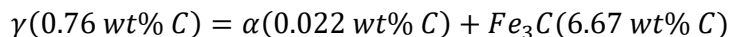# 2. Isothermal Transformation and Continuous Cooling Diagrams

2.1. Time-Temperature Transformation Diagrams

Consider again the iron-iron carbide eutectoid reaction:

$$\gamma(0.76\ wt\%\ C) = \alpha(0.022\ wt\%\ C) + Fe_3C(6.67\ wt\%\ C)$$

which is fundamental to the development of microstructure in steel alloys. Upon cooling, austenite, having an intermediate carbon concentration, transforms to a ferrite phase, having a much lower carbon content, and also cementite, with a much higher carbon concentration. Pearlite is one microstructural product of this transformation.

Isothermal transformation experiments to investigate the microstructural changes for the decomposition of eutectoid austenite can be made by using a number of small samples, each about the size of a dime. The samples are first austenitized in a furnace at a temperature above the eutectoid temperature (Figure 2-1a). The samples are then rapidly cooled (quenched) in a liquid salt bath at the desired temperature below the eutectoid temperature (Figure 2-1b). After various time intervals, the samples are removed from the salt bath one at a time and quenched into water at room temperature (Figure 2-1c). The microstructure after each transformation time can then be examined at room temperature.

Consider the microstructural changes during the isothermal transformation of a eutectoid plain-carbon steel at 705°C, as schematically shown in Figure 2-2. After being austenitized, the samples are hot-quenched into a salt bath at 705°C. After about 6 min, coarse pearlite has formed to a small extent. After about 67 min, the austenite is completely transformed into coarse pearlite.
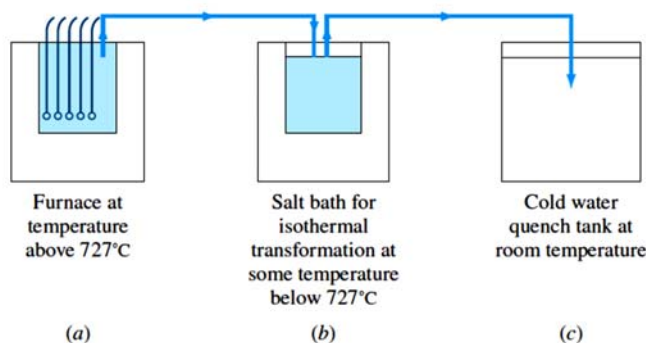

Figure 2-1Experimental arrangement for determining the microscopic changes that occur during the isothermal transformation of austenite in a eutectoid plain-carbon steel. (Source: W.F. Smith, Structure and Properties of Engineering Alloys, McGraw-Hill, 1981, p. 14.)
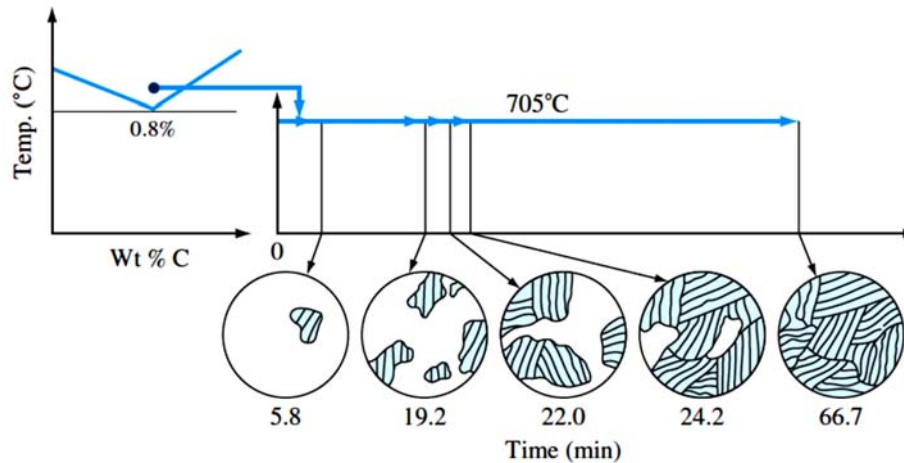
Figure 2-2 Experiment for following the microstructural changes that occur during the isothermal transformation of a eutectoid plain-carbon steel at 705°C. After austenitizing, samples are quenched in a salt bath at 705°C, held for the times indicated, and then quenched in water at room temperature.

Temperature plays an important role in the rate of the austenite-to-pearlite transformation. The temperature dependence for an iron-carbon alloy of eutectoid composition is indicated in Figure 2-3, which plots S-shaped curves of the percentage transformation versus the logarithm of time at three different temperatures. For each curve, data were collected after rapidly cooling a specimen composed of 100% austenite to the temperature indicated; that temperature was maintained constant throughout the reaction.
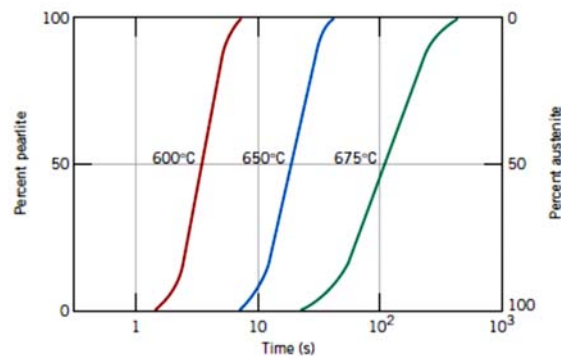

Figure 2-3 For an iron-carbon alloy of eutectoid composition (0.76 wt% C), isothermal fraction reacted versus the logarithm of time for the austenite-to-pearlite transformation.

A more convenient way of representing both the time and temperature dependence of this transformation is in the bottom portion of Figure 2-4. Here, the vertical and horizontal axes are temperature and the logarithm of time. Two solid curves are plotted; one represents the time required at each temperature for the initiation or start of the transformation; the other is for the transformation conclusion. The dashed curve corresponds to 50% of transformation completion. These curves were generated from a series of plots of the percentage

transformation versus the logarithm of time taken over a range of temperatures. The S-shaped curve [for 675 °C] in the upper portion of Figure 2-4 illustrates how the data transfer is made.
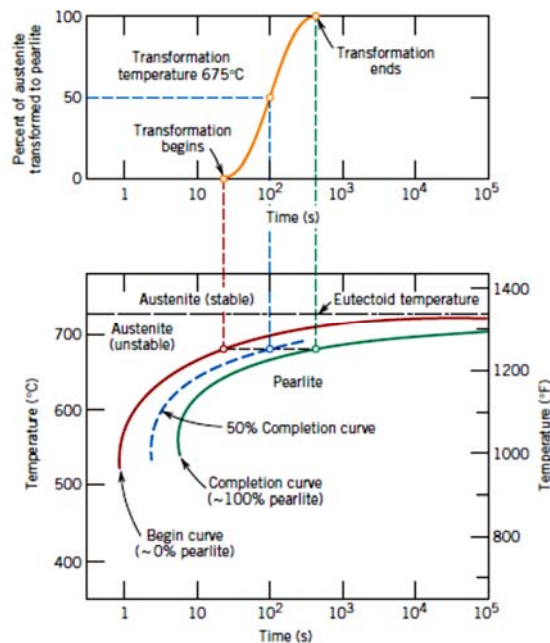

Figure 2-4 Demonstration of how an isothermal transformation diagram (bottom) is generated from percentage transformation–versus– logarithm of time measurements (top). [Adapted from H. Boyer, (Editor), Atlas of Isothermal Transformation and Cooling Transformation Diagrams, *American Society for Metals, 1977, p. 369.]*

In interpreting this diagram, note first that a horizontal line indicates the eutectoid temperature [727 °C]; at temperatures above the eutectoid and for all times, only austenite will exist, as indicated in the figure. The austenite-to-pearlite transformation will occur only if an alloy is supercooled below the eutectoid; as indicated by the curves, the time necessary for the transformation to begin and then end depends on temperature. The start and finish curves are nearly parallel and approach the eutectoid line asymptotically. Only austenite (which is unstable) will be present to the left of the transformation start curve, whereas, to the right of the finish curve, only pearlite will exist. In between, the austenite is in the process of transforming to pearlite, and thus, both microconstituents will be present.

The transformation rate at some particular temperature is inversely proportional to the time required for the reaction to proceed to 50% completion (to the dashed line in Figure 2-4). That is, the shorter this time, the higher the rate. Thus, at temperatures just below the eutectoid (corresponding to only a slight degree of undercooling), very long times (on the order of 10^5 s) are required for the 50% transformation. Therefore, the reaction rate is very slow. The

transformation rate increases with decreasing temperature such that at 540 °C, only about 3 s is required for the reaction to go to 50% completion.

Several constraints are imposed on using diagrams like Figure 2-4. First, this particular plot is valid only for an iron-carbon alloy of eutectoid composition; for other compositions, the curves will have different configurations. Also, these plots are accurate only for transformations in which the temperature of the alloy is held constant throughout the duration of the reaction. Conditions of constant temperature are termed isothermal; thus, plots such as Figure 2-4 are referred to as isothermal transformation diagrams or sometimes as time-temperature–transformation (or T–T–T) plots.

An actual isothermal heat treatment curve (ABCD) is superimposed on the isothermal transformation diagram for a eutectoid iron-carbon alloy in Figure 2-5. The near-vertical line AB indicates very rapid cooling of austenite to a temperature, and the horizontal segment BCD represents the isothermal treatment at this temperature. Of course, time increases from left to right along this line. The transformation of austenite to pearlite begins at the intersection, point C (after approximately 3.5 s). It has reached completion by about 15 s, corresponding to point D. Figure 2-5 also shows schematic microstructures at various times during the reaction's progression. The thickness ratio of the ferrite and cementite layers in pearlite is approximately 8 to 1. However, the absolute layer thickness depends on the temperature at which the isothermal transformation occurs. At temperatures just below the eutectoid, relatively thick layers of both the α-ferrite and Fe_3C phases are produced; this microstructure is called coarse pearlite, and the region at which it forms is indicated to the right of the completion curve in Figure 2-5. At these temperatures, diffusion rates are relatively high, such that during the transformation, carbon atoms can diffuse relatively long distances, which results in the formation of thick lamellae. The carbon diffusion rate decreases with decreasing temperature, and the layers become progressively thinner. The thin-layered structure produced near 540 °C is termed fine pearlite; this is also indicated in Figure 2-5. Photomicrographs of coarse and fine pearlite for a eutectoid composition are shown in Figure 2-6.
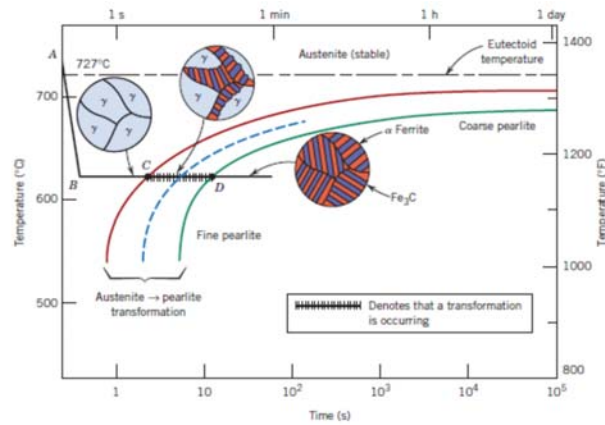
Figure 2-5 Isothermal transformation diagram for a eutectoid iron-carbon alloy, with superimposed isothermal heat treatment curve (ABCD). Microstructures before, during, and after the austenite-to-pearlite transformation are shown. [Adapted from H. Boyer (Editor), Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals, 1977, p. 28.]
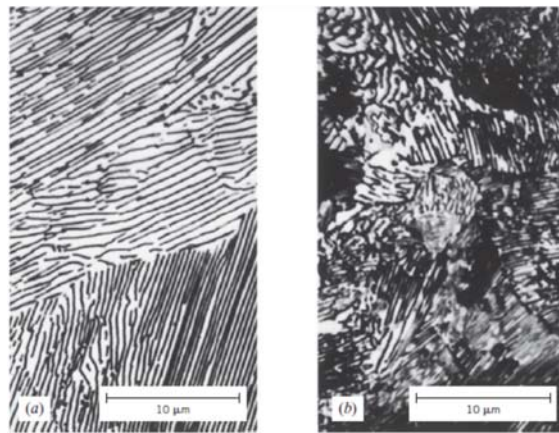

Figure 2-6 Photomicrographs of (a) coarse pearlite and (b) fine pearlite. 3000X. (From K. M. Ralls et al., An Introduction to Materials Science and Engineering, p. 361. Copyright ©1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

In addition to pearlite, other microconstituents that are products of the austenitic transformation exist; one of these is called bainite. The microstructure of bainite consists of ferrite and cementite phases, and thus, diffusional processes are involved in its formation. Bainite forms as needles or plates, depending on the transformation's temperature; the microstructural details of bainite are so fine that their resolution is possible only using electron microscopy. It is composed of a ferrite matrix and elongated particles of Fe_3C. Furthermore, no proeutectoid phase forms with bainite. The time-temperature dependence of the bainite transformation may also be represented on the isothermal transformation diagram. It occurs at temperatures below those at which pearlite forms; begin-, end-, and half-reaction curves are just extensions of those for the pearlitic transformation, as shown in Figure 2-7, the isothermal transformation diagram

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for an iron-carbon alloy of eutectoid composition that has been extended to lower temperatures. All three curves are C-shaped and have a "nose" at point N, where the rate of transformation is a maximum. As may be noted, whereas pearlite forms above the nose [i.e., over the temperature range of about 540 to 727 °C], at temperatures between about 215 and 540 °C, bainite is the transformation product. It should also be noted that pearlitic and bainitic transformations are really competitive with each other. Once some portion of an alloy has transformed to either pearlite or bainite, transformation to the other micro constituent is impossible without reheating to form austenite.
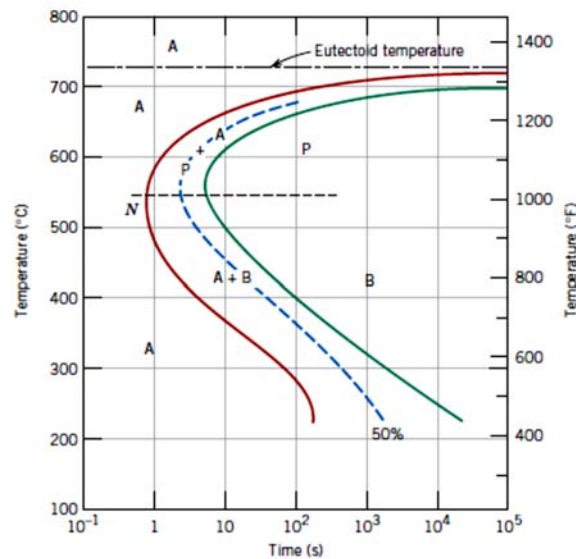

Figure 2-7 Isothermal transformation diagram for an iron-carbon alloy of eutectoid composition,including austenite to-pearlite (A–P) and austenite-to-bainite(A–B) transformations. [Adapted from H. Boyer (Editor), Atlas of Isothermal Transformation and Cooling *Transformation Diagrams, American Society for Metals,1977, p. 28.]*

Yet another microconstituent or phase called martensite is formed when austenitized iron-carbon alloys are rapidly cooled (or quenched) to a relatively low temperature (in the vicinity of the ambient). Martensite is a nonequilibrium single-phase structure resulting from a diffusionless austenite transformation. It may be considered a competitive transformation product with pearlite and bainite. The martensitic transformation occurs when the quenching rate is rapid enough to prevent carbon diffusion. Any diffusion whatsoever will result in the formation of ferrite and cementite phases. The martensitic transformation is not well understood. However, large numbers of atoms experience cooperative movements in that there is only a slight displacement of each atom relative to its neighbors. This occurs in such a way that the FCC austenite experiences a polymorphic transformation to a body-centered tetragonal (BCT) martensite. A body-centered cube has been elongated along with one of its dimensions; this structure is distinctly different from BCC ferrite. All the carbon atoms remain as interstitial

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impurities in martensite; as such, they constitute a supersaturated solid solution capable of rapidly transforming to other structures if heated to temperatures at which diffusion rates become appreciable. Many steels, however, retain their martensitic structure almost indefinitely at room temperature. Because the martensitic transformation does not involve diffusion, it occurs almost instantaneously; the martensite grains nucleate and grow rapidly— the velocity of sound within the austenite matrix. Thus, the martensitic transformation rate, for all practical purposes, is time-independent. Because the martensitic transformation is diffusionless and instantaneous, it is not depicted in this diagram as the pearlitic and bainitic reactions are. The beginning of this transformation is represented by a horizontal line designated M(start) (Figure 2-8). Two other horizontal and dashed lines labeled M(50%) and M(90%) indicate percentages of the austenite-to-martensite transformation. The temperatures at which these lines are located vary with alloy composition but must be relatively low because carbon diffusion must be virtually nonexistent. These lines' horizontal and linear character indicates that the martensitic transformation is independent of time; it is a function only of the temperature to which the alloy is quenched or rapidly cooled. A transformation of this type is termed an *athermal transformation*.

Consider an alloy of eutectoid composition that is very rapidly cooled from a temperature above 727 °C to, say, 165°C. From the isothermal transformation diagram (Figure 2-8) it may be noted that 50% of the austenite will immediately transform to martensite; as long as this temperature is maintained, there will be no further transformation.
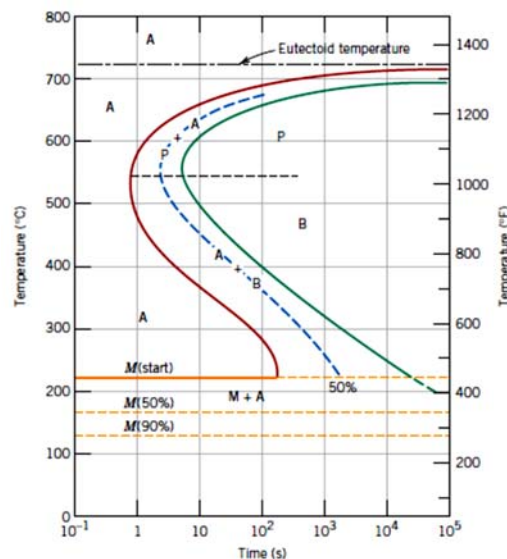

Figure 2-8 The complete isothermal transformation diagram for an iron-carbon alloy of eutectoid composition: A, austenite; B, bainite; M, martensite; P, pearlite.

Isothermal Transformation Diagrams for Noneutectoid Plain-Carbon Steels

In iron-carbon alloys with compositions outside the eutectoid point (0.76wt% carbon), pearlite coexists with a proeutectoid phase, either ferrite or cementite. Therefore, isothermal transformation diagrams (TTT diagrams) for these alloys must account for this additional transformation. Figure 2-9 illustrates the TTT diagram for a hypereutectoid composition (excess carbon compared to the eutectoid point). Compared to the eutectoid diagram, key differences emerge. Most notably, a curved line extends from the pearlite "knee" to the 880°C horizontal line, representing the diffusional process of proeutectoid cementite formation. Additionally, the martensitic reaction temperatures, like Ms, shift slightly downward. Figure 2-10 showcases a similar TTT diagram with proeutectoid ferrite formation and higher martensitic temperatures than the eutectoid steel. A crucial distinction, in this case, is the leftward shift of the hypoeutectoid steel's S curves, making it impossible to entirely quench the austenitic region into martensite. Notably, the martensitic reaction generally occurs at decreasing temperatures with increasing carbon content around the eutectoid composition region.
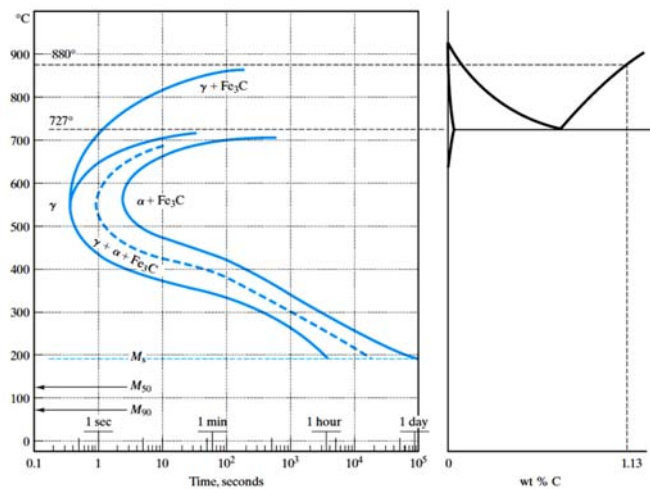

Figure 2-9 TTT diagram for a hypereutectoid composition (1.13 wt % C) compared with the Fe9Fe3C phase diagram. (TTT diagram after Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals, Metals Park, OH, 1977.)
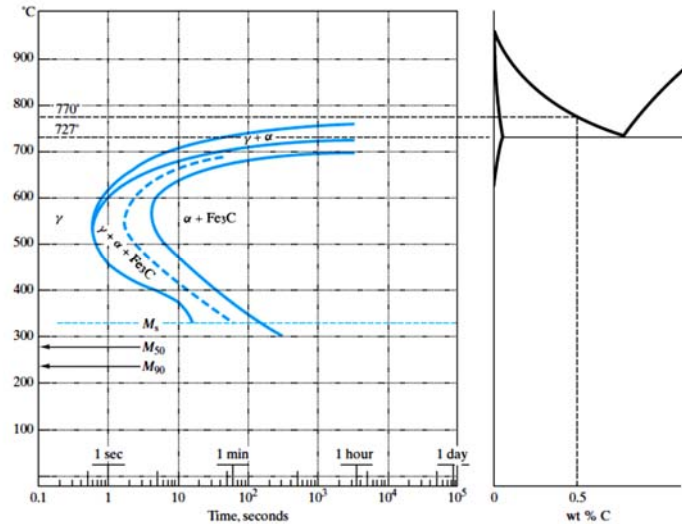
Figure 2-10 TTT diagram for a hypoeutectoid composition (0.5 wt%C) compared to the Fe-Fe₃C phase diagram.

2.2. Effect of Alloying Elements on IT Diagrams

The presence of alloying elements other than carbon (e.g., Cr, Ni, Mo, and W) may cause significant changes in the curves' positions and shapes in the isothermal transformation diagrams. These include (1) shifting to longer times the nose of the austenite-to-pearlite transformation (and also a proeutectoid phase nose, if such exists) and (2) the formation of a separate bainite nose. These alterations may be observed by comparing Figure 2-8 and Figure 2-11, which are isothermal transformation diagrams for carbon and alloy steels, respectively.
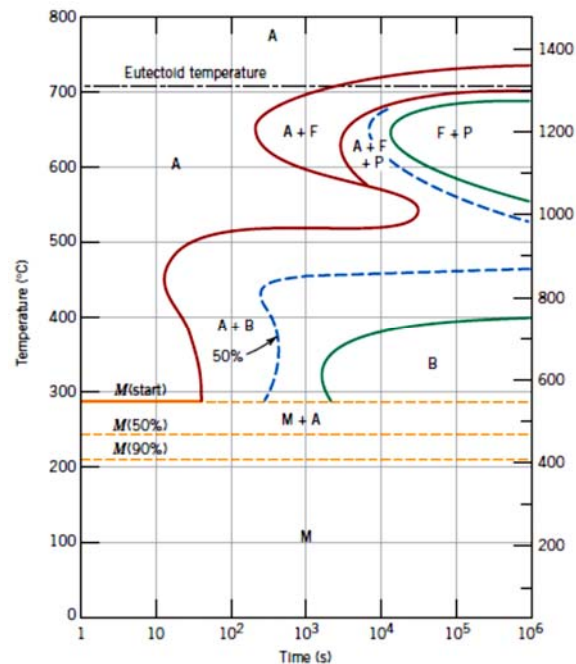
2.3. Effect of austenite grain size on TTT diagram

All austenite decomposition products in steels heterogeneously nucleate at the grain boundaries of austenite. Therefore, the prior austenite grain size is expected to affect the overall kinetics of austenite decomposition substantially. The total grain boundary area in austenite decreases as the average grain size increases. Hence, with the increase in austenite grain size, the grain boundary area available for nucleating austenite decomposition products decreases. Therefore, a longer time would be required in coarse-grained steel compared to fine-grained steel of the same composition to obtain the same fractional decomposition of austenite. This has the effect of shifting the start and the end curves of IT diagrams to longer times with increasing grain size, as schematically shown in Figure 2-12.
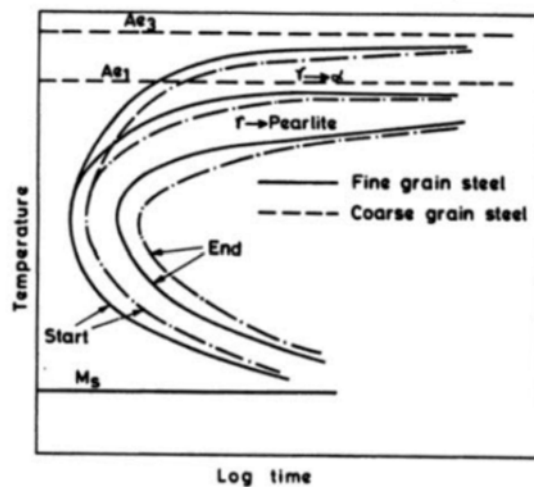

Figure 2-12 Effect of austenite grain size on TTT diagram

2.4. Applications of TTT Diagram

Austempering

Austempering is an isothermal heat treatment that produces a bainite structure in some plain-carbon steels. The process provides an alternative procedure to quenching and tempering for increasing the toughness and ductility of some steels. In the austempering process the steel is first austenitized, then quenched in a molten salt bath at a temperature just above the Ms temperature of the steel, held isothermally to allow the austenite-to-bainite transformation to

take place, and then cooled to room temperature in air (Figure 2-13). The final structure of an austempered eutectoid plain-carbon steel is bainite.

The advantages of austempering are (1) improved ductility and impact resistance of certain steels over those values obtained by conventional quenching and tempering (Table 2-1) and (2) decreased distortion of the quenched material. The disadvantages of austempering over quenching and tempering are (1) the need for a special molten salt bath and (2) the fact that the process can be used for only a limited number of steels.
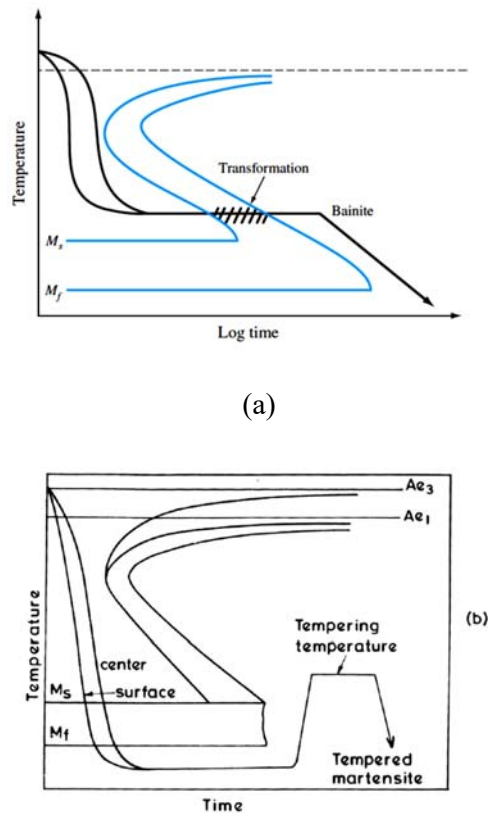

(a)

Figure 2-13 Schematic illustration of (a) Austempering, and (b) conventional quenching and tempering treatments.

Martempering (Marquenching)

Martempering (marquenching) is a modified quenching procedure used for steels to minimize distortion and cracking that may develop during uneven cooling of the heat-treated material. The martempering process consists of (1) austenitizing the steel, (2) quenching it in hot oil or molten salt at a temperature just slightly above (or slightly below) the Ms temperature, (3) holding the steel in the quenching medium until the temperature is uniform throughout and stopping this isothermal treatment before the austenite-to-bainite transformation begins, and (4) cooling at a moderate rate to room temperature to prevent large temperature differences.

The steel is subsequently tempered by the conventional treatment. Figure 2-14 shows a cooling path for the martempering process. The structure of the martempered steel is martensite, and that of the martempered (marquenched) steel that is subsequently tempered is tempered martensite. Table 2-1 lists some of the mechanical properties of 0.95% C plain-carbon steel after martempering and tempering, along with those obtained by conventional quenching and tempering. The major difference between these two sets of properties is that the martempered and tempered steel has higher impact energy values. It should be noted that the term martempering is misleading, and a better word for the process is marquenching.

Figure 2-14 Cooling curve for martempering (marquenching) superimposed on a eutectoid plain-carbon steel IT diagram. The interrupted quench reduces the stresses developed in the metal during quenching.

Table 2-1 Some mechanical properties (at 20°C) of a 1095 steel developed by austempering as compared to some other heat treatments

Heat Treatment	Rockwell C Hardness	Impact (ft · lb)	Elongation in 1 in. (%)
Water-quench and temper	53.0	12	0
Water-quench and temper	52.5	14	0
Martemper and temper	53.0	28	0
Martemper and temper	52.8	24	0
Austemper	52.0	45	11
Austemper	52.5	40	8

Source: *Metals Handbook,* vol. 2, 8th ed., American Society for Metals, 1964.

2.5. Continuous Cooling Transformation Diagrams

Isothermal heat treatments are not the most practical to conduct because an alloy must be rapidly cooled to and maintained at an elevated temperature from a higher temperature above the eutectoid. Most heat treatments for steels involve continuously cooling a specimen to room

temperature. An isothermal transformation diagram is valid only for constant temperature conditions; this diagram must be modified for transformations as the temperature constantly changes. For continuous cooling, the time required for a reaction to begin and the end is delayed. Thus, the isothermal curves are shifted to longer times and lower temperatures, as indicated in Figure 2-15 for an iron-carbon alloy of the eutectoid composition. For the CCT diagram application, consider four eutectoid steel specimens austenitized at 800 °C and cooled at different rates, as depicted in Figure 2-16.
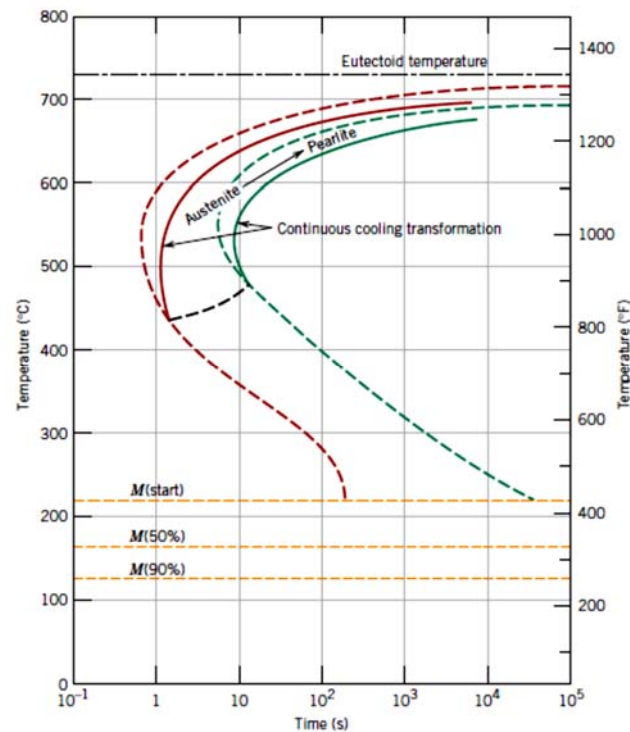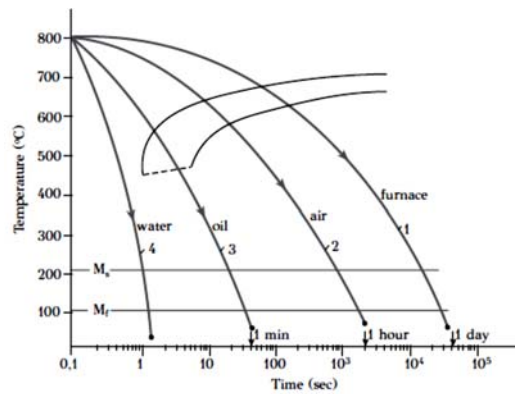

Figure 2-15 Superimposition of isothermal and continuous cooling transformation diagrams for a eutectoid iron-carbon alloy. [Adapted from H. Boyer (Editor), Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals,1977, p. 376.]
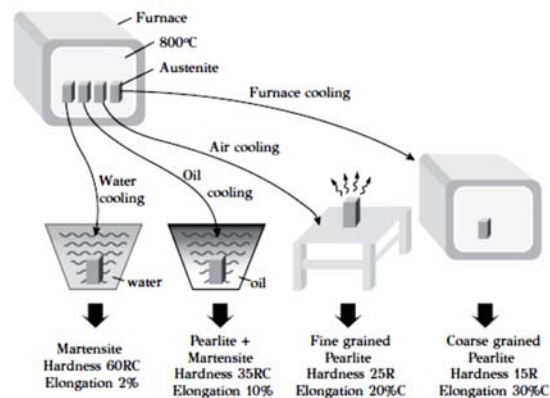
(a)

(b)

Figure 2-16(a) Four specimens of eutectoid steel austenitized at 800 C and cooled at different rates, (b) CCT diagram of eutectoid steel indicating the different cooling rates.

A plot containing such modified beginning and ending reaction curves is termed a continuous cooling transformation (CCT) diagram. Some control may be maintained over the rate of temperature change depending on the cooling environment. Two cooling curves corresponding to moderately fast and slow rates are superimposed and labeled in Figure 2-17, again for eutectoid steel. The transformation starts after a time period corresponding to the cooling curve's intersection with the beginning reaction curve and concludes upon crossing the completion transformation curve. The microstructural products for the moderately rapid and slow cooling rate curves in Figure 2-17 are fine and coarse pearlite, respectively. Normally, bainite will not form when an alloy of eutectoid composition or, for that matter, any plain carbon steel is continuously cooled to room temperature. This is because all the austenite will have been transformed to pearlite when the bainite transformation becomes possible. Thus, the region representing the austenite–pearlite transformation terminates just below the nose, as indicated by the curve AB. For any cooling curve passing through AB in Figure 2-17, the transformation ceases at the point of intersection; with continued cooling, the unreacted austenite begins transforming to martensite upon crossing the M(start) line. With regard to the representation of the martensitic transformation, the M(start), M(50%), and M(90%) lines occur at identical temperatures for both isothermal and continuous cooling transformation diagrams.
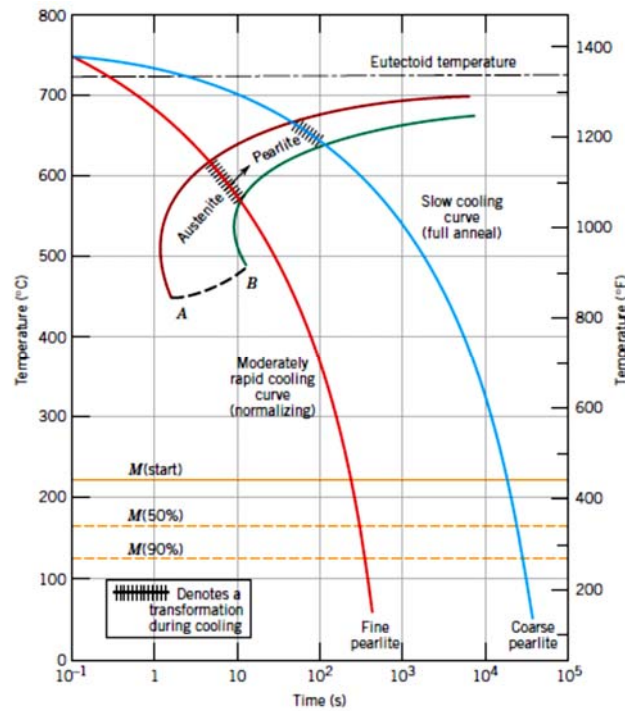
Figure 2-17 *Moderately rapid and slow cooling curves superimposed on a continuous cooling transformation diagram for a eutectoid iron-carbon alloy.*

For the continuous cooling of a steel alloy, there is a critical quenching rate, representing the minimum rate of quenching that will produce a totally martensitic structure. This critical cooling rate, when included in the continuous transformation diagram, will just miss the nose at which the pearlite transformation begins, as illustrated in Figure 2-18. As Figure 2-18 also shows, the only martensite will exist for quenching rates greater than the critical; also, there will be a range of rates over which both pearlite and martensite are produced. Finally, a totally pearlitic structure develops for low cooling rates.
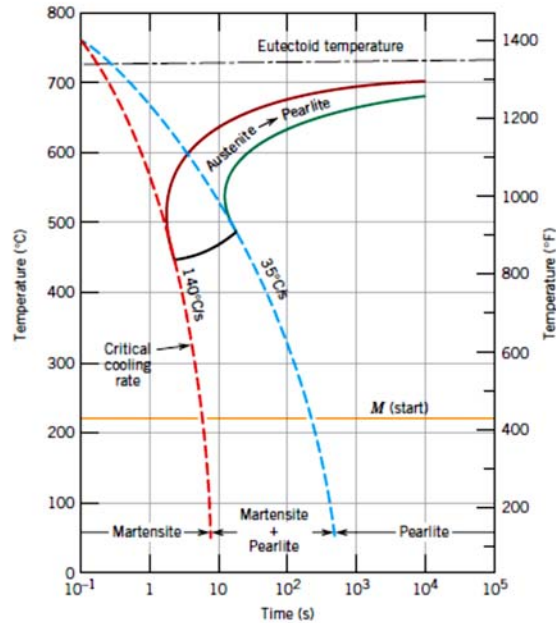
Figure 2-18 Continuous cooling transformation diagram for a eutectoid iron-carbon alloy and superimposed cooling curves, demonstrating the dependence of the final microstructure on the transformations that occur during cooling.
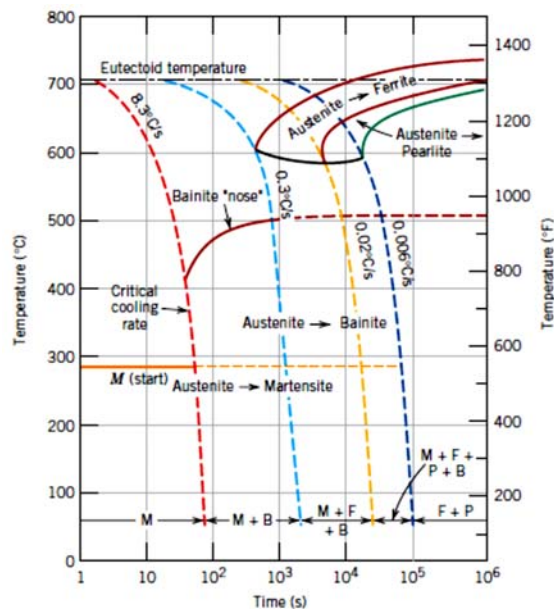

Figure 2-19 Continuous cooling transformation diagram for an alloy steel (type 4340) and several superimposed cooling curves demonstrating the dependence of the final microstructure of this alloy on the transformations that occur during cooling. [Adapted from H. E. McGannon (Editor), The Making, Shaping and Treating of Steel, 9th edition, United States Steel Corporation, Pittsburgh, 1971, p. 1096.]

Interestingly enough, the critical cooling rate is diminished even by the presence of carbon. In fact, iron-carbon alloys containing less than about 0.25 wt% carbon are not normally heat-treated to form martensite because quenching rates too rapid to be practical are required. Other alloying elements that are particularly effective in rendering steels heat-treatable are chromium,

nickel, molybdenum, manganese, silicon, and tungsten; however, these elements must be in solid solution with the austenite at the time of quenching. Figure 2-20 and Figure 2-21 show that nickel depresses the Ac_3 and Ac_1 temperatures in accord with its role as an austenite stabilizer in steels and increases hardenability (i.e., the ability to form martensite on cooling) primarily by shifting the proeutectoid and pearlite transformation to longer time periods. Although the austenite-ferrite and austenite-pearlite regions are not differentiated in Figure 2-20, the microstructures in Figure 2-22 show that equiaxed proeutectoid ferrite and pearlite are the transformation products for continuous cooling that produces DPH hardnesses of 219, 210, and 185. Figure 2-21 and Figure 2-23 show that the addition of about 0.5% Mo to the 1.4% Ni steel produces significant changes in cooling transformation characteristics and microstructure. Hardenability is greatly improved, pearlite and equiaxed proeutectoid ferrite formation are severely retarded, and the bainite transformation becomes quite prominent. The gap that sometimes forms between two mechanisms of transformation is also apparent. The strong effect of molybdenum and similar ferrite stabilizers such as chromium and silicon has been attributed to the fact that molybdenum must diffuse or partition during pearlite formation. Since molybdenum diffuses very sluggishly below Ae_1, the pearlite transformation is significantly retarded. On the other hand, ferrite formation by a shear mechanism requires no such partitioning of substitutional elements. As a result, the lower nose for Widmanstä¨tten ferrite and bainite (which is nucleated by ferrite) are prominent features of the CT diagram for the steel containing molybdenum.
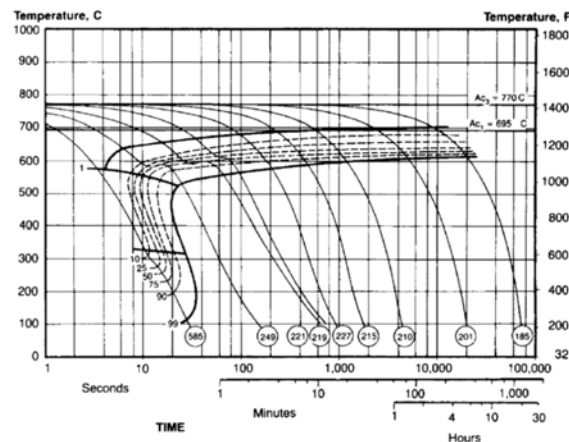

Figure 2-20 CT diagram for a steel containing 0.37% C, 0.36% Si, 0.85% Mn, 1.44% Ni, and 0.02% Mo. The steel was austenitized at 800 °C for 20 min. The circled numbers correspond to DPH hardness of microstructures produced by cooling at the rates shown.
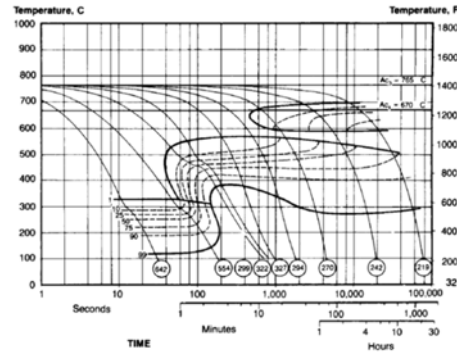
Figure 2-21 CT diagram for a steel containing 0.37% C, 0.36% Si, 0.84% Mn, 1.40% Ni, and 0.47% Mo. The steel was austenitized at 795 °C for 70 min. The circled numbers correspond to DPH hardness of microstructures produced by cooling at the rates shown.
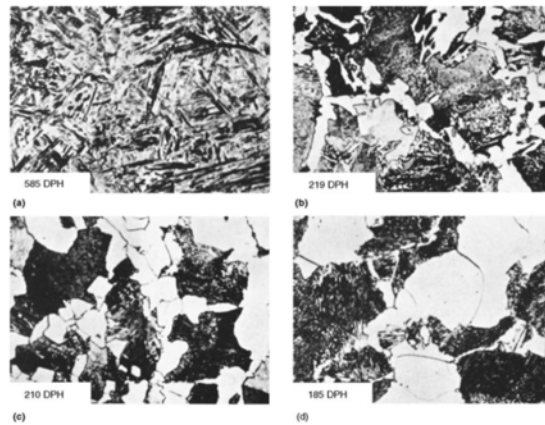

Figure 2-22 Microstructures produced by cooling steel at four rates as identified by DPH hardness, 2% nital etch, original magnification 1000X; shown here at 75%.
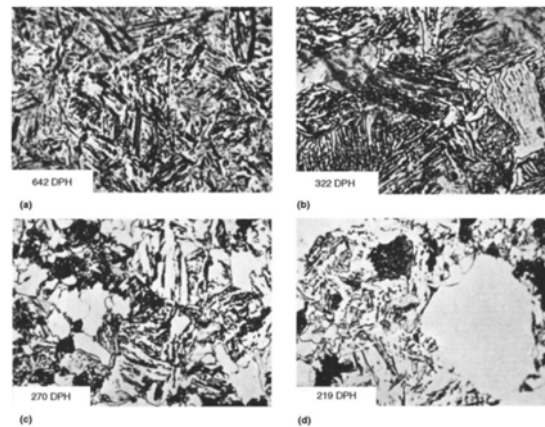

Figure 2-23 Microstructures produced by cooling steel at four rates as identified by DPH hardness, 2% nital etch, original magnification 1000X; shown here at 75%.

In summary, isothermal and continuous cooling transformation diagrams are, in a sense, phase diagrams in which time is introduced. Each is experimentally determined for an alloy of specified composition, the variables being temperature and time. These diagrams allow the prediction of the microstructure after some time period for constant temperature and continuous cooling heat treatments, respectively.

Figure 2-24 shows the CT diagram for a plain carbon steel containing 0.38% C, 0.20% Si, and 0.70% Mn. The abscissa is plotted as a bar diameter associated with air cooling, oil quenching, and water quenching. Vertical lines associated with a given diameter show the microstructures to be expected in the *center of a bar of that diameter*. For example, the vertical dashed line identified as "Air Cool" shows that a microstructure of ferrite, pearlite, and a small amount of bainite is expected in a 10 mm (0.4 in.) diameter bar that has been air cooled. Likewise, the vertical dashed lines marked "Water Quench" and "Oil Quench" indicate that martensite and bainite plus martensite, respectively, would be expected for 10 mm (0.4 in.) diameter bars quenched in the two different media. Figure 2-25 shows the CT diagram for a more highly alloyed 0.40% C steel. The diagram shows that a 10 mm (0.4 in.) bar of this steel, even if air-cooled, would be entirely martensitic and that oil-quenched bars up to 100 mm (4 in.) in diameter would be fully hardened.
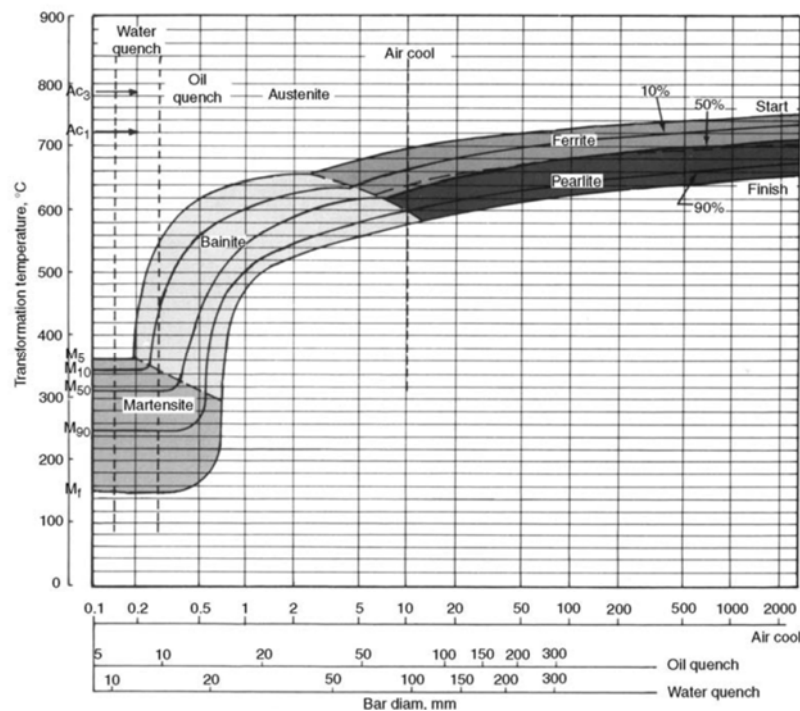

Figure 2-24 CT diagram for plain carbon steel containing 0.38% C and 0.70% Mn. Transformation and microstructures are plotted as a function of bar diameter.
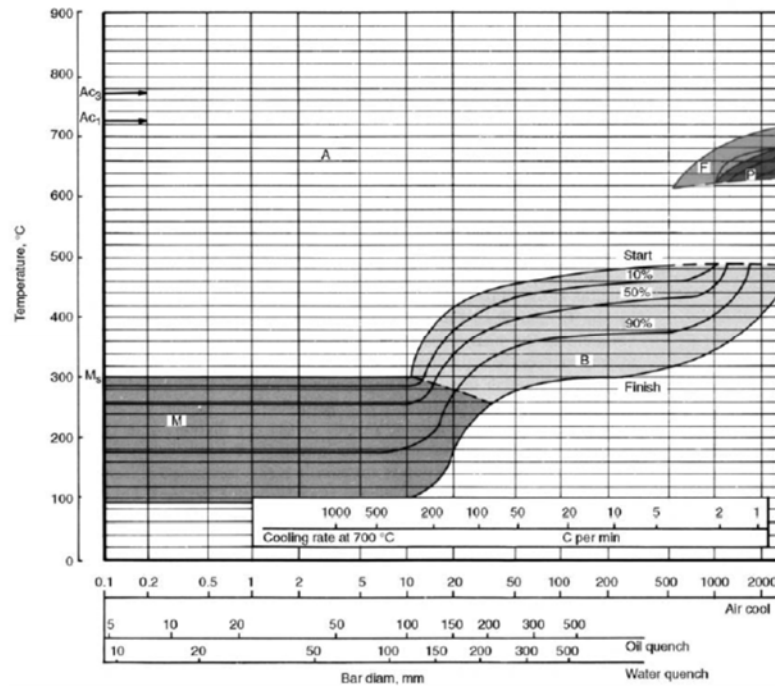
Figure 2-25 CT diagram for an alloy steel with 0.40% C, 1.50% Ni, 1.20% Cr, and 0.30% Mo, plotted as a function of bar diameter. Steel was austenitized at 850 °C; previous treatment: rolling, then softening at 650 °C

2.6. Relationship between IT and CCT Diagrams

Figure 2-26 schematically shows the relative positions of IT and CCT diagrams of plain carbon steel plotted on the same graph. The CCT diagram is generally shifted to longer times with respect to the IT diagram. This shift can be understood by considering a given continuous cooling curve shown in Figure 2-26. This cooling curve meets the start curve of the IT diagram at a point "a", which represents the time for 0.1 % transformation when the sample is quenched to T and held there isothermally. However, on continuously cooling to point "a" along this cooling curve, the sample has spent most of the time at temperatures higher than T_a. where the nucleation and growth rates are, in general, slower. Therefore, on continuous cooling to point "a", the amount of transformation would be less than 0.1 %. Hence, on continuous cooling, a 0.1% transformation would be attained beyond "a" along the cooling curve, i.e., at point "b" in Figure 2-26. By extending the argument to other cooling curves, we can qualitatively see how the relative positions of IT and CCT diagrams of the same steel would be, as shown in Figure 2-26. Transformation rates are again slowed down below the nose of the IT diagram, and the CCT curve becomes closer to the IT curve, meeting it at some temperature below the nose. The point at which IT and CCT start curves meet, below the nose of the IT diagram, is on the critical

cooling curve. At cooling rates higher than this, no non-martensitic transformation would occur in the steel.
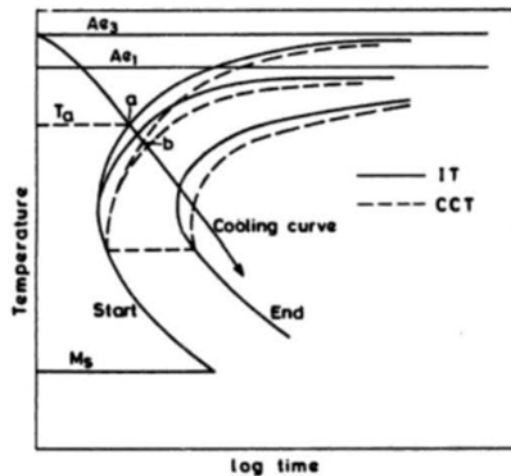

Figure 2-26 Relationship between IT and CCT diagram of a plain carbon steel (schematic).

The above analysis of the relative positions of the IT and CCT diagrams of a given steel also suggests the possibility of converting the IT diagram of a steel to its CCT diagram and vice versa. Different methods for converting an IT diagram to a CCT diagram exist. A graphical method by Grange and Kiefer is shown in Figure 2-27. According to this method, during continuous cooling along a given cooling curve which intercepts the IT start curve at temperature T_1, the transformation will start at temperature T_2, such that the time of cooling between T_1 and T_2 is equal to the time for the start of transformation during isothermal holding at temperature $(T_1 + T_2)/2$. The construction is schematically shown in Figure 2-27. Similar construction for different cooling rates will produce the CCT start curve. The same procedure may be adopted for the IT end curve or any other curve corresponding to a given amount of transformation. Thus, an IT diagram may be converted entirely to a CCT diagram. The assumptions involved in this method are not strictly valid; however, it gives reasonable results, particularly for the transformation start curve in the ferrite-pearlite transformation range.
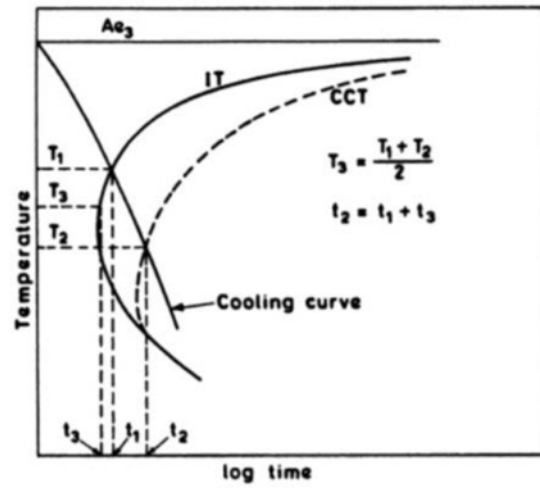
Figure 2-27 Illustration of the graphic method of converting an IT diagram to CCT diagram