



EJENS

European Journal of Engineering and Natural Sciences



e-ISSN : 2458-8156

Investigation of the Microstructure and Mechanical Properties of Gas Metal Arc Welded AISI 304 Austenitic Stainless Steel Butt Joints

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Abstract

Austenitic stainless steels exhibit very good properties such as very good formability even at low temperatures, good mechanical properties and high corrosion resistance. Austenitic steels are the grades which are produced most in quantity among all stainless steels and AISI 304 is the most widely used grade among the austenitic steels. They are used widely in several industries such as chemistry and petro-chemistry industries, food processing industry, medical and dental equipments and kitchenware. However, several difficulties such as carbide precipitation in heat affected zone, and hot cracking and formation of brittle sigma phase in the fusion zone may be encountered in fusion joining of these steels. High heat inputs involved in arc welding may even increase the occurrence of these problems. Thus, successful joining of these alloys using conventional fusion welding methods is rather important. This study aims at investigating the influence of heat input on microstructural evolution in the weld region and the mechanical properties of the welded joints in gas metal arc welding of AISI 304 austenitic steel plates. For this purpose, 5 mm thick AISI 304 plates were joined using different heat input values. Detailed optical microscopy and micro-hardness measurements in addition to tensile and bending tests were carried out to study the microstructural and mechanical properties of the welded plates produced. Furthermore, it was also attempted to determine the effect of heat input on the performance of gas metal arc welded AISI304 joints.

Key words

Austenitic stainless steel, AISI 304, heat input, carbide precipitation, weld performance

1. INTRODUCTION

Austenitic stainless steels (ASS) exhibit good corrosion resistance and superior mechanical properties such as high good formability. Thus, they are widely used in a wide spectrum of applications ranging from kitchen utilities and implants to power plants and from steel bridges to petroleum, oil and gas, nuclear and marine industries [1-5].

The major problem encountered in fusion joining of stainless steels (SS) is the formation of chromium-depleted zones (i.e., carbide precipitation along the grain boundaries in heat affected zone - HAZ). Hot cracking and

formation of brittle sigma phase may also be encountered in the fusion zone (FZ) of these steels. Somervuori et al. [6] clearly demonstrated that the Cr-depleted regions in the FZ deteriorated the corrosion behaviour. Kim et al. [7] investigated the influence of Creq/Nieq ratio on the microstructural changes and mechanical behaviour of 316L SS joints. They observed that higher Creq/Nieq ratios significantly affected the microstructure of AISI 316L joints. Shojaati and Beidokhti [8] also studied how different filler metals (ER 310, ER 316L, duplex ER 2209 and Ni-based Nichrome 80/20 filler metals) influenced the microstructural and mechanical characteristics of dissimilar AISI 304/AISI 409 SS joints. They reported that austenite with different morphologies of ferrite such as lathy, acicular and vermicular were observed in the case of 310 and 316L austenitic filler metals. A mixture of austenite and ferrite phases was seen in the microstructure obtained with the duplex filler metal. Ferrite and Widmanstätten austenite were higher in the regions next to the weld interface owing to the faster cooling here and, thus, the incomplete transformation. The joint obtained using the Ni-based weld metal displayed a microstructure consisting of a Ni-Cr-Fe matrix and Fe-based precipitates in the FZ. Furthermore, the formation of a thin layer of martensite in this joint resulted in the fusion line cracking. It was also reported that the high content of δ -ferrite in the microstructure of FZ increased the hardness and tensile strength values.

As already mentioned fully ASSs are prone to hot cracking in fusion welding. In general, it is recommended that the delta-ferrite (δ -ferrite) content in the FZ should be kept in the range of 3-10% to prevent hot cracking problem [5]. Higher amounts of delta ferrite make the FZ more sensitive to high temperatures because of the phase transformation [5,9]. Dadfar et al. [10] studied the corrosion behavior of autogenous Gas Tungsten Arc (GTA) welded AISI 316L joints and observed that the solution heat treatment enhances the corrosion resistance of the as-welded AISI 316L joint. Muthupandi et al. [11] studied the welding of super duplex stainless steels. They concluded that the heat input used should be kept as low as possible. Moreover, they claimed that higher heat inputs might also lead to the precipitation of undesirable brittle phases such as σ (sigma) or χ (chi).

Heat input is of great importance in joining of austenitic stainless steels as already pointed out in the preceding paragraph. The solid state friction stir welding technique, which is originally developed for difficult-to-fusion join low melting temperature Al-alloys [12-20] as well as Cu-alloys [21-23] and Pb [24], offers a potential to join steels including stainless steels [25,26]. Additionally, low heat input CMT arc welding method [13,27] or power beam welding techniques such as laser or electron beam welding [28-33] may also be used in joining of these steels. Due to this fact, numerous studies have been conducted on FSW of steels including stainless steels in last 30 years [26,27,34-41]. However, wear of the stirring tool is still a problem to overcome in FSW of steels since the peak temperature involved may reach over 1000 °C, and even the tools made of high temperature resistant materials may wear slowly over the time.

In this study, the influence of heat input applied to the AISI 304 plates on the microstructural evolution in the joint area and on joint properties was investigated. For this purpose, AISI 304 plates with a thickness of 5 mm were joined by gas metal arc welding (GMAW) using a filler wire of 308 with a diameter of 1.2 mm. Detailed microstructural investigations were conducted for microstructural characterization of the joints. Extensive microhardness measurements in addition to the mechanical testing were conducted to determine the joint properties. Moreover, the effect of heat input on the microstructural changes taking place in the weld region and thus on the joint performance was evaluated.

2. MATERIALS AND METHOD

The material used in this study is AISI 304 grade austenitic stainless steel plates of 5 mm thick. It was supplied in the form of large plate with the sizes of 1500x1000x5 mm³. Its chemical composition is given in Table 1.

Table 1. Chemical composition of AISI 304 grade austenitic steel plates used in this study.

Material	Chemical Composition (wt. %)									
	C	Si	Mn	P	S	Cr	Ni	N	Mo	Cu
Base Material (AISI 304)	0,019	0,42	1,56	0,035	0,002	18,2	8,1	0,053	--	--
Filler Material (ER308LSi)	0,025	0,804	1,95	0,010	0,023	20,016	9,966	0,035	0,181	0,287

The as-received 304 large plate was cut into the rectangular pieces of 250x190 mm and welding grooves were machined as shown schematically in Fig. 1, for welding trials. The surfaces to be welded were cleaned mechanically using a stainless steel metal brush prior to joining. The plates were welded by GMAW process with the use of an ER308LSi filler wire of 1,2 mm in diameter (the chemical composition of which is given in Table 1), the feeding rate was 17,5 mm/s, in two passes. The weld parameters employed in welding trials were given in Table 2. Two different heat inputs were employed in order to determine the effect of heat input on joint quality.

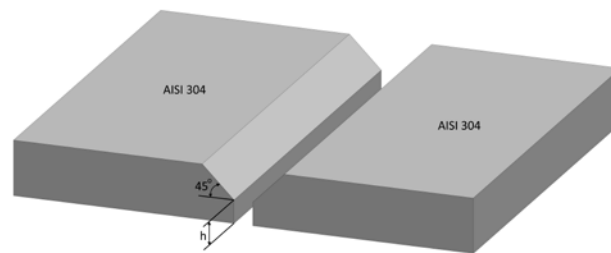


Figure 1. Preparation of the plates for welding trials.

Table 2. The weld parameters employed in welding trials (the same weld parameters were used in each pass in both welding trials).

Weld Trial	Current (A)	Voltage (V)	Weld speed (mm/s)	Wire feed rate (mm/s)	Shielding gas
Low Heat Input	ave. 385	28	4,5	17,5	Argon (99,95%)
High Heat Input	ave. 465	27	4,0	17,5	Argon (99,95%)

Following the welding trials, a metallography specimen, two bend specimens and four tensile specimens were prepared for each joint to investigate the microstructural evolutions in the weld regions of the joints and their mechanical properties. Four tensile specimens were also extracted from the base plate for comparison purpose. The metallography specimens were first ground and then polished prior to etching procedure in which the specimens were immersed in an etchant comprising of 50 ml HCl and 150 ml HNO₃ for about 15 seconds. A detailed microstructural investigation was conducted on these metallography specimens as well as microhardness measurements. Microhardness measurements were conducted on each joint along three lines across the weld region, one being almost in the center, the other two lines lying 1 mm from the surface and root of the joints, using a load of 500 g, as schematically illustrated in Fig. 2.

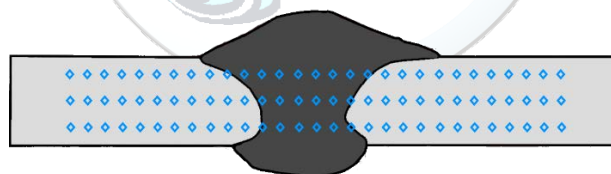


Figure 2. Schematic illustration of the conduction of microhardness measurements on each joint along three lines across the weld region, one being almost in the center, the other two lines lying 1 mm from the surface and root of the joints.

Transverse tensile specimens of the BM and the joints were also tested with a loading rate of 15 mm.min⁻¹ in order to evaluate the joint performance values and the weld qualities. In addition, the two bend specimens extracted from each joint for bend testing (180 degrees). One of them was bent in the condition of surface bend and the other in the root bend configuration and the weld center in the middle position in order to determine whether cracking occurs in the weld region or not. Furthermore, an attempt was made to determine the effect of heat input on the microstructural evolution in the HAZ and thus on weld quality and performance.

3. RESULTS AND DISCUSSION

The results obtained from this study will be discussed in two subsections, namely microstructural aspects and mechanical properties, below.

3.1. Microstructural Aspects

The macrographs illustrating the weld cross-sections of the joints produced using low and high heat inputs, respectively, are given in Figure 3. Figure 4 shows micrographs illustrating the base plate microstructure and the microstructures evolved in the FZs and HAZs of the joints produced. As seen from the micrographs, the AISI 304 grade austenitic base plate has a single phase microstructure consisting of austenite grains. Both joints showed a similar microstructural evolution within the weld region. A fine dendritic structure is observed in the FZ of both joints (Fig. 4b and c), which is very usual for this steel. No visible difference was observed between the FZ structures of both joints. Thus, there is no clear effect of heat input difference used.

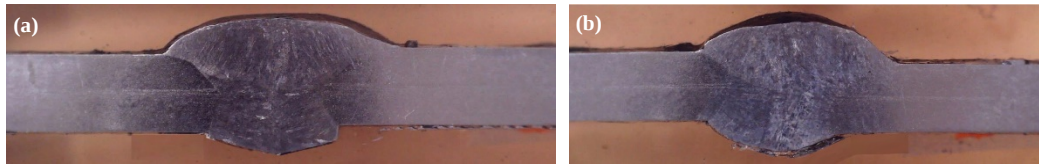


Figure 3. The macrographs illustrating the weld cross-sections of the joints produced: (a) the lower heat input joint and (b) the higher heat input joint.

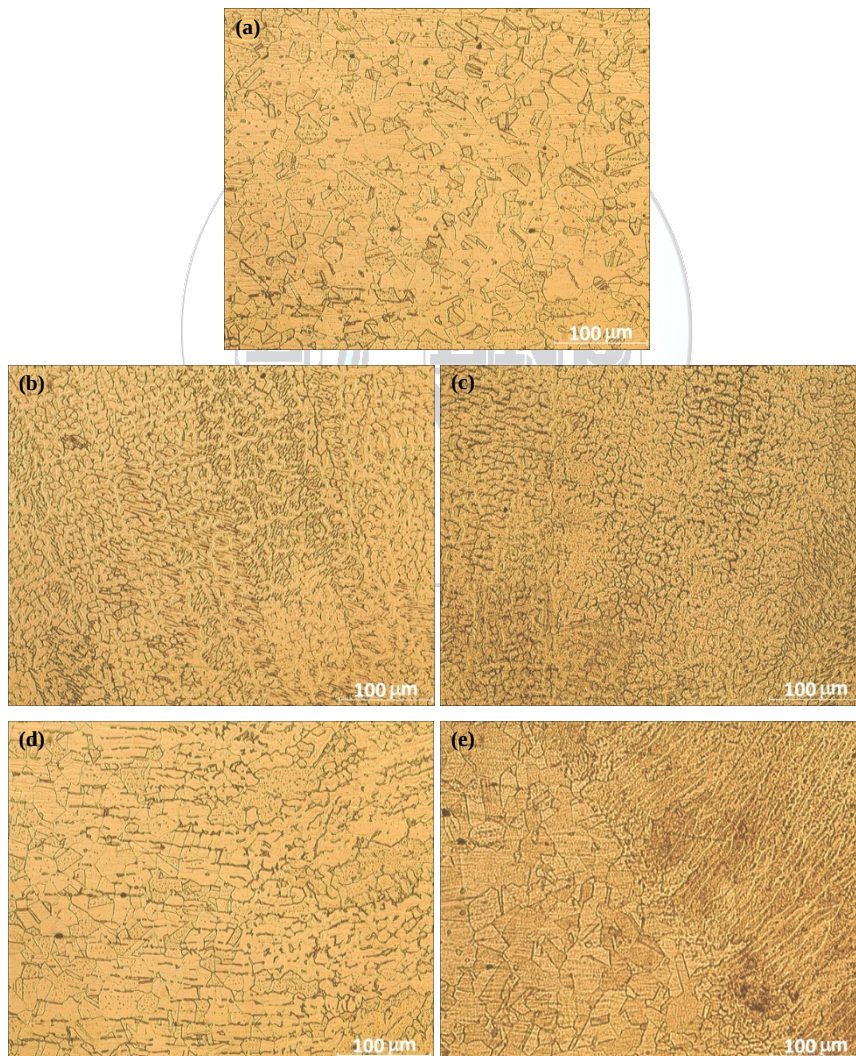


Figure 4. The micrographs illustrating the microstructures of: (a) base plate, (b) FZ of the lower heat input joint, (c) FZ of the higher heat input joint, (d) HAZ of the lower heat input joint and (e) HAZ of the higher heat input joint.

However, there is a clear difference between the microstructures evolving in the HAZs of two joints produced using different heat inputs. As seen from Figure 4(e), larger recrystallized grains of austenite phase were formed in the HAZ of the higher heat input joint. On the other hand, austenite grain size in the HAZ of the lower heat input joint is similar to that of the BM and finer compared to that of HAZ of the higher heat input joint. There are also some precipitates within the HAZ of the low heat input joint elongated in the cold rolling direction (Fig. 4d), indicating that a complete recrystallization did not occur due to lower input involved. Moreover, the fusion interface is more visible in the high heat input joint as a result of grain growth to a larger extent taking place in this joint due to the recrystallization occurring at higher temperatures compared to the lower heat input joint. In addition, there is no indication of chromium carbide precipitation within the HAZ of the higher heat input joint in contrast to the lower heat input joint as seen from Fig. 4(e).

3.2. Mechanical Properties

Figure 5 gives the hardness profiles obtained from the microhardness measurements conducted along three lines across the joints produced using low and high heat inputs. These hardness profiles show the hardness variations across the joints. As clearly seen from these profiles both joints exhibited similar hardness values across the weld region. The hardness profiles clearly show that there is neither a hardness increase (strength overmatching) nor hardness decrease (strength undermatching) in the weld region for both joints. Thus, both joints display a typical hardness profile of strength evenmatching joints. Furthermore, no significant hardness variation was observed across the weld area for both joints, indicating that the heat input variation used has no significant effect on hardness although a grain growth was detected in the high heat input joint. This implies that the slight grain growth in the HAZ of the high heat input joint does not significantly vary the hardness of this region.

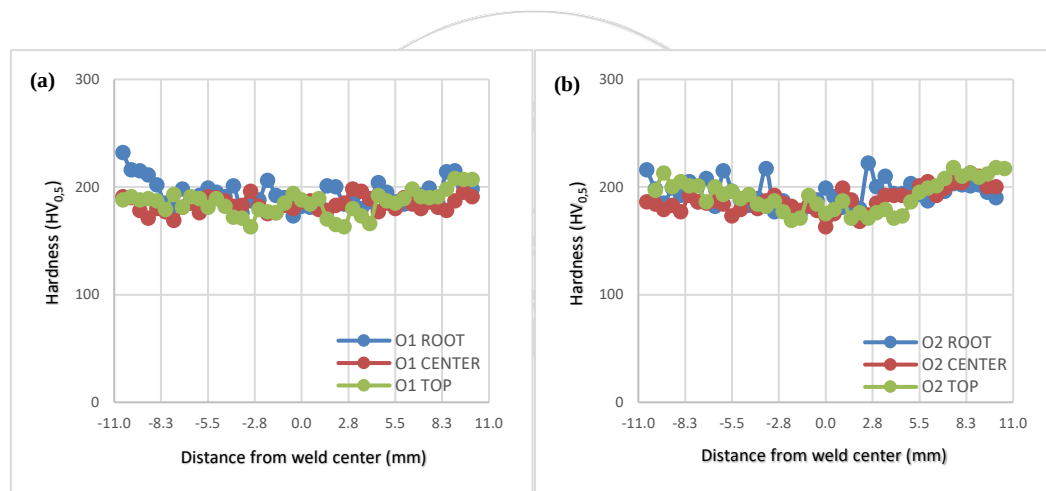


Figure 5. Hardness profiles showing the hardness variation across the joints: (a) lower and (b) the higher heat input joints.

Tensile test results obtained from the specimens prepared from the BM and the joints produced using low and high heat inputs are summarized in Table 3 and Figures 6 and 7. The AISI 304 base plate used in this study displayed a yield stress, tensile strength and elongation of 361 MPa, 636 MPa and about 48%, respectively. As clearly seen from the Table and Figures, both joints exhibited similar tensile properties to those of the BM, indicating that the performance of both joints are reasonably good. Indeed, the both joints exhibited similar tensile strength performance and ductility performance values of about 102% and 80%, respectively, indicating that the heat input variation employed in the current study does not have a significant influence on the joint performance. This results are quite reasonable since the joints did not display any weld defect and the hardness is more or less homogeneous across the joints. Figure 8 shows the fracture locations in all the tensile test specimens extracted from both lower and higher heat inputs joints after testing. As seen from this figure, all the specimens fractured in the base plate far away from the FZ. This clearly demonstrates that the weld quality, thus the joint performance, of both joints is quite good in tensile test condition.

Similar to the case in tensile testing, the heat input variation employed in this study did not have a significant effect on the joint behavior in bend testing. No cracking occurred in both surface and root bend specimens extracted from both joints (namely the lower and heat input joints) as shown in Figure 9. These results indicate that the heat input difference used in this study apparently did not have any diminishing effect on the weld

performance in bending condition despite the presence of some carbide precipitates in the HAZ region next to the fusion line of the joint obtained using lower heat input (Fig. 4d).

Table 3. Tensile test results.

Specimen	$R_{p0.2}$ (MPa)	R_m (MPa)	Elongation (%)	Strength Performance (%)	Ductility Performance (%)	Failure Location
Base Plate	366, 358, 359 (361)	643, 631, 633 (636)	48, 48, 49 (48)	----	----	--
Low Heat Input Joint	357, 374, 376, 362 (367)	650, 653, 649, 652 (651)	39, 38, 40, 40 (39)	102	81	Base plate
High Heat Input Joint	349, 366, 353 (356)	631, 648, 641 (640)	38, 38, 40 (38)	101	79	Base plate

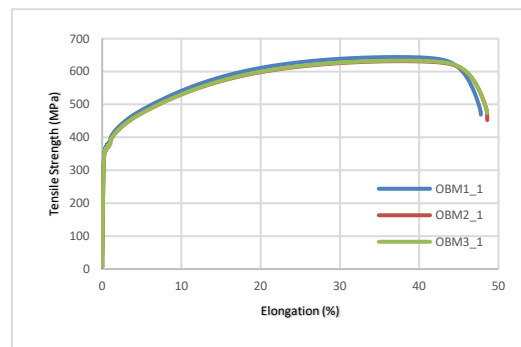


Figure 6. Stress-elongation (%) curve of the base plate AISI 304 steel used.

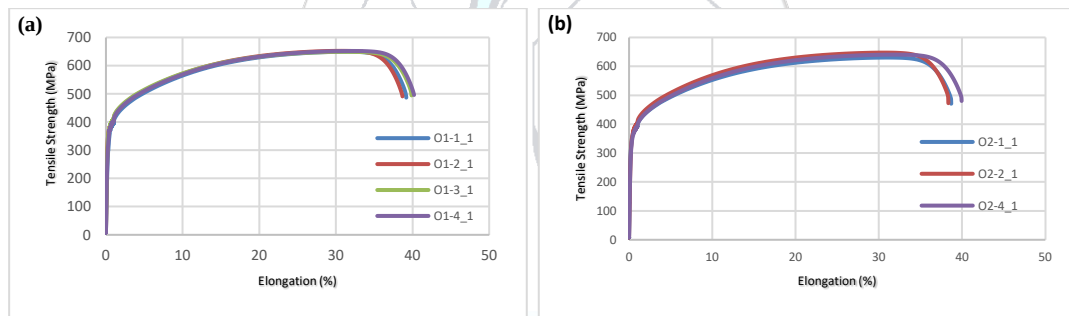


Figure 7. Stress-elongation (%) curves of the joints: (a) lower and (b) higher heat input joints.

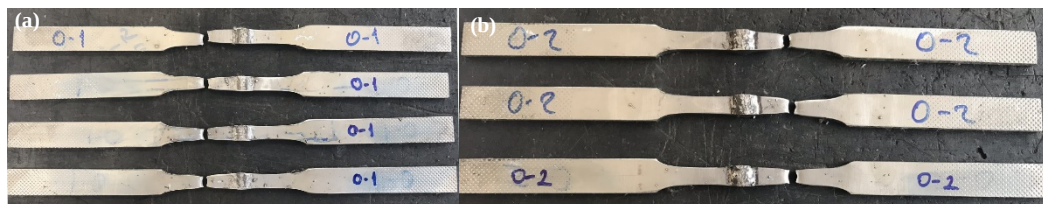


Figure 8. Macrographs showing the fracture locations in the tensile test specimens extracted from: (a) lower and (b) higher heat input joints.

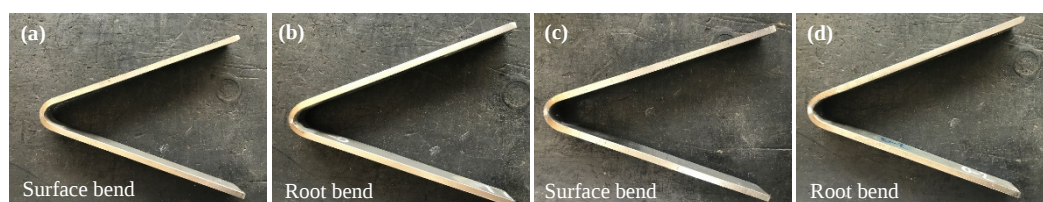


Figure 9. Macrographs showing the surface and root bend specimens, respectively, extracted from: (a) and (b) lower; and (c) and (d) higher heat input joints. Note that no cracking occurred in any of the specimens.

4. CONCLUSIONS

The influence of heat input experienced by the plates during welding on the microstructural evolution in the joint area and on joint properties was investigated for GMAW welded 5 mm thick AISI 304 plates using a filler wire of ER308 with a diameter of 1.2 mm. The following conclusions were withdrawn from this study:

- AISI 304 plates were defect-free welded in two passes by the GMAW process.
- A fine dendritic microstructure was obtained in the FZs of both joints.
- Some precipitates within the HAZ of the low heat input joint elongated in the cold rolling direction were observed while in the HAZ of the higher heat input joint larger recrystallized grains of austenite phase were formed but no carbide precipitates were observed.
- All the tensile test specimens prepared from both joints fractured in the BM far away from the FZ.
- Both joints exhibited similar mechanical properties (strength and ductility) to those of the base plate. Indeed, both joints displayed high tensile strength performance and ductility performance values of over 100% and about 80%, respectively.
- Both surface and root bend specimens extracted from both joints did not crack in bending test, indicating that the heat input variation employed in the current study does not have a significant influence on the joint performance.

ACKNOWLEDGMENT

We would like to thank Mr. Sedat UYSAL and Tuğrul YAZGAN from NOKSEL Çelik Boru Sanayi A.Ş. (Noksel Steel Pipe Inc.), İskenderun-Hatay, Turkey, for their support in conduction of the metallography and mechanical tests. The authors also thank Hikmet Gizem SARSILMAZ from Kahraman-Sarsılmaz Machinery, İskenderun, for conducting welds.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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