Influence of manufacturing processes on the selection of stress measurement techniques

M. Belassel [a], J. Pineault [a], M. Brauss [b]
[a] Proto Manufacturing Canada, mbelassel@protoxrd.com, jpineault@protoxrd.com
[b] Proto Manufacturing Inc., USA, mbrauss@protoxrd.com

Keywords: Residual Stress, X-Ray Diffraction, Measurement Techniques, MET, SET

Introduction

Residual stress (RS) measurements performed using x-ray diffraction (XRD) techniques have been widely applied to numerous materials subject to various manufacturing processes, such as machining, shot peening, heat treatment, etc. A variety of XRD techniques and associated methodologies can be applied to measure RS including: a) the multiple exposure technique (MET) in both psi and omega modes, b) the single exposure technique (SET) or double exposure technique (DET). The SET has disadvantages, many of which are well known to engineers and scientists when applied to materials subject to induced shear stress. However, in practice the appropriate technique is not always selected in the context of the manufacturing process that is being evaluated. This paper will bring to light many of the insufficiencies and commonly misunderstood issues related to XRD based RS measurements by comparing the SET and MET, as well as proposing corrective measures and best practices as deemed applicable with the goal of collecting data and results of superior quality. A variety of materials subject to different cold working processes were selected where both the SET and MET were compared with the purpose of evaluating the efficacy of each and to identify any weaknesses in either when performing RS measurements on real hardware. The results obtained indicate that surface and subsurface RS measurement data collected using the SET is in most cases misleading and erroneous and that the MET is a much more reliable measurement technique.

X-Ray Diffraction (XRD) Stress measurement technique

The XRD technique uses the distance between crystallographic planes, i.e. d-spacing, as a strain gage, and can only be applied to crystalline, polycrystalline and semi-crystalline materials [2]. When the material is in tension, the d-spacing increases and when the material is in compression, the d-spacing decreases. The presence of RS in the material produces a shift in the XRD peak angular position that is directly measured by the detector [3].

For a known x-ray wavelength radiation λ and n equal to unity, the diffraction angle 2θ is measured experimentally and the d-spacing is then calculated using Bragg's law:

$$n\lambda = 2d\sin\theta \tag{1}$$

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

$$\varepsilon = (d - d_0)/d_0 \tag{2}$$

For the $\sin^2$⍰ 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:

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

Where, ½ S_2 and S_1 are the x-ray elastic constants of the material, σ_ϕ is the stress in the direction of the measurement ϕ, Ψ is the angle subtended by the bisector of the incident and diffracted x-ray beam and the surface normal, and $\varepsilon_{\phi\Phi}$ is the crystallographic strain at a given Ψ tilt.

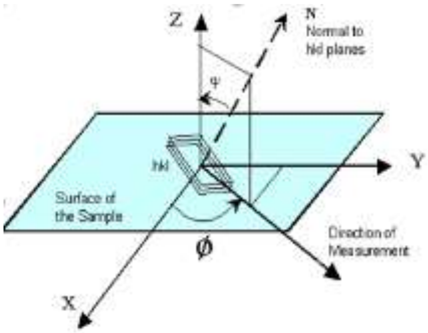

Figure 1: Definition of the axis and the direction of measurement.

Equation (3) can be employed for the calculation of RS data collected using either the SET or the MET. Typically, the MET requires a minimum of five Ψ angles (more are preferred) to determine both the normal stress σ_ϕ and the shear stress τ_ϕ, however the SET or DET requires only two Ψ angles and can only be used to determine the normal stress (i.e. the shear stress cannot be evaluated using the SET). The limitations of both techniques are well known and documented and the accuracy of results obtained using either can be adversely affected by the presence of material condition issues such as large grain size, preferred orientation, and/or stress gradients. In such cases, the MET can be used to overcome these material condition issues and results with a higher level of confidence can be obtained if the well-established methodologies to mitigate these effects are observed. The most commonly applied technique is the MET. In some instances the SET can be used under very special circumstances where the material condition is ideal i.e. the material is isotropic and homogeneous, where the strain is uniform, and where shear stresses are negligible [4].

Experiments

A variety of materials subject to different cold working processes were selected where both the SET and MET were employed for RS measurements using Proto LXRD and iXRD instruments. Samples composed of materials/alloys commonly used in industry were selected for analysis and comparison, including: iron, aluminium, nickel, tantalum, and titanium base alloys. All materials were measured in either the "as shot peened" or the "as machined" conditions. The data collection parameters summarized in Table 1 were selected based on current best practices and existing standards [5]. Subsurface RS measurements were performed by eletropolishing to the depth of interest. The depths achieved were measured using a high resolution Mitutoyo profilometer.

Table 1: RS measurement data collection parameters used for the various materials evaluated.

Material	Cold Working Process Applied	X-ray Tube Anode	Plane (hkl)	Bragg Angle (°)	½S_2 (ksi^{-1})	SET tilt angle (°) Tilts: 1, 11/13
Fe-base alloy, Structural steel	Shot peened	Cr	211	156.3	4.082.10^{-5}	±18, ±42
Fe-base alloy, Gear steel	Shot peened	Cr	211	156.3	3.683.10^{-5}	±22, ±47
Al-base alloy	Shot peened	Co	331	149	1.280.10^{-5}	±14.5, ±45.5
Ni-base alloy	Shot peened/ Machined	Mn	311	155.2	3.900.10^{-5}	±12.6, ±37.4
Ta-base alloy	Shot peened	Cu	400	139.1	4.670.10^{-5}	±4.5, ±45.5
Ti-base alloy	Shot peened	Cu	213	142	8.197.10^{-5}	±14.5, ±45.5

Results and analysis

The RS results presented in Figures 2 through 11 clearly illustrate that the SET results and the MET results are, with some exceptions, significantly different. At the surface on the shot peened materials including the Al-base, Ni-base, and Fe-base alloy samples, the residual stresses measured are in agreement within the experimental errors. However, on the shot peened surface of the Ti-base and Ta-base alloys, the surface residual stresses were not in agreement within experimental errors. Moreover, the subsurface RS measurement results were not in agreement within experimental errors when comparing the SET and MET with the exception of the shot peened tool steel sample to a depth of approximately 0.007” deep (See Figure 4). This lack of agreement between MET and SET RS results indicates that the microstructure in most materials and real world components is not ideal for SET based measurements. RS measurement results are sensitive to the presence of coarse grain size, preferred orientation and heterogeneity. RS measurement results are also sensitive to RS gradients and shear stresses. For this reason, multiple inclination Ψ angle collection is required to mitigate and often eliminate these effects [6]. Statistically, the MET should use a higher number of Ψ tilts to achieve a better distribution of the d-spacings versus $\sin^2\Psi$ data points. Therefore, the SET is directly and negatively affected by the presence of these microstructures in the material under investigation.

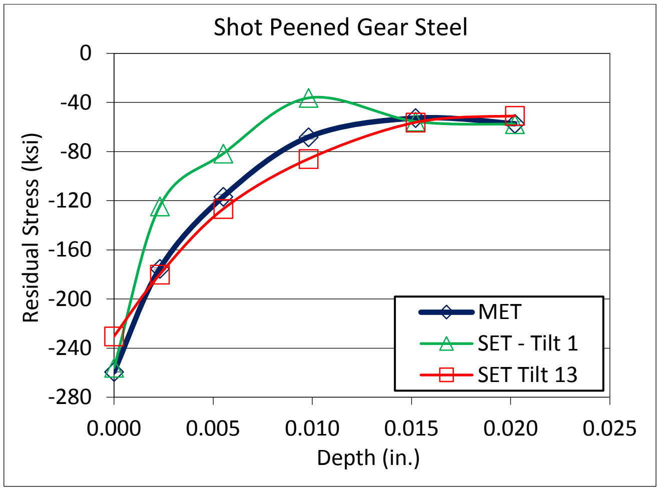

Figure 2: Plot of RS vs. depth on a shot peened steel gear.

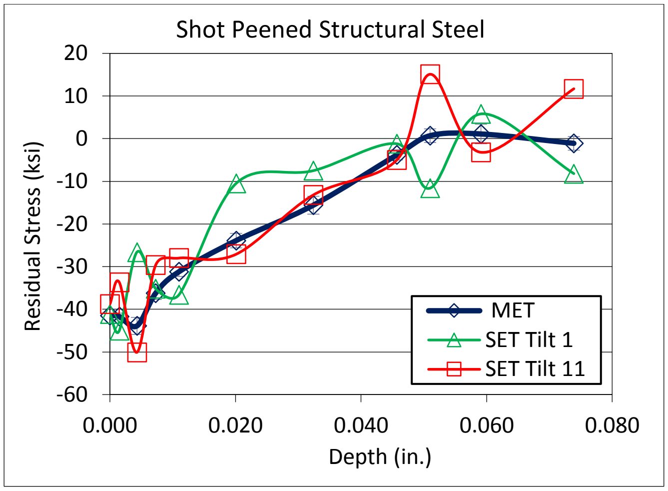

Figure 3: Plot of RS vs. depth on a shot peened structural steel member.

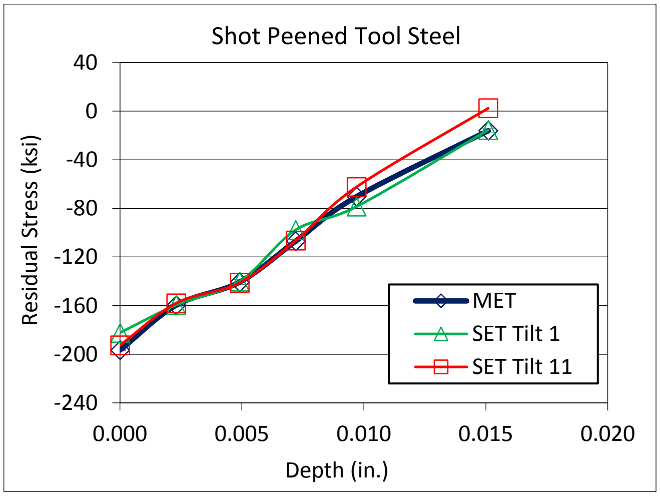

Figure 4: Plot of RS vs. depth on a shot peened tool steel sample.

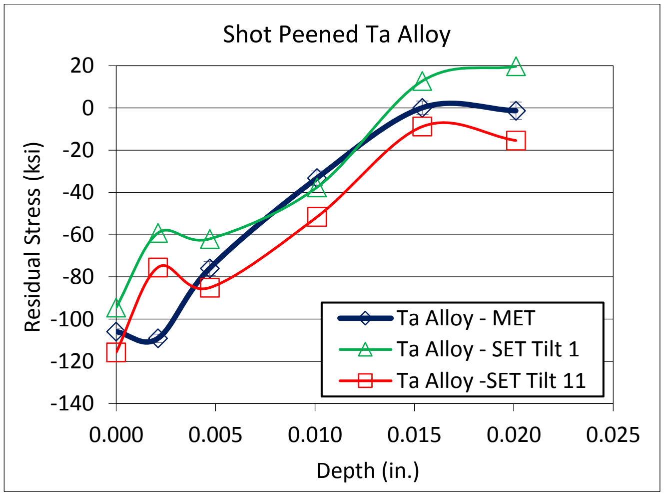

Figure 5: Plot of RS vs. depth on a shot peened Ta alloy sample.

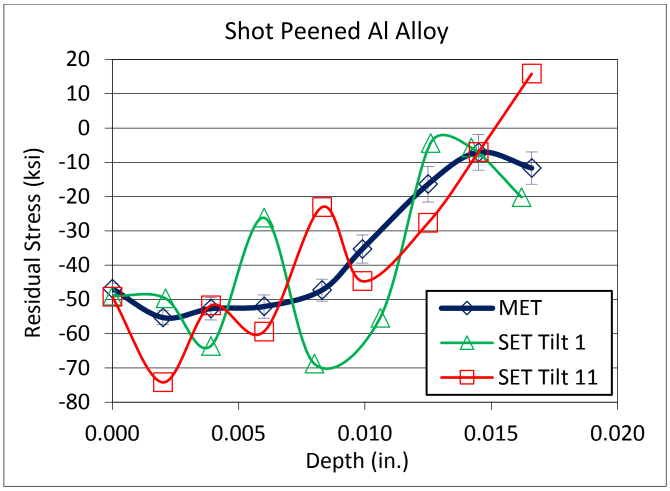

Figure 6: Plot of RS vs. depth on a shot peened Al alloy sample.

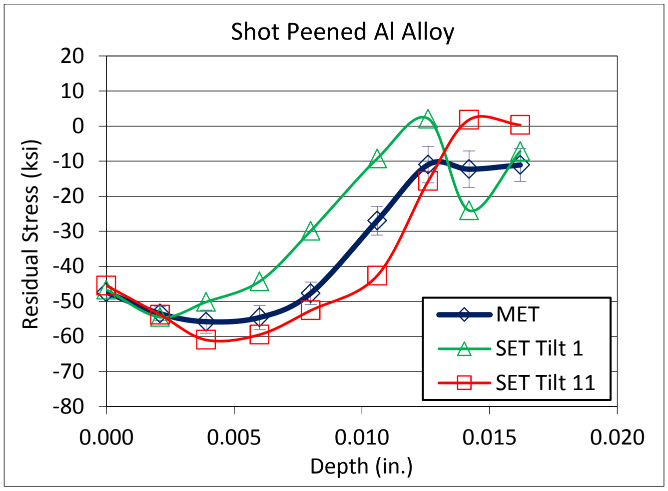

Figure 7: Plot of RS vs. depth on a shot peened Al alloy sample.

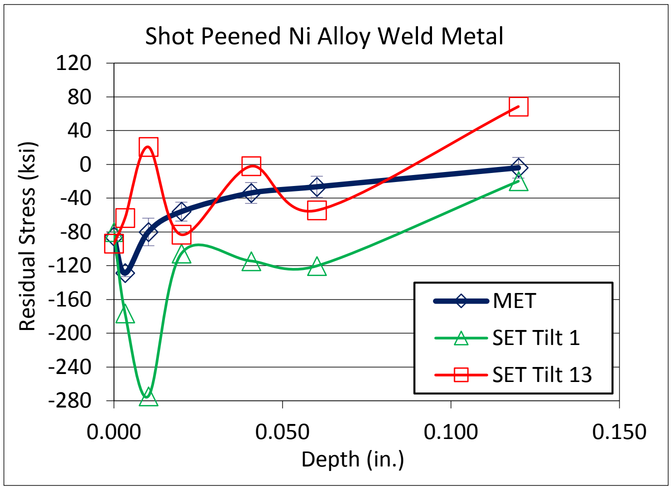

Figure 8: Plot of RS vs. depth on shot peened Ni-alloy weld metal.

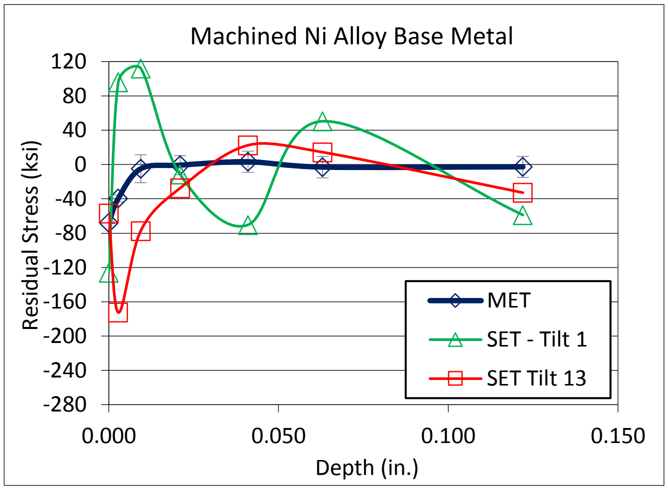

Figure 9: Plot of RS vs. depth on "as machined" Ni-alloy sample.

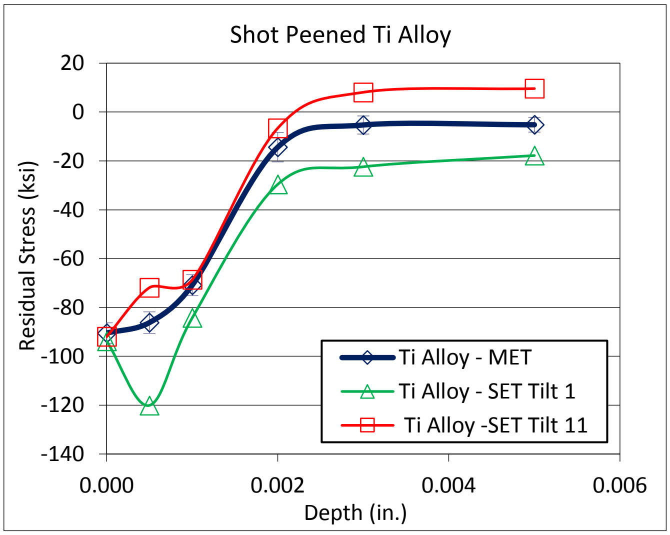

Figure 10: Plot of RS vs. depth on a shot peened Ti alloy sample.

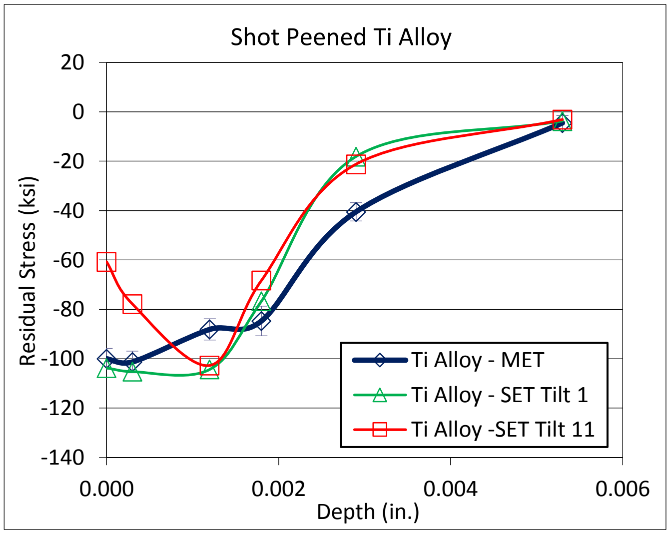

Figure 11: Plot of RS vs. depth on a shot peened Ti alloy sample.

In the case of the "as machined" and "shot peened" Ni-base alloy samples using the MET, the RS results are in agreement within experimental errors at the surface despite having been subject to different cold working processes (see Figure 12). These results make apparent the need to acknowledge that RS measurements performed at the surface alone do not by necessity indicate how the part was processed. Therefore, both surface and subsurface RS measurements are required to reliably and fully characterize the processes applied to components of interest. It becomes clear that the level of RS at the surface is not always directly linked to the processes applied, even in case of shot peening, where different peening conditions do not always lead to unique and identifiable RS levels at the surface.

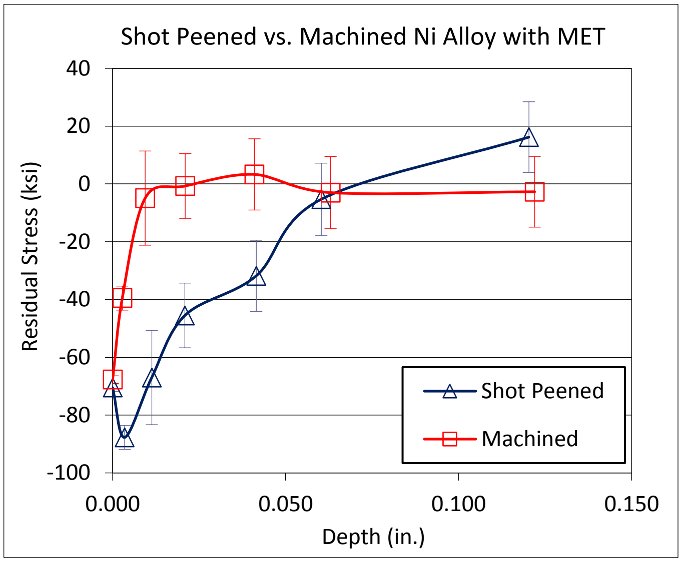

Figure 12: Plot of RS vs. depth on "as machined" and "shot peened" Ni-alloy samples.

Conclusions

It is important to understand the limitations of all XRD based RS measurement techniques to correctly characterize residual stresses in materials for development and/or quality control in production. As such, the SET is generally a technique that should be avoided whenever possible and can only be used reliably when a thorough evaluation is performed, i.e. when compared to results obtained using the MET. In most cases, RS measurement results are sensitive to the presence of coarse grain size, preferred orientation, heterogeneity, RS gradients, and shear stresses. The SET is directly affected by the presence of these microstructures in the material and as such, fails to accurately characterize subsurface RS. For this reason, multiple inclination Ψ angle collection is required to mitigate and often eliminate these effects. Statistically, the MET should use a higher number of Ψ tilts to achieve a better distribution of the d-spacings versus $\sin^2 \Psi$ data points. Moreover, surface RS measurements alone cannot reveal the true effects of processes applied to the component or sample under investigation. For this reason, the MET is the preferred technique to be used in conjunction with both surface and subsurface RS measurement profiles for accurate and reliable process characterization.

References

[1] M. Belassel et al., "Comparison of Residual Stress Measurement Techniques and Implementation Using X-Ray Diffraction", ICRS10, Materials Research Proceedings 2 (2016) 43-48
[2] Noyan I.C. and Cohen J.B., 'Residual Stress', Springer Verlag, 1987.
[3] J. Lu et al., "Handbook of Measurement of Residual Stresses", Published by the Fairmont Press, Inc., 1996.
[4] J.A. Pineault, M. Belassel, M.E. Brauss, "X-Ray Diffraction Residual Stress Measurement in Failure Analysis", Failure Analysis and Prevention, Vol. 11, ASM Metals Handbook, American Society for Metals, 2002, p. 484-497.
[5] European Standard, EN 15305, "Non-destructive Testing - Test Method for Residual Stress analysis by X-ray Diffraction", August 2008.
[6] V. Hauk, "Structural and Residual Stress Analysis by Nondestructive Methods", Elsevier, Amsterdam, 1997.