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ROLE OF PHASE TRANSFORMATIONS IN RESIDUAL STRESS DEVELOPMENT IN MULTIPASS FERRITIC STEEL WELDS AND GLEEBLE TEST BARS

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Abstract

Neutron strain scanning has proven very effective in non-destructive mapping of the distribution of residual stresses in weldments. Strain scanning of Gleeble test bars of 2 1/4 Cr-1 Mo steel has been carried out in conjunction with strain scanning investigations of a multipass weld in 0.5-in. plate of the same alloy. The residual stresses in the Gleeble bars depend on the time spent at the maximum temperature and the rate of cooling. The longitudinal strains on the Gleeble bar center-line are tensile with a maximum on either side of the central hot zone. The transverse strains are compressive but vary with thermal treatment to a higher degree than variations in the longitudinal strains. The difference between strains at the center-line and off the center-line can be significantly greater than statistical error in air-cooled Gleeble bars. The strains in the Gleeble bar have a high tensile component parallel to the direction of maximum heat transfer (viz. along the bar axis). By contrast, the large tensile strains in the heat-affected zone (HAZ) of the weldment are along the weld line which is essentially perpendicular to the direction of maximum heat transfer. The simulated conditions present in Gleeble bar test specimens are different from that observed in weld HAZ.

RESIDUAL STRESSES THAT DEVELOP IN THE heat-affected zone (HAZ) are associated with the heating and cooling of the base metal in the vicinity of the fusion zone. The thermal cycle experienced in the HAZ can be simulated by the Gleeble test. The microstructures produced in the Gleeble test bars are similar to the microstructures found in the HAZ of the weldment, and it is of interest to show that the mechanical properties in the HAZ are equally well simulated in Gleeble specimens. One of the first residual stress investigations of Gleeble test bars was carried out with X-ray residual stress analysis of austenitic stainless steel (1). The X-ray method probes the surface residual stress state, and material removal permits in-depth characterization. In this paper the development of residual strains in 2 1/4 Cr-1 Mo steel Gleeble bars is examined with neutron strain scanning and related to the strain mapping done in a 1.24-cm (0.5-in.) multi-pass weld made from the same material (3). The 2 1/4 Cr-1 Mo steel has a bainitic microstructure with a bainite start temperature of approximately 550°C. The microstructures and hardness variations within a weld of a closely related steel (3Cr-1.5Mo-0.1V) have been described by Vitek and David (2). Generally, the fusion zone consists of uniform bainitic microstructure with some retained austenite. In the HAZ there is a transition region consisting of a mixed bainite and ferrite structure with some retained austenite and then a return to uniform bainite having no retained austenite. There is a hardness minimum in the region containing ferrite, and the location of this minimum depends on the rate of cooling. The formation of bainite upon cooling generates residual stress which is added to the thermal expansion effects. Residual stress contribution from austenite to bainite transformation is due to transformation plasticity associated with the shear and dilatation of the bainite transformation (3,4).

This paper presents a short description of the neutron strain scanning method as applied to the welded plate and the Gleeble bars. The contributions of both mechanical and chemical sources of lattice strain can play a part in the study of weldments, thus measurements of "strain-free" pieces taken from the Gleeble bars are presented in this investigation as well. The effects of solid state transformation are demonstrated by comparing the ferritic and austenitic plates. Finally, the strain maps in Gleeble bars are

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interpreted, and the strain map of the welded bainitic steel plate is related to the Gleeble bar results.

Neutron Scattering Experiments

The use of neutron diffraction for residual stress evaluation is well established at most neutron research centers in the world. The method determines lattice strain from the observation of changes in lattice d-spacing obtained from diffraction peak shifts. The advantage of neutron radiation is that samples can be probed to depths up to a few centimeters. A full three-dimensional strain tensor can be determined by appropriate variation of diffraction geometry. However, measurements in a strain-free standard are needed for accurate residual stress results. Strain mapping is based on using a small diffracting region as shown schematically in Figure 1.

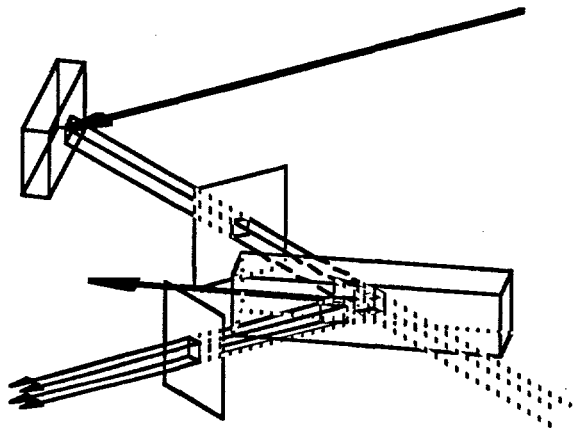

Fig. 1 - The incident beam is defined by a shielding aperture and illuminates a long column in the scattering specimen. The diffraction of neutrons in the direction of the lower arrow is then limited by a second aperture, and thereby a small diffracting volume is defined.

The neutron strain scanning experiments were done at the High Flux Isotope Reactor at Oak Ridge National Laboratory. The measurements were done on a 1.27 mm (0.5-in.) thick plate containing a multipass weld and three Gleeble bars with dimensions 1.27mm (0.5-in.) x 1.27 mm (0.5-in.) x 108 mm (4.5-in.). The compositions of the 2 1/4 Cr-1 Mo base metal and filler alloy are given in Table 1. The thermal treatment of the Gleeble test bars is given in Table 2.

Table 1.
Composition of base and filler metal, wt %

	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
Base	0.11	0.23	0.43	0.02	0.02	2.24	0.90	0.00	Bal.
Filler	0.09	0.56	0.60	0.01	0.02	2.61	1.05	0.10	Bal.

Table 2.
Thermal histories of Gleeble test bars (base metal)

	Peak temperature, °C	Hold time, s	Cooling Rate, °C/min
P1	950	5	2500
P2	950	60	100
P3	950	60	2500

The neutron spectrometers used for this work were adapted for residual strain scanning by the addition of beam collimators, a specimen translation stage, and a linear position-sensitive proportional counter(5). The (211) reflection from ferrite (body-centered cubic) was used for d-spacing determinations, and the diffracting volume was typically 2 mm x 2 mm x 2 mm. The P2 and P3 Gleeble bar samples were measured at the HB-3 spectrometer using a wavelength of 1.44 Å. The P1 and P2 Gleeble bar samples and an as-received bar were measured at the HB-2 spectrometer using a wavelength of 1.56 Å .

Stress-free samples with dimensions 12.7 x 6 x 1.7 mm were cut from the P1, P2, and P3 Gleeble test bars by electro-discharge machining. These samples were measured at the HB-2 spectrometer using a wavelength of 1.61Å. Different from the first two experiment sets, the scattering volume in the third experiment set was 1 x 1 x 10 mm. Measurements of the d-spacing variations of these samples near the center of the hot zone in the three Gleeble bars assessed variations in lattice parameter changes due to changes in chemical composition.

Results of Strain Scanning

Figure 2 shows the strain scanning data comparing the ferritic and austenitic welds (3,4). Longitudinal strains were measured at various distances normal to the weld centerline averaged over several determinations at different depths in the plate. The peak longitudinal strains are comparable, but the the longitudinal and transverse (or radial) strain in the ferritic weld exhibits a shoulder not seen in the austenitic weld. Figure 3 shows strain measurements made along the centerline of Gleeble bars that were given the thermal treatments described in Table 2. The most severe treatment in P1 which consisted of a 5-s dwell time at 950°C followed by air cooling, results in high longitudinal tensile strains and small transverse strains. In P2, which had a 1-min dwell time at 950°C and cooling at 100°C per minute, this Gleeble bar shows smaller longitudinal tensile strains and a variation in transverse compressive strains. In P3, with a 1-min dwell time at 950°C followed by air cooling, this Gleeble bar shows higher tensile strains for the longitudinal component, but not as large as in P1, and a sharp increase in the transverse compressive strains.

Gleeble bars of the 2 1/4 Cr-1 Mo alloy subjected to variations in thermal treatment are known to exhibit varying microstructures containing different phase constituents. However, the contribution of chemical composition to d-spacing variations in the P1, P2, and P3 Gleeble bars appears to be negligible in Figure 4. The largest variation is seen in samples taken from P1 which had the most severe thermal treatment. The observed strain variation shown in Figure 4 is much smaller than the range of total strains seen in Figure 3.

The Gleeble bars P2 and P3 were investigated more thoroughly by measuring strains on section planes along the length of the bar. In the Gleeble bar P2, the strains on each of the section planes were uniform in close agreement with the value determined at the center of the section plane. However, in the Gleeble bar P3 which was air cooled, the strains on the section plane showed significant variations compared to the value determined at the center of the plane. Figure 5 shows the transverse and longitudinal strains as a function of the distance along the Gleeble bar. The scatter in both the transverse and longitudinal strains for any given plane is not symmetrical about the strain measured at the center. It is apparent that the strain system is complex and that strain variations from the center to the side within the Gleeble bar are dependent on the dwell time at 950°C and the cooling rate.

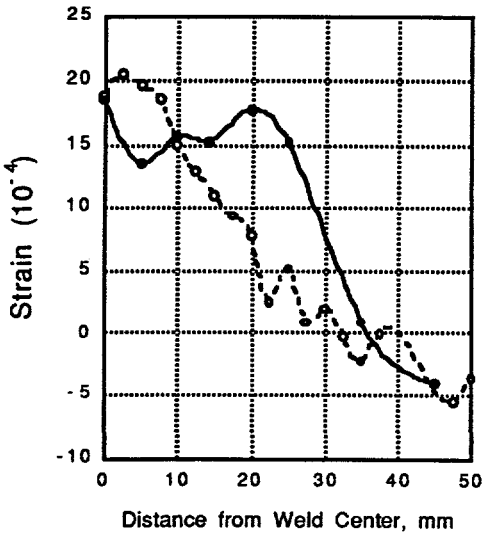

Fig. 2 - The longitudinal strain component for the ferritic weld (solid) shows a dip and a shoulder not seen in the 0.5-in. multi-pass austenitic weld (dashed).

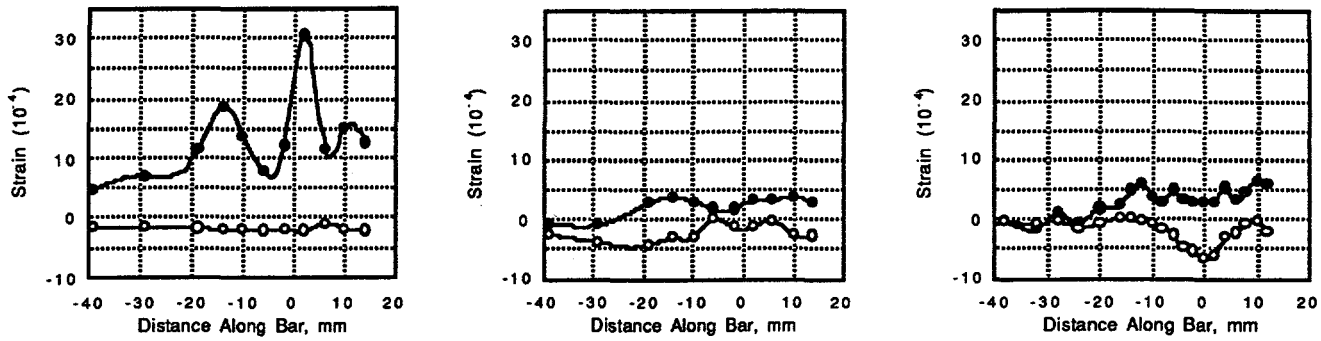

Fig. 3 - The longitudinal (filled) and transverse (open) strain components are shown for P1 (5-s dwell time and air cooled), P2 (1-min dwell time and 100°C/min cooling and P3 (1-min dwell time and air cooling. The longitudinal strains show a tensile rise in the heat-affected zone and the longitudinal component in P3 goes sharply compressive.

The longitudinal strain peaks in the Gleeble bars shown in Figure 3 are located away from the center of the hot zone in the test bars. The location of the peaks undoubtedly is the boundary between the hot region undergoing bainite formation from austenite and the cooler region in which the initial bainite structure is only tempered. The magnitude of these tensile longitudinal peaks and the behavior of compressive transverse strain depend on both the dwell time at 950°C and the cooling rate.

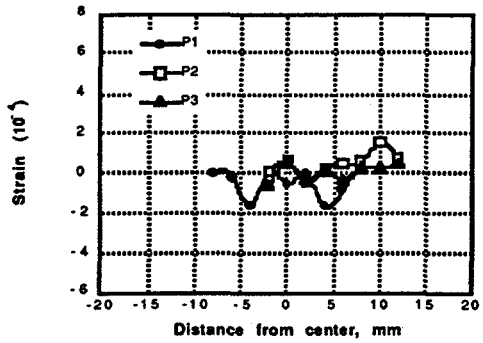

Fig. 4 - The variation in the "stress-free" d-spacings is represented as a strain. The variations for all three Gleeble samples are comparable to the estimated error in determination of strains in the test bars and thus indicate that chemically induced strain is small compared to the mechanical strain of residual stress.
the transverse and longitudinal strains for any given plane is not symmetrical about the strain measured at the center.

It is tempting to assume that the longitudinal strain variation observed in the Gleeble bars can be applied directly to the interpretation of longitudinal strains in the weldment. However, differences in mechanical constraints, geometry, and thermal conditions between the weldment and the Gleeble bar appear to influence the orientation of the strain tensor. The longitudinal tensile strain in the Gleeble bar is parallel to the direction of heat flow along the length of the bar, while the tensile longitudinal strain in the HAZ is perpendicular to the direction of heat flow, which is nto the base metal. The difference in tensile strain orientation between weld and Gleeble bar undoubtedly arises from the absence of transverse mechanical constraint in the Gleeble bar. The bainite reaction can be expected to choose quite different transformation shear variants in response to the different mechanical constraints in the two cases.

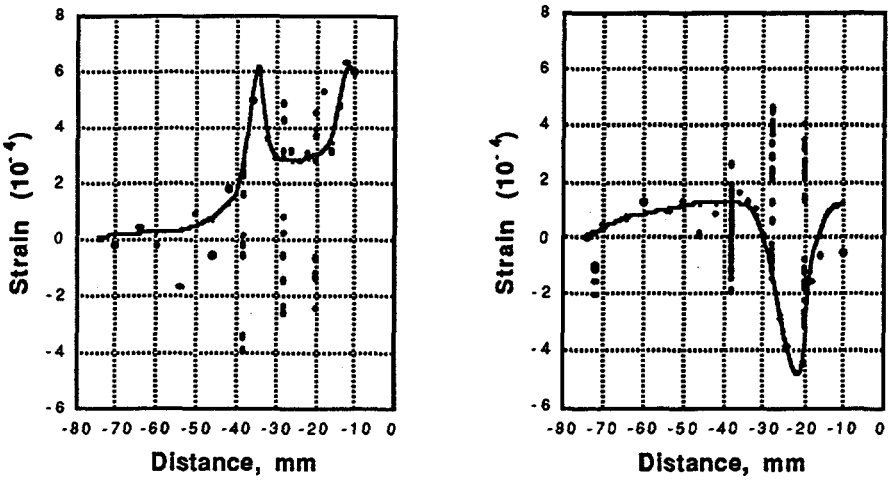

Fig. 5- The transverse (top) and longitudinal (bottom) strain components measured on the Gleeble bar centerline define the continuous line drawn in both figures. The points in groups centered away from the line are the result of measurements made at locations displaced from the bar center axis.

Summary

Fast-cooled Gleeble bar (P3) has a complex strain pattern which indicates the influence of lateral heat losses that are not seen in the slow-cooled (P2) Gleeble bar. Short dwell time appears to sharpen strain variations. The development of a tensile peak in the longitudinal strains in the Gleeble bar suggests an explanation for the "broadening" of the residual stress pattern in ferritic relative to the austenitic strain pattern. Even though the Gleeble test is known to produce the same microstructures found in welds of the same material, we have shown a difference in the orientation of the strain tensor in the weld and in the Gleeble bars. The interpretation of properties in Gleeble bars, which are sensitive to residual stress, must be done with proper consideration of these differences.

Acknowledgments

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