
3 Changes in the Deformation Structure Caused by Heating

A fraction of the energy expended during deformation is stored within the metal as crystal lattice defects, mainly dislocations. At ambient temperature, this causes *strain (work) hardening* of metals. The strain-hardened state of the deformed structure is thermodynamically unstable. The stored energy can be released and the original structure and properties can be partially or completely restored by heating (*annealing*) to elevated temperature through two main *softening mechanisms*: *recovery* and *recrystallization*.

The generalized term *recovery* is used to describe the changes of density and distribution of the deformation-induced defects of the crystal structure by heating at temperatures lower than the temperature of recrystallization, that is, before the appearance of new recrystallized grains. The stored energy is lowered by two principal recovery mechanisms:

- Annihilation of point defects (mainly excess vacancies) and dislocations of opposite sign
- Rearrangement of the dislocations into lower-energy configurations

The process of formation and migration of *low-angle boundaries* in the deformed metal during recovery is called *polygonization*. The enhanced annihilation and recombination of dislocations, assisted by increased temperature, results in a reduced number of dislocations in cell walls and a larger misorientation across the walls. Thus, the cell walls undergo a gradual transformation into low-angle boundaries.

The term *recrystallization* includes all structural processes involving migration of high-angle boundaries and the growth of new strain-free grains in the deformed structure. It results in an entirely changed microstructure: reduced dislocation density, strain-free grains with different size and shape, recrystallization texture, as well as in complete restoration of properties.

When heating a cold-deformed metal or alloy at temperatures higher than the recrystallization temperature, a *primary recrystallization* takes place. It starts by nucleation of new crystals of low internal energy (recrystallization nuclei) separated by high-angle boundaries from the surrounding deformed metal. It then proceeds by growth of the nuclei until new grains completely replace the deformed or recovered structure. In single-phase structures, the new grains nucleate in the regions of maximum accumulated energy, that is, the regions of maximum quantity of defects and lattice distortions. The grains can also nucleate at grain boundaries, large subgrains, deformation bands, or at particles of second phase, which have precipitated before or during the heating (*particle-stimulated nucleation*).

Since the recovery and recrystallization are driven by the reduction in the stored deformation energy, a relationship exists between both processes. Enhanced recovery may slow down the recrystallization by lowering the stored energy. On the other hand, if recrystallization has taken place in the deformed structure, no further recovery is possible. This “competition” between the two processes depends on the deformation temperature and ratio, the SFE, and the recrystallization temperature of the metal.

Grain growth is a process that involves migration of the high-angle boundaries of the recrystallized grains. It results in a *normal grain growth*. This process should not be confused with *secondary recrystallization* or *abnormal grain growth*, also known as coarsening, which leads to discontinuous growth of separate very large grains into the rest of the structure.

Hot deformation promotes recovery processes because they rely on thermally activated mechanisms. Two processes of “self-annealing” (metal softening) that can occur during deformation at elevated temperatures are *dynamic recovery* or *dynamic polygonization* (most distinctly seen in high-SFE alloys) and *dynamic recrystallization*. Which one of the specific mechanisms of dynamic polygonization will operate—formation of subgrains, growth of large subgrains by coalescence, rotation of subgrains—depends on both the temperature and the strain rate. The determining factors for the occurrence of dynamic recrystallization and the extent of dynamic softening are the nature of material (alloy composition and SFE value), the temperature, the amount of deformation, and the strain rate. Dynamic recrystallization can occur in commercial alloys such as austenitic-alloyed steels, heat-resistant nickel-based alloys, and brass during sufficiently high hot working.

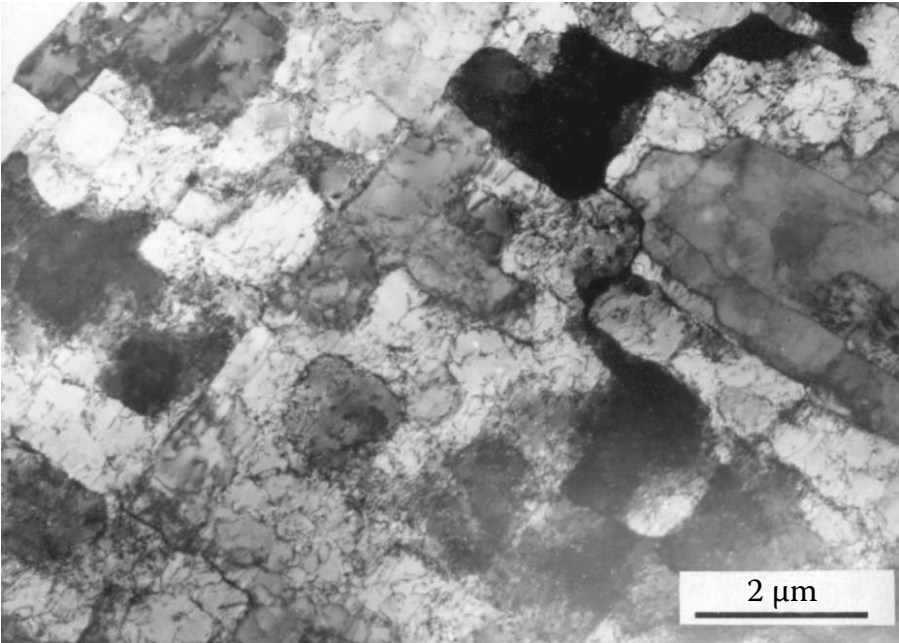


FIGURE 3.1

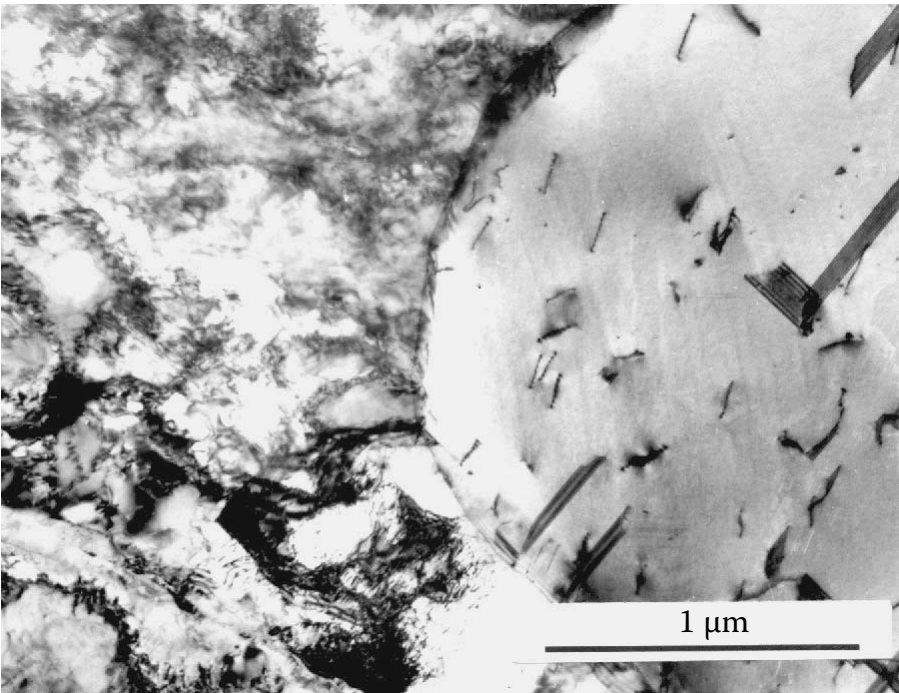


FIGURE 3.2

FIGURE 3.1 Annealing of cold-deformed metals results in the decrease of the number of dislocations in the cell's interior while the dislocation tangles in the cell walls change into more regular dislocation networks. The walls gradually transform into subboundaries, and the cells into subgrains free of dislocations. These microstructural features are the main indicators that polygonization has occurred.

Aluminum after 30% cold deformation followed by 5 min annealing at 200°C.

FIGURE 3.2 If the amount of cold deformation is low or the duration of annealing is short, recrystallization can occur only in some areas of the metal where the level of accumulated energy is higher. The new recrystallized grains of this *partially recrystallized structure* are surrounded by a deformed matrix.

Austenitic nitrogen steel Fe-18Cr-14Mn-0.6N after 50% cold rolling, followed by 30 min annealing at 900°C.

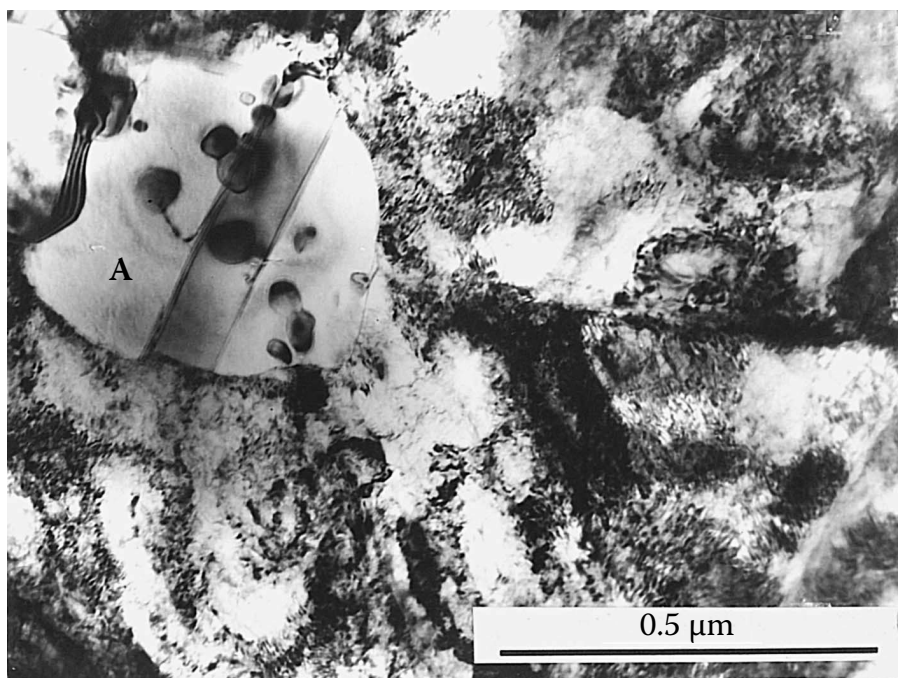


FIGURE 3.3 The nucleation of new grains very often occurs on particles of a second phase that existed in the deformed structure prior to annealing or that had precipitated before the start of recrystallization.

Austenitic nitrogen steel Fe-18Cr-14Mn-0.6N after 50% cold rolling, followed by 2 min annealing at 550°C. In the present case, recrystallization has started preferentially only in area A, where the first Cr_2N particles had precipitated, while no precipitation can be seen in the rest of the austenite, where the deformation structure remains unchanged. The incubation period for recrystallization was clearly longer than that for nitride precipitation.

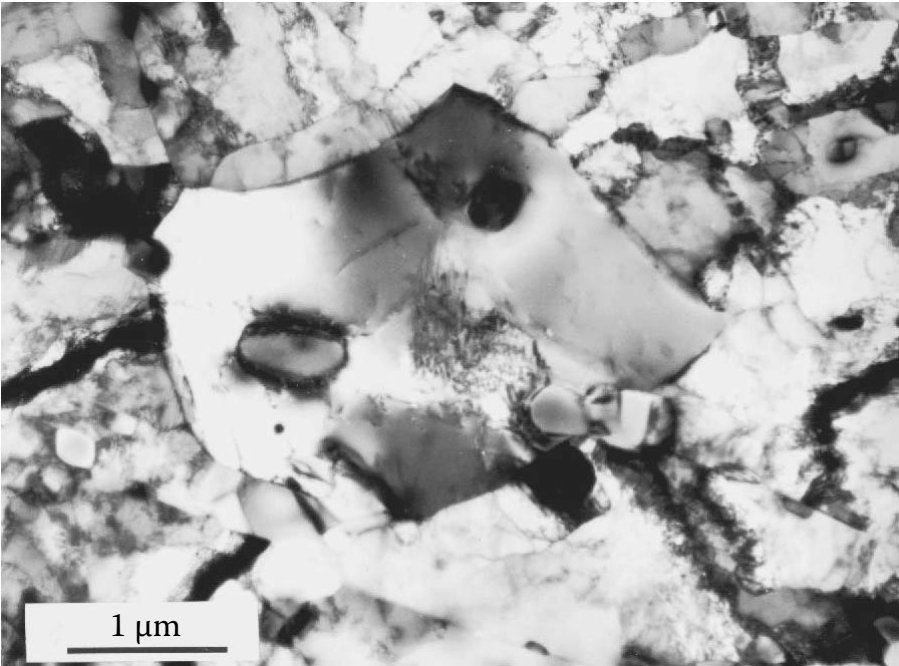


FIGURE 3.4

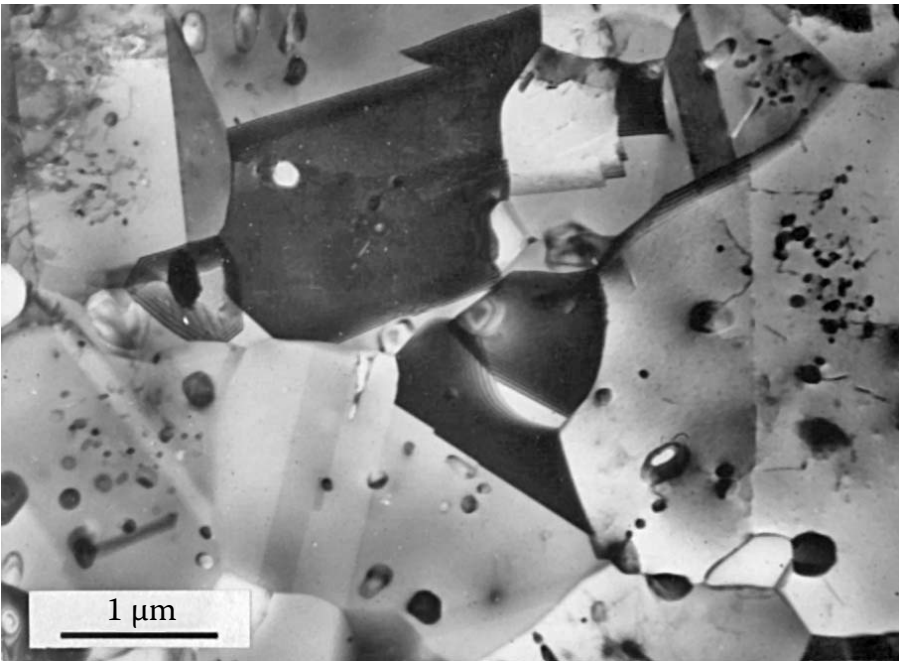


FIGURE 3.5

FIGURE 3.4 Recrystallization kinetics depends on both the size and the density of particles present in the material before annealing. Second-phase particles can serve as recrystallization centers (nuclei for new grains) only if their size exceeds some critical value specific to the given cold work reduction.

Austenitic nitrogen steel Fe-18Cr-14Mn-0.6N after 50% cold rolling, followed by 5 min annealing at 550°C. In this micrograph the Cr₂N particles have precipitated throughout the metal, but their size has reached the critical value only in the central part of the image where, as a result, recrystallization has started first. New grains of smaller size have nucleated later on the smaller particles. Polygonization commenced in the rest of the material in which no precipitation has occurred.

FIGURE 3.5 After nucleation, new recrystallized grains grow through migration of high-angle grain boundaries, a process driven by the remaining stored energy. When the annealing temperature is proper (different for the different alloys and dependent on the amount of prior deformation) and the annealing time is sufficient, the new grains totally consume the old deformed structure until the primary recrystallization is complete.

Austenitic nitrogen steel Fe-18Cr-14Mn-0.6N after 50% cold rolling, followed by 30 min annealing at 550°C. In this micrograph the primary recrystallization has finished, the size and shape of the fully recrystallized grains are now totally changed, and the structure is strain-free, with very low dislocation density.

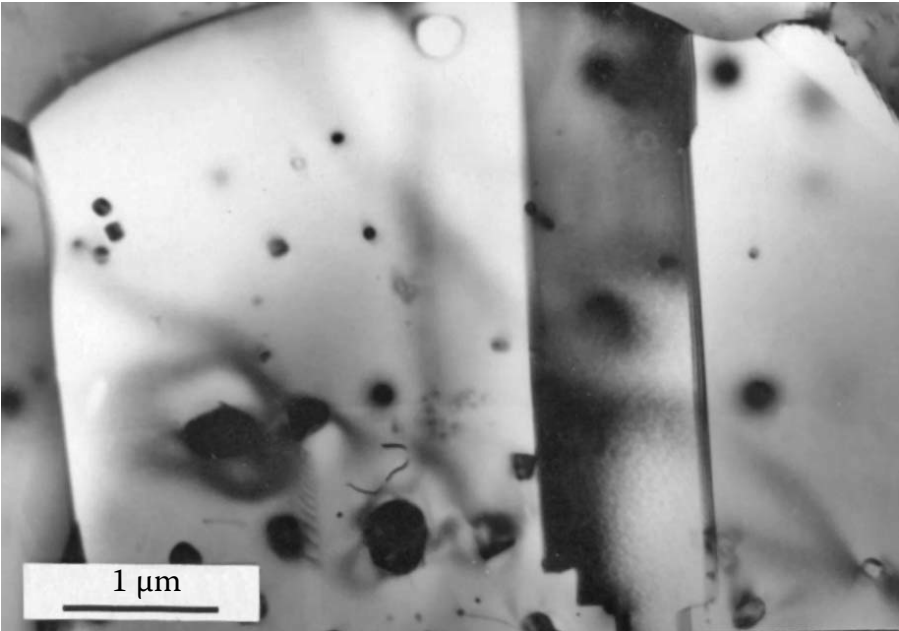


FIGURE 3.6

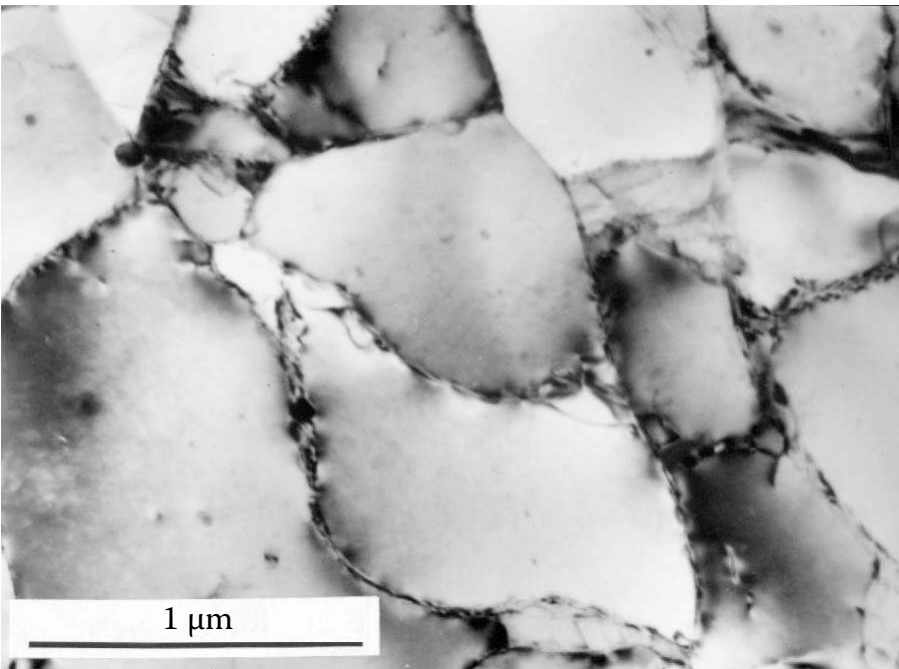


FIGURE 3.7

FIGURE 3.6 Keeping the primary recrystallized metal at a high temperature for a prolonged period of time results in normal growth of the new grains by migration of the highly mobile large-angle boundaries. It results in continuous increase of the mean grain diameter and reduction of the total number of grains. However, the crystallographic orientation and the location of some of the new grains in the structure appear to be more favorable for their growth. These grains can then grow to a larger size at the expense of their smaller-sized neighbors.

Austenitic nitrogen steel Fe-18Cr-14Mn-0.6N after 50% cold rolling, followed by 2 h annealing at 550°C. Note the annealing twin in the middle of the large grain shown; it is typical for the recrystallized structure of low-SFE metals.

FIGURE 3.7 The hot deformation of many high-SFE metals is usually accompanied by dynamic recovery. For example, during extrusion, forging, or hot rolling in commercially pure aluminum and aluminum alloys, a dynamic polygonization takes place.

Aluminum after 20% extrusion at 300°C. The polygonized substructure of the hot-deformed semifinished product is much more stable than the structure, produced by cold deformation.

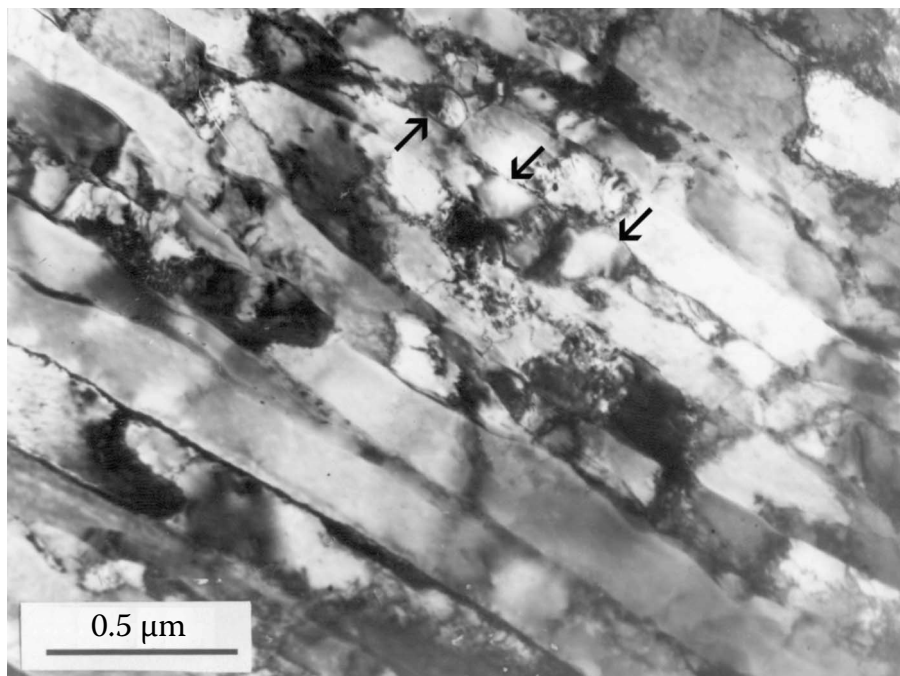


FIGURE 3.8 Dynamic recrystallization can occur in some alloys during severe, high-speed cold deformation. The signs of dynamic recrystallization can be observed only if the deformed material is rapidly cooled to prevent static recrystallization resulting from the heat generated by the intensive deformation process.

Copper after 75% cold extrusion. The small final cross-section of the extruded rod ensured rapid cooling. As a consequence, several dynamically recrystallized grains (shown by arrows) can be observed in the final structure.