

Characterization of Residual Stresses on Steel Coil Springs via X-Ray Diffraction Techniques

Frank Anthony Cuccia
Proto Manufacturing Inc.

James Pineault
Proto Manufacturing Ltd.

Mohammed Belassel
Proto Manufacturing Inc.

Michael Brauss
Proto Manufacturing Ltd.

ABSTRACT

It is well known that manufacturing operations produce material conditions that can either enhance or debit the fatigue life of production components. One of the most critical aspects of material condition that can have a significant impact on fatigue life is residual stress (RS) [1, 2].

When springs are manufactured, the spring stock may undergo several operations during production. Additional operations may also be introduced for the purpose of imparting the spring with beneficial surface RS to extend its fatigue life and increase its ability to execute the task it was designed to perform. The resultant RS present in production springs as a result of the various fabrication and processing operations applied can be predicted and modeled, however, RS measurements must be performed in order to quantify the RS state with precision. X-ray diffraction (XRD) techniques can be used to determine the RS state of such components precisely, thus enabling manufacturers the ability to accurately and quantitatively characterize and control the effects of their production processes [3].

CITATION: Cuccia, F., Pineault, J., Belassel, M., and Brauss, M., "Characterization of Residual Stresses on Steel Coil Springs via X-Ray Diffraction Techniques," *SAE Int. J. Mater. Manf.* 9(3):2016, doi:10.4271/2016-01-0420.

INTRODUCTION

Springs come in a multitude of shapes and sizes to perform various tasks in a wide variety of applications. While in use, springs may undergo very simple or complex loading which may be either static or cyclic and as such, it is important that the spring can live up to these demands without failure. A spring that fails prematurely can be the limiting factor in the service life of an assembly, potentially leading to costly repairs to replace the damaged spring or other related components.

Processes such as heat setting, shot peening, and heat treating, may be used to improve the spring's ability to perform and to extend its fatigue life [2, 4]. The importance of RS and its effect on a spring's fatigue life is often underestimated or, in some cases, completely ignored. Residual stresses may arise from the spring being cold worked, heat treated or both during its manufacture. In the case of coil springs, the process of coiling the wire typically results in tensile stresses on the inner diameter (ID) of the spring. This will increase

the spring's propensity for premature failure because, in many applications, the highest applied loads are also found on the coil ID which are additive to the RS fields imparted by the coiling process.

Applying RS management processes, such as shot peening, will impart compressive RS so as to inhibit crack initiation and propagation, thus extending the spring's fatigue life. In most instances, modeling is not practical and the only viable option to accurately and quantitatively determine the resultant RS state in a spring is by direct measurement. XRD is often used to directly measure RS on many manufactured components. The XRD technique affords the user a means by which to characterize the RS state after each manufacturing process is performed on the component of interest. For the measurement and characterization of the RS gradients from the surface and through the thickness of springs, material can be removed electro-chemically so as to avoid cold working the spring and introducing unwanted RS. The RS vs. depth

profile obtained can be used to select appropriate spring stock, as well as tailor forming, peening and heat treatment parameters to best suit the intended application.

STRESS MEASUREMENT USING XRD TECHNIQUE

The x-ray diffraction technique can only be applied to crystalline, polycrystalline and semi-crystalline materials [1]. This technique uses the distance between crystallographic planes, i.e. d-spacing, as a strain gage. When the material is in tension the d-spacing increases and when the material is in compression the d-spacing decreases. The presence of residual stresses in the material produces a shift in the x-ray diffraction peak's angular position that is directly measured by the detector [5]. For a known x-ray wavelength λ and n equal to unity, the diffraction angle 2θ is measured experimentally and the d-spacing is then calculated using Bragg's law [6,7]:

$$n\lambda = 2d\sin\theta \quad (1)$$

where λ is the wavelength of the radiation.

Once the d-spacing is measured for unstressed (d_0) and stressed (d) conditions, the strain is calculated using the following relationship:

$$\varepsilon = (d - d_0)/d_0 \quad (2)$$

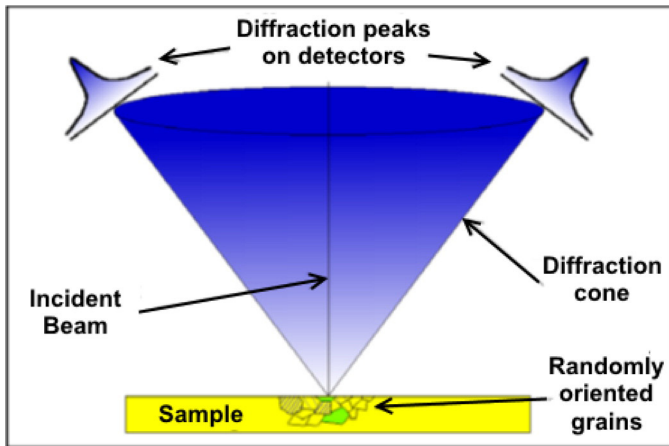


Figure 1. X-ray diffraction configuration using 2 detectors for stress measurement. The solid angle of the diffraction cone (Debye ring) is determined by the Bragg angle of the diffraction plane.

For the $\sin^2\psi$ method where a number of d-spacings are measured, stresses are calculated from an equation derived from Hooke's law for isotropic, homogeneous, fine grain materials [1]:

$$\varepsilon_{\phi\psi} = \frac{1}{2}S_2(\sigma_{\phi} - \sigma_{33})\sin^2\psi + \frac{1}{2}S_2\sigma_{33} - S_1(\sigma_{11} + \sigma_{22} + \sigma_{33}) + \frac{1}{2}S_2\tau_{\phi}\sin 2\psi \quad (3)$$

where:

$\frac{1}{2}S_2$ and S_1 are the x-ray elastic parameters of the material. σ_{ϕ} is the stress in the direction of the measurements. ψ is the angle subtended by the bisector of the incident and diffracted beam and the surface normal. $\varepsilon_{\phi\psi}$ is the strain at a given ψ tilt.

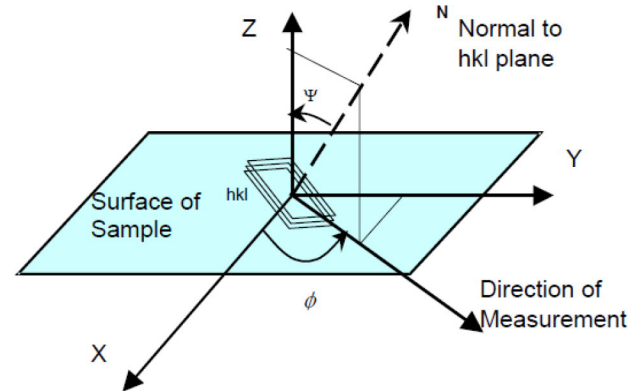


Figure 2. Definition of the axis and the direction of measurement.

Stress Calculation

Two types of stresses (normal stress σ_{ϕ} and shear stress τ_{ϕ}) can be calculated for RS measurements performed in a given direction ϕ as can be seen in Equation (3). When the d-spacing vs. $\sin^2\psi$ data are plotted, they have an elliptical form. If a shear stress is not present, the ellipse closes and becomes a straight line. If no normal stress is present, the slope of the ellipse or line is zero. The opening and slope of the ellipse or line is also dependent upon the goniometer geometry selected, i.e. if the goniometer is working in omega or psi mode or in another nonstandard mode such as modified psi or grazing incidence.

SYSTEM QUALIFICATION

System Alignment

Inherent tolerance in the XRD goniometer production and assembly is inevitable, therefore fictitious shear and normal stresses are always present. This is the reason why goniometers are equipped with an adjustment system to minimize their displacement while rotating about the center of concentricity. The acceptable resultant RS due to mechanical misalignment is stated in current guidelines and national standards. As per ASTM E915-10 [8] (when measuring steel), the stresses measured on a stress free reference material should not exceed 14 MPa and should normally be no greater than 7 MPa. Similar acceptance criteria are proposed in the European EN15305 standard using a definition in terms of the x-ray elastic constant and with 20 displacements computed. The expressions of interest in EN15305 are as follows [9]:

$$|\sigma| \leq \frac{1}{10000} \cdot \frac{1}{1/2S_2^{hkl}} \text{ and } |\Delta\sigma| \leq \frac{1}{10000} \cdot \frac{1}{1/2S_2^{hkl}} \quad (4)$$