# *Processing Effects on Residual Stress*

by Robert Stone

The goal of this paper is to address three key questions. First, what are residual stresses? Second, what causes them? And third, are they good or bad in terms of performance of springs? The first question will be addressed by beginning with some rudimentary definitions and discussion. The second will be addressed with a process-by-process evaluation of spring manufacturing. Each process will be evaluated for its contribution to the final product's residual stress state. The third question will be an expansion of the second, linking the process-induced residual stresses to the applied stresses and drawing conclusions as to whether performance will be enhanced or degraded for various types of springs.

## What are Residual Stresses?

The simplest definition of residual stresses is as follows: stresses that remain within a part after it has been deformed and all external forces have been removed[1]. More specifically, the deformation must be non-uniform across the material cross-section in order to give rise to residual stresses. The deformation can result not only from forming operations but also from thermal processes. Phase transformations during heat treating are known to induce sufficient strain to result in plastic deformation, thereby giving rise to residual stresses.

Take the example of a simple beam in bending shown in Figure 1[2]. While deflection is low, the entire beam behaves elastically. Tensile and compressive stresses develop linearly as the distance from the neutral axis increases to the beam's outer fiber as in Figure 1(a). As the deflection builds, the outer fibers will reach the yield point and plastic deformation will begin. Under further deflection, the depth of material experiencing plastic deformation grows while the core of the beam continues to behave elastically as in Figure 1(b). When the load is released as in Figure 1(c), the release of elastic strain energy allows the beam to straighten – to a point. The material that had been plastically deformed will not return to the same original length since it has been stretched or compressed, depending on whether the applies stress was tensile or compressive. The final result will leave the outer fibers in residual stress opposite in direction to the original applied stress as in Figure 1(d). When subsequent elastic stresses are applied, the starting point for the loading is the final residual stress state (Figure 1(d)) as opposed to the original unstressed condition. If the subsequent loading is in the same direction, the net stress on the upper fiber will have been reduced by the amount of the residual stress. On the other hand, if the subsequent loading is in the opposite direction, the net stress will increase by the amount of the residual stress. Therefore, the product application plays a significant role in determining whether or not a particular residual stress state is an improvement or detriment.

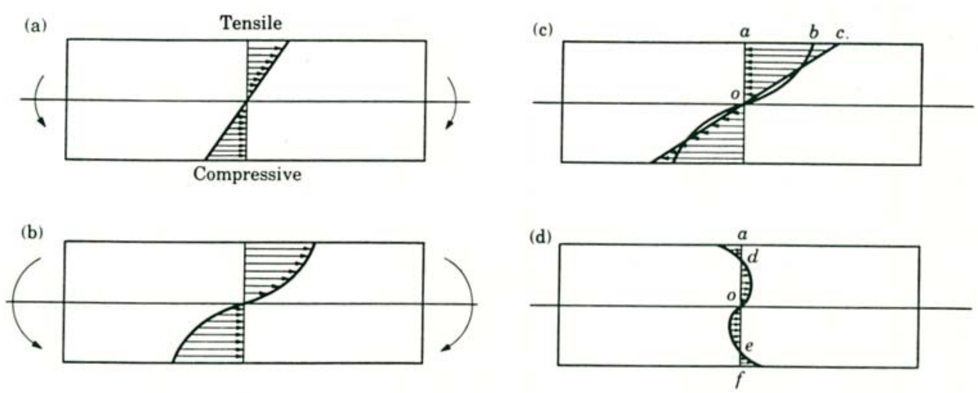


Figure 1. Residual stresses developed in bending a beam made of an elastic strain-hardening material. Note that unloading is equivalent to applying an equal and opposite moment to the part, as shown in (b). Because of nonuniform deformation, most parts made by plastic deformation processes contain residual stresses. Note that the forces and moments due to residual stresses must be internally balanced.

## What Impact does Each Manufacturing Step Have?

This section will discuss the most common processes in helical spring production. In general, they are discussed in the typical spring manufacturing sequence; however, stress relieving will be discussed first since it may be applied numerous times during the manufacture of a spring.

- **Stress Relief**

To completely eliminate residual stresses through thermal processing requires that the material be heated sufficiently to fully recrystallize. This is not practical for the spring manufacturer 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 can eliminate the majority of residual stresses without significantly deteriorating the materials strength. Please see Figure 2[3]. This recovery process is what is commonly referred to as stress relief in the spring industry. 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.) Sound recommendations for proper recovery are provided in the new SMI Encyclopedia of Spring Design[4].

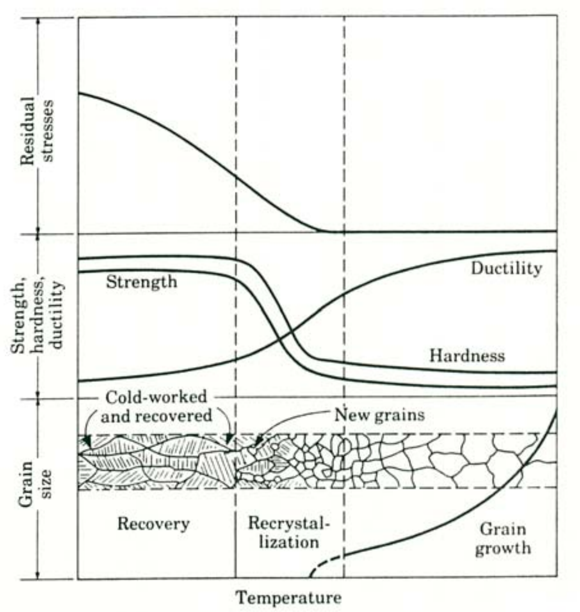


Figure 2. Schematic illustration of the effects of recovery and recrystallization on grain structure. Note the formation of small strain-free grains during recrystallization.

- **Wire Manufacture**

Even before the raw material reaches the spring manufacturing plant, residual stresses may be present in the wire. Cold drawing wire induces non-uniform deformation across the wire section. This variation in strain leads to residual stresses as is shown in Figure 3(a)[5]. Note that at the surface residual stresses are oriented both in the longitudinal and transverse (hoop) directions. Depending on the degree of reduction in area of the drawing pass, the residual stresses at the surface can be either tensile or compressive as is shown in Figure 3(b). In general, cold drawn spring wire is not stress relieved by the wire producer prior to shipment.

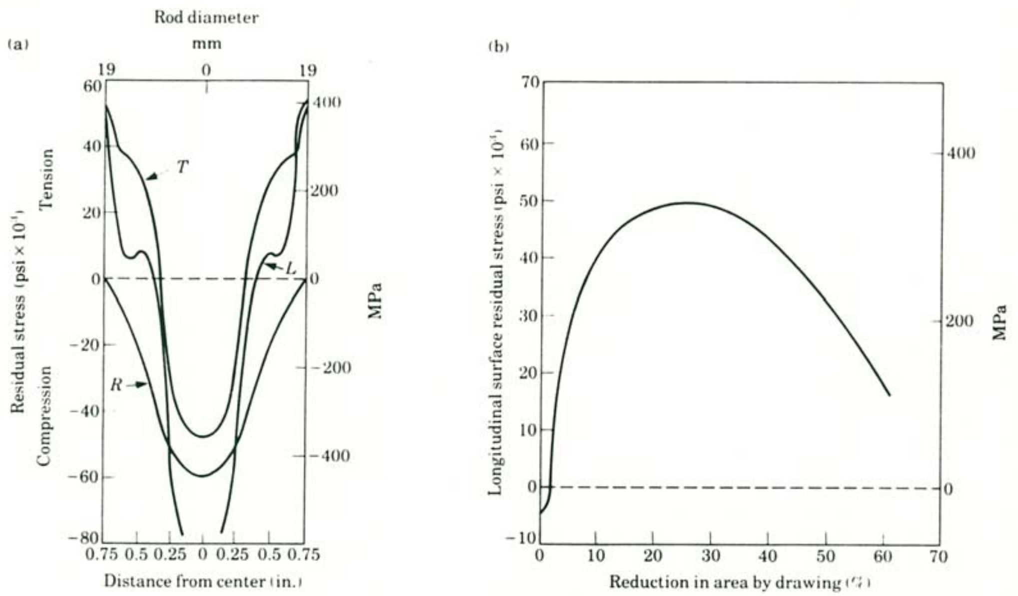


Figure 3. (a) Residual stresses in cold-drawn AISI 1045 carbon steel round rod. (b) Surface residual stress as a function of reduction by drawing. Note that very light reductions induce compressive surface residual stresses.

Oil tempered wire is also subject to residual stresses. During the quenching process, steel transforms from austenite at high temperature to martensite at the lower temperature. This involves a re-ordering of the atoms in the crystal lattice to less efficient packing, effectively making the steel expand. Since the wire is quenched in oil, the outer surface cools fastest while the core cools more slowly. This difference can give rise to significant tensile residual hoop stresses on the surface of the wire. If the stresses are sufficiently high, these hoop stresses can initiate longitudinal cracks in the brittle untempered martensite. These are commonly known as quench cracks. Tempering the wire following quenching provides sufficient stress relief that quenching residual stresses usually do not significantly impact subsequent spring manufacturing processes.

- **Coiling**

A single point coiler essentially places wire in three-point bending. At the location where the bending moment is greatest, the wire will behave much like the simple beam in Figure 1. While torsion deformation is taking place on other axes as a result of the pitch introduction, the degree of plastic deformation is negligible when compared to the bending involved in forming straight wire to the desired spring diameter. Essentially, the coiling process places the material on the inside diameter of the spring in significant tensile residual stress. Conversely, the material on the outside diameter is in compressive residual stress. Neglecting the minor torsional contribution, the tensile and compressive residual stresses are oriented along the wire axis. The magnitude of residual stress at the surface increases as spring index decreases.

- **Grinding**

There are multiple processes by which grinding can induce residual stresses in springs. Improper selection of process parameters (e.g. wheel grit and compound, wheel speed, workpiece pressure against wheel, etc.) can give rise to terrific shear stresses very near the surface. These can easily induce tensile residual stresses at the surface. Since the spring orientation to the grinding wheel is often not held constant, predicting the orientation of this residual stress is impossible.

Another mechanism has to do with excessive heat buildup during grinding. It is possible for localized phase transformations to take place, resulting with small regions of untempered martensite at or very near the surface following grinding. The combination of high residual stresses with extremely brittle untempered martensite makes this a phenomenon well worth avoiding.

In both of these cases, the resulting residual stresses are considered detrimental. Since the stress state at or near the ground surface is not generally considered during the design phase, further discussion is not warranted in this paper.

- **Shot Peening**

Shot peening is a widely utilized process that generally improves fatigue life by inducing compressive residual stresses at and very near the part surface. In this process, plastic deformation takes place by impacting the surface with small, hard particles. The compressive residual stresses result from the bulk of the surrounding elastic material attempting to force the impacted material back to its original location. The residual stresses resulting from the process are dictated by shot size, hardness, and velocity. The depth of the compressive layer is typically one-quarter to one-half the diameter of the shot used. Resulting compressive residual stresses can reach as high as one-half the base material's yield strength[6]. This process is one of very few that can create a triaxial residual stress state, meaning that compressive residual stresses are present in the longitudinal, transverse (hoop), and radial directions. While radial residual stresses may not be significant to a spring manufacturer, the longitudinal and transverse residual stresses are essentially equal in value.

- **Preset**

Presetting of helical compression springs consists of compressing the spring to a point at which plastic deformation occurs. Provided stress levels are sufficiently high to induce plastic deformation, this is typically carried out by compressing springs to or very near solid height. As a minimum, the springs should be compressed below the minimum operating height. This compression places the wire in torsion sufficient to induce plastic deformation in the outer fibers. The residual stress state is not uniform around the wire cross-section because of the curvature of the wire alters the stress state from pure torsion during the compression. Two examples of typical residual stress states are shown in Figure 4[7]. In the figure, note the impact that spring index has on the magnitude of residual stress and the relationship between residual stresses on the spring inside and outside diameters. Since the residual stress is in torsion, there will be a tensile component and a compressive component each at 45° to the wire axis. As was the case with the simple beam in bending example, the orientation of the residual stress is opposite to the orientation of the applied stress. Therefore, if loads in service are applied in the direction of the presetting load, the residual stresses from presetting will provide a net reduction in total stress under the service load.

## What are the Net Effects?

Whether or not a particular residual stress is beneficial depends on the applied stress in service.

Fatigue cracks nearly always initiate and propagate normal to applied tensile stresses. To improve fatigue life, residual stresses that are oriented such that they reduce the principal applied tensile stress will provide the best benefit. Residual stresses operating on orientations near the applied stress orientation will still have an impact; although the impact diminishes as the angle between the applied and residual stress increases. For load stability, residual stresses tending to reduce the overall stress state will provide the maximum benefit. Perhaps it will be more meaningful to consider various spring types and evaluate whether or not a process' induced residual stresses will be beneficial or detrimental to serviceability.

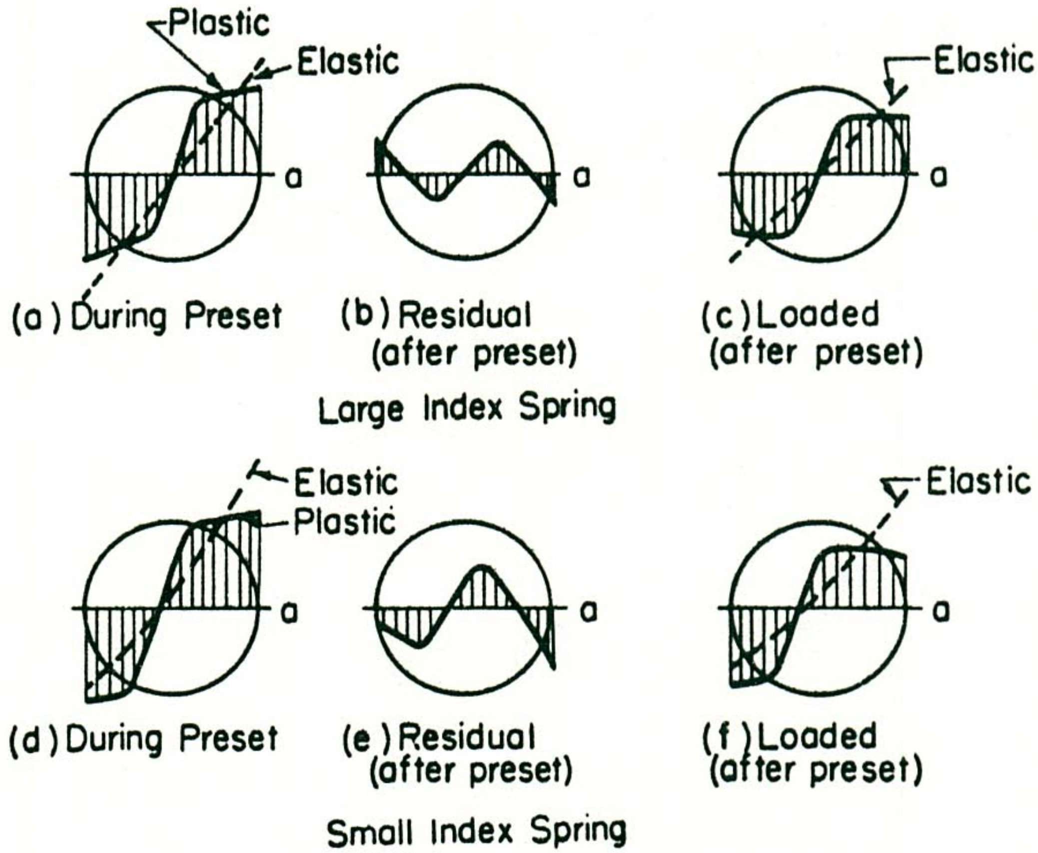


Figure 4. Plastic, residual, and load stress distribution in helical springs of small and large index *D/d* (inside of coil is at *a*).

- **Helical Compression Springs**

The primary loading of helical compression springs is in torsion. Again, this means that the wire will see tensile stresses oriented 45° to the wire axis and compressive stresses oriented 90° to the tensile stresses. The tensile applied stress has components in both the longitudinal and transverse (hoop) directions. Therefore, a helical compression spring will be adversely impacted by both longitudinal and hoop residual stresses from wire drawing, hoop stresses from oil quenching, and tensile bending stresses on the inside diameter from coiling. Elevated temperature relaxation following coiling should minimize any effect these processes have on the final product performance. Conversely, a helical compression spring will benefit from the triaxial compressive residual stresses from shot peening and the torsional residual stresses from presetting.

- **Helical Extension Springs**

The primary loading of helical extension spring bodies is in torsion. The loops are in principal bending. Both the body and end loops will be adversely impacted by longitudinal residual stresses from wire drawing and tensile bending stresses on the inside diameter from coiling. Hoop stresses from wire drawing or quenching will be detrimental to the body but will have minimal impact on the end loops. Elevated temperature relaxation following coiling should minimize any effect these processes have on the final product performance; however, care must be taken to provide a proper balance between residual stress relaxation and reduction of initial tension.

Case Study – In one particular extension spring application, stress relieving wire prior to spring coiling significantly improved the spring manufacturer's ability to control spring force output. The stress relieving operation may have been reducing variation in the residual stress state of the final spring, thereby improving product consistency.

- **Torsion Springs**

The fact that torsion springs are loaded in bending complicates the evaluation of residual stresses somewhat. The key difference in whether a residual stress is beneficial or detrimental depends on whether the spring will be loaded in a manner to tighten or loosen the coils. Table 1 provides an overview of residual stress types and their impact based on loading type.

Table 1. Process-Induced Residual Stress Benefits for Torsion Springs

| | | Torsion Load Application | |
|---|---|---|---|
| **Process** | **Residual Stress** | **Tighten Coils** | **Loosen Coils** |
| **Cold Drawing Wire** | Longitudinal and Transverse (Hoop) Tension | Bad on OD | Bad on ID |
| **Oil Tempering Wire** | Transverse (Hoop) Tension | Negligible | Negligible |
| **Coiling** | Longitudinal Tension on ID, Longitudinal Compression on OD | Beneficial | Detrimental |
| **Grinding** | N/A | N/A | N/A |
| **Shot Peening** | Triaxial Compression | Detrimental if peened on ID, Potentially Beneficial on OD | Beneficial |
| **Preset** | N/A | N/A | N/A |

## Summary

Residual stresses are created and minimized through a variety of processes in spring manufacturing. Whether or not a particular residual stress type is beneficial depends on the product type and its application. Spring designers must take care to understand these differences and select manufacturing processes that contribute positively to spring performance.

## References

1. Kalpakjian, S., *Manufacturing Processes for Engineering Materials*, Addison Wesley, Reading Massachusetts, 1985, p. 66.
2. ibid, p. 68.
3. ibid, p. 113.
4. Sebastian, D. et al., *Fundamentals of Spring Design*, SMI, Oak Brook Illinois, 2000, p. SM-5.
5. Kalpakjian, S., *Manufacturing Processes for Engineering Materials*, Addison Wesley, Reading Massachusetts, 1985, p. 380.
6. Hertzberg, R., *Deformation and Fracture Mechanics of Engineering Materials*, John Wiley & Sons, New York, 1983, p. 481.
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