Stress Relief
by Daniel H. Herring

Stress relief is a heat treatment process that relies on slow cooling to achieve its desired effect, and is influenced by a number of factors including the internal stress induced into the parts from the various manufacturing methods (e.g. bending, shearing, forging, sawing, machining, grinding, milling, turning, welding, etc.) and prior processing. The application end use ultimately defines the allowable stress state. So how does one perform a stress relief operation?

Processes which depend on slow cooling (e.g. annealing, normalizing, stress relief) do so for a number of reasons; to relieve stresses, improve chemical homogeneity, soften a material for subsequent operations (e.g. machining), refine grain size and for such reasons as embrittlement relief or magnetic properties. As a general rule, the larger or more complex the part, the greater the amount of internal stress present.

Stress relief can be differentiated from other slow cooling processes in that it is most often performed below the lower critical temperature (Ac1). Time at temperature depends on such factors as the complexity of the part and enough time must be allowed in order to achieve the desired reduction in residual stress level. Following stress relief, the steel is cooled at a sufficiently slow rate to avoid formation of or reintroduction of excessive residual thermal stresses. No microstructural phase changes occur during the stress relief process.

How Slow, is Slow?
Stress relief most often requires a “still air cool” so as not to reintroduce stress into a material, but what does this really mean? A still air cool (quench) can be defined as cooling at a rate of 22 °C (40 °F) per minute or slower to 593 °C (1100 °F) and then at a rate of 8 °C (15 °F) - 14 °C (25 °F) per minute from 593 °C (1100 °F) to 150 °C (300 °F). Below 150 °C (300 °F) any cooling rate may be used.

How Do We Perform a Stress Relief Operation?
For carbon steels, stress relief operations are typically performed at 40 °C (105 °F) - 75 °C (165 °F) below the lower critical temperature, that is in the range of 500 °C (930 °F) - 650 °C (1200 °F). It is also important to understand that the elimination of stress is not instantaneous, being a function of both temperature and time for maximum benefit. Typically one (1) hour per 25 mm (1 inch) of maximum cross sectional area (once the part has reached temperature) is required. After removal from the furnace or oven, the parts are air cooled in still air. Rapid cooling will only serve to reintroduce stress and is the most common mistake made in stress relief operations. This cycle is estimated to remove more than 90% of the internal stresses. Stress relief on alloy steels is often done at (slightly) higher temperatures.

For tool steels the process is similar; it is common to perform a stress relief operation in the temperature range of at 500 °C - 550 °C (925 °F – 1025 °F) allowing the parts to slowly cool to room temperature before subsequent operations.

For stainless steels the situation is more complex. Stress relief is done in the range of 290 °C - 425 °C (550 °F - 800 °F), which is below the sensitization range. The operation depends on the form of the material, the operation being performed (e.g. machining) or if a completed assembly is to have a stress relief performed on it.

Poor Man’s Stress Relief
In hardening, rapid cooling/quenching alone or in combination with pre-existing internal stresses can result in unwanted distortion, brittle fracture, and if near welds in certain grades of metal, stress corrosion cracking. For this reason a number of heat treaters introduce a “stress relief hold” during hardening or case hardening treatments. This involves heating of a workload to an intermediate temperature, in the range of 538 °C (1000 °F) - 705 °C (1300 °F) and soaking for a period of time equivalent to one (1) hour per 25 mm (1 inch) of maximum cross sectional area. The idea is to allow for stress relaxation so that more predictable dimensional change occurs on quenching.

Stress Relief of Springs
Stress relief is one of the most common heat treating processes used in spring manufacturing as well as the manufacture of other wire formed products. Drawing, forming and machining induce stresses in all fastener and other wire products. These stresses can cause loss of tolerance, cracking and distortion and contribute to in service failures. For these reasons stress relieving is often necessary and in many cases, mandatory.

In addition to removing stresses, stress relief

![Effects of Recovery and Recrystallization on Grain Structure](image)

Figure 1

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<th>Residual stresses</th>
<th>Strength, hardness, ductility</th>
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Temperature
returns the material to a strength level approximately equivalent to where it was prior to forming. Studies have shown that the interstitial elements pin the lattice defects in the atomic structure of the metal, resulting in this increase in mechanical strength.

To completely eliminate residual stresses in helical springs, for example, the material must be heated high enough to fully recrystallize. This is not practical in spring manufacturing since the recrystallization process significantly reduces the material’s strength and, therefore, its usefulness in spring applications. On the other hand, an elevated temperature recovery process (i.e. stress relief) can eliminate the majority of residual stresses without significantly deteriorating the material’s strength [Fig. 1]. The temperature required to accomplish the recovery process depends on the material type and processing history [i.e. carbon steel vs. alloy steel, cold drawn vs. oil tempered, etc.] The SMI Encyclopedia of Spring Design provides recommendations for proper recovery.

Temperature, time, and temperature at temperature are key process variables and these have been documented elsewhere\(^5\). In general, heating steel to a temperature of about 750 °C (1382 °F) below the transformation temperature (Ac1) for about one hour (or until the entire part reaches the temperature), will allow for the removal of most internal stresses. Typical temperature ranges are:

- 550 °C - 650 °C (1025 °F - 1200 °F) for unalloyed and low-alloy steels;
- 600 °C - 700 °C (1115 °F - 1300 °F) for hot-work and high-speed tool steels.

The results of the stress relieving process are expressed by either the Holloman-Jaffe parameter, which is a measure of the thermal effect of the process or the Larson-Miller equation (Equation 1).

\[ (1) \ P = T [C + \log t] \times 10^{-3} \]

where \( t \) is the time (in hours) at temperature \( T \) (in °K) and the value for the composition dependent constant \( C \) is calculated from a separate equation (Equation 2).

\[ (2) \ C = 21.3 - (5.8 \times \% \text{Carbon in the steel}) \]

For many alloy steels little or no stress relief occurs at temperatures less than approximately 260 °C (500 °F) while approximately 90% of the stress is relieved by 540 °C (1000 °F). The maximum temperature for stress relief is limited to 300 °C (575 °F) below the tempering temperature used after quenching from the hardening process. After removing from the furnace or oven, the wire must be cooled in still air. If cooled in any other manner, stresses are reintroduced into the part.

Many other severely cold worked or bent shapes can be heated between 205 °C (400 °F) - 425 °C (800 °F) for a relatively short time to help reduce internal stresses. Alternative stress relief processes [e.g. vibratory stress relief, rapid tempering/stress relief] are covered in the references \(^4\) \(^7\) \(^8\).

As an example, when wire is coiled into a compression spring, the steel on the inside of the coil is upset and becomes shorter due to plastic deformation and the residual stresses on the inside of the spring reduce the fatigue strength. Stress relief can be used to reduce these residual stresses. The magnitude of the residual stresses that are formed is dependent on the tensile strength of the steel wire. The amount of stress relief after coiling as a function of temperature for a CrV and CrSi wire. Typically, the CrSi wire exhibited approximately 40% greater residual stresses than the CrV wire. The residual stress as function of distance from the surface for CrV and CrSi wire after stress relieving [Fig. 2]. In addition, it was reported that the negative effects of residual stresses due to coiling were eliminated; increased residual tensile stresses resulted in improved fatigue strength.

### The Final Word

The influence of internal stress can be positive or negative, which means that one must understand the design application in order to apply the proper stress relief operation (at low or high temperature). In lightly stressed parts where dimensional tolerances are not critical, the presence of internal stress is not as great a concern as a highly stressed component that must hold dimensional stability over time or where the service application is such that excessive distortion or even fracture may occur.

### References

8. Grenier, Mario and Gingras, Roger, Rapid Tempering and Stress Relief Via High-Speed Convection Heating, Industrial Heating, May 2003.