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Effect of Current on Characteristic for 316 Stainless Steel Welded Joint Including Microstructure and Mechanical Properties

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Abstract

Gas Metal Arc Welding (GMAW) process is a clean and cost effective process in arc welding which is higher productivity and good in quality. In this study, 316 stainless steel pipes with outside diameter is 73mm and 7.0mm thickness were joint using Tungsten Inert Gas (TIG) welding process. Various current settings were used to obtain the optimum joint characteristics and minimize defects that will contribute to cost effective. Mechanical characteristics of the welded alloys were carried out is tensile tests and hardness (HV). Metallographic examination was conducted to identify and observe the various fusion zones. Results show that the increase of welding current bring about the large amount of heat input in the welding pool, the enlargement of width and deepness of the welding pool, cumulative sigma phase in the matrix and reducing the chromium carbide percentage in 316 stainless steel welded joint. Arc current of 100A has been identified of the most suitable current since it gives the lowest defects and brings the highest value of strength and hardness for this material.

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Keywords: stainless steel; TIG; microstructure; tensile property; fracture; hardness

1. Introduction

AISI type 316 stainless steel as one kind of the austenitic stainless steels is widely used within the marine exterior trim, industrial equipment as piping and super heater tube material and is an important candidate material for the commercial fast breeder reactor. A common usage of this steel is as super heater tubing exposed to temperatures up to about 650 °C [1,2]. Gas tungsten arc welding, here is TIG, produces an arc between a non-consumable tungsten electrode and the workpiece. An inert gas shields the arc, electrode, and molten pool from atmospheric contamination. When welding thinner materials, edge joints, and flanges, welders generally do not use filler metals. However, for thicker materials, welders primarily use externally fed filler metal. TIG welding is a popular technique for joining thin materials in the manufacturing industries. This type of welding achieves a high quality weld for stainless steels and non-ferrous alloys [3,4]. The properties of welds in austenitic steels in general differ from those of the base metal due to: a) precipitation, b) decomposition, and c) segregation of elements during solidification. These processes can bring about local changes in the microstructure, which may later influence corrosion resistance and mechanical properties [5]. The welding current of TIG welding effects on the morphology, microstructure, tensile property and fracture of welded joints of austenite stainless steel due to heat input. Optimized processing arc current are significant, which provide experimental guidance for the application of stainless steel. At present, there exist some processing problems, which affect the quality and property of welded joint, in the welding of grade 316 structural components. The problems like hot cracking, carbide precipitation phase and sigma phase can reduce significantly the mechanical property of this welded joint. Selection suitable welding parameters and proper material is so important to control the mentioned problems [6,7]. Therefore, there is a need to find the optimization current as one of parameters for TIG welding on 316 stainless steel to reduce welding defects and to achieve better mechanical properties. The influences of welding current on the morphology, microstructure, tensile property and fracture of welded joints of 316 stainless steel have been studied. In this paper, optimized TIG welding process parameters for 316 stainless steel pipe is proposed.

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2. Experimental procedure

2.1. Material and Experiment

316 stainless steel pipe with diameter of 73mm and 7.0mm thickness was cut using power saw and turned on the lathe machine to prepare the V surface with the angle of 37.5º ±2.5º. The V type for butt joint was chosen with the root face was 0.5mm. The chemical composition of this 316 stainless steel is in Table 1.

Table 1. Material chemical composition for 316 stainless steel

Material	Wt %	Material	Wt %
Carbom	0.08	Molybdenum	1.96
Manganese	1.51	Vanadium	0.15
Silicon	2.9	Aluminum	0.004
Chromium	17.4	Titanium	0.1
Zirconium	0.1	Nickel	9.5
Phosphorus	0.04	Cobalt	0.51

TIG welding process was carried out manually by certified welder and using a specific pipe welding fixture pipe to avoid distortion. The 316L filler is suitable with the base metal of316 stainless steel [8]. The purging backflow with flow rate of 10 liter/min was applied to avoid heat scale on the inner diameter of the pipe. The inert atmosphere is also promoting assistance to the penetration of weld counter. Table 2 shows TIG welding parameters.

Table 2. TIG welding parameters

Tungsten electrode nominal dia.	2.4mm
Filler rod dia.	2.4mm
Welding current	80, 90, 100 and 120 (A)
Welding speed	0.3 cm/s
Argon flow	15 litre/min
Backing flow	10 litre/min

2.2. Mechanical Tests and metallography

The specimens were cut approximately 5mm from the edge of the sample in transverse direction to the weld direction with Sodick EDM Wire Cut (Electrical Discharge Machining) machine. For the microstructure analysis, metallographic sections were prepared from the welded specimens in a direction perpendicular to the welding direction, and were grinded, polished and etched with the etchant solution consist of 70% nitric acid (HNO_3). Etching is accomplished by using electro-polishing machine with 5v for 40 seconds. Instron 600DX tensile testing machine was used to test the tensile strength of the joint. The morphology of fracture surface was observed by using Cam Scan MX2600FE scanning electron microscope. The microstructure of joint obtained under different parameters was examined through optical microscope, Olympus BX60. for observation and evaluation of the sigma, carbide phase and the fracture surface, Field Emission Scanning Microscopy/Energy Dispersive X-ray Analysis (FESEM-EDX) was used.

3. Result and discussion

3.1. Morphology of Welded Joint

Figure 1 shows the macro morphology of single V shape welding joints under the different current for 316 welded joint. The amount of heat input is small under low current, as a result the width and depth of the weld pool are small, and the root of welding joint is also small. The increase of welding current brings about the enlargement of the width and depth of the weld pool. Therefore, clearly by increasing the arc current the depth and width of fusion weld metal increases too.

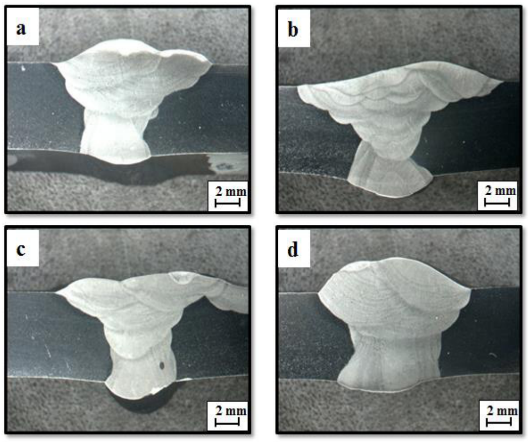

Fig. 1. Effects of welding current on the macro morphology of 316 stainless steel butt-welding joint with welding current (a) 80A; (b) 90A; (c) 100A; (d) 110A.

3.2. Microstructure Analysis

Figure 2 displays the microstructure in different parts of the welded joint for 316 stainless steel. There are some coarse dendrites in the seam center. Coarse column crystals formed along the heat dissipation direction, which is perpendicular to the interface of fusion, in the near fusion zone of the seam. From the melting boundary to the seam center, the temperature gradient decreases gradually, while the speed of crystallization increases, so the crystal morphology changes from cellular crystal to columnar crystal, and then to free dendritic crystal. The microstructure and morphology of different part in the heat-affected zone are determined by many factors, such as the peak temperature of thermal cycling, heating rate, staying time at high temperature and the subsequent cooling speed. According to the difference of microstructure, from the seam center to base metal, it can be divided into four parts: fusion zone, overheated zone, fine-grained zone and incomplete recrystallized zone. The temperature within the fusion zone is between the solidus and liquidus. Overheated zone is located in the position near the base metal. In this zone, the temperature is above the austenite formation temperature for long time that the grains grow dramatically, at last overheated coarse structure forms. The fine-grained zones are formed due to the high cooling speed of the base metal. In the incomplete recrystallization zone, since only some of the metal recrystallized, this resulted in various grain sizes [9].

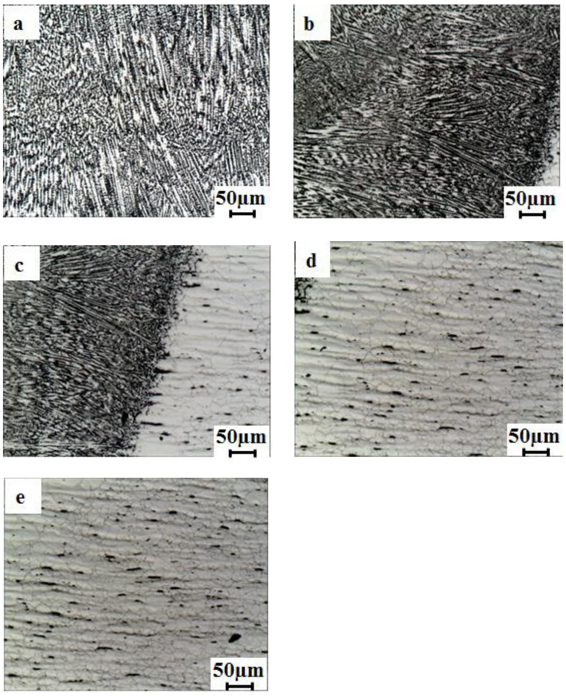

Fig. 2. Microstructure of the seam zone and the center of heat affected zone of 316 stainless steel welded joint (a) seam; (b) fusion zone; (c)&(d) overheating zone; (e) incomplete recrystallization zone

From the results of the metallographic structure, it is found that at a constant welding speed, the overheating degree of metal in the welding pool increases with the increment of the welding current (or heat input), which result in the decrease of the temperature gradient. The heat-affected zone widened with the enlargement of the welding current. The reduction of welding speed displays the same effect on the microstructure of different part in the welding joint with that of the increment of welding current. The heat input is proportional to the welding current but inversely to the welding speed. When the welding speed increases, it shortens the residence time of arc, which decreases the heat input, the width and depth of the welding pool diminish and the crystal morphology of the seam changes from dendrites to columnar dendritic crystal and then to dendritic crystal. Figure 2(e) shows the microstructure of type 316 stainless steel base metal with delta-ferrite content in an austenite matrix. This result also indicated that the stringers of delta-ferrite elongate in the rolling direction which is common for austenitic stainless steel.

3.3. FESEM – EDX Analysis

To illustrate and to recognize different phases in the microstructure FESEM-EDX is used. As expected, the presence of sigma phase and chromium carbide for 316-welded joint is definite. By using FESEM-EDX, it was found some sigma phases, carbide phases and hot cracking appeared along the diffusion zone of welded joint as shown in Figure 3. For the stainless steel grade with average carbon content (0.04% or more), chromium carbide precipitation ($Cr_{23}C_6$) in the affected zone is perfectly possible, when they are subjected to temperatures maintained for a long period and ranging between around 500 and 850º C, so 316 stainless steel cannot be immune of this welding problem. Hot cracking is so common in austenitic stainless steels where they are partially the only type of cracking the result of welding [6,7].

Figure 3 shows the microstructure of Type 316 stainless steel base metal with delta-ferrite content in an austenite matrix in heat affected zone. Austenitic stainless steel base metals and weld metals are susceptible to embrittlement by the formation of sigma phase. Its formation range is between 600 to 900ºC, and it forms most rapidly in austenitic-ferritic weld metals at around 800ºC. Figure 3a and 3b show, by increasing the heat input as the result of enlargement of arc current, the cooling rate decrease, therefore, there is more time in the development of the microstructure in the sigma phase temperature range. This causes the distribution of the sigma phase increases when the arc current increase.

3.4. Tensile Test result of 316 Stainless Steel Pipe welded joint

The results of mean tensile strength for each arc current are shown in Figure 4. Each arc current setting had three specimens. From Figure 4, it was found that the highest value of mean of tensile strength was 394.8MPa, which obtained from 100A, followed by 392.3MPa, 385.7MPa, 379.2MPa that obtained from 90A, 80A and 110A respectively. Therefore, based on these results, 100A was the most suitable arc current used to weld the 316 stainless steel work pieces [8]. Notwithstanding by increasing the arc current the distribution of sigma phase in welding zone and HAZ is increased, on the contrary hot cracking efficiency and carbide precipitation distribution is decreased by increasing the heat input as result of enlargement of arc current. Some elements have greater affinity for carbon than chromium; these elements are generally titanium and niobium. The precipitation of Ti (TiC) and niobium (NbC) carbides occurs in a temperature range higher than that in which $M_{23}C_6$ would precipitate and the carbon thus trapped cannot take part in this last precipitation. Therefore the arc current of 100A could make the balance between the mentioned reasons.

The fracture surface after the tensile test is shown in Figure 5. FESEM- EDX analysis shows the kind of defects exactly on the fracture surface. Sigma phase and carbide phases can act as stress concentration for the start of the weld joint failure. Some dispersed voids due to hot cracking, porosity and shrinkage defects are observed on the fracture surface of the samples that reduce the tensile strength of the welded joint significantly.

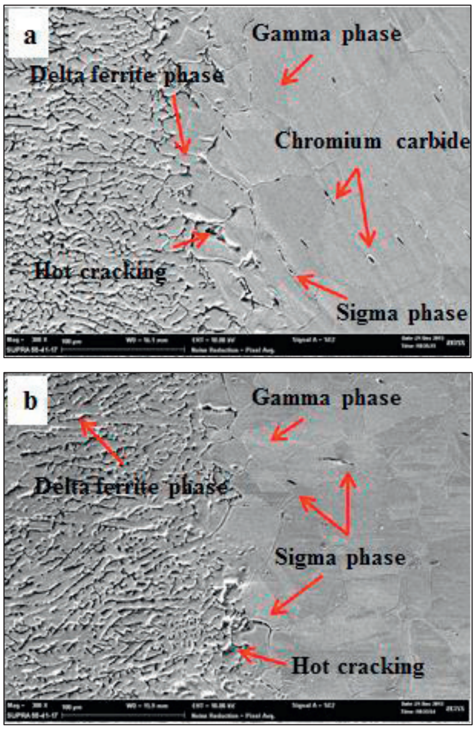

Fig. 3. Effects of welding current on the sigma and carbide phases distribution of 316 stainless steel, achieved by FESEM – EDX (a) current 90A – mag 300x; (b) current 110A – mag 300x

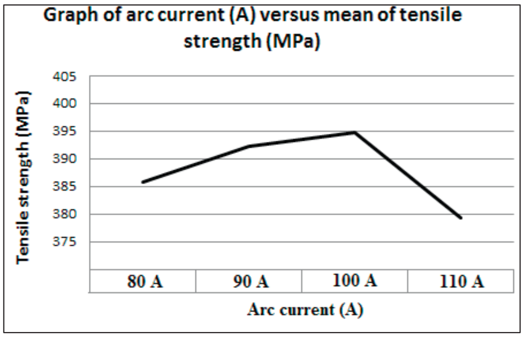

Fig. 4. Graph of arc current (A) versus mean of tensile strength (MPa) for316 stainless steel welded joint

3.5. The result of Vickers Hardness Test of 316 Stainless Steel Pipe welded joint.

The comparison of the hardness obtained for welded specimen using arc current of 80A, 90A, 100A and 110A are shown in Figure 6. The hardness varies from the base metal across the region to the HAZ, fusion line and weld metal. All specimens displayed the same result, such as the hardness value drop, starting from the base metal to HAZ zone. The filler metal is the same as 316L chemical composition while the base metal is 316 stainless steels so the content of carbon from base metal across the region to the HAZ zone, fusion line and weld metal decreases. As a result, by changing the carbon content from base metal toward the weld metal hardness value can decrease.

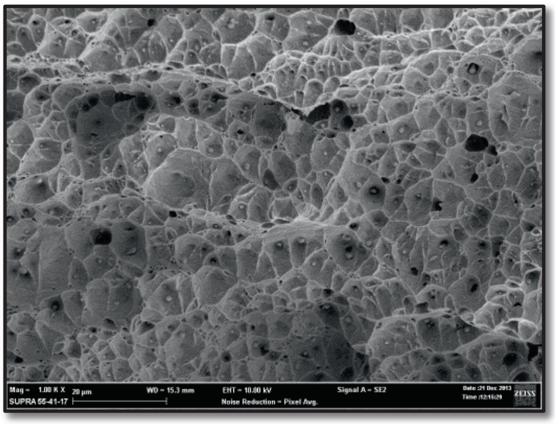

Fig. 5.Typical morphology on the fracture surface of 316 stainless steel welded joint achieved by FESEM – EDX – mag 1000x – current

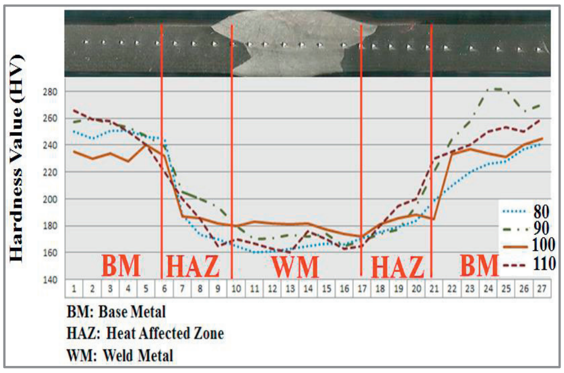

Fig. 6. Comparison of number of points versus hardness (HV) of 316 stainless steel welded joint

In Figure 6, it is found that the highest hardness value among the specimens was obtained from 100A. This indicated that 100A is the most suitable TIG arc current used to obtain a good weld joint for this material. Figure 7 and Figure 8 show the micrograph of indention effects. They show how grains near to indention are distorted. The distortion of grains decreases from left to right. Moreover, the diameter of the indention increases which show the hardness value reduces from left to right. This is agree to the carbon content differences between base metal and 316L filler.

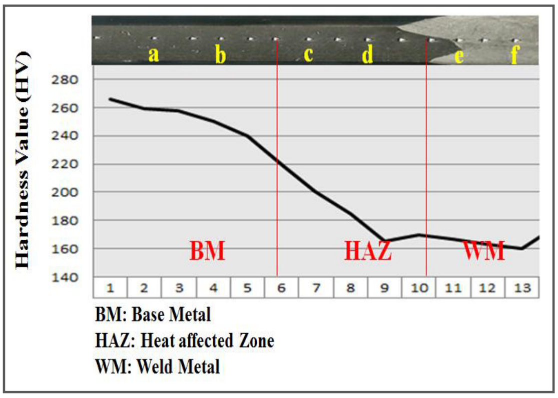

Fig. 7. Position of the hardness indentation on 316 welded joint which is taken from left to right- arc current 110A

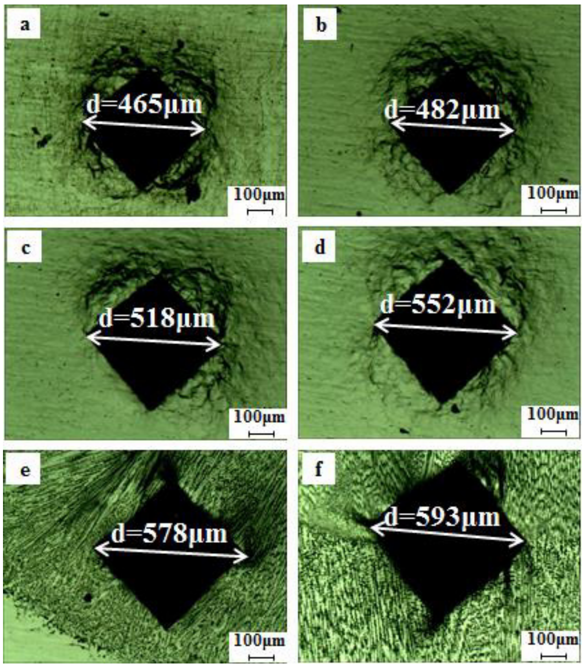

Fig. 8. The micrograph of the indention point of Figure 8

4. Conclusion

Heat input is a relative measure of the energy transferred during welding. It is a useful tool in evaluating welding procedures within a given process. The cooling rate, weld size and material properties may all be influenced by the heat input. Some welding codes place specific controls on the heat input. Based on the result, the heat input rises with the increase of welding current. It can induce the widening and deepening of the welding pool. Moreover, it can cause that the strength of welded joints goes up first and then falls down. The following conclusions can be deduced:

- It was founded that some chromium carbide and sigma phases in 316 stainless steel welded joint, and these phases cause in embrittlement of stainless steel. By increasing the heat input, the sigma phase increases in the matrix.
- The tensile fracture is ductile because of the dimples scatter fracture surface.
- Arc current of 100A has also been identified as the most suitable arc current used to weld the two and half inches 316 stainless steel pipe. Since it is already mentioned in result and discussion, by applying arc current of 100A was found the balance between increasing sigma phase distribution and decreasing of hot cracking and carbide precipitation phase in welding zone and HAZ.
- The optimum TIG welding parameter has been identified which may contribute to improve the productivity and cost effective process.

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