cementite and ferrite plates and therefore the resultant structure is lamellar in nature which can be easily seen with the help of an optical microscope. The alternate plates of ferrite and cementite can be resolved at levels of magnification obtainable in optical microscopes. The mechanism of formation of bainite differs from that of pearlite and the structure is accicular, and not lamellar, in nature. Bainite is generally formed within an intermediate temperature range. The upper limit of range coincides with the minimum temperature of pearlite formation and the lower limit approaches the temperature at which formation of martensite starts. In majority of steels, the temperature range of formation of bainite overlaps the corresponding ranges for other products. Only in a few alloy steels, a clear-cut delineation between pearlitic, bainitic and martensitic temperature ranges exists. An important feature that distinguishes pearlitic and bainitic transformation is that the former involves diffusion of both iron and carbon atoms during transformation whereas the latter involves only diffusion of carbon atoms. Austenite to pearlite and bainite transformations have been dealt with in detail in Sections 4.7 and 4.8, respectively.

4.6 TIME-TEMPERATURE TRANSFORMATION CURVES

The temperature of transformation controls the nature of decomposed product (of austenite) which in turn decides the resultant properties of steel. Therefore, the study of transformation temperature effect on the nature of decomposed product is of much importance. The kinetics of austenitic transformation can be studied best at a constant temperature rather than by continuous cooling. The constant temperature transformation is also referred to as isothermal transformation which is studied by the following experiment. A number of small samples are taken from the steel under consideration. These samples are heated to predetermined austenitizing temperature and are held at this temperature for a sufficiently long period so as to obtain a homogeneous austenite. These austenitized samples are transferred quickly to another bath maintained at a constant temperature below eutectoid temperature, selected for the study of kinetics of transformation. These samples are taken out one by one from the subcritical temperature bath after different time intervals and are quenched immediately. The quenching of samples results in the formation of martensite from the untransformed austenite. By this technique, the amount of transformed austenite can be determined as a function of time at constant temperature. The amount of transformed austenite will increase by allowing samples to remain in constant temperature bath for longer time. After a particular time, all the austenite will transform to an aggregate to ferrite and cementite at a given temperature. Figure 4.10 shows the effect of time on the amount of transformed austenite for a given transformation temperature T. It is clear from the figure that the transformation of austenite does not start immediately on quenching austenitized sample to a constant temperature bath. Transformation of austenite to ferrite-cementite mixture occurs after a definite time (equals to t_1 of Figure 4.10). This time during which transformation does not proceed is known as incubation period. The magnitude of incubation period provides a qualitative idea about the relative stability of supercooled austenite. Smaller incubation period corresponds to lesser stability of austenite.

Figure 4.10 has one important limitation, i.e. it only correlates the amount of transformed austenite with transformation time for a constant temperature. Both time and temperature of austenitic transformation have significant impact on the nature and morphology of transformed product. Thus, a diagram which can include all the three parameters, i.e. time, temperature and transformation, will be of great importance, specially to the heat treaters. Such a diagram is known as time temperature transformation (TTT) diagram. This diagram is also popularly known as isothermal transformation (IT) diagram or the C-curve. In fact, the TTT curve is an extension of isothermal transformation of austenite diagram (see Figure 4.10).

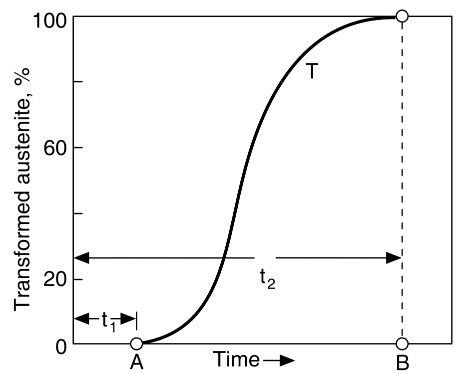


Figure 4.10 Isothermal transformation of austenite to pearlite.

For the construction of the TTT curve for a steel, a large number of small samples of the steel (say, eutectoid steel) are procured. These samples are treated in a way similar to that already mentioned for the study of isothermal transformation of austenite. The only difference now is that the same process is repeated a number of times at varying transformation temperatures instead of a single temperature. The results are shown in Figure 4.11. The amount of transformed austenite at various time periods for different transformation temperatures can be known in this way. The temperature T_1 is greater than T_2, T_3, T_4, T_5,..., and is near to the eutectoid temperature. It can be analyzed from Figure 4.11 that the higher the transformation temperature, the more is the incubation period and time required for completion of the transformation. Incubation period and transformation time decrease with the lowering of transformation temperature. However, after a particular temperature (corresponding to T_4 of Figure 4.11), the decreasing trend is reversed and both incubation period and transformation time increase again with further lowering of transformation temperature. The minimum that is observed in the incubation period can be explained as follows. With decrease in the isothermal transformation temperature, the austenite becomes more unstable. The driving force for the austenite to pearlite transformation increases. Accordingly, the rate of nucleation increases. However, with decrease in transformation temperature, the rate of diffusion, which is an exponential function of temperature, decreases.

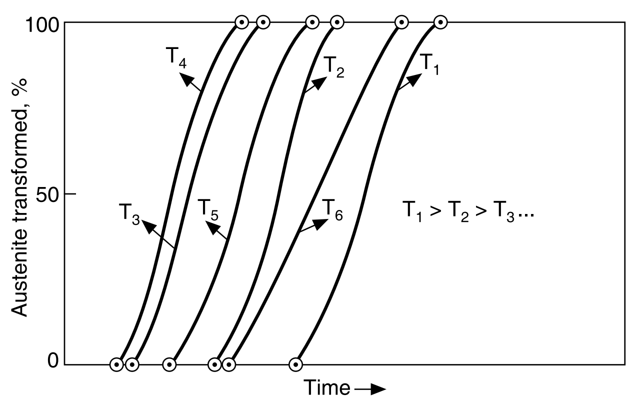


Figure 4.11 Isothermal transformation of austenite to pearlite at different temperatures.

Transformation rate depends on the overall effect of the rate of nucleation and rate of diffusion. The temperature at which the incubation time is minimum (T_4 in the above case)' is the one below which the increase in nucleation rate by decrease in temperature is more than offset by decrease in the diffusion rate as a result of decrease in temperature. Consequently, any further decrease in temperature increases the incubation time. These aspects will be considered in detail in Section 4.7.2.

As already stated, below a particular transformation temperature, the rate of diffusion becomes practically insignificant and if transformation temperature is lowered below this limit, a diffusionless product, namely, martensite, will be formed. Formation of martensite takes place instantaneously at a particular transformation temperature.

From the result of Figure 4.11, another diagram (i.e. Figure 4.12) can be constructed with time and temperature as abscissa and ordinate, respectively. Figure 4.13 shows the TTT diagram for a eutectoid steel.

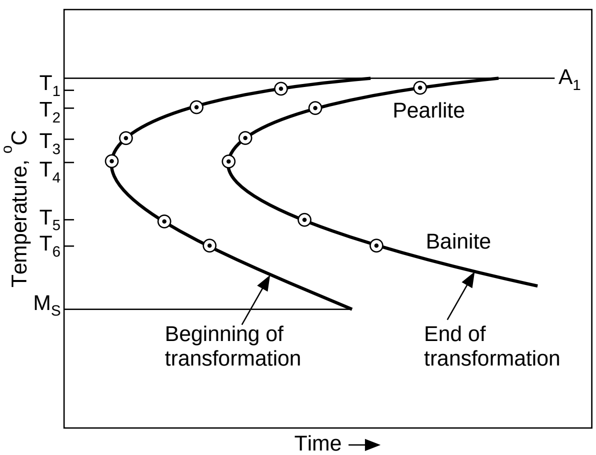


Figure 4.12 TTT diagram for transformation of austenite for steel.

Figures 4.14 and 4.15 represent the TTT diagrams for hypoeutectoid and hypereutectoid steels, respectively. A common feature of these TTT diagrams is that proeutectoid phase (ferrite for hypoeutectoid and cementite for hypereutectoid steels) separates out in upper temperature region. For hypoeutectoid steels, ferrite starts separating out from the austenite as soon as austenite is cooled below the upper critical temperature (A_3). The amount of proeutectoid ferrite decreases as austenite is undercooled more and more below the upper critical temperature. After a certain degree of undercooling, austenite will transform directly to pearlite. On further cooling, there will be no surplus ferrite.

Similarly, cementite is separated out in hypereutectoid steels from austenite on cooling below the upper critical temperature (A_{cm}). The amount of cementite decreases with increased degree of supercooling and finally reduces to zero when austenite is cooled below a particular temperature.

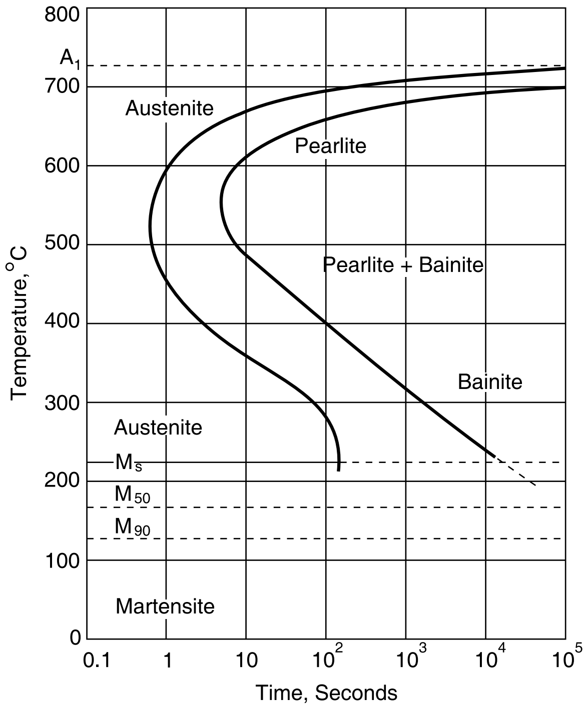


Figure 4.13 TTT diagram for eutectoid steel.

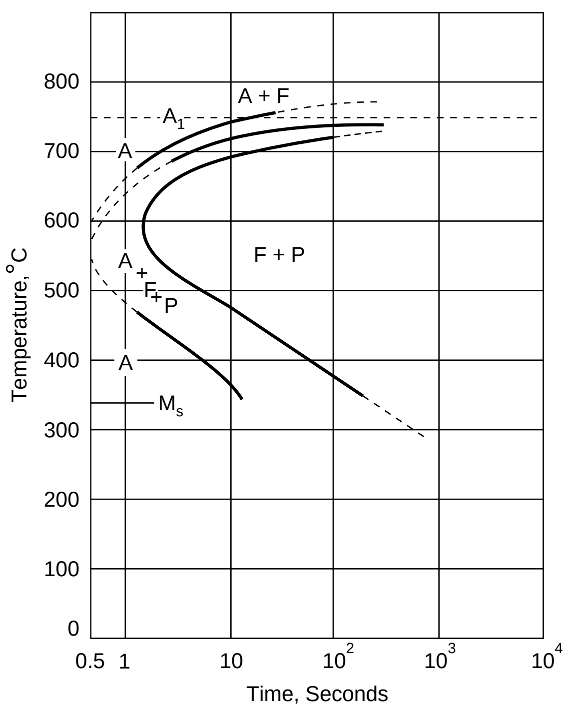


Figure 4.14 TTT diagram for hypoeutectoid steel.

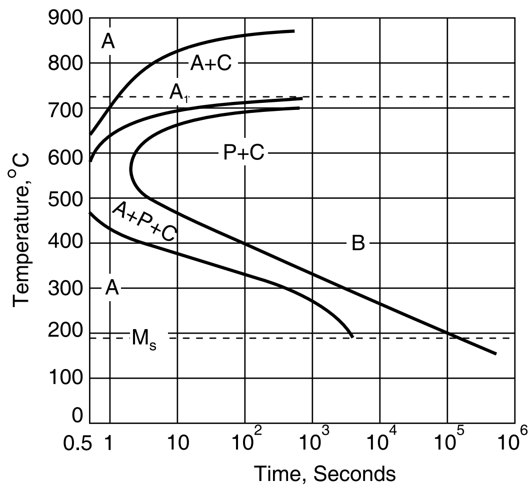


Figure 4.15 TTT diagram for hypereutectoid steel.

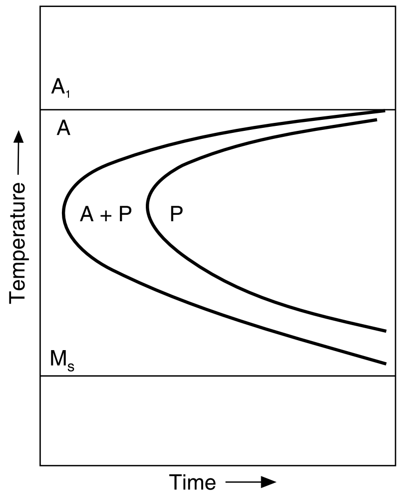
4.6.1 Effect of Alloying Elements on TTT Diagram

Almost all alloying elements, except cobalt, decrease both the tendency for and the rate of decomposition of austenite. The reason for this is obvious for austenite stabilizing elements. Ferrite stabilizers do the same job by forming carbides. Alloy carbides are more stable than cementite, and hence they retard the diffusion of carbon which in turn decrease the rate of decomposition of austenite. Strong carbide formers have more pronounced effect on the retardation of austenite decomposition than the weak carbide formers. Since pearlitic transformation involves diffusion of both carbon and metallic atoms (see Section 4.7), the effect of alloying elements is much more pronounced in pearlitic region. The effect is less pronounced in bainitic region as bainitic transformation (see Section 4.8) involves diffusion of carbon atoms only.

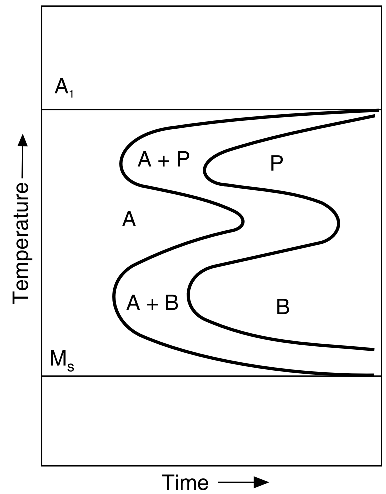
The TTT diagrams for alloy steels can broadly be classified into four types as shown in Figure 4.16. The first type of TTT diagram [Figure 4.16(a)] is similar to that of carbon steel. There is practically no difference in the pattern of austenite decomposition in the presence of non-carbide forming elements. However, in the presence of carbide forming elements, supercooled austenite decomposes to a mixture of ferrite and carbides rather than to an aggregate of ferrite and cementite.

The second type of TTT diagram [Figure 4.16(b)] differs from the remaining TTT diagrams as it consists of two minima with respect to the stability of austenite. The upper bay (at higher temperature) corresponds to the transformation of austenite to pearlite, whereas the lower bay corresponds to the transformation of austenite to bainite. Very few steels exhibit such a TTT diagram. The two types of TTT diagrams discussed above are, in general, observed for low alloy steels.

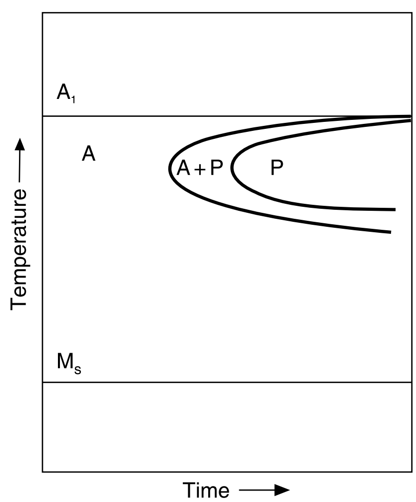
The third type of TTT diagram [Figure 4.16(c)] is peculiar in the sense that bainitic region is not present. This implies that bainite cannot be formed in such steels. Such a TTT diagram is obtained, in general, for high alloy steels, specially those in which the start of martensitic



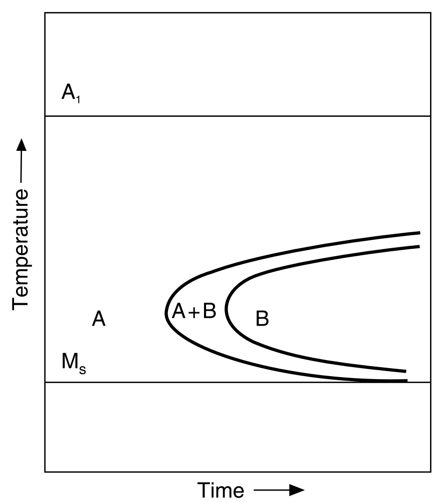
(a) with resemblance of plain carbon steel



(b) with both pearlitic and bainitic bays



(c) without bainitic bay



(d) without pearlitic bay

Figure 4.16 Various types of TTT diagrams for alloy steels.

transformation temperature has been shifted to sub-zero region. In such steels, stable austenitic structure is obtained at room temperature.

The fourth type of TTT diagram [Figure 4.16(d)] does not exhibit pearlitic bay. Here, under normal cooling conditions, either bainite or martensite is formed.

4.6.2 Continuous Cooling Transformation

The TTT diagrams have gained great importance from heat treater's point of view. This is due to the simple reason that these diagrams are extremely useful as they give information about the hardening response of steels and the nature of transformed products of austenite at varying degrees of supercooling. These diagrams have been of great practical importance to some special heat treatment processes such as austempering (see Section 5.7) and isothermal annealing (Section 5.2.2).

In practice, however, transformation during heat treatment occurs by continuous cooling, and not isothermally. Thus, TTT diagrams have limited applications. For most of the heat treatment processes, these diagrams are useful only qualitatively, and not quantitatively. A diagram, which can correlate transformation, temperature and time during continuous cooling, will be of real value to heat treaters.

Continuous cooling transformation (CCT) diagrams can be obtained by a technique which is similar to that for TTT diagrams except that, in the case of CCT diagrams, points of start and end of austenitic transformation are recorded on continuous cooling. For the construction of CCT diagram for a eutectoid steel, a large number of small samples are heated above the lower critical temperature (A_1) to get a completely austenitic structure. From this temperature, specimens are cooled at a constant cooling rate, and points corresponding to start and finish of pearlite are determined. By repeating the same process at various cooling rates, different sets of start and end points for pearlitic transformation are obtained. On joining start and end points, two curves, similar to those in TTT curves, corresponding to start and end of transformation, are obtained. Thus, a CCT diagram is obtained. The CCT diagram for eutectoid steel is shown in Figure 4.17.

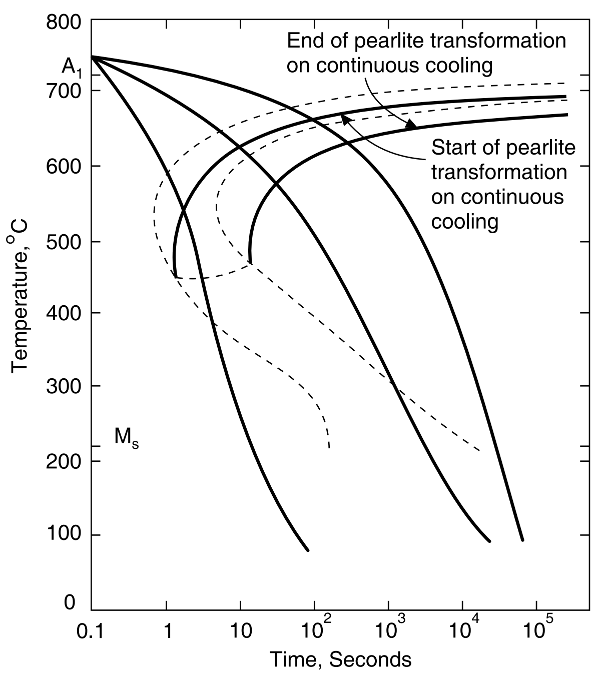


Figure 4.17 CCT diagram for eutectoid steel.