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Weldability of Dissimilar 316L and A106 Steels with GTAW and SMAW Using 309L and Inconel 82 Electrodes

Esin Tuğba ŞİMŞEK ÇELİK[1*], Başar Ersegün ÇELİK[2], Şükrü TALAŞ[3]

[1] Sivas Cumhuriyet University, Hafik Kamer Ornek Vocational School of Higher Education, Department of Transportation Services, Rail Systems Management Program, Sivas, Türkiye
[2] Afyon Kocatepe University, Institute of Natural Sciences, Afyonkarahisar, Türkiye
[3] Afyon Kocatepe University, Faculty of Technology, Department of Metallurgical and Materials Engineering, Afyonkarahisar, Türkiye
Esin Tuğba ŞİMŞEK ÇELİK ORCID No: 0000-0003-2063-7802
Başar Ersegün ÇELİK ORCID No: 0000-0002-3015-2553
Şükrü TALAŞ ORCID No: 0000-0002-4721-0844

**Corresponding author: esimsek@cumhuriyet.edu.tr*

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GTAW,
SMAW

Abstract: The mechanical properties of steel welds of different compositions are affected by the mechanical properties of the filler wires used, and it is important for practitioners to analyze the results in situ without detailed metallographic studies. In this study, the joining of the material pair A 312 TP 316L stainless steel and A106 Gr.B carbon steel was investigated by Tungsten Inert Gas (TIG) and Shielded Metal Electrode Welding (SMAW) using different welding wires and different welding parameters. In the first welding process, A 312 TP 316L stainless steel and A106 Gr.B carbon steel materials were welded by GTAW (Gas Tungsten Arc Welding) method using 2.4 mm ER309L electrode for root and hot passes and by SMAW (Shielded Metal Arc Welding) method using 2.5 mm E309L-15 electrode for filler and cover passes. In the second welding process, A 312 TP 316L stainless steel and A106 Gr.B carbon steel materials were welded by GTAW method using 2.4 mm INCONEL 82 (ER NiCr-3) electrode for root and hot passes and by SMAW method using 2.5 mm INCONEL 182 (E NiCrFe-3) electrode for filler and cover passes. Tensile test, bending test, hardness test, PMI (Positive Material Identification) test carried out and macro images of the welded parts were taken and compared. As a result, the weldability of stainless and carbon steels with different filler metals and their effects on mechanical properties were investigated. The results show that welding with E309L stainless steel gives better results than welding with Inconel 182.

Benzer Olmayan 316L ve A106 Çeliklerin, GTAW ve SMAW ile 309L ve Inconel 82 Elektrotlar Kullanılarak Kaynaklanabilirliği

Anahtar Kelimeler
Kaynak Kabiliyeti,
Inconel Elektrotlar,
316L,
A106,
GTAW,
SMAW

Öz: Farklı bileşimlere sahip çelik kaynaklarının mekanik özellikleri, kullanılan dolgu tellerinin mekanik özelliklerinden etkilenmektedir ve uygulayıcılar için detaylı metalografik çalışmalar yapmadan sonuçları yerinde analiz etmek önemlidir. Bu çalışmada, A 312 TP 316L paslanmaz çelik ve A106 Gr.B karbon çeliği malzeme çiftinin birleştirilmesi, farklı kaynak telleri ve farklı kaynak parametreleri kullanılarak Tungsten İnert Gaz (TIG) ve Korumalı Metal Elektrot Kaynağı (SMAW) ile incelenmiştir. İlk kaynak işleminde, A 312 TP 316L paslanmaz çelik ve A106 Gr.B karbon çelik malzemeler kök ve sıcak pasolar için 2.4 mm ER309L elektrot kullanılarak GTAW (Gaz Tungsten Ark Kaynağı) yöntemiyle ve dolgu ve örtü pasoları için 2.5 mm E309L-15 elektrot kullanılarak SMAW (Korumalı Metal Ark Kaynağı) yöntemiyle kaynaklanmıştır. İkinci kaynak işleminde, A 312 TP 316L paslanmaz çelik ve A106 Gr.B karbon çelik malzemeler, kök ve sıcak pasolar için 2,4 mm INCONEL 82 (ER NiCr-3) elektrot kullanılarak GTAW yöntemiyle ve dolgu ve örtü pasoları için 2,5 mm INCONEL 182 (E NiCrFe-3) elektrot kullanılarak SMAW yöntemiyle kaynaklanmıştır. Çekme testi, eğme testi, sertlik testi, PMI (Positive Material Identification) testi yapılmıştır ve makro görüntüleri alınmış ve karşılaştırılmıştır. Sonuç olarak, paslanmaz ve karbon çeliklerin farklı dolgu metalleri ile kaynaklanabilirliği ve mekanik özellikler üzerindeki etkileri araştırılmıştır. Sonuçlar paslanmaz çelik E309L kullanılarak yapılan kaynakların Inconel 182 ile yapılan elektrodlara gore daha iyi sonuçlar verdiğini göstermektedir.

1. INTRODUCTION

Austenitic stainless steels (ASSs) are extensively employed due to their superior mechanical properties and excellent corrosion resistance [1,2]. The microstructure of ASSs is primarily influenced by alloying elements like Ni and Cr, which contribute to a fully-austenitic structure, ensuring weldability, strength at room and high temperatures, oxidation resistance, and corrosion resistance [3]. These steels are often preferred for the use in seawater and various chemical environments, but the choice of a specific steel grade with an appropriate chemical composition is crucial, depending on the environmental conditions [4-6]. A 312 TP 316L steels provide, among the most commonly used ASSs, significantly enhanced strength, creep resistance, and notably, corrosion resistance, especially in highly-corrosive settings such as chloride-containing environments, seawater, chemical environments, and sub-zero temperatures [6,7]. Carbon steel alloy pipes of grade A106-Gr.B are typically employed in power plants, boilers, oil and gas refineries, as well as in ship manufacturing applications, under conditions of elevated pressures and temperatures. In the petroleum refineries, these steel pipelines play a crucial role in conveying gas, oil, and their derivatives from the production area to local markets or for export [12]. Fusion welding of A 312 TP 316L and A106 Gr.B is essential due to its widespread applications across various industries. Several fusion welding processes, including Gas Tungsten Arc Welding (GTAW) [8,9], Shielded Metal Arc Welding (SMAW) [10] have been utilized for fabricating A 312 TP 316L joints and A106 Gr.B joints. The mechanical properties and corrosion resistance of these joints are influenced by the chemical composition and solidification of the weld metal during fusion welding processes [8-11]. SMAW is a metal joining process that holds a predominant position in small-scale industries and remains extensively employed in domestic, maintenance, fabrication, and offshore applications [13], which can efficiently operate with both alternating and direct current power sources, depending on specific requirements [14,15]. On the other hand, GTAW process is an electric arc welding technique that utilizes non-consumable tungsten electrodes with filler metal is introduced through a separate filler rod using commonly used shielding gases that include argon, helium, nitrogen, hydrogen, or a mixture thereof [16]. In their study, Pahlawan et al. [17] analyzed the effect of the welding electrode on the tensile strength, macrostructure and microstructure of steel ST41 and 316L stainless steel weld metal. The two electrode types used in the study were E309-L and E6013 with SMAW process. Tensile test results showed that the welding process produced the maximum tensile strength greater than the parent material strength level. It has been found that welding with E6013 tends to have a lower corrosion resistance. In their study, Sirohi et al. [18] prepared a different welded joint from Inconel 718 and 304L austenitic stainless steel using a combined procedure with GTAW and SMAW processes using Ni-based fillers: ERNiCr-3 and ENiCrFe-3. Welded joints were investigated in terms of metallographic tests and mechanical properties, and a relationship between the microstructure and the resulting mechanical properties was established. Room temperature tensile test results showed that damage to the weld metal could result from the partition of alloying elements along the dendritic gaps. It was observed that the impact resistance of the weld metal was quite low compared to the base metals, and it was thought that this may be due to the formation of the NbC phase along the dendritic gaps. Ni-based super alloy Inconel 625 and stainless steel AISI 304L base materials were joined by TIG (Tungsten Inert Gas) method using ER310 and ERNiCrMo3 filler metals Tümer & Kerimak [19]. Due to Ni content of filler metals, all notch impact test samples displayed ductile nature after fracture. Additionally, ERNiCrMo3 filler metal displayed improved notch impact toughness results in comparison to other filler metals.

In this study, two separate welding processes were used to investigate the compatibility of Inconel 82/Inconel 182 and 309L filler metals for joining 316L and A106 carbon steels, and to observe whether sufficient mechanical properties were provided by dissimilar welds deposited by two different welding processes. Tensile tests, hardness tests, bend tests and PMI tests were carried out on the welds and their effects on weld quality were discussed.

2. MATERIAL AND METHOD

2.1. Preparation and Assembly of Test Samples for Welding Process

It is well known that increasing the carbon content of steel leads to reduced weldability due to cracking as a result of thermal stresses and the presence of hard phases such as martensite during the cooling stage. However, the situation becomes more complicated when ferrite-promoting alloying elements such as Cr are introduced during welding; the weld metal is at risk of containing carbides, reducing the mechanical properties of the weld metal. To prevent the formation of chromium carbides, Ni-containing alloys are effectively used, as was the idea behind this research. The chemical composition of the 7.11 mm thick 316L stainless steel and A106 Gr.B carbon steel used in this study is shown in Table 1. In the first welding process, A 312 TP 316L and A106 Gr.B materials were joined by GTAW method using 2.4 mm ER309L electrode, and SMAW method using 2.5 mm E309L-15 electrode. The first welding process was given the code W-309. In the second welding process, A 312 TP 316L and A106 Gr.B materials were joined by GTAW process using 2.4 mm INCONEL 82 (ER NiCr-3) electrode, and SMAW welding method using 2.5 mm INCONEL 182 (E NiCrFe-3) electrode. The second welding process was given the code of W-INC.

The base metal, electrodes, welding processes and passes used in the W-309 coded welding process and W-INC coded welding process are shown in Figure 1. The chemical compositions of the electrodes are given in Table 2.

In the W-309 coded welding process, root pass and hot pass were made by the GTAW method, filler pass and two cover passes were made by the SMAW method, whereas in the W-INC coded welding process, the root pass and the hot pass were made by the GTAW method and filler pass and two cover passes were made by the SMAW method. The weld groove and weld passes for the W-309 and W-INC coded welding process are shown in Figure 2.

The design of weld passes, operating parameters of weld deposition i.e. the welding current and voltage, weld/electrode travel speed and the total heat input values of the W-309 and W-INC welding processes are given in Table 3 and Table 4.

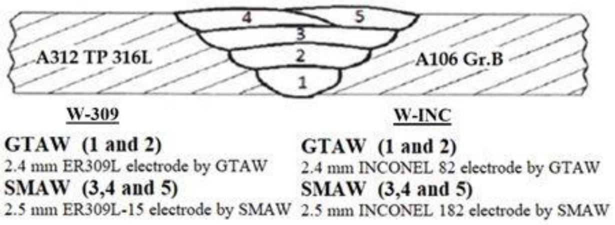

Figure 1. Base metals, electrodes, welding methods and welding passes used in W-309 and W-INC coded welding processes

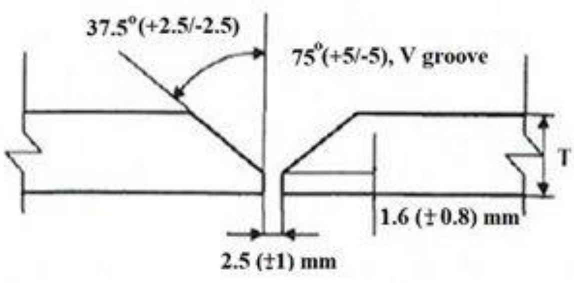

Figure 2. Weld groove measurements

Table 1. Chemical compositions of A 312 TP 316L and A106 Gr.B base metals (Fe: Bal. and in wt. %)

	C	Si	Mn	P	S	Cr	V	Mo	Ni	Cu	B	Nb	Ti	N
A106 Gr B	0.12	0.27	1.07	0.012	0.003	0.03	0.01	0.01	0.03	0.04	0.0004	0.001	0.02	-
316L	0.013	0.38	1.41	0.026	0.001	16.75	-	2.11	11.4	0.36	-	-	-	0.065

Table 2. Chemical compositions of the electrodes (wt. %)

	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Nb	Ti	Fe
ER309LSİ	0.01	0.7	2	0.01	0.01	23	0.13	13.9	0.1	-	-	-
E309L-15	0.04	0.34	2.1	0.013	0.003	23.5	0.17	13	0.05	-	-	-
ERNiCr-3 (INCONEL 82)	0.03	0.08	3.1	0.01	0.001	20.1	-	72.3	0.01	2.4	0.3	1.3
ENiCrFe-3 (INCONEL 182)	0.04	0.8	5.8	0.01	0.014	16	-	69.2	-	1.8	0.1	5.9

Table 3. Weld passes, weld current, weld voltage, weld/electrode travel speed and overall heat input values in the W-309 coded welding process

Weld Layers	Welding Process	Class	Diameter (mm)	Polarity	Weld Current Range (A)	Weld Voltage Range (V)	Travel Speed (mm min^{-1})	Heat input (KJ mm^{-1})
Root	GTAW	ER309L	2.40	DC(-)	107-111	10-12	36.00	2.22
Hot	GTAW	ER309L	2.40	DC(-)	145-150	11-13	87.00	1.34
Fill	SMAW	ER309L-15	2.50	DC(+)	70-75	24-26	84.00	1.39
Cover	SMAW	ER309L-15	2.50	DC(+)	85-90	22-23	94.00	1.32
Cover	SMAW	ER309L-15	2.50	DC(+)	85-90	22-23	93.00	1.33

Table 4. Weld passes, weld current, weld voltage, weld/electrode travel speed and overall heat input values in the W-INC coded welding process

Weld Layers	Process	Class	Diameter (mm)	Polarity	Weld Current Range (A)	Weld Voltage Range (V)	Travel Speed (mm min^{-1})	Heat input (KJ mm^{-1})
Root	GTAW	INCONEL 82	2.40	DC(-)	100-110	10-11	32.64	2.02
Hot	GTAW	INCONEL 82	2.40	DC(-)	150-160	13-14	77.63	1.61
Fill	SMAW	INCONEL 182	3.25	DC(+)	90-95	19-20	110.48	0.97
Cover	SMAW	INCONEL 182	3.25	DC(+)	80-85	18-19	114.90	0.79
Cover	SMAW	INCONEL 182	3.25	DC(+)	80-85	18-19	112.65	0.81

During the execution of GTAW, pure argon gas was used as shielding gas with flow rate of 12-16 lt min-1. ESAB

TIG 3001i make and model welding machine was used for GTAW passes.

2.2. Mechanical and Hardness Tests Applied to Welded Parts

Mechanical tests, i.e. tensile test (DIN EN ISO 6892-1), bending (ASTM E290) and hardness tests were performed on welded parts and macro images were taken after metallographic preparation. In addition, PMI (Positive Material Identification) tests were also carried out. The hardness tests were carried out using Qness brand hardness tester device with a setting of HV10 (10kgf) using Vickers tip. Instron-5989 was used as the tensile test device and a cross-head speed of 3 mm min-1 was used. In the bending tests, 4 bending test specimens (BT) from the W-309 and the W-INC coded welding processes were used. The parameters and conditions employed in the bending tests are given in Table 5.

Table 5. Parameters used for bending test

Sample	Distance Between Rollers (mm)	Diameter of Mandrel (mm)	Bending Angle
W-309-BT1	51	30	180°
W-309-BT2			
W-309-BT3			
W-309-BT4			
W-INC-BT1			
W-INC-BT2			
W-INC-BT3			
W-INC-BT4			

Hardness values were obtained from welds coded with W-309 and the W-INC welding process, on 15 points along the line for the cover pass and at 15 points along the line for the root pass.

3. RESULTS AND DISCUSSION

3.1. Microhardness Test Results

The microhardness distribution values for the W-309 coded weld are shown in Figure 3 and the hardness distribution values for the W-INC coded weld are shown in Figure 4. Microhardness values were obtained from the W-309 and W-INC coded welds at 15 points along the cover pass line and 15 points along the root pass line. The distribution of 15 points taken from the root and cover pass is as follows. Hardness measurement points 1, 2, 3 are from 316 stainless steel base material; points numbered 4, 5, 6 are from 316 stainless steel HAZ (Heat Affected Zone), points numbered 7, 8, 9 are from weld filler metal; points 10, 11, 12 are taken from A 106 Gr.B carbon steel HAZ and points 13, 14, 15 are taken from A 106 Gr.B carbon steel base material.

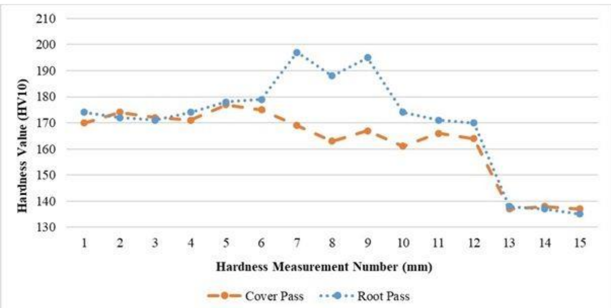

Figure 3. Hardness distribution for base metals, heat affected zones and weld metal in W-309 series

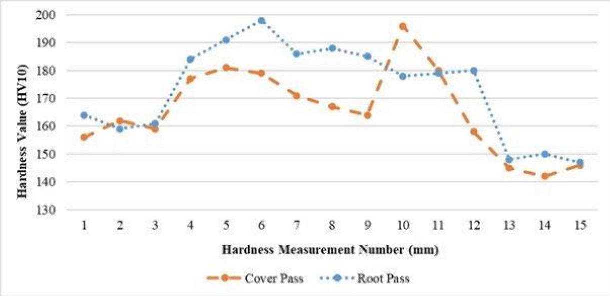

Figure 4. Hardness distribution for base metals, heat affected zones and weld metal of W-INC series

Figures 3 and Figure 4 show the microhardness values for the cover pass and root pass for W-309 and W-INC coded welds, respectively; it can be seen that the average root pass microhardness value is higher than the average cover pass microhardness value in the weld metal. The lowest hardness value is 135HV measured in the A106 Gr.B base metal zone and the highest hardness value is 197HV, which is the value in the root pass weld metal zone. Considering the average hardness values, the average hardness values for the W-INC coded welds are slightly higher. Although the base metals and number of passes are the same for both welding processes, the electrodes used are different. For W-INC, welding using INCONEL 82 (ER NiCr-3) and INCONEL 182 (E NiCrFe-3) electrodes produced higher hardness than welding with ER309L and E309L-15 electrodes. It can be assumed that the reason for such variation could be related to the matrix hardness, which caused such a small variation in hardness despite the fact that the root weld metal contains less Si. Higher Si content increases the strength and hardness of stainless steels. Si addition leads to the formation of high amount of γ phase precipitated in eutectic nodules and significantly promotes a Mo(Ni,Si)2 Laves phase in the alloys containing Mo [20,21]. Interestingly, the W-309 welds should contain a higher amount of Si, but the effect is not obviously observed as their hardness is lower on average, which may be due to Si loss or weld tempering and redistribution of elements during high heat input deposition of the cover pass. However, the W-INC series also suffers from the same effect, so it can be argued that the top layer depositions are inherently less hard due to factors such as highly tempered and reduced microstructural content and also internal stresses. The root passes and other passes are always tempered with the subsequent weld pass deposited on top of each other and therefore the grain sizes in the heat affected zone and the weld zone can be altered to a limited extent due to the heat input effect both in the base metal and in the vicinity of the weld zone [22]. The root pass weld is also annealed with the hot pass weld, but the stress development may not be as effective for surface-facing passes such as root welds, which may result in higher residual stresses in the weld and higher microhardness results. Another factor by which the hardness may increase is that the formation of intermetallics in superalloy welds [23,24], however, it is not always desirable to have intermetallics phases as they may lead to the formation of stresses leading to cracks or resulting in the excessive hardness of matrix [25,26]. In Figure 4, the cover pass and root pass hardness values are given for the W-INC coded welding joint, and it is seen that the root pass hardness value has a slightly higher hardness than the cover pass hardness value in the weld filler. The highest hardness value is 198HV, which is the Heat Affected Zone value of the root pass. The presence of higher amounts of Ni, Cr and Mo in electrode for root weld may have led to the formation of harder phases which may have increased the hardness of this zone. The lowest hardness value is 147HV in the A106 Gr.B base metal region.

3.2. Macro Image Interpretation and PMI Test Results

The macro images of the W-309 coded and the W-INC coded welding processes are shown in Figure 5a and b. It was determined that the welding method coded W-309 which involves the electrodes of ER309L and E309L-15 that are frequently used in the industrial applications in the joining of A 312 TP 316L and A106 Gr.B materials have good weld penetration property and that there is no observed discontinuity or defect on the weld surface and on base metal.

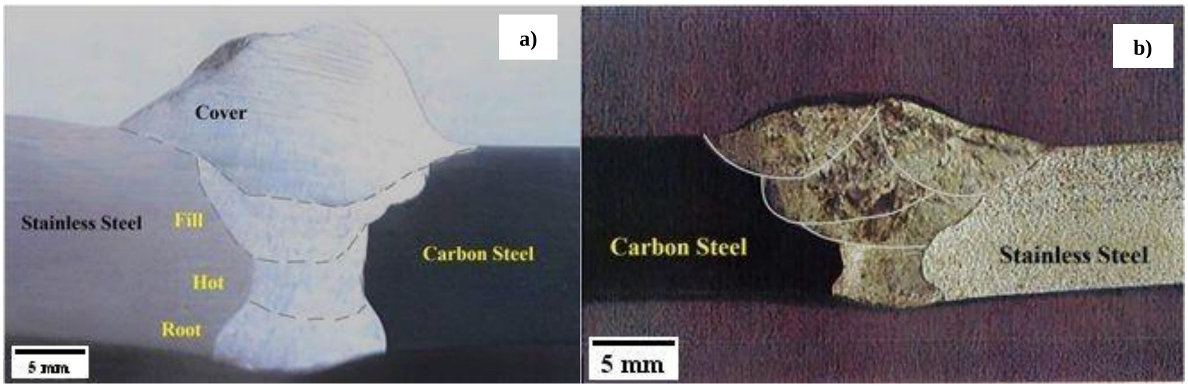

Figure 5. Macro images of **a)** W-309 coded welding process and **b)** W-INC coded welding process

As shown in Figure 5b, a discontinuity type structure was encountered in the sample welded with INCONEL 82 (ER NiCr-3) and INCONEL 182 (E NiCrFe-3) electrodes, specifically on the 316L side. In addition, the appearance of different microstructures can also be seen in the weld metal produced with INCONEL electrodes.

3.3. PMI Values After Welding Processes

PMI values for the W-309 and W-INC coded welding process were measured after each welding process and are given in Table 6.

Table 6. Positive Material Identification (PMI) values for W-309 and W-INC coded welding process

	Positive Material Identification (PMI)						
	W-309	**Cr**	**Ni**	**Mn**	**Mo**	**Ti**	**Fe**
316L	(Base Metal) BM1	16.81	11.6	-	2.08	-	Bal.
309L	(Weld Metal) WM1	22.94	13.05	-	-	-	Bal.
A106	(Base Metal) BM2	0.03	0.06	1.16	-	-	Bal.
	W-INC	**Cr**	**Ni**	**Mn**	**Mo**	**Ti**	**Fe**
316L	(Base Metal) BM1	16.51	10.29	-	2.14	-	Bal.
Inconel	(Weld Metal) WM1	16.52	61.14	-	0.073	1.02	Bal.
A106	(Base Metal) BM2	0.024	0.039	1.16	-	-	Bal.

As can be observed from Table 6 that there is a little variation in base metal compositions regarding Mn, C, Cr, N, and Mo, however, the Cr and Ni contents of weld metals in both weld processes are different with respect to electrode compositions. This may be due to the fact that the electrodes used in welding are different even though the base metals are the same. This is expected when base metals and electrode compositions are dissimilar and a mixing of base metal and electrode at a ratio of, for example, 50% is assumed to occur. This dilution is more apparent when two distinctive compositions are used for welding [26,27]. The calculations based on the Creq and Nieq values show that, 316L base steel falls within austenite or right at the border of Austenite 5% ferrite zone (Creq: 19.43, Nieq: 12.5) according to Schaffler diagram whereas the electrode materials i.e. ER309LSi and ER309L15 fall in Austenite+10% ferrite zone (Creq:24.18 + Nieq:15.25). On the other hand, weld metal composition of W-309 weld process based on Cr and Ni values shows that W-309 weld metal is fully austenitic, which can be understood from the featureless appearance of weld metal cross section, too. Elements from the electrode chemical content have a strong effect on the final composition of weld metal [28]. It is such that in the W-309 coded welding process, the weld metal has a higher Cr content (from 16.75 to 22.94 wt%) and higher Ni content (from 11 to 13 wt%) whereas the W-INC coded welding process weld metal has produced lower Ni percentages (from 69 to 61 wt%) and higher Ti content (from 0.1 to 1.02 wt%). It is interesting note that the increase in Ti content is very high compared to filler metals and base metal contents of Ti. Some losses of alloying elements apart from Ti may have occurred due to evaporation as a result of high heat released during welding process, increasing the amount of Ti in the weld metal.

3.4. Tensile Test and Bending Test Results

The samples for which tensile and bending tests were performed are shown in Figure 6. A 3-point 180° bending test was applied to the test piece samples. The samples showed successful performance in the 180° bending test, and although the materials were bent 180°, they did not break. There was no tearing was observed, and no visible discontinuity or defect was detected along the bent surface. The successful results of the samples that were exposed to 180° three point bending test showed that the welding process was carried out correctly and the selected filler metals were suitable for material combination selected for this process.

Figure 6. Tensile and 180° three point bending tested samples

Tensile test results on samples obtained from the welding process coded W-309 and coded W-INC are given in Table 7. The tensile test results are given in Figure 7.

Table 7. Cross sectional area, flow stress, Fmax, elongation and maximum tensile strength values obtained from specimen the welding process coded W-309 and W-INC

Sample	Cross-sectional area (mm^2)	$R_{0,2}$ (N mm^{-2})	Fmax (kN)	Rm (N mm^{-2})	Elongation (%)
W-309-1	138	462	77.7	563	28.33
W-309-2	138	451	76.45	554	27.33
W-INC-1	189.05	286	96.2	50884	29.9
W-INC-2	190	286.37	97.86	515.07	29.83

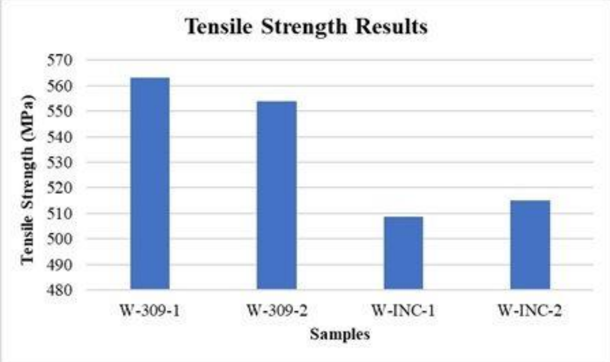

Figure 7. Comparative table for tensile strengths of W-309-1, W-309-2, W-INC-1, W-INC-2

As a general requirement for the successful joint, the tensile strength of the weld zone of the welded samples should be higher than the tensile strength of the base metal. Dissimilar joints can be, on the other hand, may differ depending on the amount and type of filler metal compositions. In this study, high amount of Ni, Cr and Nb in INCONEL filler metals results in the hardening of weld metals in W-INC series but bending tests indicate that both weld metals do not fail and but deforms in ductile manner owing to high amount of Ni present in the weld metal and stainless steel, which can be also be observed in some dissimilar steel produced with stainless steel and carbon steels [28-30]. In the test samples (Figure 6), the appearance of cracking of bent surfaces followed by the rupture occurred on A106Gr.B carbon steel side, one of the base metals. Yield and ultimate tensile strength values of welds made with ER309L and E309L-15 filler metals, are slightly higher than those of samples made with INCONEL 82 (ER NiCr-3) and INCONEL 182 (E NiCrFe-3) filler metals, as a result of high amount of austenite or Ni in microstructures of INCONEL containing welds. However, there is almost no difference in tensile strength values within the groups of welds tested for different zones of the welds.

4. CONCLUSION

Following conclusions can be drawn from this study:

1. Bending test results showed that the samples failed in base metal, namely A106Gr.B carbon steel, and no visible discontinuity or error was detected in weld metal.
2. It was concluded that yield and tensile strength values of welds made with ER309L and E309L-15 filler metals are higher than the welds made with INCONEL 82 (ER NiCr-3) and INCONEL 182 (E NiCrFe-3) filler electrodes.
3. The root pass hardness value for W-309 coded weld metal has a higher hardness than the cover pass hardness value of the weld filler metal. The root pass hardness value for the W-INC coded weld metal has a higher hardness than the cover pass hardness value in the weld filler.
4. Considering the average hardness values, the average hardness values for the W-INC coded welding process are higher; INCONEL 82 (ER NiCr-3) and INCONEL 182 (E NiCrFe-3) electrodes produced

higher matrix hardness than ER309L and E309L-15 electrodes.

5. It was determined that ER309L and E309L-15 electrodes used in the joining of A 312 TP 316L and A106 Gr.B produced good weld penetration with no discontinuity or defects in the weld surface and base metal. However, INCONEL 82 (ER NiCr-3) and INCONEL 182 (E NiCrFe-3) electrodes produced a slightly less penetration, especially on the 316L side of the welds.
6. Some changes in the compositions of weld metals have been observed after welding processes, which may be due possibly to the fact that the electrodes used in welding passes are different compared to base metals.

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