10.5W Isothermal Transformation Diagrams

PEARLITE (PRINT)

BAINITE (DETAILED VERSION)

From the discussion of the preceding section, it would seem reasonable to expect the alternating ferrite and cementite lamellae to become thinner and thinner as the isothermal transformation temperature is lowered to below that at which fine pearlite forms. Such is not the case; other microconstituents that are products of the austenitic transformation are found to exist at these lower temperatures. One of these microconstituents is called **bainite.** Furthermore, depending on transformation temperature, two general types of bainite have been observed: upper and lower bainite. Like pearlite, the microstructure of each of these bainites consists of ferrite and cementite phases; however, their arrangements are different from the alternating lamellar structure found in pearlite.

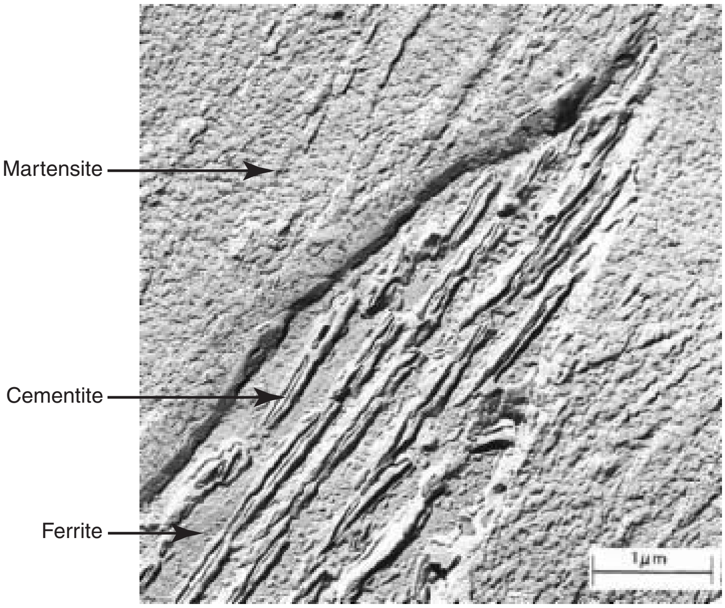
For temperatures between approximately 300 and 540°C, bainite forms as a series of parallel laths (i.e., thin narrow strips) or needles of ferrite that are separated by elongated particles of the cementite phase. Such is termed *upper bainite,* and its microstructural details are so fine that their resolution is possible only using electron microscopy. Figure 10.12*a*W is an electron micrograph that shows a grain of upper bainite (positioned diagonally from lower left to upper right); the various phases in this micrograph have been labeled. In addition, the phase that surrounds the bainite is martensite, which is a topic addressed in a subsequent section. Furthermore, no proeutectoid phase forms with bainite.

At lower temperatures between about 200 and 300°C *lower bainite* is the transformation product. For lower bainite, the ferrite phase exists as thin plates (instead of laths as with upper bainite), and narrow cementite particles (as very fine rods or blades) form within these ferrite plates. Figure 10.12*b*W is an electron micrograph of lower bainite; in this micrograph, the plates of bainite appear as needle-like structures, whereas the phase that surrounds them is martensite. Furthermore, the cementite particles within these bainite plates are so small as not to be resolvable; the schematic inset shown with this micrograph represents the detailed structure of these plates.

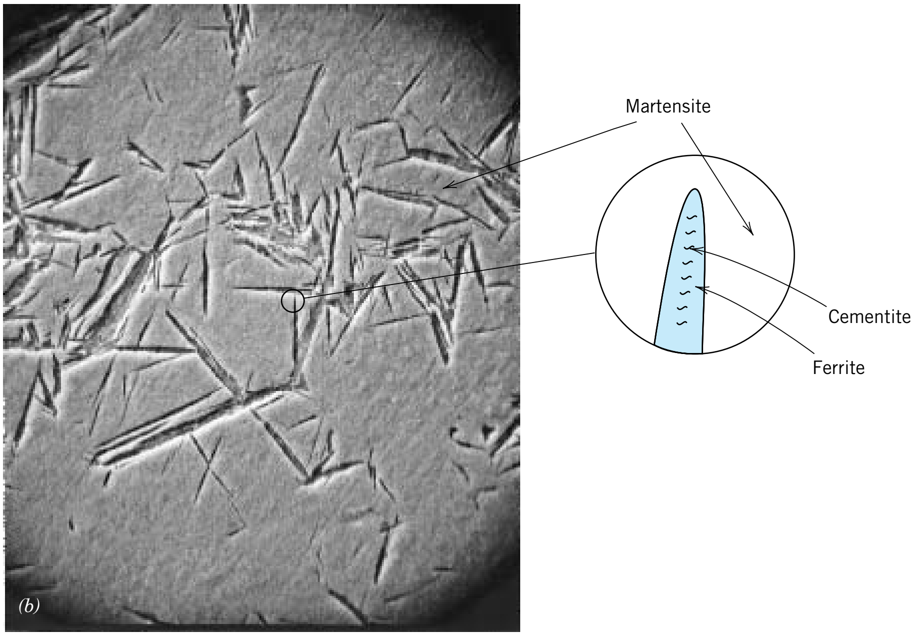
The time–temperature dependence of the bainite transformation may also be represented on the isothermal transformation diagram. The transformation occurs at temperatures below those at which pearlite forms; begin-, end-, and half-reaction curves are just extensions of those for the pearlitic transformation, as shown in Figure 10.13W, the isothermal transformation diagram 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—that is, over the temperature range of about 540 to 727°C (1000 to 1341°F)—for isothermal treatments at temperatures between about 215 and 540°C (420 and 1000°F), bainite is the transformation product. Temperature regimes over which upper and lower bainites form are indicated on Figure 10.13W.

Note also that pearlitic and bainitic transformations are really competitive with each other, and once some portion of an alloy has transformed to either pearlite or bainite, transformation to the other microconstituent is not possible without reheating to form austenite.

FIGURE 10.12W (*a*) Transmission electron micrograph showing the structure of upper bainite. A grain of bainite passes from lower left to upper right-hand corners, which consists of elongated and needle-shaped particles of Fe_3C within a ferrite matrix. The phase surrounding the bainite is martensite. 15,000×. (Reproduced with permission from *Metals Handbook,* Vol. 8, 8th edition, *Metallography, Structures and Phase Diagrams,* American Society for Metals, Materials Park, OH, 1973.) (*b*) Scanning electron micrograph showing lower bainite in a martensite matrix for an AISI steel that was transformed isothermally at 300°C. The inset shows the detail of a lower bainite grain. 2300×. (From John D. Verhoeven, *Fundamentals of Physical Metallurgy,* p. 502. Copyright © 1975 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



(*a*)



SPHEROIDITE (PRINT)

MARTENSITE (DETAILED VERSION)

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 that results from a diffusionless transformation of austenite. It may be thought of as a transformation product that is competitive with pearlite and bainite. The martensitic transformation occurs when the quenching rate is rapid enough

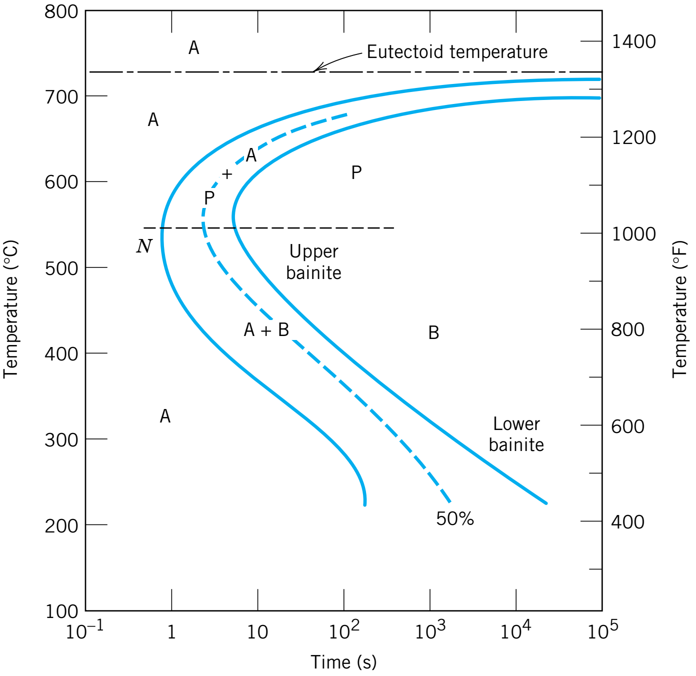


FIGURE 10.13W Isothermal transformation diagram for an iron–carbon alloy of eutectoid composition, including austenite-to-pearlite (A–P) and austenite-to-bainite (A–B) transformations. [Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams,* American Society for Metals, 1977, p. 28.]

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 unit cell of this crystal structure (Figure 10.14W) is simply a body-centered cube that has been elongated along one of its dimensions; this structure is distinctly different from that for BCC ferrite. All the carbon atoms remain as interstitial impurities in martensite; as such, they constitute a supersaturated solid solution that is 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.

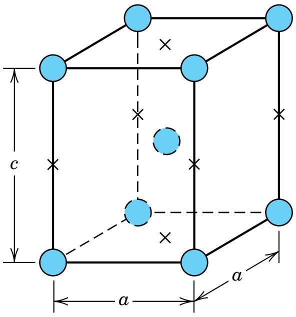


FIGURE 10.14W The body-centered tetragonal unit cell for martensitic steel showing iron atoms (circles) and sites that may be occupied by carbon atoms (crosses). For this tetragonal unit cell, $c > a$.

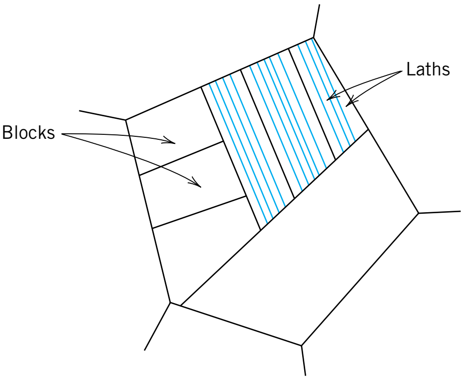


Figure 10.15W Schematic diagram showing the microstructural features of lath or massive martensite. [Adapted from A. R. Marder and J. I. Goldstein (Editors), *Phase Transformations in Ferrous Alloys,* The Metallurgical Society of AIME, 1984.]

The martensitic transformation is not, however, unique to iron–carbon alloys. It is found in other systems and is characterized, in part, by the diffusionless transformation.

Since the martensitic transformation does not involve diffusion, it occurs almost instantaneously; the martensite grains nucleate and grow at a very rapid rate—the velocity of sound within the austenite matrix. Thus the martensitic transformation rate, for all practical purposes, is time independent.

Two distinctly different martensitic microstructures are found in iron–carbon alloys: lath and lenticular. For alloys containing less than about 0.6 wt% C, the martensite grains form as laths (i.e., long and thin plates, like blades of grass) that form side by side and are aligned parallel to one another. Furthermore, these laths are grouped into larger structural entities, called blocks; the morphology of this *lath* (or *massive*) *martensite* is represented schematically in Figure 10.15W. Microstructural details of this type of martensite are too fine to be revealed by optical microscopy, and, therefore, electron micrographic techniques must be employed.

Lenticular (or *plate*) *martensite* is typically found in iron–carbon alloys containing greater than approximately 0.6 wt% C. With this structure the martensite grains take on a needle-like (i.e., lenticular) or plate-like appearance, as indicated in the photomicrograph of Figure 10.16W. Here the lenticular martensite

Figure 10.16W Photomicrograph showing the lenticular or plate martensitic microstructure. The needle-shaped grains are the martensite phase, and the white regions are austenite that failed to transform during the rapid quench. 1220×. (Photomicrograph courtesy of United States Steel Corporation.)

grains are the dark regions, whereas the white phase is retained austenite that did not transform during the rapid quench.

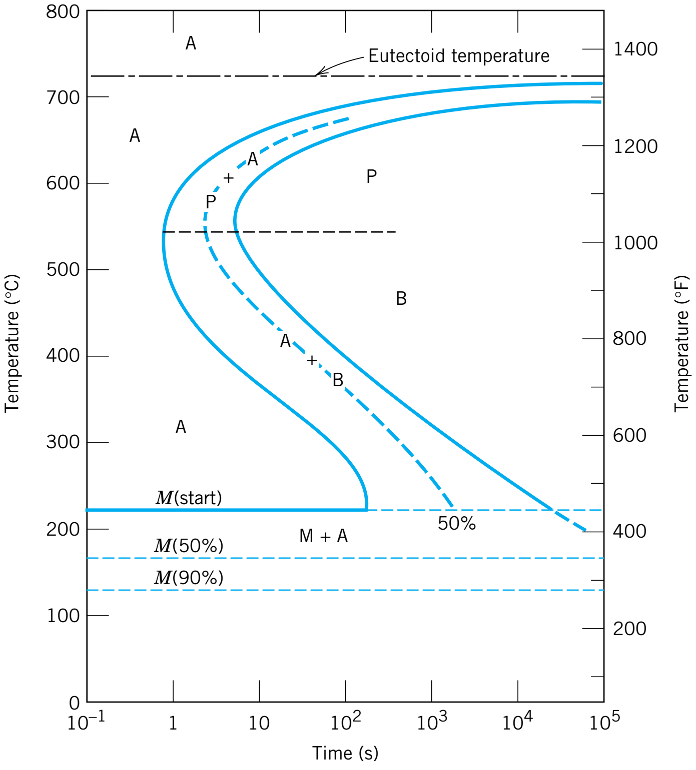
Note that, as has already been mentioned, both of these types of martensite as well as other microconstituents (e.g., pearlite and bainite) can coexist.

Being a nonequilibrium phase, martensite does not appear on the iron–iron carbide phase diagram (Figure 9.21). The austenite-to-martensite transformation is, however, represented on the isothermal transformation diagram. Since the martensitic transformation is diffusionless and instantaneous, it is not depicted in this diagram like the pearlitic and bainitic reactions. The beginning of this transformation is represented by a horizontal line designated *M* (start) (Figure 10.17W). 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, nevertheless, must be relatively low because carbon diffusion must be virtually nonexistent. The horizontal and linear character of these lines 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 (1341°F) to, say, 165°C (330°F). From the isothermal transformation diagram (Figure 10.17W) 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.

The presence of alloying elements other than carbon (e.g., Cr, Ni, Mo, and W) may cause significant changes in the positions and shapes of the curves in the

FIGURE 10.17W The complete isothermal transformation diagram for an iron–carbon alloy of eutectoid composition: A, austenite; B, bainite; M, martensite; P, pearlite.



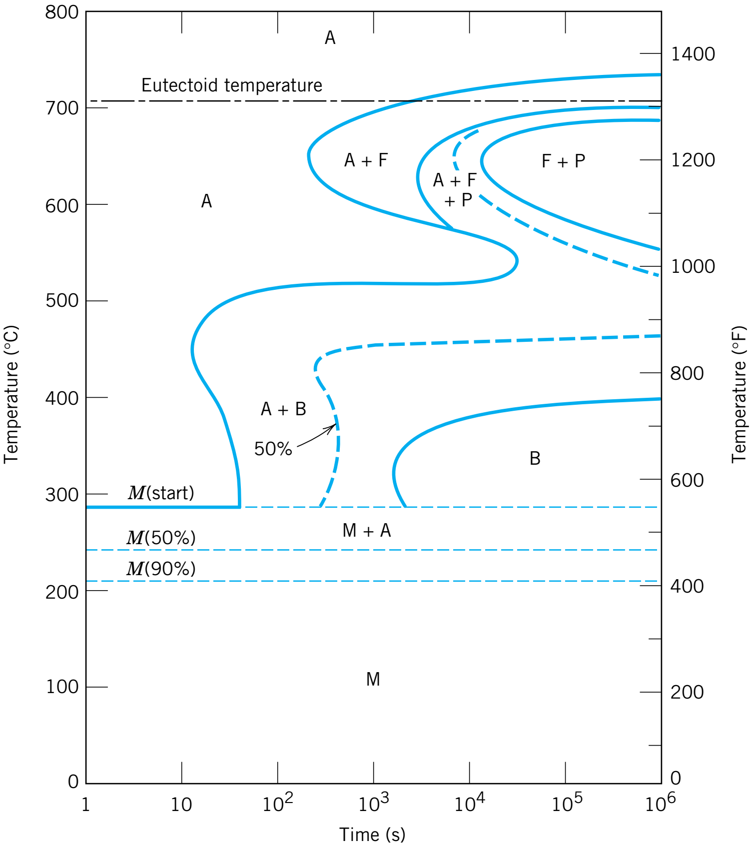


Figure 10.18W Isothermal transformation diagram for an alloy steel (type 4340): A, austenite; B, bainite; P, pearlite; M, martensite; F, proeutectoid ferrite. [Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams,* American Society for Metals, 1977, p. 181.]

isothermal transformation diagrams. These changes 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 Figures 10.17W and 10.18W, which are isothermal transformation diagrams for carbon and alloy steels, respectively.