A PRACTICAL APPROACH TO UNDERSTANDING STEELS, THEIR ALLOYING, HEAT TREATMENT AND SURFACE HARDENING

by

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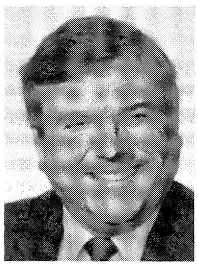

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ABSTRACT

The greatest tonnage of engineering materials used in the world are steels. Therefore, it is most helpful, and in many cases mandatory, that those who either design, fabricate or maintain components constructed of steel have a practical understanding of how this family of materials functions. Steel is a very versatile material which can exhibit a wide range of both physical and mechanical characteristics. The *diversity* of steel is never more strikingly illustrated than the use of a file to round off a rough edge or a steel cutting tool to shape another piece of steel in some form of metal working equipment. These are two pieces of the same metal so different in properties that one, without damage to itself, will actually cut the other.

The addition of various alloying elements to steel and how they affect the efficiency of thermal heat treatment, mechanical properties, dimensional stability, fatigue properties, wear and machinability will be discussed. In addition, all of the commonly used through section heat treating processes are described as they apply to steel and its alloys.

The two major classes of surface hardening techniques, namely alterations to and no alternations of the surface chemistry, will be discussed as they apply to increasing hardness, improving wear and fatigue resistance and controlling dimensional stability of mechanical components.

INTRODUCTION

When man began to utilize machinery to perform his tasks, he was immediately confronted with the problem of making components that were stronger, lighter and more resistant to wear. Early metalsmiths and, later, blacksmiths quickly learned that they could heat steels to red heat and then plunge them into water or another medium to increase their hardness and wear resistance.

How these alterations (the phenomena of allotropic transformation of the iron-carbon system) occur will be discussed without photomicrographs and with very limited use of the iron-iron carbide phase diagram. The various types of heat treatments and their applications will also be examined.

IRON CARBON SYSTEM

As an elemental metal, pure iron has very limited engineering usefulness. Carbon is the key alloy addition that changes iron from its limited application to the unique structural material known as steel. Due to its small atomic size (compared to the iron atom), carbon jams the iron matrix during the transformation from austenite to ferrite (Figure 1) and produces the hard transition structure martensite. The effects of varying the carbon content on the resultant hardness of heat treated carbon steel are shown in Figure 2 and further on the overall mechanical properties in Figure 3. It is important to recognize from these figures that as the mechanical strength increases, there is *always* a corresponding reduction in the material ductility.

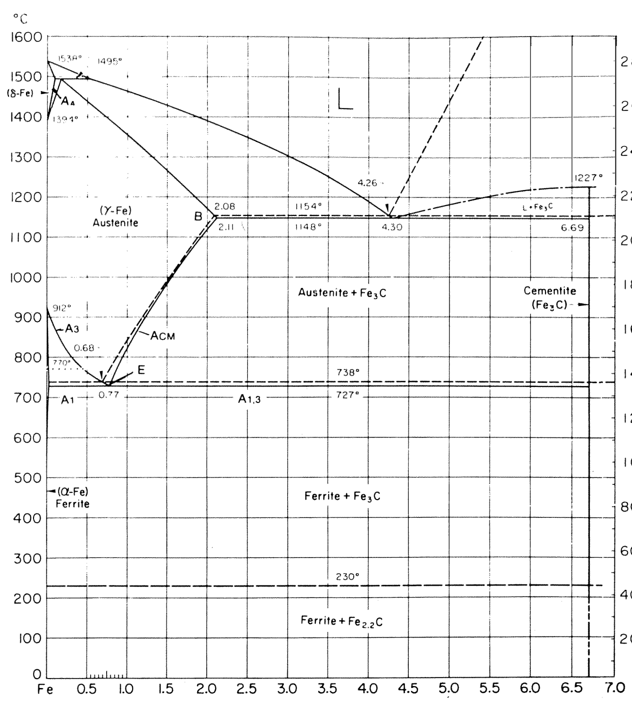


Figure 1. Iron-Carbon Phase Diagram.

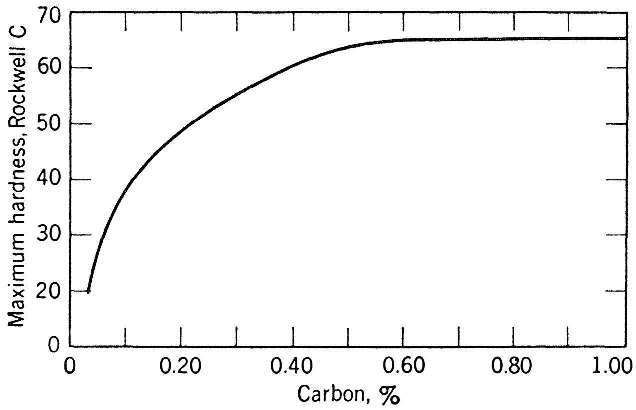


Figure 2. Maximum Hardness vs. Carbon Content in Steel (Burns, Moore & Archer).

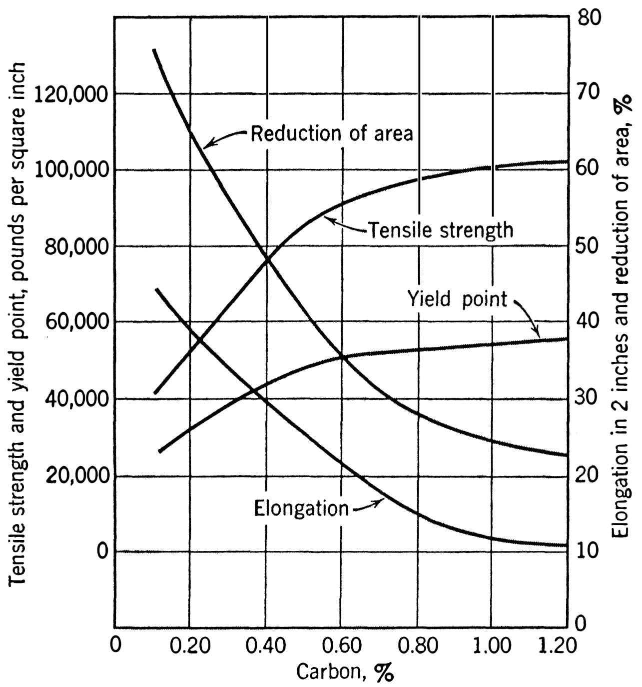


Figure 3. Effect of Carbon Content on the Mechanical Properties of Hot Rolled Carbon Steel (After Grossman).

ALLOYING ELEMENTS IN STEEL

Alloying elements are added to steel to enhance its properties. In the broadcast sense, alloy steels may contain up to approximately 50 percent of alloying elements and the enhancement of properties may be a specific and direct function of the alloying elements. The term "alloy steels" refers to the heat-treatable alloy constructional, automotive and process vessel steels which contain from one percent to four percent alloying elements. The mechanical properties of steel are dependent upon its microstructure. In the American Iron and Steel Institute (AISI) alloy steels, the effect of the alloying is indirect, i.e., through their influence on the microstructure of the material. The alloy contents of these alloy steels make it possible to attain desirable microstructures and corresponding desirable properties over a much wider range of sizes and sections than is possible with the carbon steels, as shown in Figure 4.

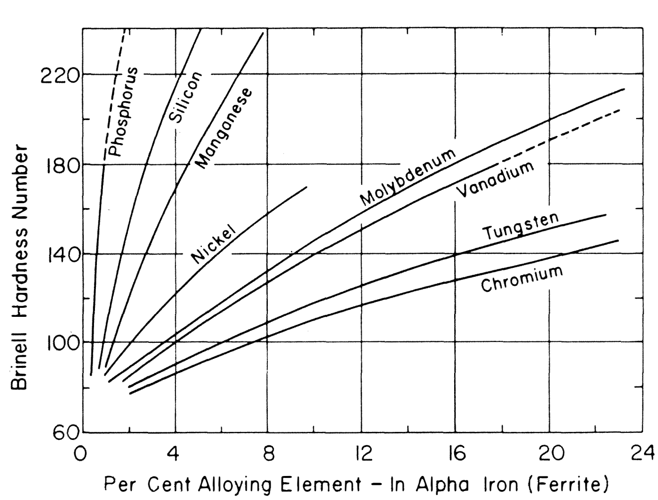


Figure 4. Effects of Increasing Percentages of Various Elements Dissolved in Ferrite on Hardening (After Bain).

Carbon

Carbon is used as a strengthening element; it is generally maintained at a level reasonably consistent with weldability and ductility.

Manganese

Manganese serves two primary purposes, first as a deoxidizer in steel production and as a strengthener. It also decreases the minimum or critical cooling rate necessary for hardening.

Fine-grained manganese steels attain unusual toughness and strength characteristics. Such steels are often used in the making of gears, spline shafts, automobile axles, steam valves, rifle barrels, cylinders for compressed gas and many other products. With a moderate amount of vanadium added, manganese alloy steels are also used for forgings too large to be properly liquid-quenched.

Silicon

Silicon in the form of a ferrosilicon is used by steelmakers as a deoxidizer and hardener in both alloy and carbon steels. When a steel's maximum silicon content is specified within the limits of 0.60 percent to 2.20 percent, it is classed as a silicon alloy steel. All other standard alloy grades are specified to a silicon range of 0.20 percent to 0.35 percent.

Nickel

Nickel increases the toughness and resistance to impact (particularly at low temperatures), lessens the distortion in quenching and improves corrosion resistance. It also lowers the critical temperatures of steel and widens the temperature range for successful heat treatment.

Nickel steels are particularly suitable for case-hardening parts, such as aircraft engine gears and roller bearings. These steels provide strong, tough, wear resistant cases and also ductile core properties.

Advantages of nickel additions are not restricted to quenched and tempered steels. With nickel, strength levels can be obtained at considerably lower carbon contents. As a result, toughness and fatigue resistance are markedly increased. Therefore, nickel steels are highly suitable for applications where a liquid quench is not employed, in high strength structural steels used in the as-rolled condition or in heavy forgings not adapted to quenching because of configuration.

Chromium

Chromium is a versatile agent. It fosters hardenability, improves resistance to abrasion and wear and promotes carburization. Of the common alloying elements, chromium ranks near the top in promoting hardenability. This property tends to make high chromium steels air-hardening; hence, it is valuable in applications where liquid quenches are undesirable or impractical.

Chromium steels are relatively stable at high temperatures and are often used where resistance to heat is important. Moreover, the presence of chromium is a vital factor in helping to retard or prevent corrosion.

The uses of chromium steels are many. Among the more familiar items that often contain chromium are hand tools, gears, springs, turbine wheels, ball and roller bearings, forged shafts and rotors.

Molybdenum

Molybdenum promotes hardenability in steel and is useful where close hardenability control is essential. It increases the hardness depth and widens the range of effective heat-treating temperatures. Moreover, it has a strong tendency to form stable carbides that inhibit grain-growth prior to quenching, thus keeping the steel fine grained and unusually tough at the various hardness levels.

Vanadium

Vanadium additions serve to form stable carbides, inhibit grain growth and act as a deoxodizer. The grain growth inhibiting effect of vanadium promotes a fine grained structure over a fairly broad quenching range, thus imparting strength and toughness to the heat treated steel. The carbides are not prone to agglomerate during the tempering operation.

Aluminum

When used in the making of alloy steels, aluminum has several important functions. Because of its great affinity for oxygen, it is a reliable deoxidizer. It produces a fine austenitic grain size. When it is present in amounts of approximately one percent, it promotes nitriding. The nitriding process is a means of obtaining a high surface or case hardness by subjecting the steel to a nitrogenous medium, commonly ammonia gas, at temperatures of 900°F to 1200°F.

Aluminum bearing steels usually show a case hardness range of 950 to 1150 diamond pyramid hardness number (DPHN). Steels in which no aluminum is present have cases of substantially lower hardness.

Boron

This element is used in steel for the purpose of increasing hardenability; that is, to increase the depth to which the steel will harden when quenched. With few exceptions, its effective use is limited to sections whose size and shape permit liquid quenching. Only a few thousandths of one percent are sufficient, and boron steels are evaluated by increased hardenability rather than chemical content.

Boron steels often require closer temperature control in heat treatment than do some of the other alloy analyses. Their cold and hot working properties are considered at least equal to those of ordinary alloy steels. In cases where boron makes possible a lower alloy content, improved machinability and cold formability frequently result.

Phosphorus

Phosphorus results in increased strength and hardness and decreased ductility and toughness. This is particularly true in higher carbon steels that are quenched and tempered. Phosphorus improves the resistance to atmospheric corrosion.

Sulfur

Sulfur decreases ductility, toughness and weldability. Sulfur is beneficial to machinability.

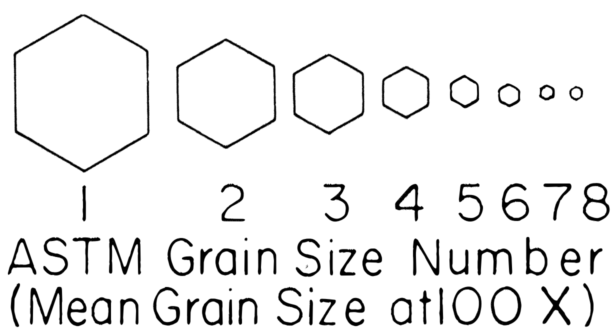
Other Elements

In some cases certain elements, such as columbium, nitrogen, titanium, copper and zirconium, are added singularly or in combination for their beneficial effects on strength, toughness, atmospheric corrosion resistance and other desirable properties.

GRAIN SIZE

The grain size of alloy steels is generally identified with the austenitic grain size. The austenitic grain size is distinguished from the ferritic grain size, which is the size of the grains in the as-rolled or as-forged condition. When steel is heated through the critical range (approximately 1350°F to 1600°F for most steels), transformation to austenite takes place. The austenite grains are extremely small when first formed, but grow in size as the temperature above the critical range is increased.

When temperatures are raised materially above the critical range, different steels show wide variations in grain size, depending on the chemical composition and the deoxidation practice used in making the heat. Heats are customarily deoxided with aluminum, ferrosilicon or a combination of deoxidizing elements. The size and density relationship as measured by the American Society for Testing and Metals (ASTM) method is shown in Figure 5.



Grain Size	Number of Grains per Sq. Inch at 100X	Range of Grain Size per Sq. Inch at 100X		
1	1	0.75	to	1.5
2	2	1.5	to	3.0
3	4	3	to	6
4	8	6	to	12
5	16	12	to	24
6	32	24	to	48
7	64	48	to	96
8	128	More than		96

Figure 5. Standard for Evaluating Grain Size in Steel.

How Grain Size Affects the Properties of Steel

Aluminum is generally used to control grain size. Steels made with aluminum additions are fine grained, while those without it tend to be coarse grained.

Fine grain steels do not harden as deeply as coarse grain steels and they have less tendency to crack during heat treatment. Fine grain steels exhibit greater toughness and shock-resistant properties that make them suitable for applications involving moving loads, high impact and low temperatures. Practically all alloy steels are produced with fine grain structures.

Coarse grain steels exhibit definite machining superiority. For this reason, parts which are intricately machined are often made to coarse grain practice. A summary of the effects of grain size in each of the metallurgical conditions is reflected in Table 1.

Table 1. Effect of Grain Size on Properties of Steel.

Condition of steel	Improvement in property caused by Fine grain	Coarse grain
Austenitic ..	Plastic formability Decomposition of austenite (more rapid)	
Annealed ...	Cold working Ductility Impact resistance	Machinability Hardness Creep resistance
Quenched ..	Impact resistance Retained austenite (less) Distortion (less) Cracking (less)	Depth of hardening

Determining the Mechanical Properties of Materials

The types of tests used to evaluate the mechanical properties of an alloy steel depend upon the end use of the steel involved. Mechanical properties are determined usually by tension, impact and hardness tests.

Tension tests provide the means of determining tensile strength, yield point, yield strength, proof stress, proportional limit, percent elongation and percent reduction of area. This type of test subjects the steel to stresses resulting from the application of an axial tensile load to the specimen ends, the load being sufficient to rupture the specimen.

Hardness tests determine the steel's resistance to penetration. This characteristic is most commonly measured by the Brinell or Rockwell test. In the former, pressure is applied to the surface of a test specimen by means of a ball 10 mm in diameter. Two diameters of the resulting impression are measured and converted to the hardness number by means of a conversion table. In the Rockwell test, the degree of hardness is read on a gauge; hardness is measured by the penetration of a diamond point or a 1/16 in steel ball. Rockwell "C" scale readings are used in connection with the diamond point and the "B" scale in connection with the steel ball. The "C" and "B" scales are the most commonly used of the several Rockwell scales.

An *impact test* is one in which a specimen, generally notched, is subjected to a sudden impact load. The results are usually expressed in terms of the energy absorbed in breaking the specimen.

Heat Treatment of Steels

Heat treatment may be defined as an operation, or series of operations, involving the heating and cooling of steel in the solid state to develop the required properties. There are in general five different forms of heat treatment used with alloy steels. These treatments modify the steel's mechanical properties to suit the end use.

These commonly used heat treating cycles are:

Quenching and tempering usually consists of three successive operations:

- Heating the steel above the critical range, so that it approaches a uniform solid solution.
- Hardening the steel by quenching it in oil, water, brine or salt.
- Tempering the steel by reheating it to a point below the critical range, in order to effect the proper combination of strength and ductility.

Normalizing is a form of treatment in which the steel is heated to a predetermined temperature above the critical range, after which it is cooled to below the range in still air. The purpose of normalizing is to *promote uniformity* of structure and to alter mechanical properties, as shown in Figure 6.

Annealing consists of heating the steel to a point above or within the critical range, then cooling at a predetermined slow rate. Annealing is used to soften the steel, to improve machinability, to reduce stresses, to improve or restore ductility and to modify other properties.

Spheroidize-Annealing is a form of heat treating which requires prolonged heating of steel at an appropriate temperature, followed by slow cooling to produce a globular condition of the carbide. This treatment produces a structure which may be desirable for machining, cold-forming or cold-drawing, or for the effect it will have on subsequent heat treatment.

Stress Relieving is the process of reducing internal stresses by heating the steel to a temperature below the critical range, and holding this temperature for a time interval sufficient to equalize the temperature throughout the piece. The object of this treatment is to restore the elastic properties of the steel or to reduce stresses that may have been induced by machining, cold-working or welding.

Some of the above mentioned heat treating cycles superimposed on a modified iron-carbon phase diagram are shown in Figure 7. Each of the five heat treatment cycles will be closely examined with more detailed explanations.

Normalizing

Normalizing is an operation in which the steel is heated to approximately 100°F above the upper critical temperature, then cooled in still or agitated air. The basic purpose of the treatment is to refine the prior structure produced by variations in finishing temperatures encountered in rolling or forging. The more uniform structure resulting from normalizing may often improve the effectiveness and uniformity of subsequent heat treatment.

At times, large steel parts cannot be liquid-quenched because of their size. In this case, the heat treatment must consist of single or multiple normalizing followed by tempering.

High temperature normalizing is sometimes used for grain coarsening low-carbon alloy steels to promote machinability. In high temperature normalizing, steel is heated to more than 100°F above the upper transformation range. At times it is possible to machine a steel in the air-cooled condition. However, the highly alloyed steels may require annealing or tempering after normalizing to decrease the hardness. It is essential when normalizing is employed that free circulation of air be provided.

Annealing

The primary purpose of annealing is to soften steel and make it more workable. Annealing, as applied to carbon and alloy steels, consists of heating the steel to a predetermined temperature above the critical temperature, then cooling it at a predetermined slow rate; or it is a process that heats the steel to a point within, and furnace cools to a point below, the critical

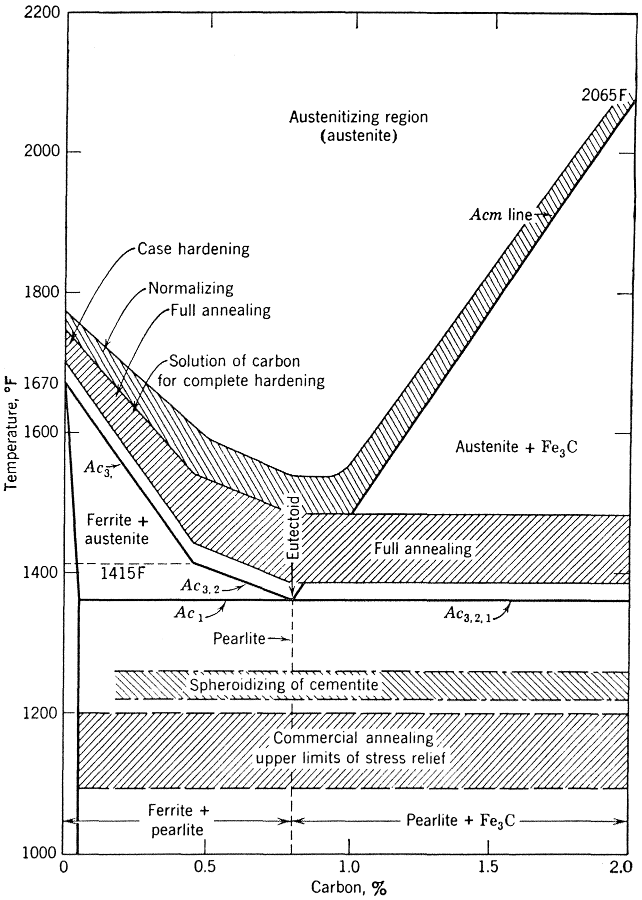


Figure 6. Tensile Properties vs. Annealing and Normalizing of Steels (After Aitchinson).

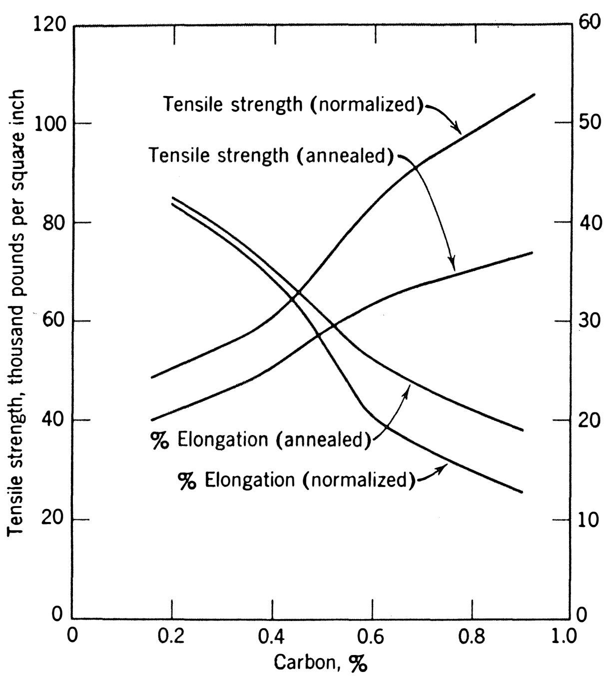


Figure 7. Temperature Regions for Some Heat Treating Processes on a Modified Iron-Carbon Phase Diagram (After Whitfield).

range. The choice depends upon the structure and maximum hardness desired. These two methods produce two entirely different metallurgical results.

Lamellar Pearlitic Structure. This structure can be obtained both as described previously and by a modified method known as isothermal annealing. In the isothermal process, the steel is heated above the critical temperature (austenitized), then cooled to and held at a temperature at which austenite transforms to a relatively soft ferrite and carbide aggregate.

Lamellar pearlitic structures are generally associated with machinability in carbon contents up to approximately 0.50 percent, provided the hardness does not exceed the optimum maximum Brinell number. This is especially true where critical tooling is involved. It is a very versatile structure, as it gives the best results in such operations as broaching, tapping, threading, deep drilling, boring, milling and tooling as applied on single and multiple spindle bar automatic machines.

Spheroidized Structure. There are two general fields of use for this type of structure when alloy steels are employed. In the low and medium carbon ranges, spheroidization is necessary for cold shaping operations, such as heading, extruding, and drawing. In the higher carbon ranges (over 0.50 percent), it is mandatory where machining is involved, because it tends to lower the hardness of the steel.

Quench and Tempering

Of the various methods of heat treating alloy steels, the most important involves quenching and tempering. The purpose of quenching is to affect a cooling rate sufficient to develop the desired hardness and structure.

Before quenching takes place, steel is heated to a point above the critical temperature. Quenching is the subsequent immersion of the heated steel in a circulated or agitated bath of oil, water, brine or caustic; or, in the case of austempering or martempering, generally in agitated molten salt baths. Austempering and martempering are preferable where a minimum of distortion is desired.

Quenching increases the tensile strength, yield point and hardness of alloy steels. It decreases the ductility (elongation and reduction of area) and resistance to impact (Figure 8). However, by subsequent tempering, it is possible to restore some of the ductility and impact resistance, but only at some sacrifice of tensile strength, yield point and hardness.

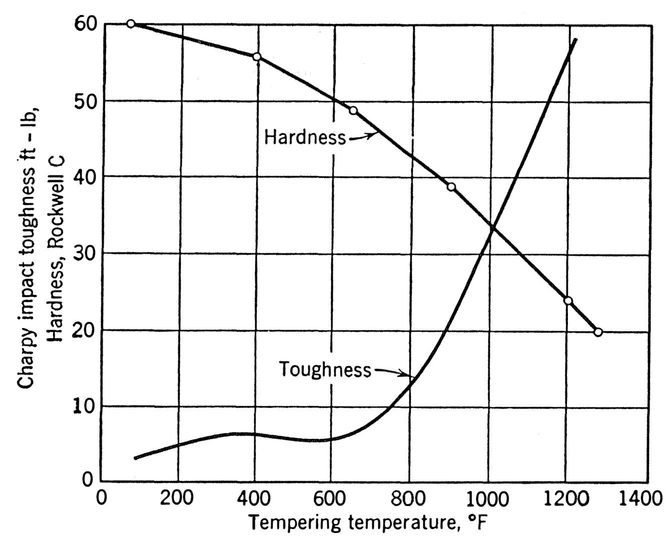


Figure 8. Hardness and Impact Toughness vs. Tempering Temperature for AISI 1045 Steel (After Grossman).

To avoid thermal cracking, liquid quenching should not be continued below 150°F. The piece should be tempered immediately. Because of residual stresses, steel should not be used in the as–quenched condition.

Tempering is reheating to a specified temperature below the lower critical range, then air cooling. It is done in furnaces, oil or salt baths at temperatures varying from 300°F to 1200°F. With most grades of alloy steel, the range between 500°F and 700°F should be avoided because of "blue brittleness". The maximum hardness and wear-resistance result from tempering at low temperatures. The maximum toughness is achieved by tempering at higher levels.

Thermal Stress Relieving

There are several important reasons for thermal stress-relieving. Among these are the following:

• The first and most fundamental purpose is to reduce residual stresses that might prove harmful in actual service (Figure 9). For example, in the production of quenched and tempered alloy steel bars, machine straightening is necessary. This induces residual stresses in varying degrees. Bars are usually stress relieved after the straightening operation. When the bars are subjected to later processing that sets up additional stresses, subsequent stress relieving may be necessary.

• A second major purpose of thermal stress relieving is to improve the dimensional stability of parts requiring close tolerance. For example, in rough machining, residual stresses are sometimes introduced, and these should be relieved to ensure dimensional stability during finish machining.

• Thermal stress relieving is also recommended as a means of restoring mechanical properties (especially ductility) after certain types of cold working. Moreover, it is required for the "safe welding" grades of alloy steels after a welding operation has been completed.

Alloy steel is commonly stress relieved in furnaces. Temperatures below the transformation range are employed, usually in the ranges of 850°F to 1200°F. The amount of time required in the furnace will vary, depending upon the grade of steel, the magnitude of residual stresses and the mass effect of steel being heated. After the part is removed from the furnace, it is allowed to cool in still air to room temperature.

The stress relieving temperature for quenching and tempering alloy products should be about 100°F below the tempering temperature. If the sress relieving temperature exceeds the tempering temperature, mechanical properties will be altered.

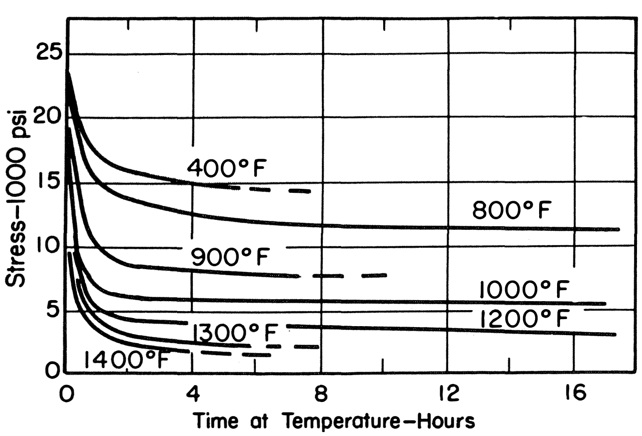


Figure 9. Stress Relaxation at Various Stress Relieving Temperatures AISI 1025 Steel (After Stewart).

Hardenability and Cooling Rates

Hardenability of a steel is the property that determines the depth and distribution of hardness induced by quenching (Figures 10 and 11). Hardenability depends upon the chemical composition of the steel and other variables. This property is very meaningful to the designer. If a steel hardens all the way through, it will be stronger than another steel which has only surface hardness and is soft in the center or core.

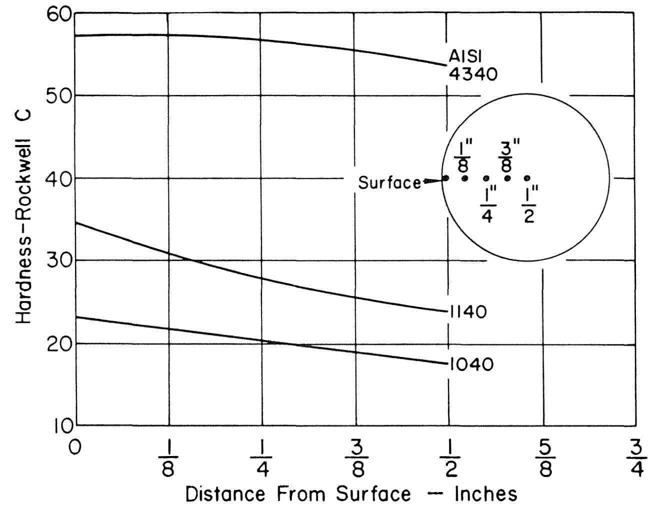


Figure 10. Alloy Content vs. Depth of Hardness When Oil Quenched.

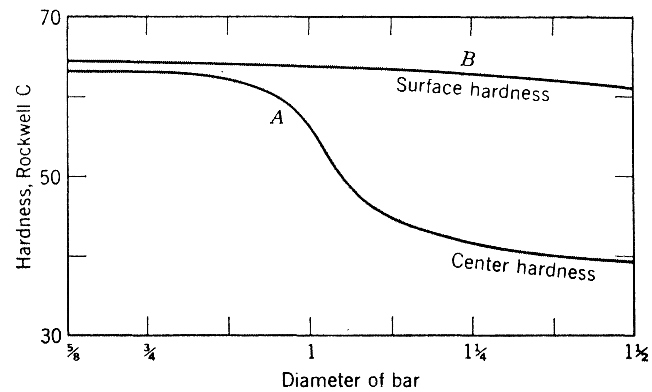


Figure 11. Center vs. Surface Hardness of Carbon-Moly Steel Oil Quenched (After Grossman).

In the heat treatment of alloy steels, time and temperature are considered together. All changes in steel structure take place at a much more rapid rate at higher temperatures. The longer the steel is held at a given temperature in the austenitic range 1) the larger the amount of carbide and alloying elements that is taken into solution, 2) the better the austenitic structure because of the diffusion of the dissolving elements and 3) the larger the austenitic grain size. The time at this maximum temperature should be long enough to attain uniformity of temperature thoughout the steel, and to bring about the desired internal changes.

In cooling from the austenitic range, there is a transformation from austenite to an aggregate of ferrite and carbide (pearlite), or to martensite. Which structure results is determined by the temperature and rate (speed) of cooling at which the transformation takes place. An isothermal transformation diagram showing the various products versus the cooling rate is presented in Figure 12.

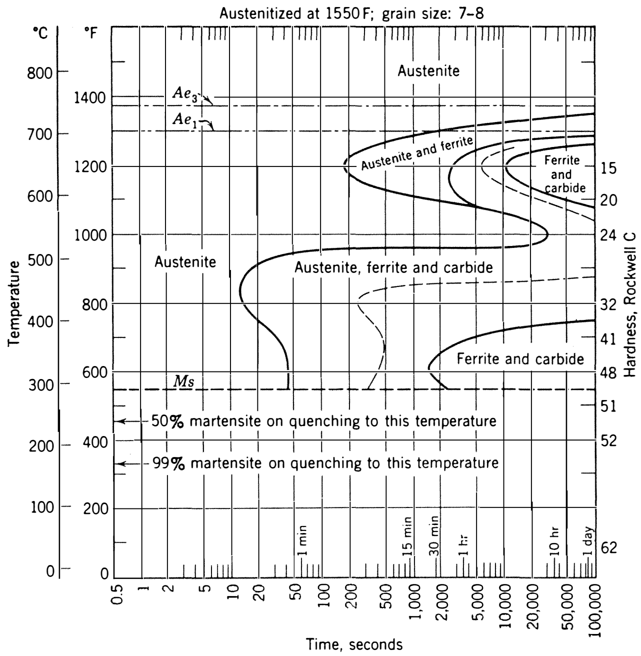


Figure 12. Isothermal Transformation Diagram for 0.30C – 2Cr Steel (U.S. Steel Corporation).

In general, at a slow rate of cooling, the resulting pearlitic structure has relatively low strength and hardness and high ductility. As the rate of cooling increases, the pearlite becomes finer, stronger, harder and less ductile. In fast cooling (such as quenching), the transformation is retarded to a point where the structure is not pearlite, but martensite—a fully hardened steel. This fast cooling rate which results in a martensitic structure is known as "the critical cooling rate," and is entirely dependent upon the composition and austenitic grain size of the steel.

Between the slow and rapid rates of cooling which result in pearlitic and martensitic structures, respectively, there are intermediate rates of cooling in which mixtures of the two structures are formed. For example, a mixed structure is always found in quenched heavy sections where the surface has cooled rapidly to form martensite, and the interior has cooled more slowly to produce the softer pearlitic structure.

It is well known that alloying elements dissolved in austenite decrease the critical cooling rate required to obtain full hardness. Thus, with sufficient alloy content, finer, harder pearlitic structures are formed at the slower rates of cooling, or there is deeper hardening at the more rapid rates of cooling as compared with carbon steels.

Surface Hardening

Surface hardening involves attaining a hard wear resisting surface on a softer, tough core. In some applications, the condition of the steel substrate is relatively unimportant compared to the outer hard wear resistant case. However, there are other uses where both a strong core and a hard outer layer are necessary for long life.

Surface hardening has some very distinct and real advantages in some applications:

- Fatigue properties can be controlled and improved.
- Large parts with very large mass effects that will not respond to quenching and tempering can be surface hardened without cracking.
- Less dimensional distortion.
- Selected surfaces can be hardened instead of the entire part.
- Inexpensive steels can be used and only their surface chemistry altered.
- Core and surface mechanical properties can be both individually and collectively adjusted.

Surface hardening is divided into two distinct categories. The first involves *changes in the surface chemistry* and in the second the *surface chemistry is not altered.*

Alteration to the Surface Chemical Composition

The four most commonly used processes are carburizing, carbonitriding, cyaniding and nitriding.

Carburizing occurs when austenitized ferrous metal is placed in contact with an environment of sufficient carbon potential to cause absorption of the carbon at the surface and diffuse it into the surface. Carburization is carried out in the temperature range of 1550°F to 1750°F with a carbon material of liquid, gaseous or solid. The relationships of time versus case depth for two forms of carburizing are shown in Figures 13 and 14.

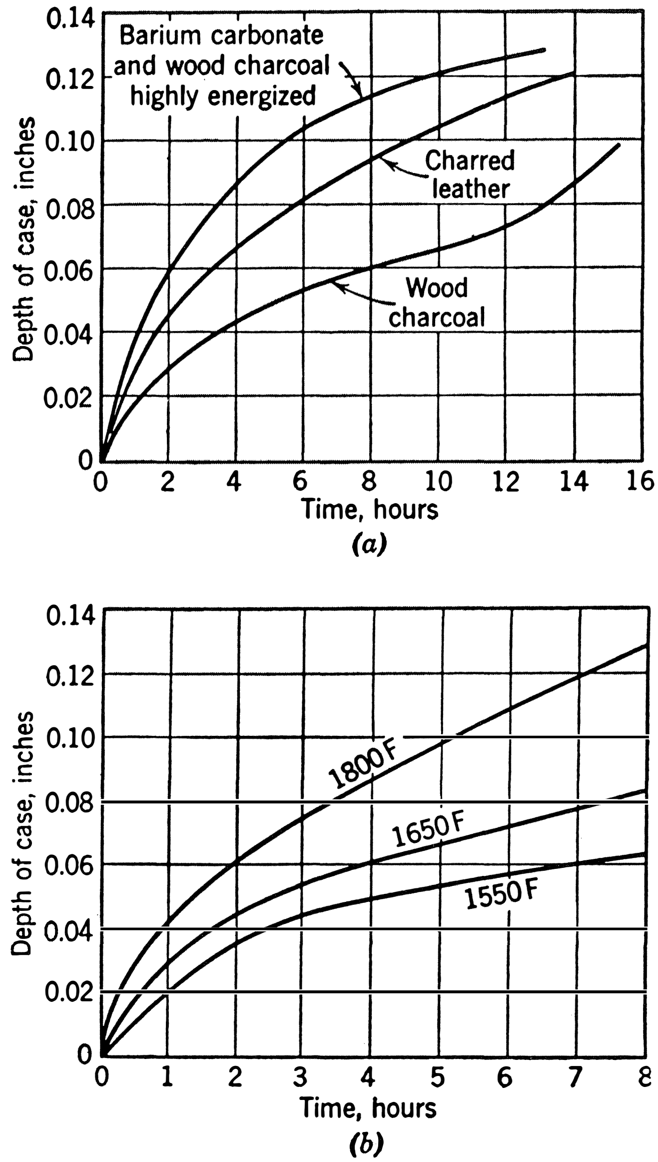


Figure 13. Time and Temperature vs. Several Solid Carburizing Mediums.

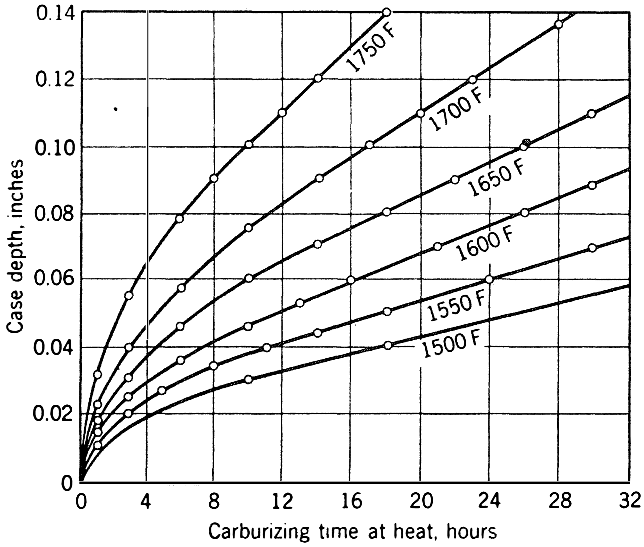


Figure 14. Time, Temperature and Case Depth of Natural Gas Carburizing.

Carbonitriding is a modified gas carburizing process by the introduction of about ten percent ammonia into the gas atmosphere. The ammonia dissociates to add nitrogen. The result is carburizing at a lower temperature and for a shorter time than with the conventional method. Its primary application is for the production of thin cases on small parts. The case has a higher hardenability than conventional gas carburizing. A typical time versus case depth at various temperatures for carbonitriding is shown in Figure 15.

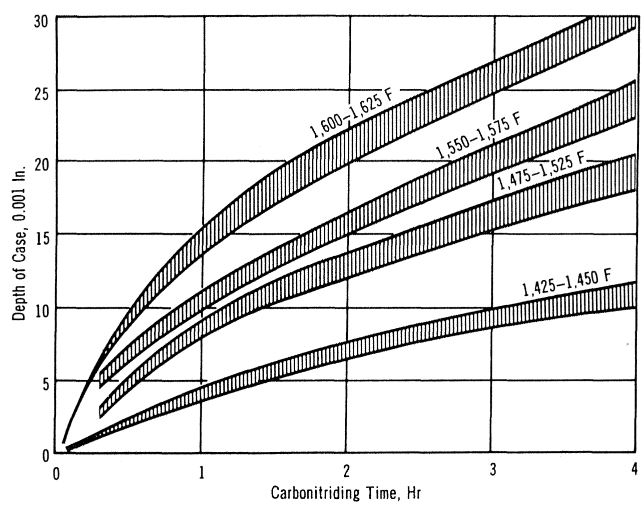


Figure 15. Carbonitrided Case Increasing with Time or Temperature.

Cyaniding, or liquid carburizing, is normally performed in a salt bath containing sodium cyanide and barium chloride. The advantage is selective carburizing without stop-off and flexibility in the bath for small and large components. (Stop-off is attained by a surface barrier coating such as copper plating, to prevent the area from being carburized.)

Nitriding is a case hardening process in which nitrogen is introduced into the surface by holding the metal at an elevated temperature in contact with a nitrogenous gas, usually ammonia. The nitrogen reacts with the alloying elements to form nitrides, resulting in extremely high hardness with the need for subsequent quenching. Nitriding steels normally contain aluminum in the range of 0.85 percent to 1.5 percent. The results of a typical nitriding heat treatment are shown in Figure 16.

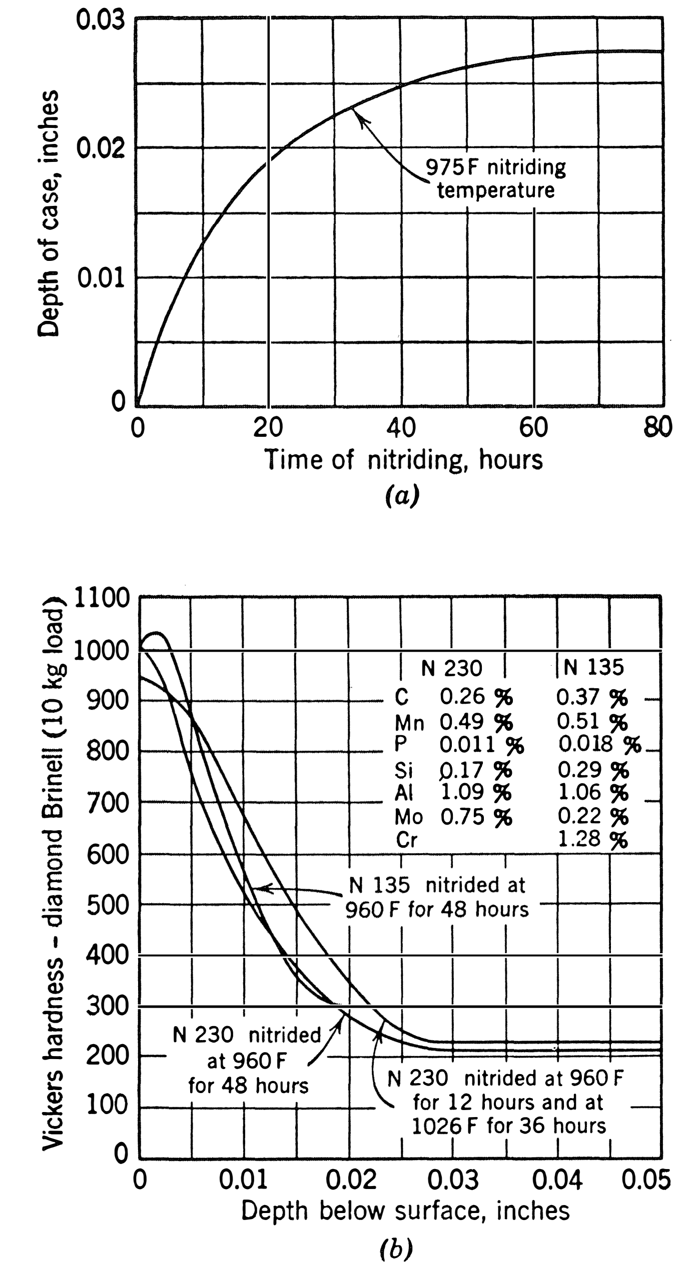


Figure 16. Variation of Time and Hardness vs. Case Depth in Nitriding.

No Alteration to the Surface Chemistry

The two most commonly used processes are:

- Flame Hardening
- Induction Hardening

Both of these processes involve the localized application of the earlier discussed quench and temper heat treatment. The basic difference is in the method of heating the surface case into the austenitizing range. The results of varying the flame speed on hardness versus case depth are indicated in Figure 17.

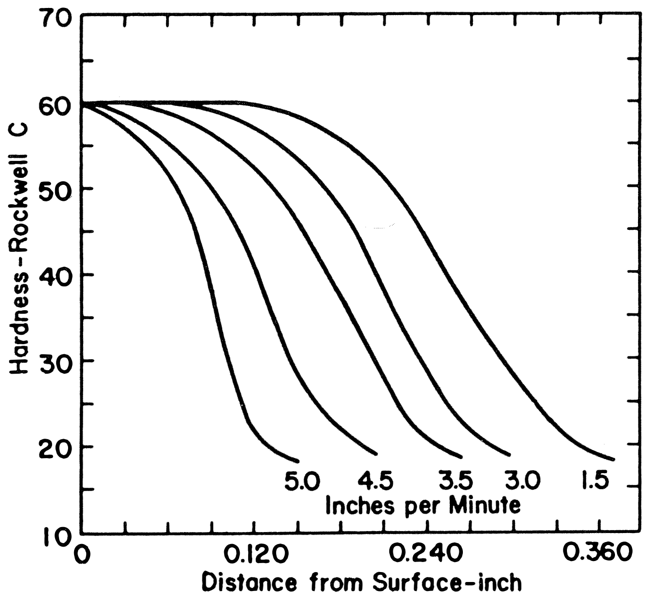


Figure 17. Flame Hardening Speed Variation as it Affects Hardness and Case Depth.

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