

PAPER • OPEN ACCESS

Features of residual stresses in duplex stainless steel butt welds

To cite this article: Tae-Hwan Um *et al* 2018 *IOP Conf. Ser.: Earth Environ. Sci.* **143** 012030

View the [article online](#) for updates and enhancements.

You may also like

- [Effect of secondary phases on 475 °C embrittlement of 1.4462 and 1.4501 duplex stainless steels at short-term heat treatment conditions](#)
Alptekin Kisasoz, Gokhan Ozer and Ahmet Karaaslan
- [Effect of temperature on microstructure evolution and localized corrosion resistance of high tungsten hyper duplex stainless steel](#)
Nithin Raj P, Sekar K and M A Joseph
- [High-temperature oxidation inducing strain for the 2205 duplex stainless steels](#)
Jinlong Lv and Zhuqing Wang



The Electrochemical Society
Advancing solid state & electrochemical science & technology

242nd ECS Meeting

Oct 9 – 13, 2022 • Atlanta, GA, US

Abstract submission deadline: **April 8, 2022**

Connect. Engage. Champion. Empower. Accelerate.

MOVE SCIENCE FORWARD



Submit your abstract



Features of residual stresses in duplex stainless steel butt welds

Tae-Hwan Um¹, **Chin-Hyung Lee**^{2, 5}, **Kyong-Ho Chang**³ and **Vuong Nguyen Van Do**⁴

¹Department of Civil Engineering, Chung-Ang University, 84, Huksuk-ro, Dongjak-ku, Seoul 06974, Republic of Korea

²The Graduate School of Construction Engineering, Chung-Ang University, 84, Huksuk-ro, Dongjak-ku, Seoul 06974, Republic of Korea

³Department of Civil and Environmental & Plant Engineering, Chung-Ang University, 84, Huksuk-ro, Dongjak-ku, Seoul 06974, Republic of Korea

⁴Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

⁵Author to whom any correspondence should be addressed: ifinder@cau.ac.kr

Abstract. Duplex stainless steel finds increasing use as an alternative to austenitic stainless steel, particularly where chloride or sulphide stress corrosion cracking is of primary concern, due to the excellent combination of strength and corrosion resistance. During welding, duplex stainless steel does not create the same magnitude or distribution of weld-induced residual stresses as those in welded austenitic stainless steel due to the different physical and mechanical properties between them. In this work, an experimental study on the residual stresses in butt-welded duplex stainless steel is performed utilizing the layering technique to investigate the characteristics of residual stresses in the weldment. Three-dimensional thermos-mechanical-metallurgical finite element analysis is also performed to confirm the residual stress measurements.

1. Introduction

Duplex stainless steels are finding increased application in the chemical, oil and gas industries, petrochemical process plants, the pulp and paper industry, pollution control equipment, transportation and for general engineering thanks to their outstanding corrosion resistance and mechanical properties. Steel structures in engineering practice are generally fabricated by welding. During welding, residual stresses are unavoidably produced in the weld region and its vicinity. The existence of weld-induced residual stresses can be harmful to the structural integrity and the service behavior of the welded structure. Therefore, accurate assessment of the residual stresses would be very helpful to ensure the sound design and safety of the structure. The effects of solid-state phase transformation on welding residual stresses are investigated in this study. This study aims to present a FE modeling procedure for characterizing the residual stress of a duplex stainless steel, and focuses on the effects of solid-state phase transformation.

2. Residual stress measurement experiment of welded part



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

In this study, microstructural analysis and residual stress measurements of duplex stainless steel butt weld were carried out to investigate the microstructural changes in the weld region and HAZ, and to determine the full volumetric change strain associated with martensitic transformation, which is required input to the FE modelling of the phase transformation effects.

2.1. Specimen

The base material used in this study is duplex stainless steel plate with 10mm thickness. 'V' butt joint configuration was prepared as shown in figure 1. The joint was welded with five passes by gas tungsten arc (GTA) welding. Welding condition is presented in Table 1 and the mechanical properties of the base metal are given in Table 2. Table 3 shows the chemical composition of the base metal and weld metal.

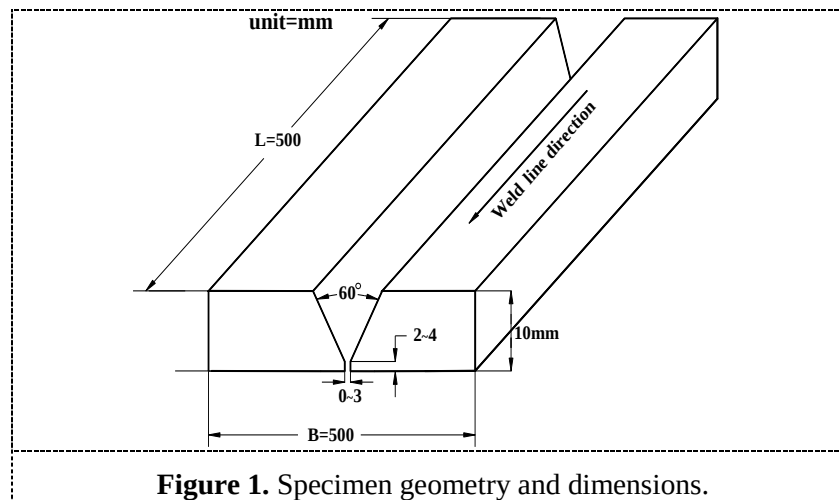


Table 1. Welding condition.

Pass	Welding time	Cooling time	Current (A)	Voltage (V)
1	9min 11sec	11min 59sec	160	12
2	4min 45sec	8min 3sec		
3	4min 50sec	10min 7sec		
4	6min 50sec	8min 58sec		
5	6min 15sec	18min		
6	8min 20sec	-		

Table 2. Material properties of the duplex stainless steel.

Duplex Stainless Steel	Yield Stress (MPa)	Tensile Stress (MPa)	Elongation (%)	Elastic Modulus (GPa)
Duplex 2205	731	824	15.8	227

Table 3. Chemical Components of Duplex and weld metal (mass, %).

Material	C	Mn	P	S	Si	Ni	Cr	Mo	N
Base metal	0.019	1.848	0.028	0.0004	0.468	5.065	22.255	2.535	0.1535
Weld metal	0.016	1.72	0.014	0.005	0.37	8.87	22.56	3.12	0.169

2.2. Microstructure and the results of measured hardness

After completion of welding, micro-structures were analysed using an OLYMPUS PME3 optical microscope. Samples used for micro-structural analysis were cut from the weld and the HAZ. Results are shown in figure 2. Figures 2(a) and 2(b), representing the weld region and the HAZ respectively, indicate the martensitic structures. Therefore, it is clear that the weld region and HAZ heated over the austenitic temperature during welding experience martensitic transformation. And Hardness is measured at each position. As shown in the table 4, the hardness of HAZ and welds is about 20 higher than the base metal due to the phase transformation.

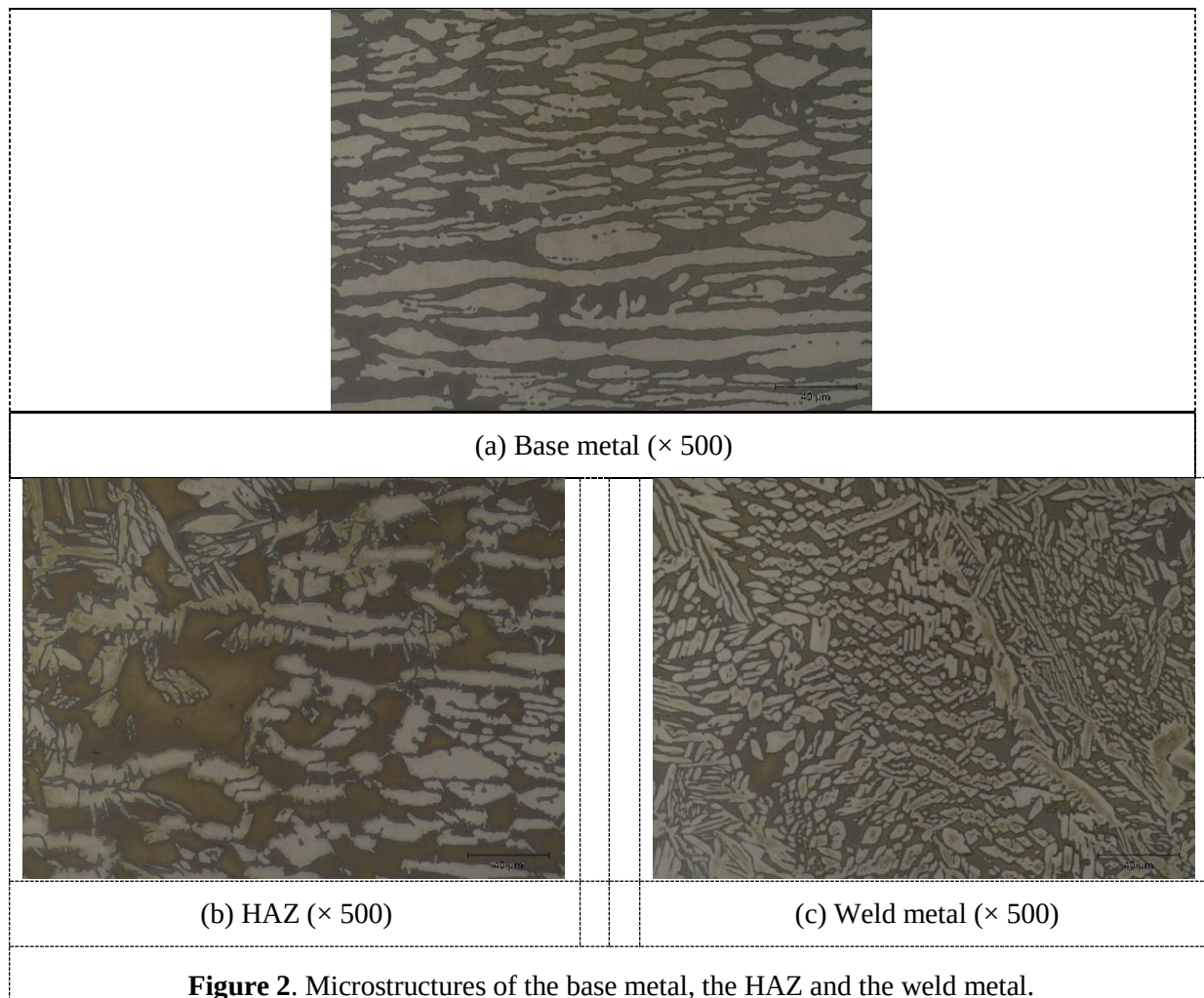


Table 4. Hardness at each position (unit: Hv).

Position		Base Metal			HAZ			Weld Metal			HAZ			Base Metal		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Result	CAP	235	235	235	244	241	243	245	248	249	248	252	252	237	237	235
	MID	237	237	237	257	254	259	252	257	257	258	260	258	236	235	236
	ROOT	235	236	234	256	261	259	258	258	260	253	253	252	234	234	235

2.3. Test for residual stress measurement

Residual stress measurements were carried out on the two axis strain gauge with the layering technique. Measuring stresses by strain gauges using the layering technique can obtain the residual stresses on the surface of the structure to be evaluated. The detailed procedure for measuring the residual stresses on the surface of the specimen is as follows. First, strain gauges are attached on the bottom surface of the specimen. Residual stresses in the small pieces are released by cutting the specimen, and longitudinal released strain and transverse released strain are measured. Longitudinal residual stress and transverse residual stress can be obtained by Equations (1) and (2) using the measured strains.

$$\sigma_x = -\frac{E}{1-\nu^2}(\varepsilon_x + \nu\varepsilon_y) \quad (1)$$

$$\sigma_y = -\frac{E}{1-\nu^2}(\varepsilon_y + \nu\varepsilon_x) \quad (2)$$

where E is Young's modulus and ν is Poisson's ratio.

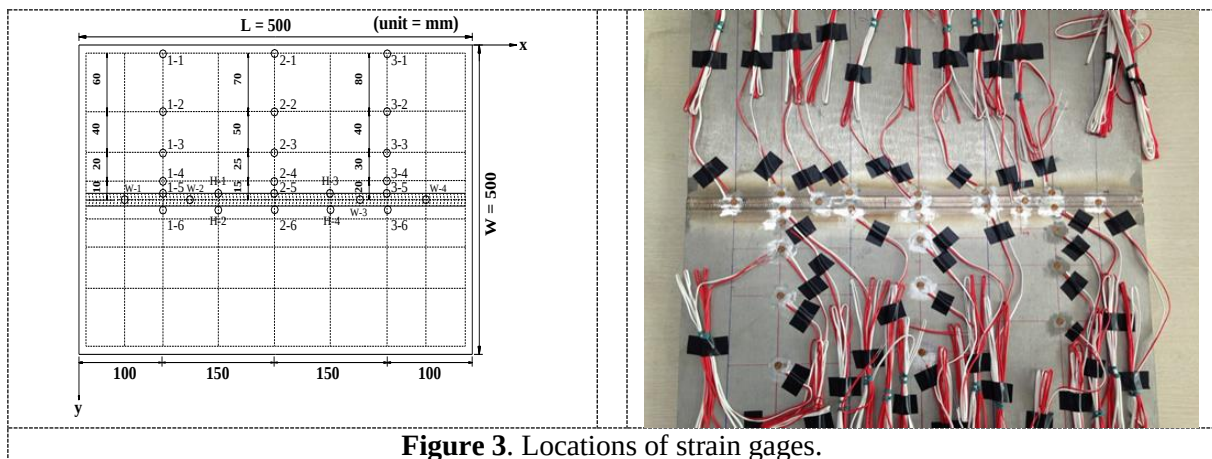


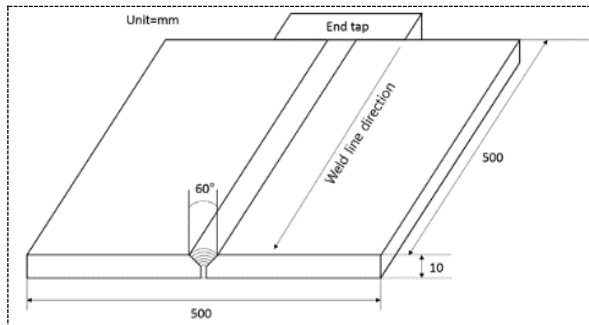
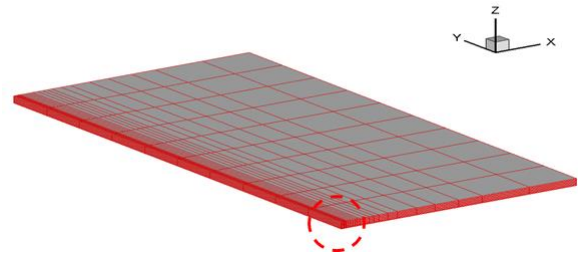
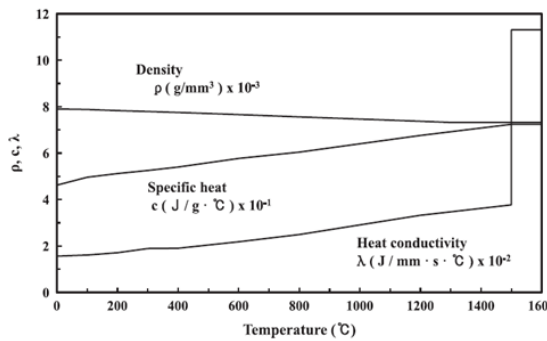
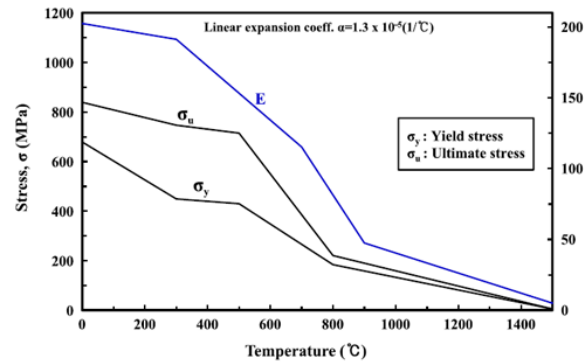
Figure 3. Locations of strain gages.

3. FE simulation of the welding process

Numerical simulation of the thermal and thermal-mechanical process associated with residual stress evolution during welding can be extremely complex since it needs to take account of the interactions between heat transfer, metallurgical transformation and mechanical fields. Complex numerical approaches are then needed to accurately model the welding process. However, as far as welding residual stress modelling is concerned, numerical procedures can be significantly simplified from the thermo-mechanical point of view, the heat input can be seen as a volumetric or surface energy distribution, and the fluid flow effect in the molten area can be simply taken into account by increasing the thermal conductivity over the fusion temperature.

3.1. Model geometry and material properties

FE simulation of the butt welding was performed on two duplex stainless steel plates with width of 250mm, length of 500mm, thickness of 10mm as shown in figure 4. The welding arc travel direction and welding start/stop position are real so shown in the figure. The type of welding process modelled was Gas Tungsten Arc Welding (GTAW) process, and six-passes welding was used to weld the plate. The 3-D FE model using eight-noded isoparametric solid elements is shown in figure 5. Because of the symmetry with respect to the weld centreline, one half of the model was selected as the computational domain. Figure 6 shows the physical constants at high temperatures of duplex stainless steel and temperature-dependent thermo-mechanical properties of duplex stainless steel are presented in Figure 7.

**Figure 4.** Specimen geometry and dimensions.**Figure 5.** Three-dimensional FE model.**Figure 6.** Temperature-dependent thermo-physical properties.**Figure 7.** Temperature-dependent thermo-mechanical properties.

3.2. Thermal analysis

During welding, the governing partial differential equation for the 3-D transient heat conduction, with internal heat generation and considering ρ , and c as functions of temperature only, is given by the thermal equilibrium equation.

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial T}{\partial z} \right) + Q = \rho c \frac{\partial T}{\partial t} \quad (3)$$

where T is the temperature, K is the thermal conductivity, c is the specific heat, ρ is the density and Q is the rate of moving heat generation per unit volume. According to the nature of arc welding, the heat input to the work piece can be divided into two portions. One is the heat of the welding arc, and the other is that of the melt droplets. The heat of the welding arc is modelled by a surface heat source with a Gaussian distribution, and that of the melt droplets is modelled by a volumetric heat source with uniform density. Heat flux distribution at the surface of the work piece within the arc beam radius r_0 is defined by the following equation:

$$q(r) = \frac{3Q_1}{\pi r_0^2} e^{-(r/r_0)^2} \quad (4)$$

where $q(r)$ is the local heat flux, r_0 is the arc beam radius and Q_1 is the heat input from the welding arc and given by

$$Q_1 = \eta AV - Q_2 \quad (5)$$

where η represents the arc efficiency factor, which accounts for radiative and other losses from the arc to the ambient environment, I is the arc current, U the arc voltage and Q_2 is the energy induced

by high temperature melt droplets. On the other hands, the heat from the melt droplets is applied as a volumetric heat source with a distributed heat flux (DFLUX) working on individual elements in the fusion zone.

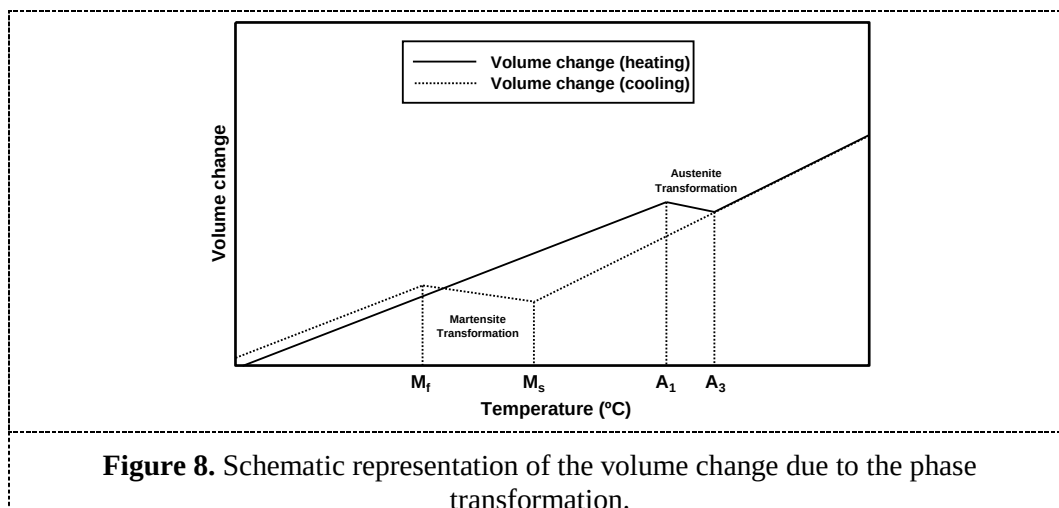
$$DFLUX = \frac{Q_2}{V_p} \quad (6)$$

where V_p denotes the considered weld pool volume and can be obtained by calculating the volume fraction of the elements in currently being welded zone. The heat of the welding arc was assumed to be 40% of the total heat input, and the heat of the melt droplets 60% of the total heat input. The arc efficiency factor was assumed as 0.85 for the GTA welding process used in the present analysis. The heat flux was applied during the time variation that corresponded to the approach and passing of the welding torch. As for the boundary conditions during the thermal analysis, convection and radiation were both taken into consideration and their combined effect was represented in the following equation for the temperature-dependent heat transfer coefficient, h

$$h = \begin{cases} 0.0668 T \text{ (W / m}^2 \text{ }^\circ\text{C)} & 0^\circ\text{C} < T < 500^\circ\text{C} \\ 0.231 T - 82.1 \text{ (W / m}^2 \text{ }^\circ\text{C)} & T > 500^\circ\text{C} \end{cases} \quad (7)$$

3.3. Solid-state phase transformation

Solid state phase transformation is responsible for changes in both volume and yield stress in steel experiencing thermal cycles during welding. In duplex stainless steel, martensitic transformation which occurs during rapid cooling immediately after intense welding heat input, is the phase transformation associated with the significant volumetric change and the yield stress change. The metallurgical structure of the steel is assumed to be pearlite-ferrite before any thermal cycles take place. During welding, when the steel is heated over the temperature A_1 (cementite disappearance temperature), pearlite-ferrite partly transforms into austenite, and when the temperature is higher than A_3 (α -ferrite disappearance temperature), its microstructure completely changes into austenite. During austenite transformation, the steel undergoes a reduction in volume as can be schematically shown in figure 8. In this study, depending on the peak temperature that an integration point of an element reached during heating process, the decision was made whether the point underwent the martensitic transformation or not, i.e., all points whose peak temperature was higher than the temperature were considered to undergo martensitic transformation when cooling to the onset temperature M_s . When the temperature during cooling reached to the end temperature M_f , the martensitic transformation was considered to be full and complete.



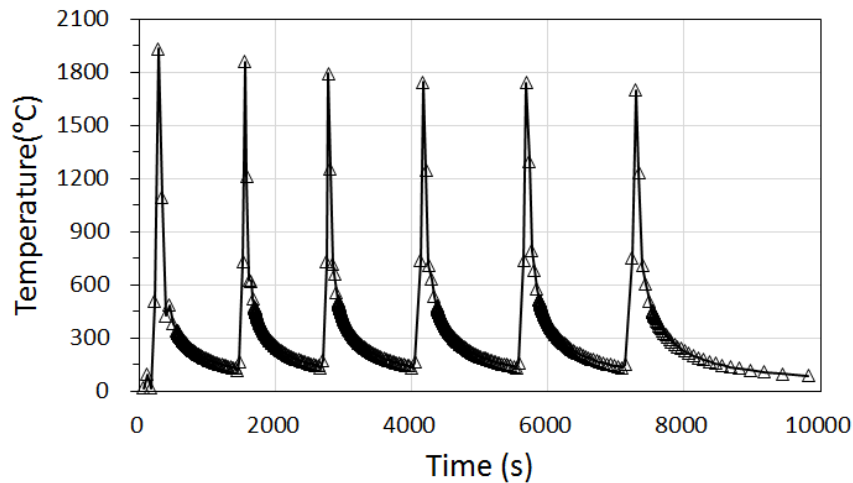
For a steel undergoing solid-state phase transformation, total strain rate can be written as the sum of the individual components of the strain rate as follows.

$$\dot{\varepsilon} = \dot{\varepsilon}^E + \dot{\varepsilon}^P + \dot{\varepsilon}^T + \dot{\varepsilon}^{\Delta Vol} + \dot{\varepsilon}^{Trp} \quad (8)$$

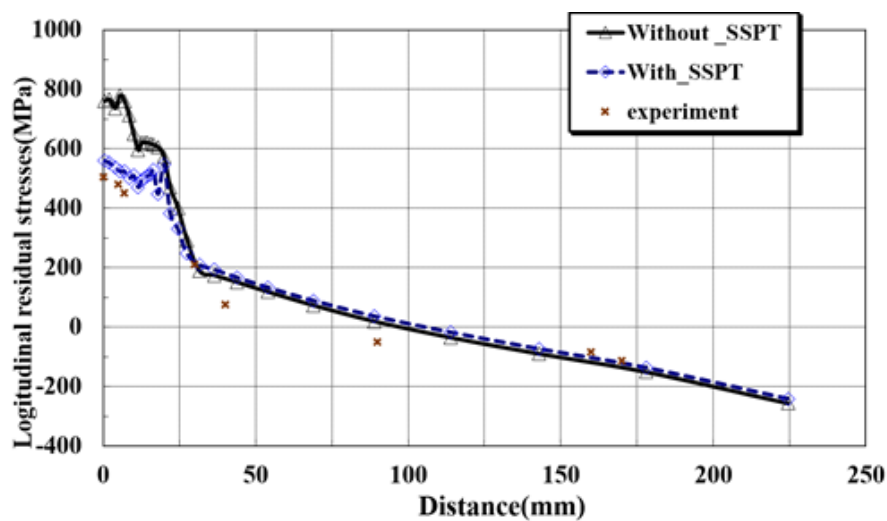
where $\dot{\varepsilon}^E$, $\dot{\varepsilon}^P$, $\dot{\varepsilon}^T$, $\dot{\varepsilon}^{\Delta Vol}$, $\dot{\varepsilon}^{Trp}$ are the strain rate components due to elastic, plastic, thermal loading, volumetric change and transformation plasticity.

4. Results and discussion

In the thermal analysis, inter-pass temperature are taken into consideration. The inter-pass temperature was assumed to be 150°C. Figure 9 shows the thermal histories of a point in the weld area where the phase transformation occurs during the welding process. Two different cases, Case 1 and Case 2, are studied to evaluate the effect of the solid-state phase transformation on welding residual stresses. Case 1 does not consider the solid-state phase transformation. On the contrary, Case 2 takes the solid-state phase transformation into consideration. It is shown that the analytical results considering the phase transformation characteristics are similar to the experimental results. This result show that the austenite to martensite phase transformation is responsible for the significant reduction of the longitudinal tensile residual stresses in the weld region and HAZ.



(a) Thermal histories



(b) Longitudinal residual stresses

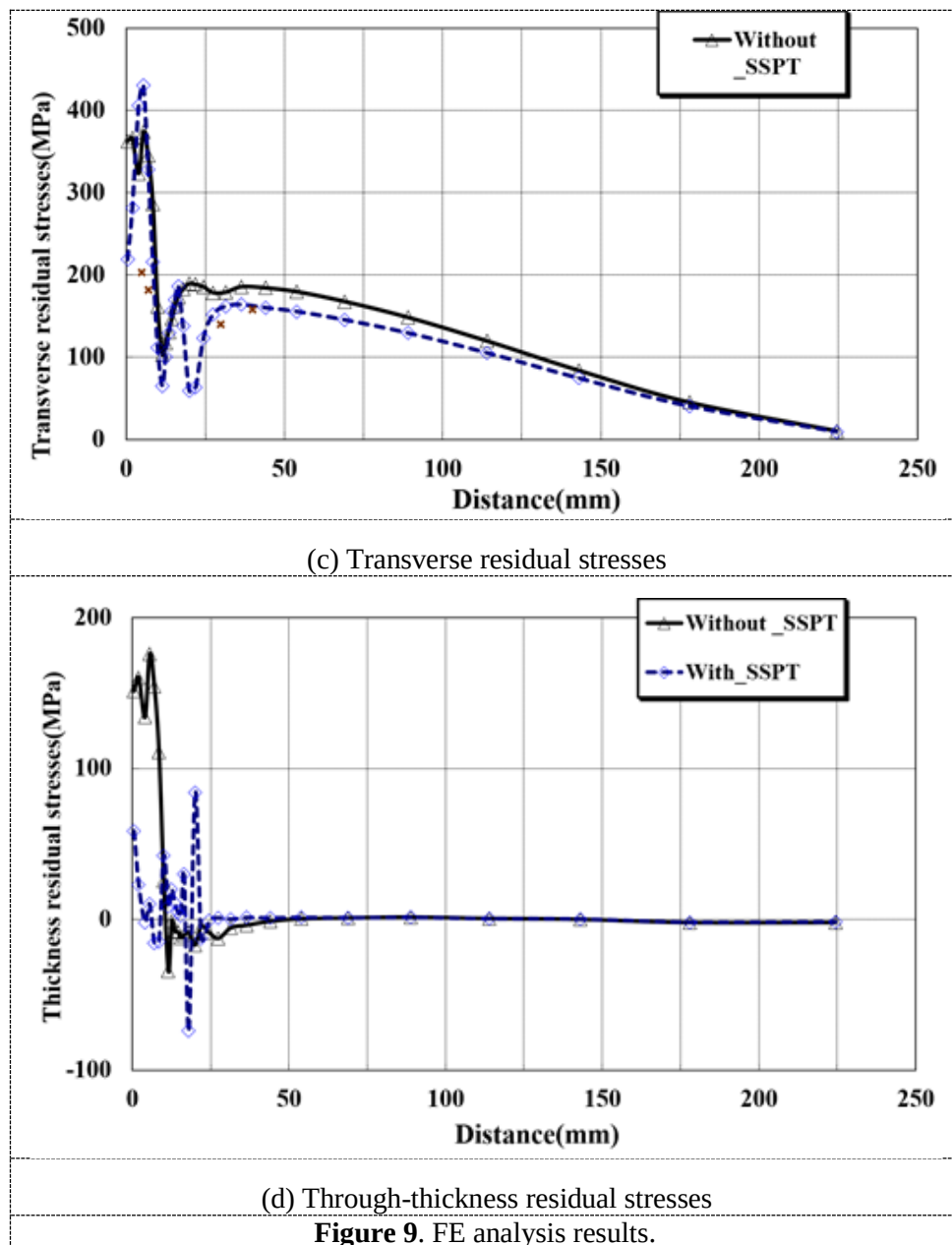


Figure 9. FE analysis results.

5. Conclusion

In this study, FE thermal simulation of the butt welding process was performed using a sequentially coupled 3-D thermo-mechanical FE analysis method whose effectiveness was verified by the comparisons with the experimental measurements to identify and compare temperature fields and welding residual stress distributions in butt-welded duplex stainless steel plate. Based on the results, the following observations and conclusions can be written.

- FE model for the numerical simulation of welding residual stresses in duplex stainless steel butt weld fabricated by multi-pass welding is presented considering solid-state phase transformation.
- The effects of solid-state phase transformation on welding residual stresses associated with the changes in yield stress due to the austenitic to martensitic transformation are taken into account.
- The effects of solid-state phase transformation on welding residual stresses are clearly demonstrated in the large difference in peak value between the longitudinal residual stress

curves and the difference in shape between the curves of transverse and through-thickness residual stress components.

- The effects of solid-state phase transformation cannot be disregarded in the simulation of welding residual stresses in the duplex stainless steel butt weld

Acknowledgments

This research was supported by Mid-career Researcher Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2015R1A2A2A01006390).

References

- [1] Anderson B A B 1978 *Thermal stresses in a submerged-arc welded joint considering phase transformation* Transaction of ASME **100** 110
- [2] Díaz J J del Coz, Menendez Rodriguez P, Garcia Nieto P J, Castro-Fresno D 2010 *Comparative analysis of TIG welding distortions between austenitic and duplex stainless steels by FEM* Appl Therm. Eng. **30** 2448
- [3] Iris A-A 2008 *Duplex stainless steels: brief history and some recent alloys* Recent Pat. Mech. Eng. **1** 51
- [4] Mourad A-H I, Khourshid A, Sharef T 2012 *Gas tungsten arc and laser beam welding processes effects on duplex stainless steel 2205 properties* Mat. Sci. Eng. A **549** 105
- [5] Satoh K, Terasaki T 1976 *Effect of transformation expansion on welding residual stresses distributions and welding deformation* J. JWS **45** 560
- [6] Satoh K, Terasaki T 1976 *Effect of welding condition on residual stresses distribution in welded structures materials* J. JWS **45** 150
- [7] Withers P J 2007 *Residual stress and its role in failure* Rep. Prog. Phys. **70** 2211