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by
S. L. West

Savannah River Site
Aiken, South Carolina 29808

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# MODELING OF RESIDUAL STRESS MITIGATION IN AUSTENITIC STAINLESS STEEL PIPE GIRTH WELDMENT

**Ming Li*, David G. Atteridge*, William E. Anderson*, Scott L. West#**

## ABSTRACT

This study provides numerical procedures to model 40-cm-diameter, schedule 40, Type 304L stainless steel pipe girth welding and a newly proposed post-weld treatment. The treatment can be used to accomplish the goal of imparting compressive residual stresses at the inner surface of a pipe girth weldment to prevent/retard the intergranular stress corrosion cracking (IGSCC) of the piping system in nuclear reactors. This new post-weld treatment for mitigating residual stresses is cooling stress improvement (CSI). The concept of CSI is to establish and maintain a certain temperature gradient across the pipe wall thickness to change the final stress state. Thus, this process involves sub-zero low temperature cooling of the inner pipe surface of a completed girth weldment, while simultaneously keeping the outer pipe surface at a slightly elevated temperature with the help of a certain heating method. Analyses to obtain quantitative results on pipe girth welding and CSI by using a thermo-elastic-plastic finite element model are described in this paper. The results demonstrate the potential effectiveness of CSI for introducing compressive residual stresses to prevent/retard IGSCC. Because of the symmetric nature of CSI, it shows great potential for industrial application.

## INTRODUCTION

Many austenitic stainless steel pipes, such as Types 304 and 316, are used in various plants including nuclear reactors because they have excellent corrosion resistance, strength at high temperatures, and fracture toughness at low temperatures. Nevertheless, intergranular stress corrosion cracking (IGSCC) may occur on the inner surface of the weld zone if the pipe exhibits: 1) tensile residual and/or applied stress, 2) sensitized (grain boundary chromium depleted) material, and 3) an "aggressive" aqueous environment; a minimum of one of these factors must be controlled in order to prevent stress corrosion cracking. In reality, it is usually difficult to control the environment to such a degree that IGSCC is impossible. Thus there is the need to study material sensitization and tensile residual stress development in weldments. The research described here addresses the factor of stress.

Welding austenitic stainless steel pipes by conventional processes results in inner surface as well as (partially) through-wall tensile residual stresses in the weldment. The introduction of compressive residual stresses in the heat affect zone (HAZ) at the pipe's inner surface by stress mitigation treatment either during or after welding has been found to prevent/retard IGSCC. A stress mitigation treatment is the application of a special thermal or mechanical process during, or after, conventional pipe girth welding, each treatments alter conventional weld induced tensile residual stresses at the inner surface, and partially through wall, into compressive residual

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* Oregon Graduate Institute, P. O. Box 91000, Portland, OR 97291-1000
# Westinghouse Savannah River Company, Aiken, South Carolina 29802

stresses (Ref. 1,2). Several techniques involving thermal processes for controlling or altering residual stresses at the inside surface of girth-welded pipes have been investigated within the piping industry. These include induction heating stress improvement (IHSI), last pass heat sink welding (LPHSW), heat sink welding (HSW) and backlay welding. These techniques are based on the principle that the residual stresses are influenced by the thermal history of the pipe. In each process, a heat sink, such as running water, is applied on the inside of the pipe while the exterior is heated. It is the means of exterior heating which distinguishes one process from the others. In the case of LPHSW, the first passes are conventionally welded and the heat sink is used only during welding of the last pass (Ref. 1,2). Generally, a high heat input is used for the last pass in an effort to get high temperature gradients through the thickness. LPHSW differs from HSW in that HSW employs a heat sink inside the pipe after the first few weld passes and maintains the normal level of welding heat input (Ref. 1,2). Backlay welding consists of reinforcing a completed girth weld with axial stringers of weld beads. A heat sink of running water is used while several layers of weld stringers are placed on the pipe (Ref. 3). The IHSI procedure entails applying a heat sink inside of the pipe while heating the exterior by an induction coil which has been placed around the pipe (Ref. 4,5,6). Since the IHSI method is based on placing an induction heating coil completely around the pipe weldment, IHSI induced residual stress distribution are more axisymmetric than the residual stress distribution resulting from welding. Hence, IHSI is appropriately represented by an axisymmetric model (Ref. 7). The key to applying the heating stress mitigation treatments is to maintain high temperature gradients through the thickness in the weldment. From the symmetry point, the IHSI is the best of the above mentioned heating stress mitigation methods. There is only one mechanical stress mitigation method reported to date (Ref. 2). This method is the mechanical stress improvement process (MSIP). Instead of using thermal force, this method applies a mechanical force to alter the stress state. From the theoretical stand point, there is no difference between the thermal and mechanical mitigation method. They both attempt to change the plastic deformation and restraint in the conventional welding joint, but by different means.

A newly proposed post-weld stress mitigation treatment is presented in this study. This new method is cooling stress improvement (CSI) which keeps a very low temperature around the inner surface of the weldment while it maintains a slightly elevated temperature around the outer surface of the weldment. The idea behind this method is the same as the above mentioned heating induced stress mitigation treatments (especially IHSI), i.e., using large through thickness temperature gradients in the weldment to alter the stress state. In CSI, thermal contraction caused by the cooling plastically yields the inner surface in tension, while the outer surface plastically yields in compression. Once the cooling cycle is terminated and pipe weldment reaches room temperature equilibrium, the expanded pipe inside diameter results in stress state reversal, leaving the outside diameter in tension and the inside diameter in compression. Because of the symmetric nature of this method and elimination of the relatively high temperatures needed to achieve stress reversal by IHSI, CSI would be expected to have great potential for industrial application.

A 2-D axisymmetric finite element model was established in this work to study the thermal and stress development during welding and CSI of 40-cm-diameter, Type 304L stainless steel (SS), schedule 40 (1.27 cm thickness) pipe. The actual experimental pipe weld that was modeled has a narrow gap groove joint configuration (as seen in Figure 1) and was welded in four continuous passes by using an automatic gas tungsten arc pipe welding system. The total length of welded pipe is about 160 cm. Table 1 shows the pipe welding parameters. The following sections describe the analysis procedures, computational results and the summary of important conclusions.

## NUMERICAL ANALYSIS

### Finite Element Code and Assumptions

The girth pipe welding and CSI process were modeled by using the computer code ANSYS 5.0 (Ref. 8). The ANSYS program is a general purpose finite element code which can be used in all disciplines of engineering - structural, mechanical, electrical, electromagnetic, electronic, thermal, fluid, and biomedical. Revision 5.0 of the ANSYS program has an elements with the death and birth feature which is critical for modeling a welding process.

The numerical approach was simplified by making certain assumptions. The major assumption is that the pipe welding process can be modeled assuming a condition of axisymmetry. The pipe welding process is certainly not an axisymmetric case. But the main purpose of this work is to study the effectiveness of the CSI method and CSI is appropriately represented by an axisymmetric model. Thus this 2-D axisymmetric approach is justified. Figure 2 shows the finite element mesh of the half pipe cross section from weld center line. The length of this section is 25.4 cm. The mesh density varies continuously from the weld center line to the end of the pipe cross section with a fine mesh around the weld center line. This work also assumes that the heat generated by the deformed solid is negligible. Thus thermal and stress analysis were conducted sequentially in the model. The numerical analysis for pipe girth welding and the CSI process has four steps: 1) thermal model for welding, 2) mechanical model for welding, 3) thermal model for CSI, and 4) mechanical model for CSI.

### Thermal Model for Pipe Girth Welding and CSI

Transient thermal analyses were performed for pipe girth welding and CSI process. Temperature dependent thermal material properties were used in the model (Ref. 9,10,11). An increase of conductivity value for temperatures above the melting point was adopted to compensate for the convection and stirring effect in the molten pool. The latent heat at melting was implemented into the thermal model by defining the enthalpy of the material as a function of temperature. A constant value of surface heat convection coefficient was assumed. In the welding model, the arc efficiency was assumed to be 73 percent (Ref. 11), the heat input from Table 1 was generated by a Gaussian distributed element heat flux and internal heat generation. The element birth capability in ANSYS was used to model the deposition of filler metal into the groove. The radiation effect was not considered in the welding model. In the CSI model, the cooling on the inner surface of the pipe was modeled by prescribing node temperature of 77 K (liquid nitrogen temperature) for a length of 3.8 cm from the weld center line, while keeping a node temperature of 323 K for a length of 5 cm from weld center line on the outer surface. The cooling cycle lasted about 6 minutes. Then the node temperatures were deleted and the pipe was naturally convected to reach the room temperature equilibrium.

### Mechanical Model for Pipe Girth Welding and CSI

Structural static analyses were preformed for pipe girth welding and the CSI process. Temperature dependent material mechanical properties were used in the analyses (Ref. 9,10,12). A bi-linear elasto-plastic stress-strain curve was used. The kinematic strain hardening option was considered to include the Bauschiger effect in the model. The associative flow rule (Prandtl-Reuss equations) in conjunction with the von Mises yield criterion was assumed in the model. The selected data points from the temperature histories of pipe girth welding and the CSI process were introduced into the mechanical model as the thermal loads.

## COMPUTATIONAL RESULTS

Figure 3 shows the computed temperature history at 1 cm from the weld center line on the pipe inner surface during girth welding of the 40-cm-diameter, Type 304L stainless steel, schedule 40 pipe. The temperature distribution along the pipe outer and inner surface during the cooling cycle of a post-weld CSI treatment can be seen in Figure 4. The temperature difference between the pipe outer surface (323 K) and inner surface (77 K) around the weld center line is the key to applying the CSI technique. Maintaining this temperature difference for a finite time (6 minute here) would eventually change the stress state upon reaching room temperature equilibrium. The axial residual stresses along the inner surface of a pipe girth weldment after welding and welding plus CSI treatment are illustrated in Figure 5. Figure 6 shows the corresponding hoop residual stresses along the inner surface of a pipe girth weldment after welding and welding plus CSI treatment. It can be seen from Figures 5 and 6 that the tensile residual stresses at the inner surface of pipe girth weldment are reversed into compressive residual stresses after CSI treatment. This clearly shows the potential effectiveness of CSI method. These computational results will be compared against experimental results in the future.

## SUMMARY

A finite element thermal and residual stress analysis of a 40-cm-diameter, schedule 40, Type 304L stainless steel pipe was conducted for girth welding and welding plus CSI treatment. The calculated results indicate that the weld induced stresses on the pipe inner surface are tensile in the weld region and remain so for a certain distance from the weld center line. CSI treatment after welding can convert the tensile weld residual stresses to compressive values. Thus, this computational modeling study demonstrates the feasibility of the CSI process and shows great promise for industrial application of this process. However, experimental work is necessary to thoroughly evaluate the effectiveness of CSI.

## ACKNOWLEDGEMENTS

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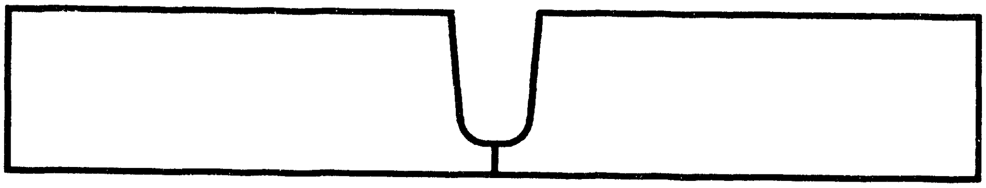
Table 1. Four-pass narrow gap groove weldment welding parameters

| Pass# | Current (A) | | Travel Speed (cm/min) | Voltage (v) | Pulse (s) | | Wire Speed Feed (cm/min) | |
|---|---|---|---|---|---|---|---|---|
| | Peak | Back-ground | | | Peak | Back-ground | Primary | Back-ground |
| 1 | 135 | 80 | 9.4 | 8.0 | 0.35 | 0.4 | 0 | 0 |
| 2 | 230 | 135 | 10.16 | 8.5 | 0.25 | 0.4 | 127.0 | 88.9 |
| 3 | 185 | 120 | 10.16 | 8.8 | 0.3 | 0.3 | 114.3 | 76.2 |
| 4 | 190 | 120 | 10.16 | 9.2 | 0.3 | 0.3 | 114.3 | 76.2 |



**Narrow Gap Groove (1 Degree at Each Side)**

Figure 1. Pipe weld groove geometry

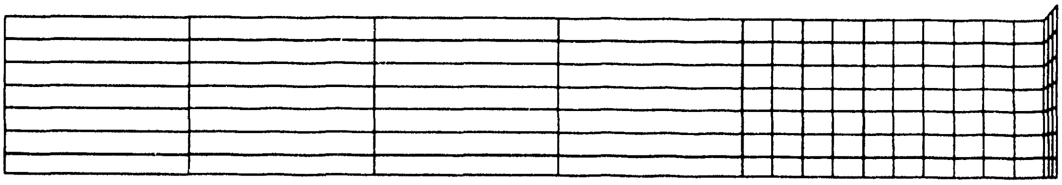


Figure 2. Finite element mesh of pipe cross section from weld center line

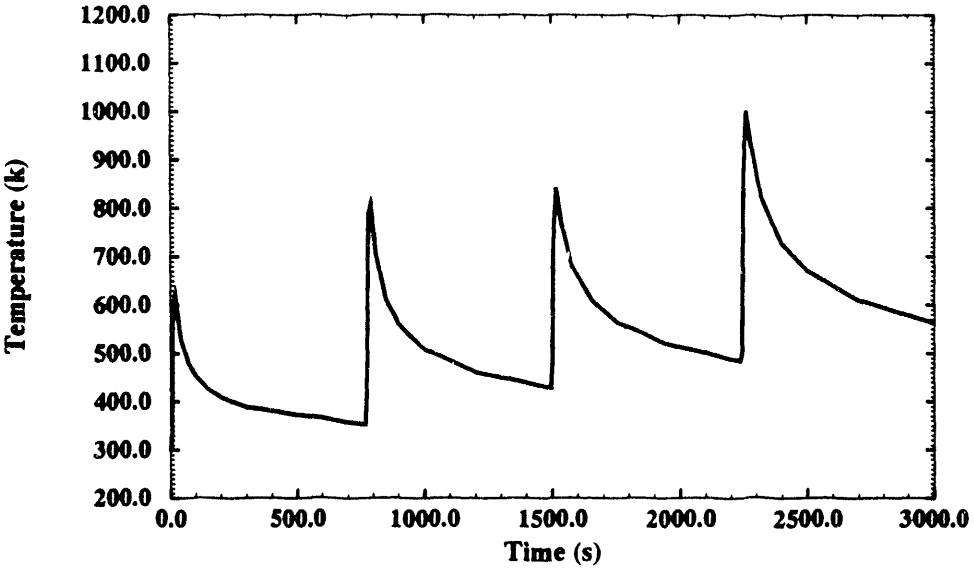


Figure 3. Computed welding thermal history at 1 cm from WCL on pipe inner surface

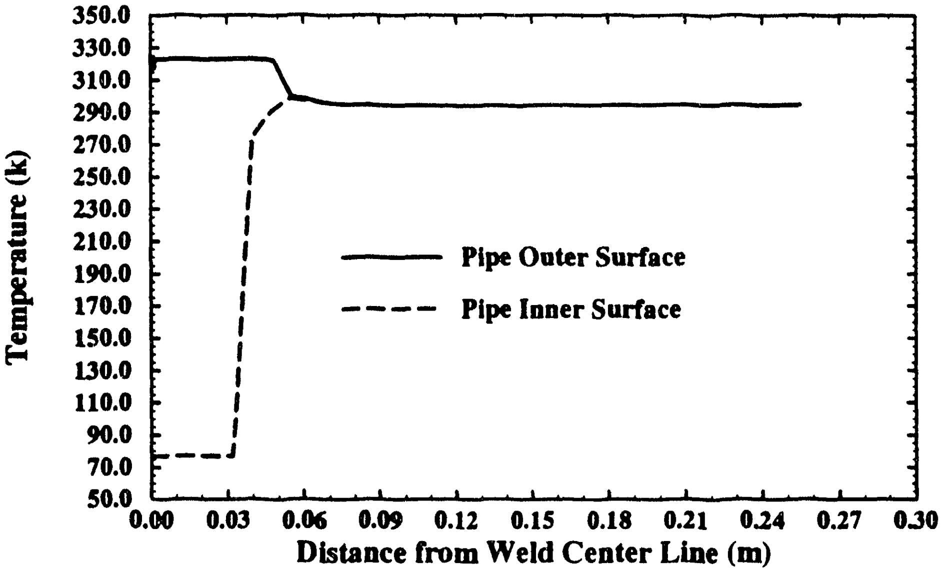


Figure 4. Temperatures along pipe inner and outer surface during cooling cycle of CSI process

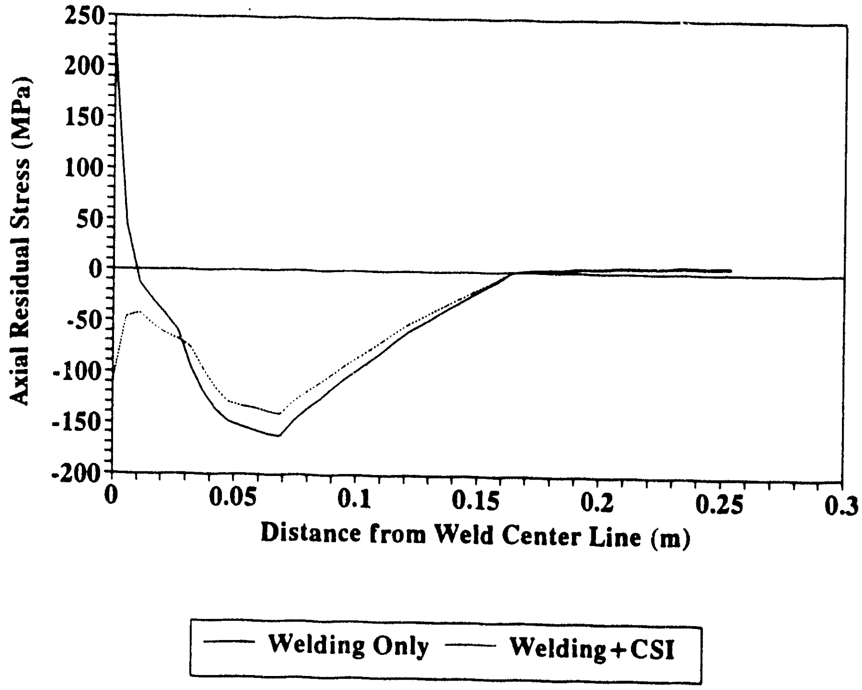


Figure 5. Axial residual stresses along the pipe inner surface after welding and welding plus CSI

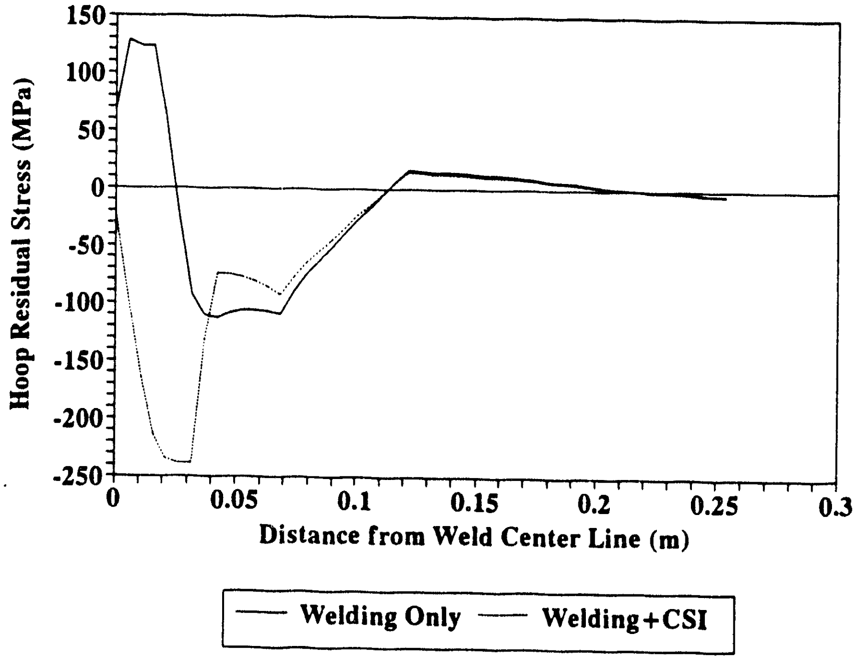


Figure 6. Hoop residual stresses along the pipe inner surface after welding and welding plus CSI

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