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Original Article

Laser welding study for further development in essential power plant part repairs

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Abstract

The objective of this research work was to study the effects of laser welding when compared with shield metal arc welding (SMAW) process on the heat input, welded deposit rate, residual stress, distortion, microstructure and micro hardness. The martensitic stainless steel grade 431 specimens were overlay welded with the stainless steel filler metals. From the results, the heat input of 0.26 kJ/mm in laser welding calculated was significantly lower than that of 1.66 kJ/mm in SMAW, and contributed to low level residual stress, minimal distortion, very small penetration depth and heat affected zone (HAZ) of less than 100 μm. The micro hardness results indicated that the maximum value from laser welding in the HAZ was 370.2 HV lower than the value from SMAW of 525.5 HV. The welded deposit rate for laser welding was with 26.5 mm^3/min remarkably lower than the rate for SMAW of 1,800 mm^3/min.

Keywords: laser welding, shield metal arc welding, heat input, residual stress, heat affected zone

1. Introduction

The Workshop and Spare Parts Division of the Electricity Generating Authority of Thailand (EGAT) has the main mission in repairing parts and equipment for thermal, combined cycle, and hydro power plants, and also for various industries both in Thailand and overseas. Welding is one of the most important processes for reconditioning worn and damaged parts in order to sustain the availability and security of power generation systems throughout the country. Although many kinds of welding processes such as shield metal arc welding (SMAW), gas tungsten arc welding (GTAW), and gas metal arc welding (GMAW) have been servicing part repair and fabrication for many decades, undesired residual stresses, distortion, damages, and microstructure of the welded part still remain in many cases which have been inevitably affected by very high heat input. For repairing power plant parts like main fuel oil pump shafts, cooling water pump shafts, induced draft fans, and generator bearing pads, welding process selection and design are significant success factors. This is because the precise dimensions of the parts after repair as well as their quality in terms of mechanical properties and microstructural aspects are necessarily required in order to well fit in assembly and hence operation efficiency in the long run.

Therefore, the Workshop and Spare Parts Division has been developing a new method in part repairing applications for power station maintenance business using laser welding. This is well known as joining process to reduce deformation with high quality weld, which is applied in many industries such as automotive, aerospace, molds and dies, and electronics. As a result, in this research work the laser welding study on stainless steel specimens was initially carried out compared to the conventional process of SMAW to in-depth

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investigate the effects of welding techniques on heat input, deposit rate, residual stress, distortion, and microstructure.

2. Materials and Experimental

2.1 Materials

The disc specimen in Figure 1 having a diameter of 220 mm with 13 mm thickness used for the welding study was martensitic stainless steel grade SUS 431 which has the nominal chemical compositions and mechanical properties in quenched and tempered conditions as illustrated in Table 1 and 2, respectively. In addition, the filler metal for SMAW welding experiment was martensitic stainless steels grade SUS410, diameter 4.0 mm, while the filler rod diameter was 7 mm for laser welding experiments; it has a chromium content of 16.41% for which its mechanical properties were not specified.

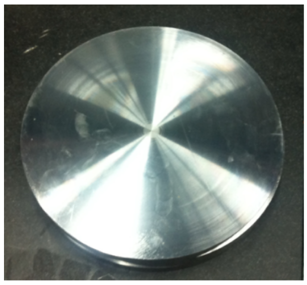


Figure 1. Stainless steel specimen grade SUS431.

2.2 Experimental

A Neodymium-Yttrium-Aluminum-Garnet (Nd-YAG) laser shown in Figure 2 with a power output of 300 watts was applied in the laser welding experiment, a conventional welding machine for SMAW was used in overlay welding on the specimen as shown in Figure 3. Pre-heating and post weld heat treatment were not applied before and after welding experiments. Experimental design for the three specimens is summarized in Table 3. The weld thicknesses were specified to be 2 and 5 mm for laser welding and 5 mm for SMAW. Residual stress measurements of all specimens after welding were conducted using X-ray diffractometer as shown in Figure 4. In addition, distortion of the specimen was investigated using a coordinate measuring machine (CMM) as shown in Figure 5 before and after welding in terms of diameter, roundness, run out, flatness, and parallelism. Microstructural analysis of the specimen shown in Figure 6 from laser welding and conventional SMAW process was performed to study the microstructures, micro hardness profile, and the welded penetration depth of the weld, the heat affected zone (HAZ), as well as the base metal area.

Figure 2. Nd-YAG Laser equipment.

3. Results and Discussion

3.1 Heat input and deposit rate

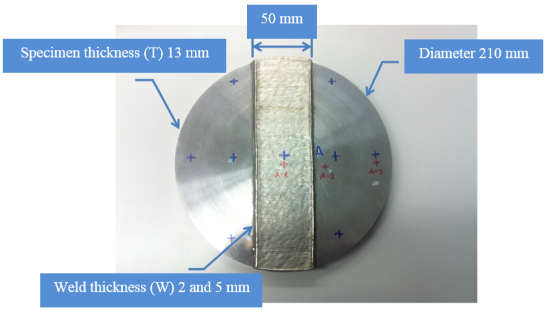
Heat input, the electrical energy supplied to the specimen to form the weld, was calculated and compared between SMAW and laser welding experiment according to equations (TWI Ltd., 2014) below,

Table 1. Chemical compositions of SUS 431 specimen and filler metal (Unit: %)

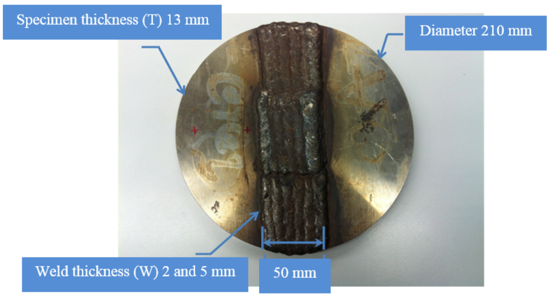
Grade	C	Si	Mn	P	S	Ni	Cr	Mo
SUS431 specimen	<0.20	<1.00	<1.00	<0.040	<0.030	1.25 to 2.50	15.00 to 17.50	-
Filler metal for SMAW	0.035	0.30	0.50	-	-	4.50	12.20	0.50
Filler metal for laser welding	0.005	0.37	0.40	0.021	0.003	4.79	16.41	0.15

Table 2. Mechanical properties of SUS 431 specimen and filler metal

Grade	Proof stress (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)	Charpy impact (J/cm^2)	Hardness (HB)
SUS431 specimen	>590	>780	>15	>40	>39	>229
Filler metal for SMAW	890	1090	12	-	-	-



a) Laser welded specimens for thicknesses of 2 and 5 mm.



b) SMAW welded specimen for thickness of 5 mm.

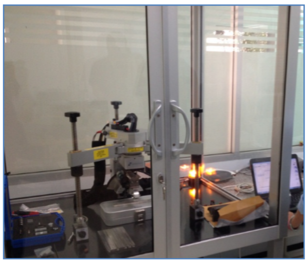
Figure 3. Welded specimens for laser welding and SMAW.

$$Heat\ input\ (kJ/mm) = \frac{(60VI)}{1000v},\quad for\ Shield\ Metal\ Arc\ Welding\ (SMAW) \tag{1}$$

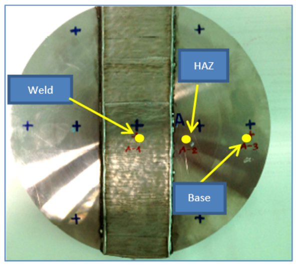
$$Heat\ input\ (kJ/mm) = \frac{60W}{v},\ for\ Laser\ Welding \tag{2}$$

where,

V is arc voltage in kilovolts (kV),
I is arc current in milliamps (mA),
W is laser power in kilowatts (kW), and
v is welding speed in millimeter per minute (mm/min).

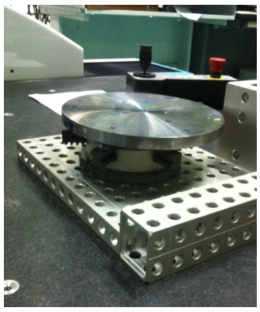


a) X-ray diffractometer measurement.

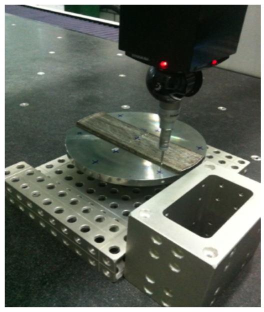


b) Points for residual stress.

Figure 4. X-ray diffractometer used for residual stress measurement on the welded specimens.



a) Specimen before welding.



b) Specimen after welding.

Figure 5. Distortion investigation using CMM of the specimen before and after welding.

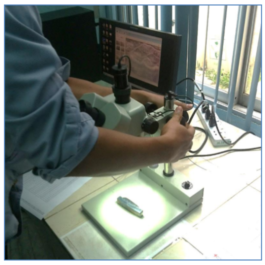


Figure 6. Microstructural analysis.

Table 3. Experimental design for welding specimens

Specimen No.	Welding process	Weld thickness (W)	Specimen thickness (T)	Weld – Specimen thickness ratio (W-T ratio)	Characterizations	
					Before welding	After welding
1	Laser	2mm	13mm	0.15	• Distortion	• Residual stress • Distortion • Microstructure • Micro hardness
2	Laser	5mm	13mm	0.38	• Distortion	• Residual stress • Distortion
3	SMAW	5mm	13mm	0.38	• Distortion	• Residual stress • Distortion • Microstructure • Micro hardness

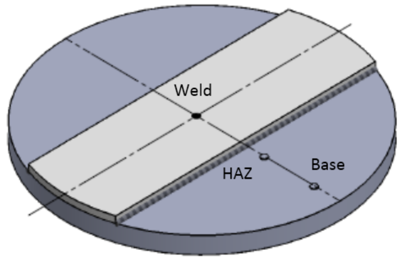
Regarding Equation 1, the heat input of the SMAW experiment could be estimated to be 1.66 kJ/mm via the arc voltage (V) of 0.026 kV, arc current (I) of 160,000 mA, and welding speed (υ) of 150 mm/min. On the other hand, for laser welding experiments with a laser power (W) of 0.3 kW and welding speed (υ) of 70 mm/min the heat input so far was calculated to be 0.26 kJ/mm according to Equation 2, about six times less than that of SMAW. This was because the 4 mm-filler metal for SMAW consumed very high energy to make a weld, while the 0.7 mm-filler metal for laser welding required less energy. As a result, the deposit rates of the weld (volume per unit time) for SMAW and laser welding were measured and reported at 1,800 mm^3/min and 26.5 mm^3/min, respectively.

3.2 Residual stress

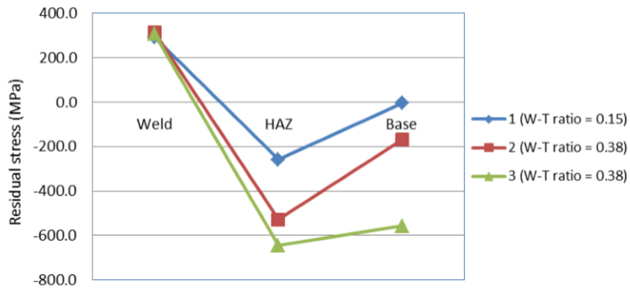
The heat flow and temperature gradient during welding promotes thermal expansion from the welded area to the adjacent base metal and causes residual stress in the welded specimen after cooled down to room temperature. Residual stress results after SMAW and laser welding experiment on the specimen are shown in Figure 7. It was found that tensile stresses at the weld approximately 300 MPa were performed, whereas compressive stresses ranging from 250 to 650 MPa occurred near the heat affected zone (HAZ) but less for the base metal area (Base) that well agreed with research work conducted by Cheng *et al.* (2007) and Sinha *et al.* (2013) for aluminum and carbon steel weld. The high level of compressive residual stress was markedly observed near the HAZ and Base for welded specimen No.3 from SMAW, larger than those of laser welded specimen No.1 and No.2. Meanwhile, the lower weld and specimen thickness (W-T) ratio in laser welding produced the lower level of residual stress. This was because low heat dissipated was less transferred to the specimen for the lower weld thickness. Zhu *et al.* (2011) stated that with increasing heat input, residual stress value gradually increased. Therefore, the heat input influenced by various welding parameters and processes has a significant effect on residual stress in the work piece.

3.3 Distortion

Dimensions and geometries of the welded specimens for SMAW and laser welding experiments were examined using the CMM in order to study the distortion after welding for the two processes. Figure 8 illustrated the measurement points for cylindrical diameter, roundness, flatness, and parallelism, and the results were displayed in Figure 9 for various weld and specimen thickness ratios. As can be seen, significant differences in diameter, roundness, flatness and parallelism of welded specimen No.3 from SMAW with the W-T ratio of 0.38 were performed, higher than those of specimen No.1 and No.2 from laser welding with W-T ratios of 0.15 and 0.38, respectively. It could be concluded that the

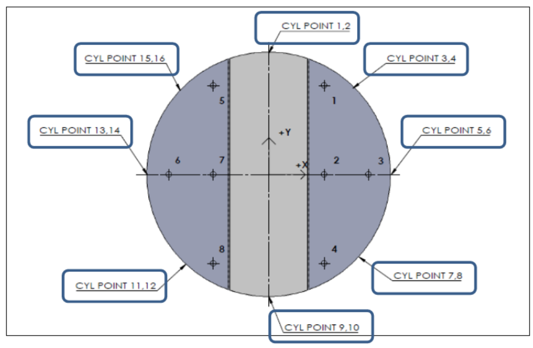


a) Residual stress measurement points on the welded specimen.

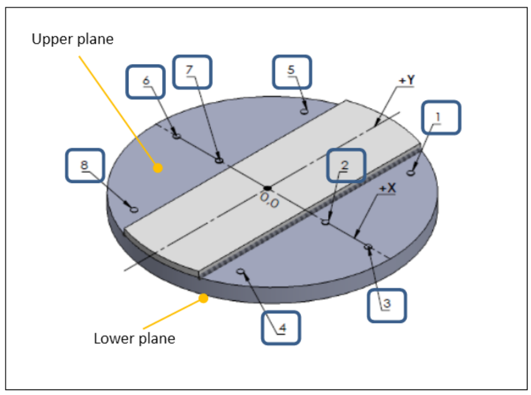


b) Residual stress results at weld, HAZ, and Base metal area.

Figure 7. Residual stress results for laser welding specimen No.1 (W-T ratio = 0.15) and No.2 (W-T ratio = 0.38) and for SMAW specimen No.3 (W-T ratio = 0.38).

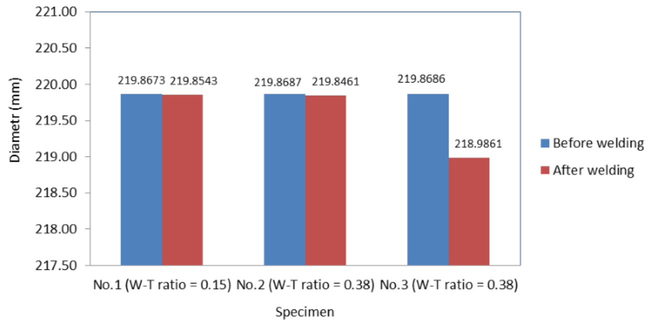


a) Measurement points for cylindrical diameter and roundness estimation.

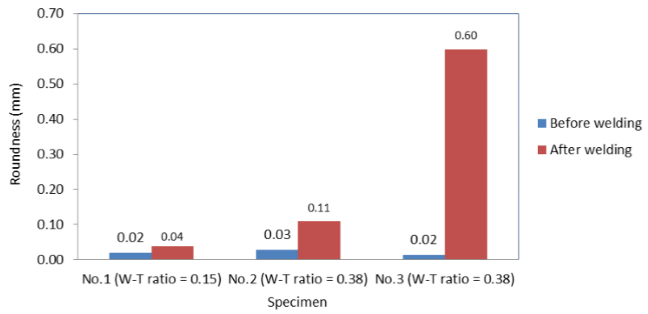


b) Measurement points for flatness and parallelism estimation.

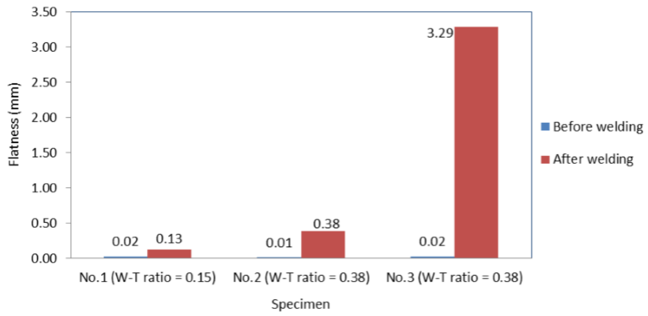
Figure 8. Measurement points for dimension and geometry estimation on the welded specimens.



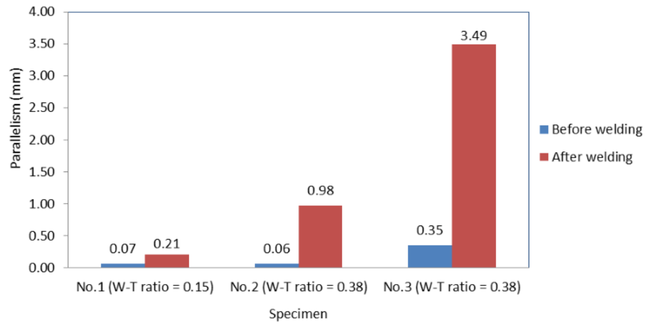
a) Diameter.



b) Roundness.



c) Flatness.



d) Parallelism.

Figure 9. Dimensions and geometries of the welded specimens before and after welding.

SMAW process contributed to a large deformation after welding when compared to laser welding because of very high heat input applied during the arc. High residual stress left in the welded specimen corresponded to the work of Bhanupratap *et al.* (2012) in submerged arc welding and Colegrove *et al.* (2009) in various welding processes. However, the lower W-T ratio in laser welding, the less dimensional and geometrical change between before and after welding, meaning deformation of the welded specimen related to the volume of the weld deposit. In a thicker weld, high heat accumulated in the specimen and more unequal heating and cooling during solidification can cause larger distortion.

3.4 Microstructures and micro hardness

Microstructures of laser welded specimen No.1 and SMAW specimen No.3 at the Weld, HAZ, and Base were illustrated in Figure 10 and 11. It could be seen that carbides were formed and dispersed in the ferrite matrixes in the weld metal and heat affected zone. For the overlay laser welding experiment in this research work, the heat affected zone of specimen No.1 was estimated ranging from 70 to 100 µm below the fusion line and the weld penetration depth was approximately 60 µm. On the other hand, HAZ and penetration depth of SMAW specimen No.3 was 4.0 mm and 2.8 mm, respectively. This could be explained that an increase in heat input can lead to more dilution of the weld during the arc and also larger heat affected zone corresponding to the work of Grajcar *et al.* (2014).

Micro hardness tests in Figure 12 were conducted with the specified load of 0.5 kgf projected on the weld, heat affected zone, and base metal area of the cross sectioned SMAW and laser welded specimen for which different filler

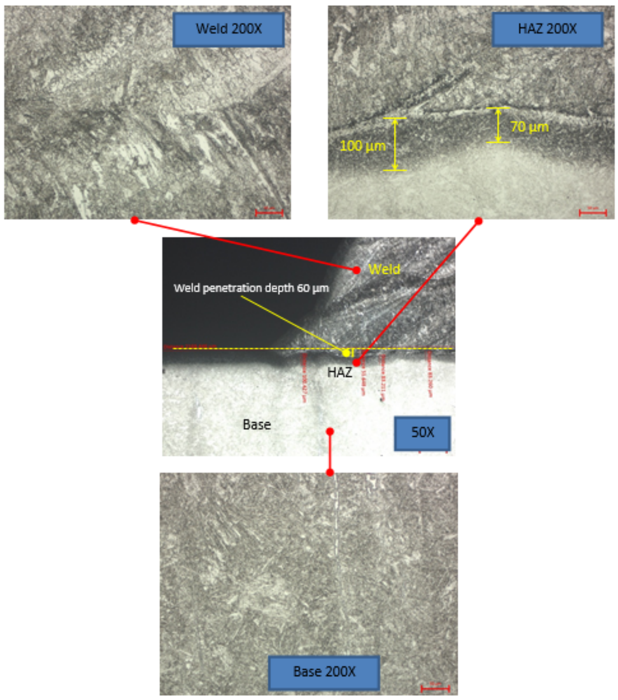


Figure 10. Microstructure of laser welded specimen No.1 at Weld, HAZ, and Base.

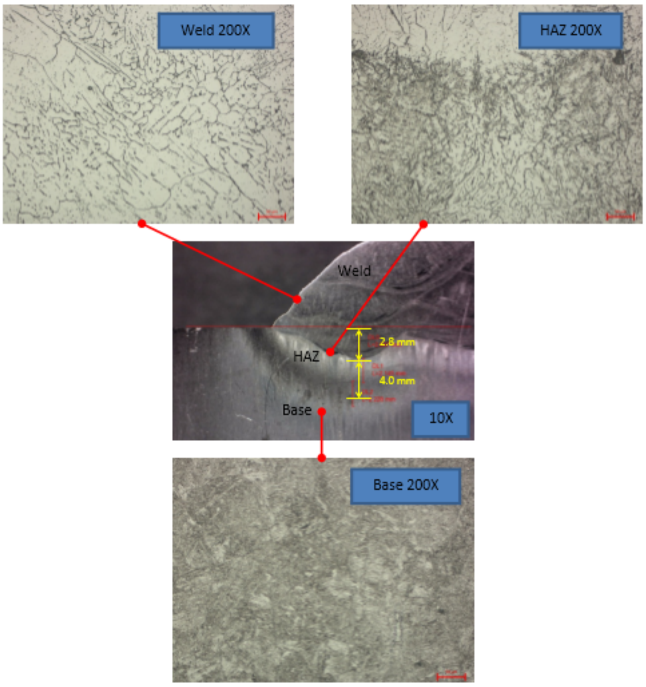


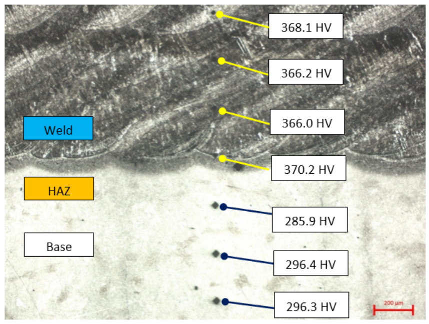
Figure 11. Microstructure of SMAW specimen No.3 at Weld, HAZ, and Base.

metals were applied. Test results of micro hardness were graphically depicted in Figure 13. It was obvious that the SMAW process gave the high hardness when compared with laser welding in particular the HAZ at which the maximum hardness was 525.8 HV although high heat input in general pays to low hardness. In contrast, the maximum hardness for laser welding was found to be 370.2 HV at the fusion line. Furthermore, the hardness of the weld for SMAW (422.6 HV) was indicated to be higher than that for the laser welded specimen (365.6 HV) in average.

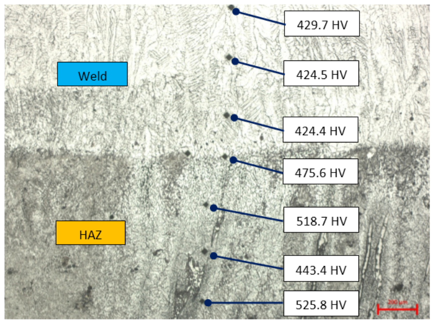
4. Conclusions and Suggestions

Outcomes of this study in laser welding when compared with the conventional shield metal arc welding process on the martensitic stainless steel specimen aiming for further development in power plant part repairs could be summarized as follows,

- Heat inputs applied and welded deposit rates were 1.66 kJ/mm and 1,800 mm^3/min for shield metal arc welding and 0.26 kJ/mm and 26.5 mm^3/min for laser welding, respectively.
- Maximum compressive residual stresses on the welded specimen measured by X-ray diffraction technique were indicated to be 645 MPa for shield metal arc welding for the welded thickness of 5 mm, 258 and 528 MPa for laser welding for the welded thicknesses of 2 and 5 mm, respectively at the area near the heat affected zone.
- Large distortions in terms of differences in diameter, roundness, flatness, and parallelism before and after welding were exhibited in the shield metal arc welding specimen. While, in laser welding the thicker welded specimen contributed to larger distortion than the thinner one.
- Microstructural analyses have shown that laser welding gave a minimal heat affected zone of 70-100 µm and welded penetration depth of 60 µm, whereas the shield metal arc welding specimen illustrated a wider heat affected zone of 4 mm and penetration depth of 2.8 mm in approximate.
- The maximum hardness located in the heat affected zone of the shield metal arc welding specimen was reported to be 525.8 HV, significantly higher than that of the laser welded specimen of 370.2 HV.



a) Laser welded specimen No. 1.



b) SMAW specimen No.3.

Figure 12. Micro hardness results of the welded specimens.

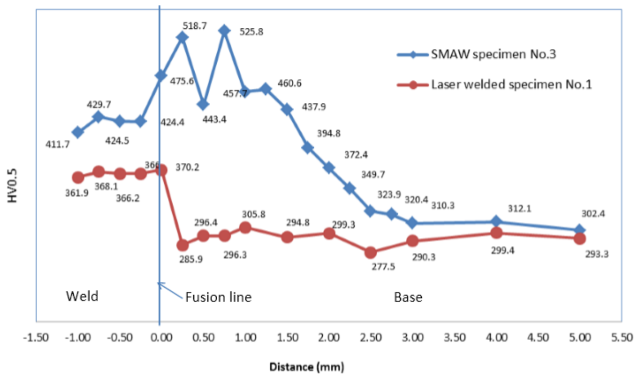


Figure 13. Micro hardness profiles of laser welded specimen No.1 and SMAW specimen No.3.

- Heat input applied on the specimen had a concern in the effect on residual stress, distortion, and also hardness.
- Experimental results in this study can be used as the basic engineering information for the consideration of welding process selections in repairing essential parts of power plants especially for very tight dimensional accuracy required in assembly work being a must.
- Effects of post weld heat treatment on the microstructure and mechanical properties of the laser welded specimen in terms of hardness, tensile and fatigue strength can be further investigated for various kinds of materials and filler metals.
- Cost and time consumption issues for laser welding in the repairing and maintenance work can be estimated and compared with conventional welding processes.
- The study of laser welding for super alloy parts used in gas turbines and low weldability materials such as cast irons used in casing pumps in many applications can be conducted for expanding the power plant parts repairing services in the future.

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