James Pineault and Mohammed Belassel | *PROTO Manufacturing*

Quantifying Residual Stress in Shot-Peened Springs

RESIDUAL STRESSES in manufactured components, assemblies, and structures can improve or diminish their service life, and this is especially true for coil springs. Because fabrication and forming operations often produce surface conditions that debit the fatigue life of production springs, peening processes are often performed to improve the surface condition and fatigue resistance of coil springs. As there are several different types of coil springs, it follows that each type may experience failure at different locations based on how they are manufactured and used. In compression springs, tensile residual stress at the inner diameter (ID) is the most common source of failure. On the other hand, torsion springs tend to fail at the outer diameter (OD), and tension springs typically fail at the inner radius of their hook. These variation in failure locations make it important to understand the residual stress present in a particular spring before and after shot peening.

When a spring wire is formed into a coil (see Figure 1) and then heat treated or heat set to obtain specific performance characteristics, a complex residual stress field is generated in the spring. Even if the spring wire is stress free prior to formation of the coil, significant tensile stresses typically reside on the ID of the set coil. As shown in Figure 2, when a stress-free wire (shown in green) is bent elastically (blue), the ID is in compression, and the OD is in tension. If the bending load is then removed from the wire, it returns to the stress-free state (green). However, if the wire is bent elasto-plastically (shown in red) beyond the yield strength of the material to form a permanent spring coil set, the wire will only partially spring back when the applied bending load is removed and will remain with the intended spring coil set. In this case, the resultant stress introduced into the part will be tensile on the ID and compressive on the OD (shown in black). Moreover, as Figure 2 demonstrates, the tensile residual stresses will also be a maximum on the ID. Since total stress is equal to residual stress plus applied stress, the compressive loading of a spring in service creates the perfect conditions for its premature failure under fatigue loading (i.e., adding tensile applied stresses to an already tensile residual stress state).

To mitigate this condition, shot peening is often applied since it is a convenient, cost-effective, and potent method of imparting compressive residual stresses near the surface of a spring. As shown in Figure 3, when an as-formed coil (black) is shot peened, a compressive residual stress layer is imparted near the surface around the circumference of the spring wire (purple). These residual stresses are redistributed, generating additional balancing tensile residual stresses below the surface, where they are more benign. This is an example of how a component's tensile stress can be redistributed into areas that will not be detrimental to the part. The compressive cold worked layer will enhance fatigue resistance through

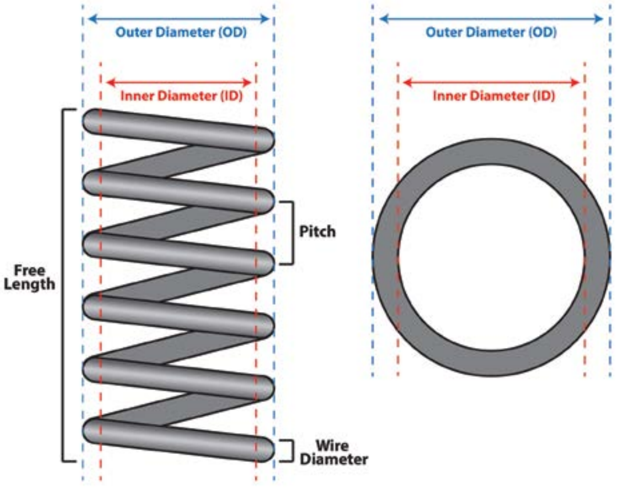


Figure 1

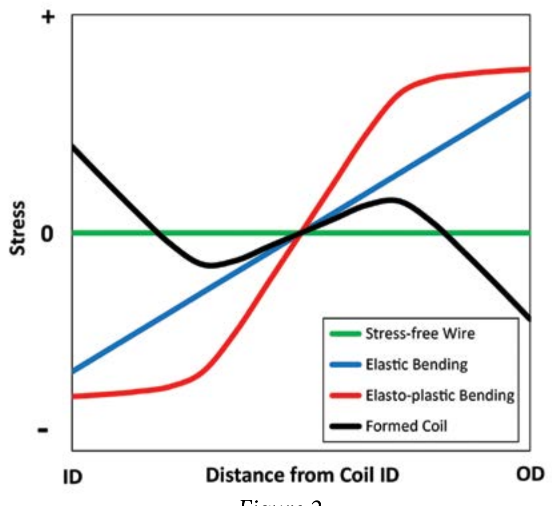


Figure 2

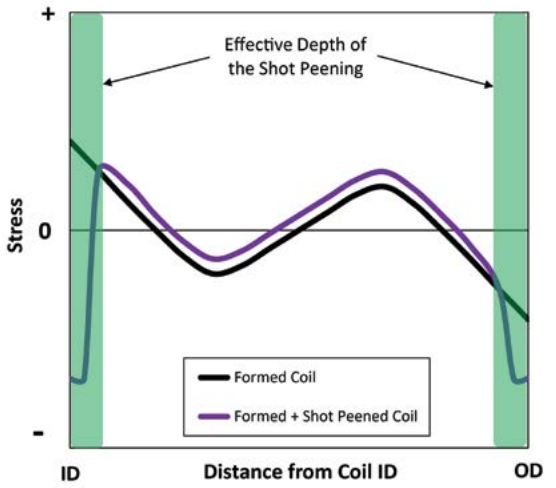


Figure 3

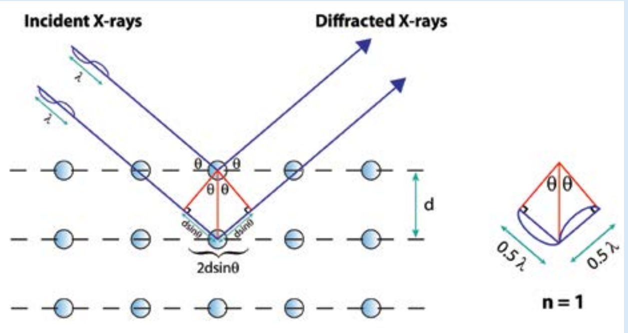
the effective depth of the shot peening (shown in green). Moreover, the effective depth, as well as the magnitude of the compressive layer imparted, varies with the material's properties and can be controlled via the applied peening pressure, the hardness of the shot relative to the coil wire, the coverage, the peening nozzle angle, etc.

The resultant peening intensity for a given set of peening parameters is normally characterized by the deflection of a suitable Almen strip—a time-tested and reliable metric for qualifying and monitoring whether a given peening process has been applied to specification. An Almen strip is a thin strip of steel that is placed in the shot peening chamber. Through a measurement of the Almen strip's deflection after peening, it can be used to quantify the intensity of the shot peening process. However, an Almen strip is unable to quantify the resulting residual stress state of the component. This direct information can only be obtained by measuring the residual stress in the component itself after the peening process. Many different residual stress fields may result from the same peening intensity measured by the Almen strip: the peened part may react differently to a given peening process as a result of its material properties, its shape, its residual stress field prior to peening, and other factors such as the peening equipment setup, nozzle angles, percent coverage, etc. Thus, the only way to understand the precise residual stress field is to measure it experimentally. Industry has long recognized that x-ray diffraction (XRD) is the method of choice for the characterization of residual stresses in shot-peened components due to its high spatial resolution and its ability to capture the often steep gradients resulting from peening at and near the surface, where it matters most (i.e., where cracks tend to initiate). XRD-based residual stress measurements have been applied to quantitatively characterize and evaluate numerous peening processes in a wide variety of applications and industries, both in the laboratory and in the field (using portable equipment). As such, XRD has been a very flexible and invaluable tool for process development and optimization where the best peening parameters for a given component must be characterized quantitatively. Components treated with conventional peening/blasting media such as cast shot, cut wire, and glass bead, as well as those treated with more unconventional treatments, such as laser shock peening, have been successfully characterized using XRD. Since peening is a value-added process, its effects can be optimized using XRD analysis to obtain a better return on investment, improve product quality, minimize the effects of fatigue and stress corrosion, decrease development and production costs, reduce component weight, and/or enhance component performance. Conditions such as over-peening or unnecessary peening time can also be minimized with great economic benefit.

Advances in technology have enabled the creation of XRD instruments that are very robust and capable of measuring on almost any component geometry. The inner diameter of coil springs (and other components with small ID) can often be measured without the need for sectioning or destroying the component when the appropriate equipment configuration is used (see Figure 4 on page 22). However, for springs that are too small to be measured directly, they can be measured by simply sectioning first to gain access to the inside of the spring.

To better understand the effects and resultant residual stress fields obtained from the application of various peening parameters, residual-stress-versus-depth profiles are typically collected using XRD measurements from the surface through the effective depth of the peening process (i.e., through the peening cold worked layer and below). To

X-rays are diffracted by atoms arranged periodically in crystalline materials such as metals and ceramics. The angle of a diffracted x-ray beam, θ is related to the atomic lattice spacing, d, via Bragg's law: $n\lambda = 2d\sin\theta$ where λ is the wavelength of the incident x-ray beam and n is an integer multiple of the wavelength. By measuring the diffraction angle for a given wavelength, the d-spacing, and thus the strain, can be calculated for the sampled volume. The stress can then easily be calculated using elasticity theory.



confirm the precise effect of the peening process, a baseline residual-stress-versus-depth profile may also be collected on an un-peened part. As shown in Figure 5, an as-formed coil spring has significantly different residual stress on the ID versus the OD. The ID profile, shown in red, is characterized by tensile residual stress, while the OD (blue) is compressive. Because measurements on the ID revealed tensile residual stress, further testing was performed on the ID to examine the effectiveness of shot peening on reducing harmful stresses at this location. Identically formed springs were peened using a 230R shot single peening process and a 460H/230R dual peening process (shown in black and green, respectively). The depth to which the peening process has affected the material can be seen in Figure 5 where the residual stress levels of the peened springs (black and green lines) meet the baseline curve (red line). Quantitative data sets can be used with fracture mechanics software to make predictions about fatigue life and damage tolerance, or data sets can be used in conjunction with fatigue testing to establish the correct level of residual stress needed to achieve the required fatigue life. Moreover, the data can be used to create a specification once the results have been verified for consistency by testing a sufficient number of samples (e.g., five) to account for part-to-part variance due to the peening process. Results can be used to establish a residual stress level at which a component's fatigue life will be increased, thus allowing the identification of a minimum threshold for peening. It may even be possible to reduce the peening specification to a single depth and residual stress value, thereby simplifying quality control processes. For example, in the profiles shown above, the specification may be to peen all springs to at least -1000 MPa at a depth of 0.075 mm. For future tests, this one depth can be tested rather than measuring at the surface, as it will be indicative of whether peening was performed adequately.

As illustrated above, XRD residual stress measurements provide the quantitative data necessary to fine-tune shot peening processes. Because concrete numbers can be attained, specifications can be accurately defined and peening processes can be optimized. For anyone who designs components that will be shot peened, obtaining a residual stress specification is necessary to ensure proper quality control.

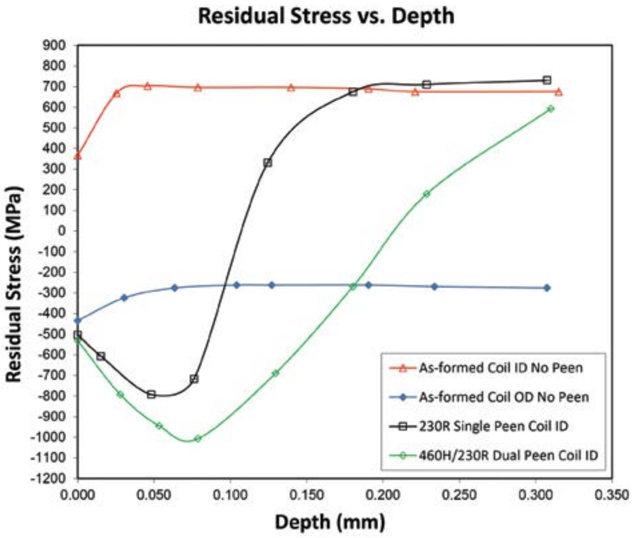


Figure 5

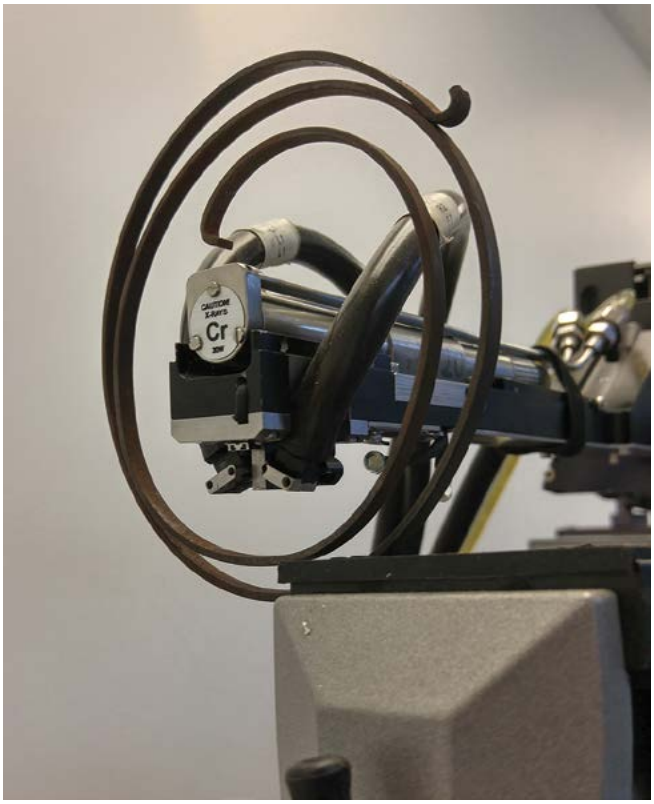


Figure 4

About PROTO Manufacturing
PROTO is a world leader in the measurement of residual stress using XRD and has been helping companies for over 35 years with the measurement of residual stresses in the laboratory, on the shop floor, and in the field. PROTO produces off-the-shelf instruments and custom solutions, and their team also offers residual stress measurement services in their laboratories.

Some examples of structures/components characterized include suspension bridges, ships, submarines, natural gas pipelines, automotive components, medical implants, power generation structures, and aerospace components.