

Research Article

Hayder H. Khaleel*, Ibtihal A. Mahmood and Fuad Khoshnaw

Optimization process of resistance spot welding for high-strength low-alloy steel using Taguchi method

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Abstract: Resistance spot welding (RSW) is considered as predominant welding technique that is used in the manufacturing of modern automobile structure. The automobile structure is made of high strength steel which is preferred by the car industry companies due to its high strength-weight ratio. This work presents an optimization method for RSW of high-strength low-alloy steel DOCOL 500 LA. Tensile test and microstructure analysis for base material (BM) were carried out to get the mechanical properties of BM and to specify the rolling direction. Taguchi method, high efficiency technique, was applied using Minitab19 software to achieve the optimization process. Tensile shear test was carried out to evaluate the strength of welding nugget, absorbed energy and failure mode. The results showed that the optimum parameters were 8,800 A for the current, 30 cycles for the welding time and 2,230 N for the electrode force and two types of failure modes could be observed which were interfacial and full pullout mode.

Keywords: resistance spot welding, high strength steel, Taguchi method, tensile shear test

1 Introduction

Resistance spot welding (RSW) is the one of most important welding techniques used in the modern automotive industry to join steel parts due to its high efficiency and low cost [1,2]. Usually, there are about 2,000–5,000 spot welds in new cars. RSW is a complicated process involving mechanical, metallurgical and thermo-electrical and many other effecting factors [3,4]. RSW is a fusion welding method in which heat is produced by the resistance of materials being welded to the flow of electrical current. In order to ensure a good contact between the parts being welded, pressure must be applied by using copper alloy electrodes which also allow electrical current to flow to the parts. Due to the resistance of materials to the electrical current, the temperature increases until it reaches the melting point of materials and the nugget begins to form between two sheets. The electrical current is then switched off and nugget begins to solidify under the force [5]. Many materials can be welded by using RSW such as plain carbon steel, high-strength steel and aluminum [6–8]. High strength steel has been used widely in automotive industry because of its advantages such as high-strength-weight ratio which leads to increase in the safety of vehicles, fuel efficiency and reduce CO₂ emissions [9]. In order to obtain good welding quality, three main parameters which are welding current, welding time and electrode force are selected to be adjusted parameters that effected on the welding quality [10]. Many methods have been used to optimize the three main welding parameters and these methods are not only useful to ensure good welding quality, but also to reduce the cost of production especially in automotive industry. Taguchi design method is considered as one of the best methods in optimization process which can reduce the number of experiments by rearranging the number of tests through an orthogonal array and specify the most effecting parameters [11]. Many researchers studied the optimization process for spot welding

* **Corresponding author: Hayder H. Khaleel**, Mechanical Engineering Department, University of Technology, Baghdad, Iraq; Aeronautical Engineering Department, Engineering Technical College, Najaf, Al-Furat Al-Awsat Technical University, 31001, Al-Najaf, Iraq, e-mail: me.19.32@grad.uotechnology.edu.iq

Ibtihal A. Mahmood: Mechanical Engineering Department, University of Technology, Baghdad, Iraq

Fuad Khoshnaw: School of Engineering and Sustainable Development, Faculty of Computing, Engineering and Media, De Montfort University, Leicester, United Kingdom, e-mail: fuad.hassankhoshnaw@dmu.ac.uk

technique for mild steel and stainless steel. P Muthu presented an experimental study for optimization of RSW for stainless steel 316L using Taguchi method. Experimental data were analyzed using signal-to-noise ratio with analysis of variance to find the most effecting parameters between electrode diameter, welding current and welding time on the spot welding process and the results showed that the electrode diameter is the most effective parameter in this study [12]. Sabah Khammass Hussein and Osamah Sabah Barrak investigated the effect of RSW parameters on shear force for two materials AISI 304L and AA 6061-T6 using DOE method to analyze the effect of four parameters which were welding time, welding current, squeeze time and electrode force. They concluded that by increasing sheet thickness and welding current led to increase in shear force, while the shear force decreased by increasing the welding time, squeeze time and electrode force, respectively [13]. Ghanbari et al. investigated the fatigue behavior of RSW for dual phase steel. They chose different experimental parameters such as welding current, electrode force and welding time by using Taguchi method L8. The results showed that the welding current was the more effective parameter on the fatigue life [14]. Yasin et al. studied the optimization process for spot welding using various parameters such as welding current, welding time and electrode force for low carbon steel. The experiments were done according to Taguchi method L9. They found that the optimum parameters were welding current 8 kA, welding time 10 cycles and electrode force 2.3 kN. The most effective parameter in their study was electrode force [15]. The main goal of this study is to design the optimization process for RSW for high-strength low-alloy (HSLA) steel DOCOL 500LA which is a new high-strength steel grade and used in a new car chassis. The microstructure scan of the base material (BM) and tensile test were performed to obtain the mechanical properties and to specify the rolling direction. Taguchi method with L9 array was used to determine the most effective parameters between the main three welding parameters (welding current, welding time and electrode force). Tensile shear test for each pattern was carried out to study the effect of welding parameters on the strength of nugget, absorbed energy and failure mode.



Figure 1: Thermo ARL 3460 optical emission spectrometer.

2 Experimental work

2.1 Material

The material used in this work was HSLA steel (DOCOL 500LA) which was purchased from Swedish Company (SSAB) and it was selected due to its characteristics such as high strength, ductility and corrosion resistance. Moreover, it is used widely in modern automotive structures. The thickness of the material sheet was 0.8 mm. The chemical composition of HSLA steel specimen was analyzed by using Thermo ARL 3460 Optical Emission Spectrometer as shown in Figure 1 (Table 1).

2.2 Microstructure scan and tensile test

The microstructure of HSLA steel specimen has a significant effect on the mechanical properties, therefore optical microscope was used to study the microstructure of the BM specimen as shown in Figure 2.

The specimens are first cleaned with acetone to remove dust or contaminations and then it is grinded by using different silicon papers (from grit 100 to grit 2,000). The next step is to polish by alumina suspension and finally it

Table 1: The chemical composition of HSLA steel

C%	Mn%	Si%	S%	P%	Cr%	Ni%	Mo%	Al%	Cu%	Fe%
0.0922	1.33	0.39	0.0063	0.0165	0.0343	0.0358	0.0064	0.0449	0.0085	Bal.

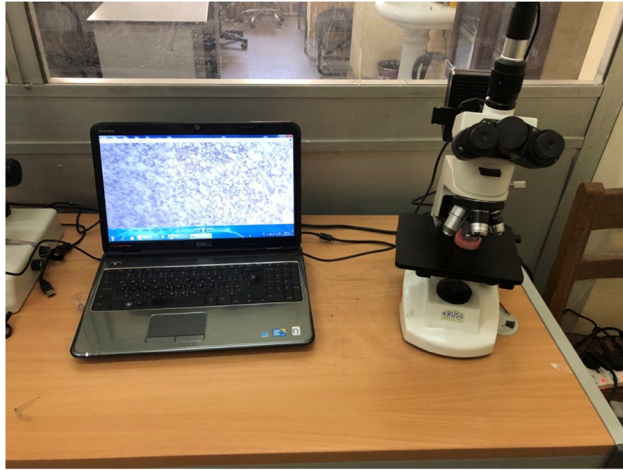


Figure 2: Optical microscope.

is etched with nital 2%. This etchant is composed of 2% volume fraction of nitric acid in 98% volume fraction of alcohol (e.g., ethanol) as shown in Figure 3.

The two specimens used to study the effect of microstructure on the rolling direction and to specify the microstructure phase for the BM from the top surface and cross section as shown in Figure 4.

FESEM test was carried out using TESCAN MIRA 3. Moreover, the tensile test was performed for two purposes. First, to know the mechanical properties of HSLA steel and second, to know the rolling direction for steel plate so that six specimens with 3 different angles (0, 45, and 90°) were used and the specimens were cut using electrical discharge machining (EDM) process to ensure

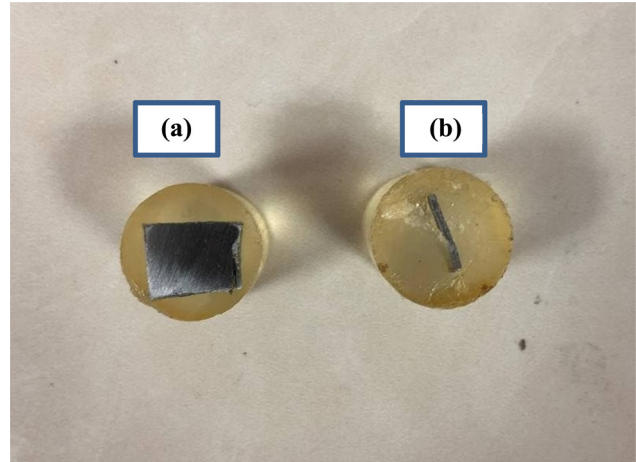


Figure 4: Microstructure specimen. (a) Top surface and (b) cross section.

the accurate dimensions for specimens as shown in Figure 5.

The tensile test was done according to ASTM E8 for metallic materials (shell type) using Tinius Olsen tensile test machine, which is connected to a computer, with maximum capacity of 50 kN under the strain rate of 2 mm/min as shown in Figure 6.

2.3 Welding process

In this study, the effect of different welding parameters such as welding current, welding time and electrode force on the strength of welding was investigated to

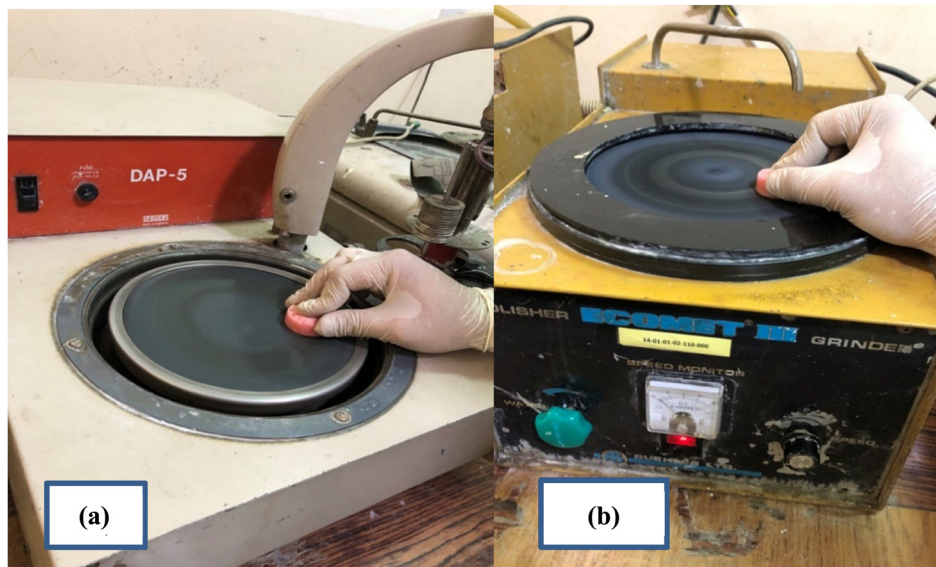


Figure 3: (a) Grinding process. (b) Polishing Process.



Figure 5: EDM cutting machine.



Figure 6: (a) Tensile test machine. (b) Tensile specimens.

assess the failure mode. The dimensions of welding samples were chosen according to ISO standards and the nugget diameter was chosen according to the American welding society (AWS). The dimensions of the specimen are shown in Figure 7.

The specimens were cut using CN machine and then cleaned with acetone to ensure good welding quality and to remove any contaminations. The welding process was carried out using WIM TOUCH 1800 digital spot welding

machine cooled by water, with diameter tip of 6 mm made of copper alloys as shown in Figure 8.

Welding parameter levels were selected according to AWS standards for high-strength steel with ultimate tensile strength from 350 to 700 MPa. Three welding parameters were selected (welding current, welding time and electrode force) with three levels as listed in Table 2 and analyzed with Taguchi method by using Minitab 19 which is a good optimization method with efficiency of approximately 95%.

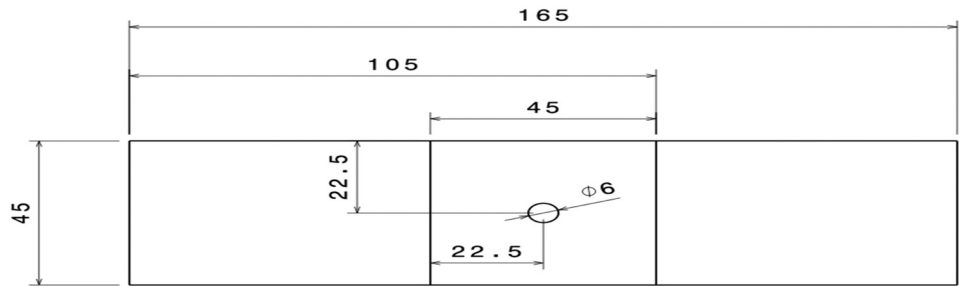


Figure 7: Spot welding specimen dimension.



Figure 8: Spot welding machine.

Table 2: Welding process parameters

Parameter	Level 1	Level 2	Level 3
Current (A)	5,700	7,250	8,800
Welding time (cycles)	9	20	30
Force (N)	1,900	2,230	2,560

Nine trails were used for each pattern to get the maximum shear force and absorbed energy as shown in Figure 9.

In this research, focus has been on the tensile shear strength, so that in Taguchi method, the larger is better equation was selected

$$\text{Larger is better } S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y^2} \right), \quad (1)$$

where S/N is the signal-to-noise ratio; n is the number of experiments; y is the magnitude of the response.

If it gets a maximum number for the tensile shear test, it indicates that it is good in tensile shear strength.

2.4 Tensile shear test

Tensile shear test was carried out to evaluate the strength of spot welding for nine specimens by using tensile test machine (SANTAM STD-600) with maximum capacity of

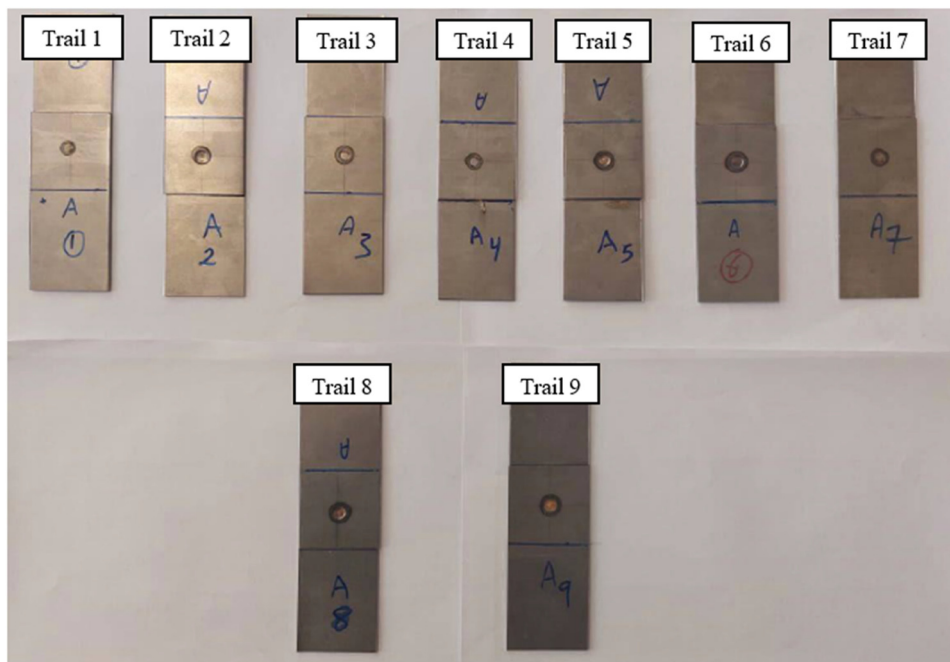


Figure 9: Welded specimens.



Figure 10: Tensile shear test.

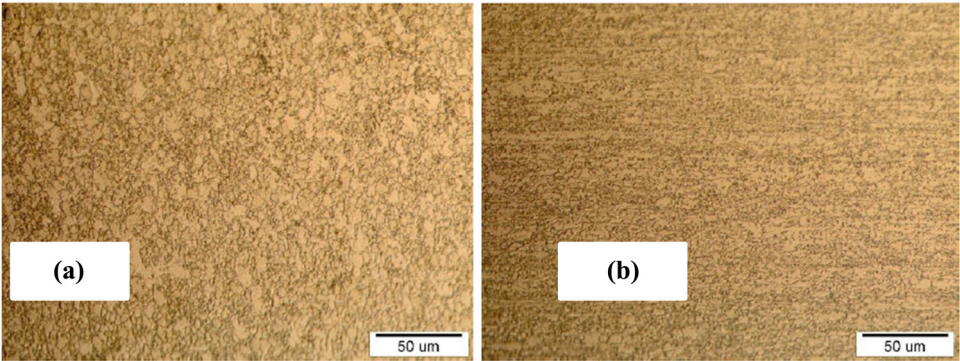


Figure 11: (a) Top surface. (b) Cross section.

600 N. The machine is connected to the computer to get force–displacement curve with strain rate of 1 mm/min as shown in Figure 10. The diameter and area of spot welding for all specimens were calculated using visual measuring machine which is connected to the computer.

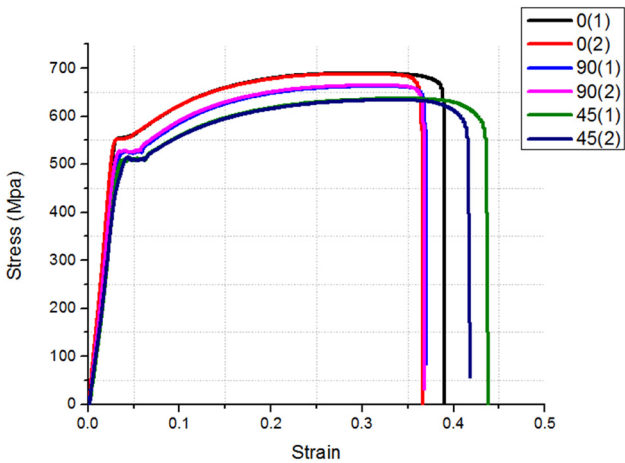


Figure 12: Stress–strain curve for HSLA.

3 Results

3.1 Results of microstructure and tensile test

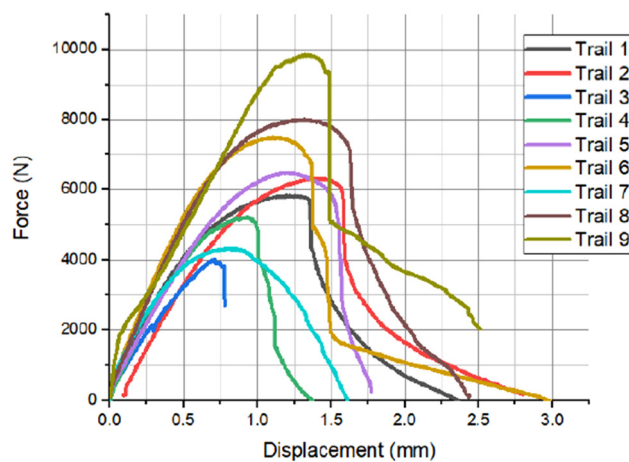
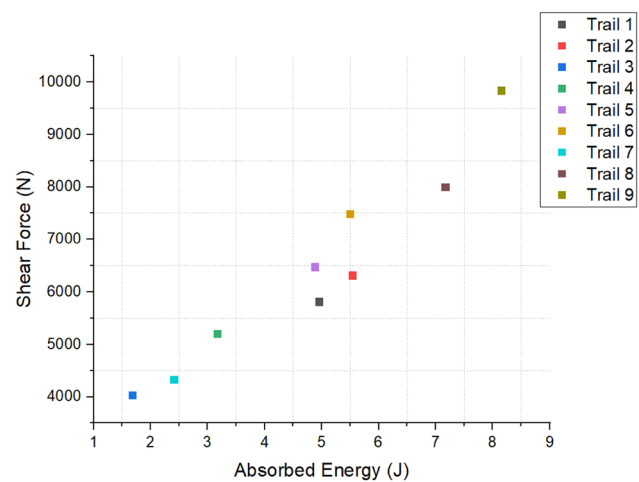
The microstructure of the base metal (Docol 500LA) was examined from either the top surface or the thickness as shown in Figure 11.

Table 3: Tensile test results for HSLA

Specimen	Yield strength (MPa)	Tensile strength (MPa)	Fracture strength (MPa)	Elongation (%)
0 (1)	549	691	677	23
0 (2)	548	689	676	22
90 (1)	518	663	656	22.4
90 (2)	516	665	655	22
45 (1)	501	637	606	27.2
45 (2)	504	635	603	26.4

Table 4: The result of Tensile shear test

Trial	Current (A)	Welding time (cycle)	Force (N)	Shear force (N)	Absorbed energy (J)	Diameter of nugget (mm)
1	5,700	9	1,900	5,817	4.95	5.86
2	5,700	20	2,230	6,318	5.54	6.1
3	5,700	30	2,560	4,032	1.68	6.42
4	7,250	9	2,230	5,209	3.17	6.37
5	7,250	20	2,560	6,475	4.88	6.6
6	7,250	30	1,900	7,485	5.5	6.55
7	8,800	9	2,560	4,326	2.41	6.59
8	8,800	20	1,900	7,995	7.17	6.76
9	8,800	30	2,230	9,839	8.15	6.26

**Figure 13:** Tensile shear results for single spot welding.**Figure 14:** Shear force vs absorbed energy.

It is well observed that the microstructure of the BM is almost completely ferritic with an equiaxed grain structure (i.e., having no certain shape and orientation). The as-received material, according to the datasheet, was hot-rolled. In the hot rolling process, it is expected that the

material undergoes dynamic recrystallization, which produces a very fine equiaxed microstructure (in accordance with microstructural observations). The average grain size of the BM was about $3.9\ \mu\text{m}$. For the tensile test results of the BMs, there is no significant difference between the

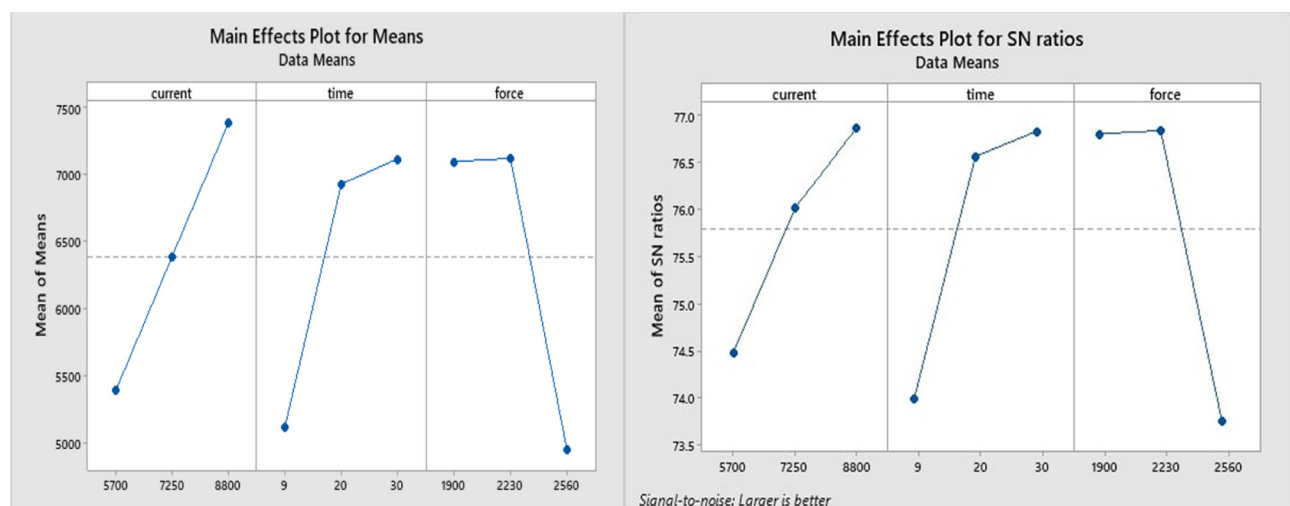
**Figure 15:** Main effect plot for SN ratio and for mean values using Taguchi method.

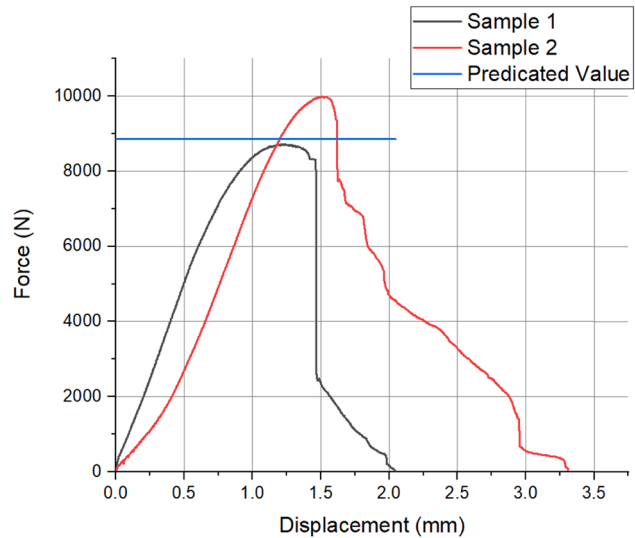
Table 5: The response table for mean values

Level	Current	Time	Force
1	5,389	5,117	7,099
2	6,390	6,929	7,122
3	7,387	7,119	4,944
Delta	1,998	2,001	2,178
Rank	3	2	1

specimens for each direction (0°, 45°, and 90°) and this is due to the microstructure of the BM as shown in Figure 12. The specimen in zero direction had the maximum yield strength which was 549 MPa and maximum tensile strength was 691 MPa while the specimen in the direction at 45° with the rolling direction had minimum yield strength of 501 MPa and the maximum tensile strength was 635 MPa. The results of tensile test for HSLA steel are listed in Table 3.

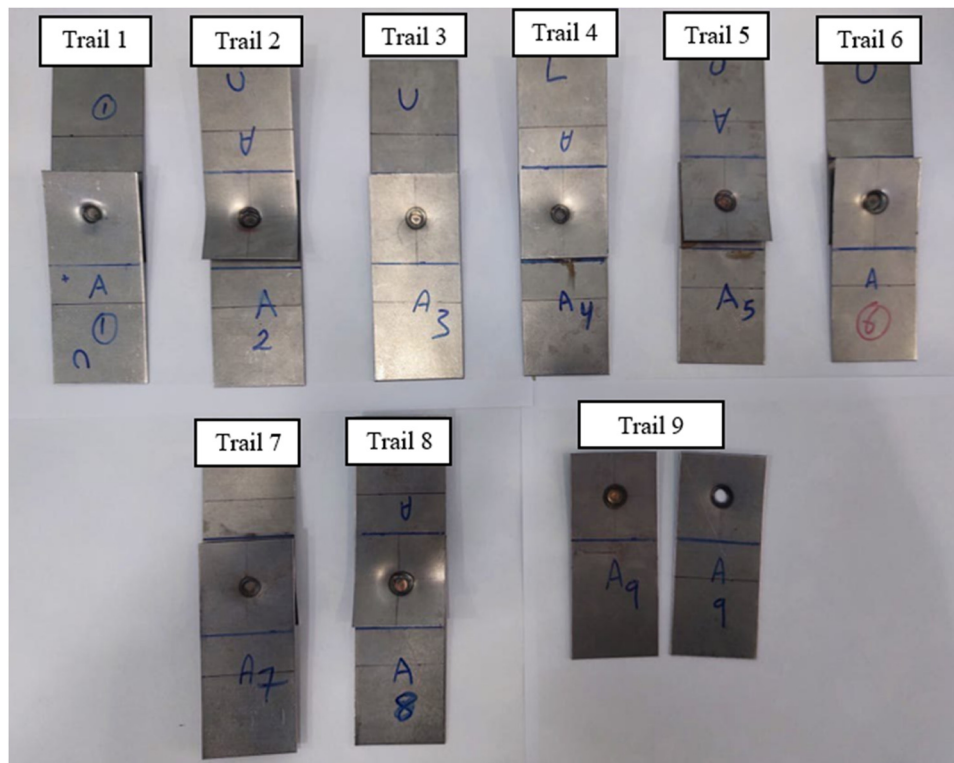
3.2 Results of Taguchi method

Taguchi optimization method was carried out and the experiments were conducted using L9 with three parameters and for three levels using Minitab 19 software as listed in Table 4.

**Figure 16:** Confirmation test.

The strength of spot welding increased by increasing the welding current and this is due to the increase in the heat input to the sheets being welded which increased the nugget area and subsequently the strength of nugget as shown in Figure 13.

Figure 14 presents the tensile shear test vs absorbed energy which is calculated from the force–displacement

**Figure 17:** Welded specimens after tensile shear test.

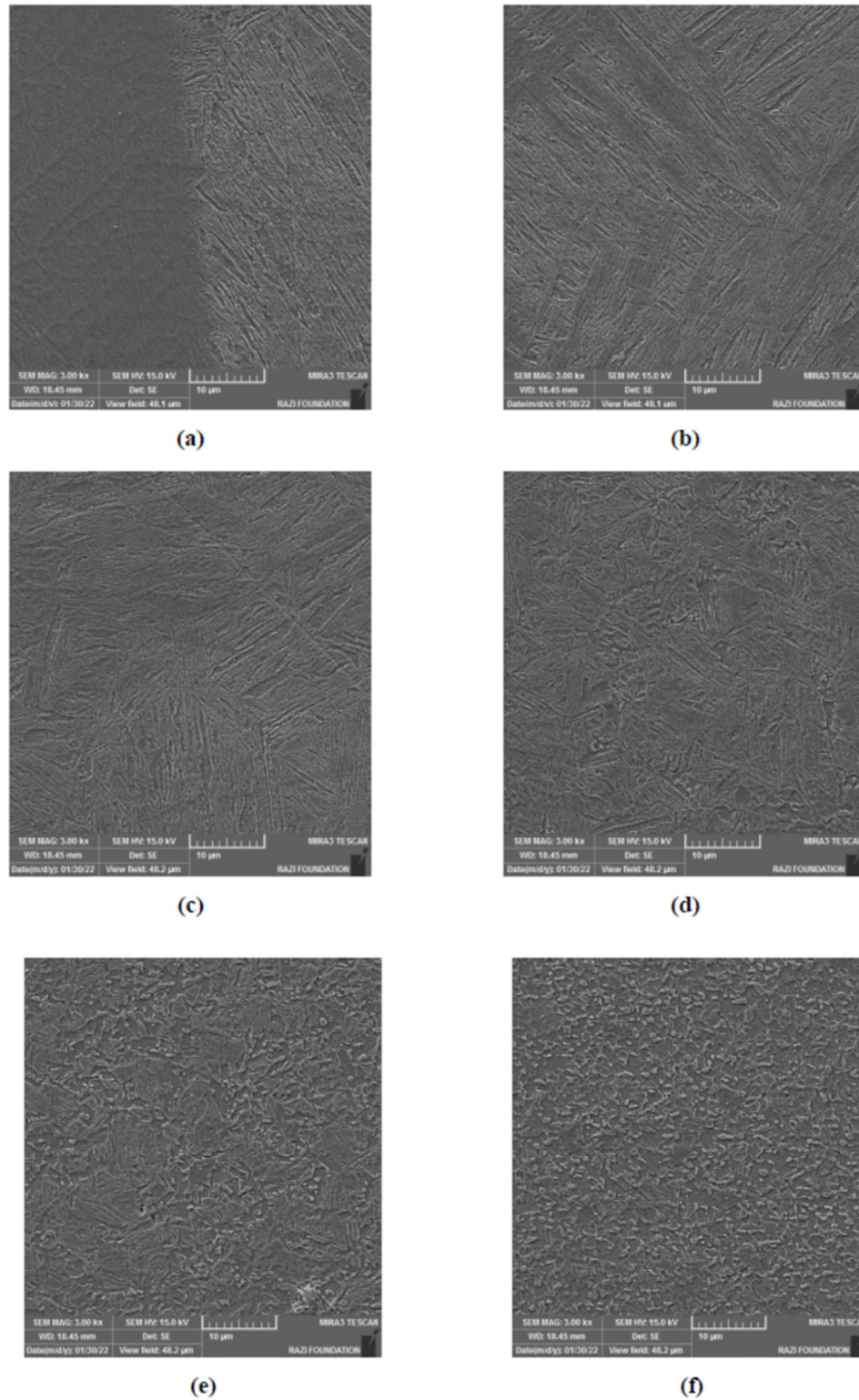


Figure 18: FESEM images from different regions of sample A: (a) nugget–HAZ interface; (b–e) from the HAZ toward the BM; (f) BM.

up to the maximum load and it shows that the absorbed energy increased with the increase in the current and subsequently increased the tensile shear force.

According to Taguchi method, the optimum design is for a current of 8,800 A, for welding time of 30 cycles, and electrode force of 2,230 N (trial 9) as shown in Figure 15.

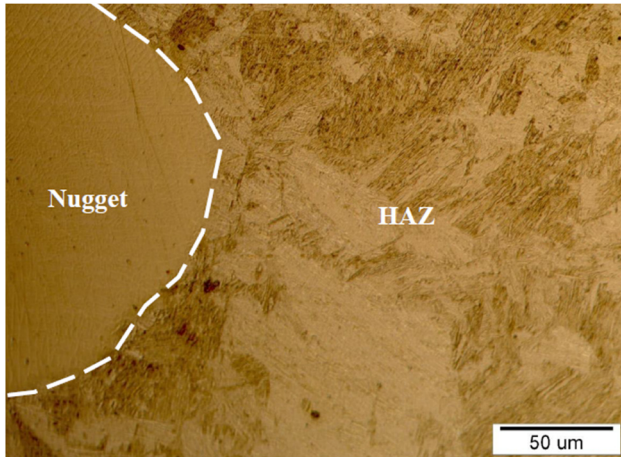


Figure 19: Optical micrograph of the interface of nugget zone and HAZ.

The response table for mean values shows that the most effective parameter was electrode force, then the welding time and finally the current and this is because of type of failure that occurred during the tensile shear test (Table 5).

The predicated value for optimum parameters according to Taguchi is 8,850 N, while that obtained from the table is 9,839 N. The confirmation test was carried out for two specimens and the results for first specimen was 8,711 N with error percentage of 1.5%, while that for the second specimen was 9,996 N with error percentage of 12% with a variation of 7% as shown in Figure 16.

The specimens after tensile shear test failed with interfacial failure mode which means that the crack propagates through the nugget diameter for the first eight trials and this is a common failure mode for high-strength steel because of the presence of element alloys while the trial number 9 failed with a full pullout failure mode which means that the nugget separates from one of the sheets and this failure mode is preferred more than the interfacial failure mode because it indicated high plastic deformation and high absorbed energy as shown in Figure 17.

3.3 Microstructure of nugget zone

The microstructure of the nugget (fusion zone) consists of columnar grains near the fusion line (elongated towards the center of the nugget zone) and small equiaxed grains inside the nugget. The heat affected zone (HAZ) near the fusion line is predominantly tempered martensite, this due to high temperature during the welding and high

rapid cooling more than 1,000°C/S, which converts the BM microstructure to martensite with some bainite. The volume fraction of martensite decreases from the nugget towards the base metal as shown in Figures 18 and 19, respectively.

4 Conclusion

This work presented the optimization process of spot welding for high-strength steel DOCOL 500LA which is used in automotive structure. The optimization was achieved using Taguchi method by analysing the data from the tensile shear test. The main conclusions can be summarized as below:

1. The optimum parameters which were obtained from the Taguchi method were 8,800 A for the current, 30 cycles for time and 2,230 N for the electrode force.
2. The failure mode for the optimum trial was full pull out, while for the other trials, it was interfacial failure mode because of high elements content.
3. The most effective parameter was electrode force, welding time and finally the current.
4. For the nugget zone, the microstructure was equiaxed grains toward the center of the nugget where the temperature was maximum, while it was martensite phase for HAZ.

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