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Finite Element Analysis for High Cycle Fatigue Socket Weld Overlay Repair – Additional Layer

1011909

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Technical Update, September 2005

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

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ABSTRACT

Socket welds are commonly used in piping systems of 2-inch and under diameter in couplings, flanges, elbows, and value joints. These welds have been prone to cracking due to high cycle fatigue, particularly from vibration loading. A weld overlay repair has been developed that allows utilities to seal the leak and reinforce the weld while at power, allowing the plant to continue operating. Testing has shown that the weld overlay repair improves the fatigue resistance of the socket weld to equal to that of a butt weld.

ASME Section XI Code Case N-666 has been drafted, which provides the design, fabrication, and examination requirements for the socket weld overlay repair. The Code Case does not specify the welding sequence, and does not require that it be demonstrated that compressive residual stresses are created at the crack tip.

The purpose of this evaluation is to determine any restrictions, such as welding sequence, or thermal boundary conditions, on the welding parameters that may apply when using Code Case N-666. These calculations are based on the weld geometry for a crack originating at the weld root and at the weld toe. Results in this report show additional weld sequences and overlay thicknesses not reported in EPRI report 1012057.

The results of this study concluded that weld overlay residual stress distribution for the overlay geometry specified in the test matrix, for various crack origin could result in compressive residual stresses at the crack tip.

Keywords

Weld overlay repair
Finite element method
Welded joints
Residual stress
Socket weld
ASME code

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1
INTRODUCTION

In References 1 and 2, the evaluation of the residual stress at the crack tip for a socket weld overlay was performed for the cases of root crack and toe crack, for both dry (air) and water back conditions on the inside surface of the pipe and fitting. In the initial study of weld conditions reported in EPRI 1012057, it was found that the residual stress at the crack tip is not very favorable for most cases of the dry back condition. It was desired to determine whether an additional layer of weld on the overlay would improve the local stress at the crack tip (make it compressive). This calculation evaluates the effect of the additional layer of weld overlay on the residual stress for overlays on a root crack and a toe crack for the dry back condition.

2
METHODOLOGY

The weld repair and weld overlay residual stress calculation were based on the methodology documented in References 3 and 4. The residual stress due to welding is controlled by the welding parameters, thermal transients, temperature dependent material properties, and elastic-plastic stress reversals. The analytical technique uses finite element analysis to simulate the multipass weld repair and weld overlay process. In order to reduce computational time, the lumped weld bead pass approach, as documented in [3, 4], was used in this evaluation.

3
ASSUMPTIONS/DESIGN INPUT

The geometry of the weld overlay repair is based on the requirements of Reference 5, for a crack originating at the weld root or weld toe. The crack is assumed to be located at the weld root extending through the weld throat or at the pipe side weld toe, extending through the pipe wall.

A half coupling [6] was used in the evaluation. Dimensions for Pressure Class Designation 3000 were used, as shown in Figure 1. The pipe was assumed to be Schedule 80, with 2.375 inch outside diameter, and 0.218 inch wall thickness.

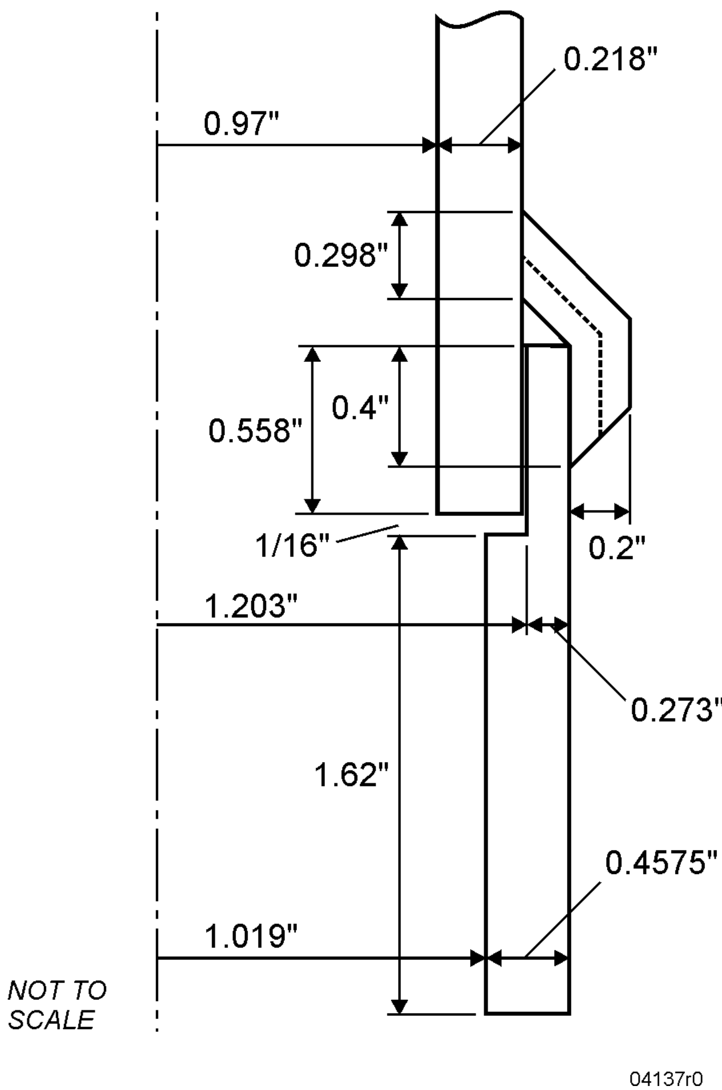


Figure 3-1: Schematic of Socket Weld Overlay of Half Coupling for Toe Crack

The material was assumed to be Type 304 stainless steel.

The material properties were obtained from ASME Boiler and Pressure Vessel Code, 1989 Edition, with all Addenda [7], summarized in Table 1.

Table 3-1: Type 304 Stainless Steel Material Properties

Temperature (°F)	Young's Modulus ($x10^6$ psi)	Coeff. of Expansion (/°F)	Conductivity ($x10^{-4}$ Btu/in-sec-°F)	Specific Heat (Btu/lbm-°F)
70	28.3	8.46	1.99	0.116
200	27.6	8.79	2.15	0.122
400	26.5	9.19	2.41	0.13
600	25.3	9.53	2.62	0.134
700	24.8	9.69	2.73	0.137
800	24.1	9.82	2.82	0.138
1000	21.5	9.82	3.06	0.142
1200	17.6	9.82	3.24	0.145
1400	13.7	9.82	3.45	0.149
1600	9.8	9.82	3.45	0.15
1800	5.88	9.82	3.45	0.151
2000	1.97	9.82	3.45	0.152
2100	0.01	9.82	3.45	0.154
2500	0.01	9.82	3.45	0.154

A bilinear kinematic temperature dependent stress-strain curve [8] was used, shown in Table 2.

Table 3-2: Type 304 Stainless Steel Stress-Strain Law

Temperature (°F)	Yield Strength (ksi)	Tangent Modulus (ksi)
70	36.0	539.7
550	25.9	364.8
1000	18.5	217.9
1300	14.9	139.0
1600	10.2	79.6
2500	2	5

The weld process is shield metal arc weld (SMAW). The welding parameters were obtained from Reference 9, and presented in Table 3. There is no preheat temperature. The interpass temperature is 450 °F. A thermal efficiency of 80% was assumed to account for the heat loss that does not transfer to the component. The bead size was assumed to be 0.1” thick and 0.25” wide.

Table 3-3: Welding Parameters

Voltage	22.4 - 23 volts
Current	80 amps
Speed	6 ipm
Thermal Efficiency	80%

A seal weld, followed by two layers of reinforcement weld, was assumed in the analyses.

A 45 degree taper angle was assumed between the reinforcement weld and the piping/fitting.

The following additional assumptions are used in the evaluation:

1. The materials were assumed to be homogeneous and isotropic.
2. The torch point heat source was modeled as a volumetric line heat source in the analytical model.
3. Yield stress and Young’s Modulus at or above 2500°F were assumed to be negligible and assigned small values to provide solution convergence.
4. The heat transfer coefficients on the inside and outside surfaces of the component were assumed to be temperature independent.
5. Heat loss due to radiation was neglected.
6. No latent heat of weld beads was assumed.
7. No hold time of the weld heat source was assumed.

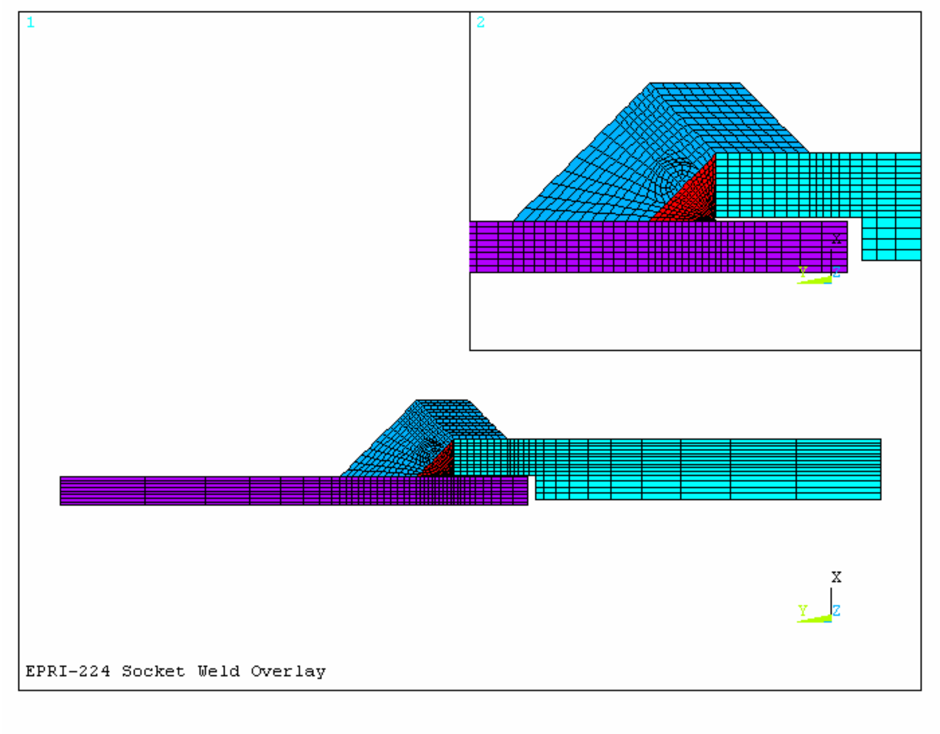
The analyses were performed using ANSYS Version 8.1 [10].

4
CALCULATIONS

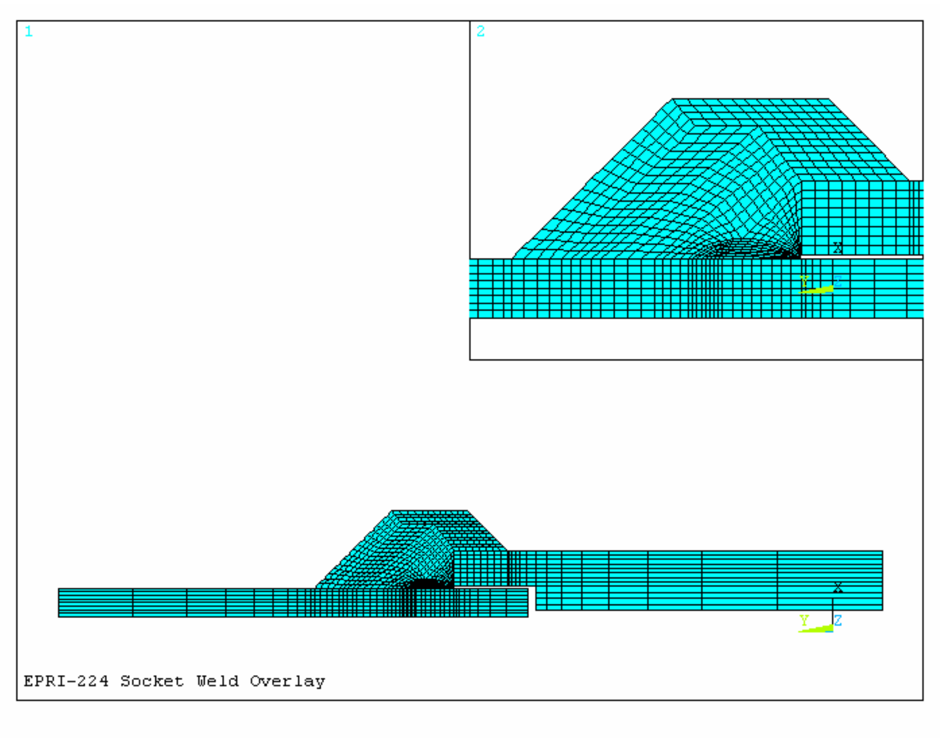
Five loading cases were evaluated:

1. One additional weld layer, dry condition, weld direction from pipe to fitting, root crack
2. One additional weld layer, dry condition, weld direction from fitting to pipe, root crack
3. One additional weld layer, dry condition, weld direction from pipe to fitting, toe crack
4. One additional weld layer, dry condition, weld direction from fitting to pipe, toe crack
5. Two additional weld layers, dry condition, weld direction from pipe to fitting, toe crack

An axisymmetric model was used to evaluate the effect of an extra weld overlay layer on the residual stress, Figure 2. For the root crack, a crack was assumed oriented in the socket weld throat direction from the inside notch location to the outside surface of the original fillet weld, Figure 2(a). For the toe crack, a crack was assumed to originate at the pipe side toe of the socket weld and extend through the pipe wall, Figure 2(b). The global Y direction is along the axial direction of the pipe and fitting. The global Z direction is in the circumferential direction of the pipe and fitting.



(a) Root Crack



(b) Toe Crack

Figure 4-1: Axisymmetric Model of Socket Weld Overlay, with one additional Weld Layer

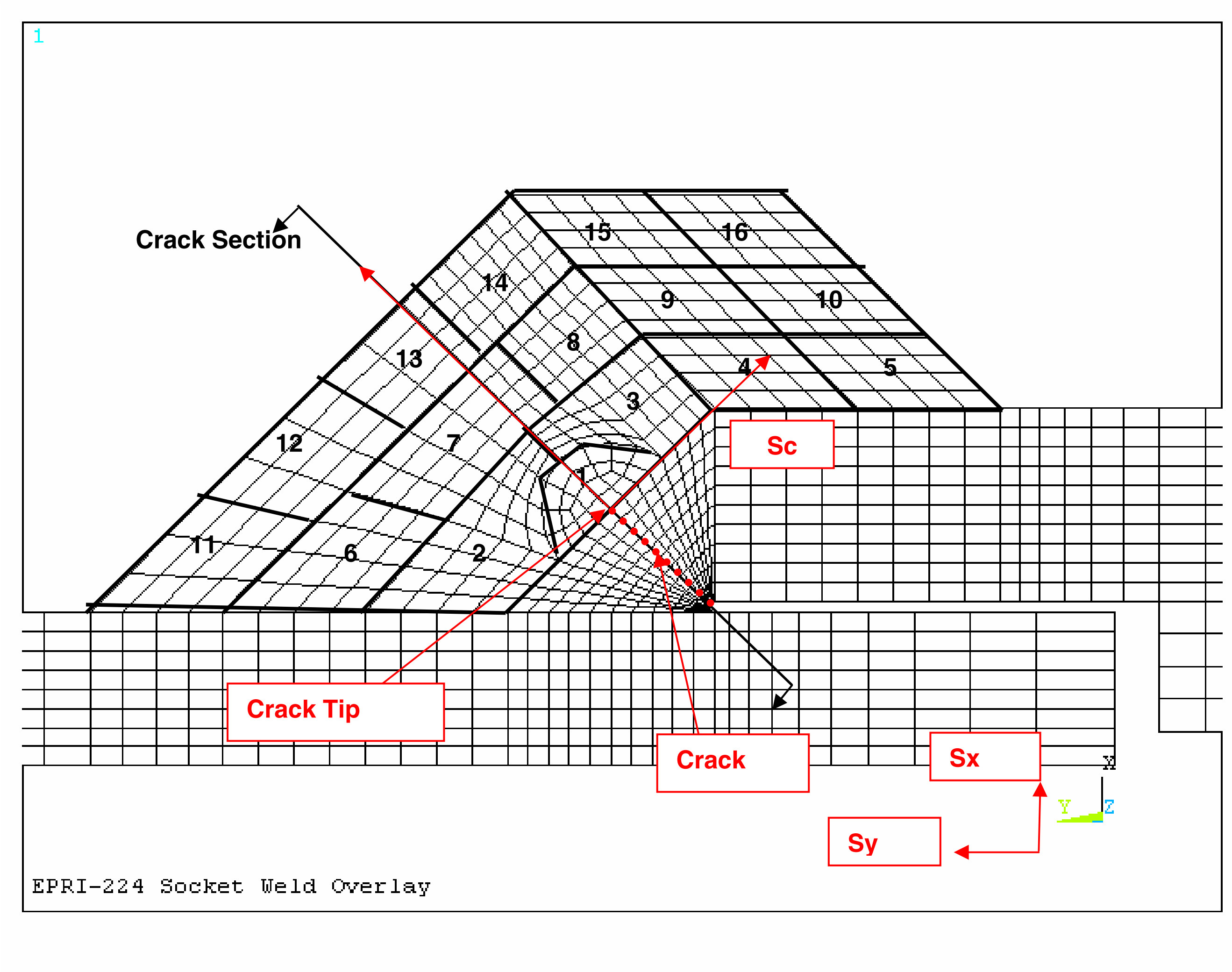
The pipe was assumed to be centered inside the fitting, i.e. the radial gaps are equally spaced. The axial gap was assumed to be 1/16 inch between the pipe and the bottom of the coupling.

The heat transfer coefficient for dry conditions inside the pipe was assumed to be 2 Btu/hr-ft^2-°F at a bulk temperature of 200 °F. The heat transfer coefficient for the outside surface was assumed to be 2 Btu/hr-ft^2-°F for the dry conditions. The bulk temperature for air outside was assumed to be 70 °F. The heat transfer boundary condition was also applied on the crack faces.

The initial temperature of the component was assumed to be 200°F. After overlay, the component was cooled down to 70°F and heated back up to a maximum operating temperature of the component of 550°F.

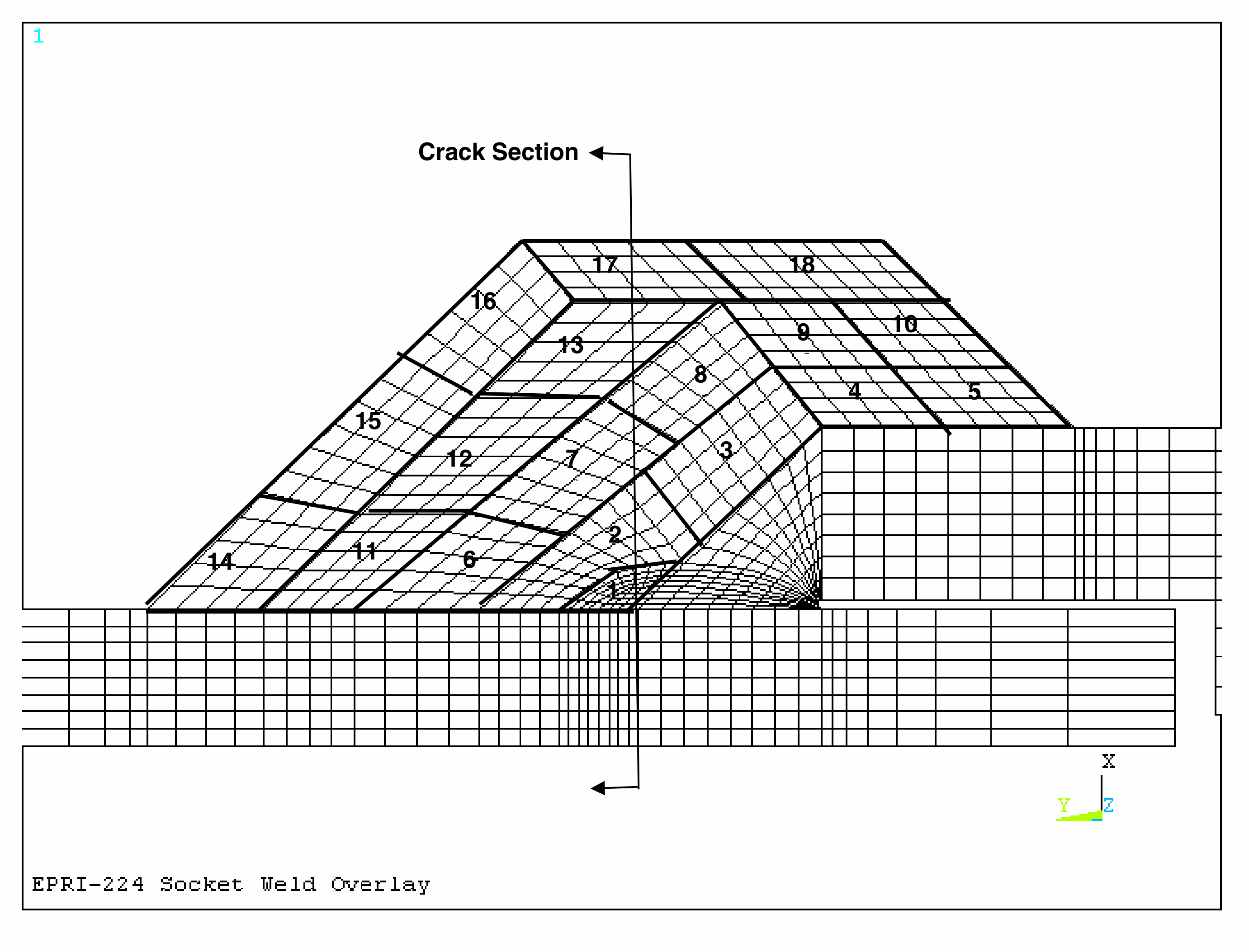
The bead sequence for the root crack (Cases 1 and 2) is shown in Figure 3. The bead sequence for the toe crack with one additional weld layer (Cases 3 and 4) is shown in Figure 4. The bead sequence for the toe crack with two additional weld layers (case 5) is shown in Figure 5. In all cases, the first bead (seal bead) is over the crack tip at the throat plane or toe of the socket weld.

The heat ramp up and ramp down cycles are assumed to be a total of 10 seconds, based on the studies presented in References 3, 4 and 11. The cooling time is adjusted until the maximum temperature in the model is below the interpass temperature.



Note: Welding sequence shown is for pipe to fitting case.
Welding sequence for weld direction from fitting to pipe is as follows:
1, 5, 4, 3, 2, 10, 9, 8, 7, 6,16, 15, 14,13, 12,11

Figure 4-2: Welding Sequence for Root Crack, with One Additional Weld Layer



Note: Welding sequence shown is for the pipe to fitting case.
Welding sequence for the fitting to pipe case is as follows:
1, 5, 4, 3, 2, 10, 9, 8, 7, 6, 13, 12, 11, 18, 17, 16, 15, 14

Figure 4-3: Welding Sequence for Toe Crack, with One Additional Weld Layer

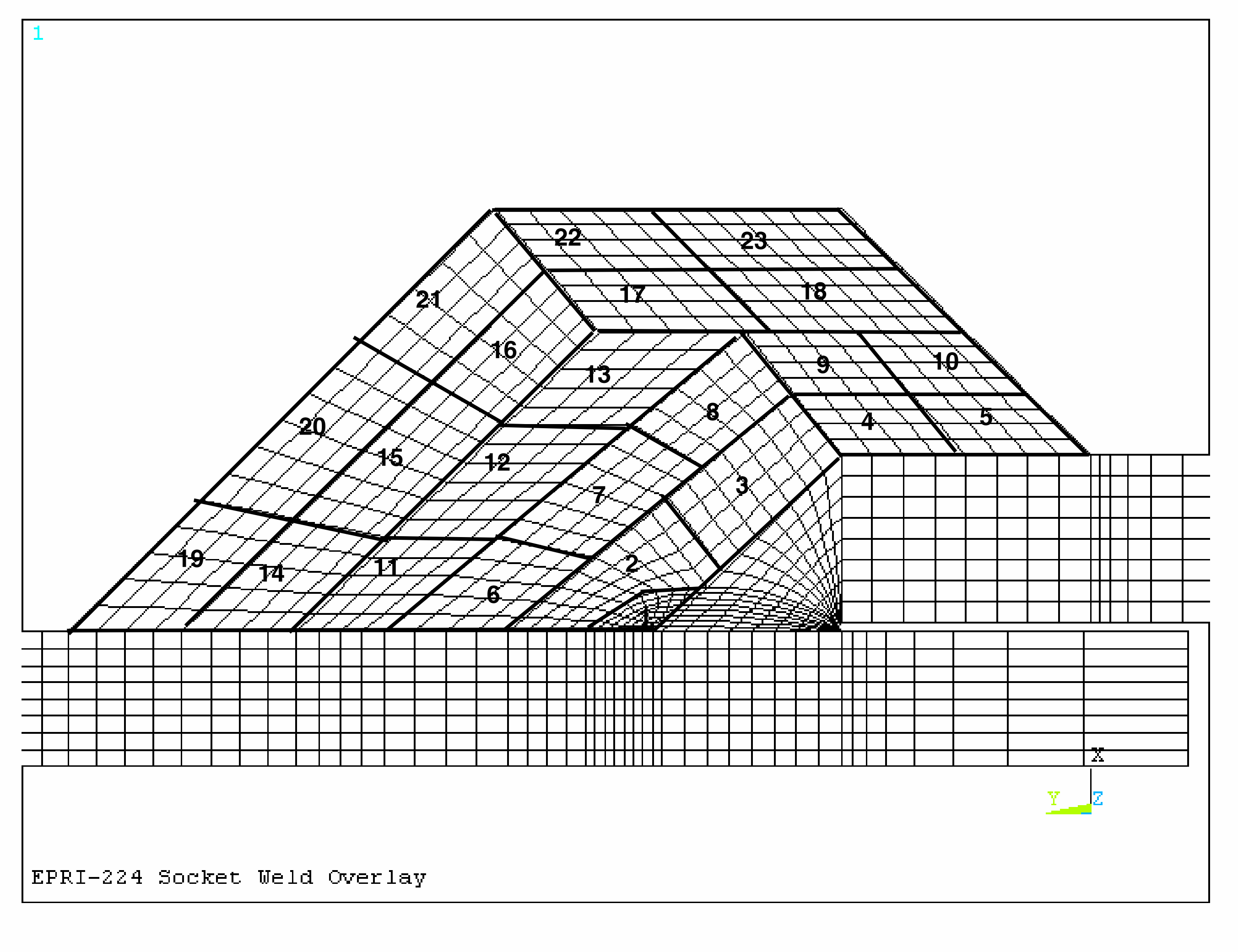


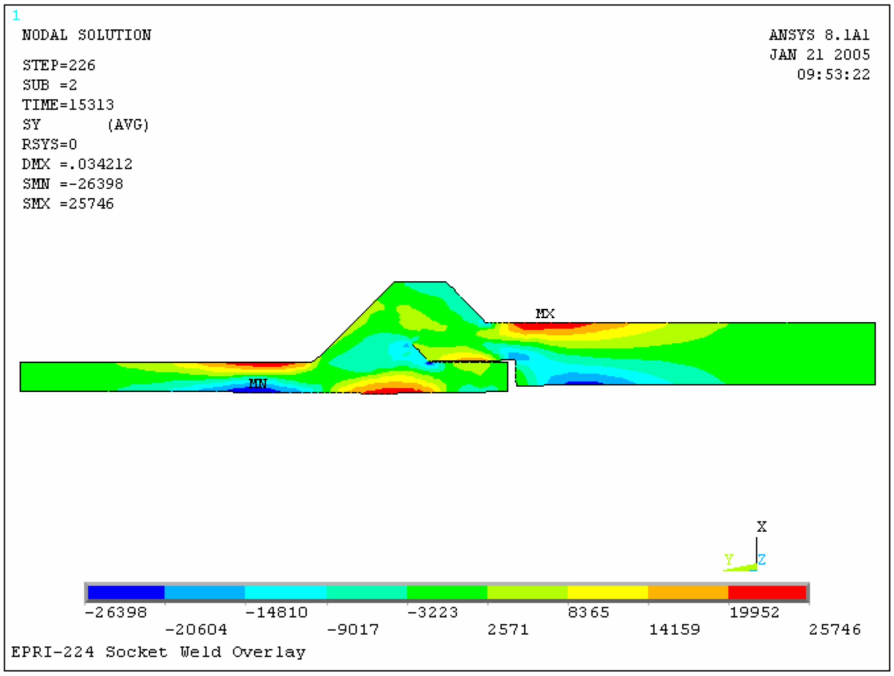
Figure 4-4: Welding Sequence for Toe Crack, with Two Additional Weld Layers

For stress analysis, a symmetrical displacement boundary condition was imposed on the thick end of the coupling.

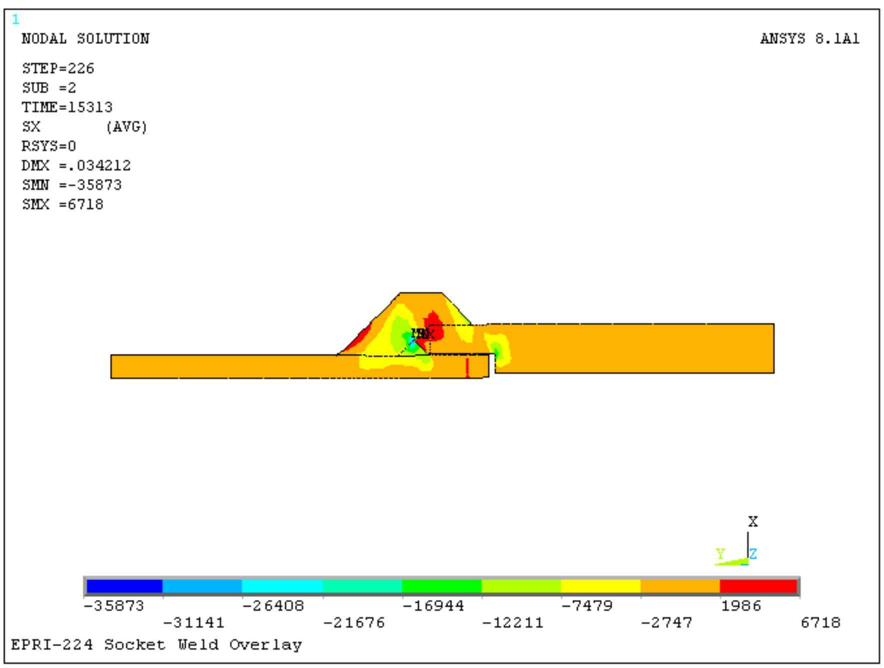
5
RESULTS OF ANALYSIS

5.1 Case (1) One Additional Weld Layer, Dry Condition, Weld Direction from Pipe to Fitting, Root Crack

The residual stress distribution for this case at 550 °F is shown in Figure 6. The global axial stress at the crack tip is compressive. The global radial stress is tension on one crack face but compressive on the other crack face. The maximum tensile residual stress on the outside surface of the joint is not at the toe of the weld overlay.



(a) Axial Stress (S_y)



(b) Radial Stress (S_x)

Figure 5-1: Residual Stress Distribution, 550ºF, One Additional Weld Layer, Dry Condition, Weld Direction from Pipe to Fitting, Root Crack

Figure 7 presents the stress distribution (at 550 °F) from the crack tip along the original crack plane extending into the overlay. The stress, S_c, is given in the local coordinate system. The direction of Sc is identified in Figure 3. The stress S_c is acting perpendicular to the crack plane. It is shown that the residual stress S_c is compressive at the crack tip.

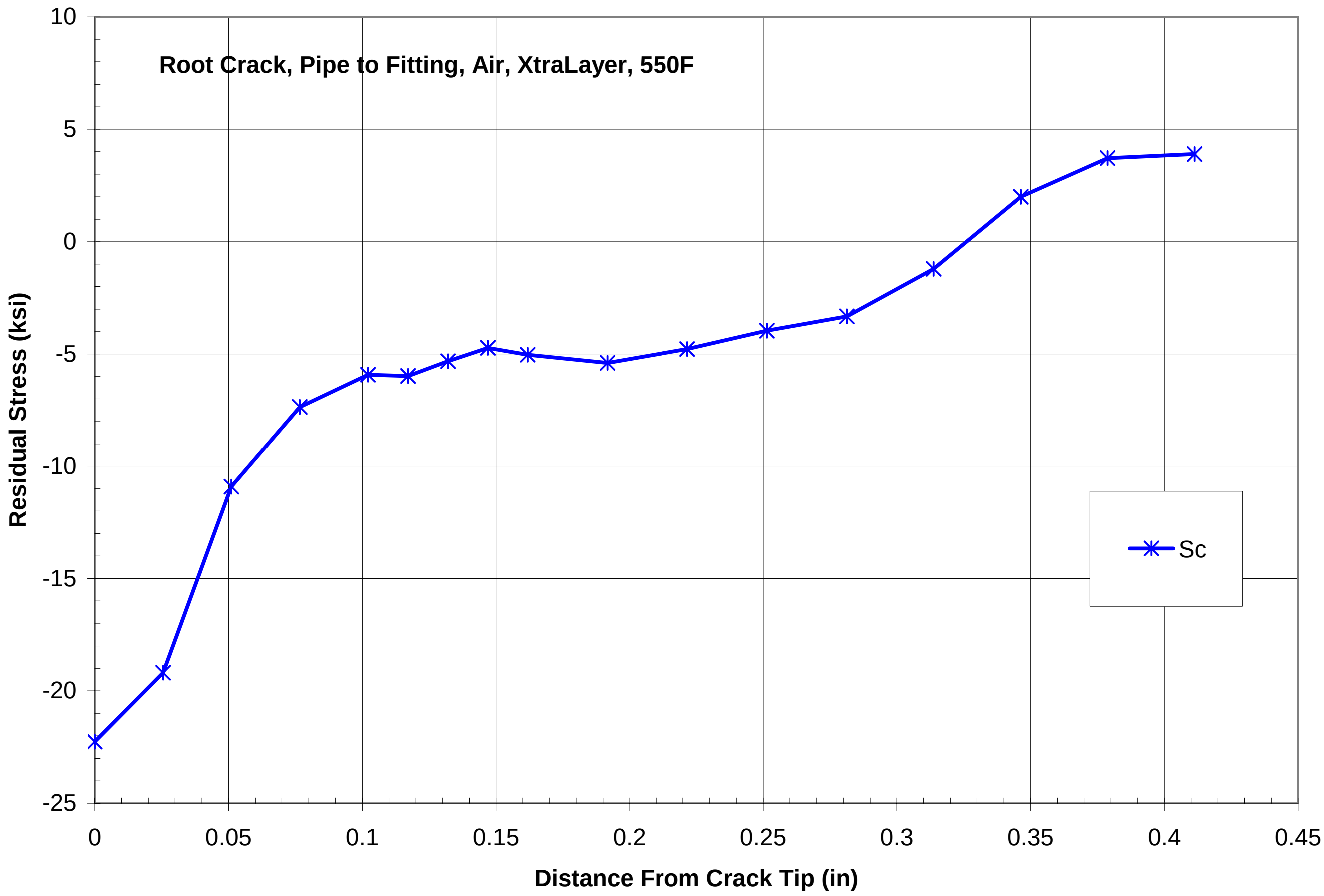
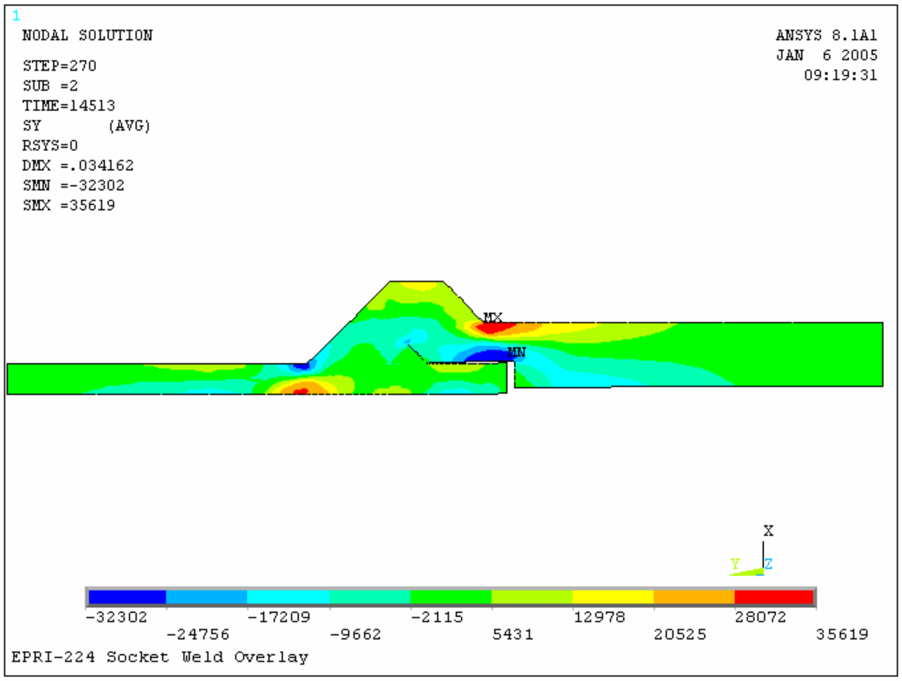


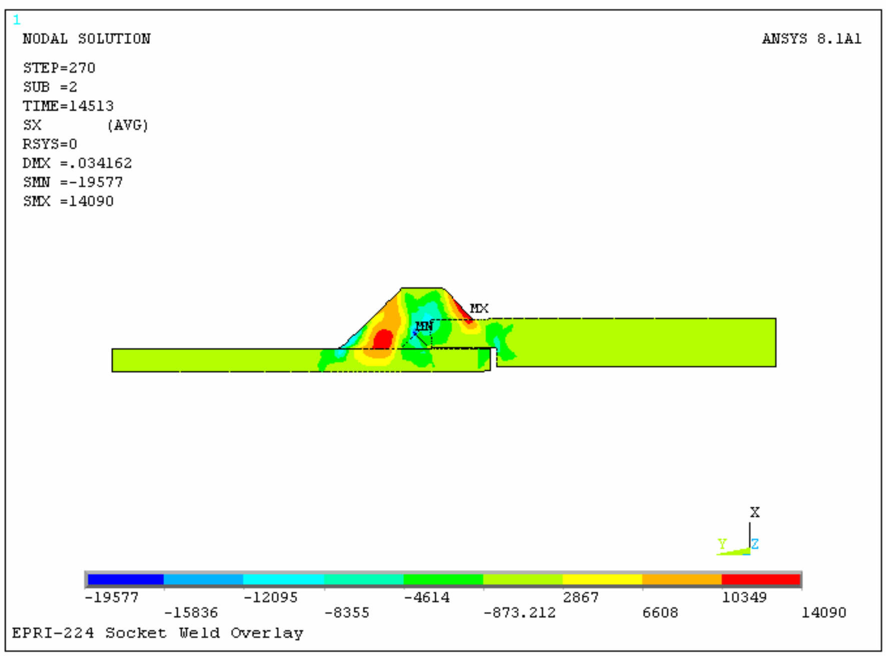
Figure 5-2: Overlay Through-wall Stress Distribution at Weld Throat Section, 550 °F, Dry Condition, Weld Direction from Pipe to Fitting, One Additional Weld Layer, Root Crack

5.2 Case (2) One Additional Weld Layer, Dry Condition, Weld Direction from Fitting to Pipe, Root Crack

The residual stress distribution for a root crack with one additional weld overlay layer, dry condition in the pipe, with weld direction from fitting to pipe, is shown in Figure 8. It shows that there is compressive residual stress at the crack tip for both axial and radial stresses. The maximum tensile axial residual stress is at the toe of the overlay on the outside surface of the fitting.



(a) Axial Stress (S_y)



(b) Radial Stress (S_x)

Figure 5-3: Residual Stress Distribution, 550 °F, One Additional Weld Layer, Dry Condition, Fitting to Pipe, Root Crack

The through wall stress distribution through the crack tip into the weld overlay is shown in Figure 9. The stresses in Figure 9 are presented in the local coordinate system with the C-direction perpendicular to the crack plane. The stress S_c is acting perpendicular to the crack plane. There is substantial compressive residual stress at the crack tip in the local C direction, perpendicular to the crack plane.

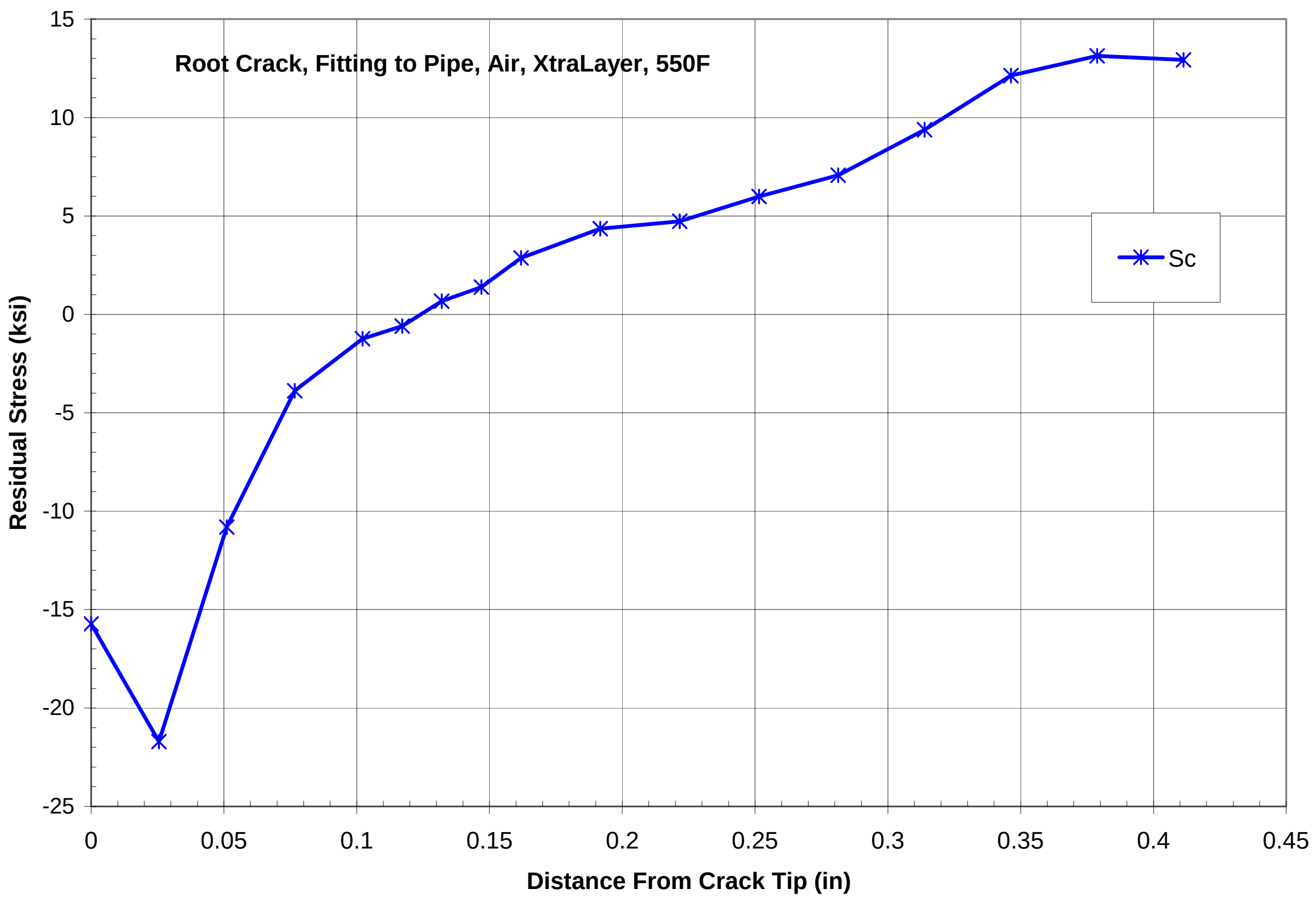
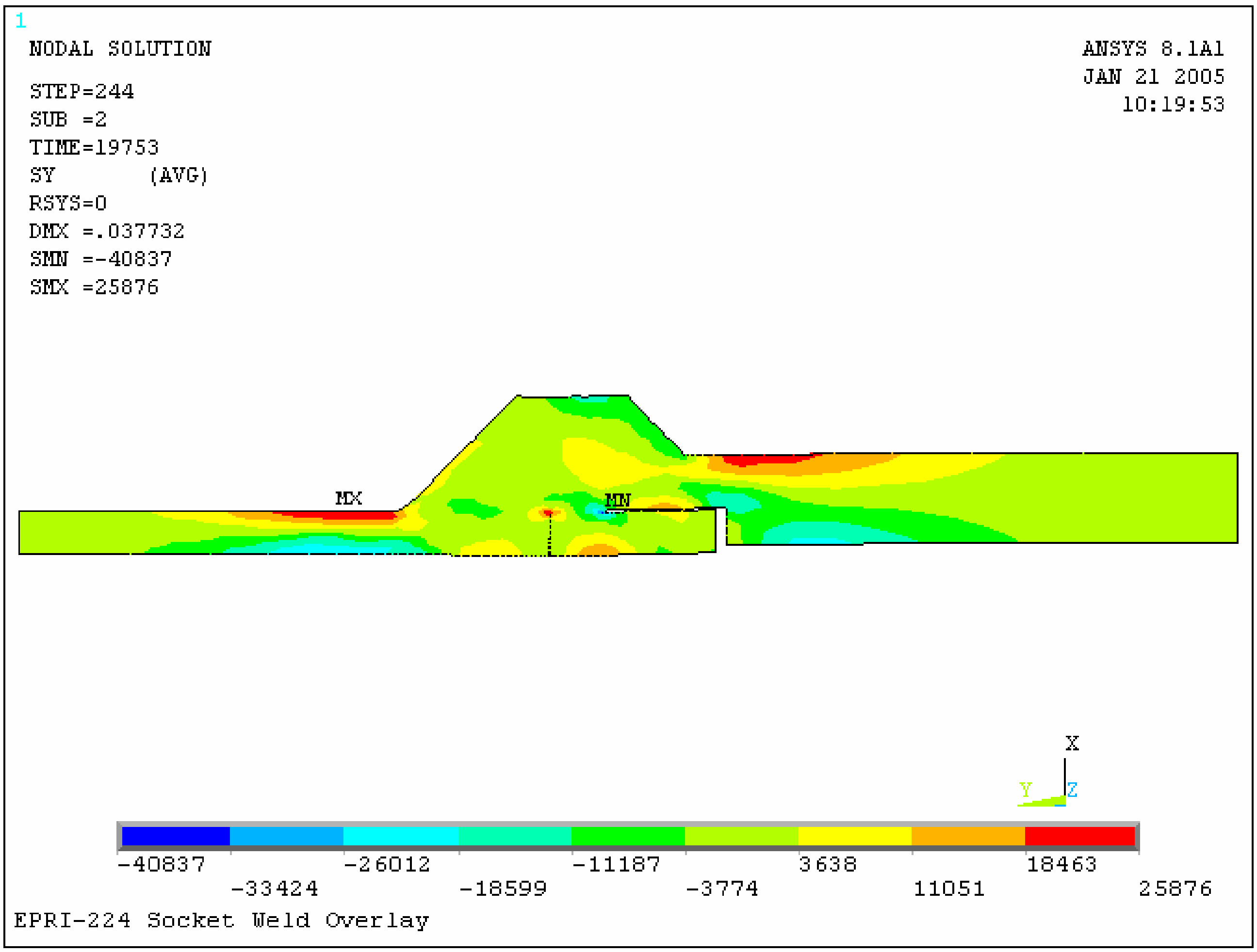


Figure 5-4: Overlay Through-wall Stress Distribution at Weld Throat Section, 550 °F, Dry Condition, Weld Direction from Fitting to Pipe, One Additional Weld Layer, Root Crack

5.3 Case (3) One Additional Weld Layer, Dry Condition, Weld Direction from Pipe to Fitting, Toe Crack

The residual stress distribution for a toe crack with one additional weld overlay layer, dry condition in the pipe, with weld direction from pipe to fitting, is shown in Figure 10. The maximum tensile axial residual stress is near the toe of the weld overlay on the pipe OD.



Axial Stress (S_y)

Figure 5-5: Residual Stress Distribution, 550 °F, One Additional Weld Layer, Dry Condition, Weld Direction From Pipe to Fitting, Toe Crack

The through wall stress distribution through the crack tip into the weld overlay is shown in Figure 11. There is substantial tensile residual stress at the crack tip in the Y direction, perpendicular to the crack plane.

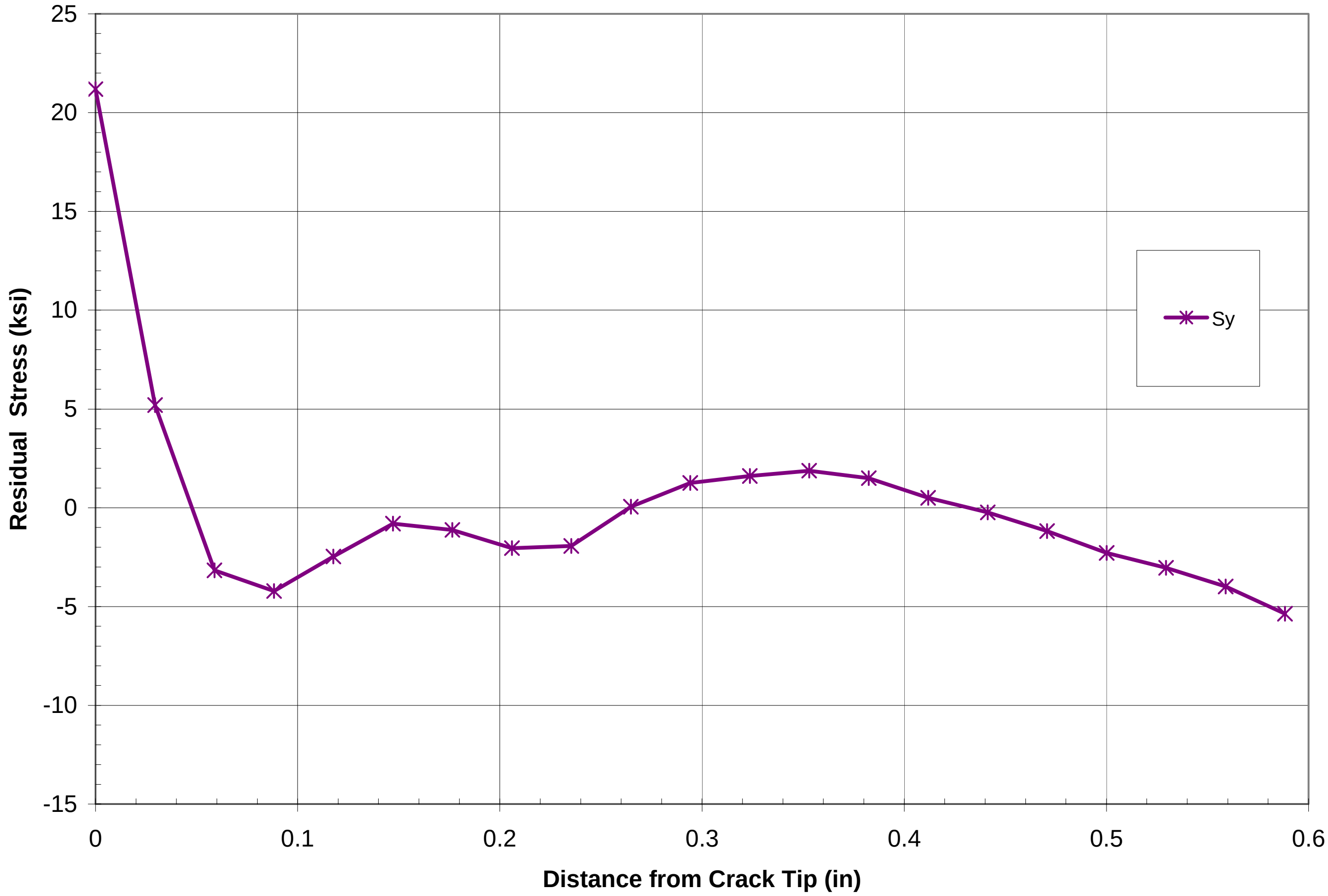
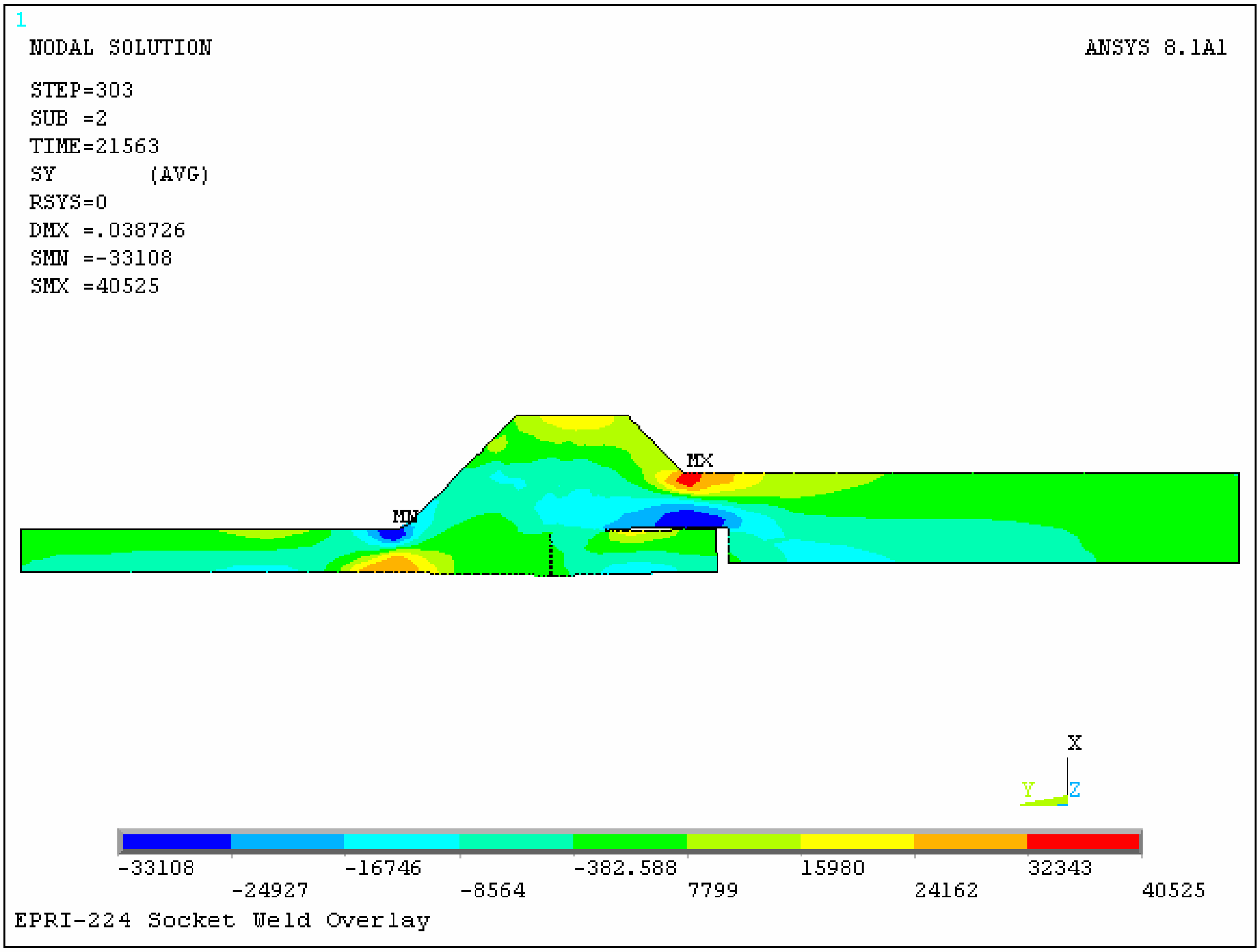


Figure 5-6: Overlay Through-wall Stress Distribution at Crack Section, 550 °F, Dry Condition, Weld Direction from Pipe to Fitting, One Additional Weld Layer, Toe Crack

5.4 Case (4) One Additional Weld Layer, Dry Condition, Weld Direction from Fitting to Pipe, Toe Crack

The residual stress distribution for a toe crack with one additional weld overlay layer, dry condition inside, with weld direction from fitting to pipe, is shown in Figure 12. The maximum tensile axial residual stress is near the toe of the weld overlay at the fitting.



Axial Stress

Figure 5-7: Residual Stress Distribution, 550 °F, One Additional Weld Layer, Dry Condition, Weld Direction from Fitting to Pipe, Toe Crack

The through wall stress distribution through the crack tip into the weld overlay is shown in Figure 13. The stresses in Figure 13 are presented in the coordinate system with the Y-direction perpendicular to the crack plane. It is shown that there is a small tensile, S_y, stress, about 1 ksi at the crack tip. It changes to compressive residual stress, -7.5 ksi, at about 0.03 inches away from the crack tip.

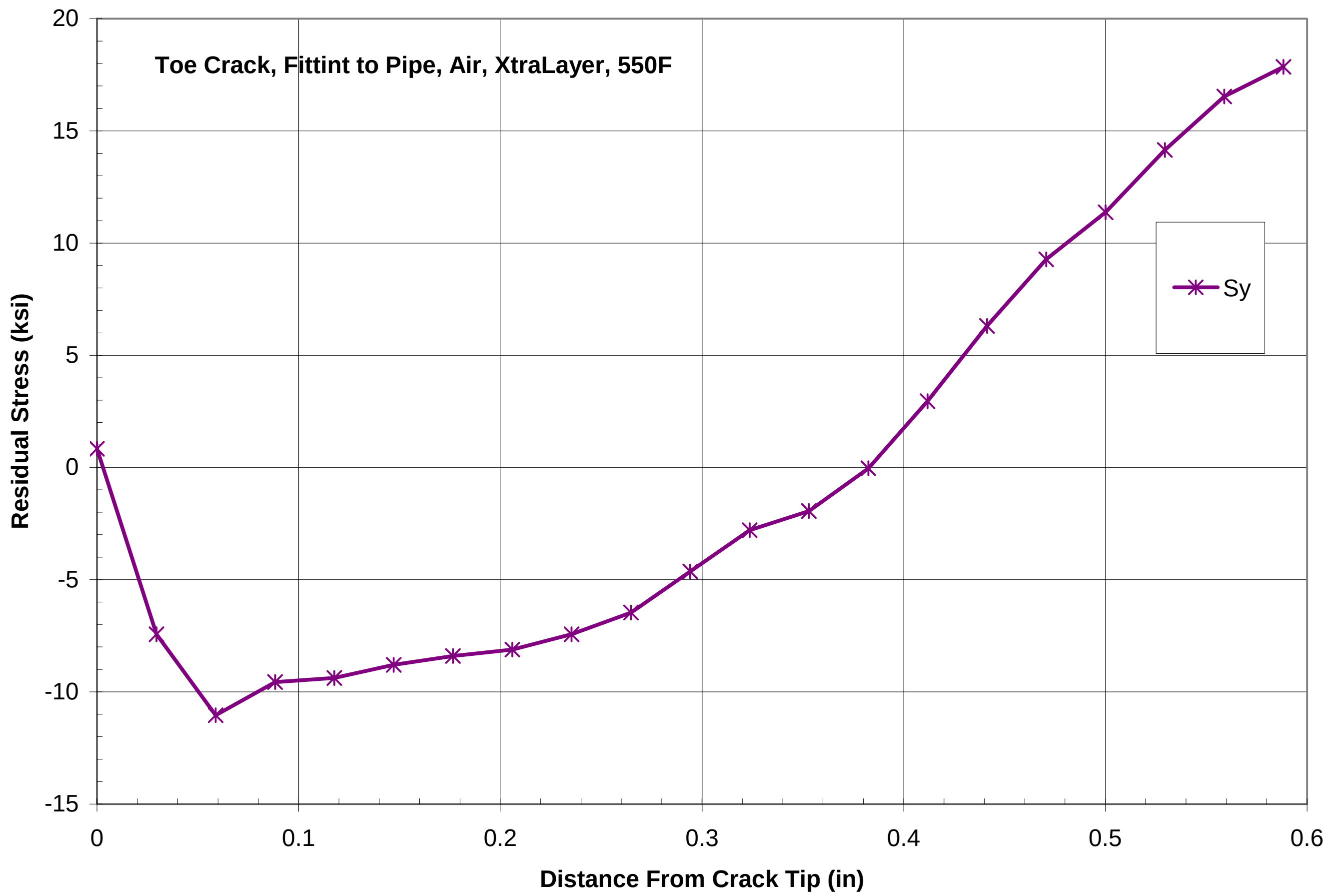
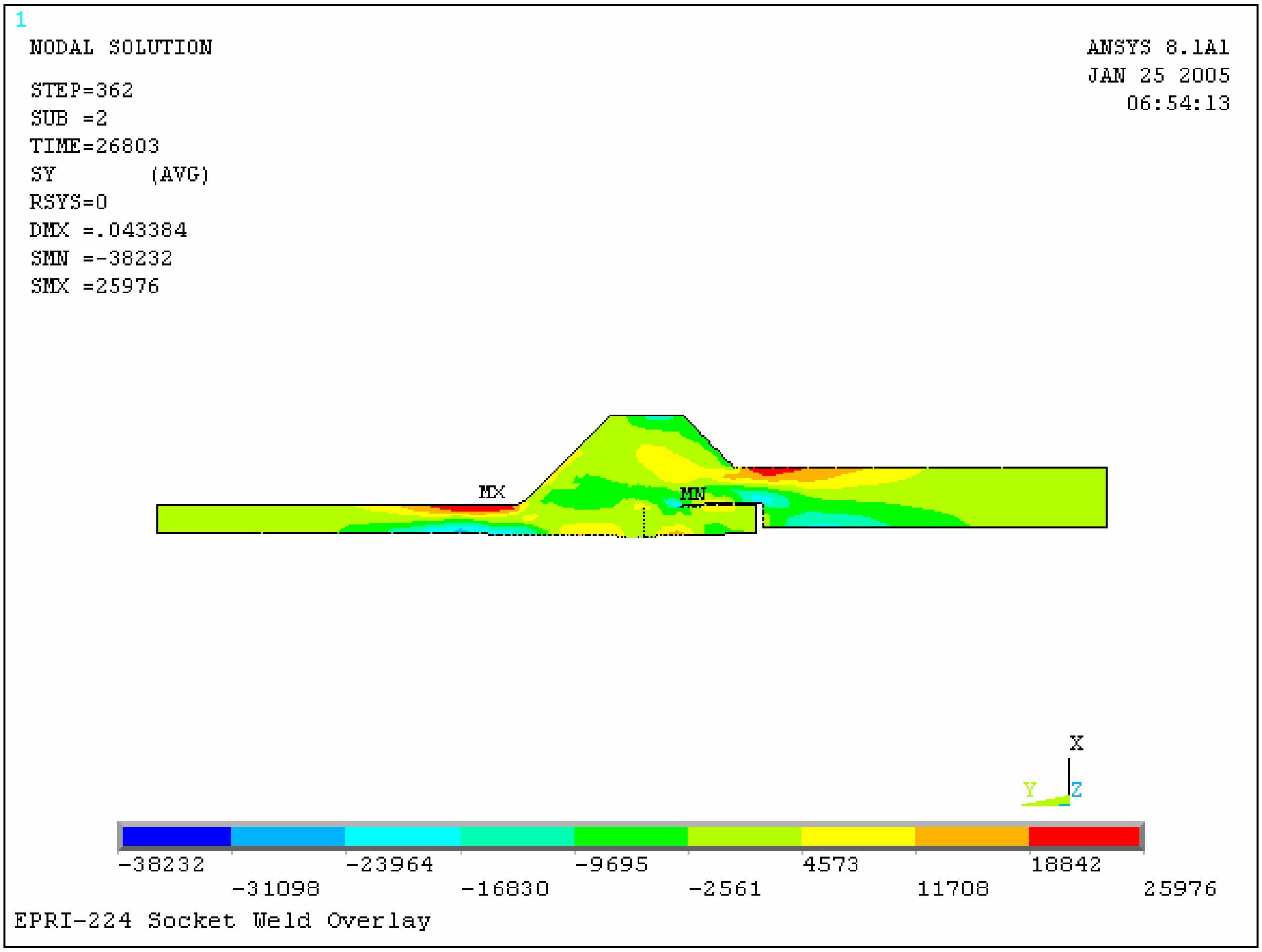


Figure 5-8: Overlay Through-wall Stress Distribution at Crack Section, 550 $^\circ$F, Dry Condition, Weld Direction from Fitting to Pipe, One Additional Weld Layer, Toe Crack

5.5 Case (5) Two Additional Weld Layer, Dry Condition, Weld Direction from Pipe to Fitting, Toe Crack

Since Case (3) does not give favorable residual stresses at the crack tip, in this case, a second extra weld overlay layer was added to the weld overlay to evaluate the effect on the residual stress.

The residual stress distribution is shown in Figure 14. There is still tensile global axial residual stress at the crack tip.



Axial Stress

Figure 5-9: Residual Stress Distribution, 550 °F, Two Additional Weld Layers, Dry Condition, Weld Direction from Pipe to Fitting, Toe Crack

The through wall stress distribution through the toe crack tip is shown in Figure 15. It is shown that the residual stress perpendicular to the crack plane (S_y) is still tensile, 10 ksi, but considerably less compared to Case (3), which was greater than 20 ksi, Figure 11.

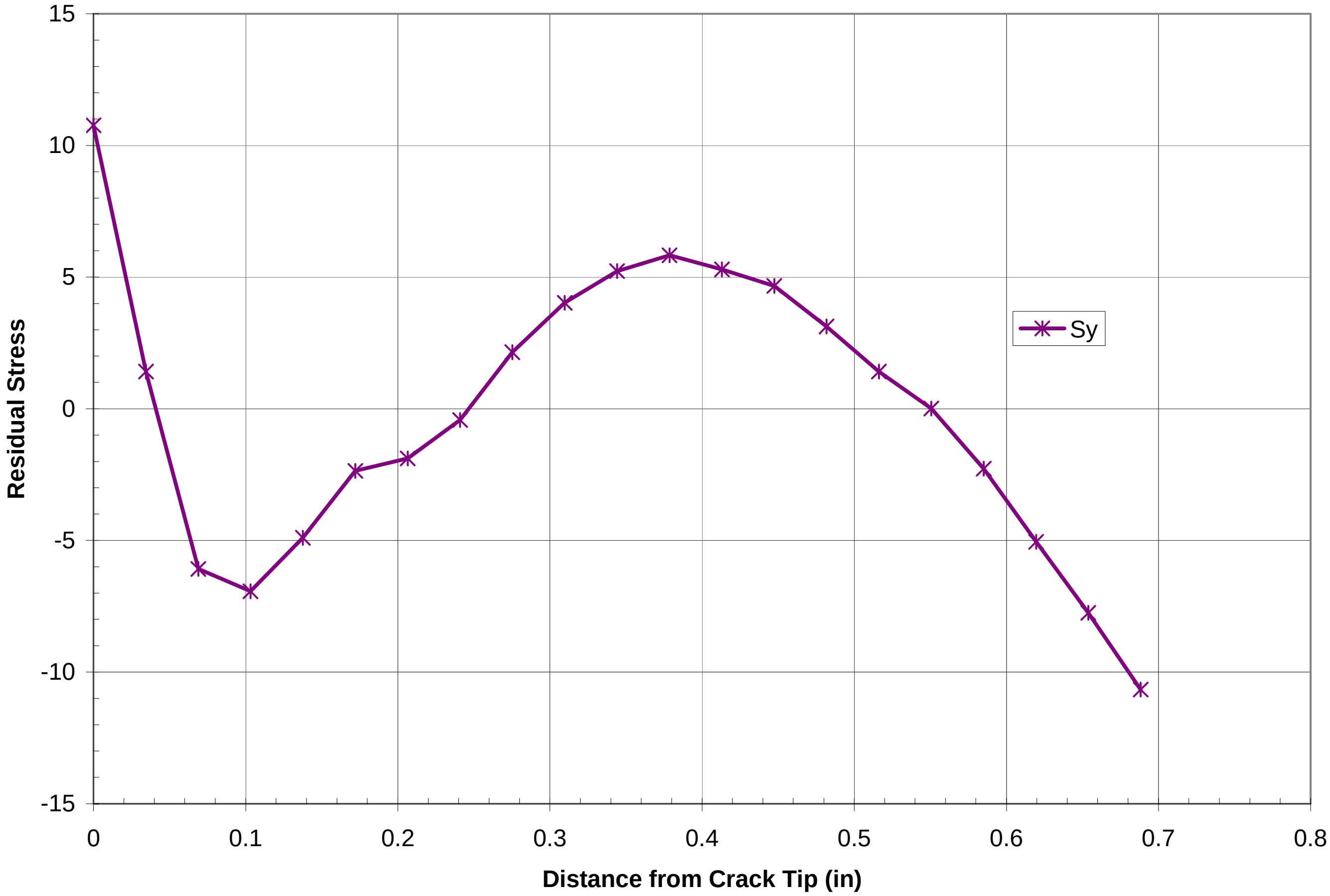


Figure 5-10: Residual Stress Distribution, 550 °F, at Crack Section, Two Additional Weld Layers, Dry Condition, Weld Direction from Pipe to Fitting, Toe Crack

6 CONCLUSIONS AND DISCUSSIONS

The effect of additional weld layers on the residual stress was evaluated for the dry condition, for both root and toe crack. It is shown that one additional weld overlay layer improves the weld residual stress perpendicular to the crack plane for all cases, except the toe crack with weld direction from pipe to fitting. Even with two weld overlay layers, the residual stress at the crack perpendicular to the crack plane, is still tensile.

Table 4 summarizes the residual stress results at the crack tip for all cases of socket weld overlay repairs, including the results for water backing. For the root crack, either weld direction or inside condition would give favorable residual stress, except an additional layer is required for the weld direction from fitting to pipe for the dry back condition. For the toe crack, only the weld direction from fitting to pipe with the water condition inside would give compressive stress at the crack tip. The cases of water back, pipe to fitting and dry back, fitting to pipe, result in marginally compressive stresses.

Table 6-1: Residual Stress Conditions Summary

Crack Loc.	Cond.	Welding Direction	Code Case Requirement	One Additonal Layer	Two Additional Layers
Root	Dry	Pipe to Fitting	Compressive	Compressive	--
		Fitting to Pipe	Tensile	Compressive	--
	Water	Pipe to Fitting	Compressive	--	--
		Fitting to Pipe	Compressive	--	--
Toe	Dry	Pipe to Fitting	Tensile	Tensile	Tensile
		Fitting to Pipe	Marginal[1]	Compressive[2]	--
	Water	Pipe to Fitting	Marginal[3]	--	--
		Fitting to Pipe	Compressive	--	--

Note:

1. Tensile 2.51 ksi at the surface changes to compressive 2.33 ksi at 0.0244 in from crack tip and stays compressive to 0.32 inches beyond the crack tip, (Figure 11, Reference 2).
2. Tensile 0.83 ksi at the surface changes to compressive 7.44 ksi at 0.0294 in from crack tip and stays compressive to 0.38 inches beyond the crack tip, Figure 13.
3. Tensile 1.5 ksi at the surface changes to compressive 5.85 ksi at 0.0244 in from crack tip and changes back to tensile 4.37 ksi at 0.0732 in beyond crack tip, (Figure 7, Reference 2.

7 REFERENCES

1. SI Calculation, EPRI-224-301, “Finite Element Analysis of Typical Socket Weld Overlay Repair Designs to Determine Residual Stresses – Root Crack Geometry,” Rev. 0, December 2004.
2. SI Calculation EPRI-224-302, “Finite Element Analysis of Typical Socket Weld Overlay Repair Designs to Determine Residual Stresses – Toe Crack Geometry,” Rev. 0, December 2004.
3. Rybicki, E. F., et al., “Residual Stresses at Girth-Butt Welds in Pipes and Pressures Vessels,” U.S. Nuclear Regulatory Commission Report NUREG-0376, R5, November 1977.
4. Rybicki, E. F., and Stonesifer, R. B., “Computation of Residual Stresses Due to Multipass Welds in Piping Systems,” Journal of Pressure Vessel Technology, Vol. 101, May 1979.
5. Code Case N-666, “Reinforcement of Class 1, 2, and 3 Socket Welded Connections, Section XI, Division 1,” ASME Boiler and Pressure Vessel Code, 12/9/03.
6. American National Standard, Forged Steel Fitting, Socket-Welding and Threaded, ANSI B16.11, 1980.
7. ASME, Boiler and Pressure Vessel Code, Section III, 1989 Edition, with All Addenda.
8. EPRI Report NP-7085-D, Project T303-1, “Inconel Weld –Overlay Repair for Low Alloy Steel to Safe-End Joint,” January 1991.
9. E-mail, Greg Frederick (EPRI)/Paul Hirschberg (SIA), “Re: Socket Weld Overlay Analysis,” September 9, 2004.
10. ANSYS/MECHANICAL, Release 8.1, (w/Service Pack 1) ANSYS, Inc., April 2004.
11. WELD3, Version 2.1, Verification Manual, Computational Mechanics, 1991

A
APPENDIX

Filename	Description
RT-F2PAIR-XTRLYR	
GEOM.INP	Geometry input file
STRSSTRN.INP	Stress-strain curve input file
F2PBDPASS.INP	Lumped bead pass input file
F2PTHMAIR.INP	Thermal analysis input file
F2PSTRSAIR.INP	Stress analysis input file
PSTCRKSCT.INP	Postprocessing input file
F2PAIRPSTSTRS.OUT	Postprocessing output file
RT-P2FAIR-XTRLYR	
GEOM.INP	Geometry input file
STRSSTRN.INP	Stress-strain curve input file
F2PBDPASS.INP	Lumped bead pass input file
F2PTHMAIR.INP	Thermal analysis input file
F2PSTRSAIR.INP	Stress analysis input file
PSTCRKSCT.INP	Postprocessing input file
P2FAIRPSTSTRS.OUT	Postprocessing output file
TOE-F2PAIR-XTRLYR	
TOEGEOM.INP	Geometry input file
STRSSTRN.INP	Stress-strain curve input file
F2PBDPASS.INP	Lumped bead pass input file
TOEF2PTHMAIR.INP	Thermal analysis input file
TOEF2PSTRSAIR.INP	Stress analysis input file
PSTCRKSCT.INP	Postprocessing input file
F2PAIRPSTSTRS.OUT	Postprocessing output file
TOE-P2FAIR-XTRLYR	
TOEGEOM.INP	Geometry input file
STRSSTRN.INP	Stress-strain curve input file
F2PBDPASS.INP	Lumped bead pass input file
TOEP2FTHMAIR.INP	Thermal analysis input file
TOEP2FSTRSAIR.INP	Stress analysis input file
PSTCRKSCT.INP	Postprocessing input file
P2FAIRPSTSTRS.OUT	Postprocessing output file

Filename	Description
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STRSSTRN.INP	Stress-strain curve input file
F2PBDPASS.INP	Lumped bead pass input file
TOEP2FTHMAIR.INP	Thermal analysis input file
TOEP2FSTRSAIR.INP	Stress analysis input file
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P2FAIRPSTSTRS.OUT	Postprocessing output file

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