THE 7th INTERNATIONAL CONFERENCE ON SHOT PEENING
ICSP 7
INSTITUTE OF PRECISION MECHANICS WARSAW, POLAND

INSTRUMENT FOR NONDESTRUCTIVE MEASUREMENTS OF STRESS DEPTH PROFILES IN SHOT PEENED ALUMINUM ALLOYS

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ABSTRACT

Controlled surface compressive stresses are often applied to critical structural materials to improve the fatigue properties by reducing the probability of crack initiation and propagation. Techniques such as shot peening, water jet peening, laser shock peening, cold working, and roll burnishing are commonly employed to impart the compressive stresses. We evaluated the feasibility of using diffraction of short wavelength radiation (deep penetrating) for evaluating average subsurface stresses in aluminum alloys shot peened to different levels of deformation. A new technique has been developed, which determines the average stress nondestructively in the range of 0-300 μm below the surface. The method is capable of measuring the complete stress tensor. We evaluated the method by comparing the measured average stresses with other techniques; X-ray diffraction using a shallow penetrating Cr radiation combined with material removal by electropolishing, neutron diffraction, and modeling. Based on this technique, an instrument has been built capable of nondestructive stress measurements in the subsurface regions. The instrument uses a CCD based fiber-optic detector developed at Hypernex.

KEY WORDS

x-ray diffraction, shot peening, residual stresses, position sensitive detector

BACKGROUND

Controlled surface compressive stresses are often applied to critical structural materials to improve the fatigue properties by reducing the probability of crack initiation and propagation. Techniques such as shot peening, water jet peening, laser shock peening, cold working, and roll burnishing are common processing techniques employed to impart the compressive stresses. Shot peening and roll burnishing in particular are regularly practiced by the manufacturers of aircraft wheels. X-ray diffraction is an ideal technique to quantitatively measure the surface compressive stress but is typically limited to first 10-30 microns of material depth. The compressive stresses, however, will extend beyond this level to a depth closer to 300 microns in the case of aluminum alloys. Furthermore, the surface measurements are often misleading since they are greatly affected by surface conditions, such as surface roughness. An example is discussed in the following section.

The inside surface of a 2014-T6 aircraft wheel (Boeing 777) was masked off for four different zones and prepared to four different Almen intensities. Almen strip is a SAE 1070 spring steel specimen (3"x 0.75"x 0.051" or so called "A" strip) used to calibrate peening impact energy. The depth of the compressive layer is proportional to Almen intensity (deflection of an Almen strip)[1]. The Almen intensities for each zone are shown in Table 1. Surface residual stresses direction were measured using Cr radiation on the ID of the wheel. The results are presented in Table 1

Table 1. Hoop stresses on ID of the wheel prior to cutting. Stress 1 and 2 represent two repeated measurements.

Zone	Almen arc hight (inch)	Residual stress (MPa)	Roughness R_z (μm)
Zone 1	0.0050	-262±20	4.2
Zone 2	0.0075	-202±20	7.5
Zone 3	0.0120	-145±20	11.2
Zone 4	0.0150	-75±20	12.1
coupon	"stress free"	-8±20	Not measured

The results presented in Table I are surprising in a sense that the highest Almen strip intensities correspond to the lowest (in magnitude) compressive stresses. One would expect that the residual stress increased in magnitude with increasing severity of shot peening. The observed (reversed) trend is due to the surface roughness. Cr radiation penetrates approximately 10 microns into aluminum, which is comparable with the surface roughness of the samples. Profilometry measurements were done on all samples and are also presented in Table 1. The surface roughness R_z (height of the irregularity) increases as the strip intensity increases and is the highest for "zone 4" samples. For zone #1 and Zone #2 the surface roughness is less then the penetration depth of Cr radiation (0.0002" to 0.0003" or 5-8 microns), for zones #3 and #4 surface roughness slightly exceeds the penetration depth. The rough surface can not support stresses and there is usually a significant stress relaxation in surfaces with roughness greater than the x-ray penetration depth [2]. The stress profiles were determined by x-ray diffraction and layer removal by electropolishing and are presented in Figure 1. The depth of modified layer and the magnitude of the compressive residual stresses increase as the Almen level increases. Surface measurements of residual stresses can not be correlated to the depth nor maximum value of the compressive stresses in the subsurface regions. However, there is a need for fast, nondestructive assessment of the effectiveness of processes, which impart compressive residual stresses.

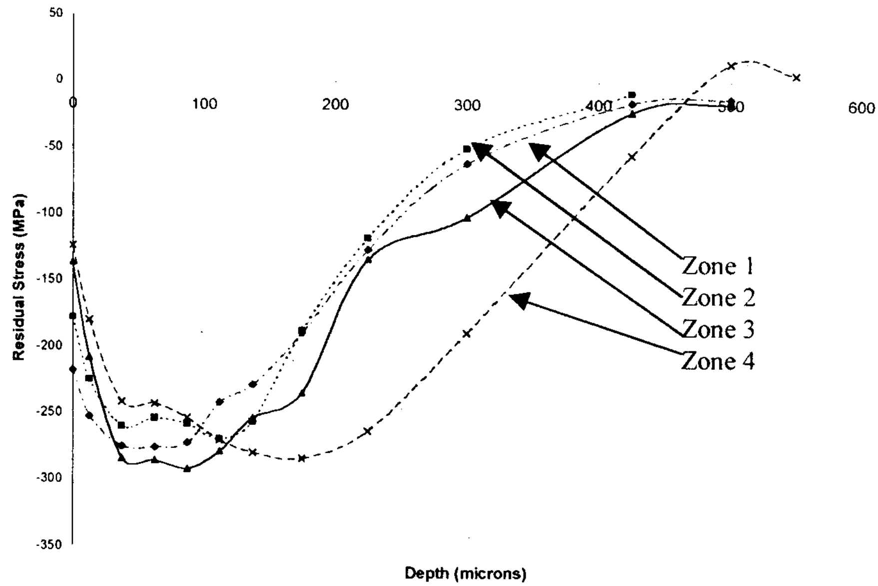

Figure 1. Depth profiles of residual stresses in 2014-T6 aluminum alloy for four different shot peening intensity levels. The error bars are ±20MPa.

X-RAY DIFFRACTION INSTRUMENT FOR SUBSURFACE STRESS MAESUREMENT

The instrument described in this paper was developed specifically for residual stress measurement in aluminum alloy aircraft wheels. It uses the MoKα x-ray radiation which has the 1/e penetration depth of 320 microns in aluminum alloy, covering therefore the whole layer modified by shot peening. The instrument is shown schematically in Figure 2. The work space is large enough to accommodate the aircraft wheels up to 70 cm in diameter (Boeing 777, B-52) which are positioned on an x-y-z stage. The residual stress is measured in χ geometry (e.g. 3) with available tilts in the full range of 0-90°. The diffracted x-rays are registered by a fiber optics and CCD based position sensitive detector described and evaluated elsewhere (4). The detector to sample distance has been optimized in such a way so that to provide for sufficient angular resolution (0.01° in 2Θ, where Θ is the Bragg angle), intensity of diffracted x-ray beam, and errors due to sample displacement (the required precision in sample positioning is approximately 50 microns and is realized by means of a mechanical gage). The position sensitive detector registers several diffraction peaks in relatively high 2Θ range providing for $2x10^{-4}$ sensitivity to strain. This sensitivity is appropriate for shot peened aluminum alloys, which usually display residual strains in the order of $5x10^{-4}$ to $5x10^{-3}$. The diffraction peaks used for analysis have been optimized for crystallographic texture which is always present in rolled and forged aluminum alloy products, and which very often hinders stress measurement by diffraction methods. The data collection time ranges from 1-10 minutes per peak depending on the condition of the sample. The diffraction data is corrected for absorption and Lorentz polarization (e.g. 3). The diffraction peaks are fitted the split Pearson VII profiles. The strains and stresses are calculated using a generalized least square method (5-6). The instrument design allows one to determine the full stress tensor in the region 0-300 microns below the surface using the methodology described elsewhere (7-9). However, such a procedure is lengthy, difficult to implement on curved surfaces and requires a skilled researcher. The method preferred in industry is a relatively quick measurement of absorption averaged stresses which gives a qualitative assessment of the shot peening level for an acceptance/rejection decision. Using a relatively narrow range of χ tilts the instrument measures absorption weighted stresses in the depth 0-300 microns. The methodology was tested through a series of comparative studies including x-ray diffraction combined with surface layer removal by electropolishing, neutron diffraction, and modeling.

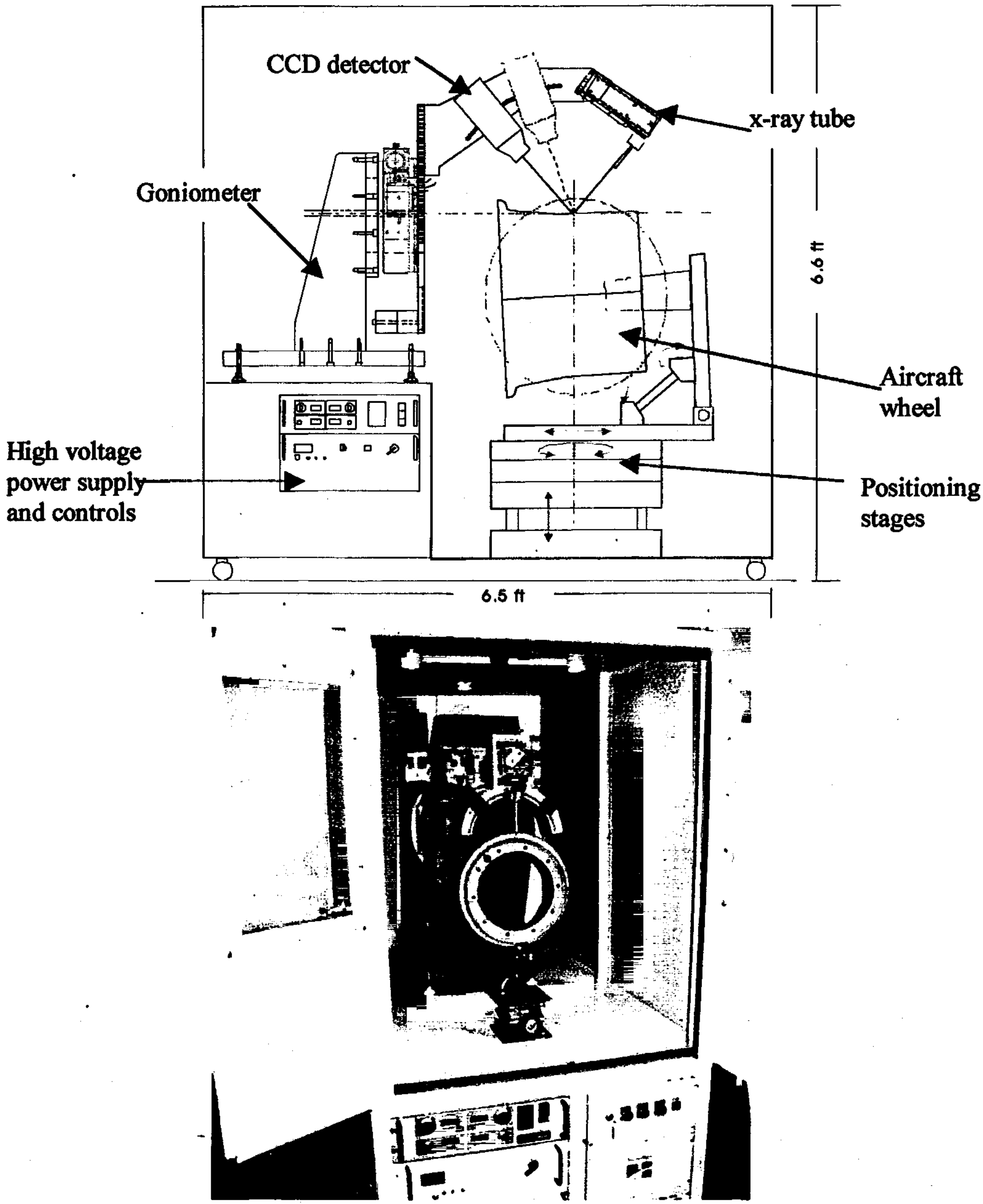

Figure 2. A schematic of a wheel stress analyzer (top) and a photograph of a test-bed system used for developmental work.

COMPARATIVE STUDIES

The comparative studies were carried out on a well-characterized set of samples. The coupons 5x5x1 cm3 were machined out of a Boeing 777 aircraft wheel (2014T6 alloy). Three samples were used for this study: in as machined condition, shot peened to 0.005" and 0.015" Almen intensity.

1. Neuron diffraction experiments were carried with the spatial resolution in the depth direction of 100 microns. Strains were measured in three principal directions and stresses recalculated using Hook's law. Due to the finite diffracting volume the measurement nearest to the surface was taken at depth of 100 microns. The neutron diffraction experiments showed that the out of plane stress component is non-existent and the state of stress due to shot peening of flat surfaces is eqi-biaxial (Figure 3). It is an important finding since most of the modeling and experimental work is based on the assumption of plane stress in shot peened surfaces.
2. X-ray diffraction and electropolishing experiments. A shallow penetrating CrKα radiation was used in conjunction with surface layer removal by electropolishing. The stresses were determined using the plane stress assumption. The stresses were homogeneous across the whole samples and truly equi-biaxial.
3. Modeling. The residual stresses were modeled using the Peenstress software (10-11). The profiles of residual stresses were modeled using the cyclic hardening law. Recognizing that the stress profiles are sample size dependent we considered two cases: a massive sample model and a finite thickness plate model.
4. X-Ray diffraction measurements using MoKα radiation. The absorption weighted residual stresses were averaged over 300 microns below the surface. The stresses were calculated using the plane stress assumption confirmed by the neutron diffraction experiments.

The results of the comparative study are shown in Figure 4.

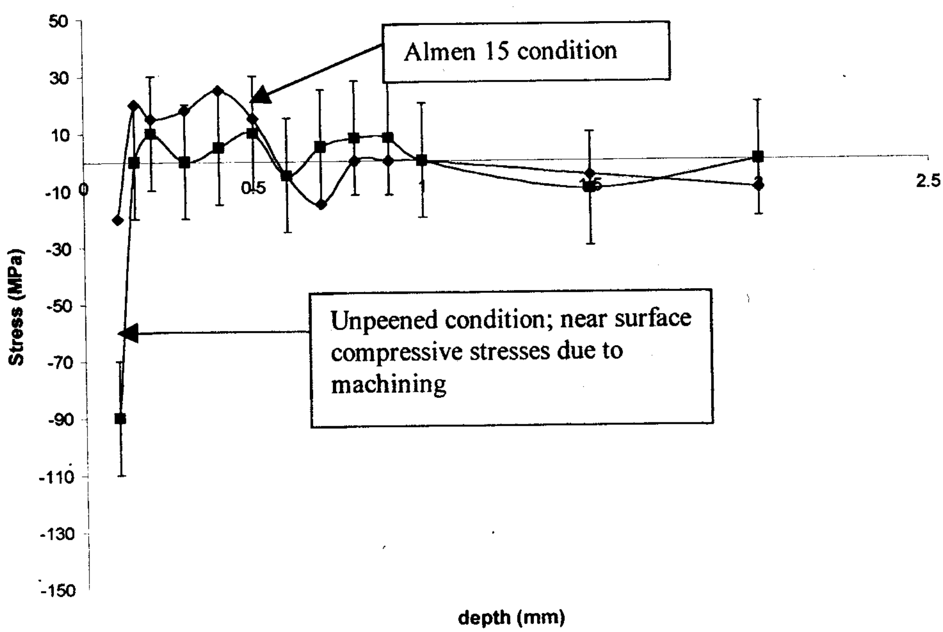

Figure 3. Normal (out of plane) stresses in Almen 15 and as machined, unpeened 2014T6 alloy.

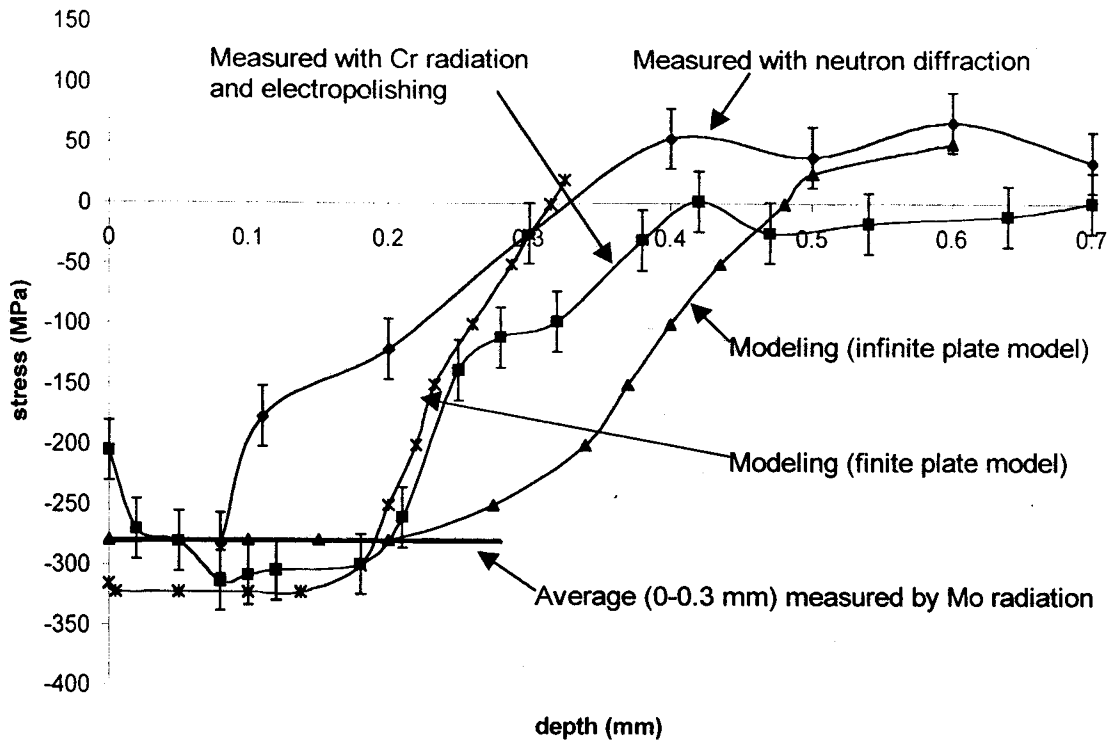

Figure 4. Comparative study of residual stress profiles in 2014T6 alloy shot peened to Almen intensity level of 0.015".

The stresses profile measured by Cr radiation and eletropolishing falls between the model predictions for infinite and finite plates, as expected. The profiles measured by neutron diffraction are shifted towards lower depths, which in part may be due to uncertainties in sample positioning with respect to the neutron beam. The stresses measured by Cr radiation and integrated (with absorption as a weighing function) over the first 300 microns (-260 MPa) are in excellent agreement with the average stress measured by Mo radiation (-280MPa).
Figure 5 shows the results of comparative studies for sample peened to 0.005" Almen intensity. The stress integrated over the 300 microns (-184 MPa) is in excellent agreement with the average stress measured with Mo radiation (-180 MPa).
Figure 6 shows the results for sample in as-machined condition. The initial neutron diffraction studies showed a slightly compressive stress in the subsurface regions they were attributed to machining stresses generated during sample manufacturing. Subsequently, the first 100 microns have been removed by gentle polishing. The surface stresses were measured by Cr radiation and the average stress in the 0-300 range by Mo radiation. The integrated stress profile measured by neutron diffraction (-45 MPa) and by Mo radiation (-42 MPa).
The summary of results of the comparison between the absorption weighted integrated stresses measured with Cr radiation and stresses measured with Mo radiation are shown in Table 2. The average stresses measured with Mo radiation are clearly indicative of the material condition. They can be used to distinguish between different levels of shot peening intensities as well as reliably separate the peened form unpeened components.

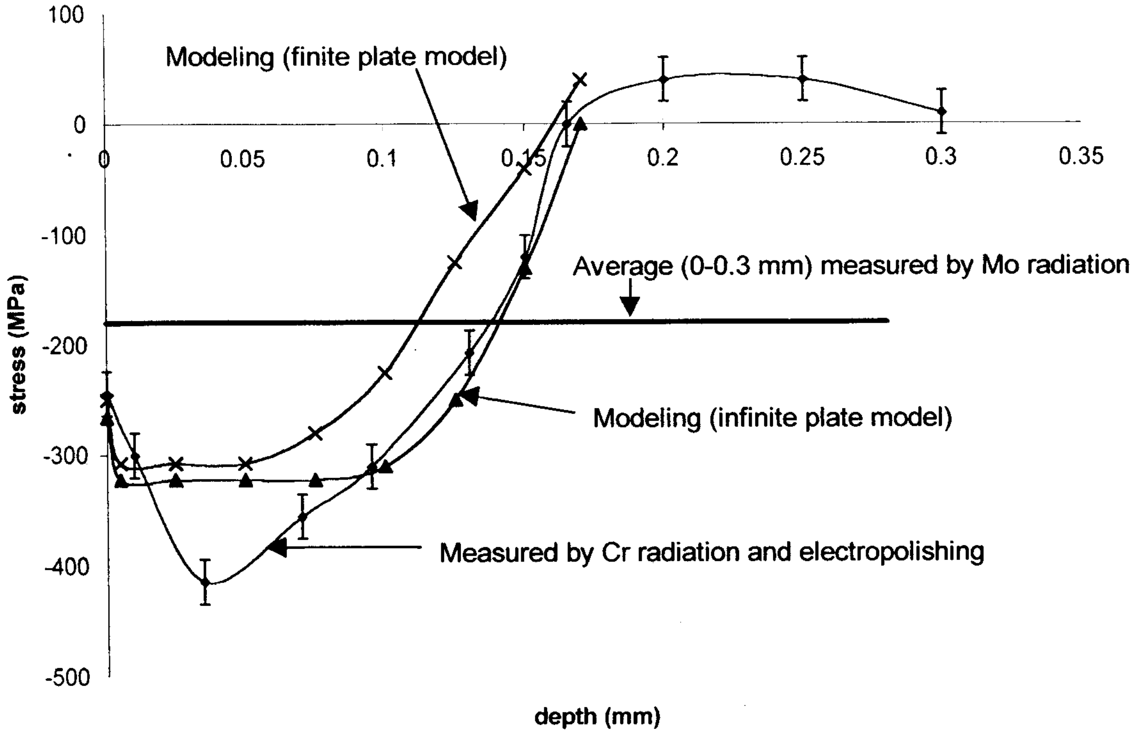

Figure 5. Stress profiles and averaged stresses for 2014T6 sample shot peened to 0.005" Almen intensity. The error bars on average stresses measured by Mo radiation are ± 50 MPa.

Table 2. Comparison between the absorption weighted integrated stresses measured with Cr radiation and stresses measured with Mo radiation. Stresses in MPa.

Specimen type	Stress measured with MoKα	Stress measured with CrKα and elctropolishing
As-machined	-42	-45
Almen 5	-180	-184
Almen 15	-282	-261

CONCLUSIONS

A new methodology has been developed to measure average stresses in the subsurface regions in the range of 0-300 microns in aluminum alloys. The new approach uses a deep penetrating MoKα radiation. The methodology has been tested by means of comparative studies with conventional x-ray diffraction/electropolishing method, neutron diffraction and modeling. The average stresses measured by Mo Ka radiation are in excellent agreement with other methods. Based on this methodology, an instrument has been built capable of mapping residual stresses on aircraft wheels with OD up to 70 centimeters. The average stresses measured with Mo radiation are clearly indicative of the material condition since they are not affected by surface conditions (such as surface roughness). They can be used to distinguish between different levels of shot peening intensities as well as reliably separate the peened from unpeened components.

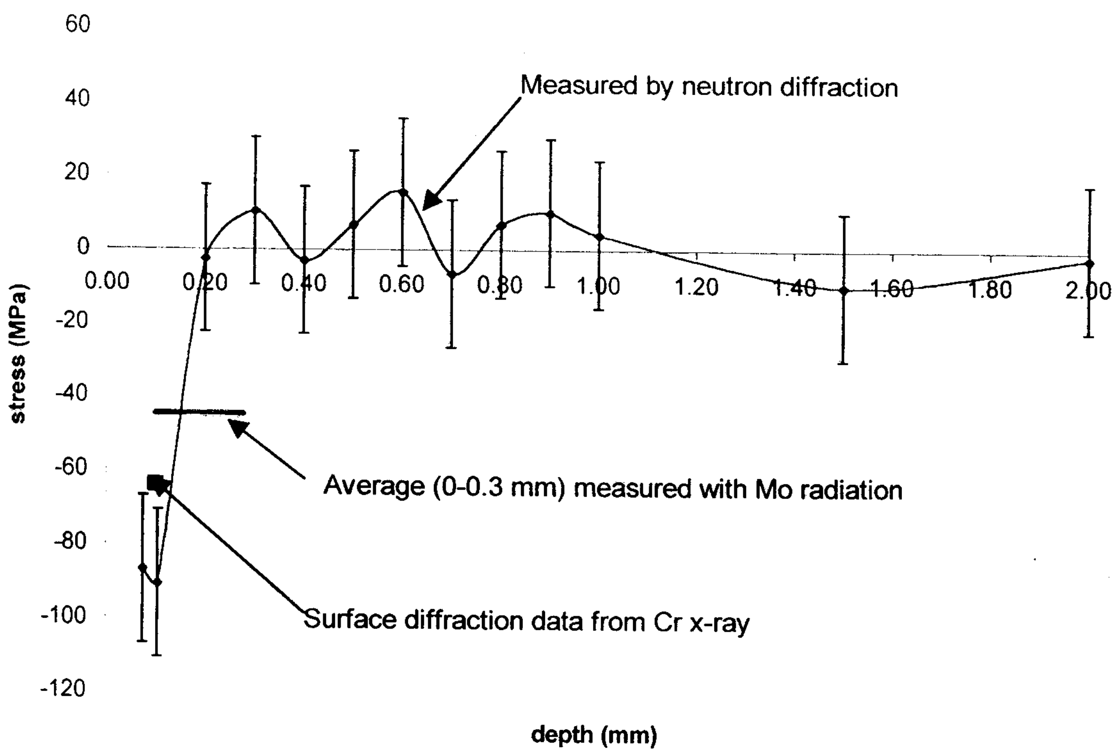

Figure 6. Stress profiles and averaged stresses for 2014T6 sample shot peened to 0.005" Almen intensity. The error bars on average stresses measured by Mo radiation are ± 50 MPa.

REFERENCES

1. Shot Peening Applications (Paramus, NJ: Metal Improvement Company, Inc.), p.6.
2. A. Li, V.Ji, J.L. Lebrun, and G. Ingelbert, "Surface Roughness Effects on Stress Determination by the X-Ray Diffraction Method," Experimental Techniques 19 (2) (1995), pp. 9-11.
3. I.C. Noyan, J.B. Cohen, Residual Stress. Measurement by Diffraction and Interpretation (New York: Springer-Verlag, 1987), p.120-126.
4. D. S. Kurtz, P. R. Moran, K.J. Kozaczek, M. Brauss, "Apparatus for Rapid $Sin^2\psi$ Stress Measurements and its Application to Titanium Alloy Jet Engine Fan Blades," The Fifth International Conference on Residual Stresses ICRS-5, ed. T. Ericson, M. Oden, A. Anderson (Linkoping University, Sweden, 1997), pp. 744-749.
5. R. A. Winholtz, and J.B. Cohen, Generalized Least-Squares Determination of Triaxial Stress States by X-ray Diffraction and the Associated Errors, " *Australia Journal of Physics*, **41** (1988) pp. 189-199.
6. J. Xue, K.J. Kozaczek, S.K. Kurtz, and D.S. Kurtz, "A Direct Algorithm for Solving Ill-Conditioned Linear Algebraic Systems," accepted for publication in *Advances in X-Ray Analysis*, at press.
7. B.L. Ballard, P.K. Predecki, and D.N. Braski, *Adv X-Ray Analysis* **37** (1994) pp. 189-196.
8. B.L. Ballard, P.K. Predecki, T.R. Watkins, K.J. Kozaczek, D.N. Braski, and C.R. Hubbard, "Depth Profiling Biaxial Stresses in Sputter Deposited Molybdenum Films: Use of the cos2ϕ Method," *Advances in X-ray Analysis*, Vol. **39** (1998) pp. 363-370.
9. X. Zhu, Ph.D. Thesis, University of Denver, Denver, CO, 1995.
10. Peenstress^{sm}, Metal Improvement Company, Paramus, NJ, U.S.A.
11. S. Slim, T. Harm, G. Ingelbert, N. Point, "Prediction of Residual Stresses Due to Shot Peening Using Modelling of the Material Behavior," *Materials and Manufacturing Processes*, **10** (9)(1995), pp. 579-588.