Non-Destructive Measurement of Residual Stress Versus Depth Using Diffraction

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Abstract

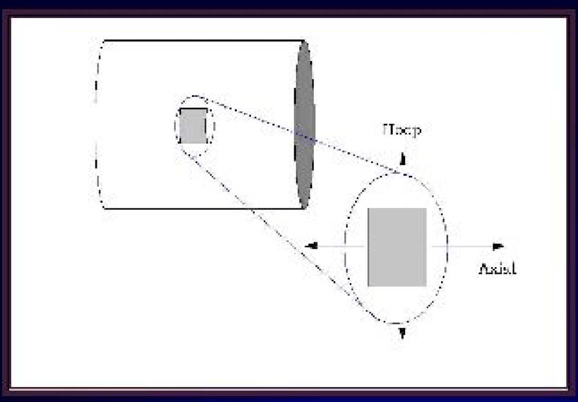
Synchrotron x-ray radiation offers many advantages over conventional sources. One of these is the ability to choose the x-ray energy/wavelength over a wide spectrum. Generally speaking, increasing the x-ray energy increases the depth of penetration. When combined with XRD residual stress techniques, this fact allows the resolution of near surface residual stresses versus depth non-destructively. Traditionally, stress versus depth measurements have been done using either neutron diffraction or a destructive XRD/layer removal technique. The neutron method is excellent for interior measurements, but due to the sampling volume size, it is not appropriate for resolving sharp stress gradients near a surface. The XRD/layer removal technique is capable of resolving these near surface stress gradients, but it is destructive, which is often undesirable.

In this study the x-ray energies selected allowed measurements to be made with the same family of planes, allowing the use of a single x-ray elastic constant generated using conventional methods. The contributions to residual stress at each depth are successively separated from each depth/volume at each energy level via linear numerical inversion method. The residual stress versus depth profiles are then generated for two 0.4% carbon steel samples with different surface treatments: 1) forged and shot peened, and 2) induction hardened and ground. The results will be compared to the XRD/layer removal and neutron measurements.

Introduction

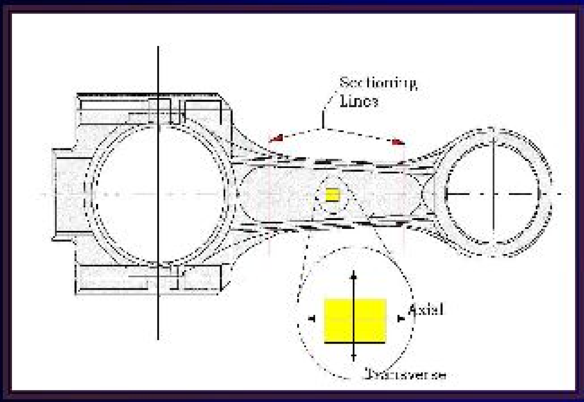
- ❖ Many processing operations have been developed, such as opening, to impart a highly compressive layer on the surface of the component
- ❖ This residual stress is of interest due to it's influence on component fatigue life
- ❖ Measurement of the residual stress profile is typically destructive, using an XRD - layer removal technique (here etching)[1]
- ❖ Non-destructive measurement of the residual stress depth profile is of interest since it would allow subsequent fatigue testing of the same component
- ❖ XRD and fatigue testing of the same components measured will increase residual stress-fatigue data correlation

Directions of Stress in Crankshaft Specimen



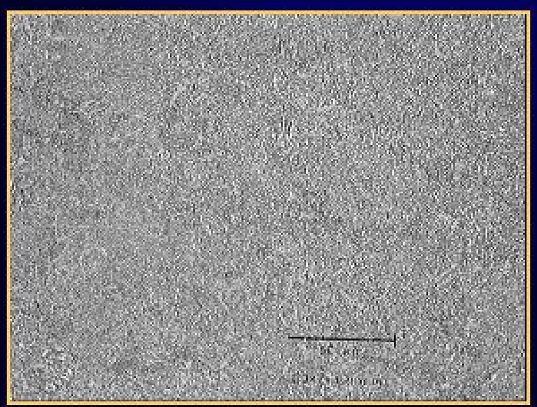
- ❖ Sample was sectioned from a finished crankshaft that had been induction hardened and ground

Directions of Stress in Connecting Rod Specimen



- ❖ The rod was forged, quench and tempered, and shot blast prior to sample sectioning

Crankshaft and Connecting Rod Samples Contain a Fine Tempered Martensite Microstructure



- ❖ The material in both sample types was a quenched and tempered 0.45% carbon steel

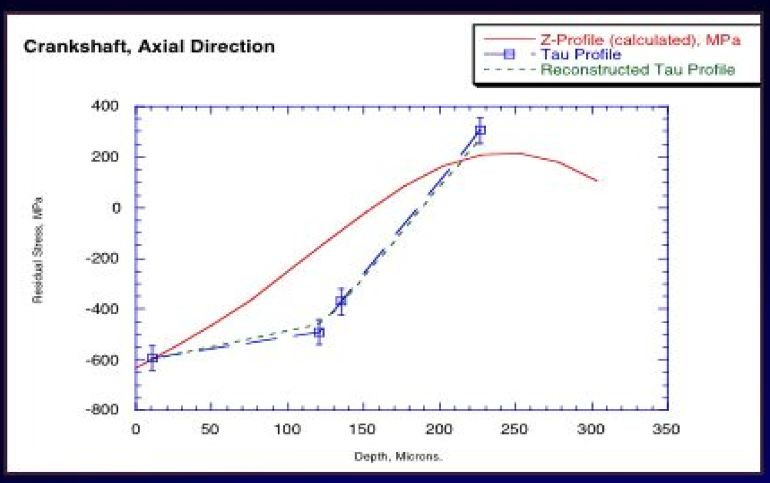
Experimental Procedure

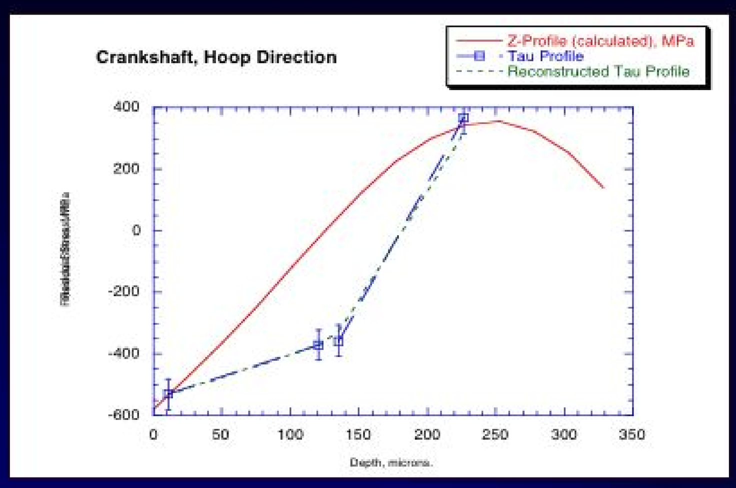
- ❖ The (211), (422) & (633) Fe peaks were selected to allow use of a single x-ray elastic constant, derived for this material
  - $(1+\upsilon)/E = 5.17 \times 10^{-12}$ Pa for [211] direction
  - E = 251 GPa assuming $\upsilon = 0.3$
- ❖ Synchrotron measurements were made at the NSLS facility at BNL and at the APS facility at the ANL
- ❖ Measurements were made at 5.35, 17.5, 26.5, and 30.0 KeV using parallel beam optics
- ❖ Neutron measurements were made at HFIR (λ = 1.65 Å) on the (211) Fe peak

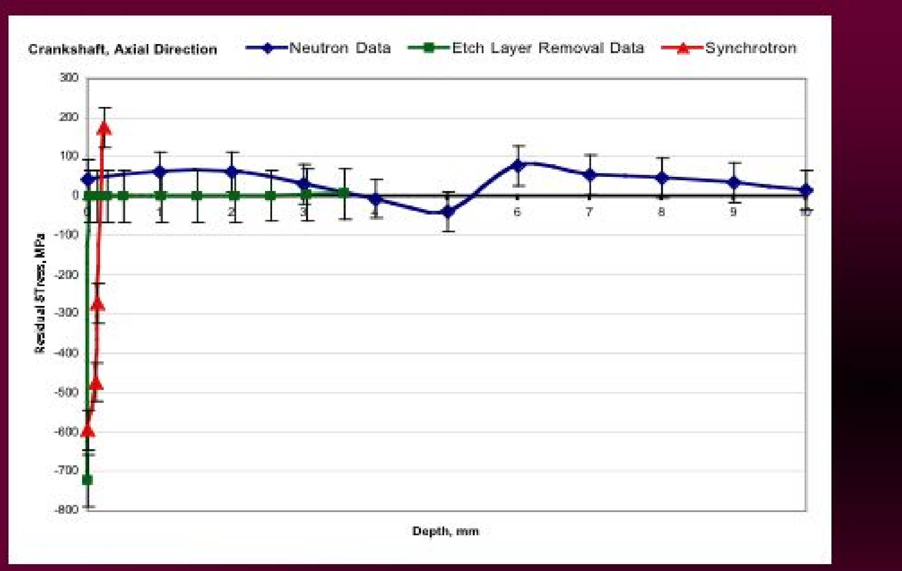
Analysis

- ❖ An exponentially weighted average of the interplanar spacing as a function of energy (depth) and ψ angle was measured
- ❖ The residual stresses were calculated using the $\sin^2 \psi$ technique[2]
- ❖ An *estimate* of the actual residual stress depth profile was calculated from the exponentially weighted averaged data using a numerical linear inversion technique[3,4]

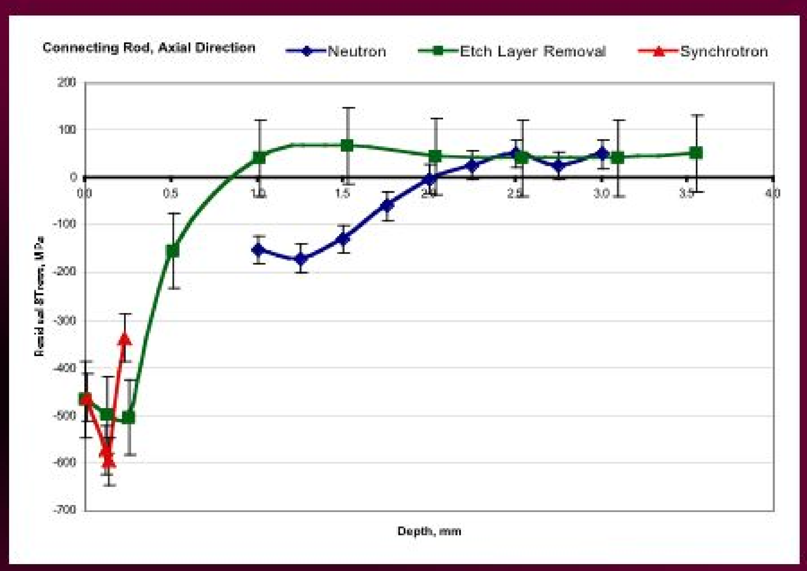
The synchrotron data for the crankshaft sample clearly shows the transition from compressive to tensile residual stress, since the depth of deformation due to the grinding operation is shallow.





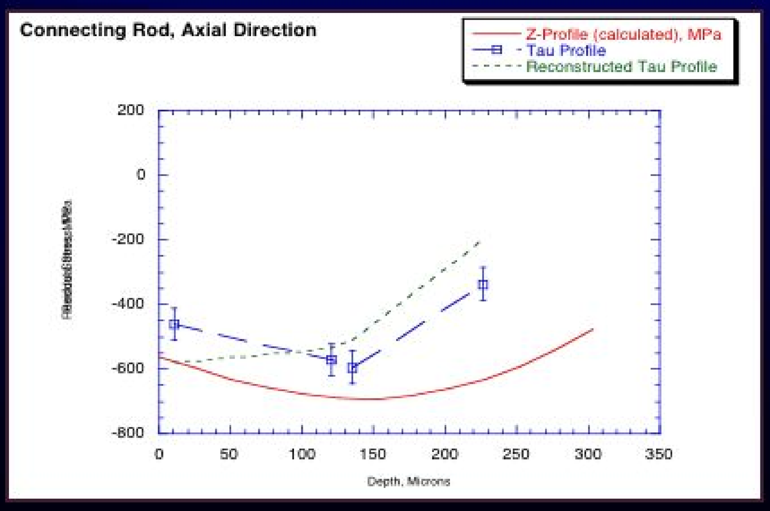


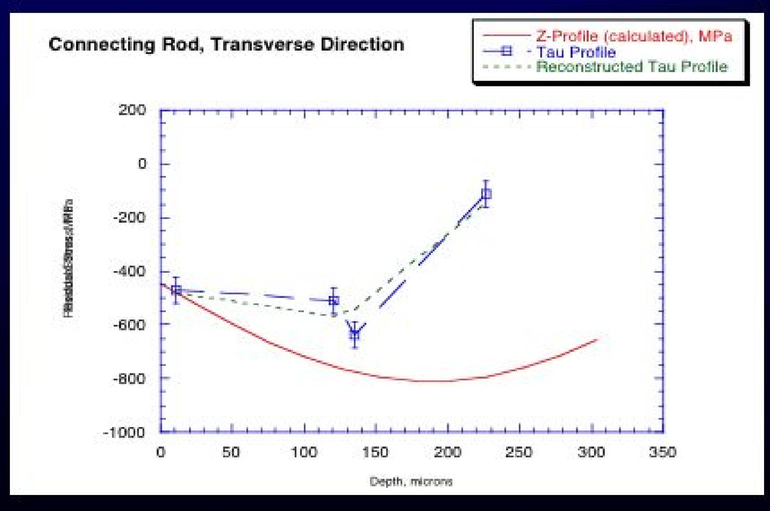
The XRD/etch layer removal data from the axial direction of the crankshaft sample shows agreement with with the synchrotron data.



The data from all three techniques in the axial direction of the connecting rod sample display trend agreement.

Due to shot peening, the connecting rod sample has a compressive layer greater than the depth measured using the synchrotron energies of this study.





Summary

- ❖ The residual stress as a function of depth was measured non-destructively by using neutrons and by varying the energy/wavelength of the incident radiation
- ❖ A linear numerical inversion method, first applied to grazing incidence x-ray diffraction data, was employed to estimate the actual stress profile from the measured data
- ❖ Some agreement between the measurements was observed
- ❖ Although destructive, the conventional x-ray diffraction / layer removal method was preferred

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