cooling that determines the resultant structure of the steel. The final structure is independent of the rate of heating, provided it has been slow enough for the steel to reach structural equilibrium at its maximum temperature. However, the subsequent rate of cooling, which determines the nature of the final structure, is critical and may vary between slow furnace cooling to sudden cooling by quenching in water.

**Annealing.** In steels, annealing usually means a heat treatment with furnace cooling from the austenitizing range (Fig. 3). Annealing is used to reduce hardness, obtain a relatively near-stable microstructure, refine grain size, improve machinability, and facilitate cold working. For hypoeutectoid steels (steels with a carbon content of less than 0.80%), full annealing consists of heating to 90 to 180 °C (50 to 100 °F) above the $A_t$ temperature, and for hypereutectoid steels (steels with a carbon content of more than 0.80%), heating above the $A_t$ temperature, followed by very slow cooling. Process annealing consists of heating steel to a temperature just below the $A_1$ eutectoid temperature for a short time. This provides stress relief, makes the steel easier to form, and is applied to low-carbon cold-rolled sheet steels to restore ductility. The temperatures used range from 550 to 650 °C (1020 to 1200 °F). Slow cooling is not essential for process annealing, because any cooling rate from temperatures below $A_t$ will not affect the microstructure or hardness. Although recrystallization can occur due to the stored energy from cold working, there are no phase changes, and the ferrite and cementite constituents remain the same throughout the process.

**Normalizing.** Steel is normalized by heating 160 to 200 °C (90 to 110 °F) into the austenite-phase field at temperatures somewhat higher than those used by annealing, followed by cooling at a medium rate. For carbon steels and low-alloy steels, normalizing means air cooling. Many steels are normalized to establish a uniform microstructure and grain size. The faster cooling rate during normalizing results in a much finer microstructure, which is harder and stronger than the coarser microstructure produced by full annealing. Steel is normalized to refine grain size, make its structure more uniform, make it more responsive to hardening, and to improve machinability. When steel is heated to a high temperature, the carbon can readily diffuse, resulting in a reasonably uniform composition from one area to the next. The steel is then more homogeneous and will respond to the heat treatment more uniformly. The properties of normalized steels depend on their chemical composition and the cooling rate, with the cooling rate being a function of the size of the part. Although there can be a considerable variation in the hardness and strengths of normalized steels, the structure usually contains a fine microstructure.

**Spheroidizing.** To produce a steel in its softest possible condition with minimum hardness and maximum ductility, it can be spheroidized by heating just above or just below the $A_1$ eutectoid temperature and then holding at that temperature for an extended period of time. Spheroidizing can also be conducted by cyclic processing, in which the temperature of the steel is cycled above and below the $A_1$ line. This process breaks down lamellar structure into small pieces that form small spheroids through diffusion in a continuous matrix. Surface tension causes the carbide particles to develop a spherical shape. Because a fine initial carbide size accelerates spheroidization, the steel is often normalized prior to spheroidizing.

**Hardening.** To harden a steel by quenching, it must be heated to a sufficiently high temperature to produce an austenitic crystalline phase and then quenched (quickly cooled). On quenching, the austenite phase transforms to martensite, which is a hard and strong but brittle crystalline phase. The quenched hardness depends on the chemical composition and the cooling rate during quenching.

Steels with higher carbon contents produce higher hardness, and the addition of alloying elements allows martensitic structures to develop through thicker sections. The carbon content is critical to the ability to harden steel. Because ductility decreases with increasing carbon content, the carbon content is held to approximately 0.45% in many engineering steels. However, when wear resistance is required, for example, in tool and die steels, it may be increased to over 1.0%. The addition of alloying elements allows thicker sections to be hardened or allows less drastic quenches. The effect of alloying elements and section size on hardenability can be illustrated by comparing the plain carbon steel 1040 with the alloy steel 4140 (Fig. 4). In this example, both the 1040 and 4140 steels contain nominal carbon contents of 0.40%, and yet, due to the alloying elements in 4140, the 4140 hardens to a much greater depth. However, as the diameter of a bar of 4140 is increased from 5 to 10 cm (2 to 4 in.), the depth of hardening