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Influence Of Welding Parameters and Titanium Powder Addition on Nugget Diameter and Mechanical Properties of Dissimilar Advanced High-Strength Steel Resistance Spot Welded Joints

Zainab N. Obaid[1] , Adnan A. Ugla[2]

[1]Department of Mechanical Engineering, University of Thi-Qar, Nasiriyah, Iraq, email: zainab.n.o@utq.edu.iq
[2]Department of Mechanical Engineering, University of Thi-Qar, Nasiriyah, Iraq, email: adnan-alomary@utq.edu.iq

Abstract: Resistance Spot Welding (RSW) is a widely used joining method employed in automotive manufacturing for Advanced High-Strength Steels (AHSS) because of its high production efficiency and suitability for joining lightweight structures. The effects of welding current, welding time and titanium powder addition on weld nugget diameter, tensile shear strength, and microstructural characteristics of dissimilar AHSS spot welds were systematically investigated. A Taguchi (L9) design was employed to evaluate the effects of the welding parameters. The joints were further examined using optical microscopy, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD) and The experimental results were statistically analyzed using ANOVA. The results indicated that the welding current exhibited the strongest influence parameter on the fusion zone diameter, and the titanium powder was the most important parameter effecting the tensile shear strength. Microstructural the sound fusion zone was formed without any visible defects including cracks, porosity and incomplete fusion. The analysis of the elemental composition performed using EDS showed there was no significant change in the elemental composition across the weld zone, and XRD analysis confirmed the coexistence of body-centered cubic (BCC) and face-centered cubic (FCC) phases without the formation of new crystalline phases throughout of RSW process. Overall, the study revealed that while the microstructure and crystal structure remained stable, the mechanical performance of the welded joints were improved by the right choice of welding parameters and the use of the titanium powder. These findings demonstrate the potential of this approach for producing reliable dissimilar AHSS welded joints for engineering applications, particularly in the automotive industry.

Keyword: Resistance Spot Welding (RSW), Advanced High-Strength Steel (AHSS), Dissimilar Welding, Titanium Powder, Tensile Shear Strength, Microstructure.

1. Introduction

Resistance spot welding (RSW) is one of the most widely used joining processes because of its high productivity, low cost, and suitability for mass production, particularly in the automotive industry. The welding current and electrode force create heat at the interface of the faying interface due to the electrical resistance at the interface, resulting in the formation of a weld nugget. The size and the quality of the weld nugget are key factors that determine the mechanical performance and reliability of the welded joint [1]. Advanced High Strength steels (AHSS) such as dual-phase (DP) and transformation-induced plasticity (TRIP) steels have been increasingly adopted by the automotive industry in increasing numbers due to their combination of high strength, good formability, high crashworthiness, and reduced vehicle weight. Among these, DP600, DP800, and TRIP steels are widely used for structural and safety-critical components in the automotive industry. RSW of dissimilar AHSS still faces challenges, mainly because of the dissimilarity in their chemical composition, microstructure, and thermal behavior, all of which affect the weld nugget formation, microstructural evolution, and mechanical performance of welded joints [2-4]. The formation of the weld nugget and tensile shear performance of the AHSS resistance spot welded joint is significantly affected by welding parameters such as welding current, welding time and electrode force [5]. Welding parameters including welding current, welding time and electrode force are also an important factor affecting the microstructure, hardness distribution and heat-affected zone (HAZ) of the resistance spot welded AHSS joints, There by influence their mechanical performance [6]. Also showed that the mechanical behaviour of resistance spot welded DP steels is dependent on the weld nugget size and that the higher the diameter of the weld nugget, the higher the mechanical behaviour of the joint [7]. DP and TRIP steels have very different microstructural features, and these determine weld-ability, as well as the formation of the weld nugget, the strength of the weld joints and failure mechanism in the RSW process [8]. The mechanical performance of resistance spot welded AHSS joints is closely associated with the evolution of weld microstructure and micro-hardness, which are controlled by the thermal conditions developed during welding [9]. Kishore et.al,[10] explained that the increase in welding current and welding time results in increase in nugget diameter, which further increases the load bearing capacity of joint in shear and Coach Peel tests. The study also revealed a critical nugget diameter (4.4 mm) beyond which interfacial failure is converted to pull-out failure, The study also addressed the formation of the weld micro-structure and the hardness variation in the various areas of the weld, and verified that one of the most significant parameters influencing the mechanical behaviour of spot-welded pieces is the nugget diameter. The shear tensile strength of the joints formed by resistance spot welding DP600 steel is also one of the most influencing factors of the welding current. A linear relationship is known to exist between the diameter of the nugget and tensile strength, with the latter increasing with the diameter of the nugget [11]. The study of the response surface methodology (RSM) on the mechanical properties and microstructure of DP800 steel joints under different welding parameters. It revealed that the shear tensile strength and hardness of the fusion zone is directly influenced by the welding current, welding time and electrode pressure. The selection of optimal parameters resulted in the maximum values of tensile strength and hardness, as shown by regression models and analysis of variance (ANOVA), and the formation of an appropriate microstructure in the fusion zone [12]. Previous studies have shown that the addition of metallic powders, particularly titanium powder, can improve the mechanical properties of resistance spot welded joints. However, limited studies have investigated the application of this approach to dissimilar AHSS, highlighting the need for further research in this area [13]. For spot welding dissimilar metals, the adding of metal powders to the welding zone has better effect than the nickel powder, and can improve the mechanical property of the joint by enhancing the bonding effect in the fusion zone [14]. The effect of welding parameters (such as welding current, welding time and electrode force) on the mechanical properties and microstructural changes of the resistance spot welded joints has been investigated by many research. Besides, some researchers have also found that the addition of metallic powders, especially titanium powder, can improve the weld quality and adjust the mechanical properties of welds. But research that focuses on the interactions of welding parameters and the addition of titanium powder, especially in the resistance spot welding of dissimilar AHSS like DP600, DP800, and TRIP steels is still scarce. Moreover, the correlation between the weld nugget diameter, the microstructural change and mechanical property under the above conditions is still not well understood. In view of this, the present study seeks to examine the effect of welding parameters and addition of titanium powder on the weld diameter of the spot welds between dissimilar AHSS materials. Moreover, the relationships between the diameter of the weld nugget, tensile shear strength, micro-hardness and micro-structure of the weld are also examined to obtain the optimum welding conditions for better weld performance.

2. Experimental Work

2.1 Materials

The experimental work three grades of advanced high-strength steel (AHSS) were used: DP600 dual-phase steel and DP800 dual-phase steel and transformation-induced plasticity steel (TRIP), due to their wide application in the manufacturing of car bodies and structural components that require a combination of high strength, formability, and impact resistance. All sheets were 1 mm thick and were joined by RSW to produce dissimilar welded joints and they were welded using the RSW technique in the form of dissimilar joints. The compositions of the used joints included: DP600/TRIP, DP800/TRIP, and DP600/DP800.

Table 1. Chemical composition of the AHSS sheets used in this investigation (wt.%).

Materials	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Ti	Fe
DP600	0.42	0.32	1.59	0.103	0.029	0.026	0.007	0.021	0.56	0.005	96.6
DP800	0.69	1.08	2.76	0.003	0.300	0.031	0.007	0.043	2.26	0.016	92.4
TRIP	0.73	0.37	2.01	0.019	0.049	0.36	0.235	0.177	2.40	0.039	92.5

The variations of alloying elements, such as carbon, manganese and silicon, directly influence the formation of the microstructure and the hardenability and behaviour of the material during the resistance spot welding process, which has a direct influence on the formation of the fusion zone and the performance of the welded joint.

2.2 Specimen Preparation

The specimens were prepared from AHSS sheets, namely DP600, DP800, and TRIP steel, with the required dimensions for the RSW process. The sheets were arranged in a lap-joint configuration according to the experimental design adopted in this study. Before welding, the faying surfaces were mechanically cleaned with emery paper for removing oxide layers and surface contaminants, thereby improving the electrical contact between the sheets and ensuring consistent weld quality. Titanium powder (Ti) was used as a metallic additive during the welding process. The required powder quantities (0, 0.25, and 0.5 g) were accurately measured using a digital balance. The measured titanium powder was then placed at the center part of the overlap area on the sheet surface of one sheet, after which the second sheet was positioned to ensure that the powder was located at the faying interface before welding. The location and quantity of the titanium powder were kept constant for each experimental condition to ensure the consistency of the welding process and to evaluate the influence of titanium powder addition on weld nugget diameter, microstructural evolution, and the mechanical properties of the resistance spot welded dissimilar joints.

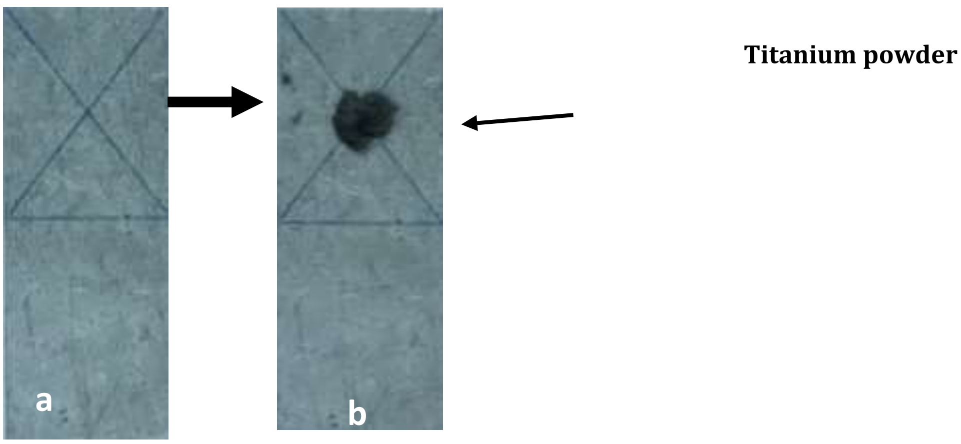

Figure 1. Specimen preparation before the resistance spot welding (RSW) process showing (a) the clean overlap region before powder addition and (b) the placement of titanium powder at the center of the overlap region prior to welding.

2.3 Resistance Spot Welding Procedure

The RSW procedure was conducted in Dhi Qar Oil Company (Japan) by using the Italian company FIMER RSW machine model FC45. The welding process was carried out with copper alloy electrodes with electrode tip measuring of 20 mm, and the process parameters were changed according to the requirements of the experimental program along with the type of joint and titanium powder added, to produce the welded joints.

Table 2. Experimental welding parameters used in this study.

Exp. No	Welding current (A)	Welding time (s)	Welding state	Titanium Powder (NA) (g)

1	5	0.2	II (TRIP-DP800)	0.5
2	5	0.3	III (DP600-DP800)	0
3	5	0.4	I (TRIP-DP600)	0.25
4	7	0.2	III (DP600-DP800)	0.25
5	7	0.3	I (TRIP-DP600)	0.5
6	7	0.4	II (TRIP-DP800)	0
7	9	0.2	I (TRIP-DP600)	0
8	9	0.3	II (TRIP-DP800)	0.25
9	9	0.4	III (DP600-DP800)	0.5

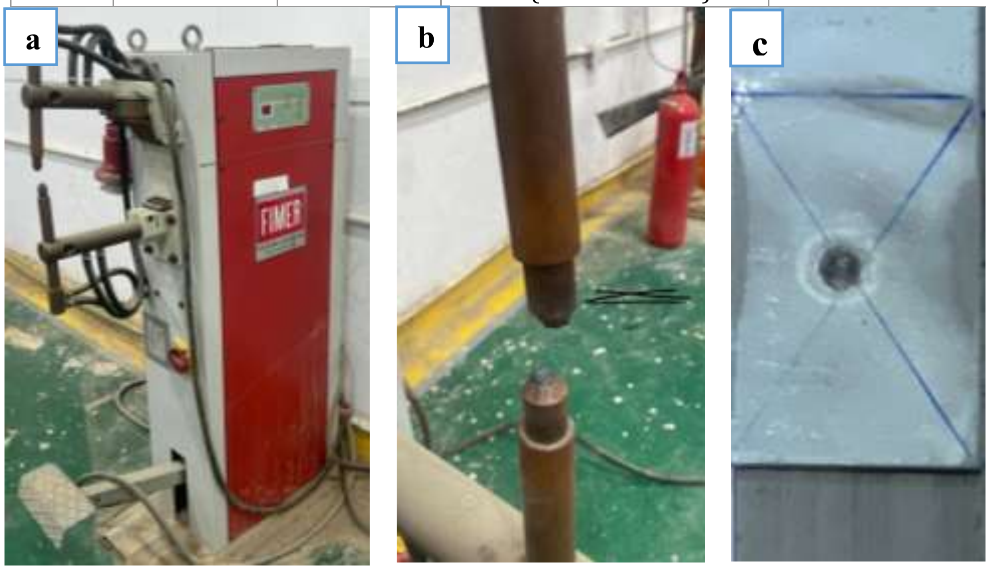

Figure 2. Experimental setup used for the resistance spot welding process: (a) FIMER FC45 resistance spot welding machine, (b) copper electrodes, and (c) dissimilar lap-joint specimen after welding.

2.4 Characterization Techniques

After the welding process, the welded joints were characterized using several experimental techniques. The mechanical properties of the welded joints were tested by means of tensile shear test, using a universal testing machine. The Vickers micro-hardness tester was used to evaluate the hardness distribution within the base metal (BM), heat affected zone (HAZ), and fusion zone (FZ) by taking micro-hardness values along the weld cross section. Microstructural evolution and fracture characteristics of the welded joints microstructure were studied by optical microscope and SEM. Furthermore, XRD analysis was performed on the sample using a diffractometer (Shimadzu LabX XRD-6000) to evaluate the crystalline phases produced following welding to correlate the phase evolution with mechanical properties and weld nugget characteristics.

Table 3. Experimental results of weld nugget diameter for all welding conditions.

EXP. No.	Input parameters				Output response
	Welding current (kA)	Welding time (s)	Welding state	NA (Ti) (g)	Measured Nugget Diameter (mm)
1	5	0.2	II	0.5	5.5
2	5	0.3	III	0	4.5
3	5	0.4	I	0.25	7
4	7	0.2	III	0.25	6
5	7	0.3	I	0.5	6.5
6	7	0.4	II	0	8
7	9	0.2	I	0	9.5
8	9	0.3	II	0.25	10
9	9	0.4	III	0.5	11

3. Results

Table (3) shows the weld nugget diameters measured under different welding parameters, such as welding current, welding time, joint combination and titanium powder addition. The experimental results were applied to assess the effect of the selected welding parameters on the formation of the weld nugget and to correlate the weld nugget diameter with the mechanical and microstructural properties presented in the next sections, Where the nugget diameter values ranged from 4.5mm to 11mm depending on the variation of welding parameters in general, the results showed that an increasing in welding current and welding time resulted in large nugget diameters, while the effect of welding condition and the addition of titanium powder was limited within the study conditions.

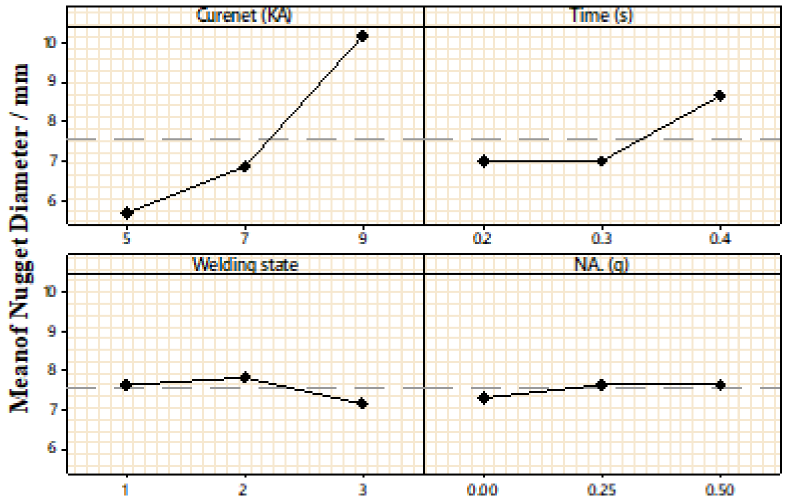

Figure 3. Main effects plot for weld nugget diameter.
Analysis of Variance

Table 4. Analysis of variance (ANOVA) for weld nugget diameter.

Source	DF	Seq SS	Contribution	F-Value	P-Value
Regression	4	35.0833	89.45%	8.48	0.031
Curenet (KA)	1	30.3750	77.44%	29.36	0.006
Time (s)	1	4.1667	10.62%	4.03	0.115
Welding state	1	0.3750	0.96%	0.36	0.580
Titanium NA. (g)	1	0.1667	0.42%	0.16	0.709
Error	4	4.1389	10.55%	-	-

The main effects plot illustrating the weld nugget diameter is provided in Figure (3) and the summary of ANOVA findings is shown in Table (4). From the observed results, the results indicate that a greatest effect of welding current on the nugget diameter was observed as the nugget weld diameter increased continuously from 5 to 9 kA. The welding time had a moderate influence and the maximum weld nugget diameter was achieved when the welding time was set at 0.4 s. The welding state and the titanium powder addition (NA), on the other hand, had a slight effect on the nugget diameter. The ANOVA showed that the welding current represented the only significant process parameter influencing weld nugget size ($P = 0.006$, 77.44%) while the welding state, welding time and addition of titanium powder were not statistically insignificant ($P > 0.05$).

Table 5. Experimental results of nugget diameter and tensile shear strength for all welding parameters.

EXP. No.	Input parameters				Output response	
	Welding current (kA)	Weldin g time (s)	Weldin g state	NA (g)	Measured Nugget Diameter (mm)	Tensile Shear Strength (MPa)
1	5	0.2	II	0.5	5.5	53.7503
2	5	0.3	III	0	4.5	527.440
3	5	0.4	I	0.25	7	61.137
4	7	0.2	III	0.25	6	47.199
5	7	0.3	I	0.5	6.5	38.447
6	7	0.4	II	0	8	287.93
7	9	0.2	I	0	9.5	170.305
8	9	0.3	II	0.25	10	47.133
9	9	0.4	III	0.5	11	33.110

The calculated tensile shear strength for the welded joints are shown in Table (5), which were determined by dividing the failure load measured during each test by the corresponding nugget cross-sectional area. The tensile shear strength obtained for the various experimental conditions showed that the welding parameters had an effect on the load capacity and weld area. Although larger nugget diameters would lead to higher tensile shear strength values (based on the ratio of the failure load to the nugget area), larger nugget diameters did not necessarily lead to higher shear stress values.

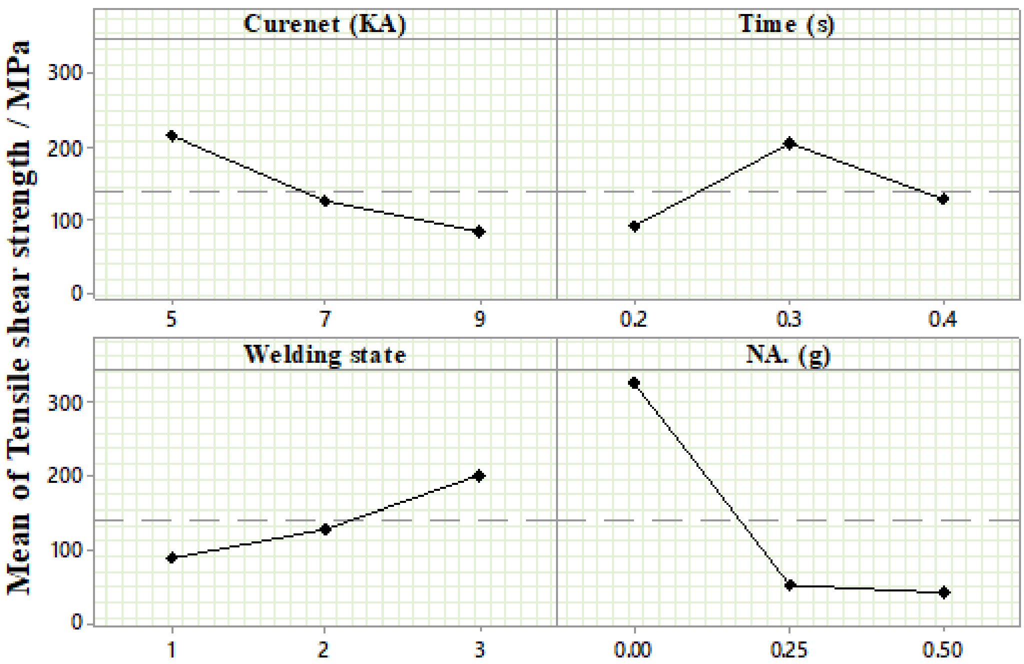

Figure 4. Main effects plot for Tensile shear strength.

Analysis of Variance

Table 6. Analysis of variance (ANOVA) for Tensile shear strength.

Source	DF	Seq SS	Contribution	F-Value	P-Value
Regression	4	170029	75.39%	3.06	0.152
Curenet (KA)	1	25582	11.34%	1.84	0.246

Time (s)	1	2051	0.91%	0.15	0.720
Welding state	1	19025	8.44%	1.37	0.307
NA. (g)	1	123372	54.70%	8.89	0.041
Error	4	55511	24.61%	-	-
Total	8	225540	100.00%	-	-

The shear tensile test results of the welded joints under various welding conditions are shown in figure (4). As the results presented, the tensile shear strength was different according to the welding parameters and the quantity of Ti powder added. It was noticed that the tensile strength of the joint was not directly proportional to the nugget diameter, so the mechanical properties of the joint are also influenced by the metallurgical properties and the microstructure of the fusion zone. The ANOVA analysis also revealed that the most significant factor affecting the shear tensile strength was the amount of Ti powder, with the higher amount of addition significantly reducing the strength of the joint. This behavior may be attributed to the presence of a lot of titanium powder at the contact surface of the plates as it can influence the melting and complete fusion process. It can also cause the generation of titanium-rich phases or brittle oxide inclusions in the weld that become stress concentration points and easy crack initiation and propagation sites when loading. These results show that the addition of more titanium powder does not necessarily lead to better mechanical properties of the joint, but a too high addition can have a negative influence on the tensile strength. It shows that it is very important to find the best quantity of titanium powder to obtain a good formability of the nugget and ensure the preservation of microstructure characteristics of the joint.

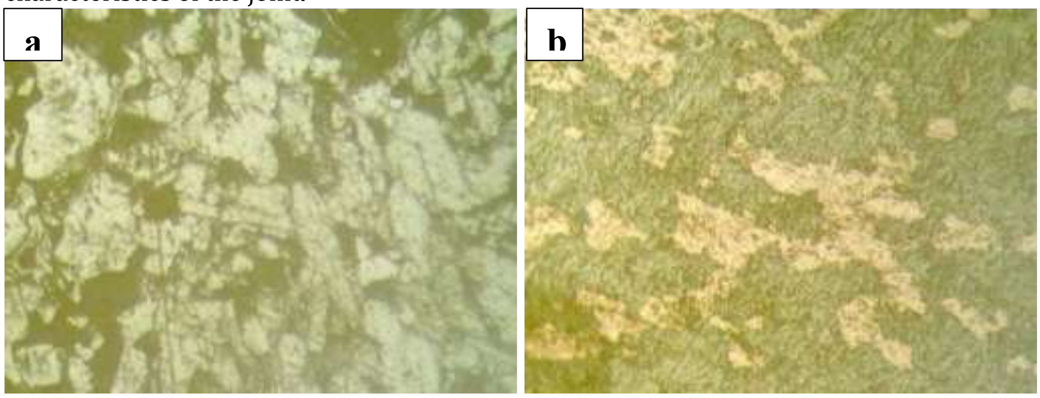

Figure 7. Optical micrographs of the fusion zone (FZ) for (a) Sample 5 and (b) Sample 7 welded using TRIP–DP600 steel.

The optical micrographs of the 5 and 7 samples welded with the same base materials (TRIP–DP600), but with different welding parameters, is shown in Figure 7(a,b). The welds in both samples were found to have a good fusion zone with no visible defects, including cracks, porosity, or lack of fusion, which suggests the quality of the welding process. Microstructure also revealed that primarily consisted of a ferritic matrix of ferrite and areas of martensite formed as a result of the rapid heating and cooling during spot welding. Sample 7 was found to have a finer and more homogeneous microstructure than the 5th sample where the grain size was larger and the grain boundaries were clearer. This difference can be attributed to the parameters of welding have an influence on the thermal cycle and cooling rate, causing the formation of various microstructures in the FZ and hence the difference in mechanical properties between the two samples.

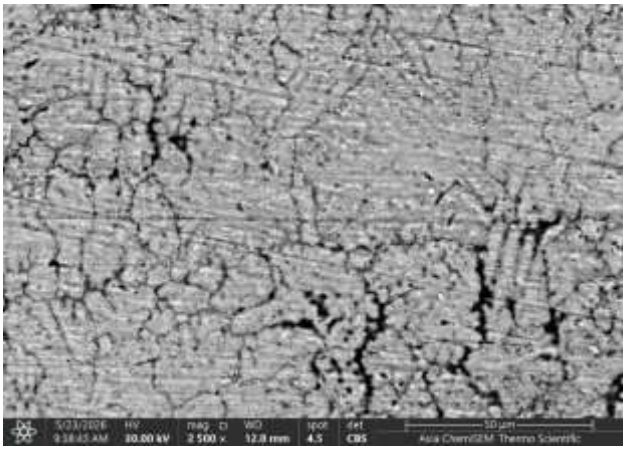

Figure 8. SEM micrograph of the fusion zone (FZ) of Sample 5 welded using TRIP–DP600 steel (×2500).

For the fifth sample welded with TRIP–DP600 steel the use of the SEM in the FZ zone was demonstrated in Figure (8). The overall metallurgical bonding in the fusion zone was satisfactory, showing no signs of welding defects like lack of fusion or significant pores, for the resistance spot welding process. The microstructural components are fine everywhere in the fusion area, and well-developed solidification features are seen everywhere, both of which are typical characteristics of the rapid heating and cooling process of RSW. Furthermore, severe propagation of cracks was not observed in the examined area, suggesting that the weld has not lost its structural integrity. Some small dark regions can be noticed, which might be associated with the different microstructural contrast formed during the solidification process. These microstructural features are consistent with the mechanical properties obtained for this sample and are found to be due to varying welding parameters as they affect the FZ.

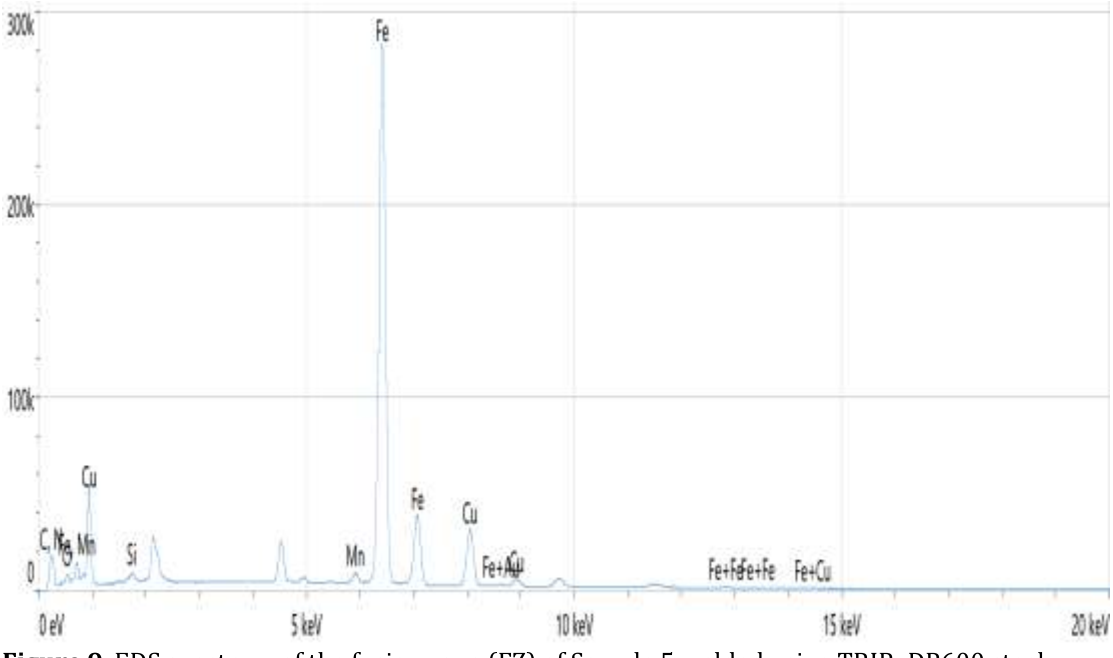

Figure 9. EDS spectrum of the fusion zone (FZ) of Sample 5 welded using TRIP–DP600 steel.

The elemental composition in the FZ was found to be similar to that of the base material from the EDS results, showing that welding conditions did not cause any significant chemical changes in the weld area, Iron remained the dominant element and no unexpected elemental peaks were detected. Therefore, the observed changes in joint performance can be primarily attributed to of the welding process as the major effect was the microstructural transformations induced by the rapid heating and cooling cycle of the metal during the welding process. Supporting the satisfactory mechanical performance of this sample is consistent with the results obtained by SEM observations, which revealed a continuous FZ, and without visible defects.

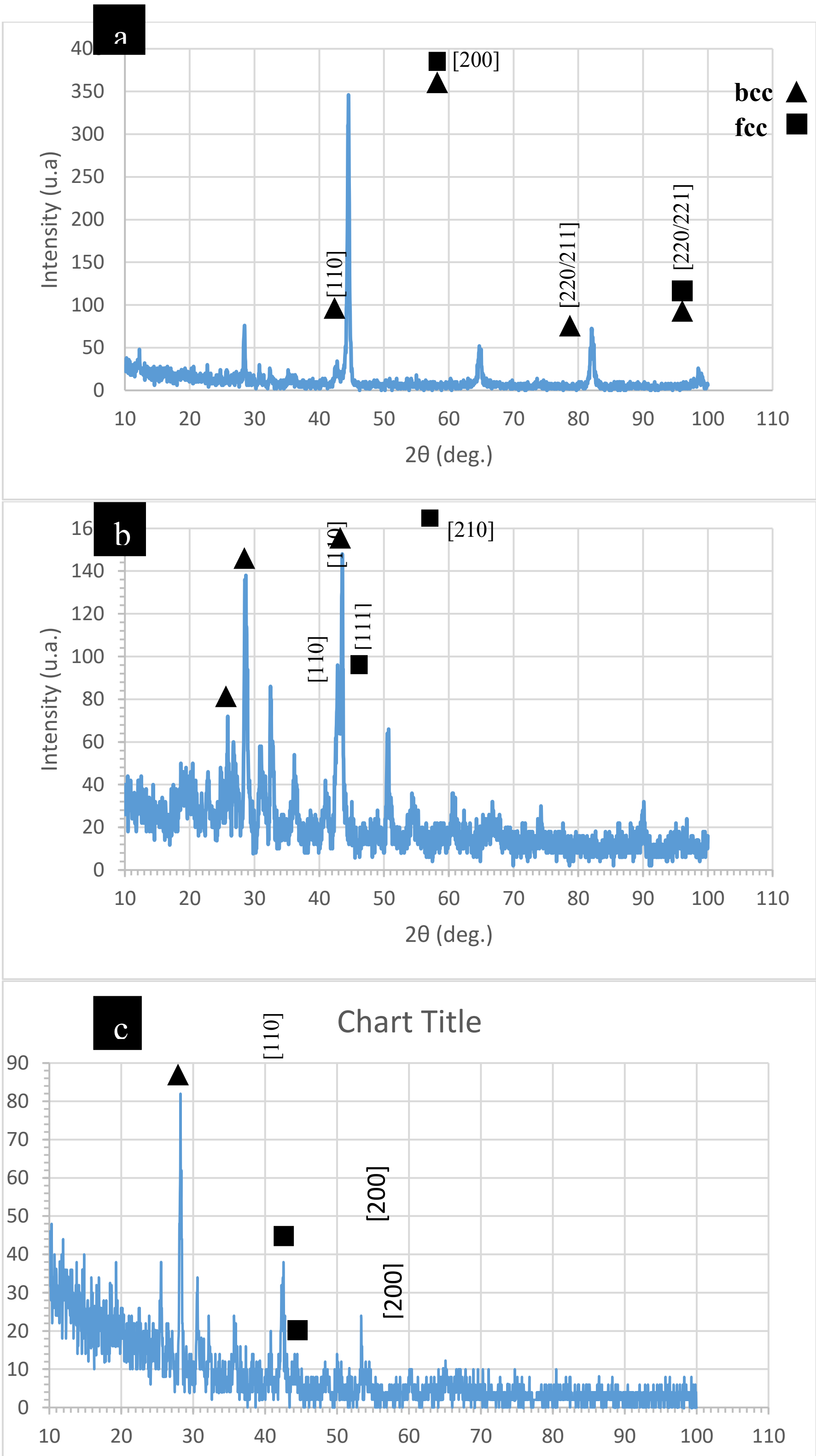

Figure 10. XRD patterns of (a) Sample 5, (b) Sample 7, and (c) Sample 9.

The XRD patterns of samples 5, 7, and 9 showed the presence of BCC and FCC phases, indicating that the spot welding process preserved the basic crystalline structure of the heterogeneous steels without the appearance of new crystalline phases. The highest diffraction intensity appeared in all samples at the angle (2θ ≈ 44°–45°) corresponding to the crystal plane (200), while other peaks appeared at the planes (110), (111), (210), and (220/221) depending on the applied welding conditions. The seventh sample showed a greater number of diffraction peaks compared to the fifth and ninth samples, indicating that the heating and cooling cycle resulting from the welding conditions led to a greater development in the distribution of crystalline phases within the melting zone. In contrast, the ninth sample showed fewer peaks and relatively lower intensity, reflecting a simpler crystalline distribution, while the fifth sample represented an intermediate case with clear appearances of BCC and FCC phases without any additional peaks indicating the formation of new phases. These results confirm that the variation in welding parameters primarily affected the phase distribution and microstructure, while the basic crystalline structure of the welded metals remained preserved. The XRD results are consistent with the results of Optical Microscopy, SEM, and EDS, which showed that the difference in the mechanical properties of the samples is primarily due to the structural development resulting from the thermal cycle of welding, rather than any fundamental chemical changes.

Conclusion

Based on the analysis on the results of this study, it is found that the investigated process parameters, including welding current, welding time, and addition of titanium powder, significantly influenced the mechanical characteristics and microstructure for the spot-welded joint of AHSS. The analysis of variance (ANOVA) revealed that welding current most greatly affected the weld nugget diameter, and the titanium powder had the greatest effect. To the tensile shear strength. The results obtained through Optical and SEM examination confirmed the formation of a sound fusion zone with no defects, including cracks, porosity or lack of fusion of the welded joints, which demonstrated the overall quality of the welded specimens produced under the selected welding conditions. The EDS analysis also indicated there were no significant chemical changes in the weld area, as iron remained the predominant elemental composition in the weld. In the meantime, the XRD results have confirmed the coexistence of BCC and FCC phases in the samples without the formation of new phases due to the RSW process. The obtained results showed that the selection of the joining parameters, but also the addition of the titanium powder, resulted in better mechanical properties of the welds and that the stability of the microstructural and crystallographic characteristics was better, which was good for the potential use of this method in welding high strength dissimilar steels for engineering applications including the automotive industry.

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