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COMPARATIVE INVESTIGATION OF THE MECHANICAL PROPERTIES AND CORROSION BEHAVIOR OF DISSIMILAR METAL WELD FUSION ZONE, HEAT AFFECTED ZONES AND BASE METALS

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Abstract: This study presents fundamental observations on the microstructure, mechanical properties and corrosion behavior of a dissimilar metal welded joint (DMWJ) formed by Austenitic Stainless Steel (304L;18/8) and Mild Steel plates of 5 mm thickness. Gas Tungsten Arc Welding (GTAW) process was used to join the metals with ER308L as filler metal on a prepared single V butt joint. The mechanical properties were examined by tensile, hardness and bending tests while the microstructural characteristics were studied using the Scanning Electron Microscope (SEM). The corrosion behavior was investigated in 3.5 wt.% NaCl using potentiodynamic polarization electrochemical method. It was observed that tensile and hardness properties of the dissimilar weld fall between that of the austenitic stainless steel and the mild steel base metals while the bending strength for the dissimilar metal joint emerges as the best. Austenitic Stainless Steel (ASS) showed more thermodynamic stability in 3.5wt% NaCl solution while the DMWJ was more resistant to corrosion than the mild steel in similar environment.

Keywords: Dissimilar metal weld, Austenitic stainless steel, Mild steel, Mechanical properties, Corrosion behavior

1. INTRODUCTION

The demand of joints of dissimilar metal combination is rapidly increasing in many structural and industrial applications for special optimization of properties as well as to save cost. Welding of dissimilar metals between stainless steel and carbon steel has been widely used in engineering practice over the years. To date, the majority of welded structures is fabricated in the form of dissimilar metal weld because it is more economical compared to the ones made of stainless steel only. One of the main issues that need critical consideration in dissimilar metals weld is corrosion resistance in the structure [1-4]. Dissimilar metal joints of stainless steel and carbon steel are widely used in pressure vessels, boilers, heat exchangers of power generation industry and petrochemical plants and oil and gas industry mainly to get tailor-made properties in a component and reduction in weight. It is worthy to note that the final properties of dissimilar joints depend on the base materials, filler metals, microstructural evolutions in fusion zone, and utilized welding technique [5-6]. Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding is an arc welding process that uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by an inert shielding gas (argon or helium), and a filler metal is normally used. GTAW is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. The process grants the operator greater control over the weld than competing processes such as shielded metal arc welding and gas metal arc welding, allowing for stronger and higher quality welds. However, GTAW is comparatively more complex and difficult to master, and furthermore, it is significantly slower than most other welding techniques [7]. Conversely, due to difference in thermo-mechanical and chemical properties of the materials to be joined under a common welding condition, it causes a steep gradient of the thermo-mechanical properties along the weld. Hence joints of dissimilar metals weld is generally more challenging and often causes problems due to differences in the physical, mechanical and metallurgical properties of the base metal to be joined [4]. Also when joining dissimilar metal welds, diffusion in the weld pool often results in the formation of inter-metallic compound in the welded region. These inter-metallic compounds can be deleterious to the mechanical properties, especially particles of primary crystals, which represent strong stress concentrators and promote the initiation of sharp micro-cracks [8-9]. The growth of micro-cracks may cause brittle fracture thereby, reducing the ductility of the joint [10]. Giridharan *et al.,* [7] carried out an experimental work to study the mechanical properties of a dissimilar welding joint between IS 2062GrC mild steel and AISI 316L stainless steel, using AISI 309L filler rod. Tensile and bend tests as well as the microstructural characteristics were studied. The result showed good bending behavior, and improved tensile strength in the weld area. Electron microscopy showed the dilution of base metals in the weld zone. Jamaludin *et al*., [11] studied the mechanical properties of welded joint by tension test. It was observed that, the yield strength and tensile strength of welded samples using mild steel welding electrode were slightly lower than welded samples using stainless steel welding electrode. Wenyong et al., [1] studied the microstructure, mechanical properties and corrosion behavior of laser welded dissimilar joints between ferritic stainless steel (FSS) and carbon steel (CS). It was observed that the FSS base metal showed the lowest corrosion current density but the FSS-CS welded joints have the largest corrosion current density which was attributed to galvanic interaction with the base metal.

In this work, dissimilar welding of austenitic stainless steel (304L; 18/8) and mild steel plates was carried out using GTAW process. Assessment of the mechanical properties, microstructural characteristics and corrosion behavior of the dissimilar joints were investigated and the experimental results were discussed.

2. EXPERIMENTAL PROCEDURE

Chemical Analysis

The major materials used for this experiment were austenitic stainless steel (ASS) (304L/18:8 (18% Cr and 8% Ni)) and mild steel in the form of a rectangular plate both with thickness of 5 mm. The chemical compositions of the base metals under study were obtained by spectrometry as shown in Table 1.

Table 1: Chemical composition of austenitic stainless steel (ASS) and mild steel (wt.%)

Elements	C	Si	Mn	P	S	Ni	Cr	Mo	N	Cu
ASS	0.091	0.430	1.310	0.039	0.011	8.050	18.09	0.220	0.038	0.350
Mild Steel	0.071	0.327	1.155	<0.001	<0.001	0.169	0.062	0.013	0.008	0.022

Welding and Sample Preparation

The base metals were cut into the desired length of 150 x 60 mm and a single-V butt joint was prepared for better root penetration. The welding operation was carried out afterwards using the Gas Tungsten Arc Welding (GTAW) and a stainless steel filler metal (ER308L). Direct Current Electrode Negative (DCEN) welding technique was used with welding speed of 150 mm/min and welding current of 110 A. The arc length, filler tip angle, filler type and size are; 2.0 mm, 60°, ER308L and 3.2 mm, respectively. Pure argon gas was used as the shielding gas to prevent oxidation of molten steel. After completion of the welding process, tensile test samples with dumbbell shapes were cut transversely from the welded joint and the base metal. Machining was also done for the hardness test, microstructural examination and corrosion test which were sectioned from the Weld metal (WM), Heat affected zone (HAZ) and the Base metal (BM).

3. PROPERTY TESTS

Determination of Tensile Properties of the Samples

Tensile test samples were prepared in accordance with ASTM A370-08A [12] and the test was carried out using Su Zhou Long Sheng universal testing machine. Three samples were tested with a load of 300 KN and crosshead speed of 5 mm/min correlating with an initial strain rate of 0.98 s^{-1}. The specimen was mounted by its ends into the holding grips of the test apparatus. The tensile testing machine was designed to elongate the specimen at a constant rate, and to continuously and simultaneously measure the instantaneous applied load and the resulting elongations. The applied load permanently deformed and fractured each sample into two parts.

Determination of Bending Properties of the Samples

The bending test was carried out by using Testometric universal testing machine in accordance with ASTM E190-92 [13] standard test method for bending properties of welded samples. The bending test was performed at the speed of 100 mm/min. Three samples were tested for each representative samples from where the average values for the test samples were used as the illustrative values.

Determination of the Hardness of Samples

This method consists of indenting the test material with a hardened steel ball indenter using Indentec hardness testing machine. Rockwell hardness test produces a much smaller indentation more suited for hardness traverses. The hardness samples were selected from three zones, which are; Base metals (BM) for mild steel and stainless steel, HAZ for mild steel and stainless steel and the weld metal (WM). The test samples were cut into 9 x 9 mm for the different zones. The indenter was forced into the test material under a preliminary minor load of 60 kgf which gradually increased to 100 kgf and 150 kgf. The test was carried out 3 times at different locations on BM, HAZ and WM and, the readings were recorded as displayed by the hardness testing machine. The average values were used for each of the zones as the illustrative values.

Determination of Corrosion Behaviour

The mild steel and austenitic steel were cut from the base metals and HAZs into equal sizes of (10 x 10) mm each, likewise from the weld metal. The samples were then connected with wire and then placed in a mounting container for cold mounting. The mounting was done by adding epoxy resin and hardener and, after few minutes, it was removed from the container. Grinding and polishing was done on the samples before exposure to corrosion test. Tafel corrosion test was then carried out using potentiodynamic polarization electrochemical method in 3.5 wt% NaCl solution environment.

⧉ Microstructural examination

The test samples were cut into 9 x 9 mm for the different zones before the microstructural observation was carried out using the Scanning Electron Microscope (SEM). The microstructural morphologies of the samples were examined using an AURIGA scanning electron microscope with an accelerating voltage of 15 kV.

4. RESULTS AND DISCUSSION

⧉ Mechanical Properties

The tensile properties (yield strength, ultimate tensile strength and the tensile modulus) were evaluated. The data used were the average of the measured values obtained as presented in Figure 1. The charts for the various tensile properties of the welded dissimilar metals were as shown in Figure 1. The plot shows the yield, ultimate tensile strength and tensile modulus of the weld and base metals. It was revealed from the results that similar trends emerged in the response of the materials to these properties. In all the properties examined, austenitic stainless steel gave the optimum performance followed by the weld and mild steel samples, respectively. This trend in terms of materials and values for the properties were ideal for structural integrity where gradual decrease in property from one end to another is essential for effective service performance. The values at the weld joints form the transitional values between that of austenitic stainless steel and the mild steel.

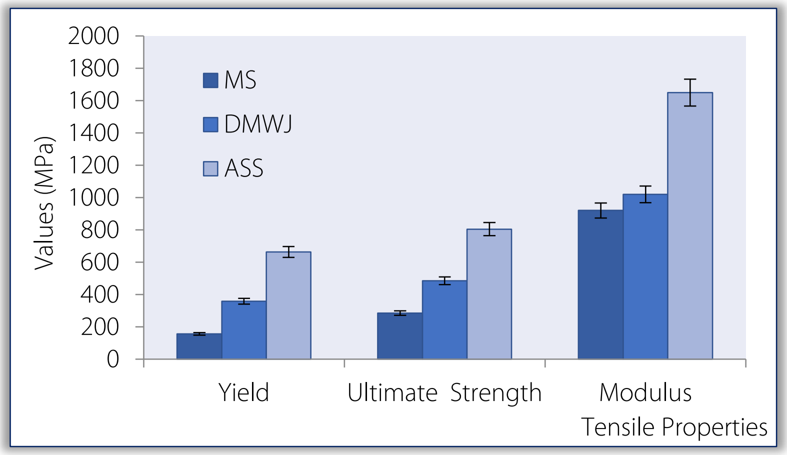

Figure 1: Charts of the tensile properties for the various zones

The austenitic stainless steel (ASS) base metal possess the highest ultimate tensile strength with a value of 805.3 MPa followed by weld sample with a value of about 486.2 MPa while the lowest was the mild steel (MS) base metal with a value of about 286.3 MPa. The results showed that ultimate tensile strength of the weld joint has been enhanced by about 38.9 % compared to the mild steel base metal. This implies that the weld joint aids transition from low strength mild steel to high strength austenitic stainless steel. The tensile yield strength and modulus follow similar trend, the highest been 664.31 and 1649.33 MPa, respectively by the austenitic stainless steel while the lowest was 157.77 and 920.77 MPa, respectively from the mild steel. The weld joint was enhanced with about 56.1 % yield strength and 9.8 % modulus compared to the mild steel base metal. The improved strength at the weld joint compared to the mild steel was due to the intermetallic that was formed between the two base metals. The intermetallic was formed from the mixture of the austenitic stainless steel, mild steel and the filler metal which produce a phase that was stronger than the mild steel parent metal.

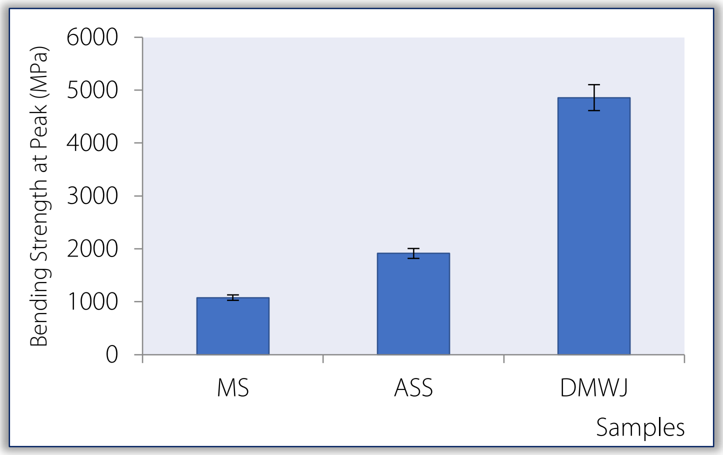

Figure 2: Bending Strengths of base metals and the dissimilar metal welded joint

The bending test was used to determine the maximum breaking load the materials can withstand before failure under bending stress as shown in Figure 2. The bending test result shows that the dissimilar metal weld joint (DMWJ) sample possess the utmost bending strength due to the highest bending resistance inherent in the zone. The DMWJ sample was with a value of about 4857 MPa followed by the austenitic stainless steel base metal with a value of 1913 MPa while the mild steel possess the lowest bending strength with a value of 1436 MPa. The reason for the obtained result was similar to what was explained in Figure 1 due to the new phase formed by the intermetallic.

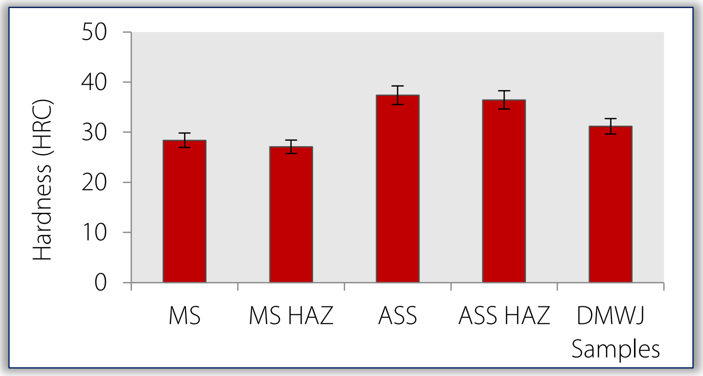

Figure 3: Rockwell hardness values of samples at different regions

Rockwell hardness test was carried out on the samples to measure the variation in hardness across the weld zones of austenitic stainless steel 304L and mild steel. Figure 3 shows the average hardness values across the weld interface covering the base metals. The hardness value obtained for ASS 304L was higher when compared to the mild steel. The highest average hardness value was 37.38 HRC for the austenitic stainless steel base metal while the lowest hardness value was 27.10 HRC for mild steel heat affected zone. The hardness value obtained at the DMWJ (31.18 HRC) fall within the two parent metal's hardness and, was higher than that of the mild steel. This implies that, there is diffusion of alloying elements in the weld pool forming different phase from the base metals which affects the mechanical properties.

In agreement with the findings of Muralimohan *et al.*, [14], it was revealed from the results that, there is an analogous tendency in hardness distribution in the various zones like that of the tensile properties in Figure 1. The reason for the variation in hardness can be due to the varying carbon content in the base metals.

Considering other mechanical properties, the response of the dissimilar metal weld shows that, it possesses good combination of mechanical properties. The dissimilar metal welded samples possess intermediate strength and hardness between austenitic stainless steel and mild steel but it possesses the best bending strength. This therefore, implies that by joining these two different metals for applications in areas where changes in structural properties are essential based on environmental effects and cost, this fabrication process will be a potential method to be adopted.

Corrosion Behaviour

Potentiodynamic polarization curves of all the samples in 3.5wt% NaCl solution was presented in Figure 4 while Table 2 showed the corrosion density (Ecorr) and corrosion currents (Icorr) demonstrated by the samples.

Table 2: Electrochemical data of the mild steel, HAZ mild steel, Fusion zone, Austenitic stainless steel and HAZ austenitic stainless steel in 3.5 wt% NaCl

SAMPLE	E corr. (mV)	I corr. (nA)	Corrosion Rate (mmpy)
Mild Steel	-592.693	58.11	0.00068243
HAZ Mild Steel	-584.661	28.546	0.00033124
Fusion Zone	-496.412	25.727	0.00029854
Aust. Stainless Steel	-121.649	15.44	0.00017917
HAZ Aust. Stainless Steel	-206.613	9.136	0.00010601

From the results, it was noticed that the samples displayed different polarization and passivity characteristics through the distinct values of the (Icorr) and (Ecorr) between the samples. Also, the corrosion current densities (Icorr) were more intense for the mild steel base metal, mild steel heat affected zone (HAZ), and the fusion zone in comparison to the austenitic stainless steel base metal and its HAZ. This could be attributed to the iron-carbide (cementite) phases dispersed across the ferrite phase. The high concentration of cementite makes the mild steel to be more susceptible to corrosion. Consequently, the austenitic stainless steel side shows more resistance to corrosion in this solution. This was as a result of the chromium oxide film created by chromium on the surface of the metal forming a passive layer that isolates and preserves the surface [15].

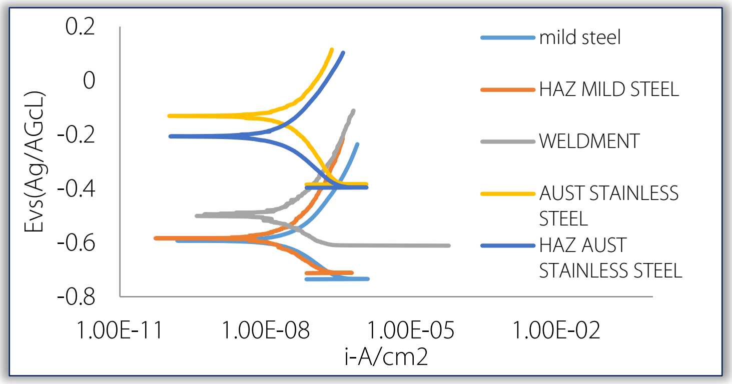

Figure 4: Potentiodynamic polarization curves of samples at different zones in 3.5 wt% NaCl

The Icorr value of the mild steel BM sample was the highest but was reduced by 55.7% in the fusion zone thereby, reducing its susceptibility to corrosion. Similarly, the corrosion rate of the mild steel BM was reduced in fusion zone from 0.00068 to 0.0003 mmpy as shown in Table 2.

The result indicates that the austenitic stainless steel, and its HAZ have a lower thermodynamic tendencies to corrode in 3.5 wt.% NaCl solution compared to mild steel, its HAZ and the fusion zone. Therefore, austenitic stainless steel are more thermodynamically stable in 3.5wt% NaCl solution while the fusion zone of the weld between the two base metal were more stable than that of the mild steel.

Microstructural Examination

The microstructure of the fusion zone of the welded sample, base metals and HAZs of the two dissimilar metals were examined with the Scanning Electron Microscope and the images were as shown in Figure 5.

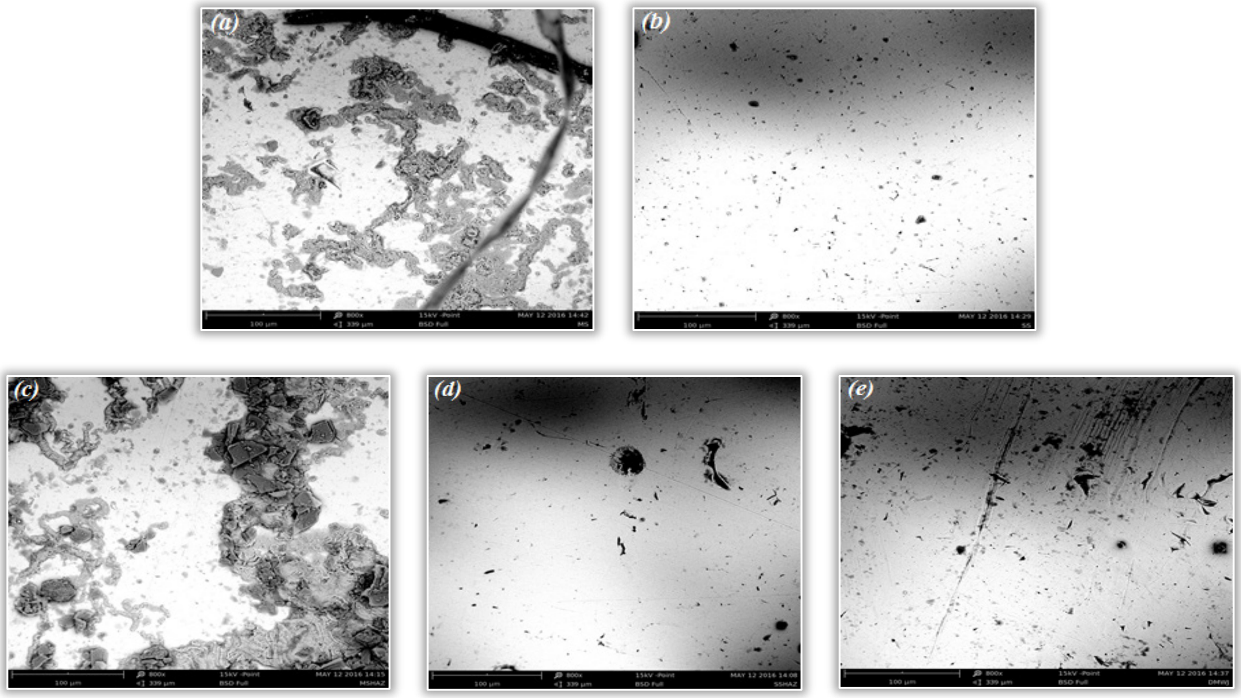

Figure 5: SEM images of *a*. BM of mild steel; *b*. BM of ASS; *c*. HAZ of mild steel;
d. HAZ of ASS; *e*. fusion zone of the dissimilar weld metal

In stainless steel welds, the microstructures were usually related to types of solidification and subsequent transformation behavior. Figures 5 (a-e) showed the various sections of the metals where it became obvious the influence of heat input and solidification on the transformation behavior. Figures 5 (a) and (c) show the micrographs of the mild steel BM and HAZ. The mild steel BM reveals a heterogeneous microstructure, consisting of ferrite (white) and pearlite (dark) where the globular and laminar pearlite phases are dispersed across the ferrite phase. The high concentration of cementite makes the mild steel (BM) to be more susceptible to corrosion. However, the mild steel HAZ revealed the presence of more coagulated pearlite dispersed in the ferrite phase as a result of recrystallization that occurred by the heat generated during welding than in the BM. Figures 5 (b) and (d) showed the micrographs of the ASS BM and HAZ. The HAZ displays high level of isolated inclusions compared to the BM. However the prevalent phase is the ferrite phase and some dispersed dots of cementite across the interface. Similar result was obtained by [16] where it was discovered that the ferrite phase is less susceptible to corrosion compared to the cementite phase. This explains why stainless steel is less susceptible to corrosion.

5. CONCLUSION

This work has been carried out to investigate the influence of dissimilar metal joint on the mechanical properties and corrosion behaviour of the base metal's HAZs and the weld fusion zone using GTAW.

From the study, it was noticed that; the welded joint (weld fusion zone) possessed the best bending strength with a value of 4857 MPa compared to 304L austenitic stainless steel and mild steel. This was followed by the ASS base metal and then the mild steel base metal.

The mechanical properties as well as the corrosion behaviour of the welded joint were improved compared to mild steel responses. The values gotten from the welded joint formed the intermediary between the values obtained for both ASS and MS, hence, a steady transition from good to weak behaviour, respectively. This changes in structural properties can be adopted in places where materials and cost are of paramount importance.

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