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RESIDUAL STRESS PATTERNS IN STEEL WELDS

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ABSTRACT

Neutron strain scanning of residual stress is a valuable non-destructive tool for evaluation of residual stress in welds. The penetrating characteristic of neutrons permits mapping of strain patterns with a spatial resolution approaching 1mm at depths of 20mm in steels. While the overall patterns of the residual stress tensor in a weld are understood, the detailed patterns depend on welding process parameters and the effects of solid state transformation. The residual strain profiles in two multi-pass austenitic welds and a ferritic steel weld are presented. The stress-free lattice parameters within the fusion zone and the adjacent heat affected zone in the two austenitic welds show that the interpretation of residual stress from strains are affected by welding parameters. An interpretation of the residual strain pattern in the ferritic steel plate can be made using the strain measurements of a Gleeble test bar which has undergone the solid state austenite decomposition.

INTRODUCTION

The penetrating power of neutrons has opened an entirely new approach to the analysis of residual stresses in welded structures [1,2,3]. The possibility for mapping complete strain tensor at a resolution of 1 mm in welds promises to provide guidance and verification for increasingly detailed finite element computations for residual stresses in welds. At the same time simple interpretations of neutron diffraction which ignore metallurgical aspects of the welding process must become more sophisticated. What was once considered the ultimate non-destructive method of residual stress analysis in fact requires destructive testing for accurate interpretation of residual strains. Despite this fact, the use of neutrons diffraction is the only method which directly probes lattice strain in as-fabricated structures. The conversion of strains to stresses is necessary for engineering application of residual stress findings. With improved calculation methods it is feasible to shift the task of stress interpretation to computer codes so that comparison of calculated and measured strains becomes an accepted practice. Therefore the need for accurate determination of the lattice strains associated with mechanical stress effects is very important. This paper presents measurements of residual stress patterns in steel welds and demonstrates some of the metallurgical factors which affect the strain measurements. The orientation of the strain tensor is glossed over by the assumption simple symmetry; the authors are aware of the inaccuracies that may be entailed in the analysis of results. The main factor under consideration in this paper is the metallurgical effects on lattice strain.

EXPERIMENTAL

Neutron scattering experiments were done on several instruments at the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory and the NRU Reactor at Chalk River Laboratories. At Oak Ridge residual stress measurements were done on the HB-2 and HB-3 spectrometers modified for strain scanning and lattice parameter measurements on the HB-4 high-resolution powder diffractometer. At Chalk River residual stress measurements were done on the L3 spectrometer and lattice parameter measurements on the DualSpec high resolution power diffractometer.

Table I.

Metal Chemistry and Welding Parameters for the Austenitic Plate

	1" Austenitic Plate			1/2" Austenitic Plate		
	Wire	Plate	Welding Conditions	Wire	Plate	Welding Conditions
C	0.015	0.016	60° V-butt	0.065	0.016	90° V-butt
Si	0.39	0.39	1/4" gap	0.43	0.39	no gap
Mn	1.76	1.78	backing plate	1.47	1.78	tack weld at ends
P	0.006	0.028	0.045" filler wire	0.018	0.028	0.045" filler wire
S	0.009	0.019	hot wire	0.009	0.019	cold wire
Cr	19.76	18.15	GTA	20.59	18.15	GTA
Ni	9.77	8.19	300 amps	10.53	9.19	180 amps
			216"/min			45"/min
	Ferrite	8%	14 pass	Ferrite	6%	11 passes

Three welded plates with a finished area of 12"x12" were joined with a semi-automatic gas tungsten arc process; 1" austenitic steel plate, 1/2" austenitic steel plate and 1/2" ferritic steel plate. The welding conditions are summarized in Tables I and II. The rate of metal deposition and the nickel and chromium compositions in austenite control phase constitution of the weld. Note that the close match between the chemistry of the filler wire and base metal in the ferritic weld.

The ferrite-to-austenite transformation occuring at high temperature in stainless steel welds are not considered to be as important as thermal shrinkage in generating residual stress. By contrast ferritic welds undergo austenite decomposition to ferrite and carbide products at low temperature where density changes generate significant residual stresses. These effects can be emulated in the so-called "Gleeble" test where a test bar is given controlled heating and cooling cycle that simulates the thermal excursions in the heat affected zone and base metal during welding. Samples of the ferritic steel were made into 1/2" x 1/2"x4" bars for Gleeble tests weld.

Table II.

Metal Chemistry and Welding Parameters for the Ferritic Plate

1/2" Ferritic Plate

	Wire	Plate	Welding Conditions
C	0.09	0.11	90° V-butt
Si	0.56	0.28	no gap
Mn	0.6	0.43	tack weld at ends
P	0.01	0.015	hot wire
S	0.02	0.023	GTA
Cr	2.61	2.24	220 amps
Ni	0.1	-	
Mo	1.05	0.9	6 passes

The residual stress analysis of these welds with neutron strain scanning have been reported previously [2,3,4]. Lattice parameter measurements were made on samples cut from the two austenitic welds; pillars 5mm x 5mm x 25mm and 4mm x 4mm x 25, cut from the 1" and 1/2" plates respectively. The pillars were rotated about their long axes on the powder diffractometer axis to minimize crystalline texture effects. The resulting patterns were refined with Reitveld-type pattern fitting programs yielding the lattice parameters and phase fractions of the ferrite and austenite phases.

RESULTS AND DISCUSSION

Residual strain was measured at several depths in the welded plates. The variation of strain with thickness was relatively small and the averages of the strain over thickness are presented in Figures 1 and 2. The pattern of residual strains in the two austenitic plates are similar except for the relative displacement of the transverse strains in the tensile direction for the 1" plate. This transverse strain is most influenced by the effects of the clamping constraints at the edges of the plate. Differences in the sequence in which the clamps are released between each welding pass may account for the transverse strain difference. The range of longitudinal strain in the 1/2" plate is large and spans a higher tensile strain to a lower compressive strain compared to the 1" plate. Since a higher power was used in welding the 1" plate and its greater mass the fusion zone and heat affected zone remain a elevated temperature longer. A self annealing effect on the residual stresses may then reduce the range of stresses in that case.

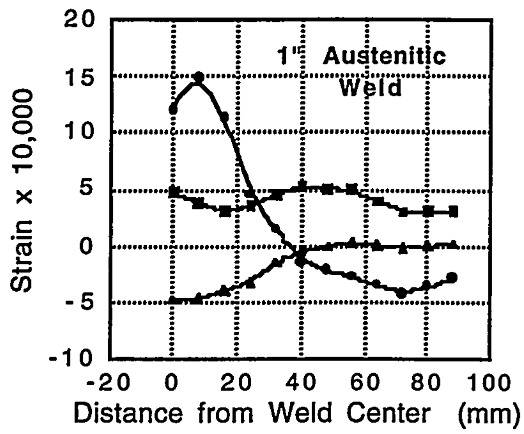

Figure 1. Longitudinal (circle), transverse (square) and normal (triangle) strain components are averaged through the plate thickness and show a maximum tensile strain in the longitudinal direction at the weld center.

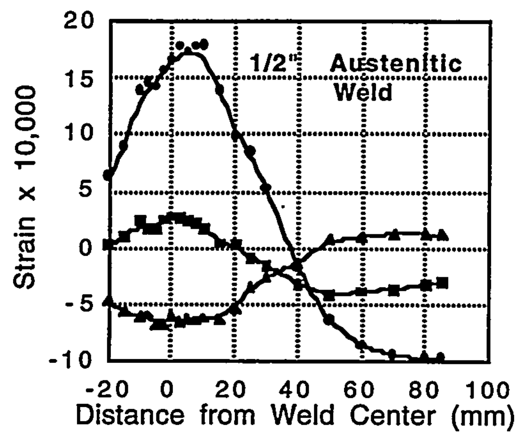

Figure 2. The corresponding components show a higher longitudinal tension and a transverse component which becomes compressive in the base metal. Faster cooling .in this plate may account for the more severe strains.

The lattice parameters were determined to a precision of one part in 10,000 and the ferrite fraction to a precision of 1%. The results of the pattern analysis are summarized in Tables III and IV. When the ferrite fractions less than 1% were omitted from the tables. The austenite lattice parameter in the fusion zone is smaller than that of the base metal. The difference is equivalent to approximately 5x10-4 strain which is a small part of the maximum longitudinal strain shown in Figure 1 or 2. In the 1/2" plate the lattice parameter difference is smaller giving an equivalent strain of 2x10-4. The distribution of ferrite in the 1/2" plate is tightly confined in the smaller fusion zone of the thinner plate and the estimated fraction is lower which is consistent with the metallurgical analysis of the filler wire in table I. The width of the ferrite distribution in the 1" plate is greater not only because the weld zone is larger but because the greater heat rejected into the heat affected zone provides the adjacent material a more sustained transient to alter the phase compositions and fractions. Alteration of the ferrite fraction is evident in the data at the center of the weld zone. The material last deposited at the top contains 10% ferrite compared to 7% at the bottom.

Table III.

Lattice Parameters and Phase Fractions in 1" Austenitic Welded Plate

Austenite Lattice Parameter				Per Cent Ferrite				Ferrite Lattice Parameter			
3.5931	3.5935	3.5933	3.5936	5.0	4.5	4.3	3.6	2.8714	2.8712	2.8726	2.8719
3.5918	3.5925	3.5933	3.5934	7.9	5.5	3.5	3.0	2.8702	2.8703	2.8710	2.8725
3.5919	3.5919	3.5920	3.5926	9.6	6.5		4.5	2.8707	2.8697		2.8694
3.5915	3.5916	3.5919	3.5918	10.0	7.8	7.4	7.5	2.8705	2.8704	2.8703	2.8698
3.5916	3.5914	3.5917	3.5917	9.9	8.1	6.9	6.1	2.8706	2.8703	2.8694	2.8689
3.5917	3.5918	3.5927	3.5930	11.5	8.8	4.7		2.8704	2.8701	2.8702	
3.5926	3.5936	3.5934	3.5931	6.6	3.1	3.0		2.8704	2.8728	2.8725	
3.5935	3.5935	3.5935	3.5935		3.8				2.8705		

Table IV.

Lattice Parameters and Phase Fractions in 1/2" Austenitic Welded Plate

Austenite Lattice Parameter				Per Cent Ferrite				Ferrite Lattice Parameter			
3.5949	3.5949	3.5948	3.5947								
3.5950	3.5948	3.5948	3.5948	4.2				2.8714			
3.5952	3.5951	3.5946	3.5945	3.6	4.9	1.7		2.8723	2.8718	2.8716	
3.5954,	3.5951	3.5949	3.5946	7.7	6.0	5.2	5.0	2.8716	2.8717	2.8718	2.8719
3.5953	3.5950	3.5946	3.5947	7.7	6.2	5.0		2.8714	2.8716	2.8718	
3.5951	3.5951	3.5949	3.5945	7.0	7.0			2.8720	2.8717		
3.5953	3.5948	3.5946	3.5947	7.5				2.8713			
3.5950	3.5950	3.5948	3.5948								

The residual strain response in the ferritic steel Gleeble test bar is shown in Figure 3. The longitudinal strain along the length of the bar shows a tensile peak on each side of the hot zone. The strain component transverse to the length of the bar is a small, constant and compressive The constancy of strain suggests the absence of significant chemical change at the 2 mm resolution of the strain scanning measurement. The

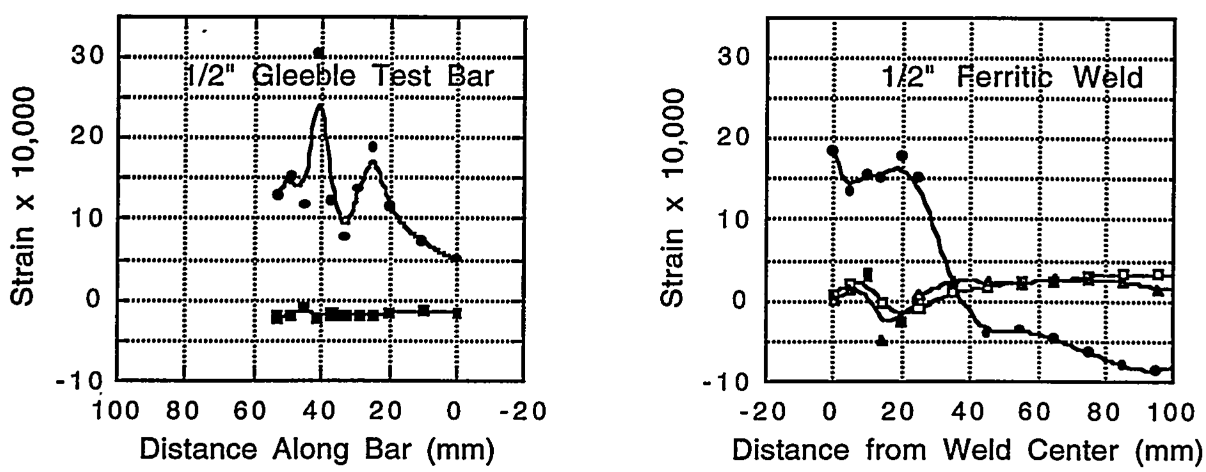

Figure 3. Longitudinal (circle) and trans verse (square) strain components in the Gleeble test bar show a tensile peak on either side of the hot zone. Austenite de – composition induces residual longitud inal strain in the untransformed base metal. No melting occurs in the test bar.

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strain is attributed to austenite decomposition which induces residual stress in the adjacent untransformed material. The absence of strain in the transverse direction is also consistent with the small transverse dimension of the test bar where there is insufficient mechanical constraint to support residual stress. The shape of the tensile longitudinal strain in the 1/2" ferritic weld appears to have a shoulder not seen in the austenitic welds. The transverse and normal strain components are small and nearly equal to each other. The strain pattern appears to be one of simple longitudinal stress along the weld line. The shoulder on the longitudinal strain component can be interpreted as the addition of residual strain arising from the austenite decomposition which is seen in the Gleeble test bar.

SUMMARY

The residual strain patterns in the two austenitic welds although generally similar are different in the behavior of the transverse strain component and the range of strains in the longitudinal component. The lattice parameter variation in the austenite differs as well with the thicker weld showing a greater change. The lattice parameter variation is 5x10-4 in the 1" weld and 2x10-4 in the 1/2" weld. This strain component is significant but small compared to the total measured strain. The ferrite fraction difference can be attributed mostly to the different filler wire composition. Annealing effects due to the sequence of welding passes is evident in the variation in the amount of ferrite from top to bottom of the fusion zone. The ferritic weld exhibits a shoulder on the longitudinal strain curve that can be attributed to the effect of strains from the austenite decomposition on the untransformed heat affected zone. From these studies it can be seen that welding conditions, weld metal chemistry and phase transformations play a significant role in the evaluation of strain in welded structures.

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REFERENCES

1. G. A. Webster, Measurement of Residual and Applied Stress Using Neutron Diffraction, edited by M. T. Hutchings and A. D. Krawitz (Kluwer Academic Publishers, Boston, 1992), p.21.
2. J. H. Root, T. M. Holden, J. Schroder, S. Spooner, C. A. Hubbard, T. A. Dodson and S. A. David, International Trends in Welding Science and Technology, Proc. 3rd Intern. Conf. Trends in Welding Research, edited by S. A. David and J. M. Vitek (ASM International, Materials Park, Ohio, 1993), p.99.
3. S. Spooner, J. A. Fernandez-Baca, S. A. David, C. R. Hubbard, T. M. Holden and J. H. Root in Proc. 4th Intern. Conf. on Residual Stresses, June 8-10, 1994, Baltimore, MD, (Society for Experimental Mechanics, Inc., Bethel, CT, 1994), p. 1205.
4. S. Spooner, X. L. Wang, C. R. Hubbard, and S. A. David in Proc. 4th Intern. Conf. on Residual Stresses, June 8-10, 1994, Baltimore, MD, (Society for Experimental Mechanics, Inc., Bethel, CT, 1994), p. 964.

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