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Several Methods Applied to Measuring
Residual Stress in a Known Specimen

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In this study, a beam with a precisely known residual stress distribution provided a unique experimental opportunity. Several methods were used to determine the residual stresses, and the results were compared to the known values. Some subtleties of applying the various methods were exposed.

Known Residual Stress Specimen

A plastically bent beam was carefully prepared in order to provide a specimen with a known residual stress profile. 21Cr-6Ni-9Mn austenitic stainless steel was obtained as 43 mm square forged stock. It was annealed at 1080°C for one hour and argon quenched. Next, the beam was machined to final shape with a 30 mm by 10 mm cross section in the gauge section. Then the beam was thoroughly stress relieved by heating in a vacuum to 1080°C for 15 minutes and slow cooling at 100°C per hour. Thermally compensated strain gages were mounted to the top and bottom surfaces of the beam. The beam was then plastically bent and unloaded in a four-point bend fixture. Strain and load measurements allowed the calculation of independent stress-strain curves for loading and unloading in both tension and compression [1]. Finally, superposition of these curves gave the residual stress profile.

This residual stress profile in this beam is characterized much more accurately than standard bent beams. In other bent-beam residual stress specimens, a tensile stress-strain curve, measured in a separate test, is assumed to describe the loading of the beam in both tension and compression. In addition, the unloading is assumed to be linearly elastic. In this study, all of the stress-strain curves are measured on the actual beam during the bending tests. The measured curves will reflect any differences between tension and compression and account for the Bauschinger effect during unloading. The tension-compression asymmetry is reflected in the results from the bend test shown in Figure 1, where the magnitude of the tensile and compressive peaks differ by about 20%.

Measurement Results

Figure 1 shows the measured residual stress profiles compared with the known profile from the bend test. Each method is discussed in detail below.

Neutron Measurements

The through-thickness residual stress profile was measured using the neutron powder diffractometer at the Los Alamos
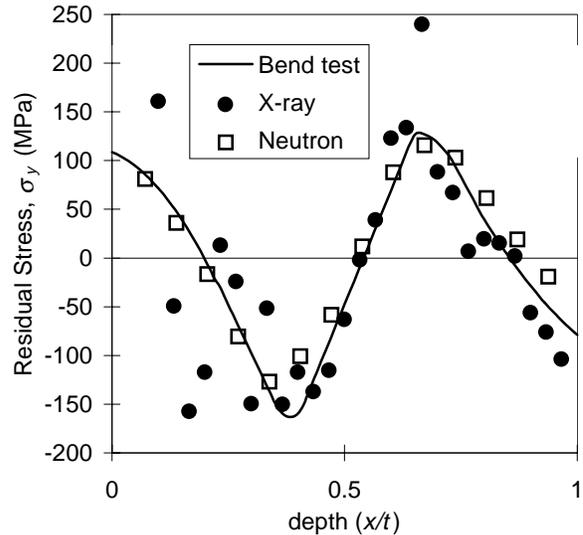

Figure 1. Measured and known residual stress profiles.

Neutron Science Center (LANSCE). The results are plotted in Figure 1. Using radial collimation [2], 16 measurements, each sampling 48 mm³, were taken through the beam thickness as shown in Figure 2. Approximately 4 hours was required for each measurement position to produce adequate counting statistics. The two measurement volumes at either edge of the beam were partially outside the beam and, therefore, could not be used in the final data analysis [3].

At a time-of-flight (TOF) neutron source, a pulse of neutrons, each with a continuous range of velocities and thus wavelengths, are directed at the sample. The flight times of the detected neutrons are recorded, resulting in diffraction spectra. The scattering vector for all the reflections recorded in a given detector lie in the same direction and hence measure the strain in that direction. Therefore, each reflection is produced by a different family of grains, oriented such that the given hkl plane diffracts to the detector. The entire spectrum is then fit using a Rietveld least squares procedure [4]. In a Rietveld refinement, a proposed crystal structure is optimized to maximize agreement with the measured diffraction pattern. The variation in observed lattice parameter d is used to calculate strains. The validity of comparing the strains obtained from various single diffraction peaks (as measured at x-ray sources or monochromatic neutron sources) with Rietveld refinement strains is considered elsewhere [5]. In general, the Rietveld

refinement results will agree better with continuum scale measurements or predictions.
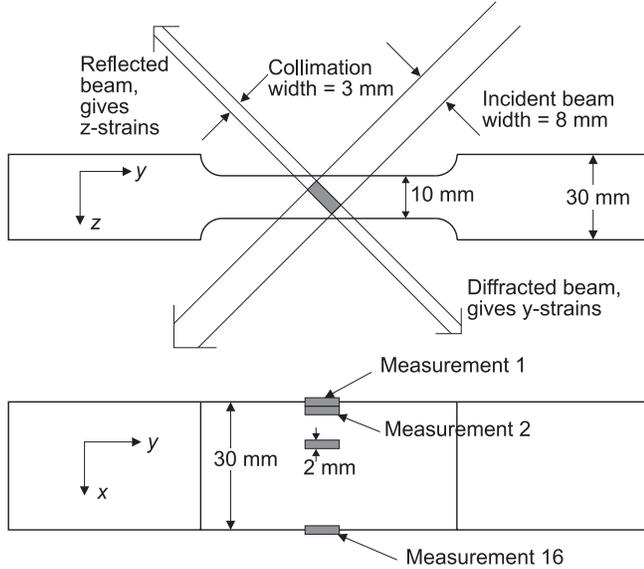

Figure 2. Measuring residual stress profile $\sigma_y(x)$ using neutron powder diffraction.

The determination of absolute strains, as opposed to relative strain changes, is dependent on the accurate measurement of a reference, or unstressed, lattice parameter d_0 [6]. In this case, we carried out three further measurements outside the gauge volume, and used the lattice parameter averaged over these positions to calculate the absolute strains.

Because the stresses through the beam thickness must satisfy equilibrium, it is possible to estimate the error in our measured d_0 using the ratio

$$\frac{\int \sigma_y(x)dA}{\int |\sigma_y(x)|dA} \qquad (1)$$

integrated over the cross section. For the stress profile in Figure 1, this non-balance index was about 16%. An adjustment of d_0 by an amount equivalent to about 50 $\mu\varepsilon$, or about 10 MPa, would result in equilibrium being satisfied. Such an adjustment would also result in slightly better agreement between the neutron results and the known residual stress profile.

Figure 1 shows residual stresses rather than strains. The Rietveld strains were converted to stresses by assuming that the residual stresses were uniaxial, i.e., $\sigma_x = \sigma_z = 0$, giving

$$\sigma_y(x) = E\varepsilon_y(x) \qquad (2)$$

where E is the elastic modulus measured during the bending test, 194 GPa.

Without the uniaxial stress assumption, or a similar assumption, one would need measurements of all three strain components to calculate stress from the measured strains. Figure 3 plots the measured transverse strain profile and the profile calculated from the measured longitudinal

strains and the uniaxial stress assumption. They should be the same but clearly are not. Some of the difference is due to the difficulty in determining d_0, which was determined separately for the transverse orientation. However, no adjustment of d_0 could make all of these values agree to within 150 $\mu\varepsilon$. Combined with a similar uncertainty in the strains in the third direction, large uncertainties would result from using measurements of all three strain components to calculate the residual stress.
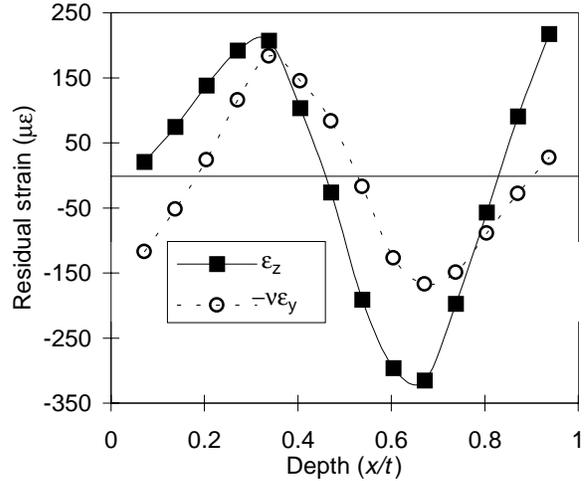

Figure 3. Measured transverse strains compared to plane stress assumption.

X-ray Measurements

X-ray diffraction (XRD) residual stress measurements were determined at the Lujan Center at Los Alamos National Laboratory. The XRD was performed with Copper Kα radiation which has a shallow penetration depth (≤ 10 μm) in the steel. Therefore, the irradiated region was assumed to be under plane stress conditions and the classical "d vs. Sin$^2\psi$" approach was used employing the (331) peak of the steel ($2\theta \approx 137^\circ$). The X-ray elastic constants for the (331) peak of 96.6 GPa was obtained from literature [7]. Stress measurements were made by collimating the X-ray beam to obtain a spot size of 3 mm diameter on the specimens. The stresses were determined at 28 positions along the height of the sample by stepping in increments of 1.0 mm. Thereby the sampling areas overlap by 2.0 mm giving a better spatial resolution. Figure 1 shows the x-ray results.
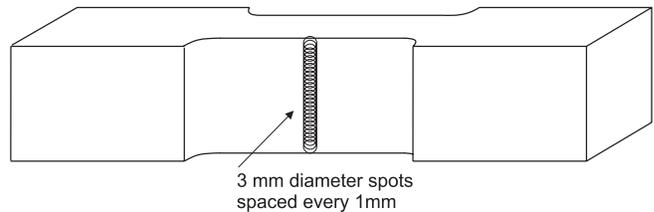

Figure 4. Measuring residual stress profile using overlapping x-ray measurements.

The scatter in the x-ray measurements was quantitatively

correlated with grain size variations in the beam. The grain sizes were determined as a function of x in the region where the x-ray measurements were taken. The area was etched with Marble's reagent, photographed at 100X, and compared with an ASTM standard E112 grain size chart. The apparently banded structure exhibited grain size that varied from ASTM 3 to 5, corresponding to 62 and 248 grains/mm^2, respectively. This grain density variation was integrated over the area of each 3 mm diameter x-ray spot to determine the number of grains sampled. Figure 5 plots the error between the x-ray results and the known residual stress vs. the number of grains sampled. Each data point corresponds to an x-ray measurement at a different location. The correlation between the stress error and the number of grains sampled is striking.
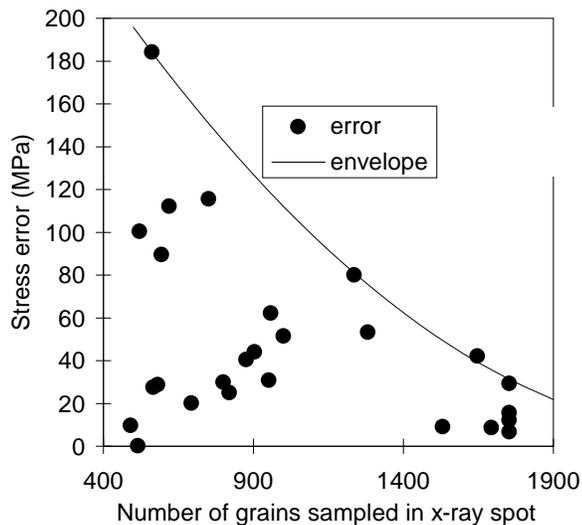

Figure 5. Error in x-ray stress measurements correlated to grain size variations.

The banded grain size variations were explained by metallographically examining a cross section of the beam. An "X" pattern of finer grains was observed, spanning diagonally opposite corners of the original 43 mm square cross section. Apparently, this arose because of working along maximum shear planes during a forming process.

Ultrasonic Measurement

It was attempted to determine the residual stress profile by measuring the transit times of ultrasonic waves. Unfortunately, the only residual stress component present in the beam, σ_y, did not prove to be amenable to measurement because of geometric constraints.

Conclusions

Time-of-flight neutron diffraction measurements combined with a Rietveld refinement proved to be a powerful and precise tool for measuring residual macrostrain. The largest source of error in this test was the determination of the unstressed lattice parameter. X-ray diffraction measurements showed large scatter in some portions of the residual stress profile. The scatter was quantitatively correlated with coarser grained regions.

Measurement of the residual stress profile using the crack compliance method [8] was not completed in time for this paper but will be reported later. In addition, the residual stress profile is being measured on a second, identically prepared specimen with the a technique involving local laser heating and speckle-correlation interferometry [9]. These results will also be reported later.

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