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Influence of Welding Process and Electrode Material on the Corrosion Characteristics of AISI 304 and AISI 316 Weldments

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Abstract. : In the present investigation, the microstructural characteristics, hardness and corrosion resistance of welded AISI 304 and AISI 316 austenitic stainless steels plates were investigated. Both AISI 304 and AISI 316 SS plates were joined using shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) techniques by different electrodes. The results revealed that for AISI304 stainless steels SMAW joints, the fusion zones (FZs) welded using E308L-16 electrode exhibited slightly higher corrosion rate when compared with those welded using E312-17 electrode. For GTAW, fusion zones welded using ER308L electrode exhibited slightly higher corrosion rate when compared with those welded using ER312 electrode. Moreover, the SMAW welded regions exhibited higher corrosion rates when compared with those welded using GTAW. For AISI 316 SMAW joints, the fusion zones welded using E312-17 electrode exhibited significantly higher corrosion rate when compared with fusion zones welded using E316L-16 electrode. Moreover, for GTAW, fusion zones welded using ER316L electrode exhibited slightly higher corrosion rate when compared with fusion zones welded using ER312 electrode.

Keywords Stainless steel, AISI 304, AISI 316, SMAW, GTAW,Corrosion.

1. INTRODUCTION

Stainless steels are Fe-based alloys that contain a minimum of 10.5% Chromium. The Chromium in the alloy procedures a self-healing protective clear oxide layer which gives stainless steels their corrosion resistance [1]. Although the corrosion resistance of stainless steels comes from the presence of Chromium, other elements such as Mo, V, Mn are added to improve the other properties such as the mechanical characteristics and weldability. These elements alter the microstructure of the stainless steels. The stainless-steel alloys are classified into five groups according to their microstructure, namely, austenitic stainless steels, ferritic stainless steels, duplex stainless steels, martensitic stainless steels and precipitation hardening stainless steels [2].

Austenitic stainless steels are the most important known stainless steels alloys. They contain a minimum of 16% Cr and 6% Ni. They are widely used in several industries such as in the chemical, fertilizer, textile, food processing, pharmaceutical, power and nuclear industries. Austenitic stainless steels have the combination of high mechanical characteristics, corrosion resistance as well as good weldability [3]. There are two subgroups of austenitic stainless steel, namely, 200 series and 300 series. The 300 series stainless steels are the larger subgroup. They include alloys such as 304, 316, 303, 321 …etc. In 300 series stainless steels achieve their austenitic structure mainly by the addition Ni.Stainless steels can be welded using several welding techniques, most commonly, gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), and plasma arc welding (PAW) as well as submerged arc welding (SAW). The selection of welding process as well as the filler materials play an important role in determining the metallurgical, mechanical and corrosion characteristics of stainless steels [4-6].

The present investigation represents a comparative study between the microstructural, mechanical and corrosion characteristics of AISI 304 and AISI 316 austenitic stainless-steel plates welded using manual SMAW and manual GTAW methods. Moreover, the influence of electrode material on the aforementioned characteristics were evaluated. In case of AISI 304 stainless steels, the plates were welded using SMAW and GTAW by two different electrodes, namely, AWS E308L-16 and E312-17 electrodes. While in case of 316 stainless steels, the plates were welded using E316L-16 and E312-17 electrodes.

2.EXPERIMENTAL PROCEDURES

In the present investigation, two types of austenitic stainless steels were used as base materials (BM), namely, AISI 304 and AISI 316 stainless steel alloys. The chemical compositions of these alloys are listed in Table 1 and Table 2, respectively. Both of the AISI 304 and AISI 316 stainless steels were obtained in the form of large hot rolled plates having 10 mm thickness. The plates were cut into smaller ones with dimensions of 50 mm (width)× 600 mm (length) × 10 mm (thickness).

Table 1. The chemical composition of AISI 304 stainless steel (wt.-%).

Base Alloy	**Elements (wt.-%)**							
	C	Si	Mn	P	S	Cr	Ni	Fe
AISI 304	0.06	0.42	1.89	0.032	0.014	18.67	8.53	Bal.

Table 2. The chemical composition of AISI 316 stainless steel (wt.-%).

Base Alloy	**Elements (wt.-%)**									
	C	Cu	Mo	Mn	Ni	Cr	Nb	W	V	Fe
AISI 316	0.08	0.31	2.07	1.32	10.42	16.49	0.02	0.05	0.10	Bal.

Before welding, the plates have been machined to get single V-groove with an angle of 60° as shown in Figure 1. Similar joints from AISI 304 and AISI 316 austenitic stainless steels plates (i.e. 304-304 and 316-316) were prepared to be welded using two different welding techniques, namely, SMAW and GTAW.

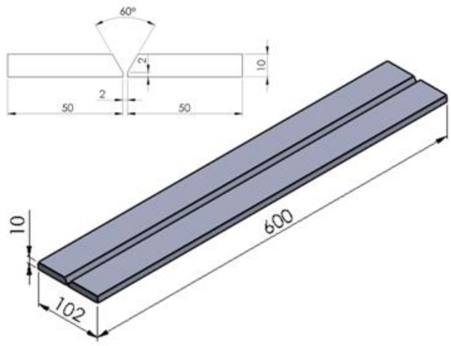

Fig 1. The welded joint configurations (dimensions in mm).

The 316 and 304 stainless steel plates were welded using SMAW and gas GTAW. The SMAW and GTAW process parameters as well as the filler materials used to weld the AISI 304 and AISI 316 stainless steels is listed Table 3 and Table4. The AWS E312-17, E316L-16 and E308L-16 filler materials used to weld the AISI 304 and AISI 316 stainless steels using SMAW process have a diameter of 3.2 mm. Table 5 lists the chemical compositions of these electrodes [7].The ER308L, ER312 and ER316L filler materials (tigrods) used to weld the AISI 304 and AISI 316 stainless steels using GTAW process have a diameter of 2.4 mm. Table 6 lists the chemical compositions of these filler materials [7].

Table 3. The welding conditions for AISI 304 stainless steel.

Base Metal	AISI 304			
Welding Method (Manual)	SMAW		GTAW	
Type of Filler Metal	E308L-16	E312-17	ER308L	ER312
Constant Voltage	30 Volts		38 Volts	
Constant Ampere	100 Ampere		210 Ampere	
Average Welding Speed	8 mm/sec		10 mm/sec	
Number of Passes	4 Passes		4 Passes	

Table4. The welding conditions for AISI 316 stainless steel.

Base Metal	AISI 316			
Welding Method (Manual)	SMAW		GTAW	
Type of Filler Metal	E316L-16	E312-17	ER316L	ER312
Constant Voltage	30 Volts		38 Volts	
Constant Ampere	115 Ampere		220 Ampere	
Average Welding Speed	8 mm/sec		10 mm/sec	
Number of Passes	4 Passes		4 Passes	

Table 5. The chemical compositions of filler materials used in SMAW process (wt.-%).

Filler Materials	Elements (wt.-%)										
	C	Si	P	S	Mn	Ni	Cr	Mo	Cu	N	Fe
E308L-16	0.03	0.78	0.02	0.01	0.7	9.7	19.4	0.02	0.03	-	Bal
E312-17	0.14	0.64	0.02	0.007	0.9	10.1	29.1	0.07	0.05	0.07	Bal.
E316L-16	0.02	0.61	0.03	0.01	0.6	11.6	18.6	2.8	0.05	-	Bal.

Table 6. The chemical compositions of filler materials used in GTAW process (wt.-%).

Filler Materials	Elements (wt.-%)										
	C	Si	P	S	Mn	Ni	Cr	Mo	Cu	N	Fe
ER308L	0.025	0.55	0.015	0.013	1.8	10.2	19.7	0.12	0.08	0.05	Bal.
ER312	0.09	0.37	0.02	<0.01	1.6	8.6	30.7	<0.1	<0.1	-	Bal.
ER316L	0.015	0.34	0.010	0.010	1.80	12.25	18.75	2.5	-	-	Bal.

All of the aforementioned electrodes used in GTAW and SMAW processes were received from ESAB, Egypt [40]. In the present investigation, the GTAW and SMAW process was carried out using (NEA, WSHE-315A, 2017, China).The microstructural examinations were carried out using optical metallurgical microscope. Finally, the polished specimens were subjected to etching in solution of 33% HCl, 33% HNO_3 and 34% H_2O for one minute according toASTM E407-07 [8].

The electrochemical corrosion experiments were carried out in a one-compartment cell with three electrodes connected to Autolab302N potentiostat /galvanostat workstation with NOVA 1.10 software. Conventional three electrodes configuration with platinum rod as a counter electrode, standard Ag/AgCl electrode as reference electrode, and the AISI 316 or AISI 304 stainless steels as working electrode (WE) were used. Before the experiments, the samples were cleaned in acetone and ethanol baths; the open circuit potential stabilized in a period of 15 min, and finally it was polarized by applying a scan rate of 10 $mV.s^{-1}$.

3.RESULTS AND DISCUSSION

3.1. Microstructural Investigations of AISI 304 Stainless Steel Welded Joints

Figures2 and 3 show the microstructure of the AISI 304 stainless steel SMAW welds, at the center of the FZ and HAZ, obtained using E308L-16 and E312-17 electrodes, respectively. Figures4 and 5 show the microstructure of the AISI 304 stainless steel GTAW welds, at the center of the FZ and HAZ, obtained using ER308L and ER312 electrodes, respectively. The center of the FZs, developed using GTAW, exhibit predominantly cellular primary austenitic grain structure (for example, see Figure 4a). While, the HAZ exhibited coarser grain structure when compared with the FZ (for example, compare Figure 5a and 5b). The FZs of SMAW weldments exhibited skeletal (vermicular) ferrite microstructure in an austenite matrix as shown in Figure 3.5a and 3.6a.

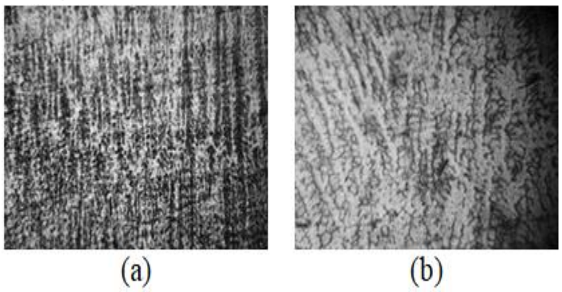

Fig 2. Microstructure of AISI 304 stainless steel region welded using E308L-16 electrode by SMAW; (a) the fusion zone and (b) the HAZ (10×).

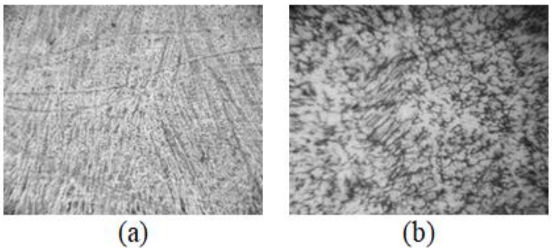

Fig 3. Microstructure of AISI 304 stainless steel region welded using E312-17 electrode by SMAW; (a) the fusion zone and (b) the HAZ (10 ×).

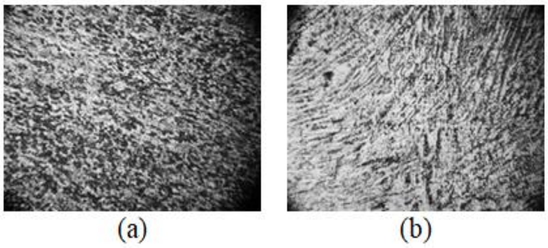

Fig 4. Microstructure of AISI 304 stainless steel region welded using ER308L electrode by GTAW; (a) the fusion zone and (b) the HAZ (10 ×).

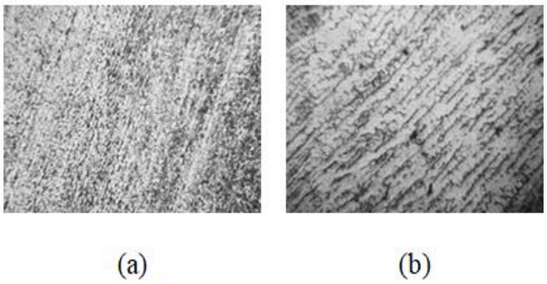

Fig 5. Microstructure of AISI 304 stainless steel region welded using ER312 electrode by GTAW; (a) the fusion zone and (b) the HAZ (10 ×).

3.2. Microstructural Investigations of AISI 316 Stainless Steel Welded Joints

Figure 6 and 7 show the microstructure of the AISI 316 stainless steel SMAW welds, at the center of the FZ and HAZ, obtained using E316L-16 and E312-17 electrodes, respectively. Figure 8 and 9 show the microstructure of the AISI 304 stainless steel GTAW welds, at the center of the FZ and HAZ, obtained using ER316L and ER312 electrodes, respectively. In the micrographs, dark-colored areas indicate δ-ferrite, while the light-colored regions indicate the γ-austenite phase.For GTAW joints, the microstructure of the FZs welded using ER316L and ER312 electrodes exhibited acicular ferrite microstructure in an austenite matrix as shown in Figure 8a and 9a. For SMAW joints welded using E316L-16 electrode, the FZ exhibited equiaxed grain structure (see Figure 6a). While joints those welded using E312-17 electrodes showed cellular austenitic grain structure (see Figure 7a).

The HAZ for GTAW and SMAW weldments showed different microstructural morphologies. The nature of the microstructure of the HAZ is determined by several factors, like the peak temperature of thermal cycling, heating rate, staying time at high temperature and the subsequent cooling speed [9]. For example, AISI 316 stainless steel GTAW joints welded using ER316L electrode showed coarse columnar grain structure (see Figure 8b). The microstructures in the FZs of GTAW and SMAW weldments are heterogeneous owing to the temperature gradient associated with the welding process, and the chemical gradient which is generated during that process.

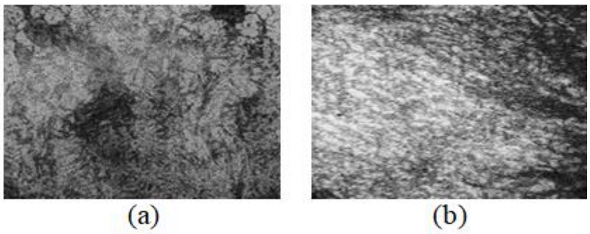

Fig 6. Microstructure of AISI 316 stainless steel region welded using E316L-16 electrode by SMAW; (a) the fusion zone and (b) the HAZ (10 ×).

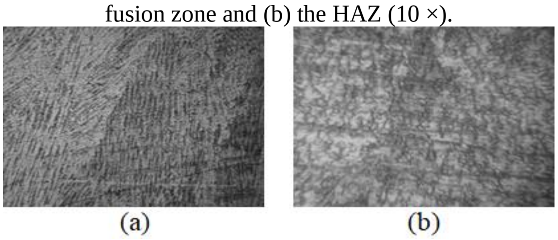

Fig 7. Microstructure of AISI 316 stainless steel region welded using E312-17 electrode by SMAW; (a) the fusion zone and (b) the HAZ (10 ×).

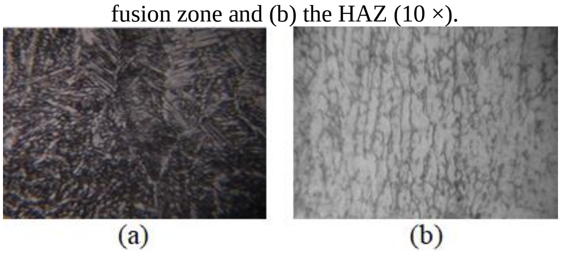

Fig 8. Microstructure of AISI 316 stainless steel region welded using ER316L electrode by GTAW; (a) the fusion zone and (b) the HAZ (10 ×).

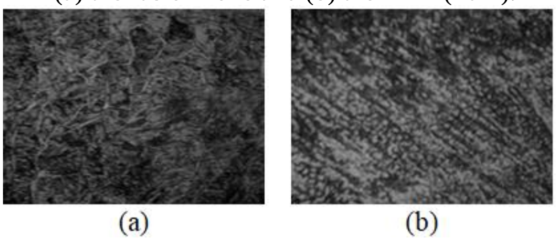

Fig 9. Microstructure of AISI 316 stainless steel region welded using ER312 electrode by GTAW; (a) the fusion zone and (b) the HAZ (10 ×).

3.3. Corrosion Resistance of AISI 304 Stainless Steel Welded Joints

The results revealed that the AISI 304 stainless steel base alloy exhibited a corrosion rate of 1.138 mm/year. The welded regions exhibited significantly lower corrosion rates when compared with the AISI 304 stainless steel base alloy. For GTAW, FZs welded using ER308L electrode exhibited slightly higher corrosion rate when compared with those welded using ER312 electrode. The FZs welded using ER308L and ER312 electrodes showed corrosion rates of 0.05411 and 0.04437 mm/year, respectively. Figure 10 shows the variation of the corrosion rate at the center of the fusion zone with the welding technique and electrode type for AISI 304 stainless steel welded joints. The results revealed that, the SMAW welded regions exhibited higher corrosion rates when compared with those welded using GTAW. The minimum corrosion rate of about 0.04437 mm/year was observed for regions welded using GTAW technique using ER312 electrode. While the maximum corrosion rate of about 0.1992 mm/year was observed for regions welded using SMAW technique using E308L-16 electrode.

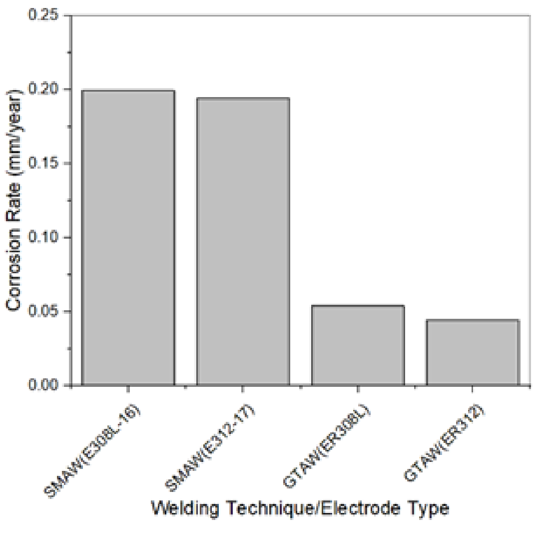

Fig 10. Variation of the corrosion rate at the center of the fusion zone with the welding technique and electrode type for AISI 304 stainless steel welded joints.

For SMAW, FZs welded using E308L-16 electrode exhibited slightly higher corrosion rate when compared with those welded using E312-17 electrode. The FZs welded using E308L-16 and E312-17 electrodes showed corrosion rates of 0.1992 and 0.1942 mm/year, respectively.

3.4. Corrosion Resistance of AISI 316 Stainless Steel Welded Joints

The results revealed that the AISI 316 stainless steel base alloy exhibited a corrosion rate of 0.0008158 mm/year. The welded regions exhibited significantly higher corrosion rates when compared with the AISI 316 stainless steel base alloy. For SMAW, FZs welded using E312-17electrode exhibited significantly higher corrosion rate when compared with FZs welded using E316L-16 electrode. The FZs welded using E316L-16 and E312-17 electrodes showed corrosion rates of 0.01912 and 0.07907 mm/year, respectively. Moreover, for GTAW, FZs welded using ER316L electrode exhibited slightly higher corrosion rate when compared with FZs welded using ER312 electrode. The FZs welded using ER316L and ER312 electrodes showed corrosion rates of 0.03546 and 0.03059 mm/year, respectively. Figure 11 shows the Variation of the corrosion rate at the center of the fusion zone with the welding technique and electrode type for AISI 316 stainless steel welded joints.

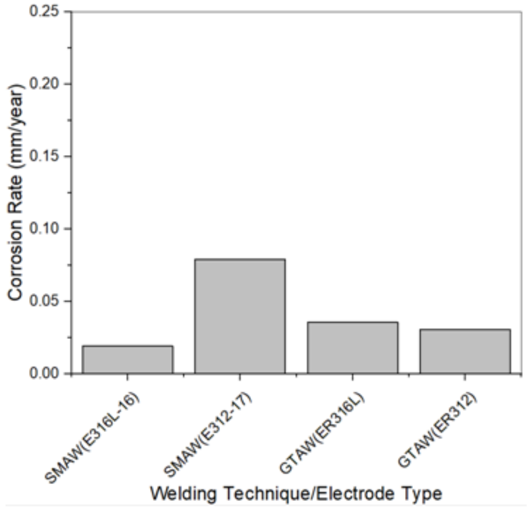

Fig 3.1. Variation of the corrosion rate at the center of the fusion zone with the welding technique and electrode type for AISI 316 stainless steel welded joints.

The minimum corrosion rate of about 0.01912 mm/year was observed for regions welded using SMAW technique using E316L-16 electrode. Moreover, the maximum corrosion rate of about 0.07907 mm/year was observed for regions welded using SMAW technique using E312-17 electrode.

4. CONCLUSIONS

1. The AISI 304 stainless steel welded regions exhibited significantly lower corrosion rates when compared with the base alloy. In contrast, the AISI 316 stainless steel welded regions exhibited significantly higher corrosion rates when compared with the base alloy.
2. For AISI304 stainless steels SMAW joints, the fusion zones welded using E308L-16 electrode exhibited slightly higher corrosion rate when compared with those welded using E312-17 electrode. For GTAW, fusion zones welded using ER308L electrode exhibited slightly higher corrosion rate when compared with those welded using ER312 electrode. Moreover, the SMAW welded regions exhibited higher corrosion rates when compared with those welded using GTAW.
3. For AISI 316 SMAW joints, the fusion zones welded using E312-17 electrode exhibited significantly higher corrosion rate when compared with FZs welded using E316L-16 electrode. Moreover, for GTAW, FZs welded using ER316L electrode exhibited slightly higher corrosion rate when compared with FZs welded using ER312 electrode.

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