATIONS	
Locomotive Parts—	
Boiler Plate . . .	2¼% Ni (low C)
Boiler Tubes . . .	2¼% Ni (low C)
Engine Bolts . . .	S.A.E. 2115—3120
Main Axles . . .	C-Va—2¾% Ni—Mn-Va
Main Rods . . .	C-Va—2¾% Ni (.25 C)—Mn-Va
Pins	C-Va—2¾% Ni—Mn-Va
Piston Rods . . .	C-Va—2¾% Ni (.25 C)—Mn-Va
Roller Bearing Parts . .	S.A.E. 3312—4615—52100
Side Rods . . .	C-Va—2¾% Ni—Mn-Va
Springs	S.A.E. *4650—6150—9260
Staybolts	2¼% Ni (low C)
Passenger Equipment—	
Car Siding and Shapes .	U·S·S Cor-Ten and Man-Ten
Diner Kitchen Equipment .	U·S·S 18-8
StreamlineSheathingandShapes	U·S·S Cor-Ten and U·S·S 18-8
Wheels	Amola (.50 C—.40 Mo)
REFINERY EQUIPMENT	
Bolts—High Temperature	S.A.E. 3140—4140—4340—6140—U·S·S 12—C-Va (.35/.45 C)
Cracking Still Tubes . .	U·S·S 18-8s—5% Cr-Mo-Ti—5% Cr-Mo-Al—5% Cr-Mo-Cb—2% Cr-Mo—9% Cr-Mo—5% Cr-Mo
Dewaxing Tubes . .	4/6% Cr-Mo-Ti—4/6% Cr-Mo-Cb
Heat Exchanger Tubes .	4/6% Cr
Pipe Valves and Fittings .	S.A.E. 2330—3140—4140
A—High Temperature .	4/6% Cr-Mo—U·S·S 18-8—U·S·S 12
B—Low Temperature . .	S.A.E. 2315—2½% Ni-Mn (.25 C)
Piston Rods and Plungers—	
High Temperature . .	S.A.E. 6150—U.S.S. 12—U·S·S 18-8

(*) Not standard S.A.E. types.

APPLICATION	STEEL
REFINERY EQUIPMENT—*Continued*	
Pressure Vessels—	
High Temperature	S.A.E. 6125—C-Mo (.50/1.00% Mo)
Low Temperature . .	S.A.E. 2320—2½% Ni (.25 C)
Linings	U·S·S 12
Staybolts	S.A.E. 3140—4140
SMALL TOOLS	
Chisels	S.A.E. 6150—7260—9260—Amola (.60/.70 C)—C-Va (.90 C)—Si-Mn-Mo (.50/.60 C)—Si-Mn-Mo-V (.50/.60 C)
Hammers	S.A.E. 5150—6150—C-Cr (.70/.80 C) —C-Va (.90 C)—Amola (.60/.70 C)
Hatchets and Axes . .	C-Cr (.70/.80) C—C-Mo (.70/.80 C) —C-Va (.90 C)
Malls and Track Hammers .	S.A.E. 9260—Si-Mn-Mo (.50/.60% C)
Pliers	S.A.E. 4150—4615—6140—6150—C-Cr (.70/.80 C)
Screw Drivers . . .	S.A.E. *4650—6150—C-Va (.90 C)—Amola (.60/.70 C)
Shovels	S.A.E. 3140—C-Mo (.70 Mo)
Wrenches	S.A.E. 4140—4150—6140—6150—C-Va (.90 C)
TRACTORS AND FARM IMPLEMENTS	
Tractors—	
Arms	S.A.E. 3140—4140
Axles	S.A.E. 3140—4140
Bearings	S.A.E. 4615—52100
Coil Springs . . .	S.A.E. 9260
Gears	S.A.E. 2345—3115—4115—4615
Knuckles . . .	S.A.E. 3140—4140
Leaf Springs . . .	S.A.E. 9260

(*) Not standard S.A.E. types.

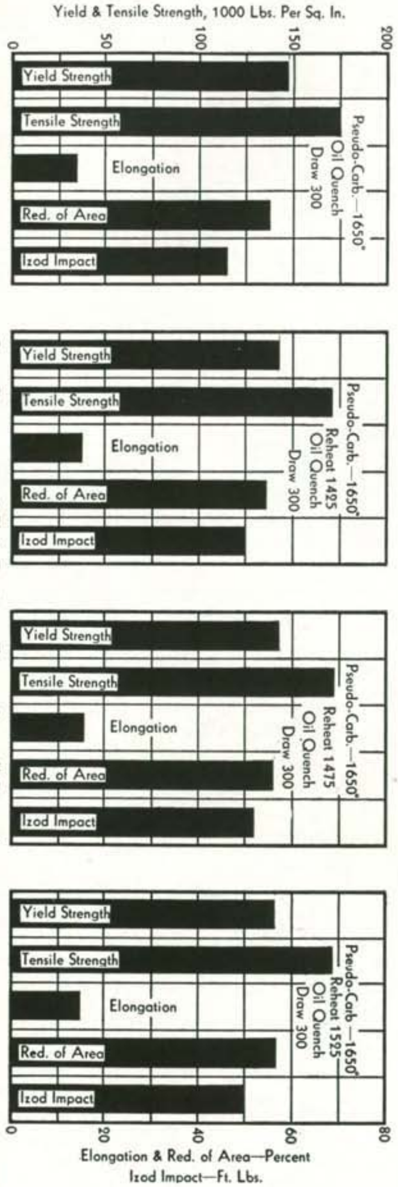
PHYSICAL PROPERTIES CARBURIZING GRADES OF U·S·S CARILLOY ALLOY STEELS DOUBLE QUENCHED

Each of the following sets of charts shows the average physical properties of the core of one carburizing grade in four different conditions of heat treatment. In all cases, specimens 1" in diameter were heated in iron chips at a temperature of 1650° to 1680° F. for eight hours. One set was direct quenched from the pot in oil, the other three sets were box cooled and then reheated to 1425° F., 1475° F. and 1525° F. respectively and quenched in oil. All test pieces were drawn at 300° F. and then machined into standard .505" tensile test specimens and standard Izod impact specimens. As an example, the core properties of S.A.E. 3312, box cooled and reheated to 1475° F., are as follows:

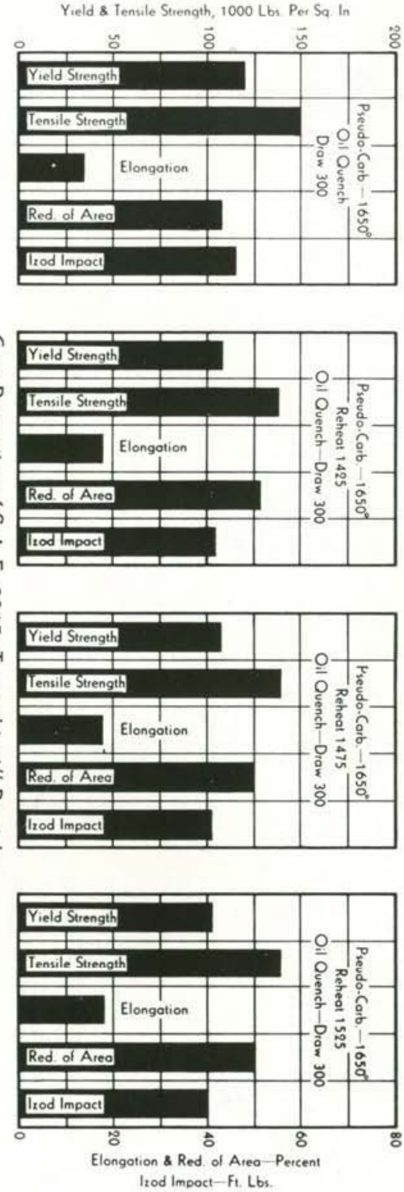
Yield strength	155,000 lbs./sq. in.	read on the left scale
Tensile strength	180,000 lbs./sq. in.	read on the left scale
Elongation	20%	read on the right scale
Reduction of Area	61%	read on the right scale
Izod impact	47 ft. lbs.	read on the right scale

It is emphasized that the values shown in the charts are average values and do not apply as minimum values for specifications, but are to represent general averages which may be expected in the sizes given.

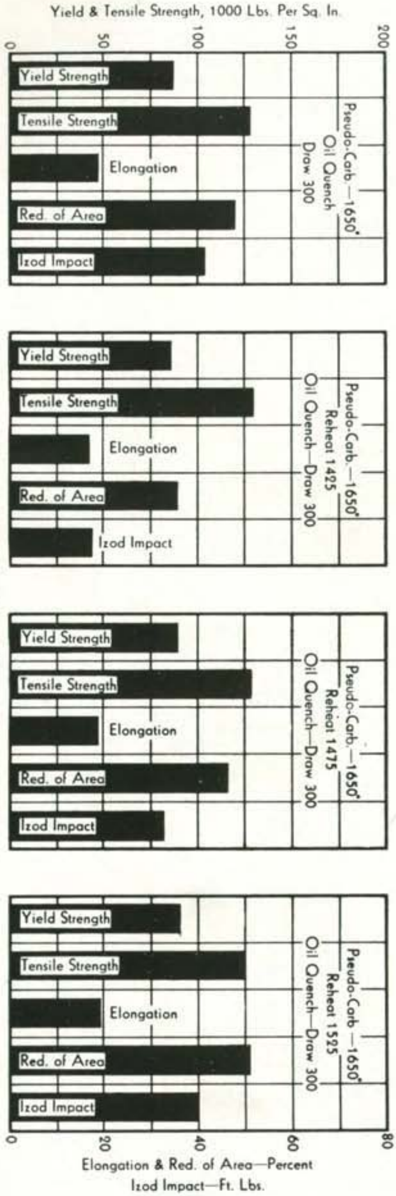
(*) Grades so indicated are not standard S.A.E. types.



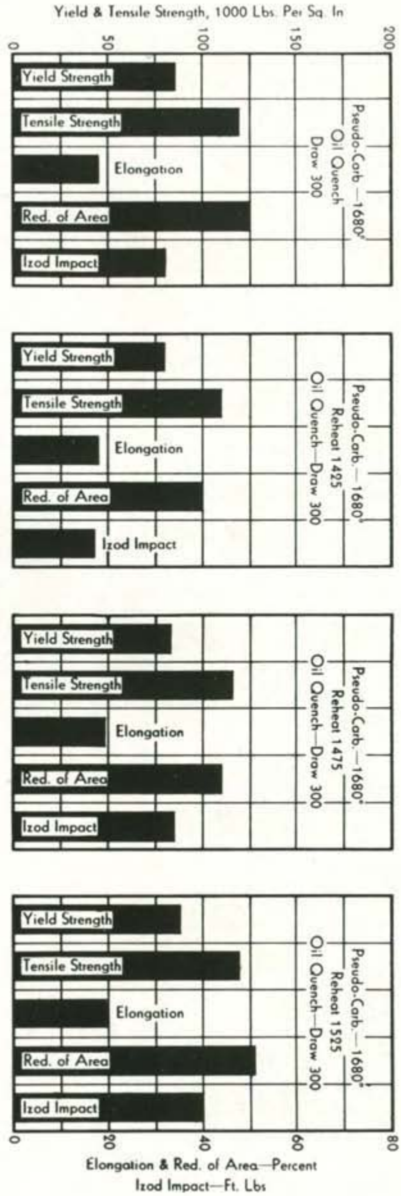
Core Properties of S.A.E. 2515 Treated in 1" Rounds



Core Properties of S.A.E. 2315 Treated in 1" Rounds

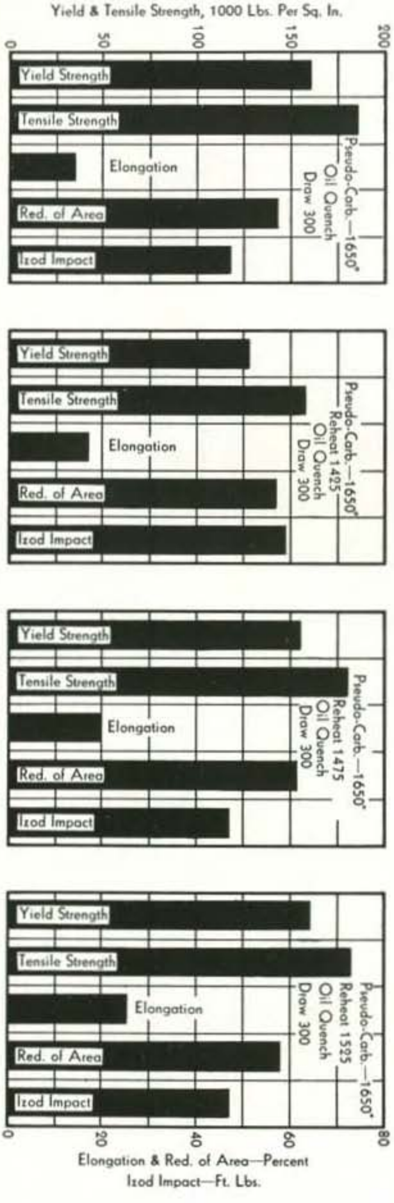


Core Properties of S.A.E. 3115 Treated in 1" Rounds

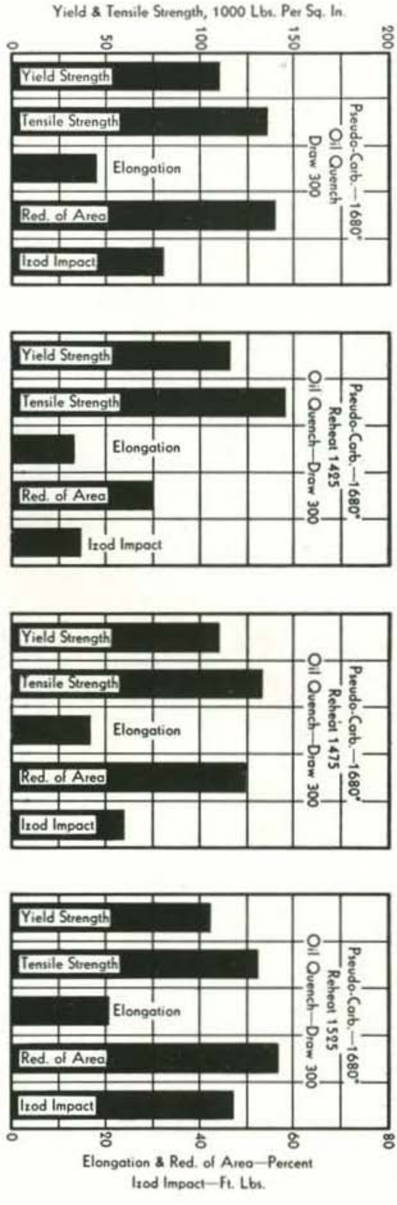


*Core Properties of Low Cr. Ni. Steel (3020) Treated in 1" Rounds

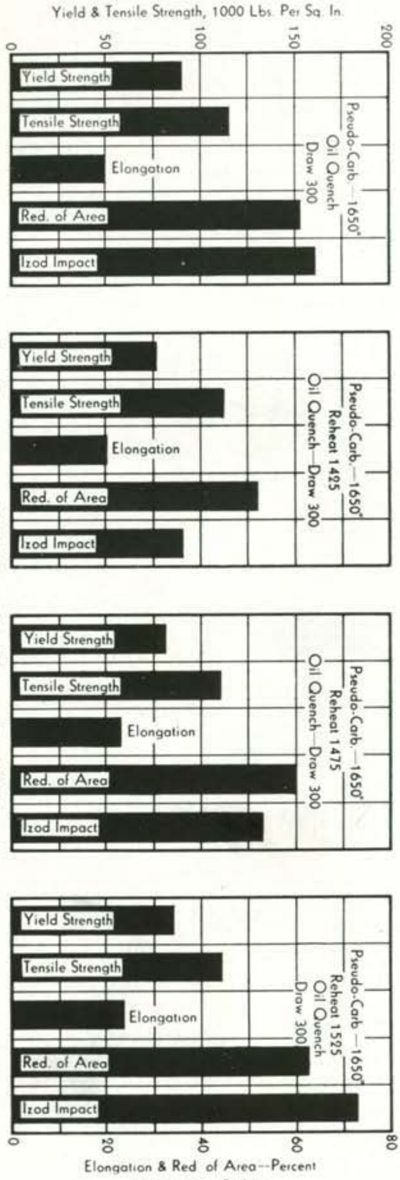
Core Properties of S.A.E. 3312 Treated in 1" Rounds



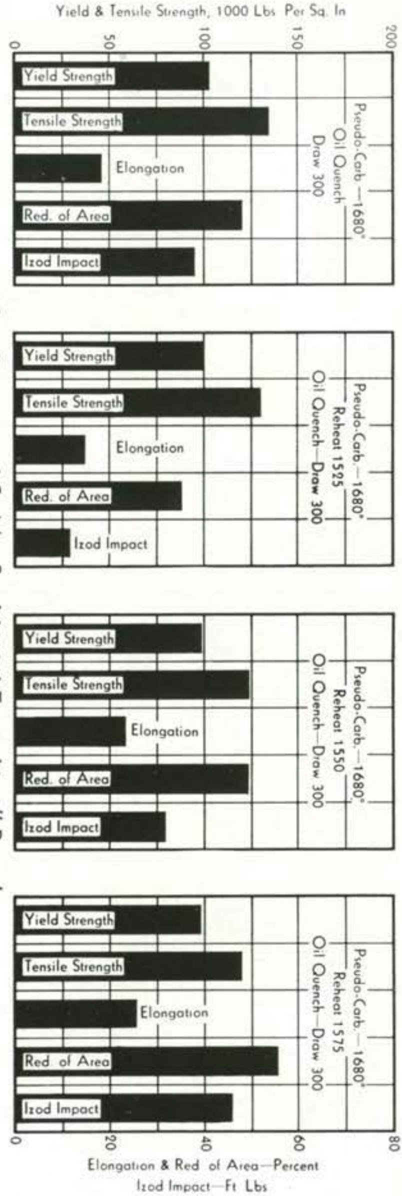
*Core Properties of 3120 (.10/.20 Mo) Treated in 1" Rounds

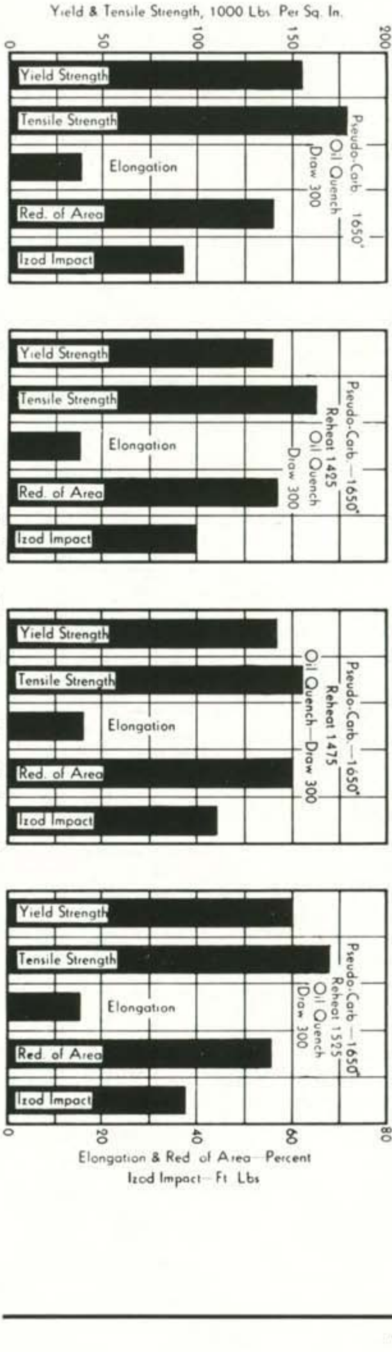


Core Properties of S.A.E. 4620 Treated in 1" Rounds

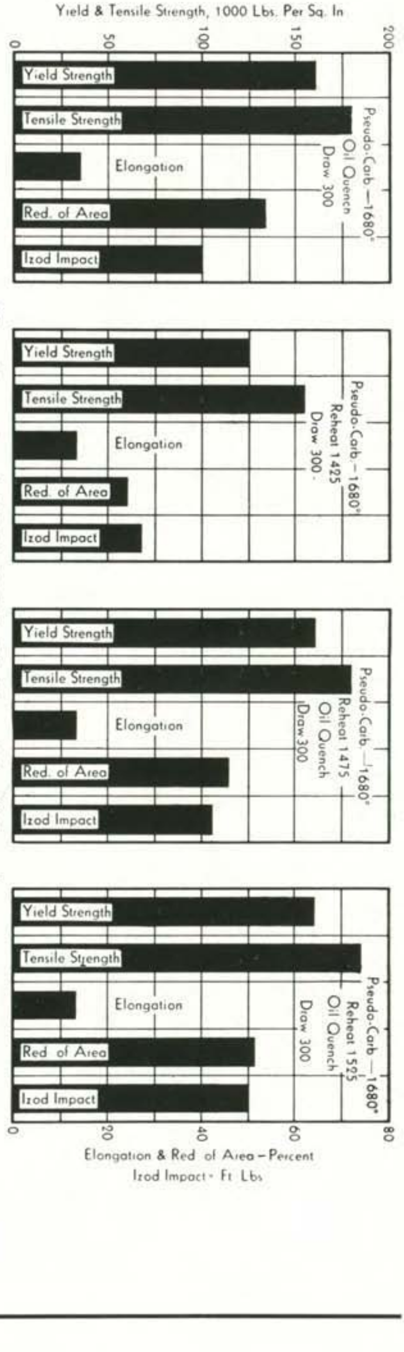


*Core Properties of Cr. Mo. Steel (4120) Treated in 1" Rounds



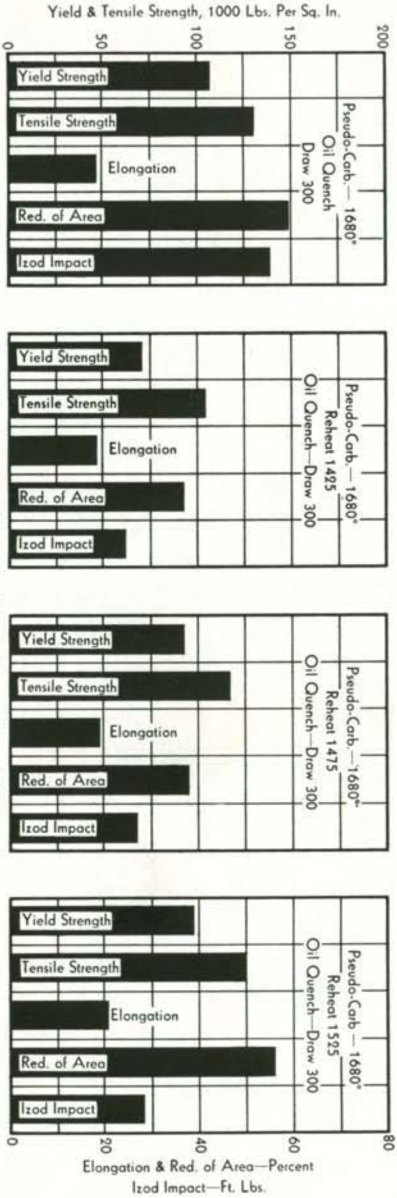


Core Properties of S.A.E. 4815 Treated in 1" Rounds

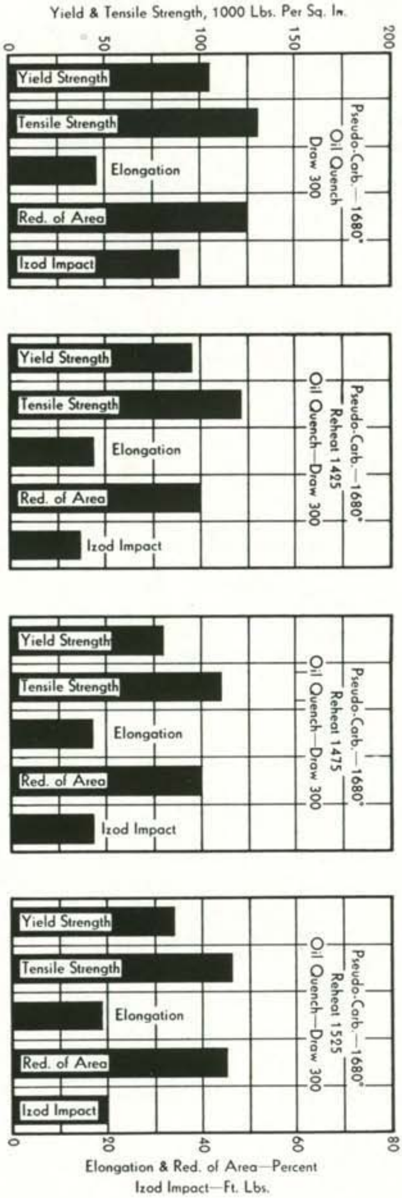


*Core Properties of 4620 (.30/.60 Cr) Treated in 1" Rounds

Core Properties of S.A.E. 6120 Treated in 1" Rounds



Core Properties of S.A.E. 5120 Treated in 1" Rounds



PHYSICAL PROPERTIES CARBURIZING GRADES OF U·S·S CARILLOY ALLOY STEELS SINGLE QUENCHED

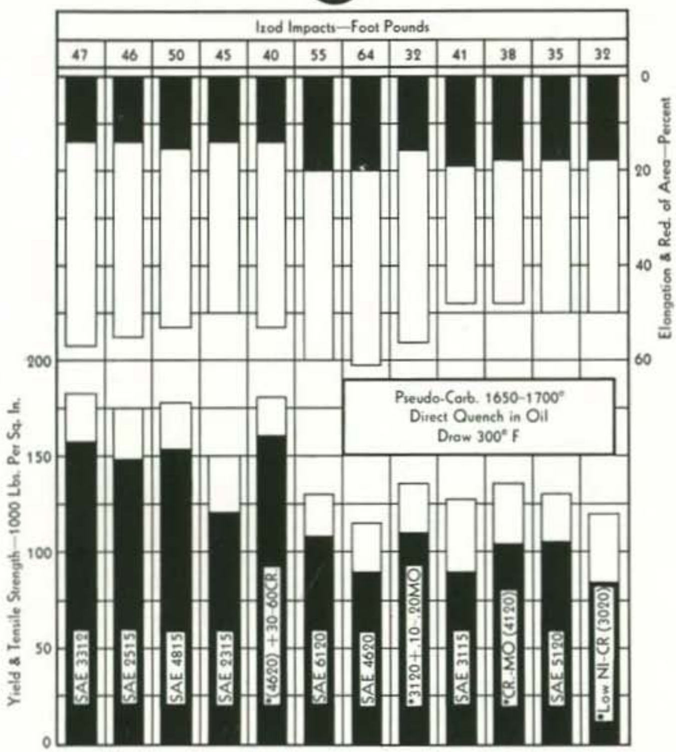
The following chart is a summary of the physical properties of carburizing grades. All of the values are for 1" specimens, "pseudo-carburized" (i.e., heated in iron chips) at temperatures between 1650° F. and 1700° F. and direct quenched in oil. All were drawn at 300° F. The physical tests were conducted on standard .505" tensile test specimens and standard Izod impact specimens. As an example, the physical properties of S.A.E. 4620 are as follows:

Yield strength	90,000 lbs./sq. in.	read the lower solid column on the lower left-hand scale.
Tensile strength	115,000 lbs./sq. in.	read the lower blank column on the lower left-hand scale.
Elongation	20%	read the upper solid column on the upper right-hand scale.
Reduction of area	61%	read the upper blank column on the upper right-hand scale.
Izod impact	64 ft./lbs.	read the number above the column.

It is emphasized that the values shown in the chart are average values and do not apply as minimum values for specifications but are to represent general averages which may be expected in the sizes given.

(*) Grades so indicated are not standard S.A.E. types.

CORE PROPERTIES OF USS CARILLOY CARBURIZING STEELS



PHYSICAL PROPERTIES OIL AND WATER HARDENING GRADES OF U·S·S CARILLOY ALLOY STEELS

The following charts show physical properties when quenched and drawn at the temperatures indicated on the lower horizontal scale. Additional information which can be read from the charts are the critical temperatures, the Brinell hardness and the physical properties in the as-rolled, normalized and annealed condition. These data apply to 1″ round specimens for the S.A.E. grades quenched in oil or water as indicated and then drawn and machined to .505″ standard tensile test specimens.

As an example, the physical properties of S.A.E. 4130 quenched in oil from 1600° F. and drawn at 1000° F. are:

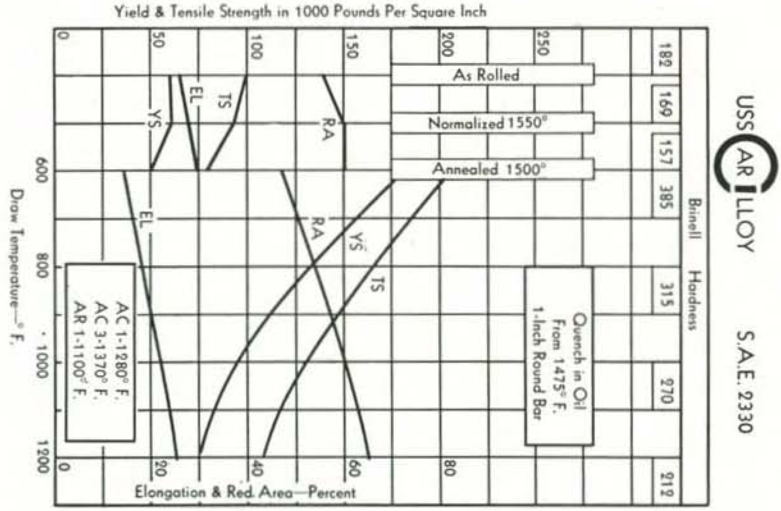
Yield strength	132,000 lbs./sq. in.	read left-hand scale
Tensile strength	150,000 lbs./sq. in.	read left-hand scale
Elongation	16%	read right-hand scale
Reduction of Area	53%	read right-hand scale
Brinell hardness	321	read number on top on 1000° F. line

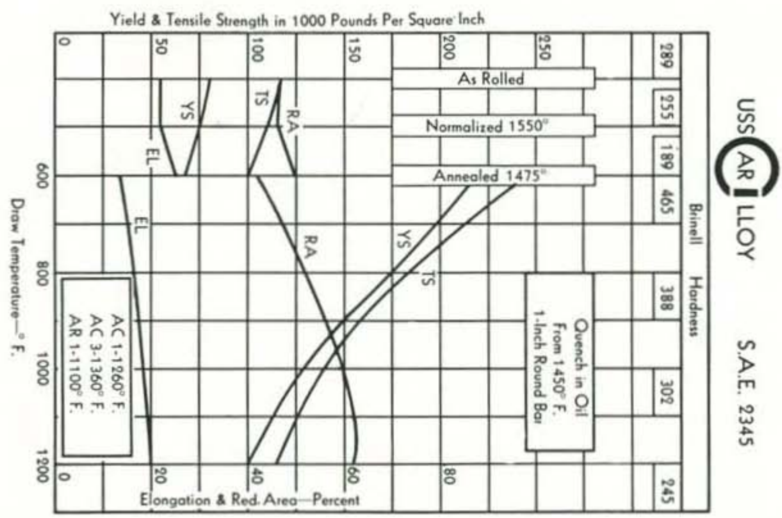
The properties in the annealed condition are as follows:

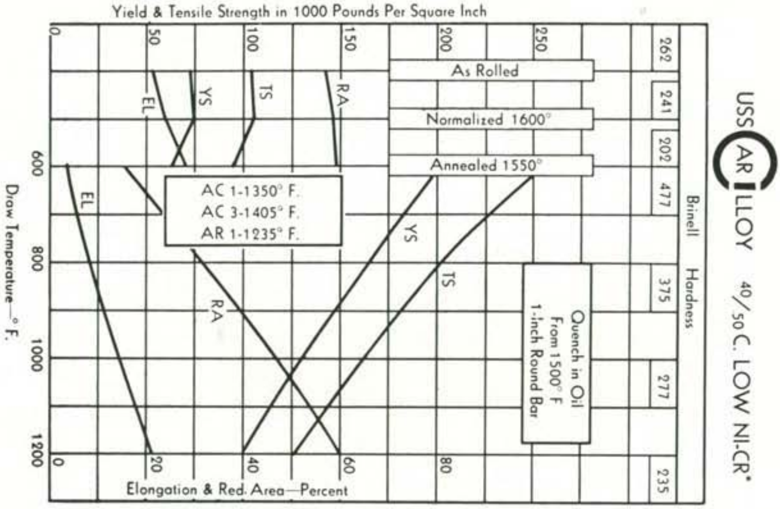
Yield strength	40,000 lbs./sq. in.	read on left-hand scale
Tensile strength	75,000 lbs./sq. in.	read on left-hand scale
Elongation	33%	read on right-hand scale
Reduction of Area	61%	read on right-hand scale
Brinell hardness	156	read number on top on 1000° F. line

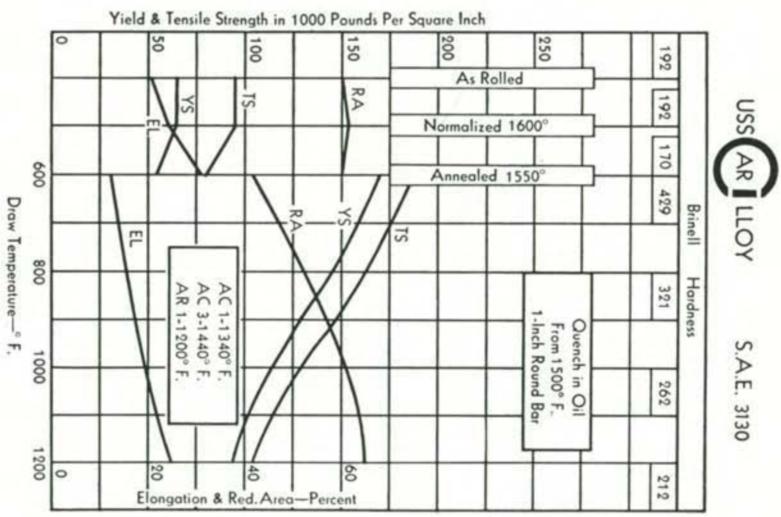
It is emphasized that the values shown in the charts are average values and do not apply as minimum values for specifications but are to represent general averages which may be expected.

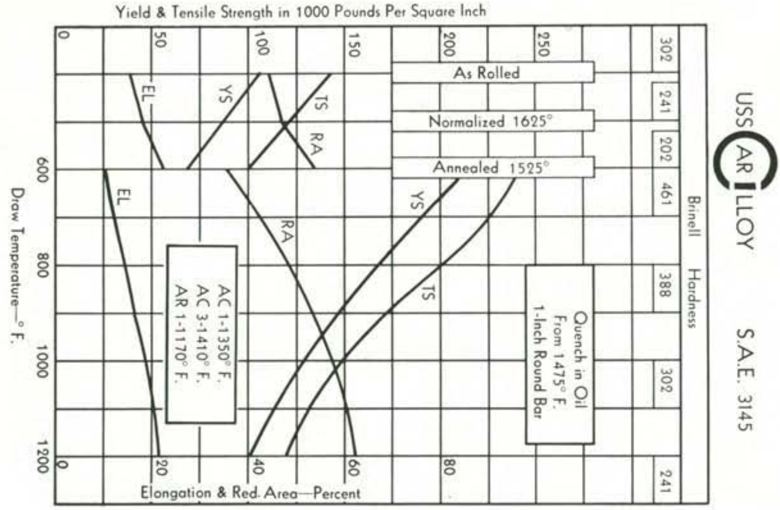
(*) Grades so indicated are not standard S.A.E. types.

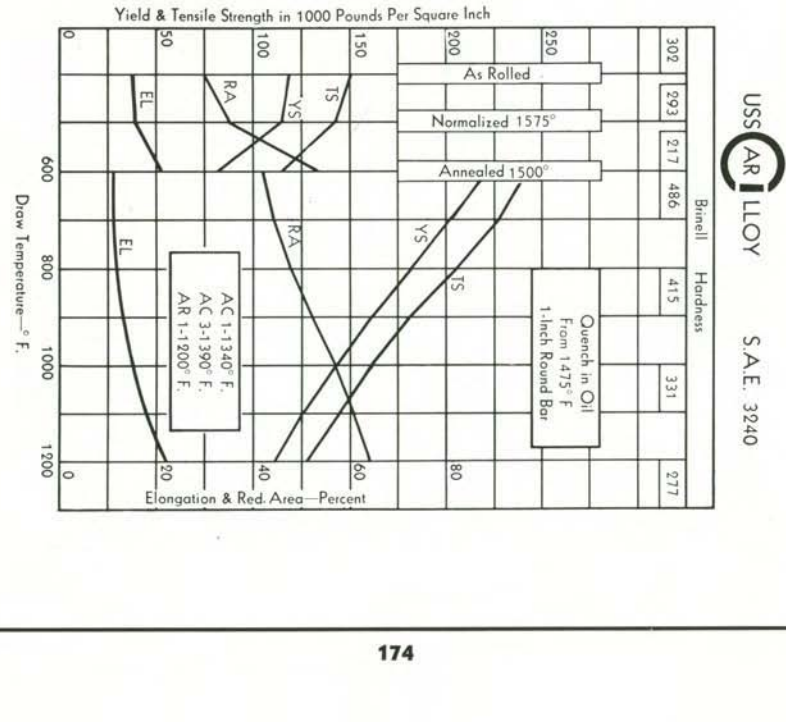

USS ARILLOY S.A.E. 2330
Yield & Tensile Strength in 1000 Pounds Per Square Inch
0
50
100
150
200
250
As Rolled
Normalized 1550°
Annealed 1500°
Brinell Hardness
182
169
157
385
315
270
212
YS
EL
TS
RA
Quench in Oil
From 1475° F.
1-Inch Round Bar
AC 1-1280° F.
AC 3-1370° F.
AR 1-1100° F.
600
800
1000
1200
Draw Temperature—° F.
0
20
40
60
80
Elongation & Red. Area—Percent

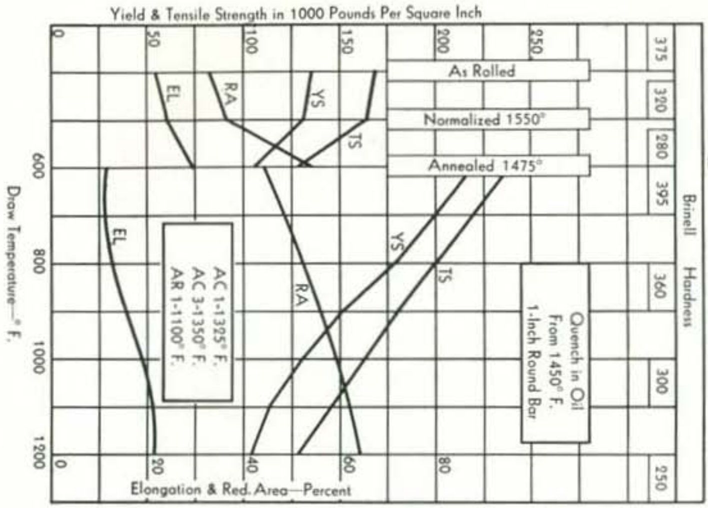

USS ARILLOY S.A.E. 2345
Yield & Tensile Strength in 1000 Pounds Per Square Inch
0
50
100
150
200
250
As Rolled
Normalized 1550°
Annealed 1475°
Brinell Hardness
289
255
189
465
388
302
245
YS
EL
TS
RA
Quench in Oil
From 1450° F.
1-Inch Round Bar
AC 1-1260° F.
AC 3-1360° F.
AR 1-1100° F.
600
800
1000
1200
Draw Temperature—° F.
0
20
40
60
80
Elongation & Red. Area—Percent


USS CARILLOY 40/50 C. LOW NI-CR*
Brinell Hardness
262
241
202
477
375
277
235
As Rolled
Normalized 1600°
Annealed 1550°
Quench in Oil
From 1500° F
1-inch Round Bar
AC 1-1350° F.
AC 3-1405° F.
AR 1-1235° F.
YS
TS
RA
EL
Yield & Tensile Strength in 1000 Pounds Per Square Inch
0
50
100
150
200
250
Elongation & Red. Area—Percent
0
20
40
60
80
Draw Temperature—° F.
600
800
1000
1200

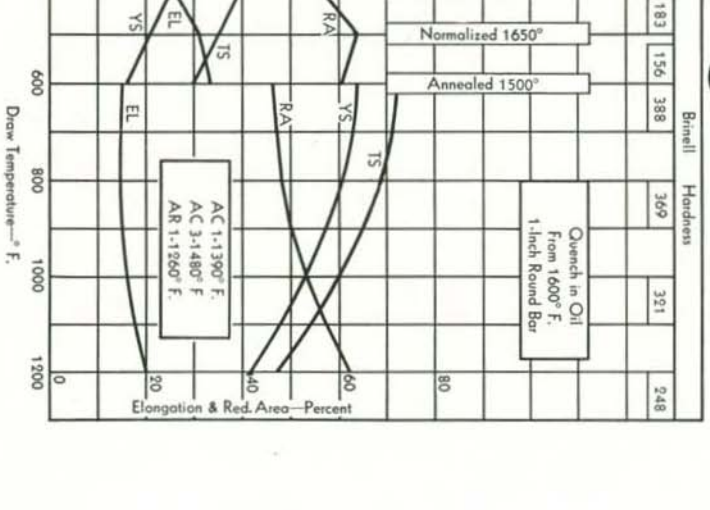

USS CARILLOY S.A.E. 3130
Brinell Hardness
192
192
170
429
321
262
212
As Rolled
Normalized 1600°
Annealed 1550°
Quench in Oil
From 1500° F.
1-Inch Round Bar
AC 1-1340° F.
AC 3-1440° F.
AR 1-1200° F.
YS
TS
RA
EL
Yield & Tensile Strength in 1000 Pounds Per Square Inch
0
50
100
150
200
250
Elongation & Red. Area—Percent
0
20
40
60
Draw Temperature—° F.
600
800
1000
1200


USS CARILLOY S.A.E. 3145
Yield & Tensile Strength in 1000 Pounds Per Square Inch
Elongation & Red. Area—Percent
Draw Temperature—° F.
Brinell Hardness
As Rolled
Normalized 1625°
Annealed 1525°
Quench in Oil From 1475° F. 1-Inch Round Bar
AC 1-1350° F.
AC 3-1410° F.
AR 1-1170° F.
EL
YS
TS
RA

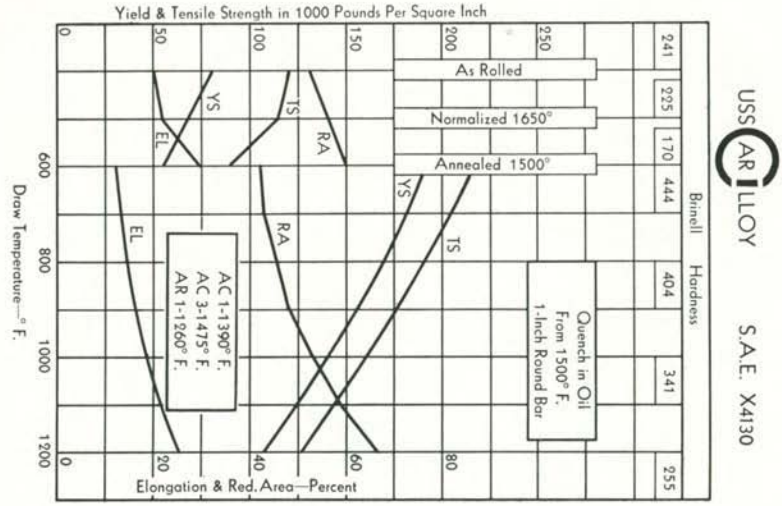

USS CARILLOY S.A.E. 3240
Yield & Tensile Strength in 1000 Pounds Per Square Inch
Elongation & Red. Area—Percent
Draw Temperature—° F.
Brinell Hardness
As Rolled
Normalized 1575°
Annealed 1500°
Quench in Oil From 1475° F 1-Inch Round Bar
AC 1-1340° F.
AC 3-1390° F.
AR 1-1200° F.
EL
YS
TS
RA

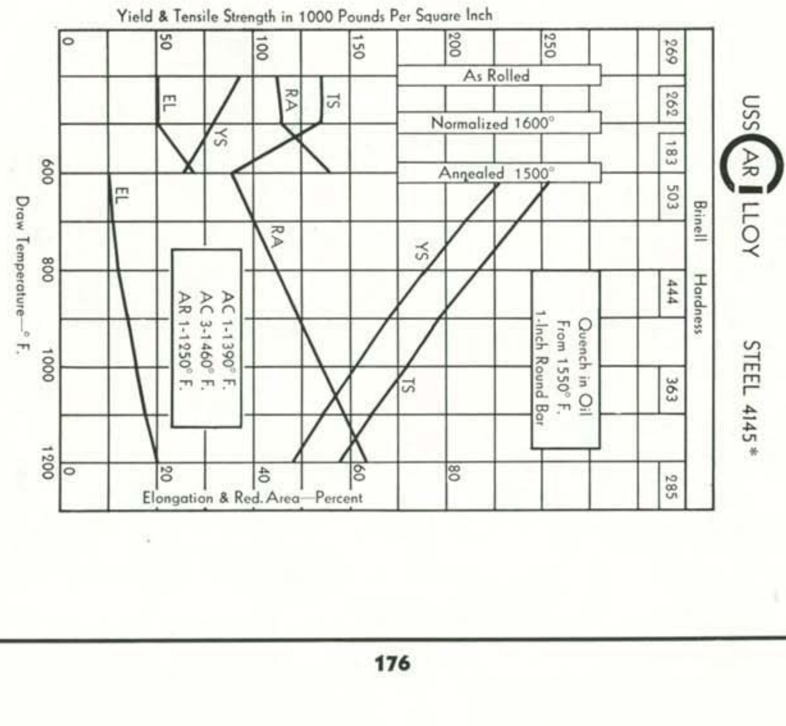


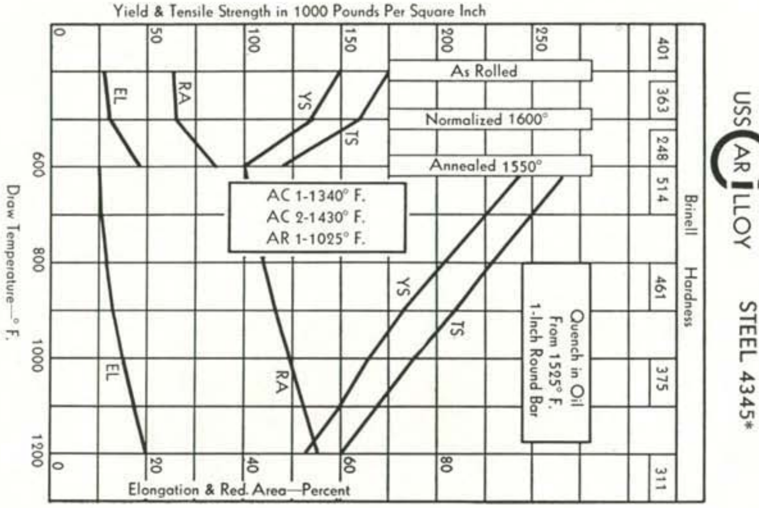
USS CARILLOY S.A.E. 3340

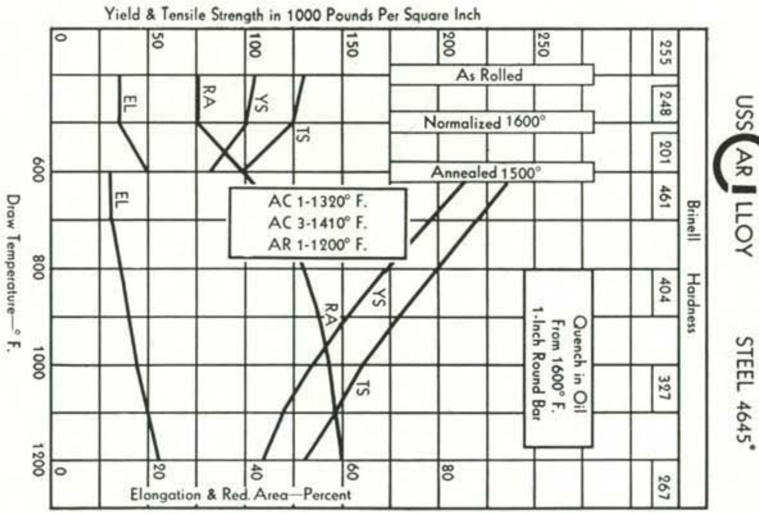


USS CARILLOY S.A.E. 4130

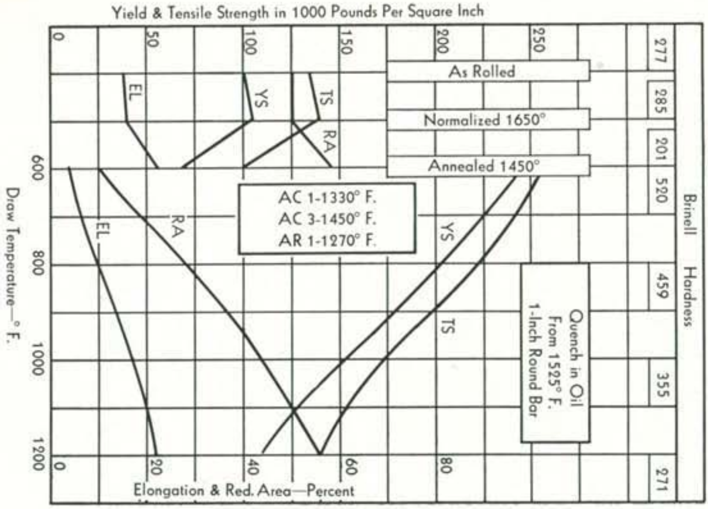

USS CARILLOY S.A.E. X4130
Yield & Tensile Strength in 1000 Pounds Per Square Inch
Elongation & Red. Area—Percent
Draw Temperature—° F.
Brinell Hardness
As Rolled
Normalized 1650°
Annealed 1500°
241
225
170
444
404
341
255
Quench in Oil From 1500° F. 1-Inch Round Bar
AC 1-1390° F.
AC 3-1475° F.
AR 1-1260° F.
YS
TS
RA
EL


USS CARILLOY STEEL 4145*
Yield & Tensile Strength in 1000 Pounds Per Square Inch
Elongation & Red. Area—Percent
Draw Temperature—° F.
Brinell Hardness
As Rolled
Normalized 1600°
Annealed 1500°
269
262
183
503
444
363
285
Quench in Oil From 1550° F. 1-Inch Round Bar
AC 1-1390° F.
AC 3-1460° F.
AR 1-1250° F.
YS
TS
RA
EL

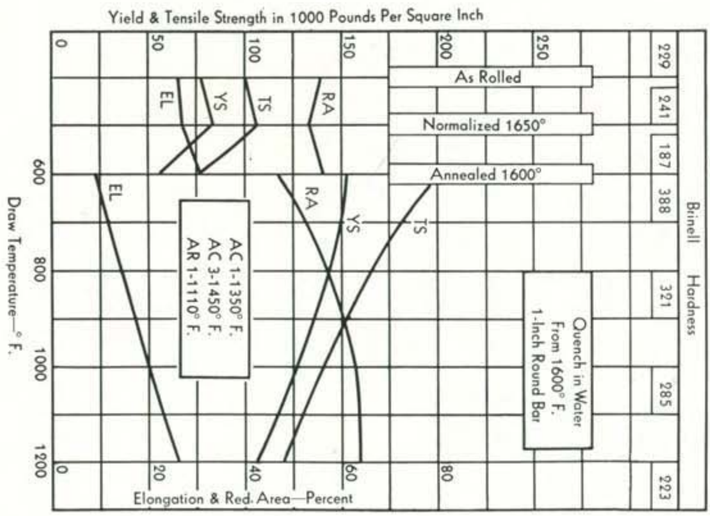

USS CARILLOY STEEL 4345*
Yield & Tensile Strength in 1000 Pounds Per Square Inch
Elongation & Red. Area—Percent
Draw Temperature—° F.
Brinell Hardness
As Rolled
Normalized 1600°
Annealed 1550°
AC 1-1340° F.
AC 2-1430° F.
AR 1-1025° F.
Quench in Oil
From 1525° F.
1-Inch Round Bar
401
363
248
514
461
375
311
EL
RA
YS
TS

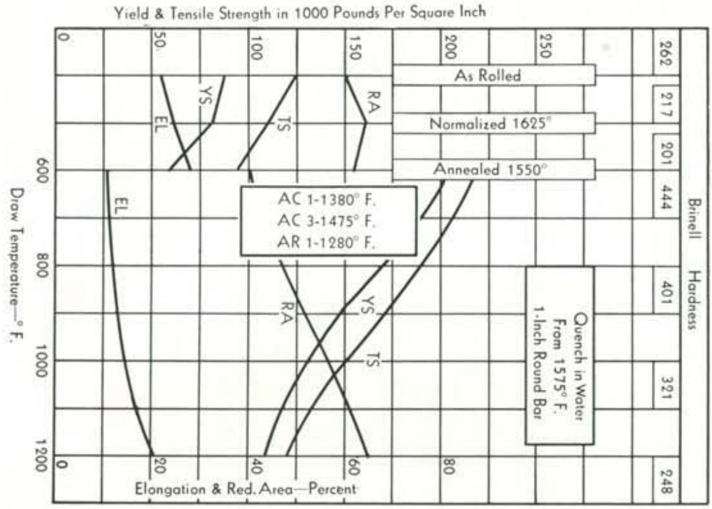

USS CARILLOY STEEL 4645*
Yield & Tensile Strength in 1000 Pounds Per Square Inch
Elongation & Red. Area—Percent
Draw Temperature—° F.
Brinell Hardness
As Rolled
Normalized 1600°
Annealed 1500°
AC 1-1320° F.
AC 3-1410° F.
AR 1-1200° F.
Quench in Oil
From 1600° F.
1-Inch Round Bar
255
248
201
461
404
327
267
EL
RA
YS
TS

USS CARILLOY S.A.E. 5150

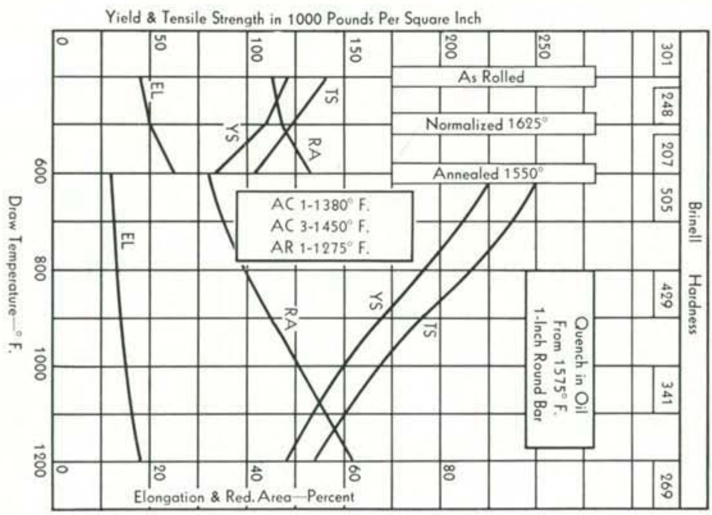


USS CARILLOY .20/.30 C. MN-V*



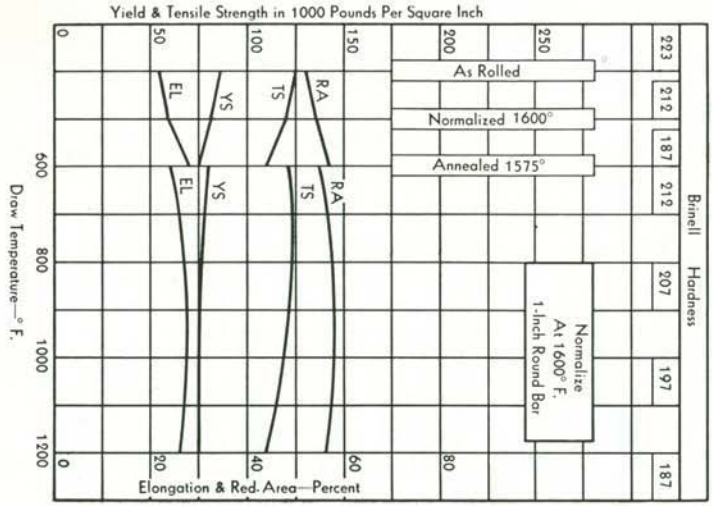


USS CARILLOY S.A.E. 6130

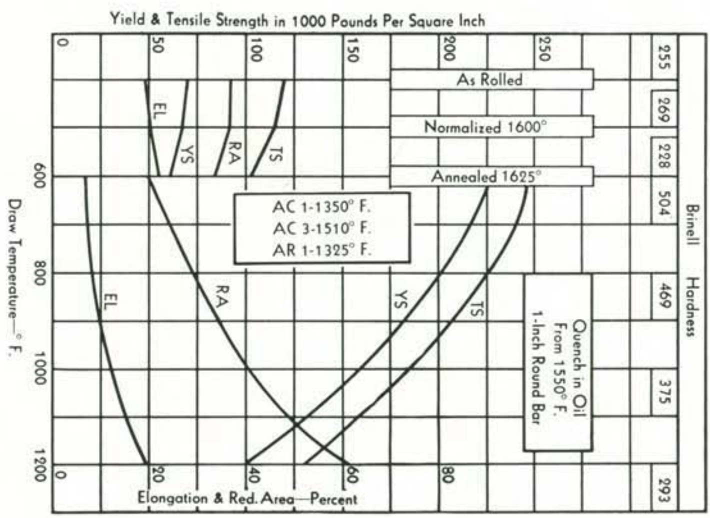


USS CARILLOY S.A.E. 6145

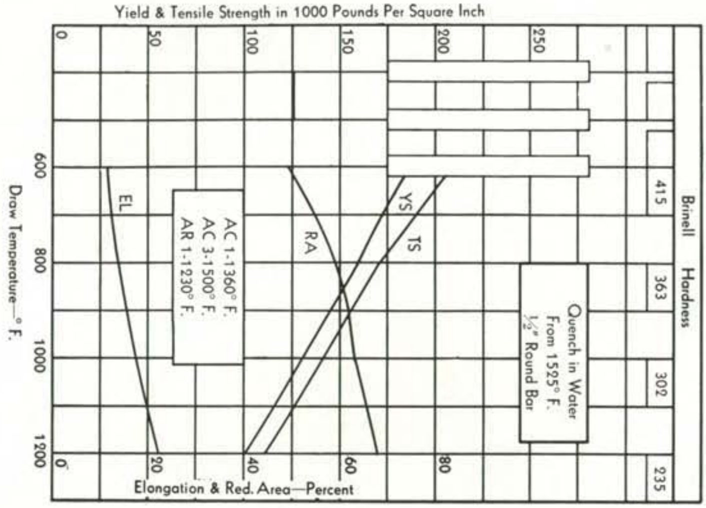
USS CARILLOY .40/.50 C. NORMALLOY*



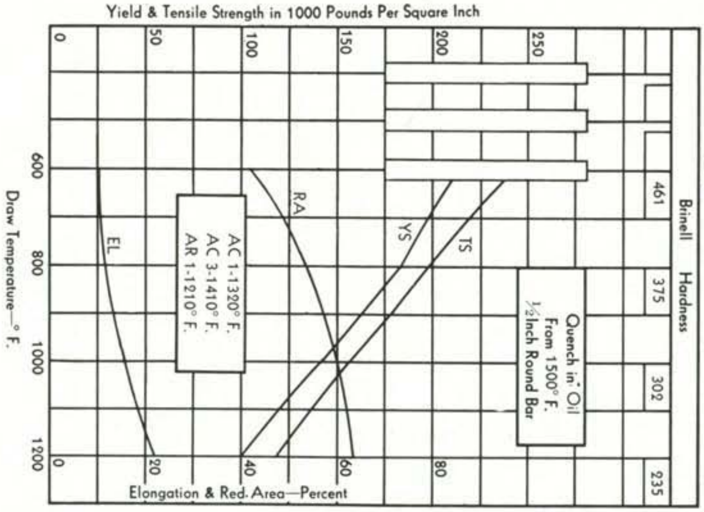
USS CARILLOY S.A.E. 9255



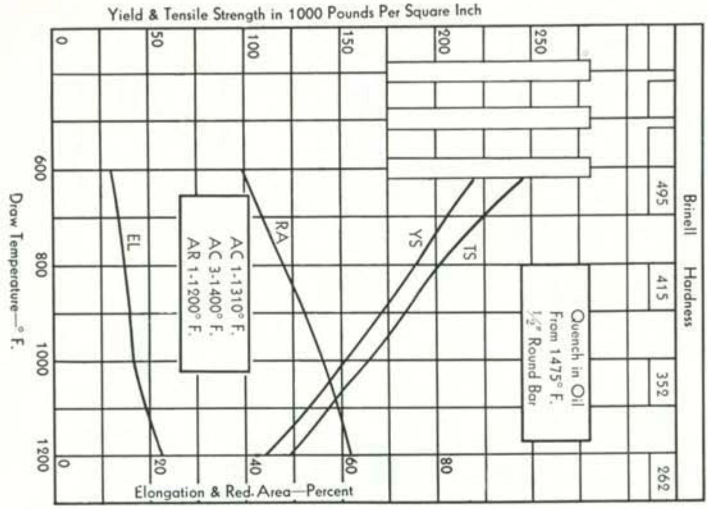
USS CARILLOY AMOLA .25/.35 C.*



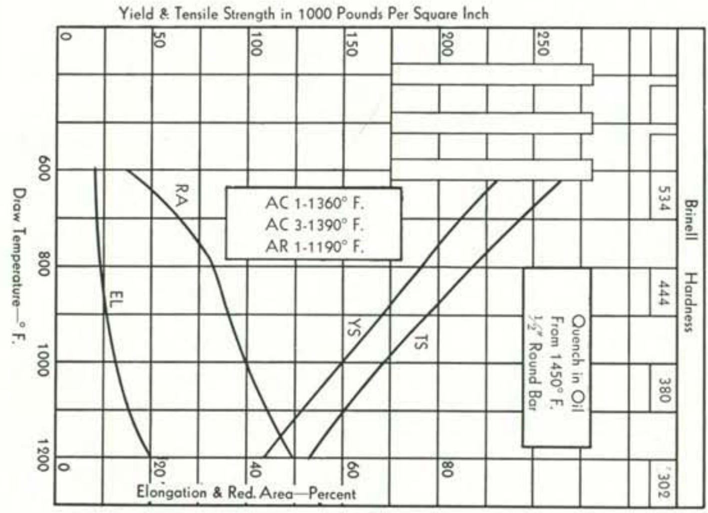
USS CARILLOY AMOLA .35/.45 C.*



USS CARILLOY AMOLA .45/.55 C.*



USS CARILLOY AMOLA .60/.70 C.*



MACHINABILITY OF ALLOY STEELS

Machinability refers to those properties of a material which make it amenable to machining operations. Good machinability is generally associated with long tool life at high cutting speeds and with ease in obtaining smoothly finished surfaces. Occasionally it also connotes low power consumption or low pressure on the tool face.

The general tendency toward the use of steels of higher strength and toughness for various types of mass production parts has been attended by an increased emphasis on machinability. Many of the characteristics of such steels which are desirable from the standpoint of good machine design and service are definitely opposed, unfortunately, to good machining properties. Thus, too great hardness interferes with machining, and high ductility, even though accompanied with great softness is also detrimental (particularly in regard to the smoothness of the machined surface). For this reason many steels, especially those low in carbon, are relatively difficult to machine when annealed to the lowest values of hardness. The ideal machining condition is a low hardness coupled with a tendency toward brittleness. To some extent this can be approached by inducing a coarse-grained structure either by finishing the steel hot in forging or rolling or by annealing or normalizing from a high temperature. However, it is sometimes not possible to obtain as smooth a finished surface with a coarse-grained structure as with a moderately fine-grained structure.

The presence of well-distributed, non-abrasive inclusions, such as sulphides, is an aid toward both tool life and surface finish. Probably each cavity containing a sulphide inclusion behaves as a minute notch, since the reinforcement due to the soft inclusion is practically nil. Because of these highly localized stress concentrations just ahead of the cutting edge of the tool, the chip comes away readily and the material behaves, at least with respect to the cutting tool, as if it were brittle. Moreover, the sulphide particles may possibly be smeared out and tend to act as a highly efficient lubricant which reduces the abrasion on the tool and aids in producing a smooth finish. Cold drawing likewise has the effect of decreasing the ductility of the steel and thereby benefits the machinability.

In many instances, surface finish is of primary importance. In fact, the useful life of a tool may be regarded as being over as soon as any roughness becomes apparent, even though the tool could continue to function for a much longer period of time before actual breakdown would occur. Where surface requirements are very strict it is necessary to control the microstructure very closely. This is accomplished by appropriate heat treatments which usually involve annealing or normalizing producing such structures as are necessary for the different cutting operations. The types of structures and the heat treatments which are designed to produce them can be roughly divided into three classifications, according to the carbon content. These several classifications will range in carbon content as follows: .10/.25%, .30/.55% and .90/1.10%. It must be emphasized that the proper heat treating cycles depend upon many factors which are peculiar to the particular machining operations, the type and size of the part being fabricated, the analysis of the steel and the type and availability of the heat treating and fabricating equipment in the plant.

In removing a chip with a cutting tool, several mechanical factors come into play, among which one of the most prominent is the ability of the chip to slide over the face of the tool. In cutting, if the coefficient of friction between the chip and the tool face were zero, every particle on the inner face of the chip would execute a sharp turn at the tool face and slide off. On the other hand, if the coefficient of friction were extremely large a considerable portion of the inner surface of the chip would be unable to slide off the tool face and would remain as a stagnant layer of metal. When observed in practice, this is commonly called a "built-up edge." Occasionally when a tool is removed from the cut, the stagnant layer of metal is found to be welded to the tip of the tool. While the "built-up edge" protects the cutting edge of the tool to some extent, it forms at best a very imperfect substitute for a sharp-edged cutting tool and the surface finish suffers correspondingly. This is particularly true when cutting the softer and more plastic metals which press into the irregularities on the tool face surface under extreme pressures and therefore exhibit a high coefficient of friction or a tendency toward seizing. A stagnant layer of metal is built up until the angle presented to the remainder of the chip is sufficiently great to reduce the normal component of pressure so that the chip can slide off. Frequently an increase in rake angles will accomplish the same effect and give a much smoother surface. However, there is a limit to the extent to which rake angles can be increased. With extreme rake

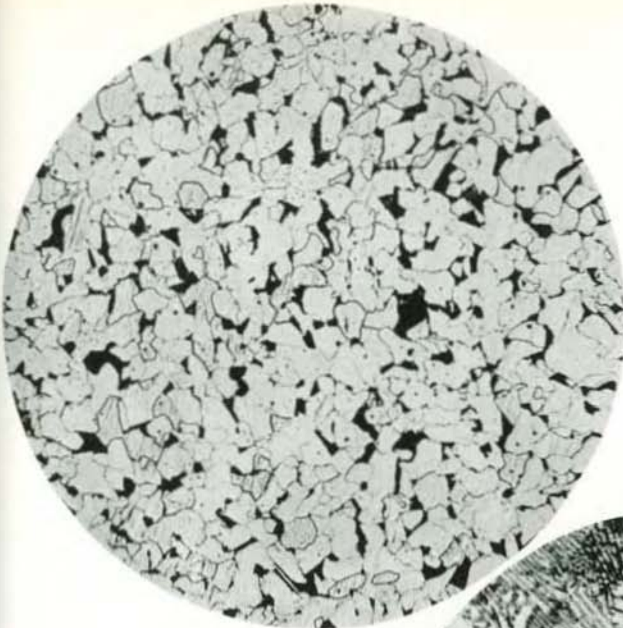


Fig. 42. Microstructure of a low-carbon steel which was readily machinable

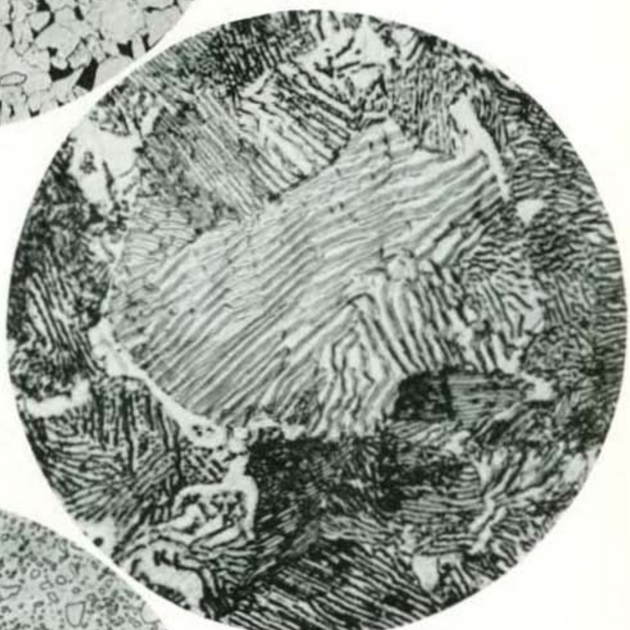


Fig. 43. Microstructure of a medium-carbon steel which was readily machinable

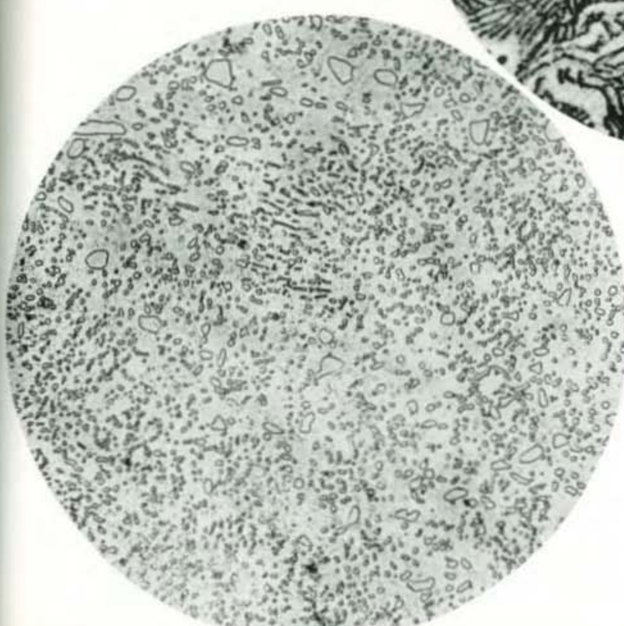


Fig. 44. Microstructure of a high-carbon steel which was readily machinable

angles there is a tendency for the tool to dig. This may cause chatter and because of the decreased volume of metal adjacent to the cutting edge, will diminish the strength of the tool and the capacity to withdraw heat from the cutting edge. The application of extreme pressure lubricants and the practice of honing, or chromium plating the tool face, helps to reduce the coefficient of friction by providing a smoother sliding surface. By these means there is a decrease in the size of the stagnant layer and a corresponding improvement in cutting conditions.

Difficulties in machining are often encountered when the microstructure of the steel consists in part of massive grains of ferrite. The soft plastic ferrite slides off the tool with difficulty and the steel drags in cutting. Generally, therefore, the low-carbon steels are normalized to induce sufficient hardness to prevent dragging.

Figs. 42, 43 and 44, respectively, show the microstructures associated with good machinability in .10/.25%; .30/.55% and .90/1.10% carbon steels as classified above; Fig. 44 shows spheroidization.

Any analysis of machinability should take due account of overall economy in manufacture. The extent to which heat-treatment for improved machinability should be employed is mainly a question of economy. The criterion is that the extra cost of heat-treatment should not exceed the savings resulting from longer tool life, increased cutting speeds, and a smaller per cent of spoilage. In addition there may be a sufficient improvement in the surface finish to warrant at least a part of the extra cost. In the selection of steels, the economy of machining should be considered along with the cost of the steel.

The actual success and economy with which a steel may be machined depends not only on its inherent machining characteristics, but also on the manner in which the operations are performed and the equipment employed. Such factors as tool shape, rigidity, manner of supporting the part and the type and manner of application of cutting compounds are recognized as being of fundamental importance frequently. Difficulties, particularly in machining new and unfamiliar steels, can be overcome by proper adjustment of these factors without resorting to expensive heat treatments or highly restrictive specifications.

PYROMETRY AND PYROMETERS

In all the processes of steel-making and steel-treating, the results depend upon the precise temperatures employed. This is particularly true of the heat-treating processes. Accurate and dependable apparatus for controlling and therefore for measuring the temperature of steel is one of the essential types of equipment in the modern plant.

THERMO-ELECTRIC PYROMETRY

Most temperatures around the steel-works are measured with the ***thermo-electric pyrometer.*** This consists of three parts: (1) thermocouple, (2) extension leads, (3) apparatus for measuring the electromotive force of the thermocouple.

The thermocouple. Take two pieces of wire, A and B, of different composition; weld one end of A to one end of B, and the other end of A to the other end of B, so that a continuous piece of wire is produced. This piece of wire is a thermocouple.

Note particularly that the piece of wire is a complete electric circuit. It is known that at the weld or junction between two dissimilar metal wires in such a circuit an electromotive force is generated. If both junctions are at the same temperature, the e.m.f.'s will be equal and opposite, and no current will flow in the wire. But make one junction hotter than the other, and there is a net e.m.f. which is capable of causing a current to flow around the circuit. If one junction, which we may call the "cold junction" or, better, the "reference junction," is held at a constant temperature, it is evident that the e.m.f. in the circuit can be used as a measure of the temperature of the other junction, the "hot junction."

The meter. The simplest method of measuring the e.m.f. is to cut the thermocouple,—anywhere,—and insert a current-measuring device such as an ammeter or a ***millivoltmeter*** (which is essentially a current-measurer). The indications will then depend upon the difference in temperature as between the two junctions, and, unfortunately, also upon the total electrical resistance in the circuit, including both thermocouple and meter, in accordance with Ohm's Law. Because the reading does depend upon the resistance, and also because of certain deficiencies of moving-coil instruments under the severe conditions met with in a steel plant, the millivoltmeter type of instrument has been replaced in many installations by the potentiometer.

The Potentiometer, in its fundamental form, balances a known and measured e.m.f. against the unknown e.m.f. in the thermocouple circuit, and its readings are consequently independent of resistance. Originally used as a hand-operated indicator only, the potentiometer has been made completely automatic in operation, and a number of types of the instrument are now available.

Extension leads. We have been assuming that the thermocouple was cut at some point in order to insert the millivoltmeter or the potentiometer. Suppose the measurement is wanted at a place some distance away. A pair of copper wires leading off to the panel board where the instrument is placed would serve the purpose ***if*** the reference junction were actually at a constant temperature. But the prevailing custom is to let the reference junction shift for itself, rising and falling in summer and winter, while its variations are compensated for by some device in the millivoltmeter or the potentiometer. This means that the reference junction must be placed ***at the instrument.*** Now some thermocouple materials capable of withstanding high temperature, such as platinum, are too expensive to be used in lengths of hundreds of feet in order to reach a distant instrument. This difficulty is taken care of by ***extension leads,*** consisting of a pair of wires of relatively inexpensive alloys which have approximately the same curve of e.m.f. against temperature (referred to some average air temperature for the reference junction) as the thermocouple itself. The thermocouple may now be cut open at the reference junction, the pair of extension leads inserted in the proper direction, and the reference junction is thereby transferred effectively to the far end of the extension leads where the meter is to be inserted.

Compensation for temperature change at the instrument must now be provided. In the millivoltmeter type a spring can be used whose elasticity changes with temperature in such a way as to balance the effect of the change in e.m.f. produced by the change in temperature of the reference junction. In the potentiometer, the compensation is electrical instead of mechanical; a resistance coil is inserted in the potentiometer circuit, of the proper material and resistance so that as it warms or cools, its effect on the balancing e.m.f. is just equal and opposite to the change in e.m.f. produced by the change in cold-junction temperature.

The foregoing picture of the thermocouple as a complete circuit has been adopted here in place of the customary picture of a pair of wires with free ends, with the deliberate purpose of emphasizing that no thermocouple can function without at least two junctions, one of which is just as important as the other.

The choice of instrument depends upon local conditions. The principal advantages of the millivoltmeter are low cost and small bulk; in most other respects, including accuracy and dependability, the potentiometer is preferable.

Thermocouple Materials. Three types of thermocouples are in current use: (1) iron-constantan, (2) Chromel-Alumel, (3) platinum-rhodium-platinum (in each case the wire which is positive at the colder junction is named first in the pair). The iron-constantan couple is used up to temperatures where the iron wire oxidizes away. Chromel-Alumel can be used to about 1900° F. but oxidizes away too rapidly at higher temperatures. The platinum combination can be used at all temperatures up to some 3000° F. (depending upon environment) and is the only one available at temperatures above 2000° F.

All Chromel and Alumel wire used in the United States is made by one company and is made to exact specifications with respect to thermal e.m.f. The e.m.f.-temperature curve of the Chromel-Alumel couple has been standardized by the National Bureau of Standards, and all of the eight or ten instrument makers who furnish steel-plant pyrometers now use the same e.m.f. curve.

The platinum-rhodium-platinum thermocouple is made in two types. Both use pure platinum as one wire, while the alloy wire contains either 10% rhodium to 90% platinum, or 13% rhodium to 87% platinum. Standard curves for both of these thermocouples have been determined by the Bureau of Standards and are now in general use.

Constantan is made in several compositions by different manufacturers. The iron of the iron-constantan couple is not the pure metal, but is a low-metalloid steel or "ingot iron." It likewise comes from several different sources. The iron-constantan couple has therefore not been standardized as to composition or e.m.f.-temperature curve.

OPTICAL PYROMETRY

Although much less used than the thermo-electric pyrometer, the ***optical pyrometer*** is essential for steel-making temperatures such as tapping and pouring temperatures. To the physicist, the optical pyrometer is a photometer, an instrument for measuring the brightness of a source of light. The brightness of a hot surface however is not alone dependent upon its temperature but also upon its ***emissivity,*** and the optical pyrometer consequently can not read temperature directly, except in the single instance of the so-called "black body," best exemplified by a furnace so uniformly heated in the interior that no details can be seen by observation through the door. On all other objects the optical pyrometer reads a ***brightness temperature*** which must be interpreted by a knowledge of the emissivity. The brightness temperature of the flat surface of a reproducible material, such as low-carbon steel, fortunately, does bear a fixed relation to its true temperature, and the optical pyrometer is therefore a reliable instrument for the reproduction of heating, rolling, welding and finishing temperatures. It is capable of very high precision, especially at the highest temperatures.

RADIATION PYROMETRY

The ***total radiation pyrometer*** measures energy rather than brightness. It absorbs all of the energy radiated from a certain area of a hot surface, both the visible radiation, and the heat radiation which at steel-making temperatures constitutes the greater part of the energy. Like the optical brightness of the surface, its energy radiation is not solely dependent on its temperature, as can easily be observed by holding the hand near a black surface and a polished reflecting surface at the same temperature. The polished surface has a much lower emissivity and feels correspondingly cooler, if not touched.

While the emissivity for total radiation of a sheet of steel coated with a thin adherent film of black oxide is less than the emissivity of a true black body, it is nevertheless reasonably constant. This fact is bringing the total radiation pyrometer into increasing use for the measurement of surface temperatures of sheets, bars, rails and similar products, from the first pass of the mill down to the cooling beds.

PHOTO-ELECTRIC PYROMETRY

Pyrometers utilizing the photo-electric (including the Photronic) cell as an impersonal eye to replace the optical pyrometer are in course of development, and have been coming into use in the steel plant, particularly for the control of roof temperatures in the open-hearth furnace and for the measurement of the brightness temperature of steel surfaces.

PYROMETER CALIBRATION AND MAINTENANCE

Thermocouples, pyrometer lamps, potentiometers and similar physical apparatus are always subject to deterioration, particularly under the severe conditions of dust, high temperature and vibration which are unavoidable in many plants. An essential feature of the pyrometric equipment of the up-to-date plant is therefore its pyrometric laboratory for calibration and maintenance of the instruments. The plant with heavy demands upon its pyrometric equipment cannot afford the frequent interruptions incident to sending pyrometers to a central calibrating station, such as the Bureau of Standards, nor can it afford the risk of spoilage incident to neglecting its pyrometric equipment for weeks at a time. The larger plants make up their own thermocouples from tested stocks of wire; calibrate the couples either by comparison with standards or by measuring the freezing points of standard samples of metals, such as tin, zinc, and copper; check the accuracy of recorders, controllers, standard cells, millivoltmeters, and milliammeters by means of portable testing sets; check optical pyrometers at frequent intervals against a standard source of brightness; and check total-radiation pyrometers by simultaneous readings on the same surface with a calibrated optical pyrometer. For small plants that cannot afford their own pyrometric laboratory, pyrometric calibrating and maintenance services are available in the larger industrial centers.

GENERAL CONSIDERATIONS

It must always be kept in mind that a thermocouple measures the temperature of its own hot junction, and an optical, photo-electric or total-radiation pyrometer measures the average apparent surface temperature of the objects seen by the instrument. For example, a thermocouple may be inserted into a flue with the hope that it will measure the temperature of the gas passing by. What it actually does is to strive for an equilibrium between heat supplied by the gas, heat conducted away along the wires, and heat radiated to or from the colder or hotter walls, and the resulting temperature of the hot junction is seldom the temperature of the gas. In heat-treating operations, it is not sufficient that the hot junction of the thermocouple is merely inside the furnace; it should be as near as possible to the piece of steel being treated. A study of the environment, and the exercise of good judgment in placing the pyrometer, are just as important as the proper selection and maintenance of the instruments.

These specifications are published as a matter of general information only. It will be noted that certain of the specifications call for chemical limits more restrictive than permitted by the Manufacturer's Standard Practice. Users should familiarize themselves with Manufacturer's Standard Requirements and should consult price cards before ordering steel.

STEEL SPECIFICATIONS IN COMMON USE

CARBON STEELS

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Chromium	Nickel
GM	R1005	.10 max.*	.25- .55	.045	.055			
Chrysler	M.S. 501	.12 max.	.30- .60	.04	.055			
SAE (GM)	1010	.05- .15	.30- .60	.045	.055			
Ford	L.C.O.H.	.05- .15	.30- .50	.04	.05			
GM	R1010	.05- .15*	.25- .55	.045	.055			
Ford	G	.08- .15	.30- .45	.03	.05	.07- .15		
Chrysler	M.S. 420	.08- .15	.30- .50	.04	.05	.15 max.		
Ford	Machine Steel	.08- .20	.35- .50	.04	.05	.10- .20		
SAE (GM)	1015	.10- .20	.30- .60	.045	.055			
GM	R1015	.10- .20*	.25- .55	.045	.055			
SAE (GM)	X1015	.10- .20	.70-1.00	.045	.055			
Chrysler	M.S. 942	.10- .20	.70-1.00	.045	.05	.15- .30		
GM	Y1015	.10- .20	.60- .90	.045	.055	.30 max.		
Chrysler	M.S. 931	.15- .20 or .12- .17	.50- .70	.045	.05	.15- .30		
GM	Z1015-A	.12- .18	.30- .60	.045	.055	.30 max.		
Ford	GG	.15- .20	.30- .45	.040	.050	.07- .15		
SAE (GM)	1020	.15- .25	.30- .60	.045	.055			
Chrysler	M.S. 210	.15- .25	.30- .60	.045	.05			
SAE (GM)	X1020	.15- .25	.70-1.00	.045	.055			
GM	R1020	.15- .25*	.25- .55	.045	.055			
Chrysler	M.S. 853	.18- .23	.50- .70	.045	.05	.15- .30		
SAE (GM)	1025	.20- .30	.30- .60	.045	.055			
GM	R1025	.20- .30*	.25- .55	.045	.055			
SAE (GM)	X1025	.20- .30	.70-1.00	.045	.055			
Ford	L	.23- .30	.35- .50	.04	.05			
Chrysler	M.S. 852	.25- .30	.70- .90	.045	.05	.15- .30		
SAE (GM)	1030	.25- .35	.60- .90	.045	.055			
Ford	E	.27- .35	.70- .90	.040	.050	.07- .15		
Chrysler	M.S. 410	.27- .37	.60- .90	.04	.05	.07- .15		
Ford	H	.27- .37	.45- .60	.040	.050	.07- .15		
SAE (GM)	1035	.30- .40	.60- .90	.045	.055			
Chrysler	M.S. 467	.33- .40	.50- .80	.045	.05	.15- .30		
SAE (GM)	1040	.35- .45	.60- .90	.045	.055			
Ford	EE	.35- .40	.70- .90	.03	.050	.07- .15		
SAE (GM)	X1040	.35- .45	.40- .70	.045	.055			
Chrysler	M.S. 331	.38- .45	.50- .80	.045	.05	.15- .30		
SAE (GM)	1045	.40- .50	.60- .90	.045	.055			
SAE (GM)	X1045	.40- .50	.40- .70	.045	.055			
GM	Y1045	.40- .50	.40- .60	.045	.055			
Ford	EEE	.40- .45	.70- .90	.030	.050	.07- .15		
Chrysler	M.S. 434	.43- .50	.50- .80	.045	.05	.15- .30		
SAE (GM)	1050	.45- .55	.60- .90	.045	.055			
SAE	X1050	.45- .55	.40- .70	.045	.055			

* ***Rimmed Steels***—On GM Rimmed Steels, designated by "R" prefixed to specification number, carbon ranges as specified are desired although .12 ranges are allowable on all except R1005. The .12 range on R1010 to be ±.06; on R1015, R1020 and R1025 —.07 + .05.

"A" Ranges—Five point carbon range of .02 under and .03 over can be secured if necessary on all GM alloy steels and on GM carbon steels with less than .60 carbon. This 5 point carbon range is specified by adding an "A" suffix to the specification number.

Nickel or Chromium—GM steels which do not specify nickel or chromium may be rejected if these elements exceed the following limits: Nickel .30 Chromium .20

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CARBON STEELS (Continued)

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Chromium	Nickel
SAE (GM)	1055	.50–.60	.60–.90	.040	.055			
SAE (GM)	X1055	.50–.60	.90–1.20	.040	.055			
SAE (GM)	1060	.55–.70	.60–.90	.040	.055			
GM	X1060	.55–.70	.35–.65	.045	.045	.12–.20		
GM	Y1060	.55–.70	.90–1.20	.040	.050	.30 max.		
SAE (GM)	1065	.60–.75	.60–.90	.040	.055			
SAE (GM)	X1065	.60–.75	.90–1.20	.040	.055			
GM	Y1065	.60–.70	.60–.90	.025	.025			
Ford	S	.60–.70	.70–.85	.03	.04	.15–.20		
SAE (GM)	1070	.65–.80	.60–.90	.040	.055			
Ford	R	.70–.80	.20–.35	.025	.03	.15–.25	.10 max.	None
SAE	1075	.70–.85	.60–.90	.040	.055			
Ford	SS	.70–.85	.70–.85	.03	.04	.10–.20		
SAE (GM)	1080	.75–.90	.60–.90	.040	.055			
GM	1082	.75–.90	.25–.50	.045	.045	.10 max.		
SAE (GM)	1085	.80–.95	.60–.90	.040	.055			
SAE (GM)	1090	.85–1.00	.60–.90	.040	.055			
SAE (GM)	1095	.90–1.05	.25–.50	.040	.055			
Ford	RR	.95–1.05	.20–.35	.025	.030	.15–.25	.10 max.	None
Ford	RRR	1.20–1.30	.20–.35	.025	.030	.15–.25		
GM	1107	.12 max.	.30–.60	.11	.07			
GM	Y1110	.05–.15	.30–.60	.08–.11	.055			

FREE-CUTTING STEELS

Type	Number	Carbon	Manganese	Phos. Max.	Sulphur Max.	Silicon
GM	1110	.08–.15	.60–.90	.060	.075–.15	
Chrysler	M.S. 200	.08–.16	.60–.90	.09–.13	.10–.20	
SAE (GM)	1112	.08–.16	.60–.90	.09–.13	.10–.20	
Ford	No. 1 Bessemer	.09–.13	.70–.90	.09–.13	.08–.15	
Chrysler	M.S. 760	.10 max.	.50–.80	.08–.11	.20–.30	
SAE (GM)	X1112	.08–.16	.60–.90	.09–.13	.20–.30	
GM	Y1112	.08–.16	.60–.90	.09–.13	.12	
Ford	F	.08–.15	.80–.99	.04	.08–.15	.10–.20
SAE (GM)	1115	.10–.20	.70–1.00	.045	.075–.15	
Ford	FF	.15–.20	.80–.99	.04	.10–.15	.10–.20
SAE (GM)	1120	.15–.25	.60–.90	.045	.075–.15	
Chrysler	M.S. 201	.15–.25	.60–.90	.06	.075–.15	
GM	1135	.30–.40	.70–1.00	.045	.075–.15	
Ford	FFF	.34–.40	.80–.99	.04	.10–.15	.10–.20
Chrysler	M.S. 238	.20 max.	.90–1.40	.04	.20–.28	
Chrysler	M.S. 738	.10–.20	1.00–1.30	.05	.08–.13	
SAE (GM)	X1314	.10–.20	1.00–1.30	.045	.075–.15	
Chrysler	M.S. 212	.10–.20	1.30–1.60	.045	.075–.15	
SAE (GM)	X1315	.10–.20	1.30–1.60	.045	.075–.15	
Chrysler	M.S. 540	.20–.30	1.25–1.55	.05	.08–.13	

"A" Ranges—Five point carbon range of .02 under and .03 over can be secured if necessary on all GM alloy steels and on GM carbon steels with less than .60 carbon. This 5 point carbon range is specified by adding an "A" suffix to the specification number.
Nickel or Chromium—GM steels which do not specify nickel or chromium may be rejected if these elements exceed the following limits: Nickel .30 Chromium .20

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FREE-CUTTING STEELS—Continued

Type	Number	Carbon	Manganese	Phos. Max.	Sulphur Max.	Silicon
SAE (GM)	X1330	.25-.35	1.35-1.65	.045	.075-.15	
SAE (GM)	X1335	.30-.40	1.35-1.65	.045	.075-.15	
SAE (GM)	X1340	.35-.45	1.35-1.65	.045	.075-.15	

MANGANESE STEELS

Type	Number	Carbon	Manganese	Phos. Max.	Sulphur Max.	Silicon
GM	X1322	.18-.26	1.20-1.50	.040	.050	
Chrysler	M.S. 908	.22-.27	1.20-1.50	.04	.05	.07-.17
SAE-T (GM)	T1330	.25-.35	1.60-1.90	.040	.050	
SAE-T (GM)	T1335	.30-.40	1.60-1.90	.040	.050	
Chrysler	M.S. 258	.30-.40	1.00-1.30	.04	.045	.15-.30
Chrysler	M.S. 308	.30-.40	1.60-1.90	.055	.05	.15-.30
SAE-T (GM)	T1340	.35-.45	1.60-1.90	.040	.050	
SAE-T (GM)	T1345	.40-.50	1.60-1.90	.040	.050	
SAE-T (GM)	T1350	.45-.55	1.60-1.90	.040	.050	
GM	1355	.50-.60	1.60-1.90	.040	.050	

NICKEL STEELS[1]

Type	Number	Carbon	Manganese	Phos. Max.	Sulphur Max.	Silicon	Nickel
SAE (GM)	2015	.10-.20	.30-.60	.040	.050		.40-.60
SAE	2115	.10-.20	.30-.60	.040	.050		1.25-1.75
SAE (GM)	2315	.10-.20	.30-.60	.040	.050		3.25-3.75
SAE (GM)	2320	.15-.25	.30-.60	.040	.050		3.25-3.75
SAE (GM)	2330	.25-.35	.50-.80	.040	.050		3.25-3.75
SAE	2335	.30-.40	.50-.80	.040	.050		3.25-3.75
SAE	2340	.35-.45	.60-.90	.040	.050		3.25-3.75
SAE (GM)	2345	.40-.50	.60-.90	.040	.050		3.25-3.75
SAE	2350	.45-.55	.60-.90	.040	.050		3.25-3.75
SAE (GM)	2515	.10-.20	.30-.60	.040	.050		4.75-5.25
Chrysler	M.S. 307	.12-.17	.30-.60	.04	.04	.15-.30	4.75-5.25
Chrysler	M.S. 815	.12-.17	.40-.60	.025	.025	.15-.30	4.75-5.25

NICKEL CHROMIUM STEELS[1]

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Nickel	Chromium
GM	X3045-A	.43-.48	.70-1.00	.040	.050		.50-.80	.50-.80
GM	3111-A	.10-.17	.30-.60	.040	.050		1.00-1.50	.45-.75
SAE (GM)	3115	.10-.20	.30-.60	.040	.050		1.00-1.50	.45-.75
Chrysler	M.S. 168	.12-.17	.30-.60	.04	.05	.15-.30	1.00-1.50	.45-.75
SAE (GM)	3120	.15-.25	.30-.60	.040	.050		1.00-1.50	.45-.75
SAE	3125	.20-.30	.50-.80	.040	.050		1.00-1.50	.45-.75
SAE	3130	.25-.35	.50-.80	.040	.050		1.00-1.50	.45-.75
GM	3130	.25-.35	.60-.90	.040	.050		1.00-1.50	.45-.75

[1] ***Silicon***—SAE and GM steels—Unless otherwise specified, silicon range of all basic open hearth alloy steels shall be .15-.30. For electric and acid open hearth alloy steels the silicon content shall be .15 minimum.

"A" Ranges—Five point carbon range of .02 under and .03 over can be secured if necessary on all GM alloy steels and on GM carbon steels with less than .60 carbon. This 5 point carbon range is specified by adding an "A" suffix to the specification number.

Nickel or Chromium—GM steels which do not specify nickel or chromium may be rejected if these elements exceed the following limits: Nickel .30 Chromium .20

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NICKEL CHROMIUM STEELS[1]—Continued

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Nickel	Chromium
SAE	3135	.30-.40	.50-.80	.040	.050		1.00-1.50	.45-.75
Chrysler	M.S. 354	.30-.40	.50-.80	.04	.045	.15-.30	1.00-1.50	.45-.75
Chrysler	M.S. 471	.30-.40	.50-.80	.04	.045	.15-.30	1.00-1.50	.45-.75
Chrysler	M.S. 559	.30-.40	.50-.80	.04	.045	.15-.30	1.00-1.50	.45-.75
GM	3135	.30-.40	.60-.90	.040	.050		1.00-1.50	.45-.75
Chrysler	M.S. 206	.35-.40 or .38-.43	.50-.80	.04	.05	.15-.30	1.00-1.50	.45-.75
SAE(GM)	3140	.35-.45	.60-.90	.040	.050		1.00-1.50	.45-.75
SAE(GM)	X3140	.35-.45	.60-.90	.040	.050		1.00-1.50	.60-.90
SAE(GM)	3145	.40-.50	.60-.90	.040	.050		1.00-1.50	.45-.75
SAE(GM)	3150	.45-.55	.60-.90	.040	.050		1.00-1.50	.45-.75
Chrysler	M.S. 512	.42-.47	.50-.80	.04	.025	.15-.30	1.25-1.75	.60-.90
SAE(GM)	3215	.10-.20	.30-.60	.040	.050		1.50-2.00	.90-1.25
SAE	3220	.15-.25	.30-.60	.040	.050		1.50-2.00	.90-1.25
SAE	3230	.25-.35	.30-.60	.040	.050		1.50-2.00	.90-1.25
SAE(GM)	3240	.35-.45	.30-.60	.040	.050		1.50-2.00	.90-1.25
GM	X3243	.38-.48	.60-.90	.040	.050		1.50-2.00	.70-.90
SAE	3245	.40-.50	.30-.60	.040	.050		1.50-2.00	.90-1.25
SAE	3250	.45-.55	.30-.60	.040	.050		1.50-2.00	.90-1.25
GM	X3250	.45-.55	.30-.60	.025	.025		1.50-2.00	.90-1.25
SAE	3312	.17 max.	.30-.60	.040	.050		3.25-3.75	1.25-1.75
SAE	3325	.20-.30	.30-.60	.040	.050		3.25-3.75	1.25-1.75
SAE	3335	.30-.40	.30-.60	.040	.050		3.25-3.75	1.25-1.75
SAE	3340	.35-.45	.30-.60	.040	.050		3.25-3.75	1.25-1.75
GM	X3410-A	.09-.14	.25-.45	.025	.025		3.80-4.20	1.40-1.60
SAE	3415	.10-.20	.30-.60	.040	.050		2.75-3.25	.60-.95
SAE	3435	.30-.40	.30-.60	.040	.050		2.75-3.25	.60-.95
SAE	3450	.45-.55	.30-.60	.040	.050		2.75-3.25	.60-.95

CHROMIUM STEELS[1]

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Chromium
GM	5045-A	.43-.48	.60-.90	.040	.050		.30-.60
GM	5115	.10-.20	.60-.90	.040	.050		.80-1.10
Ford	N	.12-.16	.35-.45	.03	.04	.10-.20	.30-.40
SAE	5120	.15-.25	.30-.60	.040	.050		.60-.90
Ford	AX	.18-.22	.65-.75	.030	.040	.10-.20	.80-.95
Ford	AA	.26-.30	.65-.80	.030	.040	.10-.20	.80-1.00
Ford	AA Select	.28-.32	.65-.80	.030	.040	.10-.20	.80-1.00
GM	X5132-A	.29-.36	.60-.85	.030	.040	.10-.20	.85-1.15
Chrysler	M.S. 221	.30-.35	.65-.80	.03	.04	.15-.30	.90-1.10
Ford	AAA	.30-.35	.65-.80	.030	.040	.10-.20	.90-1.10
Ford	AAA Select	.32-.35	.65-.80	.030	.040	.10-.20	.90-1.10

[1] ***Silicon***—SAE and GM steels—Unless otherwise specified, silicon range of all basic open hearth alloy steels shall be .15-.30. For electric and acid open hearth alloy steels the silicon content shall be .15 minimum.

"A" Ranges—Five point carbon range of .02 under and .03 over can be secured if necessary on all GM alloy steels and on GM carbon steels with less than .60 carbon. This 5 point carbon range is specified by adding an "A" suffix to the specification number

Nickel or Chromium—GM steels which do not specify nickel or chromium may be rejected if these elements exceed the following limits: Nickel .30 Chromium .20

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CHROMIUM STEELS[1]—Continued

Type	Number	Carbon	Maganese	Phos. Max.	Sul. Max.	Silicon	Chromium
Ford	AAAH	.35-.38	.65-.80	.030	.040	.10-.20	.90-1.10
SAE(GM)	5140	.35-.45	.60-.90	.040	.050		.80-1.10
Ford	AAAAL	.38-.42	.65-.80	.030	.040	.10-.20	.90-1.10
GM	5145	.40-.50	.60-.90	.040	.050		.80-1.10
Ford	AAAA	.42-.47	.70-.90	.030	.040	.10-.20	.85-1.10
GM	5148	.45-.52	.75-.95	.030	.030	.07-.20	1.00-1.20
Ford	D	.45-.52	.80-.95	.030	.040	.10-.20	1.00-1.20
SAE(GM)	5150	.45-.55	.60-.90	.040	.050		.80-1.10
Chrysler	M.S. 170	.47-.52	.60-.80	.04	.04	.15-.30	.85-1.10
Ford	AAAAA	.48-.52	.70-.90	.030	.040	.10-.20	.85-1.10
Ford	DD	.48-.52	.80-.95	.030	.040	.10-.20	1.00-1.20
GM	52095	.90-1.00	.20-.50	.030	.035		.95-1.25
SAE (GM)	52100	.95-1.10	.20-.50	.030	.035		1.20-1.50
Ford	B	.95-1.05	.20-.30	.030	.040	.20-.30	.40-.50
Ford	BB	.95-1.05	.20-.30	.030	.040	.20-.30	.90-1.10
Chrysler	M.S. 805	.95-1.05	.20-.50	.025	.025	.15-.30	.90-1.10 or 1.25-1.50
Ford	BBB	.95-1.05	.30-.40	.030	.040	.20-.30	1.25-1.50
GM	52105	1.00-1.10	.20-.50	.030	.035		1.35-1.65
Ford	Magnet	.82-.90	.30-.45	.030	.040	.25-.40	2.25-2.60

CHRYSLER CORPORATION AMOLA STEELS

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Molybdenum
Electric Furnace	M.S. 244	.65-.70	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 245	.65-.70	.70-.90	.04	.04	.20-.30	.15-.25
Electric Furnace	M.S. 246	.60-.65	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 247	.60-.65	.70-.90	.04	.04	.20-.30	.15-.25
Electric Furnace	M.S. 248	.55-.60	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 249	.55-.60	.70-.90	.04	.04	.20-.30	.15-.25
Electric Furnace	M.S. 260	.50-.55	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 261	.50-.55	.70-.90	.04	.04	.20-.30	.15-.25
Electric Furnace	M.S. 262	.45-.50	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 263	.45-.50	.70-.90	.04	.04	.20-.30	.15-.25
Electric Furnace	M.S. 266	.40-.45	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 267	.40-.45	.70-.90	.04	.04	.20-.30	.15-.25
Electric Furnace	M.S. 268	.35-.40	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 269	.35-.40	.70-.90	.04	.04	.20-.30	.15-.25
Electric Furnace	M.S. 270	.30-.35	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 271	.30-.35	.70-.90	.04	.04	.20-.30	.15-.25
Electric Furnace	M.S. 276	.25-.30	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 277	.25-.30	.70-.90	.04	.04	.20-.30	.15-.25
Electric Furnace	M.S. 290	.20-.25	.70-.90	.04	.04	.20-.30	.15-.25
Open Hearth	M.S. 291	.20-.25	.70-.90	.04	.04	.20-.30	.15-.25

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"A" Ranges—Five point carbon range of .02 under and .03 over can be secured if necessary on all GM alloy steels and on GM carbon steels with less than .60 carbon. This 5 point carbon range is specified by adding an "A" suffix to the specification number.

Nickel or Chromium—GM steels which do not specify nickel or chromium may be rejected if these elements exceed the following limits: Nickel .30 Chromium .20

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MOLYBDENUM STEELS[1]

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Nickel	Chromium	Molybdenum
Ford	Hot Work	.18-.23	.40-.60	.040	.040	.15-.25		1.40-1.60	.45-.55
Chrysler	M.S. 733	.20-.30	.30-.60	.025	.025	.15-.30		1.00-1.50	.15-.25
Chrysler	M.S. 219	.25-.30	.40-.70	.04	.045	.15-.30		.50-.80	.15-.25
SAE	4130	.25-.35	.50-.80	.040	.050			.50-.80	.15-.25
GM	4130	.25-.35	.60-.90	.040	.050			.50-.80	.15-.25
SAE	X4130	.25-.35	.40-.60	.040	.050			.80-1.10	.15-.25
SAE (GM)	4135	.30-.40	.60-.90	.040	.050			.80-1.10	.15-.25
SAE (GM)	4140	.35-.45	.60-.90	.040	.050			.80-1.10	.15-.25
GM	4145	.40-.50	.60-.90	.040	.050			.80-1.10	.15-.25
Chrysler	M.S. 208	.42-.47	.50-.80	.04	.045	.15-.30		.80-1.10	.15-.25
SAE (GM)	4150	.45-.55	.60-.90	.040	.050			.80-1.10	.15-.25
GM	X4152	.45-.57	.60-.90	.040	.050			.90-1.20	.15-.25
GM	4220	.15-.25	.30-.60	.040	.050		1.00-1.50	.45-.75	.10-.20
GM	4245-A	.43-.48	.60-.90	.040	.050		1.00-1.50	.45-.75	.10-.20
SAE	4340	.35-.45	.50-.80	.040	.050		1.50-2.00	.50-.80	.30-.40
GM	X4340-A	.35-.42	.60-.90	.025	.025		1.50-2.00	.60-.80	.30-.40
Chrysler	M.S. 666	.35-.45	.60-.80	.025	.025	.15-.30	1.50-2.00	.60-.80	.30-.40
SAE	4345	.40-.50	.50-.80	.040	.050		1.50-2.00	.60-.90	.15-.25
SAE (GM)	4615	.10-.20	.40-.70	.040	.050		1.65-2.00		.20-.30
Chrysler	M.S. 915	.15-.20	.50-.80	.04	.045	.15-.30	1.50-2.00		.20-.30
Chrysler	M.S. 793	.15-.20	.50-.80	.025	.025	.15-.30	1.65-2.00		.20-.30
SAE (GM)	4620	.15-.25	.40-.70	.040	.050		1.65-2.00		.20-.30
Chrysler	M.S. 202	.17-.22	.50-.80	.04	.045	.15-.30	1.50-2.00		.20-.30
Chrysler	M.S. 419	.17-.22	.50-.80	.025	.025	.15-.30	1.65-2.00		.20-.30
GM	X4620-A†	.18-.23	.50-.70	.025	.025		1.65-2.00	.20 max.	.20-.30
SAE	4640	.35-.45	.50-.80	.040	.050		1.65-2.00		.20-.30
GM	4640	.35-.45	.60-.90	.040	.050		1.65-2.00		.20-.30
SAE (GM)	4815	.10-.20	.40-.60	0.40	0.50		3.25-3.75		.20-.30
GM	X4815-A	.13-.18	.40-.60	.025	.025		3.25-3.75	.20 max.	.20-.30
Chrysler	M.S. 211	.15-.20	.30-.60	.025	.025	.15-.30	3.25-3.75		.20-.30
SAE	4820	.15-.25	.40-.60	.040	.050		3.25-3.75		.20-.30
Chrysler	M.S. 903	.19-.23	.30-.60	.025	.025	.15-.30	3.25-3.75		.20-.30

†Manganese plus chromium shall not exceed 0.80%.
Manganese plus chromium plus molybdenum shall not exceed 1.05%.

CHROMIUM VANADIUM STEELS[1]

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Nickel	Chromium	Vanadium	
									Min.	Desired
SAE	6115	.10-.20	.30-.60	.040	.050			.80-1.10	.15	.18
GM	6115	.10-.20	.30-.60	.040	.050			.80-1.10	.15	
Chrysler	M.S. 265	.14-.19	.40-.60	.035	.04	.15-.30	.40-.60	.45-.75	.10	
SAE	6120	.15-.25	.30-.60	.040	.050			.80-1.10	.15	.18
GM	6120	.15-.25	.30-.60	.040	.050			.80-1.10	.15	

[1] ***Silicon***—SAE and GM steels—Unless otherwise specified, silicon range of all basic open hearth alloy steels shall be .15-.30. For electric and acid open hearth alloy steels the silicon content shall be .15 minimum.

"A" Ranges—Five point carbon range of .02 under and .03 over can be secured if necessary on all GM alloy steels and on GM carbon steels with less than .60 carbon. This 5 point carbon range is specified by adding an "A" suffix to the specification number.

Nickel or Chromium—GM steels which do not specify nickel or chromium may be rejected if these elements exceed the following limits: Nickel .30 Chromium .20

These specifications are published as a matter of general information only. It will be noted that certain of the specifications call for chemical limits more restrictive than permitted by the Manufacturer's Standard Practice. Users should familiarize themselves with Manufacturer's Standard Requirements and should consult price cards before ordering steel.

CHROMIUM VANADIUM STEELS[1]—Continued

Type	Number	Carbon	Manga-nese	Phos. Max.	Sul. Max.	Silicon	Nickel	Chromium	Vanadium	
									Min.	Desired
Ford	A	.20-.24	.60-.75	.030	.040	.10-.15		.65-.80		.12-.15
SAE	6125	.20-.30	.60-.90	.040	.050			.80-1.10	.15	.18
GM	6125	.20-.30	.60-.90	.040	.050			.80-1.10	.15	
SAE	6130	.25-.35	.60-.90	.040	.050			.80-1.10	.15	.18
GM	6130	.25-.35	.60-.90	.040	.050			.80-1.10	.15	
Chrysler	M.S. 547	.30-.35	.55-.75	.04	.04	.15-.30		.80-1.00		.10-.15
SAE	6135	.30-.40	.60-.90	.040	.050			80-1.10	.15	.18
GM	6135	.30-.40	.60-.90	.040	.050			.80-1.10	.15	
Chrysler	M.S. 319	.33-.37	.55-.75	.025	.025	.15-.30		.85-2.05	.15	
SAE	6140	.35-.45	.60-.90	.040	.050			.80-1.10	.15	.18
GM	6140	.35-.45	.60-.90	.040	.050			.80-1.10	.15	
SAE	6145	.40-.50	.60-.90	.040	.050			.80-1.10	.15	.18
GM	6145	.40-.50	.60-.90	.040	.050			.80-1.10	.15	
SAE	6150	.45-.55	.60-.90	.040	.050			.80-1.10	.15	.18
GM	6150	.45-.55	.60-.90	.040	.050			.80-1.10	.15	
GM	X6150	.45-.55	.60-.90	.025	.025			.80-1.10	.15	
Chrysler	M.S. 381	.47-.52	.70-.90	.03	.035	.10-.20		.80-1.00	.10	
SAE	6195	.90-1.05	.20-.45	.030	.035			.80-1.10	.15	.18

SILICON MANGANESE STEELS

SAE	9255	.50-.60	.60-.90	.040	.050	1.80-2.20				
SAE (GM)	9260	.55-.65	.60-.90	.040	.050	1.80-2.20				

SILICON STEELS

GM	7003	.03-.08	.20-.35	.025	.025	2.60-2.80				
GM	X7005	.03-.08	.20-.35	.05	.05	.90-1.05				
Ford	Electrical Steel	.05 max.	.30 max.	.03	.03	.90-1.20				
Ford	V	.35-.45	.25-.40	.03	.04	3.60-4.20		1.85-2.50		

U•S•S HIGH TENSILE STEELS

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Chromium	Copper
U·S·S	Sil-Ten	.40 max.	.60 min.	.04	.05	.20 min.		.20* Min.
U·S·S	Cor-Ten	.10 max.	.10-.50	.10-.20	.05	.50-1.00	.50-1.50	.30-.50
U·S·S	Man-Ten	.35 max.	1.25-1.70	.04	.05	.30 max.		.20* Min.
U·S·S	Cromansil	.35 max.	.90-1.50	.04	.05	.60-.95	.30-.70	
U·S·S5	Chromium 4-6	.20 max.	.30-.50	.04	.05	.10-.30	4.00-6.00	

*If specified. **Unless specified otherwise.

[1] ***Silicon***—SAE and GM steels—Unless otherwise specified, silicon range of all basic open hearth alloy steels shall be .15-.30. For electric and acid open hearth alloy steels the silicon content shall be .15 minimum.

"A" Ranges—Five point carbon range of .02 under and .03 over can be secured if necessary on all GM alloy steels and on GM carbon steels with less than .60 carbon. This 5 point carbon range is specified by adding an "A" suffix to the specification number.

Nickel or Chromium—GM steels which do not specify nickel or chromium may be rejected if these elements exceed the following limits: Nickel .30 Chromium .20

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CHROMIUM NICKEL CORROSION AND HEAT RESISTING STEELS

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Chromium	Nickel
GM	81415	.12-.17	.50-.80	.025	.025	.15-.30	13.00-15.00	1.50-2.50
SAE	30905	.08 max.	.20-.70	.030	.030	.75 max.	17.00-20.00	8.00-10.00
GM	81805	.08 max.	.20-.70	.030	.030	.75 max.	17.00-20.00	8.00-10.00
SAE	30915	.09-.20	.20-.70	.030	.030	.75 max.	17.00-20.00	8.00-10.00
GM	81815	.09-.20	.20-.70	.030	.030	.75 max.	17.00-20.00	8.00-10.00
Ford	Rustless 18-8	.05-.10	.30-.45	.04	.05	.15-.30	16.00-18.00	7.00-9.00
301	U.S.S. 16-6	.12-.20	Optional	.030	.030	.75 max.	15.00-17.00	5.00-7.00
301X	U.S.S. 16-6	.10-.20	Optional	.030	.030	.75 max.	16.00-18.00	7.00-8.50
302	U.S.S. 18-8	.08-.20	.70 max.	.030	.030	.75 max.	17.00-19.00	7.00-9.50
303	U.S.S. 18-8 FM†	.08-.20	1.20 max.	.10-.16	.060	.75 max.	17.00-19.00	7.00-9.50
304	U.S.S. 18-8 S	.11 max.	.70 max.	.030	.030	.75 max.	17.00-19.00	7.00-9.50
305	U.S.S. 19-9	.08-.20	.70 max.	.030	.030	.75 max.	18.00-20.00	8.00-10.00
306	U.S.S. 19-9 S	.11 max.	.70 max.	.030	.030	.75 max.	18.00-20.00	8.00-10.00
307	U.S.S. 20-10	.08-.20	.70 max.	.030	.030	.75 max.	19.00-22.00	9.00-12.00
308	U.S.S. 20-10 S	.11 max.	.70 max.	.030	.030	.75 max.	19.00-22.00	9.00-12.00
309	U.S.S. 25-12	.20 max.	2.00 max.	.030	.030	.75 max.	22.00-26.00	12.00-14.00
310	U.S.S. 25-20	.25 max.	2.00 max.	.030	.030	.75 max.	24.00-26.00	19.00-21.00
316	U.S.S. 18-8 S Mo§	.10 max.	2.00 max.	.030	.030	.75 max.	16.00-19.00	14.00 max.
320	U.S.S. 18-8 Ti‡	.20 max.	.70 max.	.030	.030	.75 max.	17.00-19.00	7.00-9.50
321	U.S.S. 19-9 Ti‡	.20 max.	.70 max.	.030	.030	.75 max.	18.00-20.00	8.00-10.00
345	U.S.S. 18-8 Cb#	.15 max.	.70 max.	.030	.030	.75 max.	17.00-19.00	8.00-12.00
346	U.S.S. 19-9 Cb#	.15 max.	.70 max.	.030	.030	.75 max.	18.00-20.00	8.00-12.00
347	U.S.S. 18-8 Cb##	.15 max.	.70 max.	.030	.030	.75 max.	17.00-19.00	8.00-12.00
348	U.S.S. 19-9 Cb##	.15 max.	.70 max.	.030	.030	.75 max.	18.00-20.00	8.00-12.00

STRAIGHT CHROMIUM CORROSION AND HEAT RESISTING STEELS

501A	U.S.S. 5	.21-.25	.30-.50	.040	.050	.50 max.	4.00-6.00
501B	U.S.S. 5	.16-.20	.30-.50	.040	.050	.50 max.	4.00-6.00
501C	U.S.S. 5	.11-.15	.30-.50	.040	.050	.50 max.	4.00-6.00
501D	U.S.S. 5	.10 max.	.30-.50	.040	.050	.50 max.	4.00-6.00
	U.S.S. 5 Mo§§	.20 max.	.30-.50	.040	.050	.50 max.	4.00-6.00
SAE	51210	.12 max.	.60 max.	.030	.030	.50 max.	11.50-13.00
403	U.S.S. 12 Turbine	.12 max.	.70 max.	.030	.030	.75 max.	11.50-13.00
410	U.S.S. 12	.12 max.	.70 max.	.030	.030	.75 max.	12.00-14.00
SAE	X51410	.12 max.	.60 max.	.030	.15-.50	.50 max.	13.00-15.00
GM	X81505††	.12 max.	.60 max.	.030	.15-.50	.50 max.	13.00-15.00
416	U.S.S. 12 FM	.12 max.	.70 max.	.030	.25-.40	.75 max.	12.00-15.00
421	U.S.S. 12-2	.12-.18	.70 max.	.030	.030	.75 max.	12.00-15.00
GM	81510	.12 max.	.60 max.	.030	.030	.50 max.	14.00-16.00
SAE	51510	.12 max.	.60 max.	.030	.030	.50 max.	14.00-16.00
425	U.S.S. 15	.12 max.	.70 max.	.030	.030	.75 max.	14.00-16.00

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Nickel or Chromium—GM steels which do not specify nickel or chromium may be rejected if these elements exceed the following limits: Nickel .30 Chromium .20

†Se .15 min. §Mo 2-4%. ‡Ti = 4 times Carbon. #Cb 6-10 times Carbon. ##Cb over 10 times Carbon.
§§Mo .40-.60%. ††Nickel, molybdenum, copper and zirconium permitted provided total of all does not exceed 1.00%.

A.S.T.M. No. 7 grades. 1-27.

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STRAIGHT CHROMIUM CORROSION AND HEAT RESISTING STEELS—Continued

Type	Number	Carbon	Manganese	Phos. Max.	Sul. Max.	Silicon	Chromium	Nickel
Ford	Rustless 18	.05–.10	.30–.45	.04	.05	.50 max.	16.00–18.00	
SAE	51710	.12 max.	.60 max.	.030	.030	.50 max.	16.00–18.00	
GM	81705	.12 max.	.60 max.	.030	.030	.50 max.	16.00–18.00	
430	U.S.S. 17	.12 max.	.70 max.	.030	.030	.75 max.	16.00–18.00	
GM	X81705	.12 max.	.60 max.	.030	.030	.75–1.25	16.00–18.00	
GM	82010	.08–.17	.30–.60	.025	.025		18.00–23.00	
442	U.S.S. 21	.35 max.	.70 max.	.030	.030	.75 max.	18.00–23.00	
446	U.S.S. 27	.35 max.	.70 max.	.030	.030	.75 max.	23.00–30.00	

OPEN HEARTH GRADES

Grade	Carbon	Manganese	Phosphorus	Sulphur
1	.05–.10	.30–.60	.04 max.	.05 max.
2	.10–.15	.30–.60	.04 max.	.05 max.
3	.15–.20	.30–.60	.04 max.	.05 max.
4	.15–.20	.70–1.00	.04 max.	.05 max.
5	.20–.25	.30–.60	.04 max.	.05 max.
6	.25–.35	.60–.90	.04 max.	.05 max.
7	.30–.40	.60–.90	.04 max.	.05 max.
8	.35–45	.60–.90	.04 max.	.05 max.
9	.40–.50	.60–.90	.04 max.	.05 max.
10	.45–.55	.60–.90	.04 max.	.05 max.
11	.50–.60	.60–.90	.04 max.	.05 max.
12	.60–.75	.60–.90	.04 max.	.05 max.
13	.75–.90	.60–.90	.04 max.	.05 max.
14	.90–1.05	.25–.50	.04 max.	.05 max.

BESSEMER GRADES

Grade	Carbon	Manganese	Phosphorus	Sulphur
15	.12 max.	.60 max.	.11 max.	.08 max.
16	.15 max.	.70 max.	.11 max.	....
17	.15–.25	.90 max.	.11 max.	....
18	.25–.35	.90 max.	.11 max.	....
19	.35–.50	.90 max.	.11 max.	....

BESSEMER FREE-CUTTING STEELS

Grade	Carbon	Manganese	Phosphorus	Sulphur
20	.08–.16	.60–.90	.09–.13	.10–.20
21	.08–.16	.60–.90	.09–.13	.20–.30

OPEN HEARTH FREE-CUTTING STEELS

Grade	Carbon	Manganese	Phosphorus	Sulphur
22	.15–.25	.60–.90	.06 max.	.075–.15
23	.10–.20	1.00–1.30	.04 max.	.075–.15
24	.10–.20	1.30–1.60	.04 max.	.075–.15
25	.30–.40	1.35–1.65	.04 max.	.075–.15

BESSEMER RESULFURIZED NUT STOCK

Grade	Carbon	Manganese	Phosphorus	Sulphur
26	.08–.16	.50–1.00	.11 max.	.075–.15

OPEN HEARTH RESULFURIZED NUT STOCK

Grade	Carbon	Manganese	Phosphorus	Sulphur
27	.15–.25	.50–1.00	.06 max.	.075–.15

"A" Ranges—Five point carbon range of .02 under and .03 over can be secured if necessary on all GM alloy steels on all GM carbon steels with less than .60 carbon. This 5 point carbon range is specified by adding an "A" suffix to the specification number.

Nickel or Chromium—GM steels which do not specify nickel or chromium may be rejected if these elements exceed the following limits: Nickel .30 Chromium .20.

SQUARE AND ROUND BARS

WEIGHTS AND AREAS

Size, Inches	Weight, Lbs. per Foot		Area, Square Inches		Size, Inches	Weight, Lbs. per Foot		Area, Square Inches	
	□	○	□	○		□	○	□	○
0					3	30.60	24.03	9.000	7.069
1/16	.013	.010	.0039	.0031	1/16	31.89	25.05	9.379	7.366
1/8	.053	.042	.0156	.0123	1/8	33.20	26.08	9.766	7.670
3/16	.120	.094	.0352	.0276	3/16	34.54	27.13	10.160	7.980
1/4	.213	.167	.0625	.0491	1/4	35.91	28.21	10.563	8.296
5/16	.332	.261	.0977	.0767	5/16	37.31	29.30	10.973	8.618
3/8	.478	.376	.1406	.1105	3/8	38.73	30.42	11.391	8.946
7/16	.651	.511	.1914	.1503	7/16	40.18	31.55	11.816	9.281
1/2	.850	.668	.2500	.1963	1/2	41.65	32.71	12.250	9.621
9/16	1.076	.845	.3164	.2485	9/16	43.15	33.89	12.691	9.968
5/8	1.328	1.043	.3906	.3068	5/8	44.68	35.09	13.141	10.321
11/16	1.607	1.262	.4727	.3712	11/16	46.23	36.31	13.598	10.680
3/4	1.913	1.502	.5625	.4418	3/4	47.81	37.55	14.063	11.045
13/16	2.245	1.763	.6602	.5185	13/16	49.42	38.81	14.535	11.416
5/8	2.603	2.044	.7656	.6013	7/8	51.05	40.10	15.016	11.793
15/16	2.988	2.347	.8789	.6903	15/16	52.71	41.40	15.504	12.177
1	3.400	2.670	1.0000	.7854	4	54.40	42.73	16.000	12.566
1/16	3.838	3.015	1.1289	.8866	1/16	56.11	44.07	16.504	12.962
1/8	4.303	3.380	1.2656	.9940	1/8	57.85	45.44	17.016	13.364
3/16	4.795	3.766	1.4102	1.1075	3/16	59.62	46.83	17.535	13.772
1/4	5.313	4.172	1.5625	1.2272	1/4	61.41	48.23	18.063	14.186
5/16	5.857	4.600	1.7227	1.3530	5/16	63.23	49.66	18.598	14.607
3/8	6.428	5.049	1.8906	1.4849	3/8	65.08	51.11	19.141	15.033
7/16	7.026	5.518	2.0664	1.6230	7/16	66.95	52.58	19.691	15.466
1/2	7.650	6.008	2.2500	1.7671	1/2	68.85	54.07	20.250	15.904
9/16	8.301	6.519	2.4414	1.9175	9/16	70.78	55.59	20.816	16.349
5/8	8.978	7.051	2.6406	2.0739	5/8	72.73	57.12	21.391	16.800
11/16	9.682	7.604	2.8477	2.2365	11/16	74.71	58.67	21.973	17.257
3/4	10.413	8.178	3.0625	2.4053	3/4	76.71	60.25	22.563	17.721
13/16	11.170	8.773	3.2852	2.5802	13/16	78.74	61.85	23.160	18.190
7/8	11.953	9.388	3.5156	2.7612	7/8	80.80	63.46	23.766	18.665
15/16	12.763	10.024	3.7539	2.9483	15/16	82.89	65.10	24.379	19.147
2	13.600	10.681	4.0000	3.1416	5	85.00	66.76	25.000	19.635
1/16	14.463	11.359	4.2539	3.3410	1/16	87.14	68.44	25.629	20.129
1/8	15.353	12.058	4.5156	3.5466	1/8	89.30	70.14	26.266	20.629
3/16	16.270	12.778	4.7852	3.7583	3/16	91.49	71.86	26.910	21.135
1/4	17.213	13.519	5.0625	3.9761	1/4	93.71	73.60	27.563	21.648
5/16	18.182	14.280	5.3477	4.2000	5/16	95.96	75.36	28.223	22.166
3/8	19.178	15.062	5.6406	4.4301	3/8	98.23	77.15	28.891	22.691
7/16	20.201	15.866	5.9414	4.6664	7/16	100.53	78.95	29.566	23.221
1/2	21.250	16.690	6.2500	4.9087	1/2	102.85	80.78	30.250	23.758
9/16	22.326	17.534	6.5664	5.1572	9/16	105.20	82.62	30.941	24.301
5/8	23.428	18.400	6.8906	5.4119	5/8	107.58	84.49	31.641	24.850
11/16	24.557	19.287	7.2227	5.6727	11/16	109.98	86.38	32.348	25.406
3/4	25.713	20.195	7.5625	5.9396	3/4	112.41	88.29	33.063	25.967
13/16	26.895	21.123	7.9102	6.2126	13/16	114.87	90.22	33.785	26.535
7/8	28.103	22.072	8.2656	6.4918	7/8	117.35	92.17	34.516	27.109
15/16	29.338	23.042	8.6289	6.7771	15/16	119.86	94.14	35.254	27.688
3	30.600	24.033	9.0000	7.0686	6	122.40	96.13	36.000	28.274

SQUARE AND ROUND BARS
WEIGHTS AND AREAS

Size, Inches	Weight, Lbs. per Foot		Area, Square Inches		Size, Inches	Weight, Lbs. per Foot		Area, Square Inches	
	□	○	□	○		□	○	□	○
6	122.40	96.13	36.000	28.274	9	275.40	216.30	81.000	63.617
1/16	124.96	98.15	36.754	28.866	1/16	279.24	219.31	82.129	64.504
1/8	127.55	100.18	37.516	29.465	1/8	283.10	222.35	83.266	65.397
3/16	130.17	102.23	38.285	30.069	3/16	286.99	225.41	84.410	66.296
1/4	132.81	104.31	39.063	30.680	1/4	290.91	228.48	85.563	67.201
5/16	135.48	106.41	39.848	31.296	5/16	294.86	231.58	86.723	68.112
3/8	138.18	108.53	40.641	31.919	3/8	298.83	234.70	87.891	69.029
7/16	140.90	110.66	41.441	32.548	7/16	302.83	237.84	89.066	69.953
1/2	143.65	112.82	42.250	33.183	1/2	306.85	241.00	90.250	70.882
9/16	146.43	115.00	43.066	33.824	9/16	310.90	244.18	91.441	71.818
5/8	149.23	117.20	43.891	34.472	5/8	314.98	247.38	92.641	72.760
11/16	152.06	119.43	44.723	35.125	11/16	319.08	250.61	93.848	73.708
3/4	154.91	121.67	45.563	35.785	3/4	323.21	253.85	95.063	74.662
13/16	157.79	123.93	46.410	36.450	13/16	327.37	257.12	96.285	75.622
7/8	160.70	126.22	47.266	37.122	7/8	331.55	260.40	97.516	76.589
15/16	163.64	128.52	48.129	37.800	15/16	335.76	263.71	98.754	77.561
7	166.60	130.85	49.000	38.485	10	340.00	267.04	100.000	78.540
1/16	169.59	133.19	49.879	39.175	1/16	344.26	270.38	101.254	79.525
1/8	172.60	135.56	50.766	39.871	1/8	348.55	273.75	102.516	80.516
3/16	175.64	137.95	51.660	40.574	3/16	352.87	277.14	103.785	81.513
1/4	178.71	140.36	52.563	41.282	1/4	357.21	280.55	105.063	82.516
5/16	181.81	142.79	53.473	41.997	5/16	361.58	283.99	106.348	83.525
3/8	184.93	145.24	54.391	42.718	3/8	365.98	287.44	107.641	84.541
7/16	188.07	147.71	55.316	43.445	7/16	370.40	290.91	108.941	85.563
1/2	191.25	150.21	56.250	44.179	1/2	374.85	294.41	110.250	86.590
9/16	194.45	152.72	57.191	44.918	9/16	379.33	297.92	111.566	87.624
5/8	197.68	155.26	58.141	45.664	5/8	383.83	301.46	112.891	88.664
11/16	200.93	157.81	59.098	46.415	11/16	388.36	305.02	114.223	89.710
3/4	204.21	160.39	60.063	47.173	3/4	392.91	308.59	115.563	90.763
13/16	207.52	162.99	61.035	47.937	13/16	397.49	312.19	116.910	91.821
7/8	210.85	165.60	62.016	48.707	7/8	402.10	315.81	118.266	92.886
15/16	214.21	168.24	63.004	49.483	15/16	406.74	319.45	119.629	93.957
8	217.60	170.90	64.000	50.265	11	411.40	323.11	121.000	95.033
1/16	221.01	173.58	65.004	51.054	1/16	416.09	326.80	122.379	96.116
1/8	224.45	176.29	66.016	51.849	1/8	420.80	330.50	123.766	97.205
3/16	227.92	179.01	67.035	52.649	3/16	425.54	334.22	125.160	98.301
1/4	231.41	181.75	68.063	53.456	1/4	430.31	337.97	126.563	99.402
5/16	234.93	184.52	69.098	54.269	5/16	435.11	341.73	127.973	100.510
3/8	238.48	187.30	70.141	55.088	3/8	439.93	345.52	129.391	101.623
7/16	242.05	190.11	71.191	55.914	7/16	444.78	349.33	130.816	102.743
1/2	245.65	192.93	72.250	56.745	1/2	449.65	353.16	132.250	103.869
9/16	249.28	195.78	73.316	57.583	9/16	454.55	357.00	133.691	105.001
5/8	252.93	198.65	74.391	58.426	5/8	459.48	380.87	135.141	106.139
11/16	256.61	201.54	75.473	59.276	11/16	464.43	364.76	136.598	107.284
3/4	260.31	204.45	76.563	60.132	3/4	469.41	368.68	138.063	108.434
13/16	264.04	207.38	77.660	60.994	13/16	474.42	372.61	139.535	109.591
7/8	267.80	210.33	78.766	61.863	7/8	479.45	376.56	141.016	110.754
15/16	271.59	213.31	79.879	62.737	15/16	484.51	380.54	142.504	111.923
9	275.40	216.30	81.000	63.617	12	489.60	384.53	144.000	113.098

AREAS OF RECTANGULAR SECTIONS

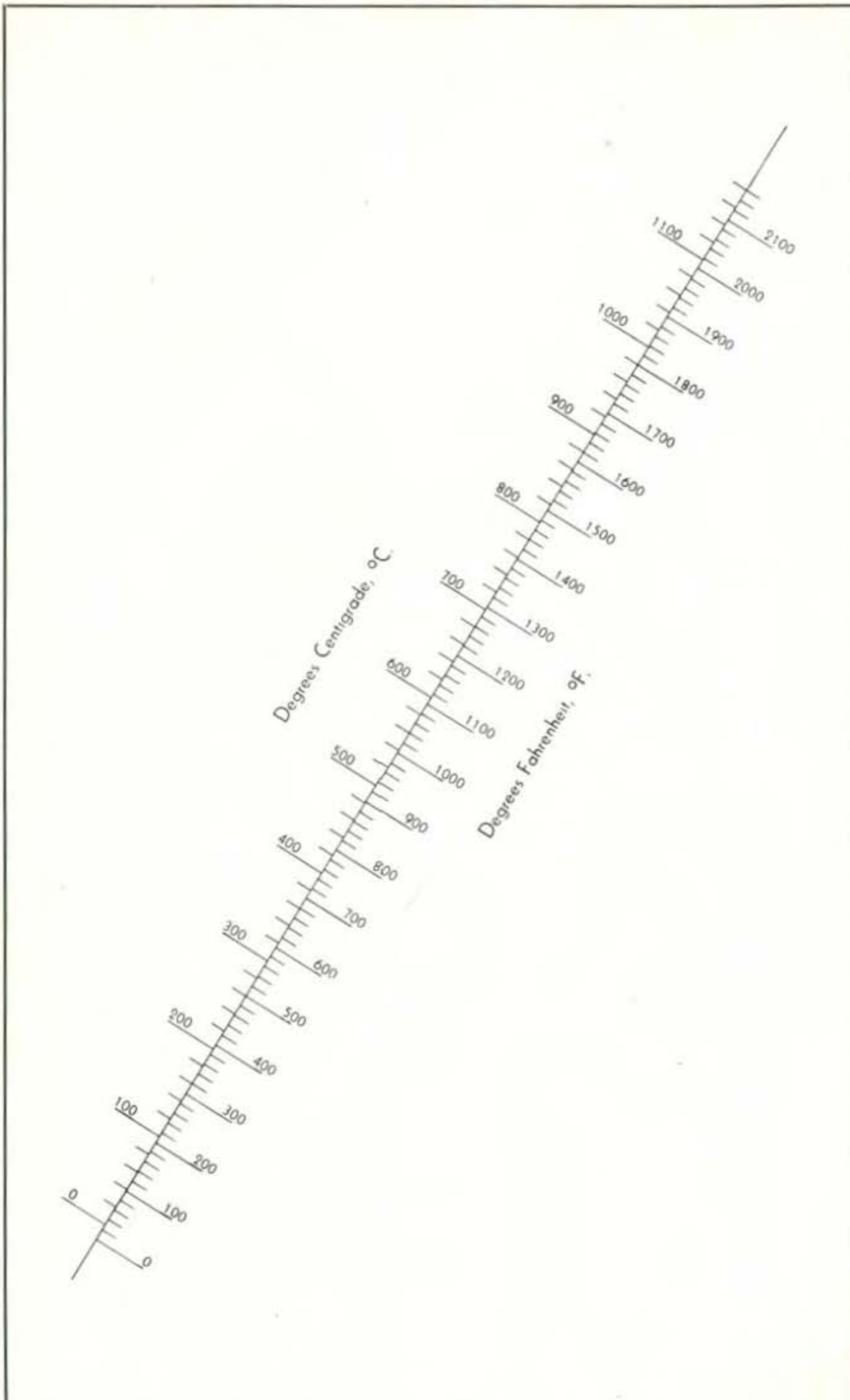
SQUARE INCHES

Width, Inches	Thickness, Inches															
	1/16	1/8	3/16	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1
1/4	.016	.031	.047	. 063	.078	.094	.109	.125	.141	.156	.172	.188	.203	.219	.234	.250
1/2	.031	.063	.094	.125	.156	.188	.219	.250	.281	.313	.344	.375	.406	.438	.469	.500
3/4	.047	.094	.141	.188	.234	.281	.328	.375	.422	.469	.516	.563	.609	.656	.703	.750
1	.063	.125	.188	.250	.313	.375	.438	.500	.563	.625	.688	.750	.813	.875	.938	1.000
1 1/4	.078	.156	.234	.313	.391	.469	.547	.625	.703	.781	.859	.938	1.016	1.094	1.172	1.250
1 1/2	.094	.188	.281	.375	.469	.563	.656	.750	.844	.938	1.031	1.125	1.219	1.313	1.406	1.500
1 3/4	.109	.219	.328	.438	.547	.656	.766	.875	.984	1.094	1.203	1.313	1.422	1.531	1.641	1.750
2	.125	.250	.375	.500	.625	.750	.875	1.000	1.125	1.250	1.375	1.500	1.625	1.750	1.875	2.000
2 1/4	.141	.281	.422	.563	.703	.844	.984	1.125	1.266	1.406	1.547	1.688	1.828	1.969	1.109	2.250
2 1/2	.156	.313	.469	.625	.781	.938	1.094	1.250	1.406	1.563	1.719	1.875	2.031	2.188	2.344	2.500
2 3/4	.172	.344	.516	.688	.859	1.031	1.203	1.375	1.547	1.719	1.891	2.063	2.234	2.406	2.578	2.750
3	.188	.375	.563	.750	.938	1.125	1.313	1.500	1.688	1.875	2.063	2.250	2.438	2.625	2.813	3.000
3 1/4	.203	.406	.609	.813	1.016	1.219	1.422	1.625	1.828	2.031	2.234	2.438	2.641	2.844	3.047	3.250
3 1/2	.219	.438	.656	.875	1.094	1.313	1.531	1.750	1.969	2.188	2.406	2.625	2.844	3.063	3.281	3.500
3 3/4	.234	.469	.703	.938	1.172	1.406	1.641	1.875	2.109	2.344	2.578	2.813	3.047	3.281	3.516	3.750
4	.250	.500	.750	1.000	1.250	1.500	1.750	2.000	2.250	2.500	2.750	3.000	3.250	3.500	3.750	4.000
4 1/4	.266	.531	.797	1.063	1.328	1.594	1.859	2.125	2.391	2.656	2.922	3.188	3.453	3.719	3.984	4.250
4 1/2	.281	.563	.844	1.125	1.406	1.688	1.969	2.250	2.531	2.813	3.094	3.375	3.656	3.938	4.219	4.500
4 3/4	.297	.594	.891	1.188	1.484	1.781	2.078	2.375	2.672	2.969	3.266	3.563	3.859	4.156	4.453	4.750
5	.313	.625	.938	1.250	1.563	1.875	2.188	2.500	2.813	3.125	3.438	3.750	4.063	4.375	4.688	5.000
5 1/4	.328	.656	.984	1.313	1.641	1.969	2.297	2.625	2.953	3.281	3.609	3.938	4.266	4.594	4.922	5.250
5 1/2	.344	.688	1.031	1.375	1.719	2.063	2.406	2.750	3.094	3.438	3.781	4.125	4.469	4.813	5.156	5.500
5 3/4	.359	.719	1.078	1.438	1.797	2.156	2.516	2.875	3.234	3.594	3.953	4.313	4.672	5.031	5.391	5.750
6	.375	.750	1.125	1.500	1.875	2.250	2.625	3.000	3.375	3.750	4.125	4.500	4.875	5.250	5.625	6.000
6 1/4	.391	.781	1.172	1.563	1.953	2.344	2.734	3.125	3.516	3.906	4.297	4.688	5.078	5.469	5.859	6.250
6 1/2	.406	.813	1.219	1.625	2.031	2.438	2.844	3.250	3.656	4.063	4.469	4.875	5.281	5.688	6.094	6.500
6 3/4	.422	.844	1.266	1.688	2.109	2.531	2.953	3.375	3.797	4.219	4.641	5.063	5.484	5.906	6.328	6.750
7	.438	.875	1.313	1.750	2.188	2.625	3.063	3.500	3.938	4.375	4.813	5.250	5.688	6.125	5.563	7.000
7 1/4	.453	.906	1.359	1.813	2.266	2.719	3.172	3.625	4.078	4.531	4.984	5.438	5.891	6.344	6.797	7.250
7 1/2	.469	.938	1.406	1.875	2.344	2.813	3.281	3.750	4.219	4.688	5.156	5.625	6.094	6.563	7.031	7.500
7 3/4	.484	.969	1.453	1.938	2.422	2.906	3.391	3.875	4.359	4.844	5.328	5.813	6.297	6.781	7.266	7.750
8	.500	1.000	1.500	2.000	2.500	3.000	3.500	4.000	4.500	5.000	5.500	6.000	6.500	7.000	7.500	8.000
8 1/4	.516	1.021	1.547	2.063	2.578	3.094	3.609	4.125	4.641	5.150	5.672	6.188	6.703	7.219	7.734	8.250
8 1/2	.531	1.063	1.594	2.125	2.656	3.188	3.719	4.250	4.781	5.313	5.844	6.375	6.906	7.438	7.969	8.500
8 3/4	.547	1.094	1.641	2.188	2.734	3.281	3.828	4.375	4.922	5.469	6.016	6.563	7.109	7.656	8.203	8.750
9	.563	1.125	1.688	2.250	2.813	3.375	3.938	4.500	5.063	5.625	6.188	6.750	7.313	7.875	8.438	9.000
9 1/4	.578	1.156	1.734	2.313	2.891	3.469	4.047	5.625	5.203	5.781	6.359	6.938	7.516	8.094	8.672	9.250
9 1/2	.594	1.188	1.781	2.375	2.969	3.563	4.156	4.750	5.344	5.938	6.531	7.125	7.719	8.313	8.906	9.500
9 3/4	.609	1.219	1.828	2.438	3.047	3.656	4.266	4.875	5.484	6.094	6.703	7.313	7.922	8.531	9.141	9.750
10	.625	1.250	1.875	2.500	3.125	3.750	4.375	5.000	5.625	6.250	6.875	7.500	8.125	8.750	9.375	10.00

WEIGHTS OF RECTANGULAR SECTIONS

POUNDS PER LINEAL FOOT

Width, Inches	Thickness, Inches															
	1/16	1/8	3/16	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1
1/4	.053	.106	.159	.213	.266	.319	.372	.425	.478	.531	.584	.638	.691	.744	.797	.850
1/2	.106	.213	.319	.425	.531	.638	.744	.850	.956	1.063	1.169	1.275	1.381	1.488	1.594	1.700
3/4	.159	.319	.478	.638	.797	.956	1.116	1.275	1.434	1.594	1.753	1.913	2.072	2.231	2.391	2.550
1	.213	.425	.638	.850	1.063	1.275	1.488	1.700	1.913	2.125	2.338	2.550	2.763	2.975	3.188	3.400
1 1/4	.266	.531	.797	1.063	1.328	1.594	1.859	2.125	2.391	2.656	2.922	3.188	3.453	3.719	3.984	4.250
1 1/2	.319	.638	.956	1.275	1.594	1.913	2.231	2.550	2.869	3.188	3.506	3.825	4.144	4.463	4.781	5.100
1 3/4	.372	.744	1.116	1.488	1.859	2.231	2.603	2.975	3.347	3.719	4.091	4.463	4.834	5.206	5.578	5.950
2	.425	.850	1.275	1.700	2.125	2.550	2.975	3.400	3.825	4.250	4.675	5.100	5.525	5.950	6.375	6.800
2 1/4	.478	.956	1.434	1.913	2.391	2.869	3.347	3.825	4.303	4.781	5.259	5.738	6.216	6.694	7.172	7.650
2 1/2	.531	1.063	1.594	2.125	2.656	3.188	3.719	4.250	4.781	5.313	5.844	6.375	6.906	7.438	7.969	8.500
2 3/4	.584	1.169	1.753	2.338	2.922	3.506	4.091	4.675	5.259	5.844	6.428	7.013	7.597	8.181	8.766	9.350
3	.638	1.275	1.913	2.550	3.188	3.825	4.463	5.100	5.738	6.375	7.013	7.650	8.288	8.925	9.563	10.20
3 1/4	.691	1.381	2.072	2.763	3.453	4.144	4.834	5.525	6.216	6.906	7.597	8.288	8.978	9.669	10.36	11.05
3 1/2	.744	1.488	2.231	2.975	3.719	4.463	5.206	5.950	6.694	7.438	8.181	8.925	9.669	10.41	11.16	11.90
3 3/4	.797	1.594	2.391	3.188	3.984	4.781	5.578	6.375	7.172	7.969	8.766	9.563	10.36	11.16	11.95	12.75
4	.850	1.700	2.550	3.400	4.250	5.100	5.950	6.800	7.650	8.500	9.350	10.20	11.05	11.90	12.75	13.60
4 1/4	.903	1.806	2.709	3.613	4.516	5.419	6.322	7.225	8.128	9.031	9.934	10.84	11.74	12.64	13.55	14.45
4 1/2	.956	1.913	2.869	3.825	4.781	5.738	6.694	7.650	8.606	9.563	10.52	11.48	12.43	13.39	14.34	15.30
4 3/4	1.000	2.019	3.028	4.038	5.047	6.056	7.066	8.075	9.084	10.09	11.10	12.11	13.12	14.13	15.14	16.15
5	1.063	2.125	3.188	4.250	5.313	6.375	7.438	8.500	9.563	10.63	11.69	12.75	13.81	14.88	15.94	17.00
5 1/4	1.116	2.231	3.347	4.463	5.578	6.694	7.809	8.925	10.04	11.16	12.27	13.39	14.50	15.62	16.73	17.85
5 1/2	1.169	2.338	3.506	4.675	5.844	7.013	8.181	9.350	10.52	11.69	12.86	14.03	15.19	16.36	17.53	18.70
5 3/4	1.222	2.444	3.666	4.888	6.109	7.331	8.553	9.775	11.00	12.22	13.44	14.66	15.88	17.11	18.33	19.55
6	1.275	2.550	3.825	5.100	6.375	7.650	8.925	10.20	11.48	12.75	14.03	15.30	16.58	17.85	19.13	20.40
6 1/4	1.328	2.656	3.984	5.313	6.641	7.969	9.297	10.63	11.95	13.28	14.61	15.94	17.27	18.59	19.92	21.25
6 1/2	1.381	2.763	4.144	5.525	6.906	8.288	9.669	11.05	12.43	13.81	15.19	16.58	17.96	19.34	20.72	22.10
6 3/4	1.434	2.869	4.303	5.738	7.172	8.606	10.04	11.48	12.91	14.34	15.78	17.21	18.65	20.08	21.52	22.95
7	1.488	2.975	4.463	5.950	7.438	8.925	10.41	11.90	13.39	14.88	16.36	17.85	19.34	20.83	22.31	23.80
7 1/4	1.541	3.081	4.622	6.163	7.703	9.244	10.78	12.33	13.87	15.41	16.95	18.49	20.03	21.57	23.11	24.65
7 1/2	1.594	3.188	4.781	6.375	7.969	9.563	11.16	12.75	14.34	15.94	17.53	19.13	20.72	22.31	23.91	25.50
7 3/4	1.647	3.294	4.941	6.588	8.234	9.881	11.53	13.18	14.82	16.47	18.12	19.76	21.41	23.06	24.70	26.35
8	1.700	3.400	5.100	6.800	8.500	10.20	11.90	13.60	15.30	17.00	18.70	20.40	22.10	23.80	25.50	27.20
8 1/4	1.753	3.506	5.259	7.013	8.766	10.52	12.27	14.03	15.78	17.53	19.28	21.04	22.79	24.54	26.30	28.05
8 1/2	1.806	3.613	5.419	7.225	9.031	10.84	12.64	14.45	16.26	18.06	19.87	21.68	23.48	25.29	27.09	28.90
8 3/4	1.859	3.719	5.578	7.438	9.297	11.16	13.02	14.88	16.73	18.59	20.45	22.31	24.17	26.03	27.89	29.75
9	1.913	3.825	5.738	7.650	9.563	11.48	13.39	15.30	17.21	19.13	21.04	22.95	24.86	26.78	28.69	30.60
9 1/4	1.966	3.931	5.897	7.863	9.828	11.79	13.76	15.73	17.69	19.66	21.62	23.59	25.55	27.52	29.48	31.45
9 1/2	2.019	4.038	6.056	8.075	10.09	12.11	14.13	16.15	18.17	20.19	22.21	24.23	26.24	28.26	30.28	32.30
9 3/4	2.072	4.144	6.216	8.288	10.36	12.43	14.50	16.58	18.65	20.72	22.79	24.86	26.93	29.01	31.08	33.15
10	2.125	4.250	6.375	8.500	10.63	12.75	14.88	17.00	19.13	21.25	23.38	25.50	27.63	29.75	31.88	34.00



Temperature Conversion Chart

TABLE XXX. MENDELEEFF'S PERIODIC TABLE OF ELEMENTS (Revised, 1925)

PERIODS			GROUP I	GROUP II	GROUP III	GROUP IV	GROUP V	GROUP VI	GROUP VII	GROUP VIII			GROUP 0
Short Periods	I		H 1 1.008										He 2 4.00
	II		Li 3 6.940	Be 4 9.02	B 5 10.82	C 6 12.000	N 7 14.008	O 8 16.000	F 9 19.00				Ne 10 20.2
	III		Na 11 22.997	Mg 12 24.32	Al 13 26.97	Si 14 28.06	P 15 31.027	S 16 32.064	Cl 17 35.457				A 18 39.91
			A B	A B	B A	B A	B A	B A	B A				
Long Periods	IV	Even Series	K 19 39.096	Ca 20 40.07	Sc 21 45.10	Ti 22 48.1	V 23 50.96	Cr 24 52.01	Mn 25 54.93	Fe 26 55.84	Co 27 58.94	Ni 28 58.69	
		Odd Series	Cu 29 63.57	Zn 30 65.38	Ga 31 69.72	Ge 32 72.60	As 33 74.96	Se 34 79.2	Br 35 79.916				Kr 36 82.9
	V	Even Series	Rb 37 85.44	Sr 38 87.63	Y 39 88.9	Zr 40 91.	Cb 41 93.1	Mo 42 96.0	Ma 43	Ru 44 101.7	Rh 45 102.91	Pd 46 106.7	
		Odd Series	Ag 47 107.880	Cd 48 112.41	In 49 114.8	Sn 50 118.70	Sb 51 121.77	Te 52 127.5	I 53 126.932				Xe 54 130.2
	VI		Ca 55 132.81	Ba 56 137.37	La 57 138.90	Ce 58 140.25							
					Also rare-earth metals 59 to 71*	Hf 72 180.8	Ta 73 181.5	W 74 184.0	Re 75 188.7	Os 76 190.8	Ir 77 193.1	Pt 78 195.23	
			Au 79 197.2	Hg 80 200.61	Tl 81 204.39	Pb 82 207.20	Bi 83 209.00	Po 84	—85				Rn 86 222.
	VII		—87	Ra 88 225.95	Ac 89	Th 90 232.15	Pa 91	U 92 238.17					
Formulas of Oxides Formulas of Hydrides			R_2O RH'	RO RH_2	R_2O_3 RH_3	RO_2 RH_4	R_2O_5 RH_3	RO_3 RH_2	R_2O_7 RH	RO_4			

*Pr 59 140.92	Nd 60 144.27	Il 61	Sa 62 150.43	Eu 63 152.0	Gd 64 157.26	Tb 65 159.2	Dy 66 162.52	Ho 67 163.4	Er 68 167.7	Tu 69 169.4	Yb 70 173.6	Lu 71 175.0

INDEX

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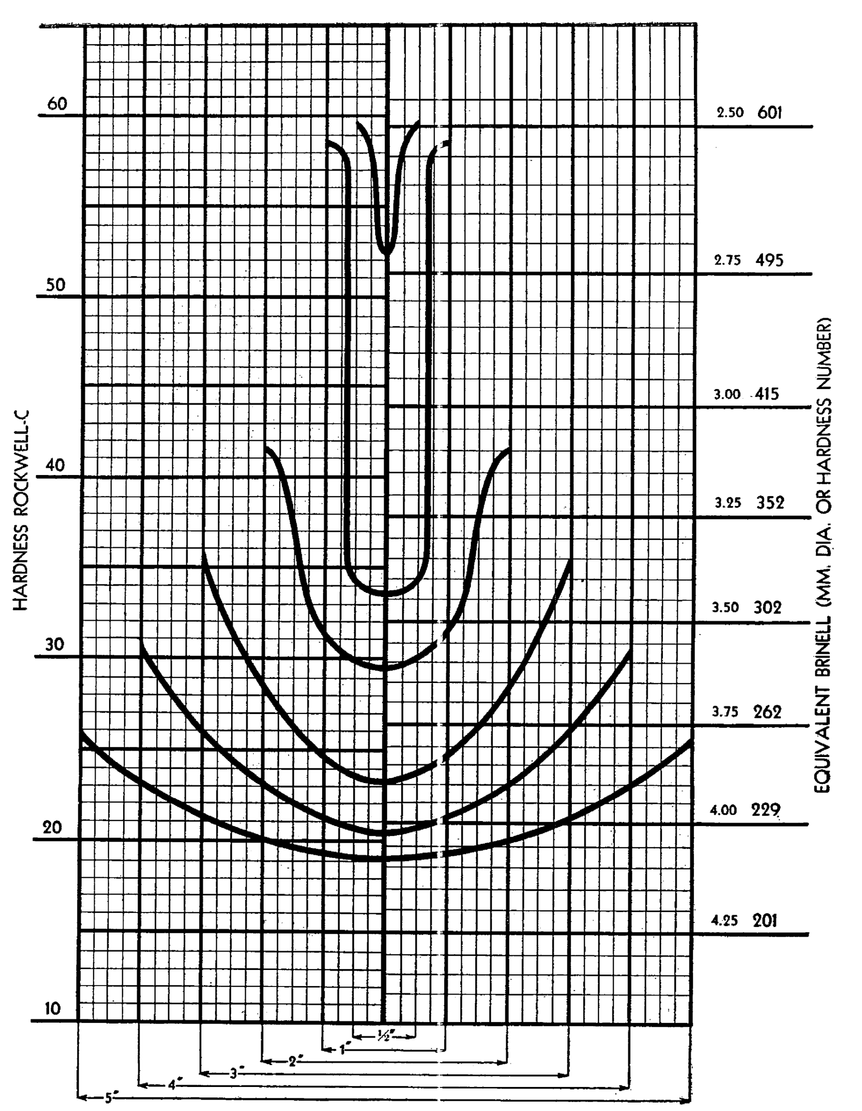

Fig. 12. Hardness distribution in various sizes of quenched round bars. *1045* Steel quenched in *Water*

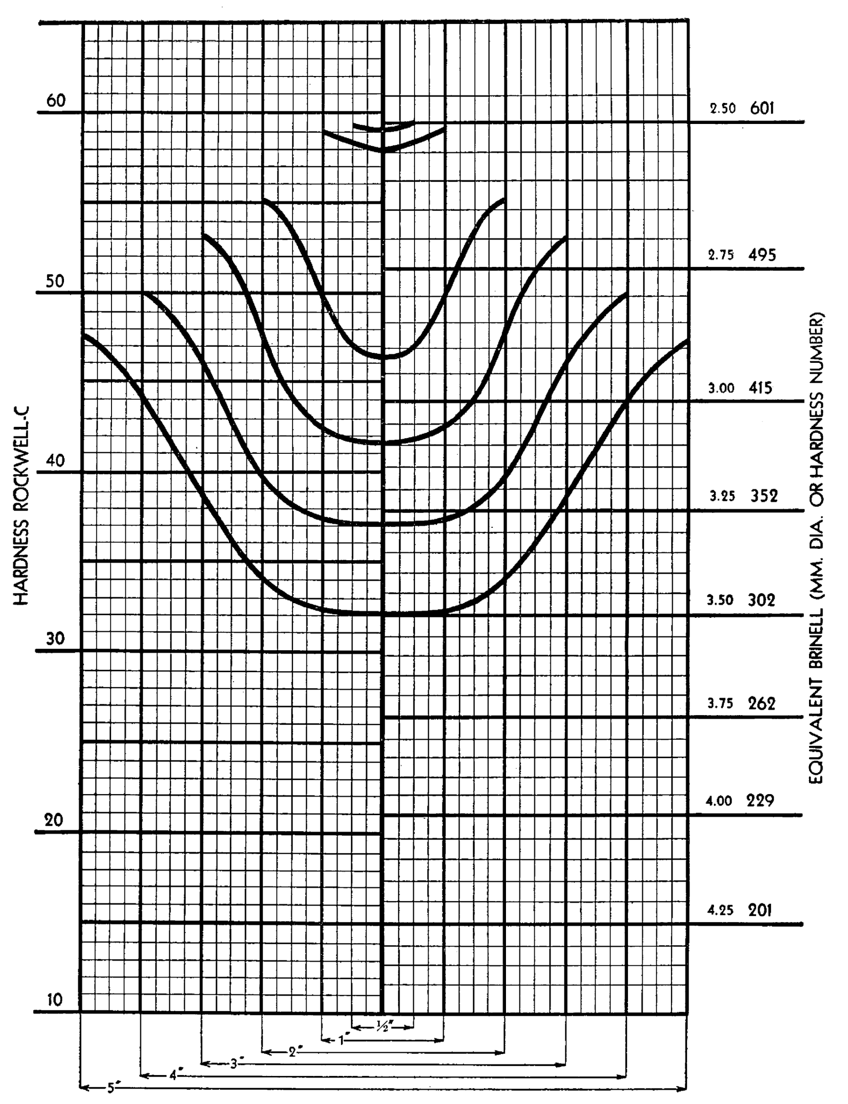

Fig. 14. Hardness distribution in various sizes of quenched round bars. *6140* Steel quenched in *Water*

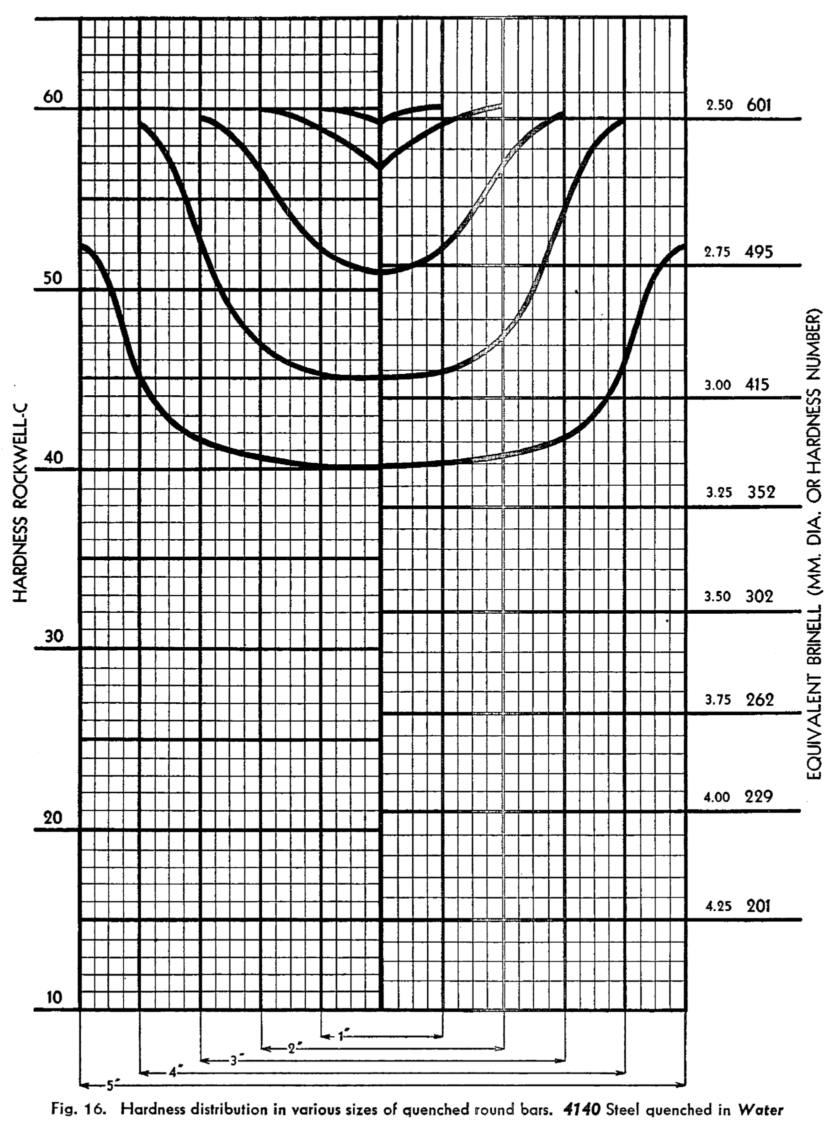

Fig. 16. Hardness distribution in various sizes of quenched round bars. *4140* Steel quenched in *Water*

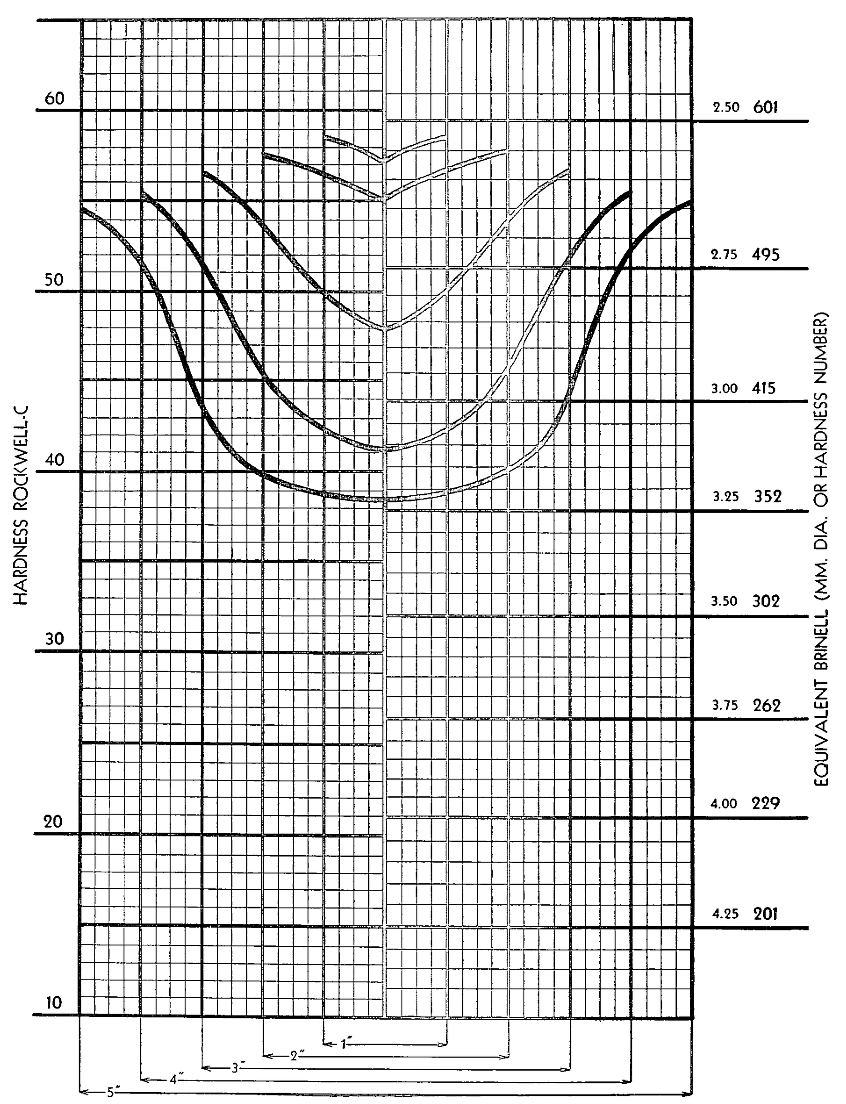

Fig. 18. Hardness distribution in various sizes of quenched round bars. *3240* Steel quenched in *Water*

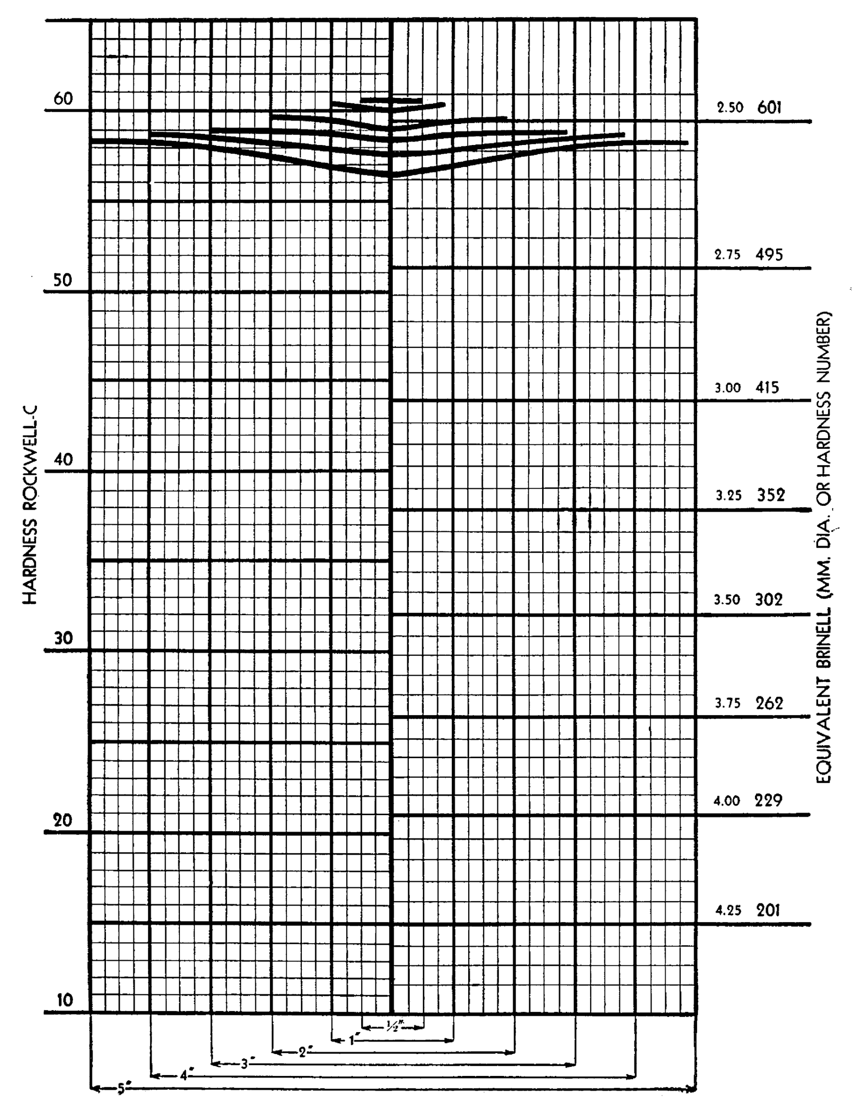

Fig. 20. Hardness distribution in various sizes of quenched round bars. *3340* Steel quenched in *Water*

Typical Hardnesses Developed in Five Different Steels in a Range of Sizes, When Quenched in Water or in Oil

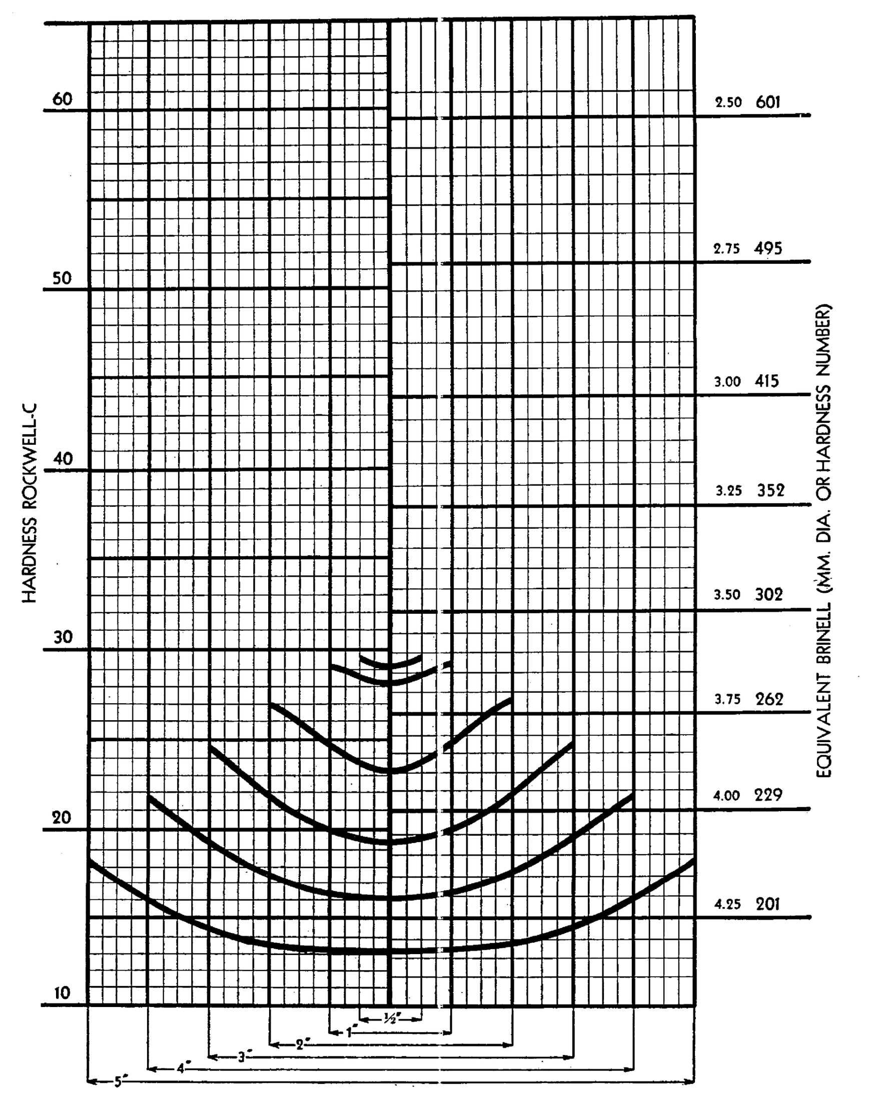

Fig. 13. Hardness distribution in various sizes of quenched round bars. *1045* Steel quenched in *Oil*

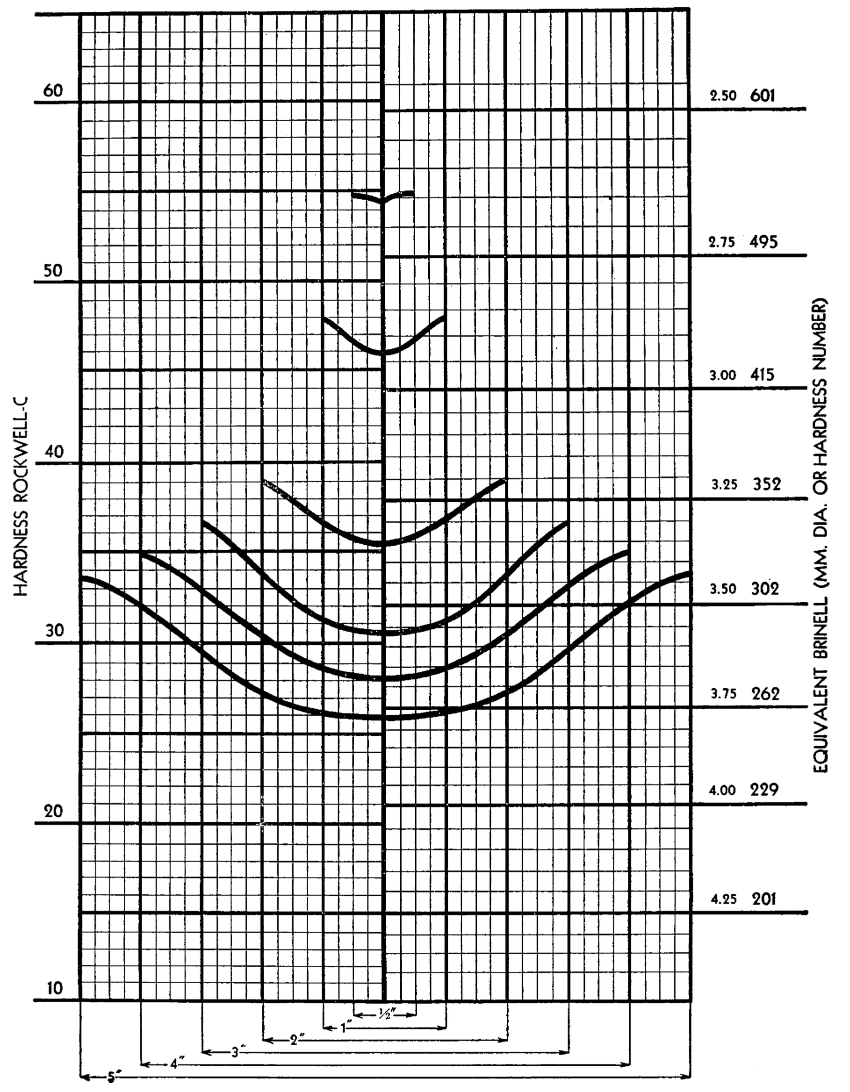

Fig. 15. Hardness distribution in various sizes of quenched round bars. *6140* Steel quenched in *Oil*

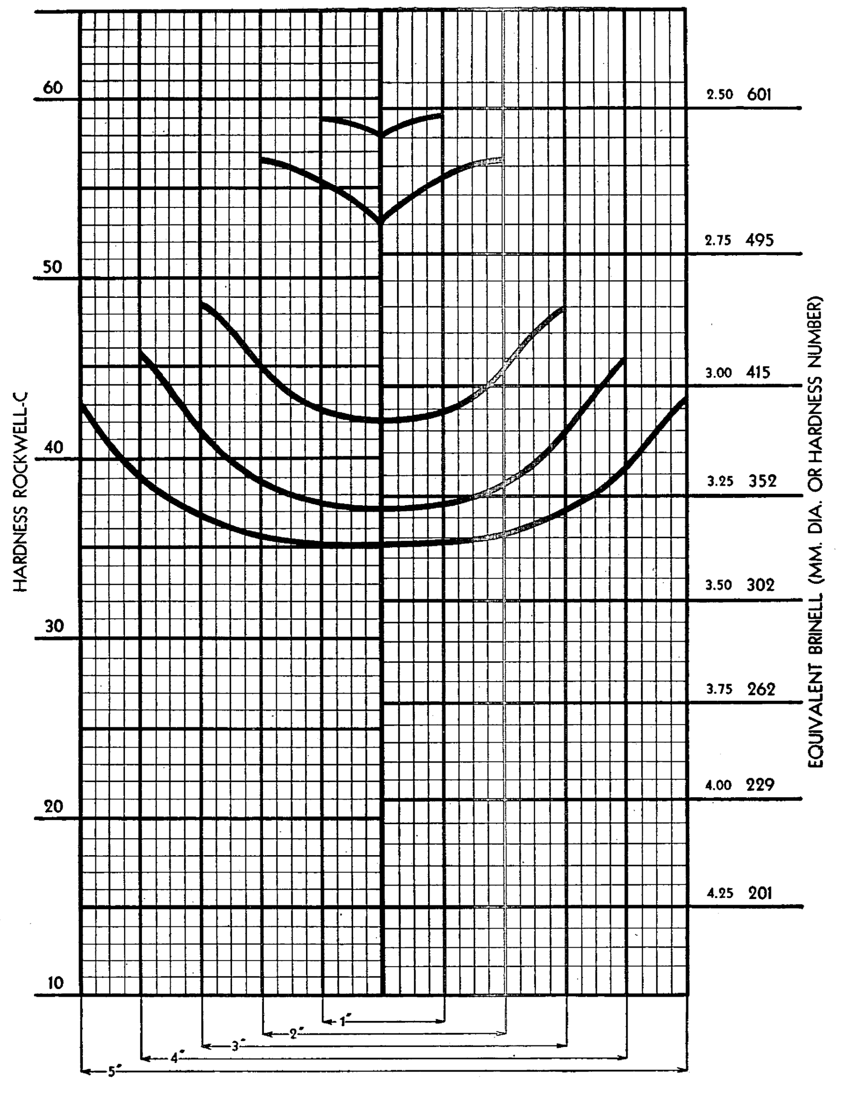

Fig. 17. Hardness distribution in various sizes of quenched round bars. *4140* Steel quenched in *Oil*

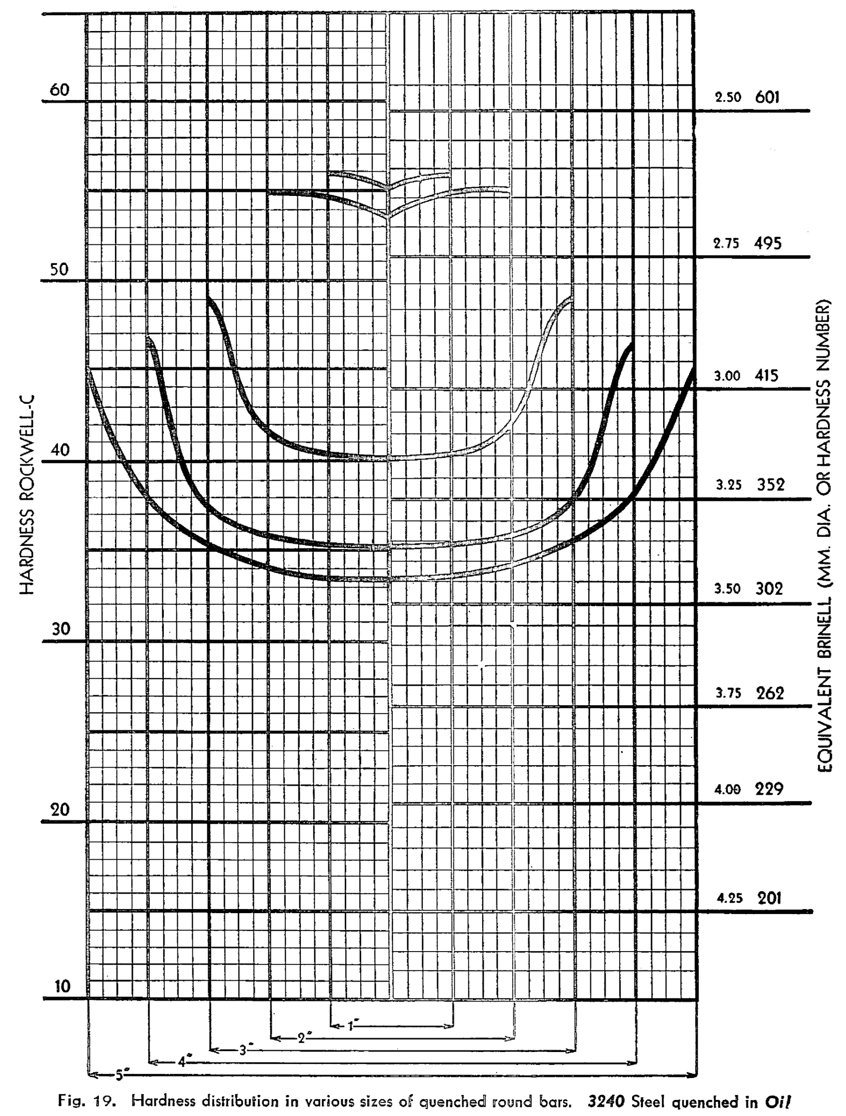

Fig. 19. Hardness distribution in various sizes of quenched round bars. *3240* Steel quenched in *Oil*

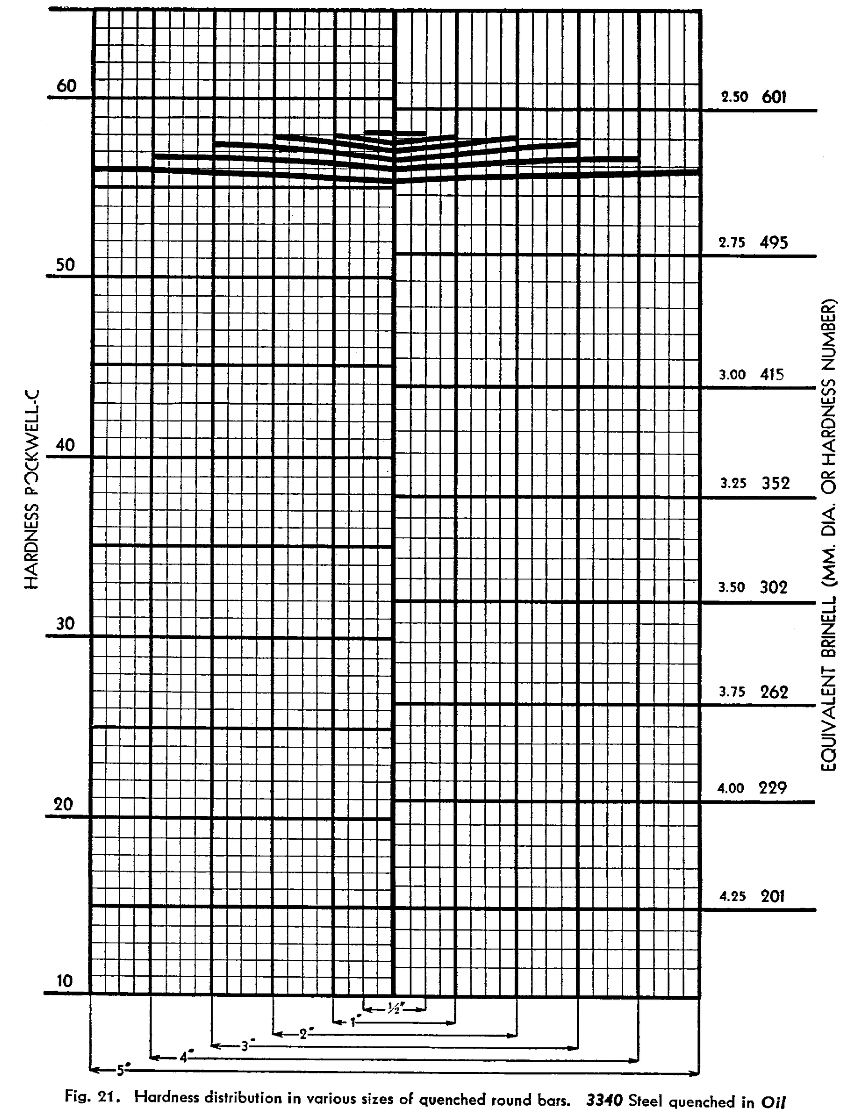

Fig. 21. Hardness distribution in various sizes of quenched round bars. *3340* Steel quenched in *Oil*

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"GRAIN SIZE IN STEEL"

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ALLOY STEELS

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CARNEGIE-ILLINOIS STEEL CORPORATION

UNITED STATES STEEL


Grain Size No. 1
Grain Size No. 2
Grain Size No. 3
Grain Size No. 4
Grain Size No. 5
Grain Size No. 6
Grain Size No. 7
Grain Size No. 8

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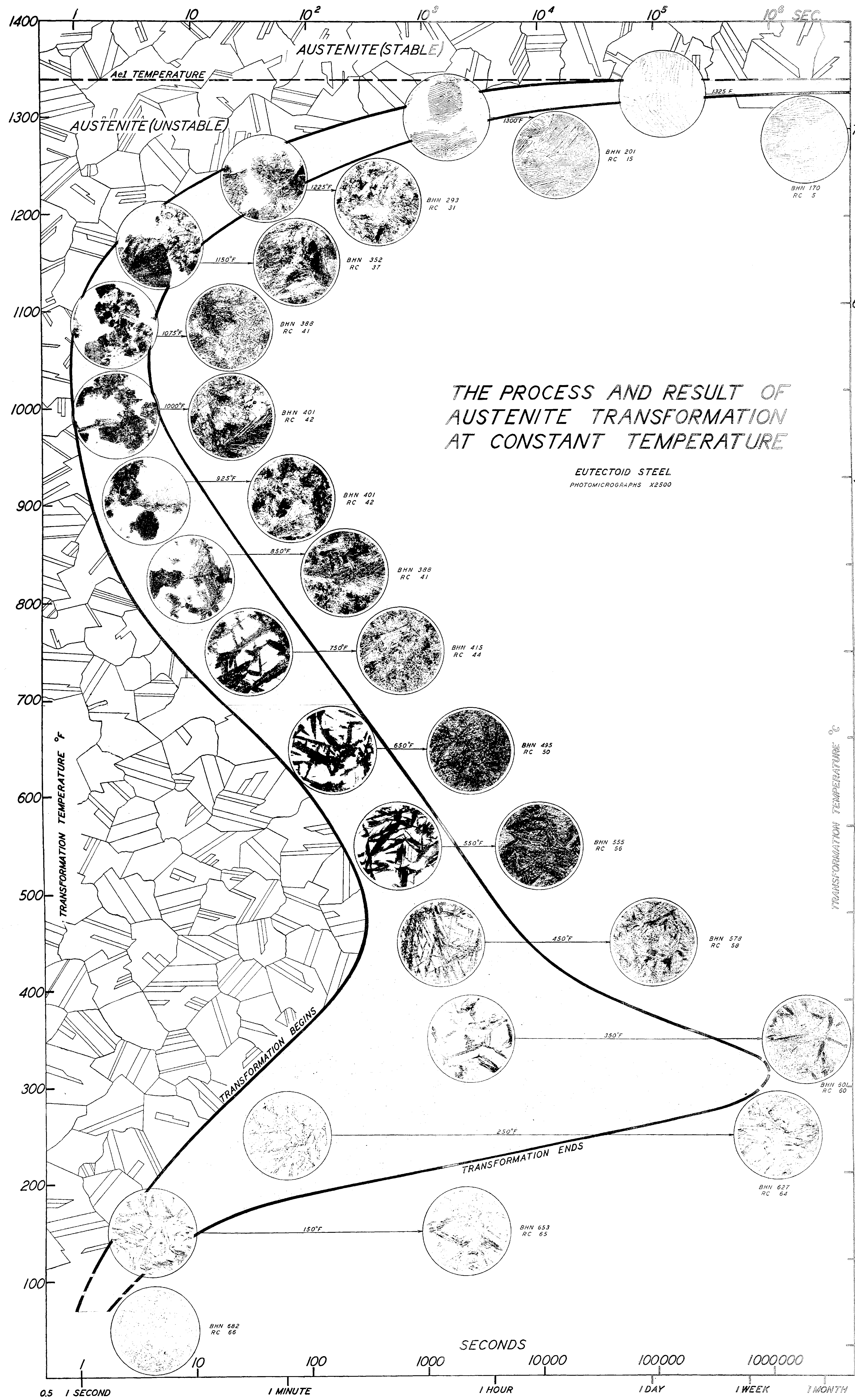
UNITED STATES STEEL



TIME ON LOGARITHMIC SCALE

UNITED STATES STEEL CORPORATION
RESEARCH LABORATORY
1935

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