STUDY ON MECHANICAL PROPERTIES AND MICROSTRUCTURE ANALYSIS OF AISI 304L STAINLESS STEEL WELDMENTS

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ABSTRACT

Manufacturing operations require joining process in a way that it is considered as an important process to be applied in almost every operation or process that involves fabricating of products. The aim of this research is to evaluate mechanical properties and analyzed Heat Affected Zone (HAZ) of austenic stainless steel AISI 304Lweldments. The welding was conducted based on three different sizes of filler wire 0.8mm, 1.0mm and 1.2mm respectively. The arc voltage used also consists of three different values 30V, 60V and 90V and the current flow for Metal Inert Gas (MIG) welding was set to constant value of 100A. The specimens were divided into five groups to undergo tensile test, hardness test, impact test, HAZ temperature variation study and followed by microstructure observation. The experimental result showed that tensile strength, hardness and impact resistance were increased with the used of biggest size of filler wire which is 1.2 mm. The relations then were compared with HAZ temperature variation analysis and the image analyzer showed that the transformation from austenite to martensite at HAZ created a hard and brittle structure near the fusion zone. The results revealed that different filler wire size and different arc voltage applied could enforce the austenitic stainless steel structure.

***KEY WORDS**: MIG, HAZ, MIG, Austenic, Martensite*

1.0 INTRODUCTION

Welding is a fabrication or sculptural process that joints materials, usually metals or thermoplastics. Welding involves in bringing the surfaces of metals to be joined close enough together for atomic bonding to occur as the natural consequence of atoms seeking to create for themselves a stable electron configuration. In general, welding includes any process that causes materials to join through the attractive action of inter-atomic or inter-molecular forces as opposed to purely macroscopic or even microscopic mechanical interlocking forces. Welding has become a prevalent mechanical joining methodology in various industries because of its advantage over other joining methods including design flexibility, cost savings, overall weight reduction and structural performance enhancement (Song et. al., 2003). Mainly, in order to gain an acceptable weldments outcome, the recommended approaches such like welding type selection, controlling welding process parameters and modifying the structural configuration must be considered (Song et.al., 2003). Stainless steels belong to iron-base alloys family. The steels have excellent resistance to corrosion. Normally, the stainless steels have good low temperature toughness and ductility. Most of the steels contain good strength properties and corrosion resistance. All stainless steel contain iron as the main element and chromium (11% to 30%). The chromium has the basic corrosion resistance that supplements the trademark of stainless steels. Welded structures made of stainless steel are commonly used in the power generation, oil and gas, marine transportation, petrochemical industries due to their higher mechanical strength and better corrosion resistance (Hsiao et. al., 2008). There are only a few studies have been done to evaluate the effect of filler wire diameter and voltage setting on weldments of austenitic stainless steel. Besides, it is hardly found the study on the microstructure of Heat Affected Zone (HAZ) in the austenitic stainless steel weldment area. Thus, this work is undertaken with the aim to study the effect of different stainless steel filler wire diameter on stainless steel weldments. In addition this study also investigates the effect of different voltage settings, mechanical properties in weldments area and Heat Affected Zone (HAZ).

2.0 EXPERIMENTAL DETAILS

An experimental activity was conducted to determine the mechanical properties and also weldment area and HAZ microstructure of AISI 304L weldment. The concentration initially is on preparing the plate specimen (total 9 specimens) by cutting them into pieces of 20mm x 15mm. After that a 30^0 V-groove shape was prepared in order to obtain an acceptable welding result. The process was done by using milling machine. Then the welding activity was taken place and followed by mechanical properties evaluation, and HAZ analysis.

A. Specimens Preparation

The stainless steel plate was cut into desired size of 20mm x 15mm accordingly. Altogether there were 18 pieces of plate. Laser cutting machine (model: LVD Helius 2513) was used to cut the plates. Laser cutting machine was used due to its accurateness in cutting the stainless steel in appropriate time consumed (Figures 2.1, 2.2).

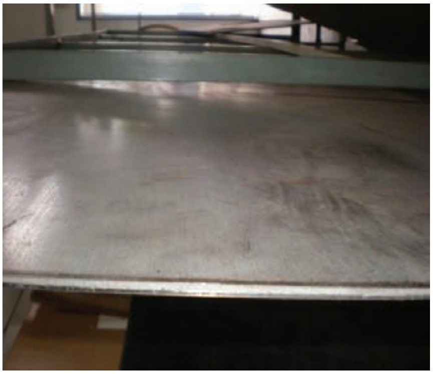

FIGURE 2.1
AISI stainless steel plate before cutting

FIGURE 2.2
AISI 304L stianless steel after cutting process

B. V-Groove Preparation

The V-groove shape was prepared by using milling machine (model: Bridgeport Turret Milling, AEM BR 2J2). The groove angle was 30^0 in order to obtain good welding quality thus saving the weld cost. A root opening was adjusted to fit with the sizes of filler wire to obtain good fusion at the root (Lincoln, 2000).

C. MIG Welding Operation

The welding process was conducted by using MIG Weld 210S (WIM). The welding was set continuously by using pure argon as shielding gas. The setting for arc voltage is 30V, 60V and 90V respectively. Meanwhile, the filler wire speed was set at 3.5 seconds for every voltage value. The filler wire (ER308L) diameter consists of three different sizes (0.8mm, 1.0mm and 1.2mm). Each filler wire required different contact tip to fit on the MIG gun.

D. Welding Parameters and Voltage Setting

The experiment was started based on three different sizes of filler wire and three different arc voltages value. In order to obtain good welding quality, a V-groove shape was done in advance to allow acceptable penetration of weld metal between the plates. A root face of 3mm was determined to avoid melt through of the weldment metal and reduce distortion and contraction on weldment area (Lincoln, 2000). **TABLE 1** shows a ding parameter.

TABLE 1 Welding Parameter

Voltage (V)	Current (A)	Travel Speed (cm/min)	Plate thickness (mm)	Sample amount (pieces)
30	100	60	5	1
30	100	60	5	1
30	100	60	5	1
60	100	60	5	1
60	100	60	5	1
60	100	60	5	1
90	100	60	5	1
90	100	60	5	1
90	100	60	5	1

E. Microstructure Analysis

Microstructure analysis was conducted by using Image Analyzer (model: Buehler Omniment).This equipment was specialized in analyzing the metallography structure of materials. Areas that involve in this analysis were weldment area and heat affected zone (HAZ). In addition, the boundary between weldment area and HAZ also were investigated. Two types of magnification are set. The magnifications are 100X and 200X.

F. Temperature Variations Measurement

The variations measurement is taken using Infrared Thermometer (model: TMIRL, CPS-Tempseeker). The temperature is measured in a distance of approximately 10cm from the heat affected zone (HAZ) area. There were five readings captured in a distance of 8mm, 16mm, 24mm, 32mm and 40mm from the weld metal. The distance is decided after determining the HAZ area that almost penetrates approximately until 4cm from the fusion zone. The reading was taken in respect of different filler wire and arc voltage effect to temperature and mechanical properties behavior.

G. Tensile Test Measurement

The tensile specimens were cut into length of 70mm and width of 15mm. To obtain the dog bone shape, milling process was conducted to machine the designated area. Maximum stress was determined by dividing the maximum forces applied (kN) versus specimen area (mm^2). The stress and strain data were obtained and analyzed.

H. Hardness Measurement

The hardness specimens were cut into length of 60mm and width 10mm. Milling process is conducted to obtain the dog bone shape. There were three indentation points recorded on the weldment area and HAZ.

I. Impact Test Measurement

The impact specimens were cut into length of 60mm and width 10mm. The angle degree for the pendulum was set 90^0. The data were collected and analyzed for each specimen according to different filler wire diameter and arc voltage setting.

3.0 RESULTS AND DISCUSSION

In this experiment, parameter of filler wire diameter 0.8mm and 1.0mm with 30V, 60V and 90V arc voltage, the weldment condition were satisfying. There were no crack and porosity detected. On the other hand, for weldment using 1.2mm filler wire, crack and porosity were found (Figure 2.3). The HAZ width was monitored occurring in a distance of maximum 4cm from the weld metal or fusion zone for every filler wire diameter and arc voltage. For example, HAZ minimum width (3cm) was monitored when using 0.8mm filler wire (30V) while maximum width (4cm) when using 1.2mm filler wire (90V). The HAZ was also observed clearly when using 0.8mm than 1.2mm filler wire (regardless of arc voltage value).

FIGURE 2.3 Weldment of 1.2mm filler wire diameter

Meanwhile, Figure 2.4 shows the penetration of weldment for different filler wire but with same arc voltage of 60V. From the figure, the behavior of weld pool proved better during 0.8mm filler wire than 1.2mm filler wire. This concluded that in this experiment, based on weld metal porosity for each filler wire diameter, filler wire (ER308L) with diameter size 1.2mm was not suitable for welding AISI 304L base metal. Further study and adjustment need to be taken in order to get the acceptable outcome if the 1.2mm filler wire needed in application.

FIGURE 2.4 Weld pool 0.8mm, 60V

The trend of temperature variations is shown in graphs below (Figure 2.5- 2.8). From the graphs, the trend of temperature increased was tended to follow the arc voltage value. The higher the arc voltage, the higher temperature recorded (Correia et. al., 2005). Furthermore, the thicker filler wire diameter, the higher temperature recorded (Cui et. al., 2006). It can be concluded, at 0.8mm filler wire size for 30V arc voltage, the temperature effect on the HAZ is the lowest while at 1.2mm filler wire size for 90V arc voltage, the temperature effect on the HAZ is the highest. According to current flow activity, it is understood that at 1.2mm filler wire, the current flow energy is the highest compare to 0.8mm and 1.0mm filler wire respectively. The temperature also felt drastically when using 30V arc voltage power source compare to 90V.

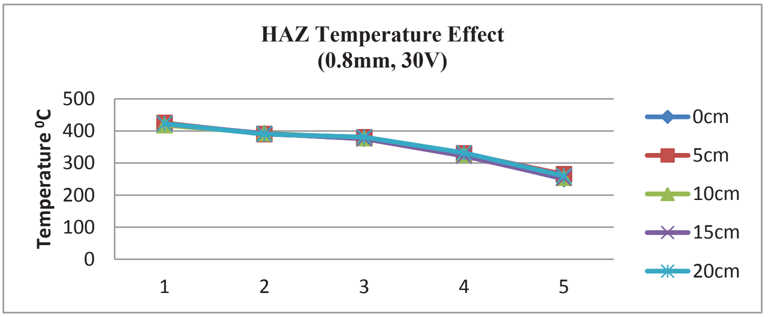

FIGURE 2.5 Temperature variations for 0.8mm, 30V

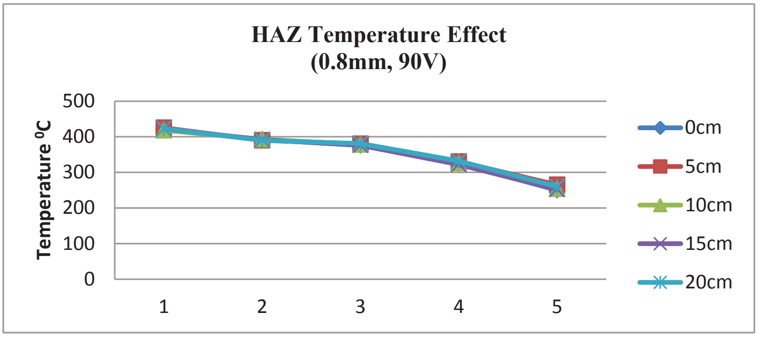

FIGURE 2.6 Temperature variations for 0.8mm, 90V

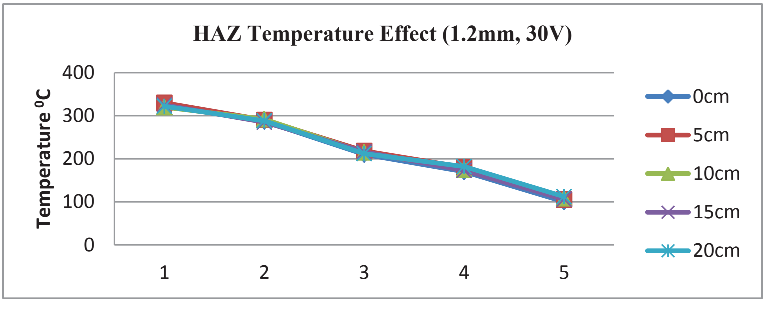

FIGURE 2.7 Temperature variations for 1.2mm, 30V

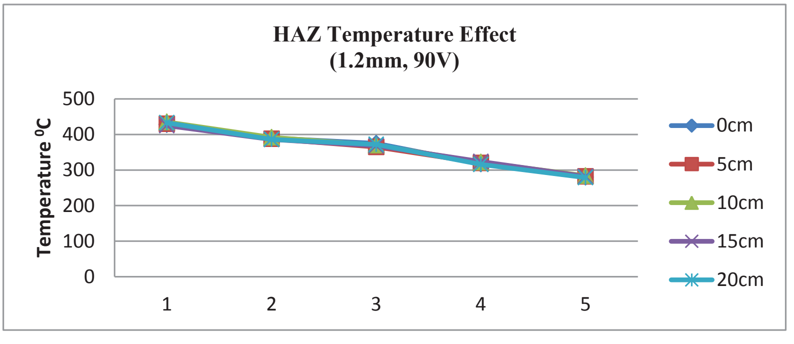

FIGURE 2.8 Temperature variations for 1.2mm, 90V

The average of the maximum force and maximum stress for every 2 sample were taken for analysis. By referring to Figure 2.9 which shown the result for 0.8mm filler wire, the maximum force getting higher following the increasing of arc voltage. The gap getting bigger when the arc voltage is 60V with the maximum stress value recorded at 204.55 N/mm^2. The graph trend shows a same pattern when using 1.2mm filler wire. But the value of maximum stress recorded at 90V is higher at 318.66 N/mm^2. Whereas by using 1.0mm filler wire, the maximum stress increased radically at 90V with value of 257.62 N/mm^2. From the observation, the higher the arc voltage, the penetration of the weld metal is getting good. Bigger filler wire diameter also contribute in strengthened the weldment area. The filler wire size and arc voltage value worked in parallel to ensure the strength of weldment structure. Although the porosity and crack were observed for 1.2mm filler wire, due to its penetration is better than 0.8mm and 1.0mm filler wire, the structure of weldment is the strongest compare to others.

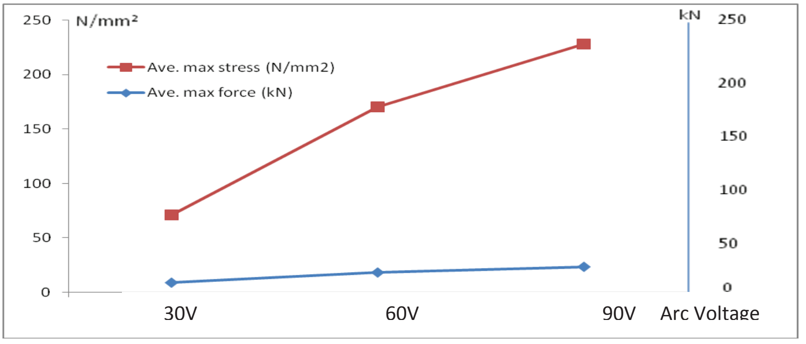

FIGURE 2.9 Average max force and max stress for 0.8mm filler wire

The hardness value for weldment area (fusion zone) is always lower than HAZ. This is because at HAZ, the microstructure is the hardest due to the transformation of microstructure from austenite to martensite caused by heat treatment during welding. Whereas at weldment area, the structure hardness is the lowest due to overheat treatment received inside the fusion zone. Besides, the microstructure of weldment area shows solidification process that formed ferrite at high temperature. Meanwhile, hardness for base metal stands between HAZ and weldment area due to the structure didn't experience any heat treatment process and stay as austenite. Figure 2.10 shows the increasing of hardness not as radically as during 1.2mm filler wire. The observation is almost the same for 1.0mm. Here the trend shows that for every different filler wire size, the bigger the size, the hardness increased radically. This can be aligned with the data from tensile test that mentioned the max stress getting higher with the increasing in filler wire size.

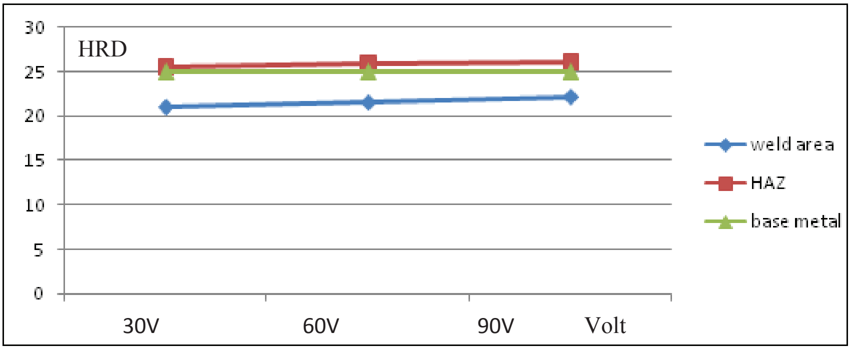

FIGURE 2.10 Weld area, HAZ and base metal hardness (0.8mm)

The impact test was conducted on two samples for each specimen. Based on the result, the higher arc voltage supplied, the higher energy absorbed. The trend showed that the energy absorbed increased radically. Meanwhile, same observation also appeared for 1.0mm filler wire. The energy absorbed is perpendicular with the voltage applied. At 90V, the energy absorbed tend to reduce a bit. The possibility here is the energy absorbed getting lower due to weldment structure for 1.2mm filler wire content with porosity and crack. Figure 2.11meanwhile shows the average energy absorbed for every filler wire diameter concerning the arc voltage applied. From the graph, suggestion can be made that higher arc voltage with bigger filler wire diameter tend to absorb higher energy. Although the 1.2mm filler wire contribute to weldment that full with porosity and crack, high penetration ratio that occurred when welding helps in strengthened the structure. Weldment distortion and contraction that occurred due to higher current flow has further tightened the weld area.

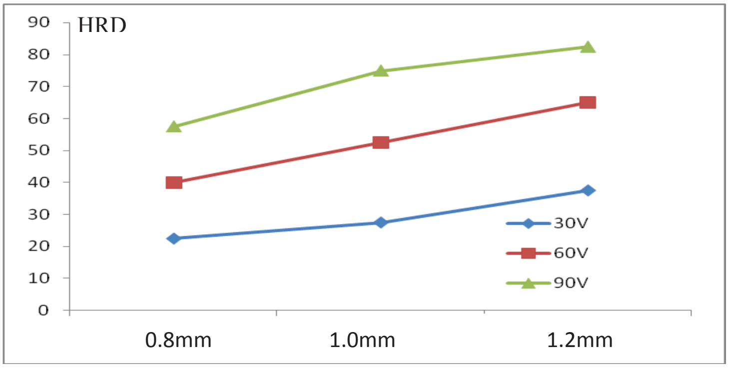

FIGURE 2.11 Average impact test result

For microstructure analysis, all HAZ and weldement area microstructures exhibit almost the same behavior (Figure 2.12-2.17). The grain looked coarser. Meanwhile, at 0.8mm and 1.0mm, the grain exhibit skeletal morphology structure. This occurred due to when weld cooling rates are moderate, or when the Cr is low but still within Ferrite Austenite (FA) range, skeletal ferrite morphology appeared. This is a consequence of the advance of the austenite consuming the ferrite until the ferrite is sufficiently enriched in ferrite promoting elements (chromium and molybdenum) and depleted austenite promoting elements (nickel, carbon and nitrogen) (Jang et.al., 2005). It is stable at lower temperatures where diffusion is limited. At 1.2mm, where the heat is the highest during welding, the weldment area showed a solidification subgrain boundary (SSGB). This occurred in Ferrite Austenite (FA) and Ferrite matrix (F) modes (Lee et. al., 2006).

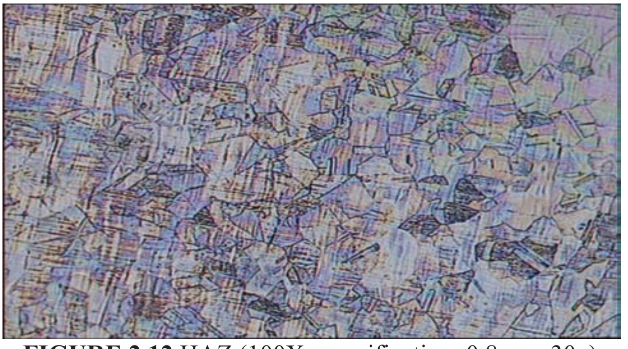

FIGURE 2.12 HAZ (100X magnification: 0.8mm, 30v)

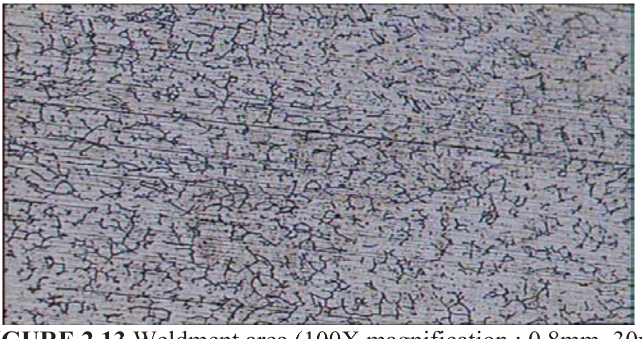

FIGURE 2.13 Weldment area (100X magnification : 0.8mm, 30v)

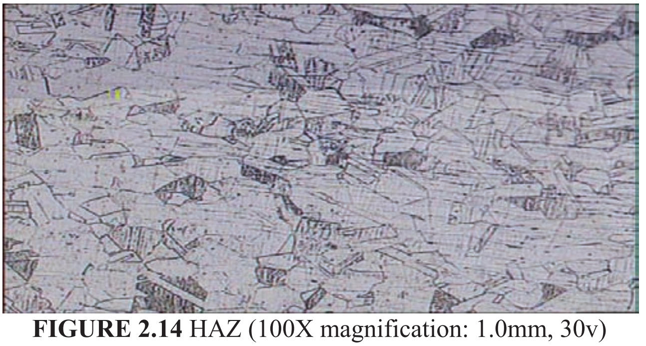

FIGURE 2.14 HAZ (100X magnification: 1.0mm, 30v)

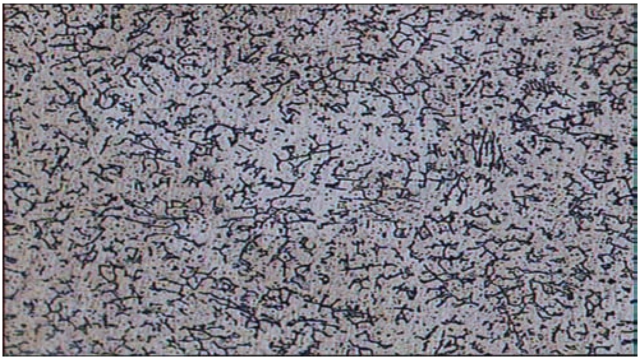

FIGURE 2.15 Weldment area (100X magnification : 1.0mm, 30v)

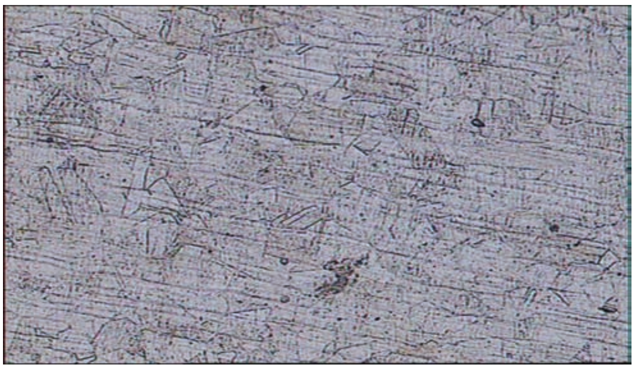

FIGURE 2.16 HAZ (100X magnification: 1.2mm, 30v)

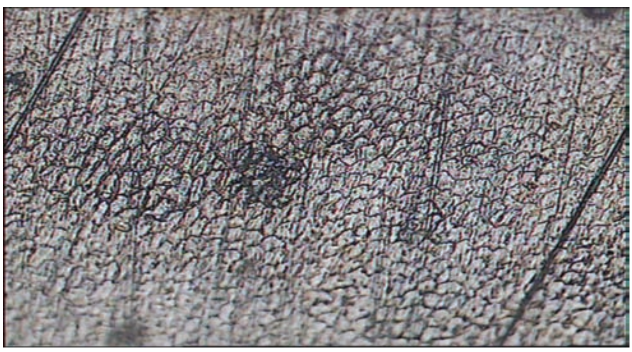

Figure 2.17 Weldment area (100X magnification : 1.2mm, 30v)

4.0 CONCLUSION

The effect of welding parameters as stated previously that has link with arc voltage and filler wire diameter on AISI 304L stainless steel have been investigated. All the observations and analysis for the welded specimen and samples are subjected to normal inspection and testing methods. Overall, three main investigations related with mechanical properties (consists of tensile and impact test) and HAZ temperature effect analysis were conducted accordingly. The HAZ temperature variations analysis showed that filler wire diameter had a significant role in weldment strength. This is because, different filler wire size can produce different heat that gives effect to the weldment distortion and contraction thus delaying the cooling time. As for an example, in 1.2mm filler wire, the penetration of weld metal through V-groove area is relatively better compared with 0.8mm and 1.0mm filler wire. The cooling ratio is also tent to reduce steadily and this has contributed to stable microstructure transition. Meanwhile, tensile test proved that penetration of weld metal acts as the main subject that contributed to the increasing of weldment strength. Regardless of porosity and crack, but with the assist of higher voltage (90V) and stable cooling rate, with additional bigger filler wire size (1.2mm), maximum stress is the highest contributing by well penetration. This can be concluded that melting rate of filler wire reduce the possibility of weldment failure due to porosity and crack. The result of hardness test proved that the filler wire size and arc voltage contribute in strengthening the structure of HAZ. This is because the existing of amount of heat during weldment according to filler wire size and arc voltage applied further increased the heat treatment process received by HAZ thus contributed in strengthening the structure (Al-Haidary et. al., 2006). Whereas the microstructure analysis revealed that the ferrite to austenite formation contribute in increasing the weldment strength, whereby at weldment area (fusion zone) ferrite form occurred due high temperature during welding. This makes the structure strength at weldment area weaker compare to HAZ and base metal (Lippold et. al., 2005). As for impact test, the result also shown that energy absorbed for 1.2mm filler wire is the highest.

The result has relation with tensile test as stated previously. Only at 1.2mm filler wire, the energy absorbed was reduced a bit at 90V was due to crack and porosity existence. But in general, the energy absorbed for 1.2mm filler wire was the highest compare with 0.8mm and 1.0mm filler wire regardless of arc voltage supplied. Here, the current affect that melt-up the filler wire supplied permissible energy for the weld metal to penetrate smoothly.

5.0 RECOMMENDATION

There are some activities that highly recommended in the future work:

a) To study the effect of different groove angle on the weldment strength. The results obtained from this experiment are only focused on 30^0 groove angle. In the future, various angles can be tested and observation on the weldment strength and its microstructures can be further investigated. The result shall be compiled and identification of the appropriate groove angle that contributes to the better strength of all could be understood. The relation of melt through, filler wire melting rate also can be studied. For further expanding the scope, root face for every groove angle can be set as parameter to determine the weldment strength obtained.

b) To study the effect of welding time and speed on the HAZ by using robot welding. The welding time and speed are easy controlled if the application using robot welding. The HAZ is smoothly obtained and the result accuracy will be increased. Systematic approach by using robot welding will enhanced the data collected thus better comparison can be clearly made. Welding time and speed will act as parameters and analysis will be conducted on the HAZ obtained by referring to the microstructures transformation and behavior. All the observations then can be related to weldment strength, penetration effect and weld metal porosity by conducting mechanical and microstructural analysis following standard recommended.

6.0 ACKNOWLEDGEMENTS

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7.0 REFERENCES

J. Song, J. Peters, A. Noor and P. Michaleris. 2003. "Sensitivity Analysis of the Thermomechanical Response of Welded Joints", International Journal of Solids and Structures, Vol. 40, Issue 16, pp. 4167-4180, 2003.

W.Y. Hsiao, S.H. Wang, C.Y. Chen, and W.S. Lee. 2008. "Effect of Dynamic Impact on Mechanical Properties and Microstructure of Special Stainless Steel Weldments", Materials Chemistry and Physics, Vol. 111, Issue 1, pp. 172-179.

James F. Lincoln Arc Welding Foundation. 2000. "The Procedure Handbook of Arc Welding: Fourteenth Edition", James F. Lincoln Arc Welding Foundation, P.O. Box 17035, Cleveland, Ohio, USA.

D.S. Correia, C.V. Goncalves, S.S. da Cunha Jr. and V.A. Ferraresi. 2005. "Comparison between Genetic Algorithm and Response Surface Methodology in GMAW Welding Optimization", Journal of Materials Processing Technology, Vol. 160, Issue 1, pp. 70-76.

Y. Cui, C.D. Lundinand, V. Hariharan. 2006. "Mechanical Behavior of Austenitic Stainless Steel Weld Metals with Microfissures'. Journal of Materials Processing Technology, Vol. 171, Issue 1, pp. 150-155.

K.C. Jang, D.G. Lee, J.M. Kuk, and I.S. Kim.2005. "Welding and Environmental Test Condition Effect in Weldability and Strength of Al Alloy", Journal of Materials Processing Technology, Vol. 164-165, pp. 1038-1045.

W.S. Lee, C.F. Lin, C.Y. Liu, and C.W. Cheng. 2006."Effects of Strain Rate and Welding Current Mode on Microstructural Properties of SUS 304L PAW Welds", Journal of Materials Processing Technology, Vol. 183, Issues 2-3, pp. 183-193.

J.T. Al-Haidary, A.A. Wahab, and E.H. Abdul Salam. 2006. "Fatigue Crack Propagation in Austenitic Stainless Steel Weldments" Metallurgical and Materials Transactions A, Vol. 37, Issue 11, pp. 3205-3214.

J. C. Lippold, and D. J. Kotecki "Welding Metallurgy and Weldability of Stainless Steels". 2005. John Wiley & Sons, Inc., Hoboken, New Jersey.