

Residual Stress Analysis of an Overlay Weld on a Dissimilar Metal Weld

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1 ABSTRACT

In recent years, the dissimilar metal welds, Alloy 82/182 welds, used to connect the stainless steel piping and low alloy steel or carbon steel components in a nuclear reactor piping system have experienced a cracking due to a primary water stress corrosion (PWSCC). It is well known that one reason for the cracking is the residual stress by the weld. But, it is difficult to estimate the weld residual stress exactly due to many the parameters for welding process. In this paper, a Butt model weld specimen of was manufactured and the residual stresses of the weld specimen were measured by the X-Ray method and a Hole Drilling Technique. These results were compared with the result of the Butt FEM Model to confirm the confidence of the FEM input. Also, an analysis of the 3 FEM models made by the ABAQUS Code was performed to estimate the weld residual stress on a dissimilar metal weld exactly. 3 FEM models are the Butt FEM model, the Repair FEM model and the Overlay FEM model and are made as the 2D plane-strain model. A thermal analysis and a stress analysis were performed on each model and the residual stresses for each model were calculated and compared respectively.

2 INTRODUCTION

The components and piping systems in PWRs include many dissimilar metal welds. The weld connection of a carbon steel SA508 Gr3 and a stainless steel 316L is a typical example. This dissimilar metal has been welded by using Alloy 82 or Alloy 182. In recent years, the dissimilar metal welds, Alloy 82/182 welds, used to connect the stainless steel piping and low alloy steel or carbon steel components in a nuclear reactor piping system have experienced a cracking due to a primary water stress corrosion (PWSCC) ([King, 2003], [Brust et al., 1997] and [Dong et al., 2000]). It is well known that one reason for the cracking is the residual stress by the weld. Thus, it is important to estimate the weld stress exactly but it is difficult to estimate the weld residual stress exactly due to many the parameters for a welding process. Much research has been done to estimate the residual stress on a dissimilar metal weld ([King, 2005],[EPRI, 2007], [Fricke, 2006], [David, 2005] and [Kim, 2008]). There are many methods to estimate the weld residual stress. FEM (Finite Element Method) is generally used due to the advantage of the parametric study and the X-ray method, a Hole Drilling Technique for an experimental method are also usually used. In this paper, the experimental method and FEM were used to estimate the weld residual stress. First, a Butt weld specimen was manufactured. SA 508 Gr3 plate (330x330x40 mm) and SUS 316L (330x330x40 mm) were welded by Alloy 182. The residual stress of this weld specimen was measured by the X-Ray method and the Hole Drilling Technique. Second, a Butt FEM Model was made and analyzed by the ABAQUS Code (ABAQUS, 2004). A thermal analysis and a stress analysis were performed and the residual stresses were calculated. These FEM results were compared with the experimental values. Third, a Repair FEM Model was made and analyzed by the ABAQUS Code in order to simulate, as follows. In case that the crack is generated at the bottom of the weld part, the bottom part including the crack is removed and the groove is welded again by Alloy 182. Forth, an Overlay FEM Model was made and analyzed by the ABAQUS Code. Overlay weld is a typical method in order to moderate the stress distribution of the weld part and method to lower the possibilities of a PWSCC. Totally, 3 layers were overlaid on the dissimilar weld part and the distribution of the residual stress was investigated whenever each layer was overlaid.

3 METHODS AND RESULTS

3.1 Experimental measurement of the residual stress

The material and the thermal properties for each dissimilar metal are shown in Table 1. The number of pass at the dissimilar weld part is 31 and the heat input of the welding condition was presented in Table 2. Butt weld specimen is shown in Fig. 1. The plate size of the SUS 316L and the SA 508 Gr3 is 330x330x40 mm respectively. The edge of the SA508 plate became the buttering by Alloy 182 and two plates were welded by a filler. The material of the filler and the buttering was Alloy 182. The size of the groove bottom and the buttering was 3 mm and 6 mm respectively. The measurement dislocations for the residual stress are shown in Fig. 2. The X-Ray measurement equipment and the Hole Drilling measurement equipment are shown in Fig. 3 and Fig. 4 respectively.

Table 1. Material and thermal properties @ 21 °C

	E (GPa)	Poisson's Ratio	Thermal Expansion	Thermal Conductivity (W/mm °C)	Specific Heat (J/Kg °C)
SA 508	192	0.29	1.15E-5	5.19E-2	460.24
SUS 316L	195	0.27	1.53E-5	1.29E-2	451.45
Alloy 182	214	0.27	1.22E-5	9.72E-3	397.48

Table 2. Heat input of the welding condition

	Weld method	Current (A)	Voltage (V)	Weld speed (cm/min)
Pass 1-2	GTAW	120-130	10-12	9-10
Pass 3-11	SMAW	120-130	21-24	13-15
Pass 12-31	SMAW	135-140	23-26	15-16

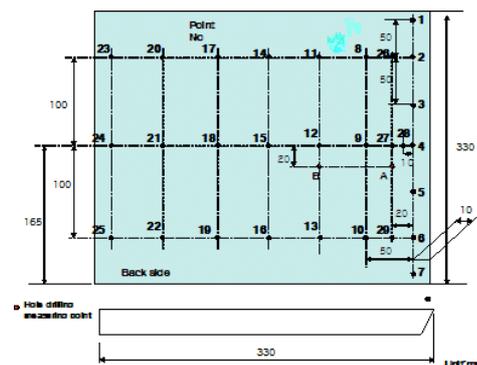


Figure 1. Butt weld specimen

Figure 2. Dislocation of the measurement



Figure 3. X-Ray measurement equipment

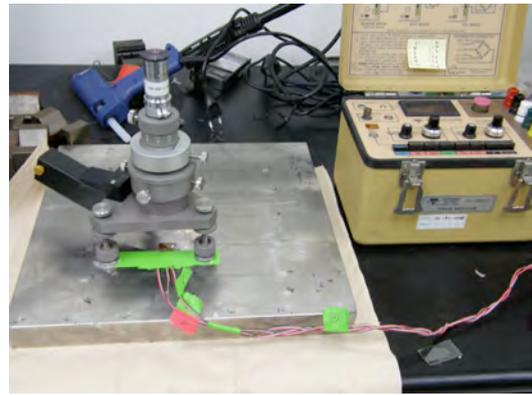


Figure 4. Hole Drilling measurement equipment

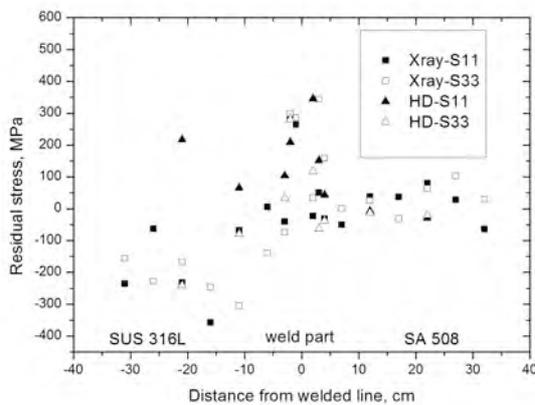


Figure 5. Results of the experimental measurement

The results of the experimental measurement are shown in Fig. 5. Where, $S_{11}(x)$ is the transverse stress in the welding direction and $S_{33}(z)$ is the stress in the welding direction. As shown in Fig. 5, X-Ray measurement values and Hole Drilling measurement values show a trend which is in agreement at the weld part and SA 508 plate. But, the S_{11} values of X-Ray and Hole Drilling measurement values at the SUS 316L plate show a big deviation.

3.2 Butt FEM Model

Butt FEM Model is shown in Fig. 6 and consists of the SUS316 plate (330x330x40 mm) and the SA508 plate (330x330x40 mm). This model is made by the ABAQUS/CAE Code and the 2D plane-strain model. A thermal analysis and a stress analysis were performed on this model and the residual stresses were calculated. “Element birth” technique for the meshing and a lumping method for the bead simulation were used. 10 passes were used by the lumping method instead of the actual 31 passes. The fixed boundary condition was applied at the end the SUS 316 plate and a roller boundary condition at the end of the SA 508 plate.

4-node DC2D4(Diffusive Heat Transfer or Diffusion Elements) was used for the thermal analysis and the 4-node CPE4R(Plane Strain Elements) was used for the stress analysis. The total nodes and elements of this model are 7140 and 7409 respectively. $10 \text{ W/m}^2 \text{ } ^\circ\text{C}$ as the convection coefficient was used for the weld convection and the phase transfer was not considered.

Total weld passes consist of 10 passes for the Butt FEM model and the temperature distribution in the case of the 6th pass is shown in Fig. 7. The results of the stress analysis are shown in Fig. 8 and Fig. 9 respectively. Fig. 8 is the stress distribution of $S_{11}(x)$ and Fig. 9 is the stress distribution of $S_{33}(z)$. The residual stresses measured by the X-Ray method and the Hole Drilling Technique were compared with the results of the Butt FEM model. These results are represented in Fig. 10.

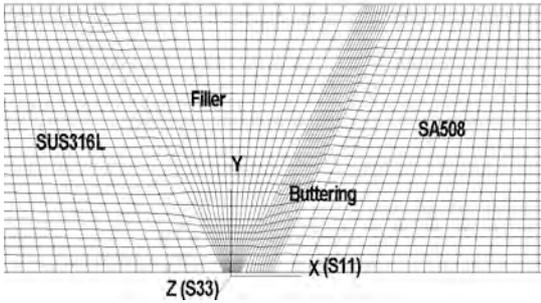


Figure 6. Butt FEM Model

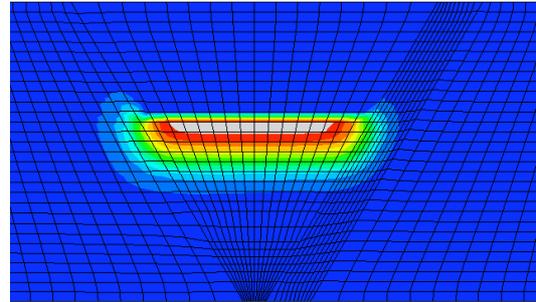
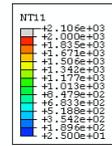


Figure 7. Temperature distribution of the 6th pass



Figure 8. S11(σ_x) distribution of the Butt FEM Model

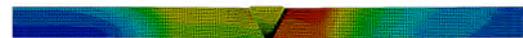


Figure 9. S33(σ_z) distribution of the Butt FEM Model

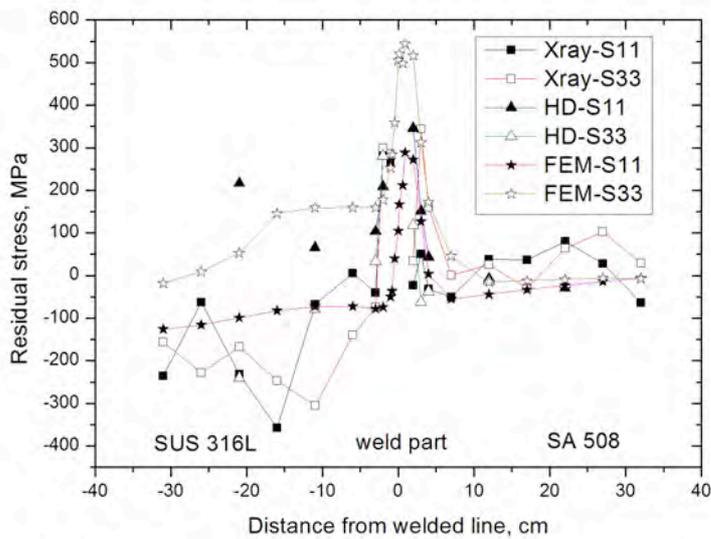


Figure 10. Comparison of the experimental values and the Butt FEM model

Where, $S_{11}(x)$ is the transverse stress in the welding direction and $S_{33}(z)$ is the stress in the welding direction. As shown Fig. 10, The experimental values(S_{11}) by the X-Ray method and the results of the Butt FEM Model have an especially large deviation at the SUS 316L plate, but as a whole, these experimental values have a trend which is in agreement with the Butt FEM Model.

3.3 Repair FEM Model

Repair FEM Model is shown in Fig. 11. A half of the plate thickness from the bottom part was removed and welded again by using a filler (Alloy 182).

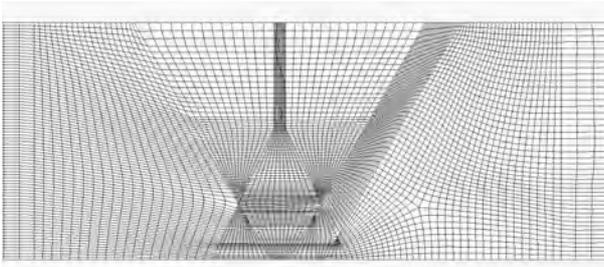


Figure 11. Repair FEM Model

The total nodes and elements of this model are 10867 and 10648 respectively.

For the Repair FEM model, 8 passes were used by the lumping method instead of the actual 20 passes and the temperature distribution in the case of the 7th pass is shown in Fig. 12. The results of the stress analysis are shown in Fig. 13 and Fig. 14 respectively. Fig. 13 is the stress distribution of $S_{11}(x)$ and Fig. 14 is the stress distribution of $S_{33}(z)$.

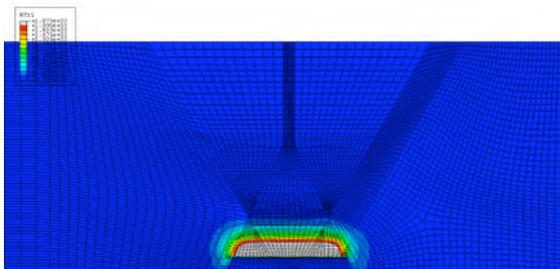


Figure 12. Temperature distribution of the 7th pass

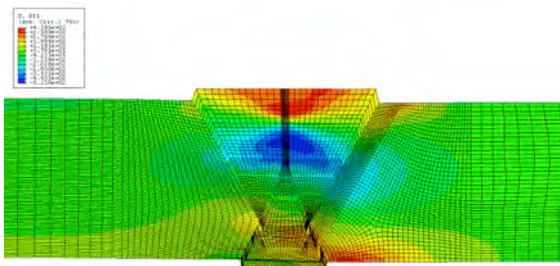


Figure 13. $S_{11}(x)$ distribution of the Repair FEM Model

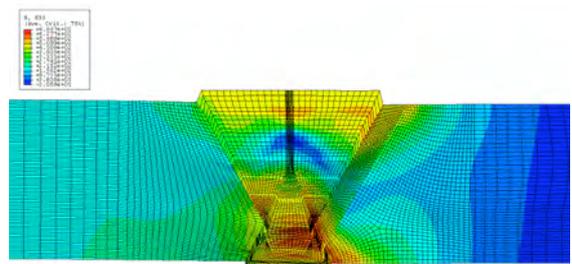


Figure 14. $S_{33}(z)$ distribution of the Repair FEM Model

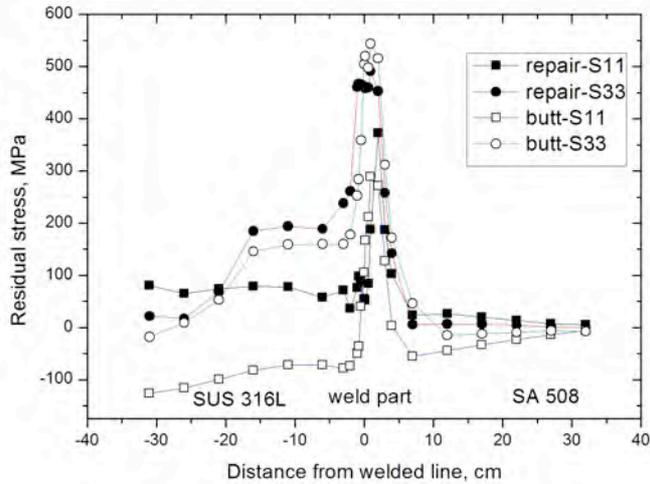


Figure 15. Result comparison of the Repair FEM Model and the Butt FEM model

The analysis results of the Repair FEM model and the Butt FEM Model are represented in Fig. 15. We know that the stresses of the Repair FEM Model are on a whole higher than that of the Butt FEM Model. Therefore, we know that the Overlay weld is needed to lower the stress level at the weld part, the SUS 316L plate and the SA 508 plate.

3.4 Overlay FEM Model

Overlay model is shown in Fig. 16. The top part of the plate was overlaid by the filler (Alloy 152).

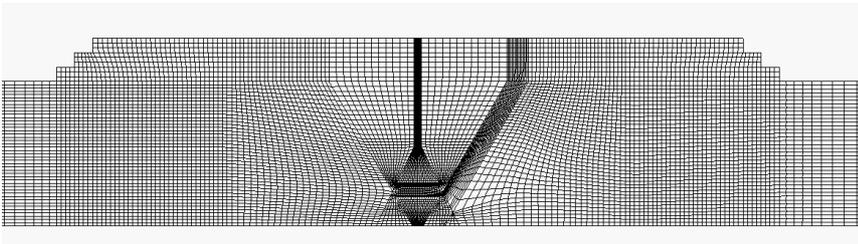


Figure 16. Overlay FEM Model

Totally, 3 layers were overlaid. The total nodes and elements of this model are 12119 and 11835 respectively. Total weld passes consist of 3 passes for the Overlay FEM model and the temperature distribution in case of the 2nd pass is shown in Fig. 17. In case that the 2 layer was overlaid, the results of the stress analysis are shown in the Fig. 18 and Fig. 19 respectively. Fig. 18 is the stress distribution of S11(σ_x) and Fig. 19 is the stress distribution of S33(σ_z).

Whenever each layer was overlaid, a thermal analysis and a stress analysis were done respectively. The stress results according to the distance from the welded line on the 1st layer weld, the 2nd layer weld and the 3rd layer weld are presented in Fig. 20 and Fig. 21. Also, the results of the Repair weld are presented in Fig. 20 and Fig. 21. The stress results in the thickness direction of the weld part in case of the 1st layer weld, the 2nd layer weld and the 3rd layer weld are presented in Fig. 22 and Fig. 23. Also, the results of the Repair FEM Model and the Butt FEM Model are presented in Fig. 22 and Fig. 23.

As shown in Fig. 20 and Fig. 21, we know that the Overlay FEM Model lowers the stresses elevated by the Repair FEM Model. The stress value (S11= σ_x) by the Overlay weld is lowered from 373 MPa to 75 MPa. In contrast to this, the stress value (S33= σ_z) by the Overlay weld is elevated from 373 MPa to 531 MPa. This

means that the stresses in the welding direction ($S_{33} = \sigma_z$) due to the overlay weld were elevated. In case that the loads are applied in the welding direction at the plate structure including the dissimilar weld part, the structure might be weak. Therefore, more parametric studies (change of boundary condition etc.) are need. The stress results for the 1st layer weld, the 2nd layer weld and the 3rd layer weld at the weld part are presented in Table 3. As shown in Table 3, we know that the stresses of S_{11} and S_{33} are lowered by increasing the number of layers. If the 4th layer will be overlaid, the stresses of S_{11} and S_{33} will be lowered more.

Conclusively, we say that the Overlay weld lowers the stress in the welding part because the result stress is the resultant value of the S_{11} and S_{33} . The S_{11} stress and the S_{33} stress in the thickness direction at the weld part are presented in Fig. 22 and Fig. 23 respectively.

As shown in Fig. 22, the S_{11} stress level in the thickness direction at the weld part converges to nearly 0 MPa according to an increasing number of layers and the S_{33} stress as shown in Fig. 23 converges to nearly 500 MPa according to an increasing number of layers. This means that the stress changes of the tension and the compression stress become constant. Therefore, we can say that the Overlay weld has good benefits with a view to a stress relaxation and a PWSCC.

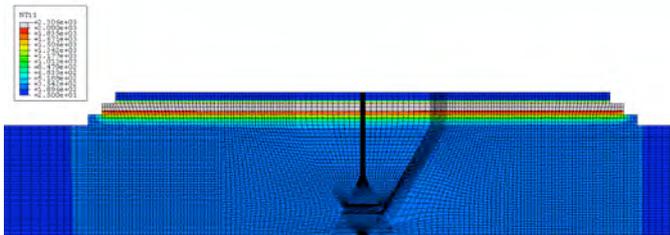


Figure 17. Temperature distribution of the 2nd pass

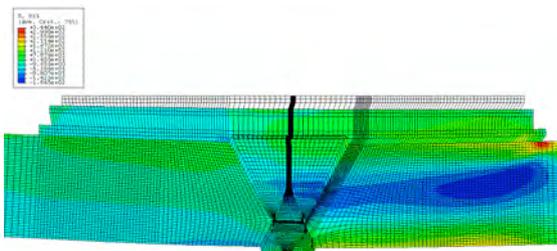


Figure 18. $S_{11}(x)$ distribution of the Overlay FEM Model

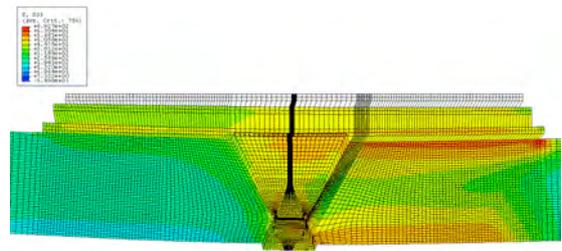


Figure 19. $S_{33}(z)$ distribution of the Overlay FEM Model

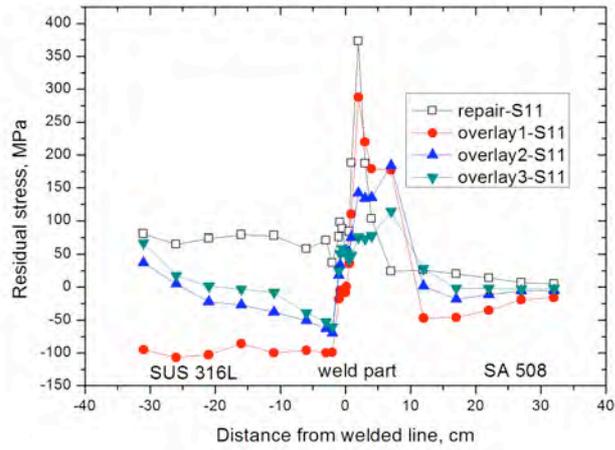


Figure 20. Results of the Overlay FEM Model (S11)

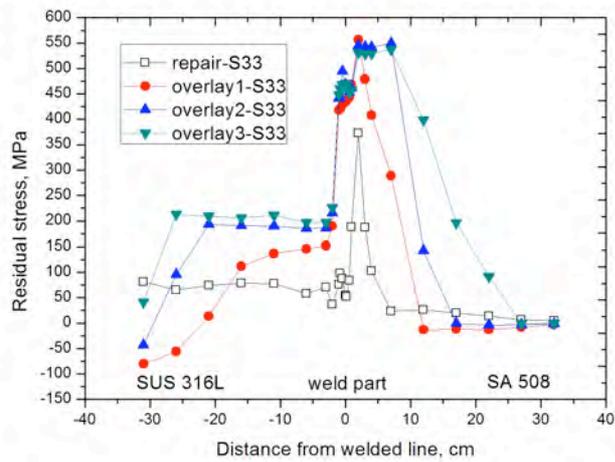


Figure 21. Results of the Overlay FEM Model (S33)

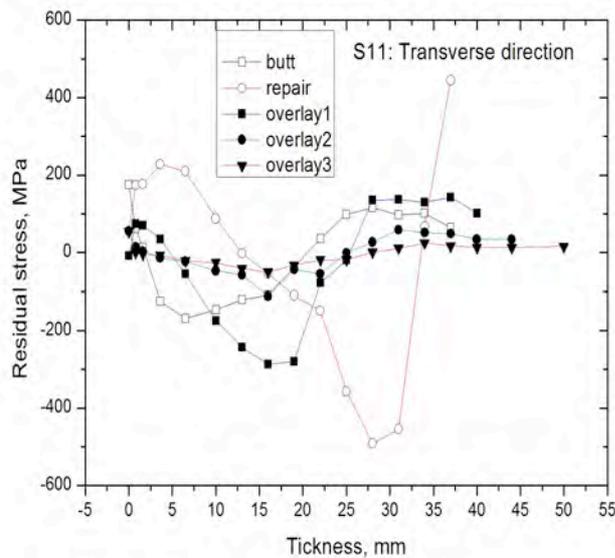


Figure 22. FEM results of the Overlay weld (S11 through thickness)

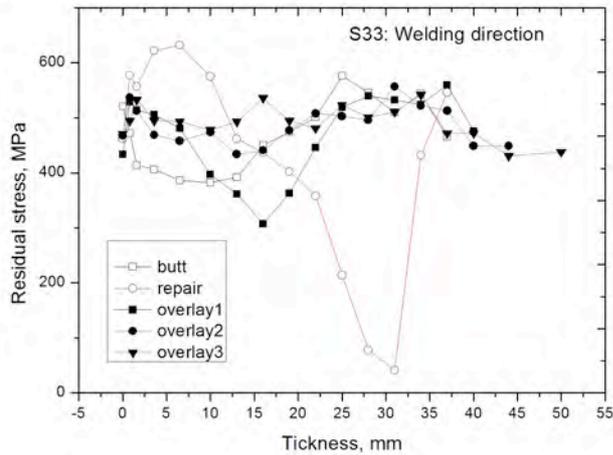


Figure 23. FEM results of the Overlay weld (S33 through thickness)

Table 3. Stress results for each layer at the weld part

	S11 (MPa)	S33 (MPa)
Overlay 1	288	557
Overlay 2	142	545
Overlay 3	75	531

4. CONCLUSIONS

The experimental values by the X-Ray method and the Hole Drilling Technique for the Butt weld have a trend which is in agreement with the Butt FEM results. On a whole, the Repair weld elevated the stresses. We know that an Overlay weld for a relaxation of the stress at the welding part is needed. Overlay weld lowers the stress at the welding part. The stresses of S11 and S33 are gradually lowered by increasing the number of layers. The S11 stress in the thickness direction at the weld part converges to nearly 0 MPa according to an increasing number of layers and the S33 stress converges to nearly 500 MPa according to an increasing number of layers. This means that the stress changes of the tension and the compression stress become constant. Therefore, we can say that the Overlay weld has good benefits with a view to a stress relaxation and a PWSCC.

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