

X-RAY DIFFRACTION CHARACTERIZATION OF RESIDUAL STRESSES PRODUCED BY SHOT PEENING

Paul S. Prevéy
Lambda Research

ABSTRACT

A brief overview of the theory and practice of x-ray diffraction residual stress measurement as applied to shot peened materials is presented.

The unique ability of x-ray diffraction methods to determine both the macroscopic residual stress and the depth and magnitude of the cold worked layer produced by shot peening is described. The need to obtain a complete description of the subsurface residual stress distribution, in order to accurately characterize the residual stress distributions produced by shot peening, is emphasized.

Non-destructive surface residual stress measurements are shown to generally be inadequate to reliably characterize the residual stresses produced by shot peening. Practical applications of x-ray diffraction methods for quality control testing are considered. Examples are presented for steel and nickel base alloys.

Keywords

X-ray diffraction, residual stress, shot peening, non-destructive

INTRODUCTION

SHOT PEENING IS COMMONLY USED to produce a layer of compressive residual stress at the surface of components subject to fatigue or stress corrosion failure. The shot peening process is controlled by monitoring the Almen intensity. However, no simple relationship exists between the peening intensity measured with the Almen strip and the residual stress-depth distribution produced. The Almen arc height depends upon the form of the residual stress-depth curve, and quite different stress distributions can produce equivalent arc heights. Conversely, peening to the same Almen intensity with

different shot sizes will generally produce different subsurface residual stress distributions. The stress distribution produced by shot peening depends upon the properties of the material being shot peened, prior processing, and the specific peening parameters used. Shot peening can only be reliably controlled and optimized by measuring the subsurface residual stress distributions produced.

X-ray diffraction (XRD) is the most accurate and best developed method of quantifying the residual stresses produced by surface treatments such as shot peening. XRD offers a number of advantages when compared to the various mechanical methods, or the non-linear-elastic ultrasonic or magnetic methods currently available. XRD is a linear-elastic method in which the residual stress in the material is calculated from the strain measured in the crystal lattice. XRD methods are not significantly influenced by material properties such as hardness, degree of cold work, or preferred orientation. XRD is capable of high spatial resolution, on the order of millimeters and depth resolution on the order of microns, and can be applied to a wide variety of sample geometries. The macroscopic residual stress and information related to the degree of cold working can be obtained simultaneously by XRD methods. XRD is applicable to most polycrystalline materials, metallic or ceramic, and is non-destructive at the sample surface. XRD methods are well established, having been developed and standardized by the SAE⁽¹⁾ and ASTM⁽²⁾.

The most common problems encountered in using XRD techniques are due to the high precision required for measurement of the diffraction angles, which in turn requires accurate sample/instrument alignment and precise methods of diffraction peak location⁽³⁾. XRD methods are limited to relatively fine-grained materials and often cannot be applied to coarse-grained castings.

The shallow depth of penetration of the x-ray beam, on the order of 8 μm , is an advantage for high resolution subsurface profiles but can be a disadvantage when

trying to characterize a stress distribution produced by shot peening with only surface measurements. Rarely, extreme preferred orientation or near-surface stress gradients and associated shear stresses can cause errors.

XRD methods of residual stress measurement have been widely used for forty years in automotive and aerospace applications, and interest in the use of XRD stress measurement for quality control testing is increasing. Specifications now exist requiring minimum levels of compression produced by shot peening and limiting the tensile stresses produced by EDM and grinding. Commercial XRD residual stress measurement equipment, designed for both laboratory use and portable measurement in the field or shop environment, is readily available. However, a basic understanding of the theory and assumptions behind XRD techniques and caution in the interpretation of the results is necessary for reliable application.

This paper briefly describes the theory, methods, and limitations of XRD residual stress measurement as applied to the study of residual stress distributions produced by shot peening. Special mention is made of problems commonly encountered in both obtaining and interpreting data from shot peened samples.

THEORY

Macroscopic Residual Stress Measurement

Because the depth of penetration of the x-ray beam is extremely shallow, the diffracting volume can be considered to represent a free surface under plane stress. As shown in Fig. 1, the biaxial surface stress field is defined by the principal residual and/or applied stresses, σ_1 and σ_2 , with no stress normal to the surface. The stress to be determined is the stress, σ_ϕ , lying in the plane of the surface at an angle, ϕ , to the maximum principal stress, σ_1 . The direction of measurement is determined by the plane of diffraction. The stress in any direction (for any angle, ϕ) can be determined by rotating the specimen in the x-ray beam. If the stress is measured in at least three different directions, the principal stresses and their orientation can be calculated.

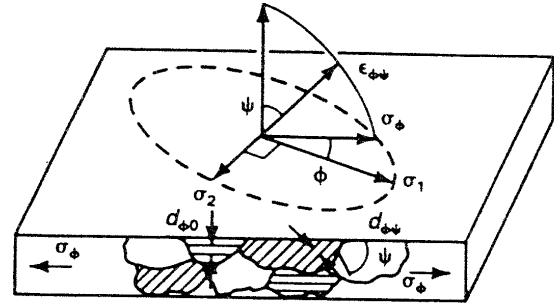


Fig. 1 Plane Stress at a Free Surface

Consider the strain vector, $\epsilon_{\phi\psi}$, lying in the plane defined by the surface normal and the stress, σ_ϕ , to be determined. $\epsilon_{\phi\psi}$ is at an angle ψ , to the surface normal, and can be expressed in terms of the stress of interest and the sum of the principal stresses as,

$$\epsilon_{\phi\psi} = \frac{1+\nu}{E} \sigma_\phi \sin^2 \psi - \left(\frac{\nu}{E} \right) (\sigma_1 + \sigma_2) \quad (1)$$

A typical metallic sample will consist of a large number of small grains or crystals, nominally randomly oriented, as shown schematically in Fig. 1. The crystal lattice consists of planes of atoms identified by their Miller Indices, (hkl). The spacing between a specific set of lattice planes, for example, the (211) planes in a steel, will be equal regardless of orientation relative to the sample surface in a stress-free specimen and will be expanded or compressed elastically by an amount dependent upon orientation by any stress present in the specimen. The state of stress can, therefore, be determined by measuring the lattice spacing at different orientations.

The only crystals which diffract x-rays are those which are properly oriented relative to the incident and diffracted x-ray beam to satisfy Bragg's Law,

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

where λ is the x-ray wavelength, n is an integer (typically 1), θ is the diffraction angle, and d is the lattice spacing. XRD can be used to selectively measure the lattice spacing of only those crystals of a selected phase which have a specific orientation relative to the sample surface by measuring θ and calculating d from Equation 2.

The lattice spacing can be determined for any orientation, ψ , relative to the sample surface by merely rotating the specimen. It can be seen intuitively that if σ_ϕ is a tensile stress, the spacing between lattice planes parallel to the surface will be reduced by a Poisson's ratio contraction, while the spacing of planes tilted into the direction of the tensile stress will be expanded. If we express the strain in terms of the crystal lattice spacing

$$\epsilon_{\phi\psi} = \frac{d_{\phi\psi} - d_o}{d_o} \quad (3)$$

where d_o is the stress-free lattice spacing, our "strain gage" becomes the lattice spacing measured in the direction ϕ, ψ . Substituting Equation 3 into Equation 1 and rearranging, the lattice spacing measured in any orientation can be expressed as a function of the stresses present in the sample and the elastic constants in the (hkl) crystallographic direction used for stress measurement,

$$d(\phi, \psi) = \left(\frac{1+\nu}{E} \right)_{hkl} \sigma_\phi d_o \sin^2\psi - \left(\frac{\nu}{E} \right)_{hkl} d_o (\sigma_1 + \sigma_2) + d_o \quad (4)$$

It should be noted that the elastic constants in the (hkl) direction may differ significantly from the values obtained by mechanical testing because of elastic anisotropy and should be determined empirically⁽⁴⁾.

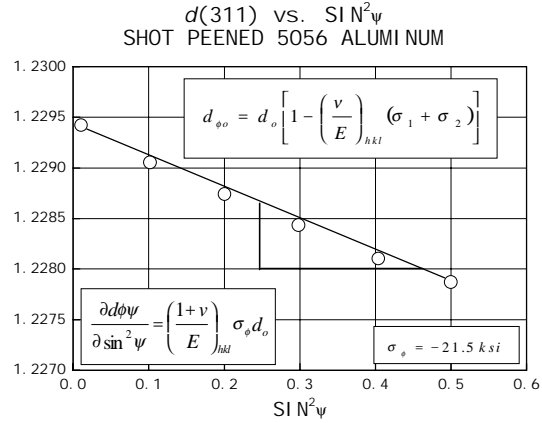


Fig. 2 Linear Dependence of Lattice Spacing with Sine-Squared-Psi in Shot Peened Aluminum

Examination of Equation 4 shows that the lattice spacing measured at any angle, ψ , in the plane defined by θ_ϕ in the surface normal, will vary linearly as a function of $\sin^2\psi$. The actual lattice spacing of the (311) planes plotted as a function of $\sin^2\psi$ for shot peened 5056 aluminum is shown in Fig. 2. The intercept of the plot is equal to the unstressed lattice spacing, d_o , minus the Poisson's ratio contraction caused by the sum of the principal stresses. The stress is determined from the slope, knowing the elastic constants, and the unstressed lattice spacing which is generally unknown. Because the value of the lattice spacing measured at $\psi = 0$ differs by not more than 0.1 percent from the stress-free lattice spacing, the intercept can be substituted for d_o . The residual stress can then be calculated without reference to a stress-free standard.

XRD macroscopic residual stress measurement provides the arithmetic average stress in a diffracting volume defined by the size of the irradiated area and the depth of penetration of the x-ray beam. The residual stress in that volume is assumed to be uniform both along the surface and as a function of depth. Rapid variation of the stress within the depth of penetration of the x-rays is a significant source of error. The errors caused by the presence of a subsurface stress gradient can be corrected if material is removed in thin layers by electropolishing (so as not to induce residual stresses); and a series of measurements is made as a function of depth. Correction may then be necessary for the stress relaxation caused by electropolishing⁽⁵⁾.

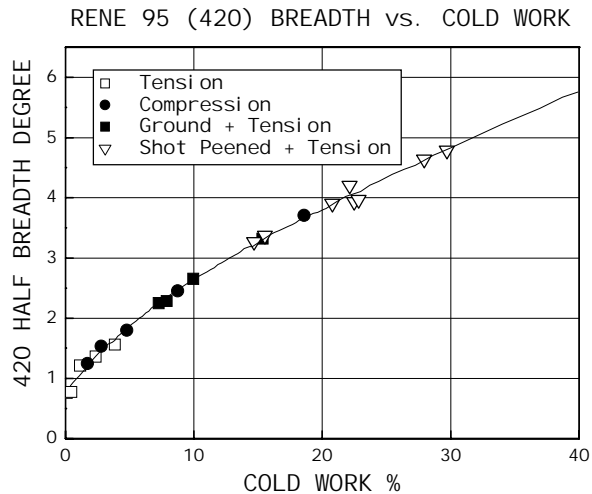


Fig. 3 The Variation of the (420) Diffraction Peak Width with Cold Work (True Plastic Strain) for Rene 95

Line Broadening and Cold Working

When a metallic material is cold worked by a process such as shot peening, the crystals are severely plastically deformed. The non-uniformity of this plastic deformation with depth causes the compressive macroscopic residual stresses produced by shot peening. As the crystals are deformed, lattice defects and dislocation tangles develop, producing microstrain (strain over the dimensions on the order of the crystal lattice) and a reduction in the crystallite size (the perfect regions within the crystals which are free of defects).

Both the increase in microstrain and the reduction in the crystallite size cause broadening of the diffraction peak used for measuring the macroscopic residual stress. This line broadening information can be used to quantify the degree to which the material has been plastically deformed by the shot peening process.

Fig. 3 shows an empirical line broadening curve developed for the (420) diffraction peak of the nickel base alloy, Rene 95. The peak half-breadth is a nearly linear function of the amount of cold work, calculated as the true plastic strain. Fig. 3 was developed using a series of specimens deformed in tension, compression, and by prior grinding or shot peening followed by tension. Line broadening is independent of the mode of deformation and is additive as damage to the crystal structure accumulates. Similar line broadening curves

have been developed for a variety of alloys to date. The degree to which the material has been cold worked can be calculated from the width of the peak used for XRD residual stress measurement. The amount of cold work, expressed as true plastic strain, can then be used to determine the variation of such properties as yield strength as a function of depth after shot peening.

LIMITATIONS IN APPLICATION TO SHOT PEENED SAMPLES

Shot peened metallic alloys are nearly ideal specimens for XRD residual stress measurement. However, problems do develop, some related to the method itself, and some related to the nature and form of the samples.

General

First, XRD methods require expensive precision apparatus, usually computer controlled, and extensive data processing, to reliably determine the position of broad diffraction peaks to the required accuracy on the order of 0.01 deg. Technicians must be well-trained with an understanding of both basic crystallography and stress analysis. These requirements may be difficult to meet in the field or shop environment. Errors in XRD residual stress measurement may arise from a variety of sources and are often difficult to detect.

Second, the areas of primary interest, such as bolt holes, fillets, the root area of gear teeth, dovetail slots, etc., are often inaccessible to the x-ray beam. In these cases, sectioning is required to allow access to the surface of interest. The likelihood of residual stress relaxation during sectioning requires that the surface be strain gaged without altering the near-surface residual stress distribution in order to measure the sectioning stress relaxation. Any sectioning stress relaxation which occurs can be calculated and used to correct the XRD results obtained on the sectioned part.

Stress Gradients

Near surface residual stress gradients, the rapid change of residual stress with depth at the surface, is a primary source of error⁽⁶⁾, and impacts directly upon the use of XRD methods for non-destructive surface measurement. Many surface treatments produce

residual stress distributions which vary rapidly near the surface of the material. Shot peening of work hardening materials, particularly after prior surface deformation caused by turning, grinding, etc., can produce a pronounced "hook" in the form of a rapid increase in compression just beneath the sample surface. Typical subsurface residual stress gradients are evident at the surface of the residual stress profiles shown for various methods of processing Inconel 718 in Figs. 4, 5 and 6.

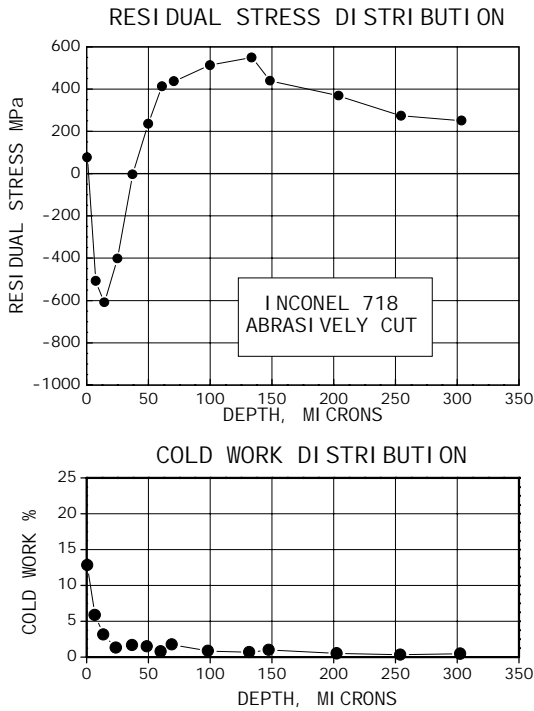


Fig. 4 Residual Stress and Cold Work Distributions Produced by Abrasive Cutting of Inconel 718

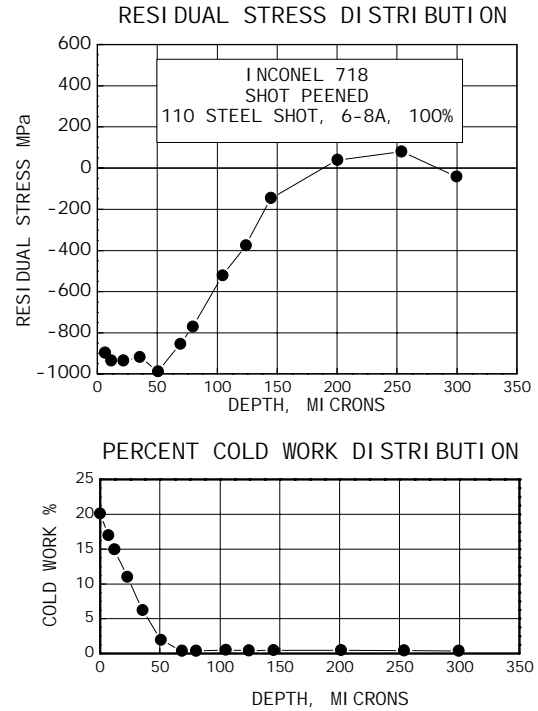


Fig. 5 Residual Stress and Cold Work Distributions Produced by Shot Peening (6-8A) Inconel 718

The rate of attenuation of the x-ray beam can be determined by calculating the linear absorption coefficient from the density and composition of the alloy. If XRD measurements are made at fine increments of depth by electropolishing, the true residual stress distribution can be calculated from the apparent distribution⁽⁷⁾. Failure to make the correction can lead to errors as high as 300 MPa and can even change the sign of the surface results. Non-destructive surface XRD stress measurements cannot be corrected and must, therefore, be used with caution.

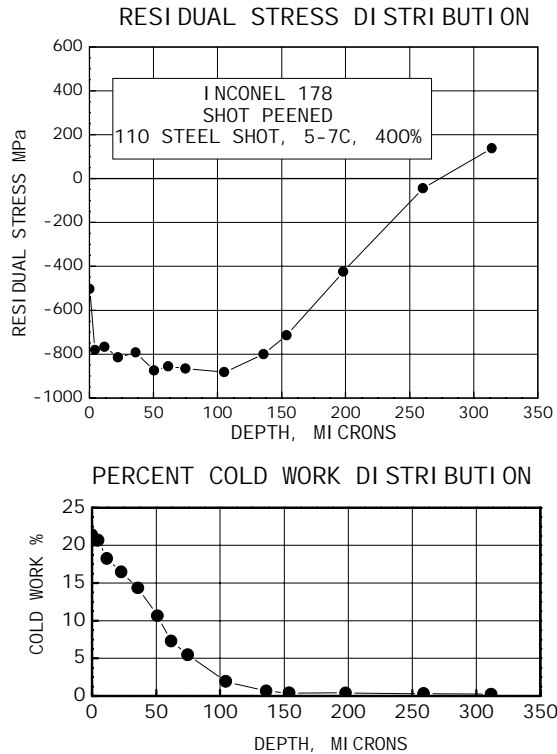


Fig. 6 Residual Stress and Cold Work Distributions Produced by Shot Peening (5-7C) Inconel 718.

Effects of Prior Processing

When employing residual stress measurement to monitor shot peening, it is important to realize that the residual stress distribution after shot peening will depend not only on the peening parameters used, but also on the prior processing of the material as well. Fig. 7 shows the near-surface residual stress distributions produced by shot peening carburized 8620 steel to 22A intensity with 230H steel shot for 200% coverage. The stress distributions are shown immediately beneath the surface for areas on the same sample on the original surface, with a decarburized surface layer, and after electropolishing to remove the decarburized layer. A reduction in surface residual stress is evident in the decarburized area, even though the two areas were identically shot peened. The presence of the decarburized layer is evident in the (211) peak width distribution shown at the bottom of Fig. 7. Without subsurface residual stress measurement, the anomalous results would likely be attributed to the shot peening process rather than the prior heat treating.

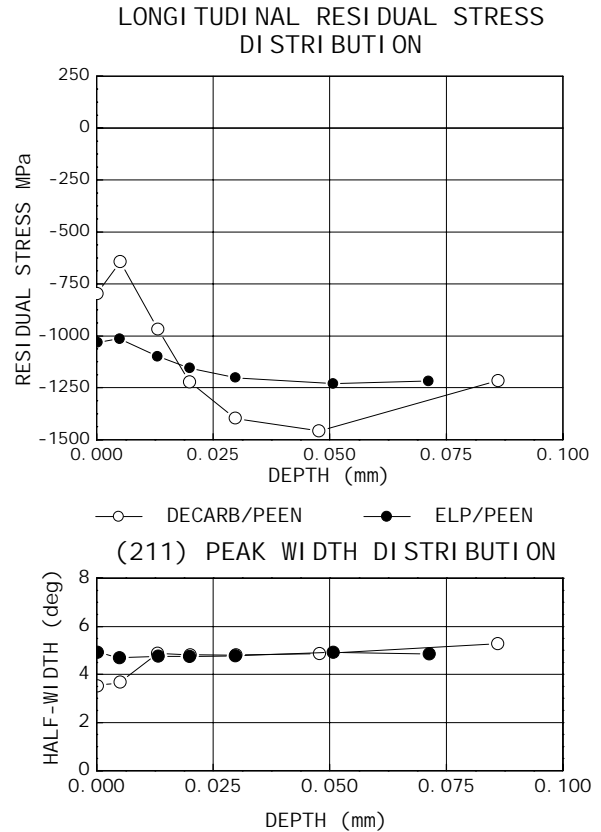


Fig. 7 Residual Stress and Peak Width Distributions Produced by Shot Peening (22A) Decarburized and Electropolished Surfaces of 8620 Steel.

Ambiguity of Surface Results

Non-destructive surface XRD residual stress measurement is often inadequate to characterize residual stresses produced by shot peening or other surface treatments. Virtually all cold-abrasive processes, such as grinding, wire brushing, polishing, sand blasting, shot peening, etc., will produce compressive surface stresses, often of comparable magnitude. The desirable compressive residual stress distributions produced by shot peening are characterized not only by the surface stress, but also by the magnitude of the peak subsurface compressive stress and the depth of the compressive layer. Figs. 5 and 6 show the residual stress and percent cold work distributions produced by shot peening Inconel 718 to 6-8A and 5-7C intensities, respectively. The surface residual stresses are virtually identical, approximately -600 MPa; and the surfaces have both been cold

worked to approximately 20%. The surface stress, even on the abrasively cut specimen shown in Fig. 4, would be nearly identical if a few microns were removed by etching. Fig. 8 shows comparable surface residual stresses developed by shot peening to an 18A intensity and grinding the surface of the same coupon of 8620 steel.

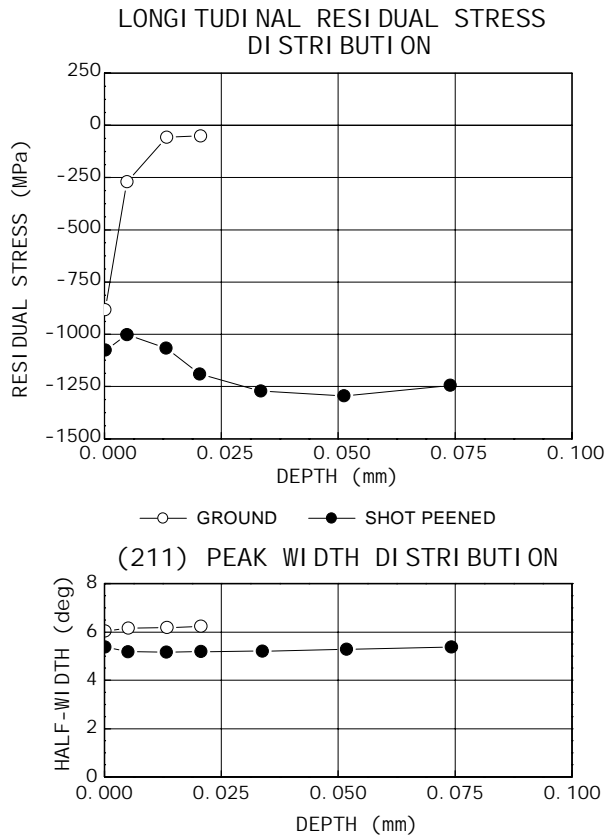


Fig. 8 Residual Stress and Peak Width Distributions Produced by Shot Peening (18A) and Grinding of Carburized 8620 Steel.

The interpretation of surface results is further complicated by the fact that the greatest variation in stress will generally occur at the surface of shot peened or machined specimens. Surface residual stress measurements alone are simply inadequate to properly characterize the residual stress distributions produced by shot peening or other surface treatments.

CONCLUSIONS

1. X-ray diffraction (XRD) residual stress measurement is the best developed and most accurate method available for the characterization of the residual stress distributions produced by shot peening. However, a thorough understanding of the method and proper technique are required to achieve accurate results. Caution is warranted in interpreting the results obtained, particularly non-destructive surface measurements.

2. The residual stress distributions produced by shot peening will depend upon the prior thermal-mechanical history of the surface layers. Residual stress measurement alone may be inadequate to verify that shot peening was performed to a specific specification. Subsurface measurement, coupled with line broadening information, offers the most reliable tool for quality control of shot peening.

3. A given level of surface compressive residual stress is a necessary, but not sufficient, condition to indicate that shot peening was performed properly. Many surface treatments other than shot peening produce similar levels of surface compression, as will shot peening to different Almen intensities.

4. Subsurface residual stress measurement, with correction for penetration of the x-ray beam and stress relaxation caused by electropolishing, is necessary to accurately and reliably characterize residual stress distributions produced by shot peening.

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