
PROBLEMS WITH NON-DESTRUCTIVE SURFACE X-RAY DIFFRACTION RESIDUAL STRESS MEASUREMENT

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ABSTRACT

Because surface measurements are nondestructive, x-ray diffraction is often considered as a method of residual stress measurement for quality control testing. Unfortunately, errors caused by the presence of a subsurface stress gradient and difficulties in interpreting surface results often limit the usefulness of surface data. The magnitude of the potential errors, both in measurement and in interpretation, depends upon the nature of the subsurface residual stress distribution which can only be determined destructively. Although residual stress distributions subject to these problems are commonly encountered in practice, the question of the validity of non-destructive surface results is seldom adequately considered.

Examples are presented showing common residual stress distributions produced by grinding, nitriding and shot peening which are subject to errors in measurement and/or interpretation when measured only at the surface. The methods for determining the subsurface residual stress distributions and correction for penetration of the x-ray beam are discussed along with examples of their application. The need to determine the subsurface stress distribution in order to verify the accuracy of surface measurements is emphasized.

INTRODUCTION

X-ray diffraction (XRD) methods of residual stress measurement have been widely used for forty years, particularly in automotive and aerospace applications, and interest in the use of XRD stress measurement for quality control testing is increasing. Specifications now exist requiring that minimum levels of compression be achieved by shot peening, and limiting the tensile stresses allowed on EDM'd and ground surfaces. Commercial XRD residual stress measurement equipment, designed for both laboratory use and portable measurement in the field or shop environment, is readily available. However, there are problems with both measuring and interpreting XRD surface residual stress results which must be considered.

XRD provides an accurate and well established^(1,2) method of determining the residual stress distributions produced by surface treatments such as machining, grinding and shot peening. XRD methods offer a number of advantages compared to the various mechanical, or the non-linear-elastic ultrasonic or magnetic methods currently available for the measurement of near-surface stresses. XRD methods are based upon linear elasticity, in which the residual stress in the material is calculated from the strain measured in the crystal lattice, and are not usually significantly affected by material properties such as hardness, degree of cold work or preferred orientation. XRD methods are 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 methods are applicable to most polycrystalline materials, metallic or ceramic, and are non-destructive at the sample surface.

The most common problems encountered in using XRD methods of residual stress measurement are related to the high precision required for measurement of the diffraction angles, which in turn require accurate sample/instrument alignment and precise methods of diffraction peak location^[1]. XRD methods are applicable only to relatively fine-grained materials, and often cannot be applied to coarse-grained castings. The shallow depth of penetration of the x-ray beam can be a disadvantage when trying to characterize a subsurface stress distribution with only surface measurements. Rarely, extreme preferred orientation and sheer stresses at the sample surface cause errors.

This paper briefly describes the assumptions, theory and limitations of XRD residual stress measurement as applied to the study of residual stress distributions produced by such processes as machining, grinding and shot peening. Special mention is made of problems commonly encountered in both obtaining and interpreting surface data from such 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 Figure 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.

$$\begin{aligned} \sigma_3 &= 0 \\ \epsilon_3 &\neq 0 \end{aligned}$$

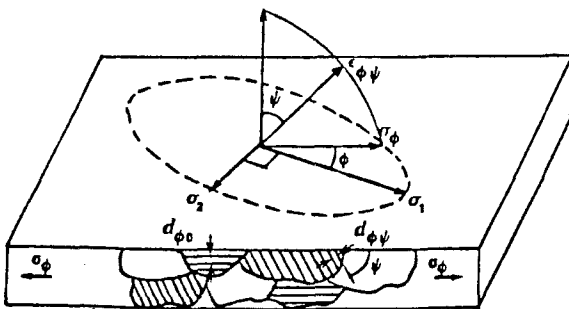


Fig. 1 Plane Stress at a Free Surface

Consider the strain vector, $\epsilon_{\sigma\psi}$, lying in the plane defined by the surface normal and the stress, σ_ϕ , to be determined. $\epsilon_{\sigma\psi}$ 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,

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

The sample is assumed to consist of a large number of small grains or crystals, nominally randomly oriented, as shown schematically in Figure 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 the orientation of the lattice planes relative to the sample surface in a stress-free specimen. The lattice spacing will be expanded or compressed elastically (by an amount dependent upon the orientation of the lattice planes) by any stress present in the specimen. The state of stress within the depth of penetration of the x-ray beam can be determined by measuring the lattice spacing at different orientations to the sample surface.

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

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

where λ is the known 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 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. 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,

$$(3) \quad \epsilon_{\sigma\psi} = \frac{d_{\sigma\psi} - d_0}{d_0}$$

where d_0 is the stress-free lattice spacing and $d(\phi, \psi)$ is the lattice spacing measured in the direction defined by ϕ and ψ . By substituting Equation 3 into Equation 1, 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.

$$(4) \quad d(\sigma, \psi) = \left(\frac{1+\nu}{E}\right)_{hkl} \sigma_\phi d_0 \sin^2 \psi - \left(\frac{\nu}{E}\right) d_0 (\sigma_1 + \sigma_2) + d_0$$

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]

Examination of Equation 4 shows that for the plane-stress model assumed, the lattice spacing measured at any angle, ψ , to 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 Figure 2. The intercept of the plot is equal to the unstressed lattice spacing, d_0 , minus the Poisson's ratio contraction caused by the sum of the principal stresses. 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_0 . The stress is determined from the slope, the elastic constants and the value of d measured at $\psi = 0$. The residual stress can then be calculated without reference to a stress-free standard.

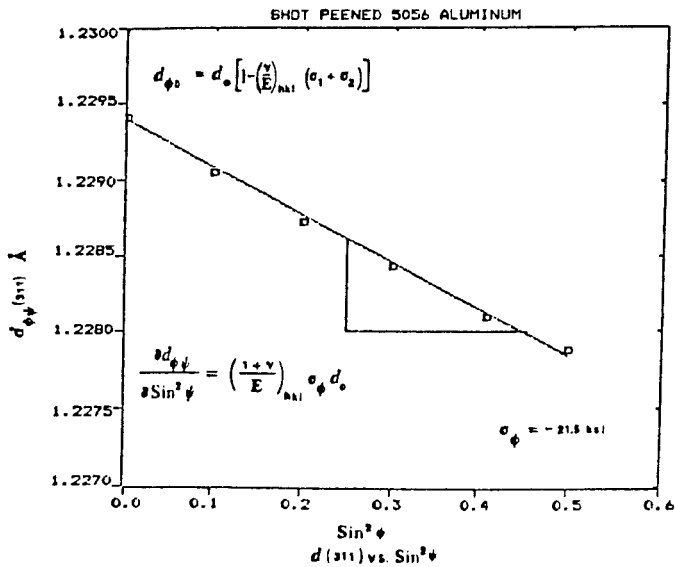


Fig. 2 Linear Dependence of Lattice Spacing With $\sin^2\psi$ in Shot Peened Aluminum

average stress in a diffracting volume defined by the dimensions of the irradiated area and the depth of penetration of the x-ray beam. The residual stress in that volume is assumed to be constant both in the plane parallel to the surface and as a function of depth. Unfortunately, the stress distributions encountered in many samples of practical interest violate these assumptions, especially at the surface where measurements may be performed non-destructively.

PROBLEMS WITH SURFACE MEASUREMENT

There are three primary difficulties associated with both obtaining and interpreting surface x-ray diffraction residual stress results. First, the surface residual stresses present on many samples of practical interest simply are not representative of the processes which produced them. Second, many machining and grinding practices produce variations in the surface residual stresses which are so large that surface results are of little value. Third, many material removal and surface treatment processes produce subsurface stress distributions which vary significantly within the depth of penetration of the x-ray beam, and can cause significant experimental error in the measurement of the surface stress.

SURFACE STRESSES MAY NOT BE REPRESENTATIVE

Many of the processes of common interest, such as grinding, shot peening, nitriding, etc., can produce nearly identical surface residual stresses for a wide range of processing variables. This feature of the stress distribution may prohibit the use of non-destructive surface residual stress measurements, regardless of measurement accuracy, from being useful for quality control testing.

In the case of grinding, where x-ray diffraction is frequently considered as a means of detecting tensile stresses, the surface stress may be nearly independent of the grinding parameters. Figure 3 shows three classic representations of gentle, conventional and abusive grinding of 4340 steel measured by a mechanical technique of layer removal and stress relaxation. The near-surface residual stresses range from only 0 to 140 MPa for an extreme range of grinding conditions. Similar surface stresses produced by completely different surface treatments are commonly revealed by x-ray diffraction, as in Figure 6.

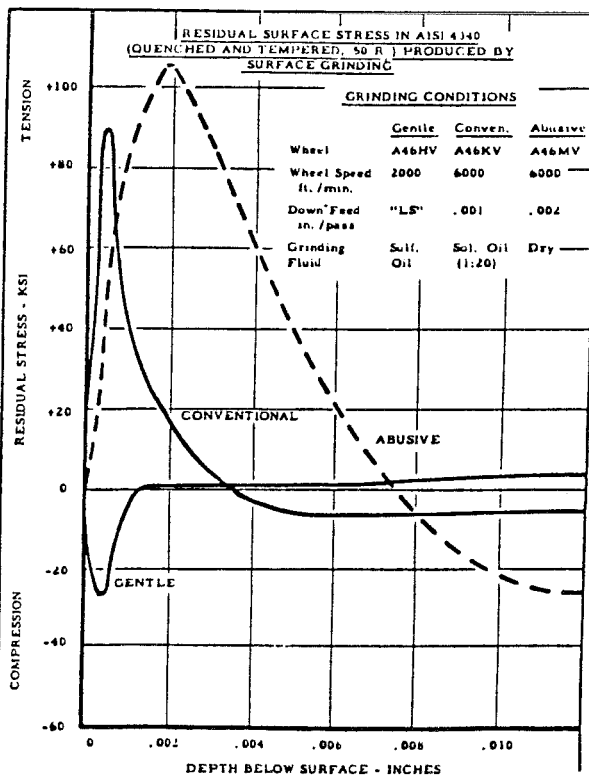


Fig. 3 Subsurface Stress Distributions Produced by Diverse Grinding Conditions in 4340 Steel [6]
XRD macroscopic residual stress measurement yields the arithmetic

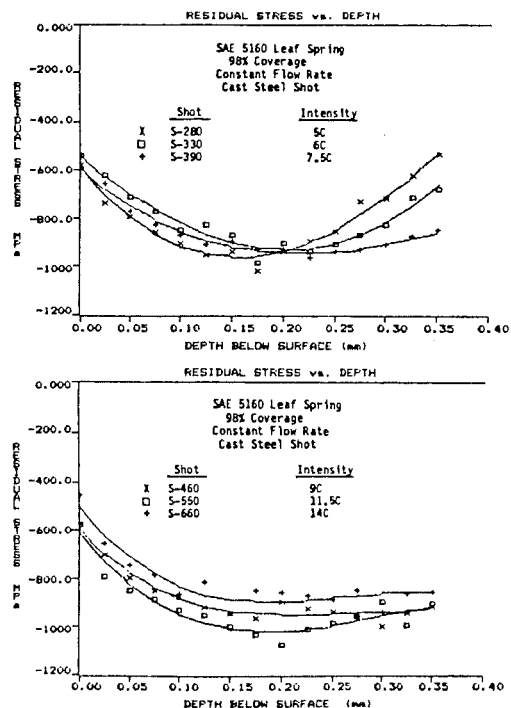


Fig. 4 Subsurface Stress Distributions Produced by Shot Peening SAE5160 Steel, Showing Similar Surface Values [7]

Shot peening also frequently produces nearly identical surface residual stresses for a wide variation in peening parameters, including shot size and Almen intensity. Figure 4 shows results for 5160 steel leaf springs shot peened from a 5C to 14C intensity with shot sizes ranging from S-280 to S-660. The surface residual stresses are virtually identical for all six peening methods, although significant differences are observed in the depth of the peened layer. Figure 5 compares the stress distributions produced by shot peening Inconel 718 to 6-8A and 5-7C intensities. The results near the surface are, again, virtually identical, but there is a pronounced variation in the depth of the compressive layers. Similar surface results are observed on shot peened 8620 steel gears as well, even though the fatigue life is well correlated to the depth of the peened layer. Figure 6 shows comparable surface residual stresses in carburized 8620 steel produced by grinding and shot peening to an 18A intensity. Non-destructive surface residual stress measurement could not be used to distinguish whether the part was in the ground or shot peened condition. A variety of other cold abrasive processes such as sand or grit blasting, wire brushing and even polishing with abrasive paper will produce surface residual stresses indistinguishable to those achieved by shot peening.

Alternately, the irradiated area may be made large enough to provide a useful average surface stress, but then the assumption of uniform stress in the irradiated area may be violated. The surface stress measured will be the arithmetic average within the irradiated area, and will be dependent upon the details of technique such as the ψ angles used during measurement.

Figure 7 shows the surface residual stress measured using an irradiated area of 12mm x 0.5mm across a 19mm wide surface of a ground 4340 steel sample. The surface stresses vary by nearly 600 MPa from a region of maximum compression near one edge of the sample to maximum tension in a burned area. The use of a larger irradiated area, plotted as a line through the individual data points, yields the arithmetic mean.

Subsurface measurements at the points of minimum and maximum surface stress shown in Figure 8 reveal subsurface tension at both locations. Comparable variations in the surface residual stress are seen in Figure 9 for milled Inconel 718. The stress variation is greatest at the sample surface. Extreme local variation of the surface stress often encountered on the machined and ground samples, may prohibit the use of x-ray diffraction residual stress measurement for quality control testing.

A given level of surface residual stress is necessary but not a sufficient condition to indicate that a critical component may have been correctly processed. The surface residual stress measured non-destructively by x-ray diffraction, or any other means, is frequently inadequate for process control testing.

SURFACE STRESS VARIATION

Many metal removal processes, particularly those involving chip formation such as machining and grinding, can generate pronounced local fluctuations in the surface residual stress. Variation in the depth and magnitude of the deformed layer and the heat input near the surface during chip formation can result in large differences in the resulting surface residual stresses over distances on the order of millimeters.

The apparent surface residual stress measured by x-ray diffraction will then be dependent upon both the size and the positioning of the irradiated area used for measurement. If a small irradiated area is used, the assumption of uniform stress within the irradiated area may be satisfied, and the stress variation at the sample surface will be revealed. The surface stress variation can be so pronounced as to render non-destructive measurement useless for process control.

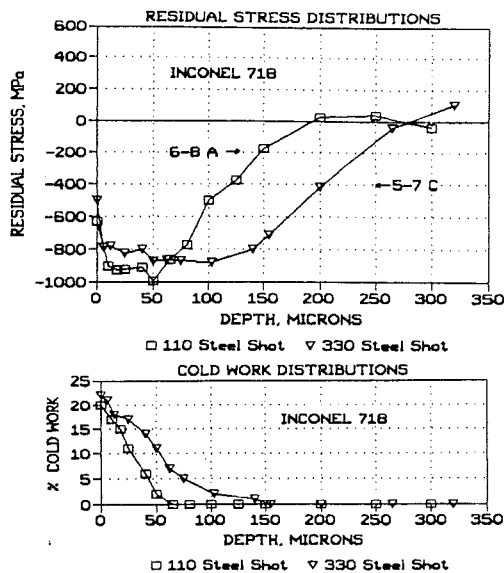


Fig. 5 Variation in Depth of the Stress Distributions Produced in Shot Peened Inconel 718, Showing Similar Surface Results [8]

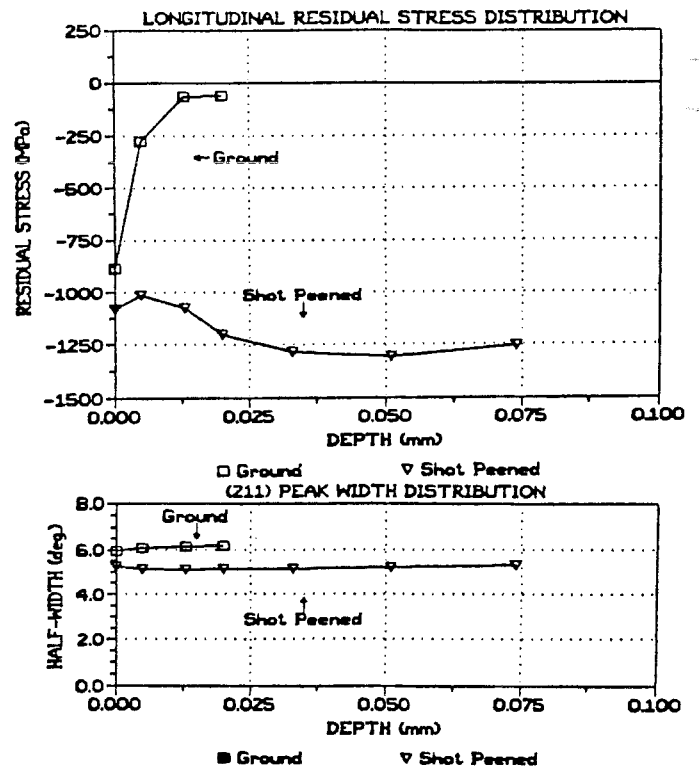


Fig. 6 Residual Stress and Peak Width Distributions Produced by Shot Peening (18A) and Grinding of Carburized 8620 Steel.

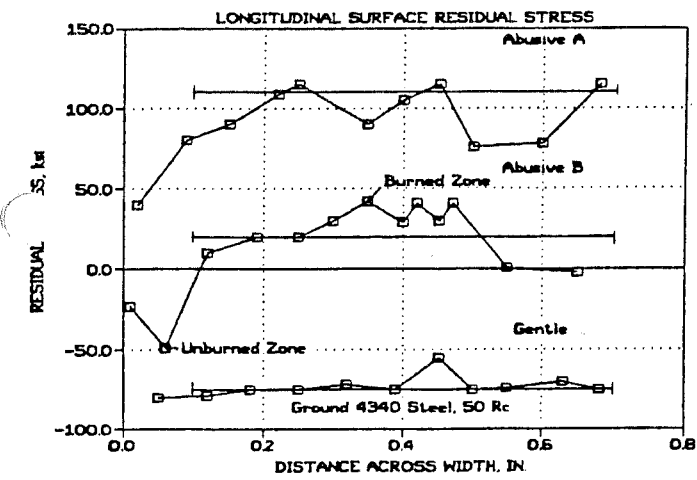


Fig. 7 Variation in Surface Residual Stress Across the Surface of Ground 4340 Steel [9]

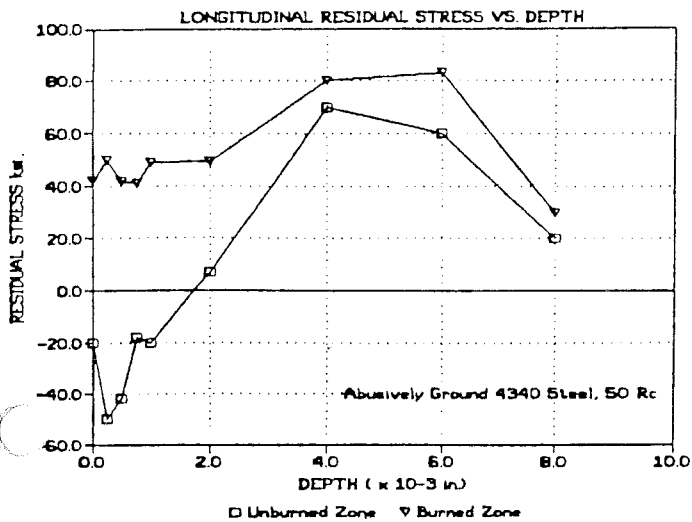


Fig. 8 Subsurface Stress Distributions in Adjacent Areas of Ground 4340 Steel Showing Surface Stress Variation and Similar Subsurface Peak Stress [9]

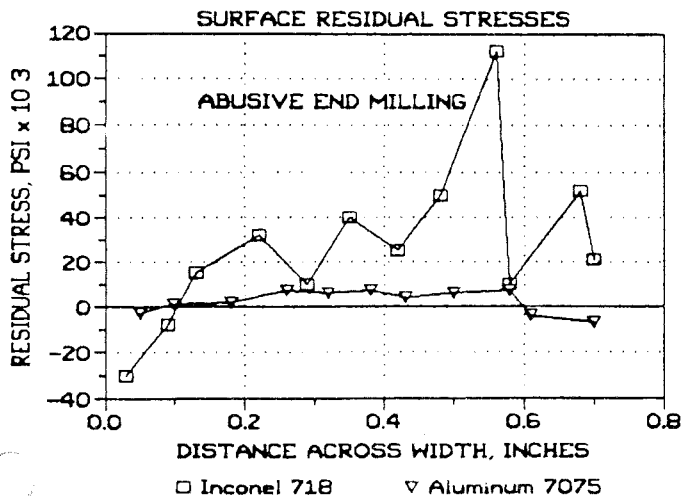


Fig. 9 Surface Stress Variation in End Milling of Inconel 718 and Aluminum [9]

ERRORS DUE TO SUBSURFACE RESIDUAL STRESS GRADIENTS

For most materials of practical interest and the radiations used for residual stress measurement, the effective depth of penetration of the x-ray beam is quite shallow. Nominally 50% of the diffracted radiation originates from a depth of less than 10 μm . However, the x-ray beam is attenuated exponentially as a function of depth. The rate of attenuation is governed by linear absorption coefficient, which depends upon the composition and density of the specimen and the radiation used.

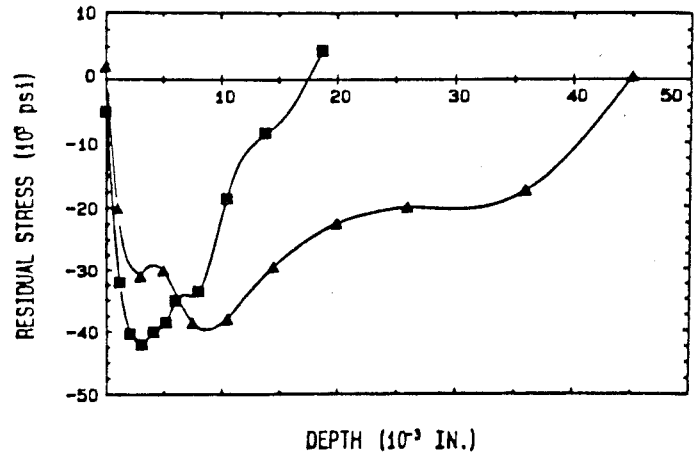


Fig. 10 Subsurface Stress Distributions Produced by Nitriding AISI 52100 Steel, Showing Pronounced Near-Surface Stress Gradient [10]

Any "surface" measurement is, therefore, actually an exponentially weighted average of the stress at the surface and in the layers immediately beneath it. As noted in the theory section, the assumption was made that the residual stress is constant throughout the depth of penetration of the x-ray beam. Unfortunately, for many samples of practical interest, the stress varies rapidly with depth beneath the surface, and the assumption of constant stress is violated. The result can be errors as large as 600 MPa.

The sign and magnitude of the potential error is dependent upon the subsurface stress gradient; i.e., the direction and rate of change of stress with depth into the sample surface. Because the depth of penetration of the x-ray beam also varies with the angles ψ and 2θ , the apparent surface residual stress will depend upon the details of the technique chosen, specifically the radiation and ψ angles selected, if a significant subsurface stress gradient exists.

Figure 10 shows examples of large subsurface stress gradients produced by two different methods of nitriding 52100 steel. The grinding stress distributions shown in Figure 3 show large stress gradients at the surface, both positive and negative. Figure 5 shows a pronounced gradient in the "hook" commonly seen at the surface of shot peening stress distributions. Figure 11 depicts a complete reversal of the stress distribution within 50 microns of the surface observed on abrasively cut Inconel 718.

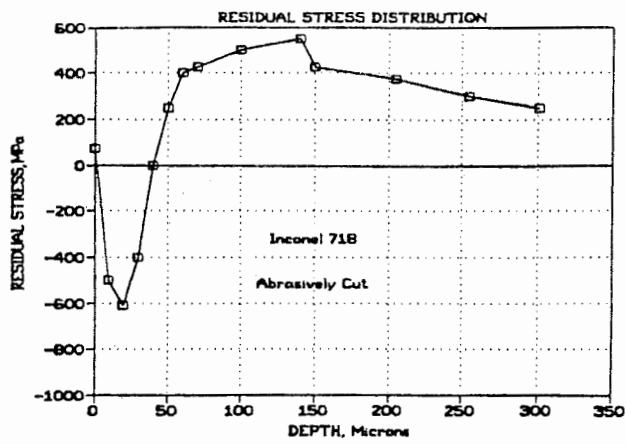


Fig. 11 Subsurface Stress Distributions in Abrasively Cut Inconel 718, Showing Complete Stress Reversal Near the Surface [8]

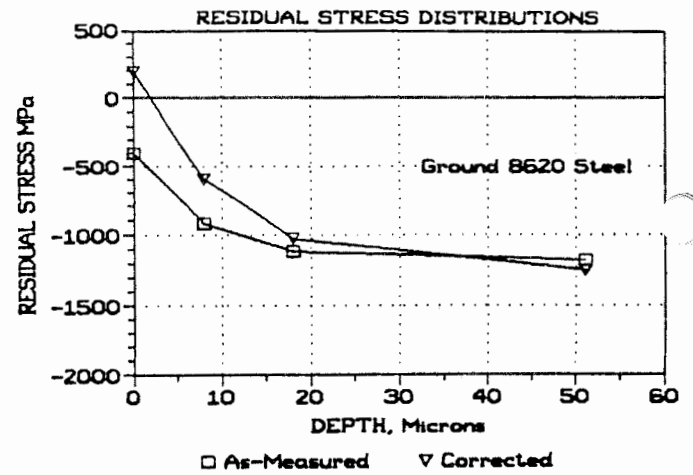
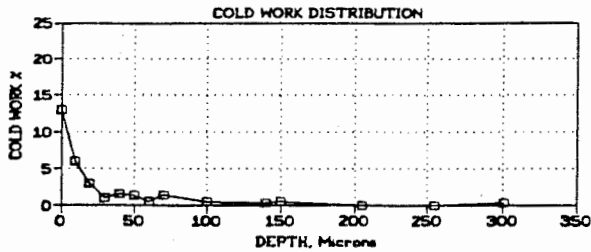


Fig. 13 Effect of Correction for Penetration of the X-ray Radiation into a Subsurface Stress Gradient, Showing a Change of Sign at the Surface

It is possible to correct for the errors caused by the penetration of the x-ray beam into the stress gradient, provided subsurface measurements are made by electropolishing to remove layers with sufficient depth resolution to accurately establish the stress gradient. Koistinen and Marburger [5] developed a method of calculating the true residual stress by unfolding the exponential weighting caused by penetration of the x-ray beam. Their often cited example of agreement between x-ray diffraction and mechanical methods of residual stress measurement in ground steel, reproduced in Figure 12, shows agreement only because the correction was applied. The figure is reproduced exactly as it appears in their original publication.

Figures 13 and 14 show positive and negative corrections, respectively. As seen in Figure 13, the uncorrected surface stress may even be of the wrong sign.

Non-destructive surface residual stress measurements cannot be corrected for errors caused by penetration of the x-ray beam into a varying stress field. Therefore, surface results must be interpreted with caution. The true surface stress frequently cannot be accurately determined by surface measurement alone.

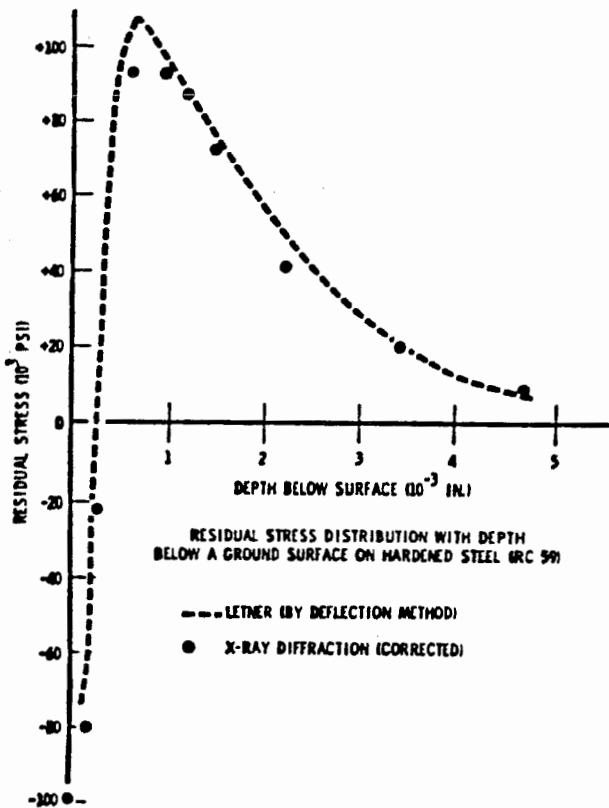


Fig. 12 Subsurface Stress Distribution in Ground Steel Measured by Mechanical and X-ray Diffraction Methods with Correction for the Near-Surface Stress Gradient [11]

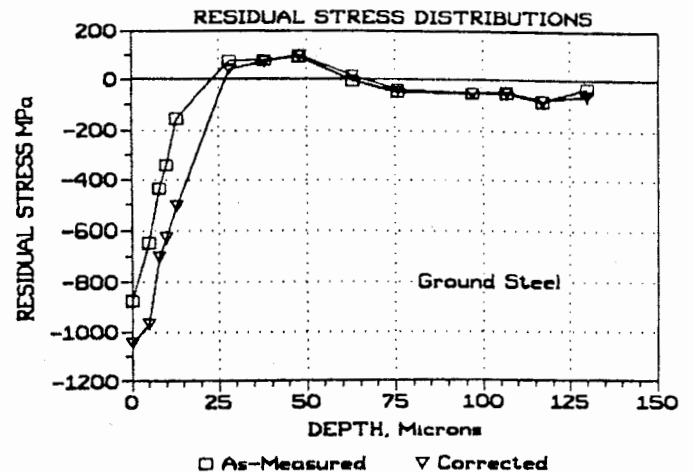


Fig. 14 Effect of Correction for Penetration of the X-ray Radiation into a Stress Gradient in Ground Steel

CONCLUSIONS

The limitations inherent in the use of surface x-ray diffraction residual stress measurements have been shown to result in three areas of

concern, which must be considered before non-destructive surface results may be used reliably.

First, there frequently is no correlation between the surface residual stress and the method of processing which produced the stress distribution. Subsurface stresses often differ significantly from the surface value.

Second, the surface stresses produced by many material removal processes, particularly machining and grinding, will often vary significantly over short distances. The surface stress measured is then dependent upon the details of the measurement technique, such as the irradiated area size and positioning.

Third, many processes of practical interest result in a rapid change in the residual stress immediately beneath the surface, within the depth of penetration of the x-ray beam. This results in errors which can approach 600 MPa and even alter the sign of the apparent results. The effects of penetration of the x-ray beam can only be corrected if subsurface results are obtained.

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