HEAT TREATMENT OF STEEL

The American Society for Metals

METALS ENGINEERING INSTITUTE

HEAT TREATMENT OF STEEL
(Home Study and Extension Courses)

THE AMERICAN SOCIETY FOR METALS
METALS ENGINEERING INSTITUTE

CONTENTS

MICROSTRUCTURE AND MECHANICAL PROPERTIES

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The fact that steel can possess a wide range of useful mechanical properties is of extreme economic importance. This is clearly illustrated in the railroad industry, for example. To move a train from one location to another we use a locomotive which has the ability to pull a given total load. This load is composed of the weight of the cars or deadweight, and the weight of the freight being transported, or the payload. If the freight cars are made of low strength steel, the structural members must be relatively large to support the load, and hence heavy. If a freight car is made of high strength steel, the structural members can be relatively small and the car will be lighter as well as stronger. This means that the amount of freight can be increased, the ratio of payload to deadweight becomes greater, and more profit can be realized per trip. Similar situations concerned with the mechanical properties of steel exist in the other industries.

Effect of Alloying Elements   If we are to make intelligent use of the varying mechanical properties of steel, we must learn the scientific reason for these properties and how to reproduce and control them. For instance, if we desire to make a lighter and stronger freight car, it would be useless to specify a stronger steel for its structural members unless we know how to make the steel stronger.

A large percentage of the steel produced is supplied to the consumer in the "natural" or as-forged or as-rolled condition. In the rolling or forging operation, steel is heated to roughly $1900^\circ F$ to $2200^\circ F$, where it is still solid but quite weak and plastic. While in this condition the steel is forced through shaped rolls or hammered between dies to some intermediate form (such as a bar) which will later be machined or formed to some specific shape such as a gear, etc. After the forging or rolling operation, the steel is frequently allowed to cool in air to room temperature. Steels of the type processed in this manner will usually have moderate strength and hardness. For plain carbon steel, the as-rolled or as-forged strength will vary with the amount of carbon, as shown in Table 2:1.

Table 2:1. Effect of Carbon Upon Tensile Strength (Normalized)

Percentage of Carbon of the Steel	Tensile Strength, psi, for Diameter of Bar Processed			
	$\frac{1}{2}$-inch	1-inch	2-inch	4-inch
0.30	77,500	77,500	74,000	72,500
0.40	88,250	85,500	84,250	83,500
0.50	111,500	108,500	106,250	100,000
0.60	113,000	112,500	110,000	108,250
0.80	150,000	146,500	141,000	134,000

The values shown in the table are not actually those of the steels in the as-rolled or as-forged condition but are for steels which have been normalized. Normalizing consists of heating the steel to a "red-hot" condition (to temperatures substantially below those usually used for rolling or forging) and then allowing it to cool in air to room temperature. Normalizing is one of the heat treating operations and makes more uniform (homogenizes) the microstructure found in steels in the as-forged or as-rolled conditions. The mechanical properties which result from the normalizing treatment are approximately the same as those obtained in as-forged and as-rolled steels. It, as well as the other heat treating procedures described briefly in this lesson, will be considered more fully later in the course.

From Table 2:1, it is apparent that the strength of the steel is a function of the amount of carbon present. Alloying elements also have a similar effect, as shown in Table 2:2. In this table, there are listed a series of tensile strengths which resulted when various alloying elements were added to a plain 0.40% carbon steel. These steels were normalized, as were those in Table 2:1.

It is apparent that the strength obtained with any given carbon or alloy content decreases as the diameter of the bar is increased. This effect is known as the effect of mass. It is important for the student to recognize that in addition to chemical composition, mass (size) has an important effect upon the hardness and strength which can be attained in steel.

From Tables 2:1 and 2:2, it is apparent

that the tensile strength of as-rolled or as-forged steel can be increased considerably by adding relatively small amounts of carbon and other alloying elements. It is also apparent that some alloying elements are more effective than others in causing an increase of tensile strength. For instance, in a 0.40% carbon steel a total alloy content of 2.73% resulted in a tensile strength of 129,250 psi (1" diameter), while in a steel of the same carbon content a total alloy content of 1.55% (manganese plus chromium plus molybdenum) resulted in a tensile strength of 148,000 psi in a bar of the same size, an increase of about 15%.

From these results it would appear that the solution to securing a stronger steel is quite simple, i.e., add more carbon and/or alloy to the steel. Unfortunately, the alloying elements are relatively costly, and to develop a high strength steel by alloying alone would be quite expensive. The economics involved would defeat the purpose of such steels except for unusual circumstances.

Quenching and Its Effect

Fortunately, the strength of steel can be increased through another method. From observation of a blacksmith, or reading the technical literature, we know that if a piece of soft steel is heated to a "red hot" condition and then plunged into a bucket of cold water (or other liquid quenching medium) the steel will become both harder and stronger. The temperature to which the steel is heated prior to rapid cooling in liquid is usually lower than that used in normalizing. This procedure is called quenching, and its effect is demonstrated in Table 2:3, where the relative tensile strengths of steels of varying carbon

Table 2:2. Effect of Alloy Content on the Tensile Strength of Normalized 0.40% Carbon Steel

| % Alloy | | | | Total Alloy Content | Tensile Strength, psi, for Diameter of Bar Tested | | | |
Mn	Ni	Cr	Mo		$\frac{1}{2}$-inch	1-inch	2-inch	4-inch
1.77	-	-	-	1.77	132,000	121,250	120,000	120,000
0.90	1.21	0.62	-	2.73	148,500	129,250	119,250	118,000
0.40	-	0.94	0.21	1.55	148,500	148,000	140,000	117,000

Table 2:3.　Effect of Quenching on the Tensile Strength of Steel

(1-inch Diameter Bars)

Carbon Content of Steel %	Tensile Strength in psi	
	Before Quenching	After Quenching
0. 15	61,500	75,500
0. 20	64,000	89,000
0. 30	77,500	122,000
0. 40	85,500	130,000
0. 55	110,000	162,000

content are shown before and after thermal treatment.

From these figures it is evident that the procedure of quenching results in a gain of strength which may well overshadow the effects of alloying alone. For instance, a steel of only 0.40% carbon content can, after quenching, have a tensile strength slightly greater than a normalized 0.40% carbon steel to which alloying elements up to 2.73% have been added. It should be noted, however, that the gain in strength realized by quenching is not limited to carbon steels only. The alloy steels will also show a large increase in tensile strength if they are quenched. In Table 2:4, the hardness of a plain 0.30% carbon steel is compared to that of a similar carbon steel containing some alloy. Both steels are in the as-quenched condition.

It should be noted that the hardness data listed in Table 2:4 represent the highest values attainable with the steels and sizes processed. In other words, quenching produces the highest hardness and strength values attainable. No other heat treatment can produce higher values.

Thus, both the plain 0.30% carbon steel and the alloy steel containing 0.30% carbon achieved the same maximum hardness, Rockwell C 50. No higher hardness value can be secured with a steel containing 0.30% carbon, regardless of the alloying content or thermal treatment. For each carbon content which may be present in steel there is a related maximum attainable hardness. This hardness value may not be realized in commercial quenching because of mass effect, but if a small enough piece is processed and the quenching conditions are severe

Table 2:4.　Comparative "As-Quenched" Hardness of a Plain Carbon and Alloy Steel

(Water Quenched)

Percentage Composition of the Steel			Location of Sample	Hardness Rockwell C			
				Diameter of Bar Processed			
C	Cr	Mo		½-inch	1-inch	2-inch	4-inch
0. 30	-	-	Surface	50	46	30	20
			1/2 Radius	50	23	13	7
			Center	23	21	9	3
0. 30	0. 91	0. 20	Surface	50	50	47	45.5
			1/2 Radius	50	50	32	25
			Center	50	44	31	24.5

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enough, it can be attained. This fact leads to one of the very important rules of heat treatment: maximum attainable hardness is a function of the carbon content of the steel. Alloy content does not contribute to the maximum attainable hardness.

At this point, the student will consider Table 2:4 and observe that in larger size categories the alloy steel is harder than the plain carbon steel both at the surface and interior positions. This is a fact, but it does not contradict the previous statement that maximum attainable hardness is a function of the carbon content independent of the alloy content. It will be noted that, for the alloy steel, nowhere has a hardness in excess of Rockwell C 50 been realized. What has happened is that the alloy content has reduced the effect of mass. The presence of the alloy content in the steel has allowed it to approach more closely the maximum attainable hardness indicated by the carbon content. The ability of steel to harden throughout its cross section is a field of study in itself and will be more completely considered later in the course.

It should be noted that in the vast majority of cases, steel is not used after quenching without being subjected to further thermal processing. In the "as quenched" condition, steel is very highly stressed and quite brittle, conditions not conducive to good service life.

Prior to placing a hardened part in service it is usually tempered. Tempering consists of heating the steel to a relatively low temperature (considerably below that used for hardening) and then air cooling it. Such procedure reduces the hardness slightly but renders the steel a great deal more ductile and eliminates a large portion of the stress incurred during the quenching operation.

Having established the fact that high strength can be developed in a steel by adding carbon and then quenching, let us turn to the problem of utilizing such a material. In order to be of value to us, the steel must be in some useful form such as a gear, an axle, etc. This generally means that the steel must be machined to the desired shape. As noted in our discussion of mechanical properties in Lesson 1, the stronger and therefore harder a piece of steel is, the more difficult it is to machine. Thus, it would appear that the designer is "between the devil and the deep blue sea". If he hardens the part to gain maximum strength, he cannot machine it, and if he can machine it, the part may not have sufficient strength for its intended application. In some grades of steel, the as-forged or as-rolled hardness exceeds the bounds of economical machining, apparently adding to the problem.

Annealing and Its Effect   Fortunately, there is an escape from this seemingly impossible situation. If steel is heated to a "red hot" temperature (somewhat below that used for hardening but higher than that used for tempering) and, instead of being quenched, is very slowly cooled to room temperature, the tensile strength will be lower than that resulting from quenching or normalizing. The steel has been made more ductile and weaker by a process called annealing and is now quite readily machined.

Annealing is any process of heating and cooling intended to reduce the hardness of steel and restore its ductility. With the steel in the soft condition it is readily machined to shape, and after machining may then be further heat treated and made strong and hard.

Heat Treatment   Thus, for a single composition of steel a wide range of mechanical properties can be secured by the relatively simple procedure of heating to a "red hot" condition and then cooling at different rates. For example, the mechanical properties of a 0.40% C, 0.94% Cr, 0.21% Mo steel vary with the thermal treatment, as shown in Table 2:5.

Table 2:5. Variation in Strength and Hardness by Heat Treatment.

Condition of Steel	Tensile Strength	Hardness
Annealed - soft	95,000 psi	197 Bhn
Normalized	148,000 psi	302 Bhn
Quenched - hard	266,000 psi	534 Bhn

Other values of strength could also be secured by using cooling rates intermediate to those described. The general term applied to these procedures of hardening and softening of steel is called heat treatment. Heat treatment is defined as an operation, or combination of operations, involving the heating and cooling of a metal or alloy in the solid state for the purpose of obtaining certain desirable properties.

It should be emphasized that the properties of steel can be altered at will, and the effects of any single heat treatment operation are not final and irrevocable. If the steel is hard, it can be made soft for machining, and after machining it can again be hardened. If a mistake has been made in machining and not detected until after hardening, the part may be annealed, the error corrected, and the part again hardened to the desired strength.

The value of heat treatment is by now apparent. What is not apparent is how the heating and cooling cycles cause the mechanical properties to change. If we place two machined pieces of steel side by side, one in the hard condition and the other in the soft condition, no difference would be apparent to the eye. Since the characteristics of the steel are vastly different, something must have occurred internally during heat treatment to account for the difference in mechanical properties. The problem of what occurs during heat treatment was a troublesome one for many centuries.

Iron was known and used in tools and ornaments as early as 4000 B.C. The intentional addition of carbon to iron, quenching, and the general advantages of heat treatment were later developments but were employed many centuries before the Christian era. While it was recognized in early times that carbon (the oldest intentional alloy addition made) was necessary for hardening, the method by which the steel actually hardened when quenched was not known.

As a result, the hardening of steel became an art, the secrets of which were closely guarded. There is a legendary method of heat treating the fabulous Damascus sword blades which well illustrates the mystery and "hocus-pocus" connected with hardening in these early times. The hard-

ening procedure consisted of tying a slave face down on the sacrificial block of the god Bal-hal. Then, while the artisan recited a prayer, the sword was heated in cedar wood coals until its color was that of "the red of the rising sun". The heated sword was passed through the buttocks of the slave until it became "the color of the purple of the king". The sword was then tested and considered acceptable if, without cracking or breaking, the slave's head could be lopped off with one stroke and the sword could be bent around his body.

With the passage of time and the rise in the cost of slaves, their use as a quenching medium passed out of the picture, but the belief that hardness was due to some mystical property of the material into which the steel was quenched persisted. All sorts of weird concoctions were used and great emphasis placed upon the value of water from specific places. In 1558, the preacher Mathesius observed in one of his sermons that one water would harden steel better than another and this was the reason that armor made at Innsbruck was so good. As late as the early 1900's, hardening was considered an art and a secret craft, and at Solingen the apprentices had to take an oath not to leave the country and not to teach the craft to anyone but their sons.
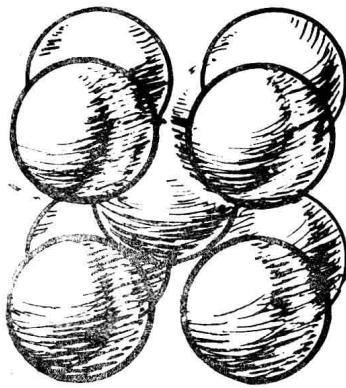
THE CONSTITUTION OF STEEL

Although the basic reasons for the changes in mechanical properties in heat treatment were not understood, a useful working knowledge of how to harden and soften steel was gradually developed by trial and error. It was not until the early part of the 20th century that scientific understanding of the fundamental changes which occur during heat treatment was developed. Since these changes do not manifest themselves in the external appearance of the steel, they must be internal and invisible to the unaided eye.

From our preceding discussions, it is established that the basic component of steel is the element iron. The ability of the iron to become stronger and more useful is due to the presence of carbon. The actual changes in the strength of steel are produced by a procedure of heating and cooling called heat treatment. It logica'

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follows that the changes in mechanical properties which occur upon heating and cooling must be due to changes induced in the iron and carbon. Therefore, if we are to understand heat treatment, we must understand the effect of heating and cooling upon iron and carbon, the basic constituents of steel.

Atomic Arrangement   In order to accomplish this aim, it is necessary to consider iron in terms of its smallest unit particle, the atom. While the atom is an extremely small unit, it can be measured with the assistance of precision apparatus. For our purpose, it is convenient to think of each atom as a small ball of iron, having a definite weight and a definite attractive force for all neighboring atoms. In metals this attractive force is such that the atoms arrange themselves in definite geometric patterns. The arrangement of the atoms with respect to each other is called the crystal structure or lattice. At room temperature the iron atoms arrange themselves into what is known as the body-centered cubic lattice illustrated in Fig. 2:1. In this unit of construction, an iron atom is located at each of the eight corners of a cube and a ninth atom is centrally located within the cube. The attractive force between the

atoms and their neighbors keeps them "balanced" at these locations.

Iron is an allotropic element, that is, it can assume several different lattice modifications depending upon temperature. The body-centered cubic modification, commonly called the alpha modification, exists to a temperature of 1670° F. After a temperature of 1670° F has been exceeded, the atoms in the iron rearrange themselves into the face-centered cubic, or gamma modification, shown in Fig. 2:2. Here it is seen that the same basic cubic structure remains with an atom located at each of the eight corners of the cube. However, instead of a single atom being located in the geometric center of the cube, there is now an atom located in the center of each face of the cube. The gamma modification exists between 1670° F and 2552° F. A third modification, called delta, exists between 2552°F and 2802°F. If the iron is heated higher than 2802°F, it becomes molten and is no longer solid. Fig. 2:11 (page 17) depicts the changes that occur in pure iron as it cools from the molten state to room temperature. The phase changes, and also the magnetic change, cause horizontal jogs or lags in the cooling curve illustrating that heat is evolved when these changes occur. All of the heat treating operations we will consider take place well below 2552 F so that the delta

Ferrite
(∝ Iron)

Austenite
(ɤ Iron)
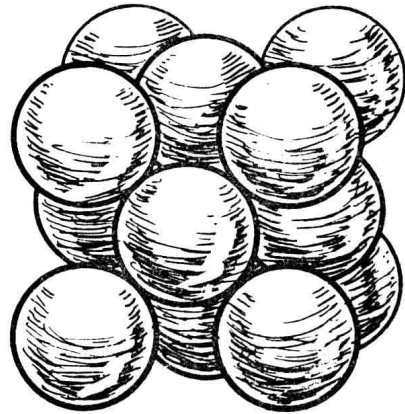
Fig. 2:1. Body-Centered Cubic Structure of Alpha Iron.

Fig. 2:2. Face-Centered Cubic Structure of Gamma Iron.

Each ball represents an atom of iron.

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modification is of no importance to us. We will be concerned only with the alpha and gamma crystallographic structures of iron.

The lattice modifications of iron, being temperature-dependent, are reversible. Alpha iron changes to gamma iron upon heating, and the gamma iron changes back to the alpha form upon cooling. It should be noted that one unit of the lattice structure is extremely tiny. In even a small piece of steel, millions of such units are arranged row upon row, in three dimensions, to make up the mass of the steel. The effect may be compared to bricks neatly stacked into a large pile, the individual bricks being comparable to the individual lattice cubes and the pile of bricks being comparable to the piece of steel.

Solid Solution   The effect of temperature upon iron has now been explained. What is the role of carbon during these changes? Before considering this, it is necessary to understand the phenomenon of solid solution. We are all familiar with liquid solutions. When a lump of sugar is placed in a cup of coffee, the sugar dissolves and apparently disappears. However, by tasting the coffee we know the sugar is present in liquid solution. When iron is molten, it too takes certain elements into liquid solution in the same manner. When the iron cools and becomes solid, it is still capable of retaining certain elements in solution. This solution in the solid state is called solid solution and is as true a solution as that formed in the liquid state. Solid solutions are not unusual in metals. Iron takes many other metals into solid solution.

Solid solutions can result from solidification of a liquid solution, or they can be formed in the solid state. For instance, if suitable carbonaceous material is packed around a piece of pure iron and the temperature raised until the iron is "red hot", the iron will take the carbon into solution although the iron remains solid at all times and does not even approach the melting point. In similar fashion it can be demonstrated that iron, while hot and solid, can dissolve numerous other elements and form a solution with these elements.

The degree of solubility of elements in solid solution may vary considerably. Some

elements may be completely soluble in all proportions at all temperatures. Some may be completely soluble at high temperatures but only partially soluble at lower temperatures, and still others may be soluble at high temperatures but completely insoluble at low temperatures.

Carbon is soluble in both alpha and gamma iron in various degrees, depending upon both the lattice structure and the temperature. These solutions are, of course, solid solutions. It is important to note that as carbon is added to iron, the temperature at which gamma iron can exist is lowered, as indicated by the line GS in Fig. 2:3. When 0.80% carbon has been added, the maximum effect of carbon with respect to lowering the temperature at which gamma iron can exist has been reached.
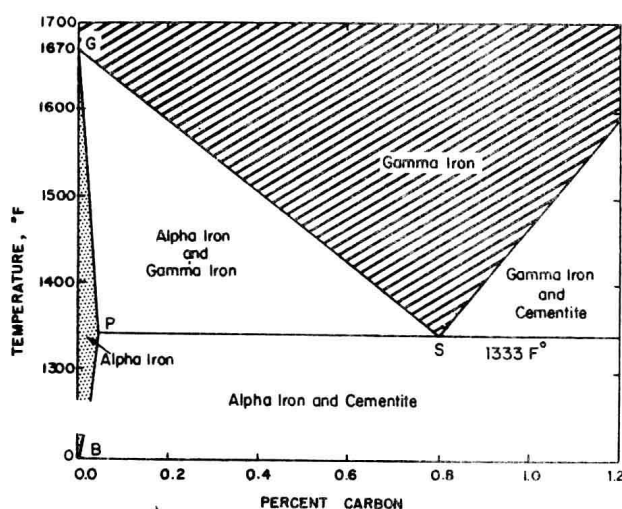

Fig. 2:3. Effect of Carbon Content on the Alpha-Gamma Transformation.

For plain carbon steels, as represented in Fig. 2:3, it is apparent that alpha iron may exist between room temperature and some elevated temperature ranging from 1333°F to 1670°F, depending on the carbon content. Alpha iron is capable of dissolving very little carbon. At room temperature, only 0.008% C is soluble; at 1333°F, the solubility increases but only to 0.025% C. At temperatures above 1333°F, the carbon solubility decreases.

The solid solution of carbon in alpha iron is called ferrite (after ferrum, the Latin word for iron; the chemical symbol Fe

also derives from the Latin word). Most steels which are heat treated contain more than 0.025% carbon. The carbon in excess of the small amount held in solid solution in the alpha iron is present as the inter-metallic compound iron carbide (Fe_3C), which is usually called <u>cementite</u>. The cementite is present as small particles more or less evenly distributed throughout the ferrite. The cementite particles are clearly visible under the microscope if the steel is properly prepared.

When ferrite is heated above 1333° F, the atoms in the alpha iron rearrange themselves into the gamma modification. Gamma iron can hold much more carbon in solid solution than alpha iron. As soon as gamma iron is formed, it can hold up to 0.80% carbon in solid solution. As the temperature of the gamma iron is increased above 1333° F, its ability to hold carbon in solid solution also increases and reaches a maximum at 2066° F, where it can hold 2.0% carbon. The solid solution of carbon (and other elements) in gamma iron is called austenite (named for W. C. Roberts -Austen, pioneer English metallographer).

When austenite forms, it usually does so at a cementite-ferrite interface. Since there are many such interfaces in steel, the formation of austenite is initiated at many spots. Under conditions favorable to continued formation of austenite, each small grain formed at an interface acts as a nucleus around which growth continues in all three dimensions until an expanding sur-face of an austenite grain contacts the surface of another expanding austenite grain. At a temperature favorable for the steel to be completely austenitic, it consists of a great number of grains of austenite. The various regions in which ferrite, cementite, and austenite exist in the plain carbon steels is diagrammed in Fig. 2:4. This is called a constitution diagram and its values are determined under equilibrium conditions of heating and cooling. This diagram is actually the same one shown in Fig. 2:3 but relabeled to reflect the new terminology. An additional line showing the limit of solid
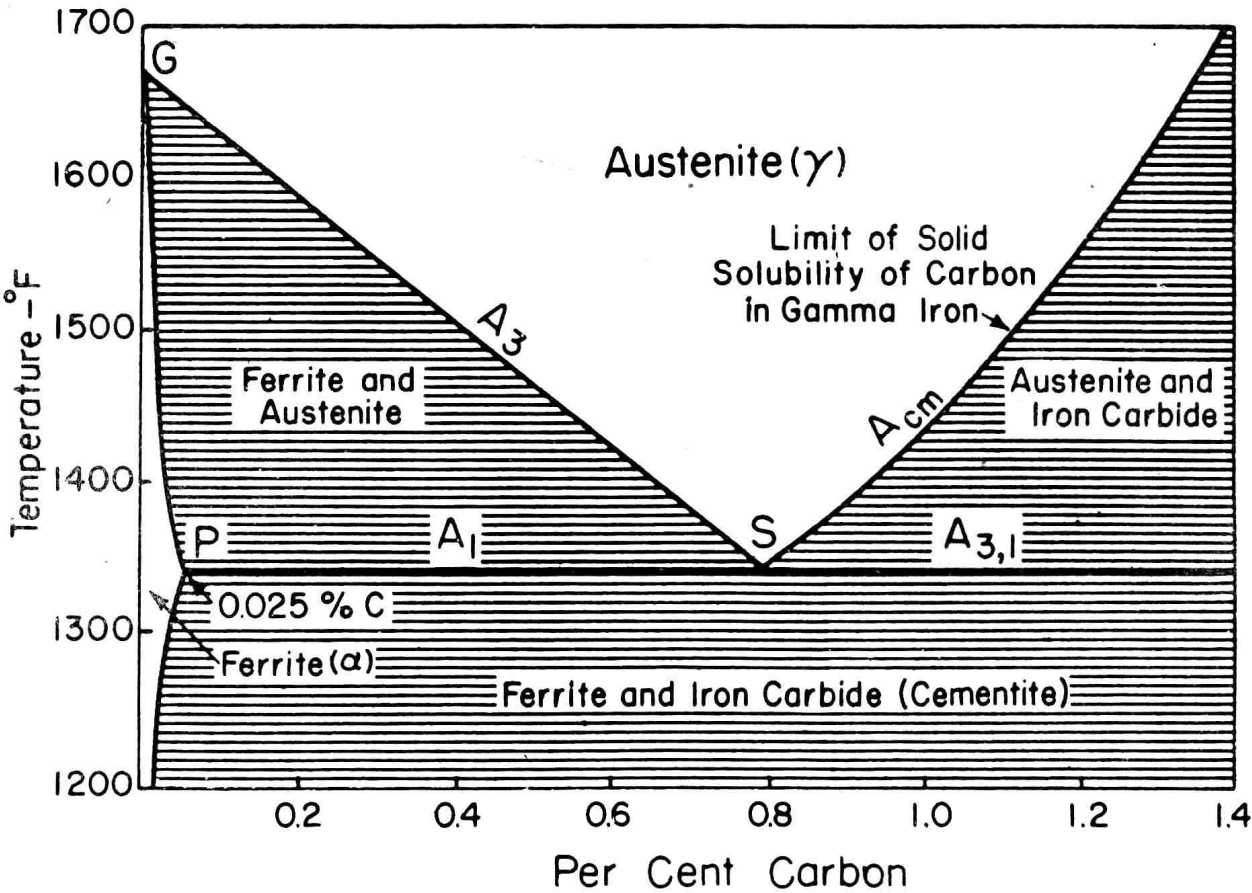
Fig. 2:4. Partial Constitution Diagram.

This shows regions of existence of ferrite, austenite, and cementite.

solubility of carbon in gamma iron has also been added.

It is interesting to note that for a steel having 0.80% carbon content, the change from ferrite to austenite occurs at a single temperature, 1333°F, where all of the carbon is taken into solid solution on heating. Such a steel is called eutectoid. For steels containing more than 0.80% carbon, the change from ferrite to austenite also occurs at 1333°F, but not all the iron carbide can be dissolved. Higher temperatures represented by the A_{cm} line must be reached before complete solution of iron carbide can occur.

Iron-carbon alloys containing more than 0.80% carbon are known as hypereutectoid steels. If a steel contains less than 0.80% carbon, the change from ferrite to austenite takes place over a temperature range as indicated in Fig. 2:4. Such steels are called hypoeutectoid steels. Again, it should be emphasized that the diagram is for plain carbon steels heated and cooled at very slow rates. As the modifications which occur in steel, such as change of lattice and solution of carbon, are not instantaneous, they require time in which to take place. Very slow rates of heating and cooling allow ample time for the reactions to occur and proceed to the degree of completion indicated by the lines in the diagram. Faster rates of heating and cooling, as well as alloy additions, affect the construction of the diagram, as we will see shortly.

When austenite is cooled, the reverse transformations occur, and as the temperature drops, the ability of austenite to retain carbon in solution decreases from 2.0% at 2066°F to 0.8% at 1333°F. Below 1333°F, austenite transforms to ferrite and cementite precipitates, since ferrite can hold only 0.025% C or less, as shown by line PB in Fig. 2:3.

MICROSTRUCTURE

When the carbon separates from the solid solution, it forms cementite particles which may be located either in the grain boundaries of the original parent austenite grain or within the confines of the grain. Similarly, ferrite may be found in the grain

boundaries as well as within the grain. In either case, during the cooling of austenite, the formation of ferrite and cementite may assume any of several patterns and be present in some definite proportions. This internal arrangement of the microconstituents in metals constitues its microstructure.

As previously stated, a careful examination of a piece of polished metal, either with the eye or the microscope, will not reveal a microstructure. This is because the smooth surface of the metal reflects the light and acts as a mirror so that we cannot see behind the flat surface layer.

In order to see the internal microstructure of a metal, it is first necessary to prepare the metallic surface by grinding and polishing it until smooth. Then, if we apply an acid to the surface of the polished metal, certain phases or areas will be attacked more readily than others, resulting in "hills and valleys" on a microscopic scale. Grain boundaries, for instance, are attacked more severely than the grains; and the grains themselves are attacked to varying degrees because of orientation differences.

When an acid-etched metal is placed under the microscope, the shadows caused by the depressions in the metal make the grain boundaries clearly visible. By a similar procedure, other particles or phases within the grains may also be made visible. On account of the extremely fine size of some of the constituents, the microstructures must necessarily be observed under the microscope, using magnifications ranging from 100X to 1000X or more. The science of determining the internal structure of metals is called metallography and is a field of effort in itself.

Steel When steel has been cooled from above A_3 to room temperature, any of four possible microstructures can result, depending on the nature of the carbide distribution in ferrite. These are spheroidite, pearlite, bainite, and martensite. (Martensite is usually reheated to impart some ductility and is then referred to as tempered martensite.)

Each microstructural constituent has a particular range of hardness, strength, etc. The various microstructures and the corresponding hardness and strength values for a 0.80% plain carbon steel are shown in Fig. 2:5. Although the same microstructures can be developed in all steels, the corresponding values of hardness and strength will vary somewhat according to the chemical composition of the steel. It should also be noted that in a given steel there are no sharp lines of demarcation between the various microstructures, but they blend into each other gradually. As a result, the individual microstructures possess a range of hardness and strength, rather than a single specific value, as presented in the simplified data in Fig. 2:5.

It should be clear from the preceding how the mechanical properties of the steel are controlled by the processes of heat treatment. Steel before heat treating has its carbon distributed in some manner which results in a microstructure with less than optimum properties. In order to eliminate the undesired microstructure, the steel is heated to some elevated temperature where austenite forms and the carbon is taken into solid solution. The previous microstructure, along with its undesired properties, is thereby "erased". In order to form a new microstructure having desired properties, the austenite is cooled to room temperature. During cooling, the austenite transforms to different products of decomposition. This causes the amount of carbon which can be held in solid solution to be greatly reduced. By controlling the conditions of cooling, the carbon which comes out of the solid solution can be made to assume a new manner of distribution, different from that which originally existed. The new microstructure is, of course, selected to afford the properties desired in the steel.

TRANSFORMATION TEMPERATURES

Obviously, if the heat treater is to control the manner in which the carbon is distributed in the steel and hence the final mechanical properties, it is imperative that he know the temperature at which carbon enters solid solution in austenite, as well as the temperature at which austenite transforms and redistributes the carbon in the steel. In Fig. 2:4, the temperatures at which the various constituents can exist are clearly outlined. This diagram illustrates the changes which occur in plain carbon steels under conditions of very slow heating and cooling. The temperatures at which the phase changes occur are called the transformation temperatures or the critical temperatures, the former being the preferred term.

Under conditions of slow heating, it will be noted that the hypoeutectoid steels have a lower transformation temperature (indicated by line A_1) where austenite begins to form, and an upper transformation temperature (indicated by line A_3) above which the transformation from ferrite to austenite is complete. Between these two temperatures a mixture of ferrite and austenite exists. This region is called the transformation range or the critical range. Under similar conditions of heating, the eutectoid steel and the hypereutectoid steels act somewhat differently in that the phase-change of the former is completed at a single temperature; this is represented by the A_1 line.

In hypereutectoid steels, the line A_{cm} must be exceeded in temperature if all of the carbon is to go into solid solution. At temperatures between the A_{cm} and the $A_{3,1}$ line, the steel will consist of a mixture of austenite and cementite, as indicated in Fig. 2:4. In the hypoeutectoid steels, the carbon in the cementite goes into solution in the gamma iron when the A_1 line has been passed. At this low temperature, only a small amount of austenite has been formed, and since it holds all of the carbon it is relatively rich in this element. As the temperature is raised, more austenite forms which is initially lacking in carbon. However, by a process of diffusion, some of the carbon in the high-carbon content austenite which was first formed passes over to the newly formed, carbon-poor austenite, so that eventually this element is evenly distributed throughout the steel.

SPHEROIDITE
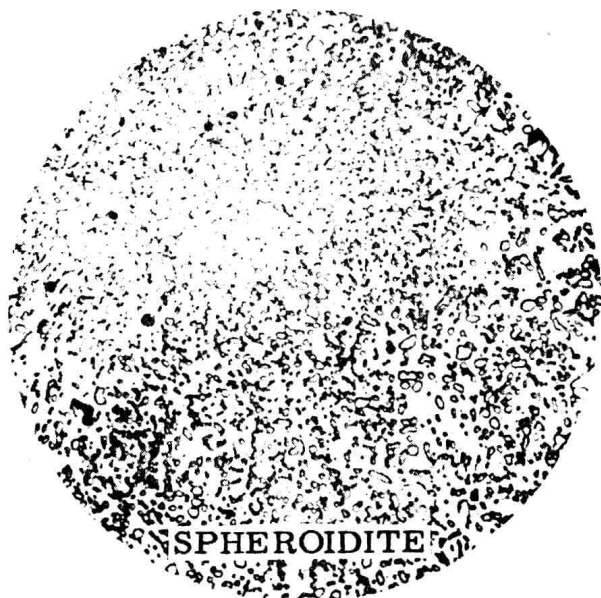
Typical Hardness - 160 Bhn
Tensile Strength - 82,000 psi

PEARLITE
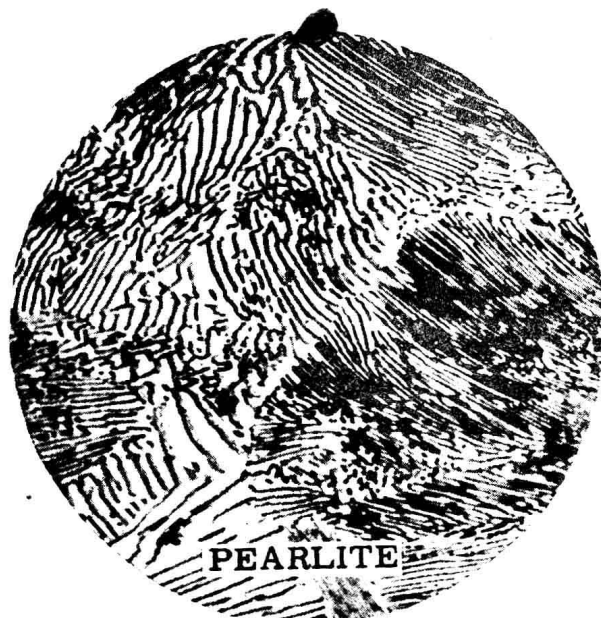
Typical Hardness - 235 Bhn
Tensile Strength - 116,000 psi

BAINITE

Typical Hardness - 495 Bhn
Tensile Strength - 247,000 psi

MARTENSITE

Typical Hardness - 653 Bhn
Tensile Strength - 324,000 psi

Fig. 2:5. Microstructures Showing Effect of Varying Distributions of Carbon on the
Hardness and Strength of 0.80% Carbon Steel.

Spheroidite - an aggregate of spheroidal carbides in ferrite.
Pearlite - so called because of its lustrous appearance.
Bainite - named for E. C. Bain, its discoverer.
Martensite - named for A. Martens, pioneer metallographer.

Diffusion   The diffusion mechanism has been observed by all of us at one time or another and can readily and clearly be demonstrated. If a small puddle of white paint is placed in a container and several drops of red paint are added in the middle of the puddle, it appears that we have two entirely different materials, each with clearly defined area limits.

As time passes, the sharp lines of demarcation blur, and the white paint in the vicinity of the red drops begins to assume a reddish tinge. With the passage of more time, we can no longer distinguish red from white but have a homogeneous pink puddle. We can then say that diffusion has taken place in that the two dissimilar colors have blended and assumed an average color value of pink. It will be noted that diffusion is a relatively slow process requiring time in which to arrive at the end result. Under the conditions of slow heating described here, sufficient time for diffusion to occur is allowed. Homogeneity of carbon content in the austenite developed in eutectoid and hypereutectoid steels is also achieved by the process of diffusion.

Under normal heat treating conditions, the rates of heating and cooling usually employed are much more rapid than those used to determine the constitution diagram shown in Fig. 2:4. A wide variety of steels other than plain carbon steels are also frequently processed in most heat treatment shops. These steels may, in addition to the full range of carbon contents shown in the constitution diagram, contain one or several alloying agents in amounts ranging from relatively small to relatively large. It is natural, therefore, for the student to inquire just how various rates of heating and cooling, as well as different amounts and types of alloys, will affect the temperatures at which austenite forms and transforms.

Both the rate of heating and cooling and the type and amount of alloy addition have an appreciable effect on the location of the transformation temperatures. When advanced rates of heating are employed, both the lower and upper heating transformation temperatures are elevated. In similar fashion, advanced rates of cooling lower both the upper and lower cooling transformation temperatures. The effect of advanced rates of heating and cooling is illustrated in Fig. 2:6. New terminology is used here to designate the lines representing the
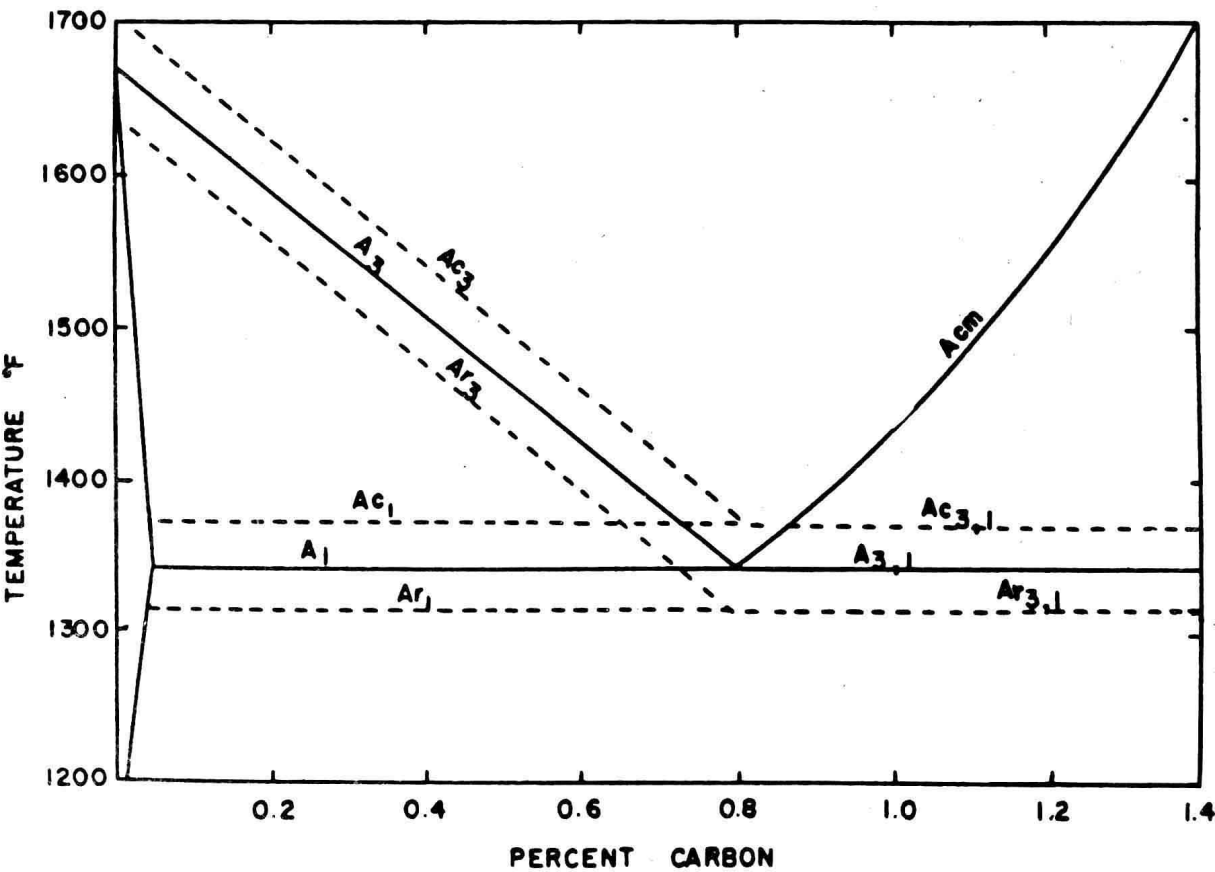

Fig. 2:6. Effect of Advanced Rates of Heating and Cooling on the Transformation Temperatures of Steel.

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limiting temperatures of the various phase-changes. On heating, the lower transformation temperature of the hypoeutectoid steels is designated as the A_{c_1}, and the upper transformation temperature as the A_{c_3}. In the eutectoid and hypereutectoid steels, the line $A_{3,1}$ becomes $A_{c_{3,1}}$.

When the steel is cooled at advanced rates, the upper cooling transformation temperature of the hypoeutectoid steels is designated as the A_{r_3}, and the lower cooling transformation temperature as the A_{r_1}. The cooling transformation temperature of the eutectoid and hypereutectoid steels is designated as $A_{r_{3,1}}$. The A_{cm} line, representing the maximum solid solubility of carbon in austenite, is relatively unaffected by changes in the rate of heating and cooling.

The addition of alloying elements to the steel has a pronounced effect on the location of the transformation temperatures. Depending upon the type and amount of these elements, the constitution diagram as shown for the plain carbon steels may be altered considerably in appearance. For the time being, the specific effects of alloys need not concern us.

The first step in any heat treating operation consists of heating the steel from room temperature to some preselected elevated temperature. For a successful heating procedure the operator should know the following:

1. The lower heating transformation temperature (A_{c_1}) where the austenite begins to form.

2. The upper heating transformation temperature (A_{c_3}) where the steel is entirely austenitic.

3. The heating transformation range and the degree to which austenite transformation has proceeded.

4. The extent and uniformity of carbon solution in the austenite.

Dilatometric Method — This information is necessary for the particular steel being processed and for the particular rate of heating which is to be employed. Numerous methods exist

for the determination of the transformation temperatures. Probably the most widely used method is the dilatometric method, which consists of placing a piece of the steel in a suitable furnace where the rate of heating can be accurately controlled. Attached to the steel sample is a sensitive device which measures and magnifies any longitudinal or volumetric changes which may occur. The equipment is usually designed so that both the temperature and
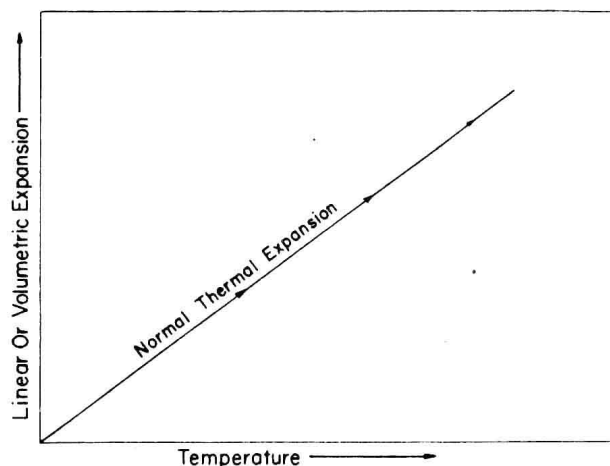

Fig. 2:7. Normal Thermal Expansion.

Note proportional expansion of steel when heated below the critical range.

volume changes are recorded, or the values plotted on a graph.

As the steel is heated above room temperature a normal thermal expansion occurs. The thermal expansion is proportional to the increase in temperature and may be graphically represented as in Fig. 2:7. This behavior continues until the lower transformation temperature is reached and the alpha iron alters to the gamma form; the rearrangement of the atoms from body-centered cubic to face-centered cubic then causes the lattice to be more closely packed, and a contraction occurs in the steel. The extent of the contraction is sufficient to offset the normal thermal expansion and causes the plotted line to assume a downward slope, as in Fig. 2:8. The overall contraction continues throughout the transformation range in spite of the increase in temperature. After the alpha to gamma transformation is complete, the steel resumes its normal thermal expansion.
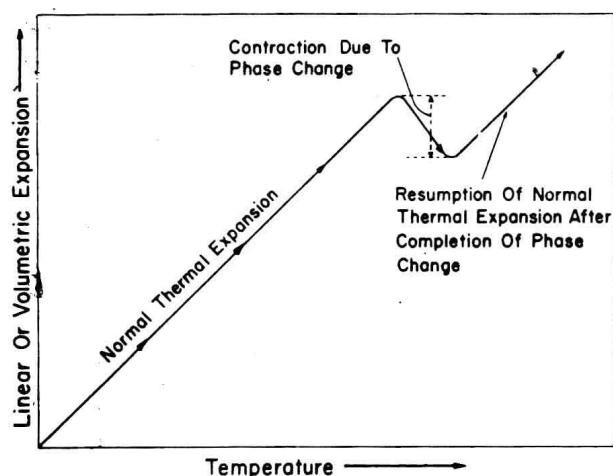
Fig. 2:8. Contraction vs. Expansion.

Diagram shows how contraction caused by transformation offsets normal thermal expansion during heating.

From the plotted line representing temperature versus length or volume change, it is a simple matter to determine the lower heating transformation temperature (A_{C_1}). This is done by noting the temperature where the first deviation from normal thermal expansion occurs. The upper heating transformation temperature (A_{C_3}) is represented by the point where the contraction due to phase-change ends, and the plotted line representing temperature versus dimensional change resumes its normal upward slope.

The significance of the designations A_{C_1} and A_{C_3} can be appreciated readily. The letter A stands for the French word "arrêt", which means stop or arrest. The letter c represents the word "chauffage" or heating. The numerals 1 and 3 indicate the sequence of the arrests. The numeral 2 following A_c designates the temperature at which a change in magnetic properties of alpha iron occurs. It is of little consequence to the heat treater.

When the steel is cooled, the reverse changes occur. Upon cooling, a normal thermal contraction takes place proportionally to the drop in temperature. When the temperature is reached at which the gamma to alpha modification occurs, the rearrangement of the atoms from face-centered cubic to body-centered cubic causes a lattice expansion. The lattice expansion is sufficient to offset the normal thermal cooling contraction, and the line plotting temperature

versus dimensional change assumes an upward slope. This continues throughout the cooling transformation range. When the cooling transformation is complete, the steel again contracts and the plotted line assumes its original downward slope. The A_{r_3} and A_{r_1} are respectively represented by the temperature where the curve first deviates from normal thermal contraction and where it resumes normal thermal contraction.
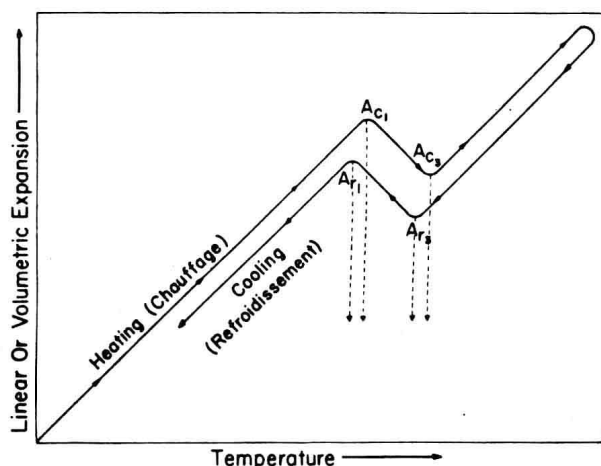

Fig. 2:9. Schematic Dilatometer Curve Showing Relationship Between Heating and Cooling Criticals.

The letter r in the designation represents the French word "refroidissement" for cooling. It will be noted in Fig. 2:9 that the range of heating transformation is higher than the cooling transformation range.

When the transformation temperatures are determined at very slow rates of heating and cooling, the gap between the A_c and A_r temperatures no longer exists, and, as was demonstrated earlier, the lower (and upper) heating and cooling criticals coincide and are designated by the letter A followed by the suitable numeral or numerals. Frequently, the transformation temperatures are indicated by the designation A_e followed by one or more numerals. In this case, the letter e designates the word equilibrium and indicates that heating and cooling have taken place at very slow rates.

Heat Measurement   In addition to the method described, several other procedures are available for determining the transformation temperatures It is one of our natural laws