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MODELING OF RESIDUAL STRESSES IN HY-100 WELDMENTS

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ABSTRACT

The residual stress distribution in a HY-100 steel disk, induced by gas tungsten arc (GTA) spot welding, was analyzed using finite element (FE) formulations and measured with the neutron diffraction technique. The computations used temperature-dependent thermophysical and mechanical properties. The predictions from the FE models are in very good agreement with the neutron diffraction measurements in the far heat affected zone (HAZ) and in the base metal. The predicted residual stresses in the fusion zone and the near HAZ were higher than those measured by the neutron diffraction method. This discrepancy was attributed to the microstructural changes and associated material properties in the HAZ and fusion zone due to phase transformations during the weld thermal cycle.

MASTER

INTRODUCTION

Some major problems in welded structures are residual stresses and distortion. Residual stresses that develop in and around the welded joint are detrimental to the integrity and the service behavior of the welded part. High tensile residual stresses in the region near the weld might promote brittle fracture, change or aid the fatigue strength and stress corrosion cracking. Not only can they combine with stresses from service but even before the weldment sees service, residual stresses can lead to crack formation and failure of the structural member.

Residual stresses develop in a material due to uneven distribution of inelastic strains caused by localized heating during welding and subsequent uneven cooling of the material. Due to localized heating, complex thermal and transformation stresses are generated during welding. Several factors may contribute to the formation of residual stresses (Smith, et al., 1989; Murti, et al., 1993; Balagner, et al., 1989; Mahin, et al., 1991; Roelens, 1996). The plastic deformation produced in the base metal is a function of structural, material, and fabrication parameters. Structural parameters include geometry, thickness, and joint design. Material parameters reflect the metallurgical condition of the base material and the weld filler metal. Fabrication parameters include welding process, procedure, parameters, and the degree of restraint.

The objective of this study is to analyze the residual stress state in an HY-100 disk after the welding process. A finite element (FE) model was developed for residual stress analysis in spot welds. Results of the analysis were compared with carefully conducted neutron diffraction measurements (Feng, et al., 1995).

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EXPERIMENTAL

A GTA welding process without filler metal was used to make a spot weld on a HY-100 steel disk. The disk measured 19mm in height and 75mm in diameter. The weld was located at the center of the disk surface. The following welding parameters were used: Electric current I = 320A, voltage U = 15V, and 4mm electrode diameter. Welding arc time was 5s with argon shielding and followed by a 5 seconds post purge. No constraint was used during welding and subsequent cooling. Figure 1 shows the welding setup.

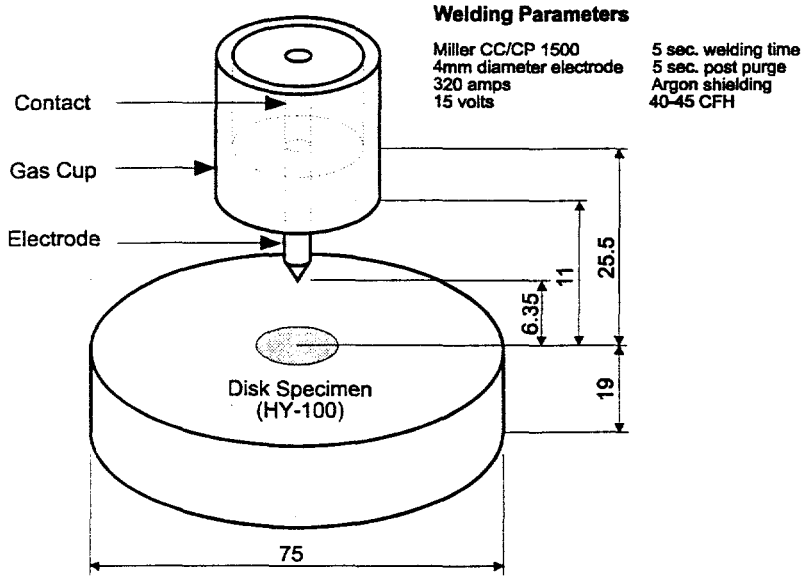

Figure 1. Welding setup.

Neutron diffraction measurements were performed on the BEAM Tube-6 (BT-6) triple-axis spectrometer at the National Institute of Standard and Technology Research Reactor. Measurements were made using a nominal gauge volume of $3 \times 3 \times 3$ mm. Figure 2 shows the positions and relative sizes of the measurement points which are located on the radial section plane. Instrument details and measurement methodology have been discussed elsewhere (Prask, et. al., 1991; Brand, et. al., 1994).

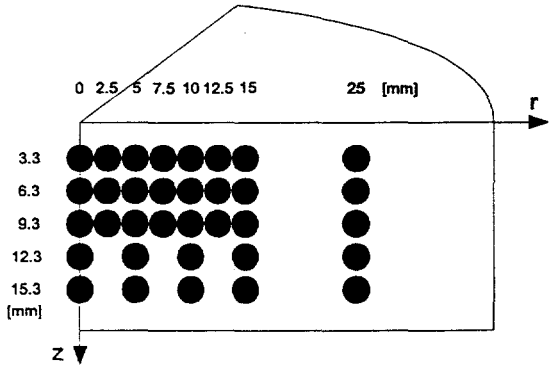

Figure 2. HY-100 disk with ND measurement locations.

RESULTS AND DISCUSSION

The residual stress distribution in a GTA spot welded HY-100 steel disk was analyzed using thermo-mechanically uncoupled FE formulation. The computations used temperature-dependent thermo-physical and mechanical properties of the base metal (BM). The thermal analysis was based on the heat conduction formulation with the Gaussian heat input from the arc. An axisymmetric FE model was developed which considerably simplifies the modeling effort. One half of the actual disk cross section was meshed by linear four-noded finite elements. Computations were performed by using a general purpose FE code.

Two computational steps are required to compute the residual stresses in welding. In the first step, the heating/melting of the material is modeled by applying the heat flux. Cooling transients are calculated in the second step when the heat source is removed and the disk is cooled to room temperature. The heating time is five seconds, whereas the disk is cooled until the isotherm ambient temperature is reached. Figure 3 shows temperature profiles at specific distances from the weld centerline.

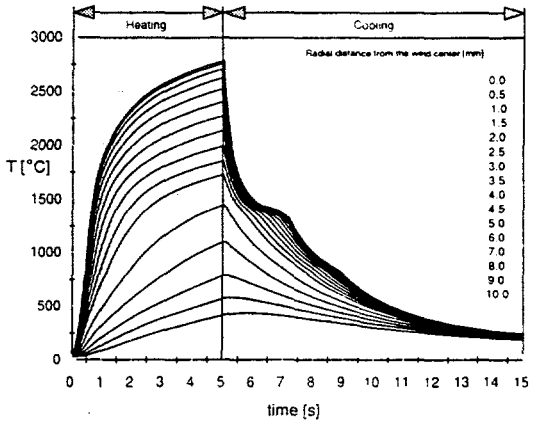

Figure 3. Temperature transient at depth of 1 mm.

Rate-independent, elasto-plastic constitutive equations were constructed from the uniaxial tensile test results of the base metal under various temperature conditions. Both yield and ultimate stresses were reduced to 5.0 MPa at the melting temperature to simulate low strength at high temperatures. Elastic modulus and Poisson's ratio were also given as a function of temperature. The elastic modulus was reduced to a small value (1.0 GPa) at high temperatures. Phase transformation effects due to rapid cooling on mechanical properties of carbon steel were not included at this stage of the analysis.

The same FE mesh as in the thermal analysis was used in the mechanical analysis, except for the element type and different boundary conditions. The analysis is based on the temperature gradients calculated in the thermal analysis which represent the input information or loading. The disk was restrained in the axial direction on the bottom surface to appropriately model the actual welding conditions.

Residual stresses and elastic strains were evaluated after the welding process was completed and disk had cooled to room temperature. Comparison with the ND results was made at this point and is shown in Fig. 4.

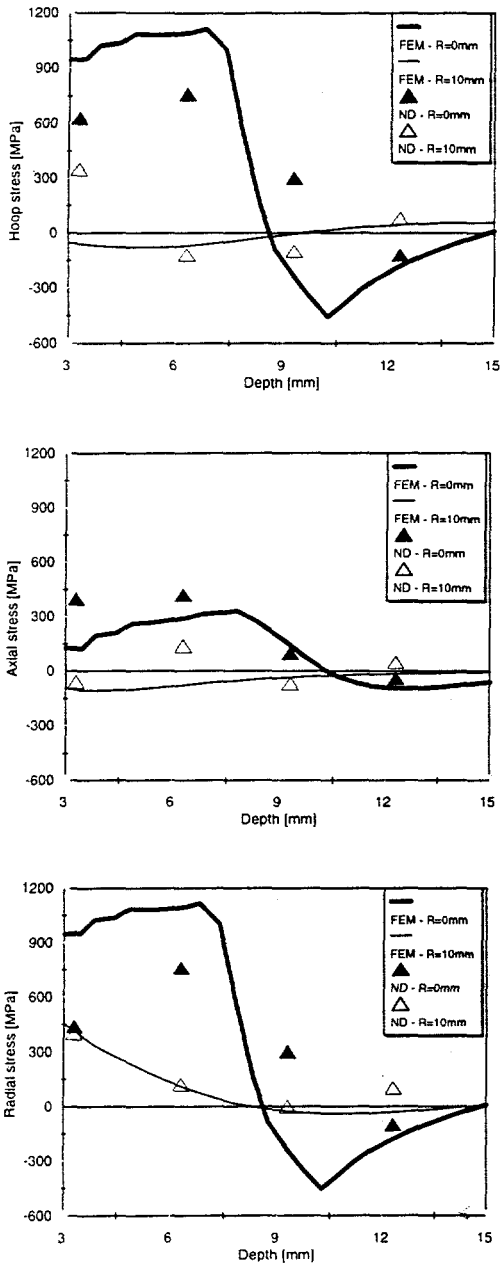

Figure 4. Comparison of FE and ND results in radial, axial, and tangential direction.

The predictions of the finite element model are in good agreement with the neutron diffraction residual stress results in the far heat affected zone (HAZ) and BM. The model over-predicted the actual residual stress field in the fusion zone and the near HAZ.

The discrepancy was attributed to the phase transformations and associated changes in material properties in the HAZ and fusion zone (FZ), that occur during welding thermal cycle. Martensitic transformations that occur in the FZ and HAZ have opposite effects on the residual stress. The higher yield strength tends to increase the residual stress level in the FZ and HAZ since these areas experience plastic deformation. At the same time, the associated volume expansion tends to minimize the effect of thermal contraction thereby reducing the residual stress level in the FZ and HAZ. The formation of cracks in the FZ is another factor that possibly contributes to lower measured residual stress values.

Based on these initial results, a model was developed to study the effect of volumetric changes that occur during phase transformation on residual stress. At this stage, the volume change was approximated by the introduction of a modified thermal expansion coefficient. The thermal expansion coefficient for the austenitic phase (α_γ) was modified with a coefficient α_{tr}, which simulated a linear increase in volume at a certain temperature range due to the presence of the martensitic phase. The overall thermal expansion (ε_{tot}) was obtained by superimposing the thermal expansion due to phase transformation (ε_{tr}) to the constitutive thermal expansion curve of HY-100 (ε_γ). Figure 5 shows the overall thermal expansion coefficient of HY-100 (α_{tot}), which corresponds to ε_{tot}. Note that in this case the reference temperature for defining the thermal expansion coefficient equals the melting temperature.

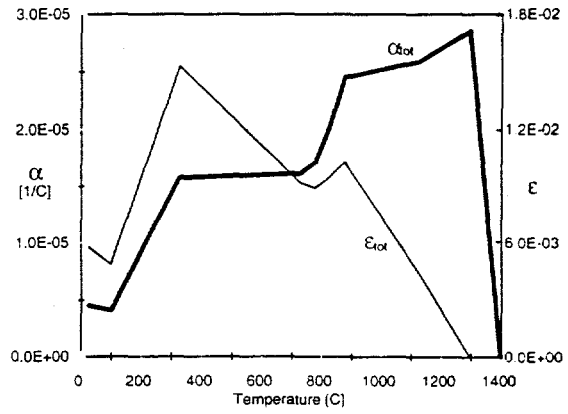

Figure 5. Thermal expansion coefficient, α_{tot}.

The effect of phase transformation on the weld volume change was analyzed with respect to the quantity of transformed product. An average weld volume increase of 1% at the transformation temperature range was assumed. The actual expansion in HAZ and FZ depends upon the volume fraction of martensite, which is a function of the local cooling rates, local grain size, and local composition of the austenite. Comparison of the calculated and ND results are presented in Figs. 6-8 for the weld centerline ($R = 0$) indicating good agreement.

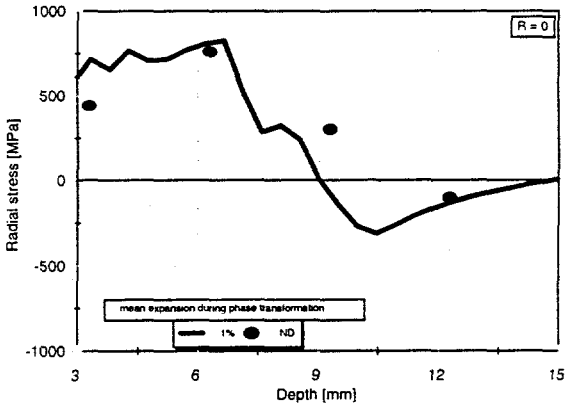

Figure 6. FE and ND radial stress at R = 0.

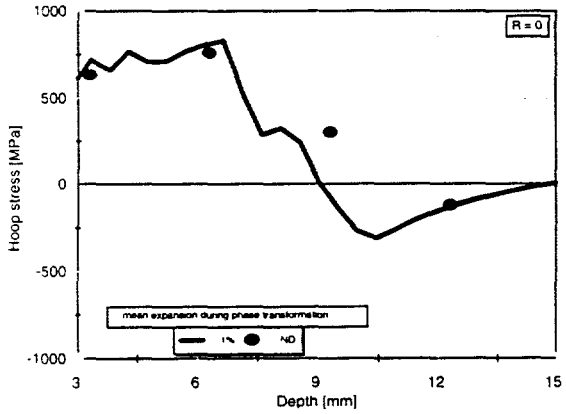

Figure 7. FE and ND hoop stress at R = 0.

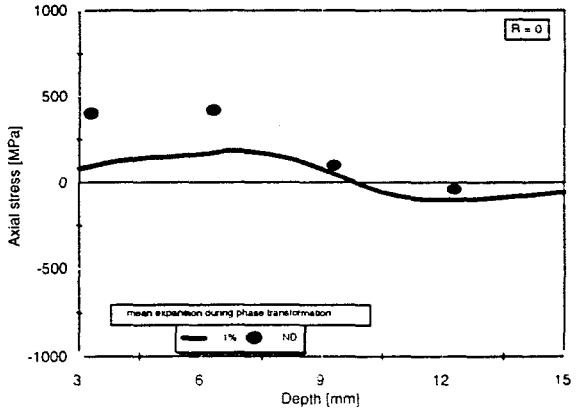

Figure 8. FE and ND axial stress at R = 0.

CONCLUSIONS

The predicted residual stresses are in very good agreement with the neutron diffraction measurements. The results show a significant effect of volume change due to phase transformation on residual stresses in the FZ and the HAZ. The model tends to over-predict the measured residual stresses in the FZ and the near HAZ when the effect of phase transformation and associated change in the material properties are not included. The overall agreement of FE residual stress results, assuming 1% volume increase in the weld region, and ND results is very good.

ACKNOWLEDGMENTS

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