Abstract

Three dimensional finite element simulations of thermal and mechanical response of a 304L stainless steel pipe subjected to a circumferential autogenous gas tungsten arc weld were used to predict residual stresses in the pipe. Energy is input into the thermal model using a volumetric heat source. Temperature histories from the thermal analysis are used as loads in the mechanical analyses. In the mechanical analyses, a state variable constitutive model was used to describe the material behavior. The model accounts for strain rate, temperature, and load path histories. The predicted stresses are compared with X-ray diffraction determinations of residual stress in the hoop and axial directions on the outside surface of the pipe. Calculated stress profiles fell within the measured data. Reasons for the observed scatter in the measured stresses are discussed.

Introduction

Three dimensional simulations of structures constructed using welding can be costly due to the computational resources required. However, it has been shown [1-3] that, especially for multi-pass welds, three dimensional analyses are required to achieve the correct structural deformations. Several researchers [e.g. 4-6] have performed simulations and experimental determinations of residual stresses due to welds. Agreement between simulated and experimentally determined stresses has been mixed. This is especially true near the weld centerline and for stress components normal to the welded structure's cross-section when plane strain 2D analyses are used.

In this work we focus on residual stresses in and near the weld of a girth-welded 304L stainless steel pipe subjected to an autogenous gas tungsten arc (GTA) weld. Hoop, axial, and through-thickness stress profiles are presented. X-ray diffraction determinations of hoop and axial stress were performed to assess the validity of the modeling strategy and the constitutive model.

Welding Procedure

Figure 1 shows a schematic of the pipe and the location of the weld. Pipes were annealed before welding. Thermocouples were placed near 6 and 12 mm from the weld centerline (weld fusion zone width was approximately 5 mm on the pipe's outer surface). Teflon tape was used to minimize heat transfer to the jaw chuck holding and rotating the pipe. The weld was at the mid-length of the pipe. Axial caliper measurements were made before and after the weld at 45 degree increments around the circumference to obtain shrinkage data. Four pipes were welded with nominally identical weld process parameters. Welding parameters were 1 rpm rotation speed, 8.7 V, and 75 A.

Grain sizes in the weld cross-section were estimated to be up to 3 mm long and 1 mm wide in the fusion zone, ASTM 1 (~0.25 mm) in the heat affected zone, and ASTM 6 (0.07 mm) in the base material.

Computational Procedures

The 3D sequentially coupled finite element analysis was performed using the heat conduction code JACQ3D [7], and the structural code JAS3D [7-9]. JACQ3D uses a non-linear conjugate gradient solver and JAS3D has conjugate gradient and dynamic relaxation solvers. The mesh is shown in Figure 2.
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Due to axial symmetry, only half of the pipe was modeled. The mesh was constructed using 12960 8-node hex elements. Thermal and mechanical analysis procedures closely follow those discussed in [10], so some details will be omitted here.

**Thermal Model** - Energy was deposited using a volumetric heat source [11]. A circular shape was used on the surface of the part. An ellipsoidal shape was used for the heat source in the thickness direction of the weld. The heat source distribution was assumed to be Gaussian in all directions (depth, axial, and circumferential). Heat source dimensions were half the weld width on the surface of the pipe. The heat source depth equaled the part thickness. Process efficiency was 65% [12]. The efficiency incorporates forced convection losses due to shielding gas as well as radiation and evaporation losses from the weld pool.

Thermal losses from the OD of the workpiece due to free convection and radiation were included in the analysis. The inside of the pipe was assumed to be thermally insulated. Material properties were temperature dependent based on data from [13]. Convection effects in the weld pool were accounted for by using an effective thermal conductivity of 3.5 times the solidus conductivity based on [14].

**Mechanical Model** - Temperature histories from the thermal analyses were applied to the workpiece in the mechanical analyses. A plane of symmetry was defined normal to the pipe’s axis at the middle of the workpiece’s length. Nodes were free to move in the plane of the pipe’s cross-section here but were constrained from any axial motion.

The Bamann-Chiesa-Johnson (BCJ) constitutive model [15,16] was used to describe the material’s mechanical response. The BCJ model accounts for temperature, strain rate, and load path effects through the use of scalar and tensor internal state variables. State variable evolution is motivated by dislocation mechanics and cast in a hardening minus recovery format. The hardening description is based on dislocation storage mechanisms. Dynamic recovery is related to dislocation cross slip. Static or thermal recovery is based on diffusional climb of dislocations.

Yield strength as a function of temperature is shown in Figure 3. Elastic properties as a function of temperature are shown in Figure 4 and are based on information from [17-19]. Thermal expansion data up to melt were found in [13]. The BCJ model as implemented for this problem (1) capped the temperature at 1700 K when computing material properties, (2) required hardening be non-negative, and (3) set the deviatoric stresses and internal state variables to zero at and above the melt temperature.

**Evaluation of Residual Stresses Using X-ray Diffraction**

**X-ray Diffraction** - The d vs. \( \sin^2\psi \) X-ray diffraction method measures strains in the surface layers of a material [20-21]. The measurement of residual stress by diffraction utilizes the spacing of the lattice planes as a gauge length for measuring strain. A change in stress results in a modification of the interplanar spacings (d) which alters the angular position of the diffraction peaks. The interplanar spacing (d) of a specific set of planes is obtained from grains of different orientations to the surface normal. The variation of the interatomic spacing is determined as a function of \( \psi \), the angle between the surface normal and the direction of the measured strain. This is determined by tilting (by an angle of \( \psi \)) and rotating the specimen (by an angle of \( \phi \)) with respect to the incident X-ray beam.
beam. The change in interplanar spacing \( d_{xy} \) as a function of orientation is due to surface strains and this can be related to the surface stresses by an analysis employed by Noyan [21]. Accordingly, for known values of \( d_{xy} \) and \( d_0 \) (strain-free), the average strain along the \( \phi - \psi \) direction with respect to the surface normal can be written as

\[
(\varepsilon_{33})_{\phi, \psi} = \frac{d_{xy} - d_0}{d_0}
\]

\((\varepsilon_{33})_{\phi, \psi}\) can be related to the surface stresses by the conventional elasticity equations. For classical X-ray stress analysis, these strains are a linear function of the angle \( \psi \) and the surface stress state in the sample can be determined by a linear relationship between \((\varepsilon_{33})_{\phi, \psi}\) and \(\sin^2\psi\) [20].

\[
<\varepsilon_{33}>_{\phi, \psi} = \frac{d_{xy} - d_0}{d_0} = \frac{(1 + \nu)}{E} \left[ <\sigma_{\phi}> \sin^2\psi - \frac{\nu}{E} <\sigma_{11}> + <\sigma_{22}> \right]
\]

where \( \nu \) (Poisson's ratio), and \( E \) (Young's modulus) are elastic constants, and \( \sigma_{11}\cos^2\phi + \sigma_{22}\sin^2\phi = \sigma_\phi \), the stress in the direction of \( \sigma_\phi \).

If \(<\varepsilon_{33}>\) is plotted versus \(\sin^2\psi\) then Eq. 2 represents the equation of a straight line with the slope proportional to \(\sigma_\phi\). In this study, the assumption of a bi-axial plane stress state is generally valid since the average depth of penetration of Cu-K\( \alpha \) X-rays in this alloy has been computed to be about 9 microns (at \( \psi = 0^\circ \)) and 4 microns (at \( \psi = 60^\circ \)).

**Measurement Procedures** - Two weld specimens (pipe-2 and pipe-3) were provided to Los Alamos National Laboratory, Los Alamos, New Mexico for determining stress profiles in the hoop and axial directions. Specimen pipe-3 was chemically polished using a concentrated solution of phosphoric acid at 60\(^\circ\) C and at 18 V for approximately 5 minutes to remove any ambiguity due to surface effects on residual stress measurements. The chemical polishing resulted in a removal of \( \approx 10 \) microns on the outside diameter of the specimens.

Stress measurements were performed using standard methodology as outlined in SAE-J784A [20] with a HUBER stress goniometer operating at 40 kV and 200 mA. All measurements used Cu radiation (wavelength 1.153\( \AA \)) for which the (331) reflection occurs at \( = 137^\circ \) (20). The X-ray beam was collimated using a 2 mm diameter collimator on the incident side to the sample for hoop stress measurements. For the axial stress measurements a 3 mm collimator was used on the incident side of the X-ray beam. The distance from the sample surface to the tip of the collimator was 40 mm. Stress measurements were performed at circumferential location of \( = 135^\circ \) from the start of the weld, along the length spanning \( \pm 40 \) mm for the hoop direction and \( \pm 15 \) mm for the axial direction from the approximate center of the fusion zone. The hoop and axial stresses were mapped across the length using an increment of 1 mm. Stress measurements in positive and negative \( \psi \) tilts were recorded to check for the presence of shear stresses. The \( \psi \) angles ranged from 0 to 60\(^\circ\) in increments of 15\(^\circ\). 20 scans from 20\(^\circ\) to 160\(^\circ\) were recorded in the fusion zone, plastic zone and in the elastic zone for Rietveld structure refinements using 'Generalized Structural Analysis System' (GSAS) [22]. The diffraction pattern was used to verify the crystal structure and check for any preferred orientations exhibited across the welded regions. At all regions across the weld the diffraction pattern revealed a single phase having a face centered cubic structure (Fm3m). Stresses in the hoop and axial directions were calculated using an X-ray elastic constant of \( 6.3 \times 10^8 \) MPa [21].

Along with the measurements of stresses in the axial and hoop directions, a study was also conducted to determine the systematic errors which would effect the measurements. Silicon powder was dusted on the fusion zone surface and stress measurements repeated in the powder and the region across the fusion zone using a 3 mm spot size. The silicon powder which should measure "zero stresses" provides a check on the accuracy of the stress determination using the \( d \) vs. \( \sin^2\psi \) technique. Besides, this approach also factors other possible effects which cause erroneous stress calculations such as, curvature effects, coarse grain size, texture, and sample displacement from the goniometer center. Figure 5 shows the \( d \) vs. \( \sin^2\psi \) plots for the powder in the fusion zone. The slope for the powder which should ideally be "zero" shows a negative slope indicative of \( \approx 40 \) MPa compressive stresses. Therefore 40 MPa was added to the measured axial stress. The slope for the fusion zone axial stress is also negative but higher in value than the powder, and, despite the scatter in the data it is clear that axial stresses in the fusion zone are in compression.

![Figure 5. d vs. sin^2\psi plot at point in fusion zone. Solid line is least squares fit to open symbols obtained for axial stress. Dashed curve is least squares fit to filled symbols, obtained using stress free Si powder.](image)

**Comparisons of Model and Experimental Results**

**Thermal Response** - Figure 6 shows good agreement between measured and simulated thermal histories 6 and 12 mm from the weld centerline. The experimental thermal histories are representative of the thermal data. Average fusion zone width at the pipe OD in the simulation was within 10% of the experimental value.
Figure 6. Comparison of predicted and measured temperature histories 6 mm and 12 mm from weld centerline, 180 degrees away circumferentially from the weld starting point.

Mechanical Response - Axial Shrinkage - For comparisons of axial shrinkage, measurements of four specimens were obtained. The average axial shrinkage from all tests, measured between the pipe ends at 45° increments around the circumference, was 0.39 mm. The average axial shrinkage in the model was 0.38 mm. Variation in the axial shrinkage as a function of circumferential distance from the weld start point (from caliper measurements of pipe length) was observed and is shown in Figure 7.

Figure 7. Variability in axial shrinkage as a function of circumferential position for four welded 304L stainless steel pipes with nominally the same weld process parameters.

Residual stresses - Contour plots of axial stress show that from approximately 45° to 330° the stresses at the centerline OD are relatively constant around the circumference. This is consistent with the region of the weld in which the temperature histories were likely to have been relatively constant with circumferential position. The predicted weld centerline stresses are shown in Figures 8 and 9 along the outside and inside of the pipe, respectively. At the OD, the axial stress is between 150 and 300 MPa in compression between about 30° and 320°. The hoop stress is in compression from near 70° to almost 360°. On the inside diameter, stresses are only in compression between approximately 35° and 100°. The axial stress between 350° and 20° is in tension through the entire thickness of the pipe. Nowhere is the hoop stress in tension through the pipe thickness at the weld centerline. Radial stresses are small everywhere.

Comparison of Hoop Stresses - From the X-ray diffraction measurements, residual hoop stresses for specimen pipe-2 are in compression averaging -73 (-51) MPa over a distance spanning ±15 mm across the welded region, except for a single tensile value of 149 MPa at approximately the center of the fusion zone (Figure 10). This point is suspect because the fit to the d vs. sin²θ plot returned a low correlation value (< 0.5) at this location. To check whether the compressive stresses extended further, four stress measurements were made at ±18, 29, 31, 32 mm from the approximate center of the weld based on model predictions. At these “far field” locations the hoop stresses were more tensile than in the central region and averaged 70 MPa ±15 and -40 ±15 respectively on the two sides of the weld. There was some indication of an asymmetric lateral stress distribution as evidence by the average stress values.

As confirmation of the first set of measurements on sample pipe-2 in the as-received condition, measurements were repeated in the chemically polished sample pipe-3 holding fixed all parameters used for sample pipe-2. While there is significant scatter in the data it is clear that compressive stresses are present ±15 mm on either side of the center of the weld. The compressive stresses seem to drop and approach zero or cross over to tensile stresses beyond ±20 mm both sides of the weld.

Figure 8. Predicted OD axial, circumferential, and radial stresses at the weld centerline as a function of angle from the weld start.

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Figure 9. Predicted ID axial, circumferential, and radial stresses at the weld centerline as a function of angle from the weld start.

The results for pipe-2 (as received) and pipe-3 (polished) are similar suggesting that the surface state of the welded samples is not a concern.

Due to the scatter in the data (Figure 10), it is difficult to make a definitive statement regarding the validation of the predicted stresses. This is also complicated by the fact that the predicted stresses show strong variation in the maximum and minimum values in the region where the measurements show similar compressive stresses. This may indicate that the resolution of the X-ray stress mapping is spatially insensitive to pick up the trends as shown by the predictions. A combination of high energy and spatial resolution, as offered by synchrotron X-rays, may capture the predicted stress profiles. This may be especially true outside the fusion and heat affected zone regions (distances greater than \(-2.5\) mm from weld centerline) where grain size is sufficiently small to insure a large number of grains is sampled.

Comparisons of Axial Stresses - The axial stresses for sample pipe-3 are shown in Figure 11. The trends are clear, with a maximum compressive stress of about \(-280\) MPa in the fusion zone. This changes to a tensile stress at \(\pm 9\) mm from the center of the fusion zone. Similar to the observation in the hoop direction, a few tensile axial stresses are indicated in the fusion zone region.

There is relatively less scatter than in the hoop direction, and the trends between the predictions show qualitative agreement. Some disparity between measured and simulated stresses exists between the ranges (maximum and minimum) as seen in Figure 11. One reason for less scatter is the larger spot size (3 mm vs 2 mm) used in the axial measurements compared to the hoop measurements. It has been shown [24] that scatter in X-ray diffraction measurements of lattice spacing decrease exponentially as the number of grains sampled increases. The other reason could also be that the stresses are varying over a distance large enough that the X-ray stress mapping is able to capture successfully. The disparity in the magnitudes can be affected by not using the exact elastic constants in calculating the stresses.

Figure 10. Comparison of predicted and measured hoop stresses vs axial distance from weld 135 degrees from weld starting position.

Figure 11. Comparison of predicted and measured axial stresses vs axial distance from weld 135 degrees from weld starting position.

Discussion

Use of the 331 reflection in these diffraction measurements may involve ambiguities by virtue of the possibility of plastic anisotropy. Measurements using other reflections might be warranted for added confidence in the results [23]. Scatter in the stress distributions may be due to non-uniform grain size, large grain size, and texture effects which are more pronounced in the fusion zone.

Summary and Future Work

Residual stresses, displacements, and temperatures in a 304L stainless steel pipe subjected to an autogenous GTA weld have been calculated using finite element models and compared with measurements from instrumented experiments and X-ray diffraction determinations of stress. Good agreement was achieved between temperature histories and average axial shrinkage. Predicted axial and circumferential stresses on the specimen's outside surface as a function of axial distance from the weld centerline fell within stress data obtained using X-ray
diffraction techniques.

Future work will focus on continuing to evaluate the predictive capability of the BCJ constitutive model and the finite element modeling technique within which it is imbedded for welding and other complex loading histories. This could involve modifications to the constitutive model, evaluating the sensitivity of the model to uncertainties in material properties, and consideration of the material's pre- and post-weld microstructures (texture, grain size, etc.) when using non-destructive residual stress evaluation techniques. The effects of boundary condition assumptions also should be examined.

Experimentally, when grain sizes are large relative to the X-ray spot sizes that can be used, oscillation and other averaging techniques can be considered to provide better statistics for the measurements. Use of reflections from other planes, for example 311, might also prove advantageous. Using stress free powder techniques can be considered to provide better statistics for the boundary condition assumptions also should be examined.

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