Effects of Heat Input on Microstructures, Hardness, and Residual Stress of GMA Weld Dissimilar butt joints between Stainless Steel SUS 316 and Marine Steel AH 36

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The present study investigates the dissimilar metal weld between SUS 316 and Naval Steel AH 36. The joints were fabricated with the gas metal arc welding with ER309L filler wire with two different heat inputs (0.8 kJ/mm and 1.5 kJ/mm). The weld joints were subjected to metallurgical and mechanical characterization as well as residual stress measurement by neutron diffraction several locations from the center of a weldment. The microstructural examination was carried out to reveal the defect in the weld joints and structural transformation in the weld zone. The results showed that the tensile residual stresses for the low heat input present in the axial direction and compressive residual stress in the direction of normal and transverse at stainless steels 316 welds. While the tensile residual stresses on the low heat input of marine steel AH 36 present in the direction of normal and transverse, but the compressive residual stress is in the axial direction. However, in contrast, the high heat input of dissimilar weld produces the compressive stress in the normal and transverse directions and tensile residual stress in the axial direction. The hardness value tends to proportional to the amount of residual stress. The dissimilar welds with low heat input produce a relatively higher residual stress compared to welds with high input that experienced balanced tensile and compressive residual stress.

Keywords: Dissimilar metal weld, Neutron diffraction, GMAW, Marine steel AH 36, and Stainless steel SUS 316

1. Introduction

Residual stress is stress experienced in a volume of the body in externally unloaded condition and at equilibrium state with its surrounding. The residual stress may significantly reduce fatigue lifetime, corrosion-resistant, dimensional stability, distortion, and brittle fracture.[1] Unexpected failure has occurred due to the presence of residual stresses which have combined with the service.

The residual stress measurement method consists of the principle of how to measure strain or physical materials that shape change.[2] Residual stress measurement conducted using the neutron diffraction method in the multiaxial direction inside the volume of material. Compared to X-Ray diffraction, it is limited to the surface residual stress measurement with the biaxial surface stress to shorten components that live severely.[2][3] Difficulty and complexity level to control residual stress in the welding process may affect dissimilar welded material. This problem is due to the difference in microstructure, chemical, mechanical, and thermal properties. As the temperature increased, phase transformation and microstructure change, which may produce complex residual stress distribution.[4] When the weld bead temperature reaches the melting point, high heat conduction into different base metals may produce different conduction rates and temperature distribution. During the cooling process, phase change, shrinkage, restrained, and thermal stress may produce multiple residual stress.[5] To control residual stress in the welded structure, needed to explain how welding variable and process parameters affect residual stress profiles on dissimilar welds.

The problem of residual stress is occurring due to the heat absorbed during welding. It is complicated when subjected to differences in the coefficient of thermal expansion and thermal conductivity between the welded components. The austenitic stainless steel used in this study has a thermal conductivity of one-third of carbon steel. The austenitic stainless steel grades have a 50% greater thermal expansion than carbon steel. Coupled with a lower thermal conductivity, they are prone to unequal expansion and distortion when joined together.

In recent years, the DC-LSND or CO2 cooling method has been applied to reduce residual stress (RS) and distortions in welding processes.[8–11] Nevertheless, the potential benefits of this technique have not been an investigation on dissimilar welds, where a mixture of dissimilar produced a mixed composition, and this, as a result, leads to metal phase transformation.

This study focuses on the experimental implementation of the effects of heat input on microstructures, hardness, and residual stress of GMA weld dissimilar butt joints between stainless steel SUS 316 and marine steel AH 36.

2. Experimental Methods

2.1 Material preparation and welding experiments

Welded materials consist of two AH 36 plates and two SUS 316 plates with plate dimensions are 150 x 100 x 10 mm. Weld design is a single beveled weld joint with a 75° opening angle, 2 mm root gap, and 2 mm root face. The welding process used was gas metal arc weld (GMAW) with a 2.0 mm diameter of the ER 309 electrode. The welding position is in the flat (1G) position.
The welding heat input (HI) parameters are set into about 0.8 kJ/mm and 1.5 kJ/mm. The heat input of 0.8 kJ/mm is grouped into the Low Heat Input (LHI), and the heat input of 1.5 kJ/mm is grouped into the High Heat Input (HHI). During the welding process, the temperature measurement on base material was set at the position of 10 mm and 20 mm from the weld centerline for each base material using a K-types thermocouple probe and connected into Lutron Data Logger to record temperature data per 2 seconds. After the welding process, the welded sample was examined using radiographic testing. The arrangement of weld design and thermocouple position is shown in Fig. 1.

![Weld design and thermocouple position](image)

**Figure 1. Weld design and thermocouple position**

### 2.2 Residual Stress Measurement

Residual stress measurement using the neutron diffraction method was conducted at the DN-1 neutron diffractometer facility in the National Nuclear Energy Agency at PUSPIPTEK Serpong, Indonesia. The neutron diffractometer used a neutron flux, having a power level for this experimental research from 15 MWt to 30 MWt at the multipurpose research reactor of GA-Siawabessy. The experiment layout and equipment setting is shown in Figure 2.

![Neutron Diffraction setting for the experiment layout](image)

**Figure 2. Neutron Diffraction setting for the experiment layout**

Measurement of residual stress using neutron diffraction consists of 3 steps. A reference sample from similar material used in the welded sample was required for measuring a bulk Elastic modulus and plane elastic modulus, as in Fig. 3. After that, a referenced sample is attached in the tensile machine to determine the bulk elastic modulus for AH 36 and SUS 316, as in Fig. 4.

![Reference Sample dimension](image)

**Figure 3. Reference Sample dimension**

**Figure 4. Tensile test of a reference sample schematically**

The measuring of the plane elastic modulus of $E_{\text{ref}}$ and Poisson ratio of $\nu_{\text{ref}}$ was used neutron diffraction shot on a reference sample in the loaded or stressed condition.

Residual stress measurement was conducted in the center of the weld (0), 3, 5, 7, 13, 20, 30, and 45 mm from each side of AH 36 and SUS 316 at 3 mm depth. The three orthogonal stress measurements are obtained at every point: axial stress, transversal stress, and normal stress.

### 2.3 Metallography and Hardness Test

Optical microscopy and Vickers hardness tests were conducted in weld metal in the same area with residual stress. The number of phases formed during welding is essential to correlate to the residual stress of welds.

### 3. Result and Discussion

#### 3.1 Welding Results

As in Table 1, the welding results showed that the heat input of LHI welds was in the range from 0.68 kJ/mm to 0.74 kJ/mm. Moreover, the heat input of HHI welds was from 1.17 kJ/mm to 1.28 kJ/mm. Due to lower welding speed in HHI welds, the deposition rate may increase and have a lower number of weld pass for the same welding volume than LHI welds. The welding voltage kept constant in the range from 26 volts to 28 volts.

Temperature fluctuation during the welding process can be analyzed using temperature distribution data. The peak temperature at position 10 mm from the weld center of SUS 316 was on the LHI samples is 469°C, and at the HHI samples is 528°C. In LHI welds, there is a rapid cooling rate of 2.38 °C/sec, and a lower cooling rate of 1.8 °C/sec is in the HHI samples.

| No. | Pass | Current Ampere | Welding Pass Area | Actual HI (kJ/mm) |
|-----|------|----------------|-------------------|------------------|
| 1   | Root | 137-147       | 302               | 0.73             |
| 2   | Filler | 132-150     | 310               | 0.68             |
| 3   | Filler | 128-136     | 298               | 0.71             |
| 4   | Capping | 135-153    | 315               | 0.74             |

**Table 1. Welding parameters during the experiment**

For the welding position is in the flat (1G) position. After the welding process, the welded sample was examined using thermography testing. The residual stress measurement method consists of the neutron diffraction technique have not been an investigation on dissimilar welds, low thermal conductivity, they are prone to unequal expansion and distortion when joined together.

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![Residual stress measurement using the neutron diffraction](image)

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3.2 Metallography of Dissimilar Welds

In the metallography analysis of AH 36 steel for LHI and HHI welds, the grain refining has occurred in the HAZ. Grain size in weld metal was in the average size of 40 to 50 µm, and the HAZ grain size is from 10 to 15 µm. There is a bit different grain size in the HAZ between LHI and HHI samples, where LHI HAZ is finer than the HHI HAZ grain size, as shown in Figure 5. This result is due to the difference in the cooling rate between LHI and HHI samples. The HAZ phases are mainly formed fine ferrite-pearlite phases. This result is in line with the value of the HAZ hardness, in which the hardness of LHI is higher than the HHI HAZ samples.

3.3 Hardness and Tensile Test Result of Dissimilar Welds

Hardness measurement in the range between -30 mm and 30 mm from the weld center, the hardness average of LHI samples is higher than the HHI sample. Hardness drops significantly in the distance of -5 mm at AH 36 HAZ, as shown in Figure 6. It is because the coarse grain of AH 36 HAZ occurred.

The tensile test was conducted on a reference sample of AH 36 and SUS 316. Based on the tensile curve, the elastic modulus of AH 36 is about 238.3 GPa, and it is having a higher value than SUS 316 of 195.6 GPa.

3.4 Residual Stress Measurement Result

Residual stress (RS) measurement in LHI welds, as Figure 7, revealed a significant maximum compressive RS in the axial direction (-537 MPa) and the maximum tensile RS in the normal direction (315 MPa). Residual stress measurement in HHI welds, as Figure 8, revealed a significant maximum tensile RS in the axial direction (448 MPa) and the maximum compressive RS in the axial direction (-247 MPa).

Fig. 7 and Fig. 8 showed that RS changes significantly in the weld metal and HAZ areas. In both the LHI and HHI welds, the base metal of SUS 316 has the same RS behavior with the tensile RS in the axial direction and the compressive RS in the normal and transversal direction gradually into maximum in the weld center. For AH 36 marine steel, in the LHI welds, the compressive RS occurred in the axial direction at HAZ, and the tensile RS is in the normal and transversal direction. In the HHI welds of AH 36 steel, the compressive RS occurred in the normal and transversal direction, but the maximum tensile RS occurred in the axial direction.
According to Masubuchi [1], the difference in residual stress is due to the difference in the number of welding passes. The effect of transient metal movement is due to heat expansion in the first pass in which the sample is separated and has a higher degree of freedom in movement. The next pass produces limited movement because the two metals have been joined by fusion welding; hence each metal of different types produced the residual stresses of different directions and magnitudes. The high value of residual stress would be concentrated in the heat-affected zone (HAZ) due to the expansion resulted from phase change during cooling.[1] Therefore higher residual stresses occur in the HAZ on the steel side of ferritic/austenitic (F/A) joints.

The temperature during welding affected the residual stress of welds. [12-15] It was found that the cooling rate for the LHI welds is higher than the HHI welds. Aside from the temperature peak in the HHI welds is higher than the LHI welds, the HAZ on HHI welds is wider than the LHI welds. For AH 36 steel, this temperature fluctuation significantly affects grain size and hardness than the SUS 316 welds. The hardness of AH 36 has higher for the LHI welds than that of HHI welds, as shown in Fig. 6. A higher cooling rate on the LHI of AH 36 welds may affect the grain size and the microstructure, as in Fig. 5 (a) and (b).

4. Conclusion

The cooling rate of LHI welds (2.38 °C/sec) resulted in a faster cooling rate than HHI welds (1.8 °C/sec). Therefore, residual stress (RS) in the axial direction for SUS 316 weld was in the tensile RS, but the normal and transverse direction was in the compressive RS. In AH 36 welds, there is a significant difference in the RS direction. For LHI welds, the normal and transverse direction may result in the tensile RS, but the axial direction was in the compressive RS. Furthermore, for HHI welds, the normal and transverse direction may result in the compressive RS, but the axial direction was in the tensile RS occurred.

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References

[1] K. Masubuchi, "Prediction and Control Residual Stress in Welded Structure," Transactions of JWI. 25(2), (1996), pp. 53-67.
[2] P. J. Withers and H. K. D. H. Bhadeshia, "Residual Stress Part 1 - Measurement Techniques," Materials Science and Technology Vol. 17, (2001), pp. 355-265.
[3] P. J. Withers dan H. K. D. H. Bhadeshia, "Residual Stress Part 2 - Nature and Origins," Materials Science and Technology Vol.17, (2001), pp. 366-375.
[4] P. B. Guimarães and A. P. M. Pedrosa, "Determination of Residual Stresses Numerically Obtained in AH36 Steel Welded by TIG Process," Materials Science and Application, (2013), pp. 268-274.
[5] N. S. Rossini, M. Dassiti, K. Y. Benyounis dan A. G. Olabi, "Methods of measuring residual stress in components," Material and Design, (2012), pp. 572-588.
[6] I. A. E. Agency, "Technical Series No. 477 - Development and Application of Residual Stress Measurement Using Neutron Beams," IAEA, 2014.
[7] A. Jacob, J. Oliveira, A. Mehmensarfat, F. Hosseinzadeh, and J. Kelleher, "Residual stress measurement in offshore wind monopole weldments using neutron diffraction technique and contour method," Theoretical & Applied Fracture Mech., (2018), pp. 418-427.
[8] Joseph, A., Rai, S. K., Jayakumar, T., and Murugan, N.; Evaluation of residual stresses in dissimilar weld joints. Int. J. Press. Vessel. Pip. 82(9): (2005), 700-705.
[9] Richards, D. G., Prangnell, P. B., Withers, P. J., Williams, S. W., Nagy, T., and Morgan, S.; Simulation of the effectiveness of dynamic cooling for controlling residual stresses in friction stir welds.; 7th Int. Symposium Friction Stir Welding, TWI, 2008.
[10] Han, W. T., Wan, F. R., Li, G., Dong, C. L., and Tong, J. H.; Effect of trailing heat sink on residual stresses and welding distortion in friction stir welding Al sheets.; Sci. Technol. Weld. Join. 16(5): (2011), 453–458.
[11] Luan, G., Li, G., Li, C., and Dong, C.; DC-LSND friction stir welding, TWI. 7th Int. Friction Stir Weld. Symposium Osaka, Japan.; 2008.
[12] H. Eisazadeh, E. A. Payzant, P. A. Cornwell, J. R. Bunn, and D. K. Aidun, "Exploring the Cooling Process for Residual Stress Reduction in Dissimilar Welds," Welding Journal, vol. 97, no. October, (2018), pp. 315 - 325.
[13] H. Alipooramirabad, A. Paradowskab, and G. Reza, "Investigating the effects of welding process on residual stresses, microstructure and mechanical properties in HSLA steel welds," Journal of Manuf. Processes, (2017), pp. 70-81.
[14] Houman Alipooramirabad, Anna Paradowska, Reza Ghomashchi, Andrei Kotousov, Mark Reid, Quantification of residual stresses in multi-pass welds using neutron diffusion, Journal of Materials Processing Technology, Vo. 226, (2015), pp 40-49.
[15] A. S. Aloraia, R. N. Ibrahim and J. Ghjole, "Eliminating Post Weld Heat Treatment in repair welding by temper bead technique in metallurgical changes," Journal of Materials Processing Technology, (2004), pp. 153-154.