2.11 Residual Stresses

Residual stresses may develop when workpieces are subjected to plastic deformation that is not uniform throughout the part; these are stresses that remain within a part after it has been formed and all the external forces (applied through tools and dies) are removed. A typical example is the bending of a metal bar (Fig. 2.30). Note that the external bending moment first produces a linear elastic stress distribution (Fig. 2.30a); as the moment is increased, the outer fibers in the bar reach a stress level high enough to cause yielding. For a typical strain-hardening material, the stress distribution shown in Fig. 2.30b is eventually reached, and the bar has now undergone permanent bending.

Let's now remove the external bending moment on the bar. This operation is equivalent to applying an equal but opposite moment to the bar; thus, the moments of the areas *oab* and *oac* in Fig. 2.30c must be equal. Line *oc*, which represents the opposite bending moment, is linear, because all unloading and recovery are *elastic* (see Fig. 2.3). The difference between the two stress distributions gives the residual stress pattern within the bar, as shown in Fig. 2.30d.

Note the presence of compressive residual stresses in layers *ad* and *oe*, and tensile residual stresses in layers *do* and *ef*. Because there are now no external forces applied to the bar, the internal forces resulting from these residual stresses must be in static equilibrium. It should be noted that although this example involves residual stresses in the longitudinal direction of the bar only, in most cases residual stresses are three dimensional and hence more difficult to analyze.

The removal of a layer of material from the surfaces of the bar, such as by machining or grinding, will disturb the equilibrium of the residual stresses shown in Fig. 2.30d. The bar will then acquire a new radius of curvature in order to balance the internal forces. Such disturbances of residual stresses cause **warping** of parts (Fig. 2.31). The equilibrium of residual stresses may also be disturbed by *relaxation* of these stresses over a period of time; see below.

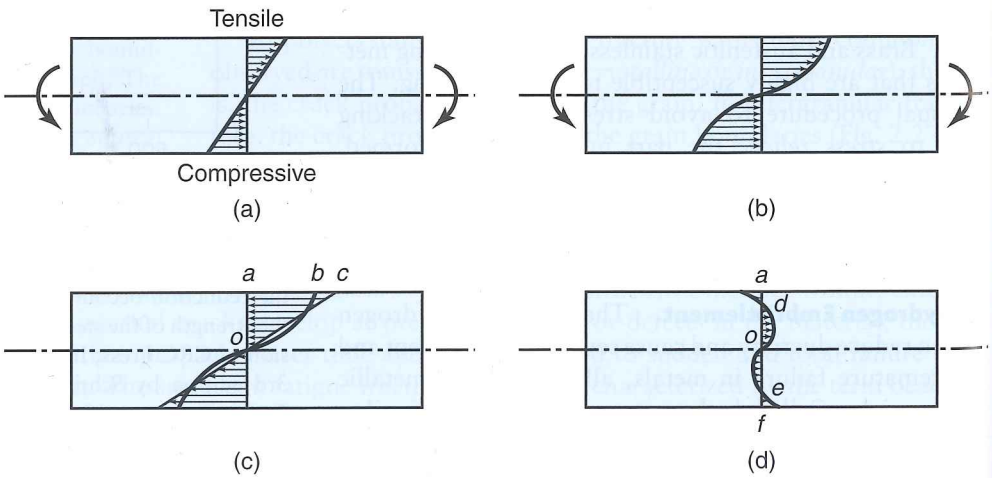

FIGURE 2.30 Residual stresses developed in bending a beam having a rectangular cross-section; note that the horizontal forces and moments caused by residual stresses in the beam must be balanced internally. Because of nonuniform deformation, especially during cold-metalworking operations, most parts develop residual stresses.

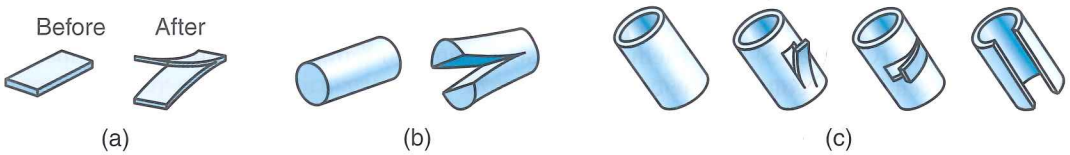

FIGURE 2.31 Distortion of parts with residual stresses after cutting or slitting: (a) flat sheet or plate, (b) solid round rod, and (c) thin-walled tubing or pipe.

Residual stresses can also be developed by *temperature gradients* within the part, such as occur during cooling of a casting or a hot forging. The local expansions and contractions caused by temperature gradients within the part will produce a nonuniform deformation, such as described in the permanent bending of a beam.

Tensile residual stresses on the surface of a part are generally undesirable, as they lower the fatigue life and fracture strength of the part. This is because a surface with tensile residual stresses cannot sustain additional tensile stresses (from external forces) as high as those that a surface free from residual stresses can. This reduction in strength is particularly characteristic of brittle or less ductile materials, in which fracture takes place with little or no plastic deformation preceding fracture.

Tensile residual stresses can also lead, over a period of time, to *stress cracking* or *stress–corrosion cracking* of parts (Section 2.10.2). Compressive residual stresses on a surface, on the other hand, are generally desirable. In fact, in order to increase the fatigue life of components, compressive residual stresses can be imparted to surfaces by such techniques as shot peening and surface rolling (Section 34.2).

Reduction and Elimination of Residual Stresses. Residual stresses can be reduced or eliminated either by *stress-relief annealing* (Section 4.11) or by a further *plastic deformation* of the part, such as stretching it. Given sufficient time, residual stresses may also diminish at room temperature, by *relaxation* of residual stresses. The time required for relaxation can be greatly reduced by raising the temperature of the workpiece.