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Residual Stresses in Metals

Residual stresses are locked-in stresses within a metal, even though it is free of external forces. Residual stresses arise when metal is plastically deformed and the deformation is not uniform throughout the entire cross-section of the metal. Plastic deformation occurs when the stress on a metal exceeds its yield strength. As a result of the non-uniform deformation, when the loads that caused the plastic deformation are removed, regions that have been plastically deformed prevent adjacent elastically deformed regions from complete relaxation of their elastic strains. These unrelaxed elastic strains are the source of residual stress.

Residual stresses can be tensile or compressive. In fact, tensile and compressive residual stresses co-exist within a component. Also, residual stresses can be harmful or beneficial depending on whether they are tensile or compressive. Tensile residual stresses at the surface of a component are normally harmful because they can lead to reduced fatigue resistance. Compressive residual stresses at the surface normally increase fatigue resistance.

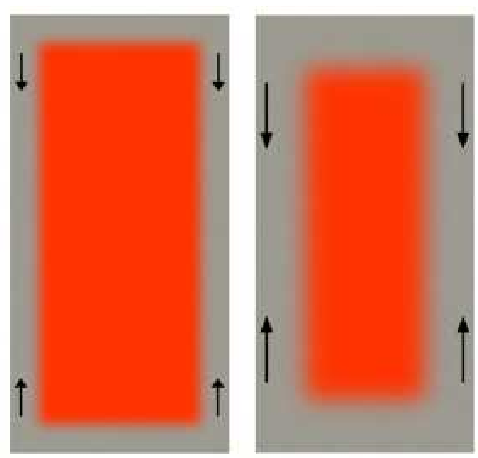
Causes of residual stress

Residual stresses have several causes, including the following:

- Non-uniform plastic deformation during mechanical processing, such as that during rolling, forming operations (bending or drawing), machining, and mechanical surface treatments (shot peening and roller burnishing).
- Phase transformations during cooling from elevated temperatures
- Non-uniform plastic deformation during heating or cooling
- Case hardening steel, such as carburizing and nitriding
- Various surface treatments (enameling, electroplating PVD and CVD coating)

This article discusses the first three causes.

Residual stress due to temperature variations

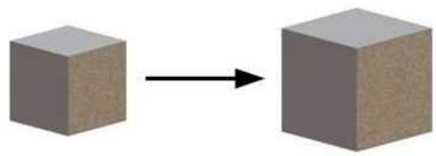


In parts cooled from elevated temperatures, residual stresses are caused by temperature variations in the metal during cooling. Cooling from elevated temperatures occurs during heat treating and welding.

Temperature variations in a metal during cooling from an elevated temperature result in localized variations of the amount of thermal contraction. Thermal contraction develops non-uniform stress due to different rates of cooling experienced by the surface and interior of the metal. During cooling, the outer portion of a component cools first and that portion of the metal contracts, compressing the hotter inner metal. As the inner portion of the component cools, the metal tries to contract, but is constrained by the already cooled outer portion. Consequently, the inner portion will have a residual tensile stress and the outer portion of the component will have a residual compressive stress.

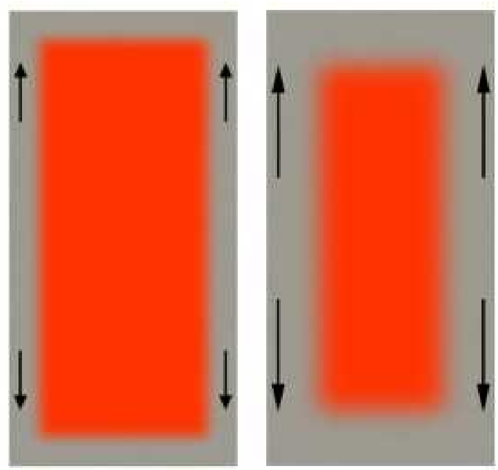
Residual stress due to phase transformation
A phase transformation is a change in the metallurgical phases present in an alloy. For example, the transformation from austenite to martensite in steel during through hardening is a phase transformation.

Residual stresses that arise during a phase transformation are due to the volume difference between the newly forming and initial metallurgical phases. The volume difference causes expansion or contraction of the metal.



For phase transformations that occur during cooling from an elevated temperature, such as in steel, the outer portions of the metal cool first and undergo the phase transformation first. If the volume of the new phase is different from the volume of the initial phase, then the transformed volume of metal will change as the new phase forms. As the interior of the metal cools it will also try to increase or decrease in volume. However, the volume change of the metal interior will be constrained by the cooler outer layer of metal that has already transformed.

When the volume of the new phase is larger than the volume of the initial phase, the center portion of the component will be under compression and the surface will be under tension. When the volume of the new phase is less than the volume of the initial phase, the center portion of the component will be under tension and the portion of the metal at and near the surface will be under compression.

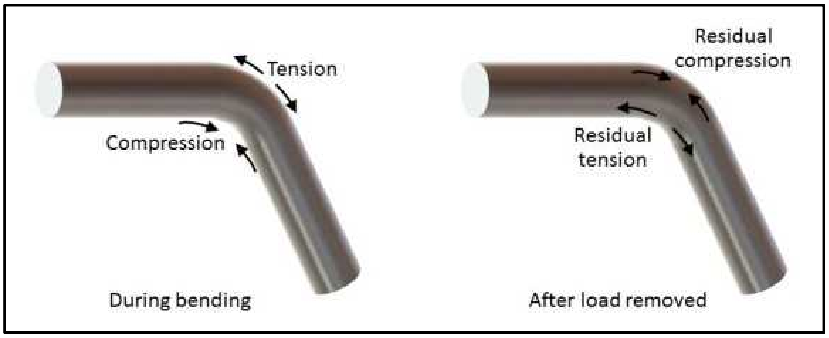


For example, during through hardening of steel during a quench, austenite transforms to martensite, with the martensite having a volume that is about 4% greater than austenite. During the quench, the steel at the surface transforms to martensite first since the surface cools the fastest. As the metal at the interior continues to cool, it transforms to martensite. However, its volume expansion is restricted by the hardened, cooler surface layer. This restraint causes the interior to be under compression and the outer surface under tension (see Metallurgy of Steel Through Hardening).

In some conditions, the volume changes can produce residual stresses large enough to cause plastic deformation, leading to component warping or distortion. With severe quenching the quenching stresses can be so large that they cause cracking.

Residual stresses caused by mechanical treatment

Residual stresses also arise when plastic deformation is non-uniform through the cross-section of an item being deformed such as during bending, drawing, rolling, and extruding. When a metal undergoes plastic deformation, a portion of the deformation is elastic (discussed in Tensile Testing). After the load causing the deformation is removed, the metal tries to recover the elastic portion of the deformation. However, the elastic recovery is incomplete because it is opposed by the adjacent plastically deformed material.



Consider a metal item that has been bent. Regions adjacent to the bend will have been only elastically deformed, and this region will try to recover, a phenomenon known as springback. After removing the external force, the regions which have been bent prevent the adjacent regions from undergoing complete elastic recovery to the non-deformed condition. These regions are left in a state of residual tension and the regions which were plastically deformed are in a state of residual compression.

In general, the sign of the residual stress produced by non-uniform deformation will be opposite the sign of the plastic deformation which produced the residual stress.

Effects of residual stress

Residual stresses can be beneficial or detrimental, depending on whether the stress is tensile or compressive. Tensile residual stresses can be large enough to cause component distortion or cracking. Also, fatigue and stress corrosion cracking require the presence of tensile stresses. Because residual stresses are algebraically summed with applied stresses, surface residual tensile stresses combined with an applied tensile stress can reduce the reliability of components. In fact, a residual tensile stress is sometime sufficient to cause stress corrosion cracking.

Surface residual compressive stresses are generally helpful because they reduce the effects of applied tensile stresses. In most cases, surface compressive stresses contribute to the improvement of fatigue strength and resistance to stress-corrosion cracking.

Controlling residual stress

Controlling the type and magnitude of residual stress is important for applications in which components will be exposed to fatigue or stress corrosion cracking conditions or if the residual stresses are large enough to cause component deformation or cracking. This can be achieved through mechanical treatment, stress relief heat treatment, control of heat treating processes, and alloy selection.

Mechanical treatments such as shot peening, light cold rolling, stretching, and small amounts of compressing are used to intentionally induce a compressive residual stress at the surface of a component.

Because metal yield strength decreases as its temperature increases, metals can be stress relieved by heating to a temperature where the yield strength of the metal is the same or less than the magnitude of the residual stress. At this temperature, the metal can undergo microscopic plastic deformation, thus releasing at least a portion of the residual stress. After stress relieving, the maximum residual stress that can remain is equal to the yield strength of the material at the stress-relieving temperature.

From a component processing perspective, residual stresses can be minimized by using reduced cooling rates to reduce temperature variations and allow for phase transformations to occur more uniformly throughout a componentõs cross-section. Also, alloys can be selected that alloy for slower cooling rates to be used, while still getting the desired phase transformations to occur. For example, for carbon steel components to be through hardened, low-alloy carbon steels enable the use of slower cooling rates compared to plain carbon steels.

Measuring residual stresses

X-ray diffraction is used for measuring residual stress nondestructively. With this technique, strains in the metalõs atomic crystal lattice are measured, and the residual stresses are then calculated based on the strain measurements.

Bibliography

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