AN ATTEMPT TO MEASURE ELASTIC STRESS WITH POSITRONS

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INTRODUCTION

It is well known that residual stress can be measured with varying degrees of success by x-ray diffraction methods [1]. Nonetheless, it would be well to have additional nondestructive techniques capable of this kind of measurement. Positron annihilation is one potential alternative, which has previously been applied to the study of shot peening [2]. Although shot peening produced readily detectable changes in the positron annihilation measurements, it was not possible to relate these changes directly to the residual stresses produced. Since residual stresses are elastic, the intention of the present research was to use positron annihilation to initially measure applied uniaxial elastic stresses and then extend the technique to measure actual residual stresses.

EXPERIMENTAL DETAILS

The two alloys used in this study were AISI 321 (an austenitic stainless steel) and aluminum alloy 3003 (a nonheat-treatable Al-Mn alloy). The nominal compositions of these alloys are given in Table 1. The AISI 321 material was obtained in the form of 0.063-inch thick sheet in the solution-treated condition. The Al 3003 material was obtained in the form of 0.123-inch thick sheet in the strain-hardened condition. Flat tensile

TABLE 1

Nominal Compositions of Alloys (wt. %)

	Cr	Ni	C	Ti	Fe
AISI 321	18	10.5	0.08	0.40	Bal.
	Mn	Cu	Al		
Al 3003	1.2	0.12	Bal.		

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samples were machined from both alloys. Tensile samples 321•T2A and Al•3003•T2A were annealed at nominally 1050°C and 430°C, respectively, for one hour and furnace cooled (the annealing was performed in an argon-purged furnace).

An intrinsic germanium gamma ray detector, main amplifier, biased amplifier, multichannel analyzer, digital spectrum stabilizer, and personal computer were used to record and analyze data describing the Doppler energy shift spectrum of gamma rays accompanying positron annihilation, as described elsewhere [3]. A fixture was designed to statically load the samples in uniaxial tension. An internally gaged screw in series in the load train of the fixture served to both apply and measure the load. To obtain positron data, a window was machined into the tensile fixture to permit access of the gamma ray detector to one side of the specimen. With the fixture placed in front of the gamma ray detector, a radioactive ^{68}Ge positron source was placed against the opposite side of the tensile specimen from the detector. Positron data were then acquired at each desired load. Zero load readings were taken before and after each load series to check the stability of the positron system.

X-ray residual stress measurements were performed on AISI 321 samples at Northwestern University on a Picker diffractometer with an omega tilt stage. Residual stress values normally are determined from slopes of d (interplanar spacing) versus sin^2 psi curves [1] where psi is a tilt angle.

RESULTS AND DISCUSSION

The positron data obtained on the loaded tensile samples are summarized in Figs. 1 and 2 for AISI 321 and Al 3003 respectively. A different symbol is used to represent each series of tests with the same specimen. In Fig. 1, the error bars are the same size as the symbols, and in Fig. 2 representative error bars are shown. Samples 321•T1, 321•T3, and Al•3003•T3 are in the as-received condition. Samples 321•T2A and Al•3003•T2A are in the annealed condition. For all of the samples tested, no significant change was observed in the P/W parameter as a function of applied tensile stress.

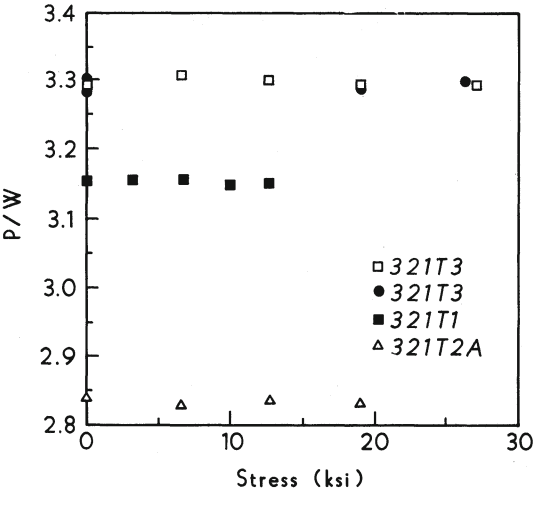

Figure 1. P/W parameter versus applied stress (ksi) for AISI 321 stainless steel. Samples T3 and T1 as received; sample T2A annealed.

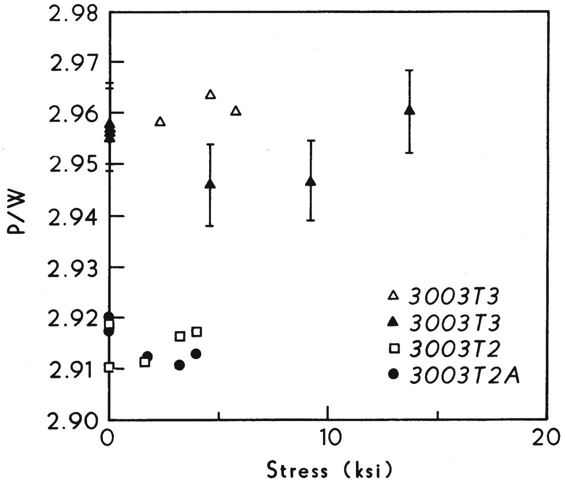

Figure 2. P/W parameter versus applied stress (ksi) for Al 3003 alloy. Sample T3 as received; sample T2A annealed.

Two other works are helpful in interpreting the above lack of response. Both involve Doppler broadening experiments on metals at high pressure: Radousky et al. [4] in iron and Jeffery and Sendezera [5] in Cu, Cd, Al and Pb. For all of the metals studied, the P parameter (similar to our P/W) decreased linearly as the pressure increased. As the metal ions are brought closer together (and possibly vacancies leave), positrons are more likely to annihilate with high-momentum electrons, resulting in lower values of their P parameter. The present results can be understood in a similar manner. When our samples were loaded elastically in tension, they underwent a slight elastic increase in volume. This can be calculated from

$$\Delta V/V = \varepsilon_x + \varepsilon_y + \varepsilon_z = \frac{\sigma_x}{E} (1 - 2\nu) \qquad (1)$$

Using values of $\sigma_x = 14 \times 10^3$ psi, $E = 12.2 \times 10^6$ psi and $\nu = 0.283$ for our aluminum sample, one obtains a maximum fractional volume increase of 4×10^{-4}. The change in the P parameter for a given pressure-induced volume change can be calculated from the results presented by Jeffery and Sendezera [5] using the relationship

$$\frac{\Delta P}{P_o} = \beta \frac{\Delta V}{V_o} \qquad (2)$$

where β is the slope of the P parameter versus pressure curve. Using their reported value of $\beta = 1.14$ for aluminum, a volume change of 4×10^{-4} would produce a change in P parameter of only 0.05%, which is the same order of magnitude as our experimental error. Thus it appears that the magnitude of the effect was too small to be detected in the present loading mode.

During the machining of one tensile blank of AISI 321 from 0.063 to 0.035 inches, extensive warpage was noted, suggesting that residual stresses were present in the as-received material. This warped blank was found to have a P/W value of 2.917 (with a standard deviation of 0.008) as compared to a value 3.006 (with a standard deviation of 0.009) for the unmachined as-received material. This difference is in the wrong direction to be explained by the presence of dislocations introduced by machining and bending, since such new dislocations would increase the value of P/W. This suggests that perhaps the positron technique may be sensitive to residual stress. To pursue this question, it was decided to alter the residual stress distribution in the as-received material by chemical milling. This milling was done simultaneously from both sides of an as-received piece so as not to produce any distortion or surface damage.

The positron data for the chemically milled samples is shown in Fig. 3. The P/W parameter clearly decreases as more material is removed. The points designated as annealed represent samples of different thicknesses prepared and annealed to assure that we were not picking up any effect simply due to an increasing fraction of positrons getting through thinner samples, annihilating in the air and thus altering P/W. Clearly such was not the case. Before attributing these changes to differences in residual stress, we performed x-ray measurements of stress as described in the previous section. The x-ray results gave a nonlinear d versus $\sin^2$ psi response which unfortunately leads into a controversial area in which there is no clear agreement on how such data should best be analyzed [1]. If indeed the positron data in Fig. 3 represent residual stress changes, then one is faced with explaining (again) why the tensile applied stresses caused no change in P/W.

To do this, it is first well to recall that dislocations do indeed cause an increase in P/W. Consider a sample which has a gradient in dislocation density with the density being highest at the surface and decreasing toward the interior. The P/W values for such a sample would decrease as material was removed from its surface. Such a dislocation density distribution can be produced by nonuniform platic deformation, which also would result in the production of residual stress. An example of this is sheet which receives only a slight reduction in thickness in rolling such that plastic deformation only occurs close to the surface. Due to this local plastic deformation, the surface during the rolling process tries to elongate with respect to the central region of the sample, with the result that, upon release from the rolling mill, the outer regions of the sheet go

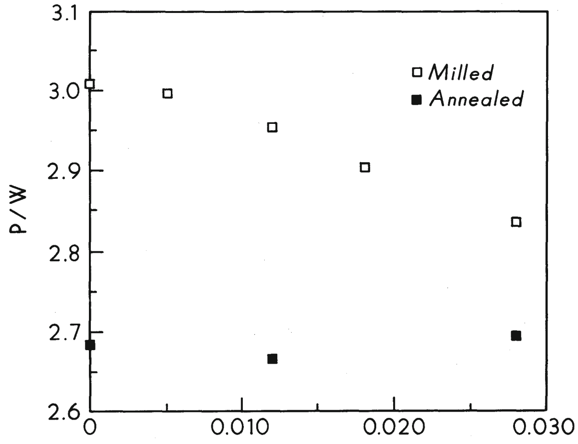

Figure 3. P/W parameter versus thickness removed (in units of 0.001 inch) by chemical milling of AISI 321 stainless steel.

into elastic compression, and the central region goes into elastic tension. In the present case, this situation evidently existed, since the machined side of our as-received AISI 321 blank become convex, indicative of removal of a layer which had been in compression prior to machining; i.e., release of a residual compression layer permits tension to act on that side, resulting in convex curvature on the side from which material is removed [6].

CONCLUSIONS

We see no correlation between positron annihilation parameters and applied elastic tensile stress in either AISI 321 or Al 3003. The decrease in P/W with chemical milling from both sides simultaneously in the AISI 321 suggests that a gradient of dislocation density had been present with the higher value toward the outer surfaces. This gradient in turn could produce a residual stress distribution of the right kind to produce the type of curvature observed when only one side was machined [7]. Thus, although low values of elastic tensile stress are not detectable by our positron measurements, the presence of residual stress produced by nonuniform plastic deformation can be inferred from the detection of gradients in dislocation density.

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REFERENCES

1. I. C. Noyan and J. B. Cohen, Residual Stress Measurement by Diffraction and Interpretation, (Springer-Verlag, New York, 1987).
2. S. Saterlie, M. L. Johnson, P. Alexopoulos, F. Seppi, R. Ure, and J. G. Byrne, Physica Status Solidi, 41(a), K175 (1977).
3. Yi Pan and J. G. Byrne, Review of Progress in Quantitative NDE, Vol. 6B, edited by D. O. Thompson and D. E. Chimenti, (Plenum Publishing Corp., New York (1987).
4. H. G. Radousky, R. L. Reichlin, and R. H. Howell, Proc. 7th Intl. Conf. on Positron Annihilation, edited by P. C. Jain, R. M. Singru, and K. P. Gopinathan, (World Scientific Publishing Co., Singapore, 1985).
5. R. N. Jeffery and E. J. Sendezera, Proc. 6th Intl. Conf. on Positron Annihilation, (Wayne State Univ. Press, Detroit, 1982), pp. 410-412.
6. N. H. Polakowsky and E. J. Ripling, Strength and Structure of Engineering Materials, (Prentice-Hall Inc., Englewood Cliffs, 1966).
7. J. J. Gilman, Acta Met., 3 (1955), 277.