Optimization the Resistance Spot Welding Parameters of Austenitic Stainless Steel and Aluminum Alloy Using Design of Experiment Method

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Received on:16/9/2015 & Accepted on:20/1/2016

ABSTRACT
This research aims to study the effect of RSW parameters on the sheer force of the spot welded for two materials {AISI 304L and AA 6061-T6} with (0.5 and 0.7 mm) thickness. Three values for each welding parameters (welding current, electrode force, squeeze time and welding time) are to be used. The effect of those parameters has been analyzed by using design of experiments (DOE) in order to determine and reduce the number of the tested specimens.
The experimental tests have been done that are; shear, micro hardness tests and microstructure examination. It was found that the maximum shear force in welding of similar material AISI 304L is (F = 4.78 KN for t = 0.7 mm), while in the joint of dissimilar material (AA 6061-T6 with AISI 304L), the maximum shear force is (F = 1.42 KN for t = 0.7 mm). These values have been optimized to reach (F =5.13 KN & F =1.54 KN) respectively by using DOE. The minimum shear force was (F = 0.07 KN in t = 0.5 mm).
It was found that, increasing the welding current and sheet thickness gave an increase in the shear force, but at the same time the reduction in shear force has occurred during the increasing in electrode force, squeeze time and welding time. From micro hardness tests, it was found that the maximum value of hardness was at the center of nugget zone (NZ) and it reduces slightly until reaching constant values away from nugget zone.
Keywords: resistance spot welding, dissimilar welding, DOE

INTRODUCTION
Resistance spot welding (RSW) emerged in the 1950s, and is today the main assemblage method in the automotive manufacturing. RSW is considered as the dominant process for joining sheet metals in automotive industry. Typically, there are about 2000–5000 spot welds in a modern vehicle. Simplicity, low cost, high speed (low process time) and automation possibility are among the advantages of this process [1]. To make a spot weld, two or additional metal sheets are pushed jointly by electrodes, and an electric current is passed. Heat is engendered by the metal resistance, and the sheets are welded in concert by resources of restricted metal fusion. No welding material is extra in this method. Three regions are recognized in a spot weld: a weld nugget with cylindrical profile, a heat affected zone (HAZ) and the base material sheets. These

https://doi.org/10.30684/etj.34.7A.11
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regions have different material properties. For example, the yield stress in the nugget is up to three time's upper than in the base material, and the plastic properties of the HAZ are non-homogeneous [2].

Resistance spot welding is a welding process wherein coalescence is formed by the heat acquired from resistance to the electric current flows during the work portions held together below pressure from electrodes. The control function of the welding machine defines the welding cycle. The particular steps controlled are squeeze, welding, and hold time [3].

The domestic heating generated at the weld zone is due to the flow of RSW machine current through the resistance of the welded materials. The pressure through the electrode tips, in which the current is flow, carries the exerted portions to be welded at close connection before, during and after the current cycle welding. The requisite magnitude of the current time is selected depending on the material thickness and type the quantity of flow current and the area of the cross-sectional for the contact surfaces of welding tip [4].

The aim of this work is to optimize the mechanical properties of the resistance spot welding of Aluminum Alloy using design of experiments.

Experimental work

Materials Properties

Two types of materials are used; AISI 304L Stainless Steel and AA6061-T6 Aluminum sheets. For each material, two different thicknesses have been used (0.5 and 0.7 mm). The specific chemical compositions and mechanical properties are listed in tables (1 and 2).

Table (1a): Chemical Composition of AISI 304L

wt %	C	Mn	Cr	Ni	P	S	Si	Mo	Cu	Fe
Nominal value [5]	0.03	2	18-20	8-12	0.045	0.03	1	-	-	Remainder
Actual value	0.027	1.1	19.7	10	0.005	0.005	0.501	0.001	0.25	Remainder

Table (1b): Chemical Composition of AA6061-T6

wt %	Si	Mn	Mg	Ti	Cr	Cu	Fe	Zn	Al
Nominal value [6]	0.4-0.8	0.15	0.8 -1.2	0.15	0.04-0.35	0.15-0.4	0.7	0.25	Remainder
Actual value	0.7	0.13	1.1	0.1	0.148	0.329	0.5	0.017	Remainder

Table (2): Mechanical Properties of stainless steel AISI 304L and Aluminum AA6061-T6 sheets

Material		Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
AISI 304L [5]	Nominal	210	564	58
	Actual	290	605	62
AA6061-T6 [6]	Nominal	240	290	10
	Actual	270	305	12

Specimen's dimensions

Two values of thickness were tested (t= 0.5 and 0.7 mm). The Specimens dimensions were selected in accordance with American welding society, AWS [7], as shown in Fig. (1).

Spot Welding Machine

The welding of samples was performed on 50Hz power supply a standard rocker arm (Bay Kay) resistance spot welding machine type (SL-AJ30-400-Rectifier Press Spot Welding Machine Daiden, Japan) with single phase (220 Volt). Figure (2) represents this machine.

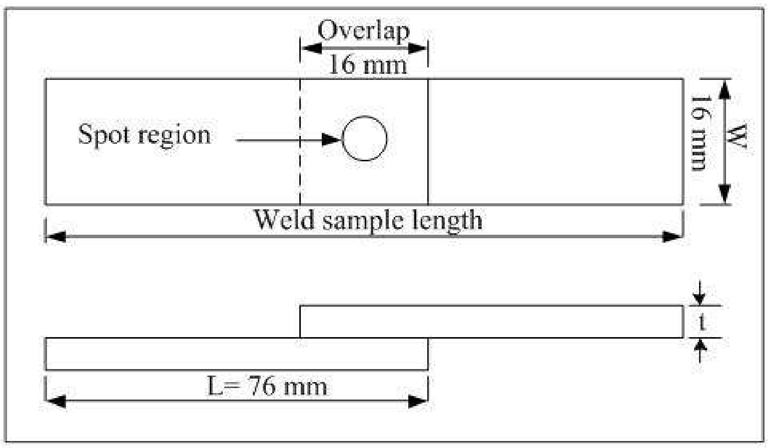


Figure (1) Overlapping of two welded plates

Figure (2) Spot welding machine

Taguchi method

Based on the fact that the welding parameters play an important role in determined the weld joint quality, design of experiments method (DOE) was used for identifying the optimal weld parameters and their settings for enhanced performance. The four spot welding parameters used in this investigation are; welding current (Amp.), electrode force (KN), squeeze time (cycle) and welding time (cycle).

By applied the Taguchi method (L9,Orthogonal Array OA) as a DOE tool, and made the parameters above as variables in the experimental works, the welding process modeling is applied for each thickness (0.5 and 0.7 mm).The process variables (and notations) are shown in table (3).

Table (3) Parameters of Taguchi Method

		Welded specimens								
		similar AISI 304L			similar AA 6061-T6			AISI 304L with AA 6061-T6		
Specimen No.	Force (KN)	Welding Current (A)	Squeeze Time (c)	Welding Time (c)	Welding Current (A)	Squeeze Time (c)	Welding Time (c)	Welding Current (A)	Squeeze Time (c)	Welding Time (c)
1	1.6	8200	7.5	12	11000	22.5	7	11000	30	25
2	2.55	8200	15	15	11000	30	10	11000	40	30
3	3.5	8200	22.5	18	11000	37.5	13	11000	50	35
4	1.6	9600	15	18	12300	30	13	12300	40	35
5	2.55	9600	22.5	12	12300	37.5	7	12300	50	25
6	3.5	9600	7.5	15	12300	22.5	10	12300	30	30
7	1.6	11000	22.5	15	13600	37.5	10	13600	50	30
8	2.55	11000	7.5	18	13600	22.5	13	13600	30	35
9	3.5	11000	15	12	13600	30	7	13600	40	25

Samples of the welded specimens in this work are shown in Figure (3).

Figure (3) the welded specimen

Mechanical Tests

Shear Strength Test

The shear strength test was performed on a rectangular specimen, 76 mm in length and 16 mm in width, as shown in Figure (1). All the welded specimens shown in figure (3) have been tested.
The tension-shear tests were performed at a cross head speed of 10 mm/min. The specimens were gripped as shown in Figure (4) with shims of thickness equal to that of the specimen. Figure (5) illustrates the tested specimens for tension- shear test.

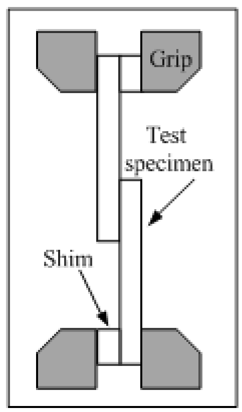


Figure (4) Schematic of tensile strength test

Figure (5) the tested shear force specimen

Micro Hardness Test

The main aim of this test is specify the hardness number for base metal (BM), nugget zone (NZ) and the heat affected zone (HAZ).

The specimen preparation included grinding and polishing process according to ASTM E90-82 [8]. Micro hardness locations have been taken along straight line starting from the center of spot-weld (NZ) through HAZ until reaching to unaffected base metal.

Microstructure Test

To examine the microstructure of BM, NZ and HAZ, and also to describe welding zone after complete the welding process, the microstructure test is carried out and includes the following steps:

Cutting the welded specimen along line through weld metal and made cold mounting for the specimens due to its small dimensions. Grinded the mounted specimens by using silicon carbide grinding papers,(200, 400, 600, 800, 1000, 1200, 2000 grains per square inch respectively) with a rotating speed of 2000 rpm of universal polishing and grinding machine for metallographic specimen preparation. Water was applied as a cooling liquid. After the grinding stage was completed, polishing stage started directly, it included using polishing cloth, alumina (Al_2O_3) solution, and rotating speed of disc. Etching process was started right after the grinding stage, etching stage included immersion of specimen in etching solution as in table (4). The final step is applying the upper solutions for few second, after this, the specimens were washed with water and directly dried with hot forced air to prevent surface oxidization, according ASTM E 407- 99[9].

Table (4) Etching solution

Materials	Solutions
Stainless Steel	10mL HNO_3, 10mL acetic acid, 15mL HCL ,and 5 drops of glycerol
Aluminum	2mL HF , 3mL HCL , 5mL HNO_3 , and 190mL water

Results

The experimental results of tensile shear force can be summarized in the following figures (6 and 7). In general, the higher values of shear force are obtained in the welding of similar stainless steel specimens. The lower values of shear force are found in the welding of similar aluminum specimens. Welded specimen of thickness (0.7 mm) gave a good strength as comparing to that of thickness (0.5 mm).

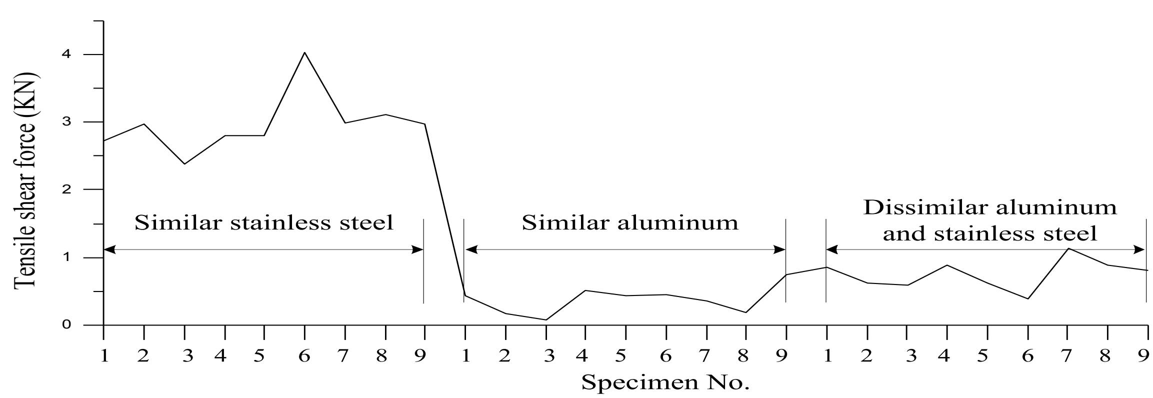


Figure (6) shear force of the welded specimen with thickness (t=0.5 mm)

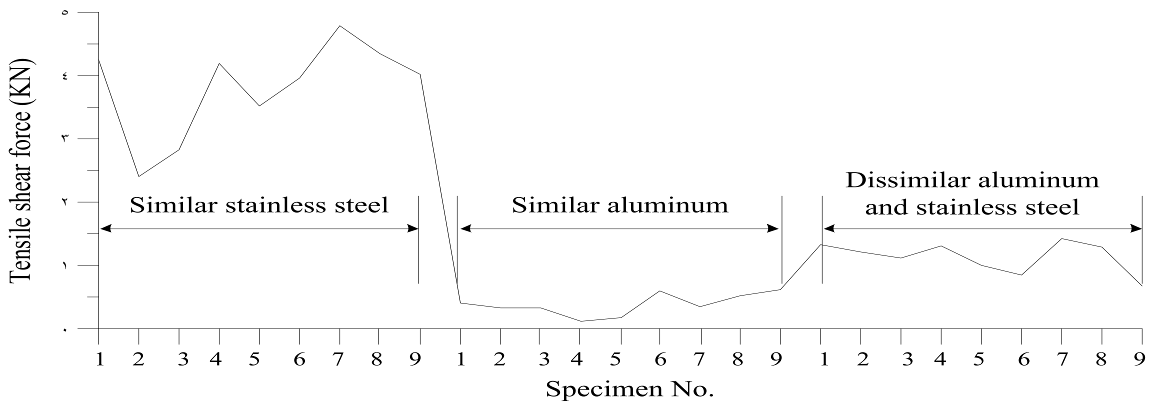


Figure (7) shear force of the welded specimen with thickness (t=0.7 mm)

DOE Results

A Minitab program is used to input and analysis the shear strength data. For input variables, un-coded units are used. That means the same data in Table (3) are used in this program.

Main Effect Plot

The main effects plot shows that all the factors appear to be having an effect upon the response variable (shear force).This method is used to study the effect of each welding parameter separately and its impact on the shear force, it was obtained the following results, figure (8-10):-

The following table (5) represents the ranges of spot welding parameters that increase the shear force for each thickness:

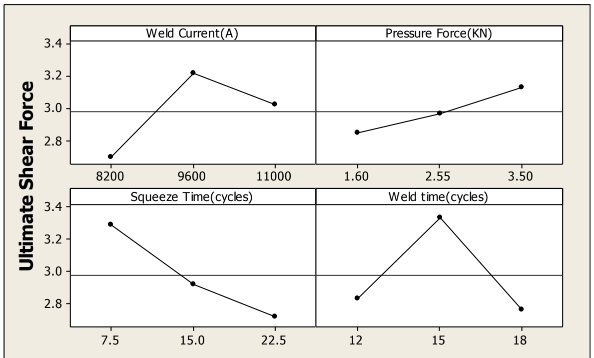
Table (5) the ranges of spot welding parameters that increase the shear force

The Joints	Thickness (mm)	Welding current (Amp.)	Electrode force (KN)	squeeze time (c)	Welding time (c)
Similar AISI 304L	0.5 ; fig.(8,a)	8200 - 9600	All range	-	12 – 15
	0.7 ; fig.(8,b)	All range	2.55 – 3.5	15 – 22.5	15 - 18
Similar AA 6061-T6	0.5 ; fig.(9,a)	11000 – 12300	2.55 – 3.5	22.5 – 30	-
	0.7 ; fig.(9,b)	12300 – 13600	All range	-	7 - 10
Dissimilar AISI 304L with AA 6061-T6	0.5 ; fig.(10,a)	12300 – 13600	-	All range	30 - 35
	0.7 ; fig.(10,b)	12300 – 13600	-	40 - 50	All range

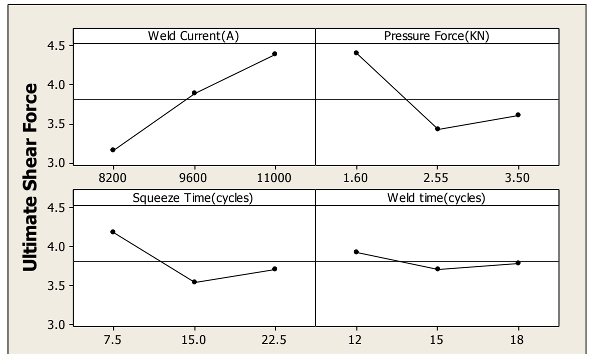
Also, table (6) represents the ranges of spot welding parameters that decrease the shear force for each thickness:

Table (6) the ranges of spot welding parameters that decrease the shear force

The Joints	Thickness (mm)	Welding current (Amp.)	Electrode force (KN)	squeeze time (c)	Welding time (c)
Similar AISI 304L	0.5 ; fig.(8,a)	9600 - 11000	-	All range	15 – 18
	0.7 ; fig.(8,b)	-	1.6 – 2.55	7.5 –15	12 - 15
Similar AA 6061-T6	0.5 ; fig.(9,a)	12300 – 13600	1.6 – 2.55	30 – 37.5	All range
	0.7 ; fig.(9,b)	11000 – 12300	–	All range	10 - 13
Dissimilar AISI 304L with AA 6061-T6	0.5 ; fig.(10,a)	11000 – 12300	All range	–	25 - 30
	0.7 ; fig.(10,b)	11000 – 12300	All range	30 - 40	–

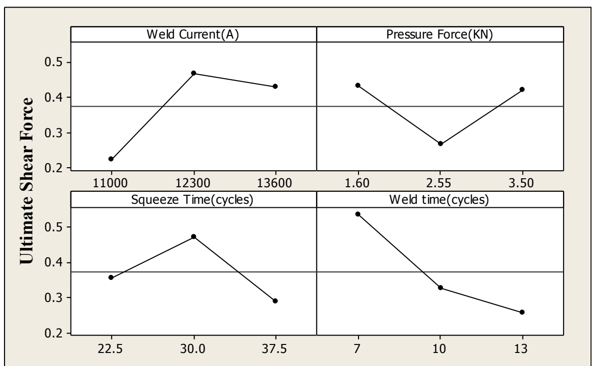


(a) t = 0.5 mm

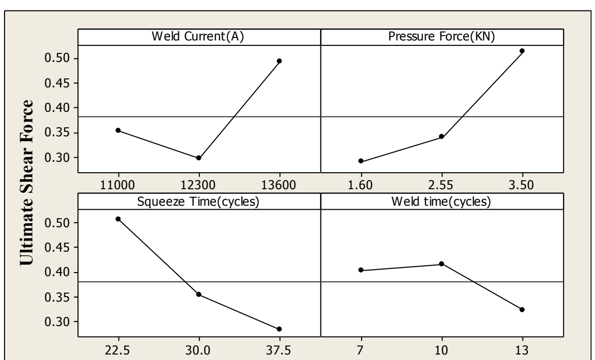


(b) t = 0.7 mm

Figure.(8) Main effects plot of shear force for similar joints of AISI 304L



(a) t = 0.5 mm



(b) t = 0.7 mm

Figure.(9) Main effects plot of shear force for similar joints of AA 6061-T6

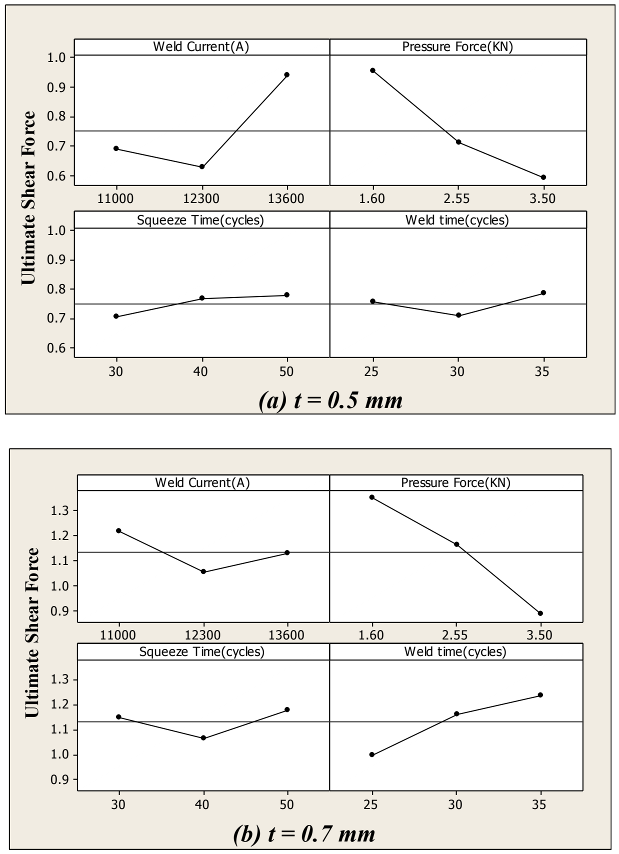


Figure.(10) Main effects plot of shear force for dissimilar joints of AISI 304L with AA 6061-T6

Interactions Plot

The interactions plot shows the interactions effect of all factors on the response variable (shear force). Interactions Plot is use to establish which factors having effect of each two welding parameter separately and its impact on shear. Tables (7 and 8) explain those effects for each thickness (t = 0.5 and 0.7 mm) respectively, with the aid of figures (11-13):-

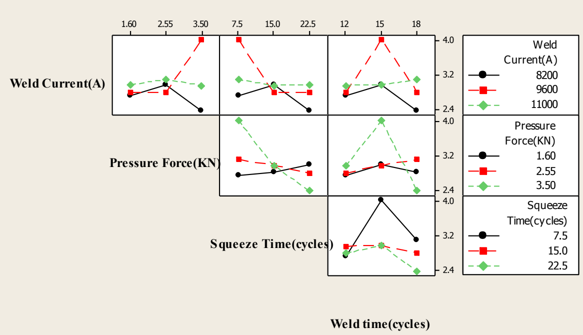
Table (7): interaction parameter effect on shear force with 0.5mm thickness

Fig.	Welding current	Electrode force	Squeeze Time
11a	• The 8200A gives the same effect on the other welding parameters. • The 9600A gives alternating effect. • The 11000A has a small effect on the other welding parameters.	• The (1.6 and 2.55 KN) give the same effect. • The (3.5KN) give a greater impact with squeeze time which reduces the shear force.	• The (7.5c) give an alternating behavior with welding time. • The (15 and 22.5 c) nearly have the same effect.

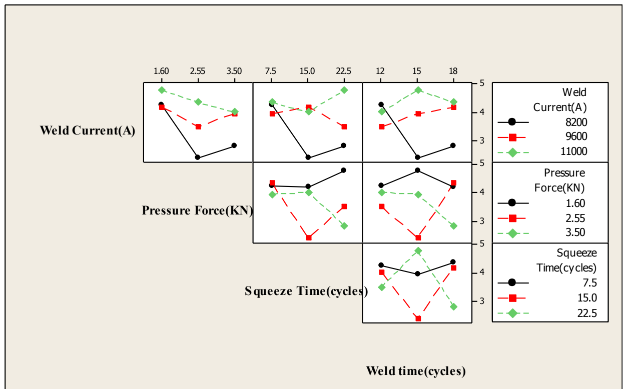
12a	• The 11000A give a small effect on the other welding parameters. • The 12300A give a same effect on the other welding parameters. • The 13600A give alternating effect.	• The (1.6 and 2.55 KN) give alternating effect. • The (3.5 KN) give a greater impact with squeeze time which reduce the shear force.	• The (22.5 and 37.5 c) nearly have the same effect. • The (30 c) has an alternating behavior with welding time.
13a	• The 11000A gives the same effect on the other welding parameters. • The 12300A has a small effect on the other welding parameters • The 13600A has alternating effect.	• The (1.6 , 2.55 and 3.5 KN) give alternating effect, but the 1.6 KN gave highest value of shear force .	• The (30,40 and 50 c) have an alternating behavior with welding time.

Table (8): interaction parameter effect on shear force with 0.7mm thickness

Fig.	Welding current	Electrode force	Squeeze Time
11b	• The (8200, 9600, and 11000 A) give alternating effect, but the 11000A gave highest value of shear force.	• The (1.6, 2.55 and 3.5 KN) give alternating effect, but the 1.6 KN gave highest value of shear force.	• The (7.5, 15 and 22.5 c) give an alternating behavior with welding time.
12b	• The (11000 A) give a small effect on the other welding parameters. • The (12300 and 13600 A) give alternating effect.	• The (1.6 and 3.5 KN) give alternating effect. • The (2.55 KN) give greater impacts with (squeeze time and welding time) which reduce the shear force.	• The (22.5 and 37.5 c) have an alternating behavior with welding time. • The (30c) has a greater impact with welding time which reduces the shear force.
13b	• The (11000)A has the same effect on the other welding parameters. • The (12300 and 13600 A) have alternating effect.	• The (1.6, 2.55 and 3.5 KN) have alternating effect, but the 1.6 KN gave highest value of shear force.	• The (30,40 and 50 c) have an alternating behavior with welding time

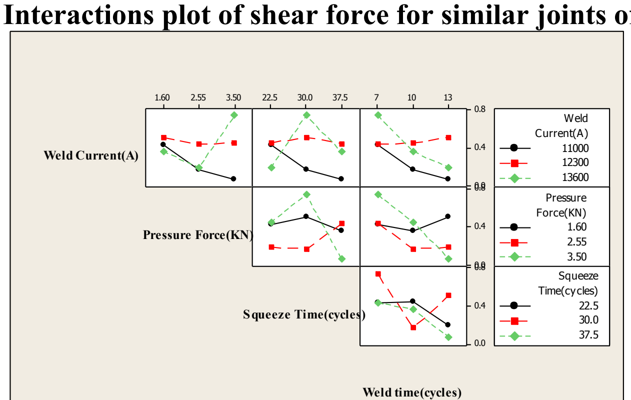


(a) t = 0.5 mm

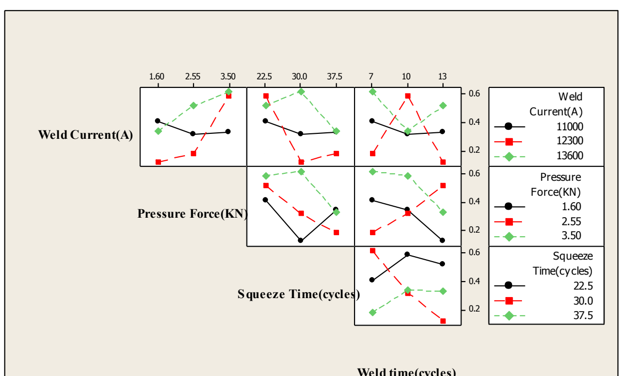


(b) t = 0.7 mm

Figure (11) Interactions plot of shear force for similar joints of AISI 304L

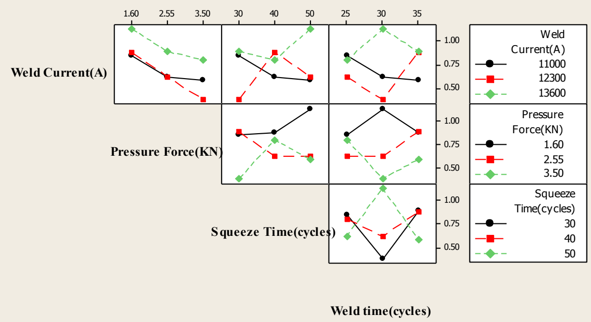


(a) t = 0.5 mm

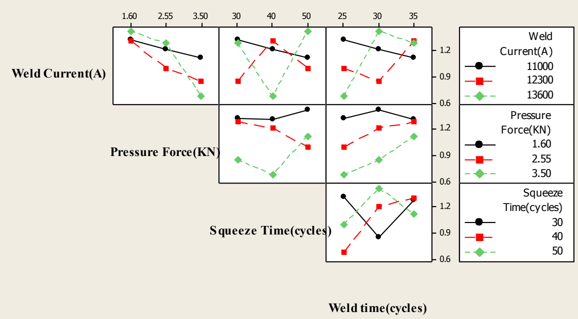


(b) t = 0.7 mm

Figure (12) Interactions plot of shear force for similar joints of AA 6061-T6



(a) t = 0.5 mm



(b) t = 0.7 mm

Figure (13) Interactions plot of shear force for dissimilar joints for AISI 304L with AA 6061-T6

Pareto Chart

Pareto charts are very helpful for analyzing the parameters requiring interest primarily, since the longer bars at the chart clearly shows the variables that have the most significant effect on a given system. Those parameters are summarized in in Table (9) from figures (14, 15 &16).

Table (11) the effective parameter on the shear strength.

Joint type	Main parameter(s) effect		Figure
	t = 0.5 mm	t = 0.7 mm	
Similar joint AISI 304L	Squeeze time	Welding current	14
Similar joint AA 6061-T6	Weld time	Force and squeeze time	15
Dissimilar joint AISI 304L AA 6061-T6	Electrode force	Electrode force	16

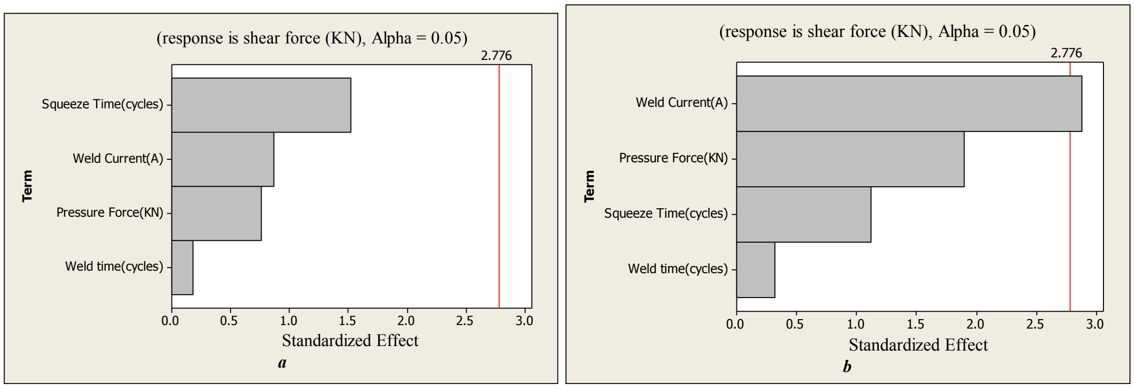


Figure (14) Pareto chart of similar joints for AISI 304L, (a)t = 0.5 mm (b) t = 0.7 mm

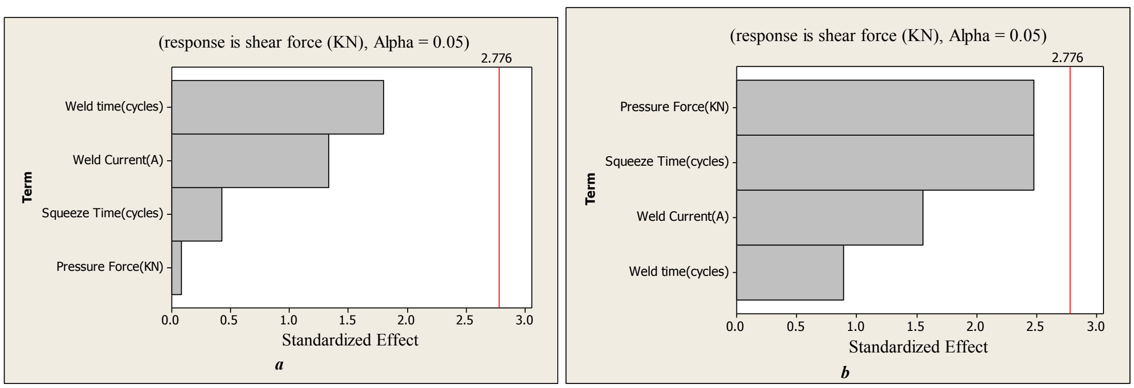


Figure (15) Pareto chart of similar joints for AA 6061-T6, (a)t = 0.5 mm (b) t = 0.7 mm

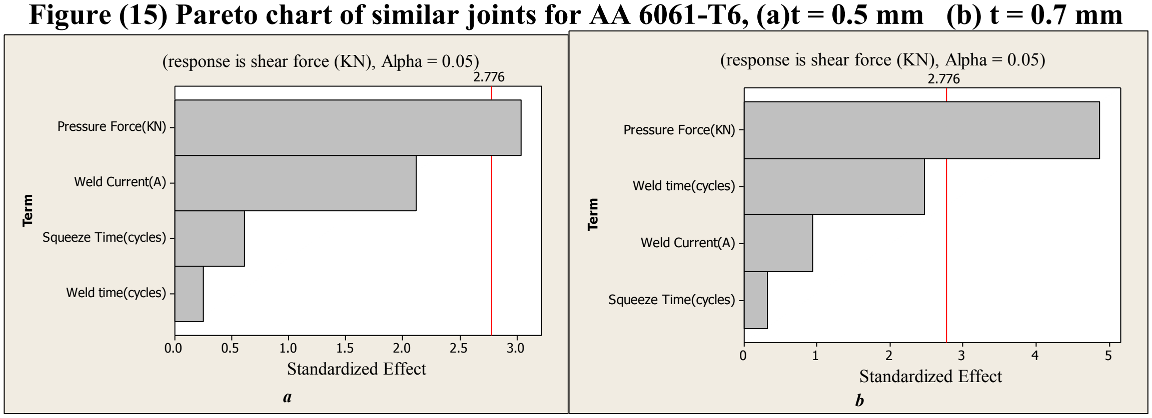


Figure (16) Pareto chart of dissimilar joints for AISI 304L-AA 6061-T6, (a) t = 0.5 mm (b) t = 0.7 mm

Response Optimizer

The response optimizer method is used to show which factors have effect on welding parameter separately and their impact on the shear. This method gave the best value for the response variable (shear force). Table (10) represents the analysis of optimizer response from (DOE) for shear force, fig. (17, 18 and 19):-

Table (12) Shear force optimizer response

Joint type	Thickness (mm)	Welding current (A)	Electrode force(KN)	Squeeze time (c)	Welding time (c)	Optimum Shear force (KN)	Figures
Similar joint for AISI 304L	0.5	11000	3.5	7.5	12	3.6	(15)
	0.7	11000	1.6	7.5	12	5.13	
Similar joint for AA 6061-T6	0.5	13600	1.6	22.5	7	0.6567	(16)
	0.7	13600	3.5	22.5	7	0.7144	
Dissimilar joint for AISI 304L with AA 6061-T6	0.5	13600	1.6	50	35	1.11	(17)
	0.7	11000	1.6	50	35	1.54	

The shaded cell represents the common welding parameters values which give the optimum shear force value for each case.

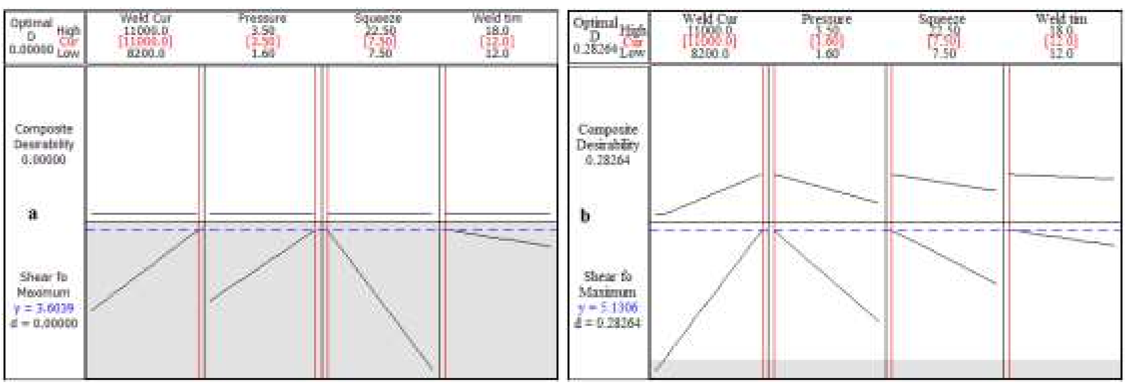


Figure.(17) Response optimizer of similar joints for AISI 304L, (a) t = 0.5 mm (b) t = 0.7 mm

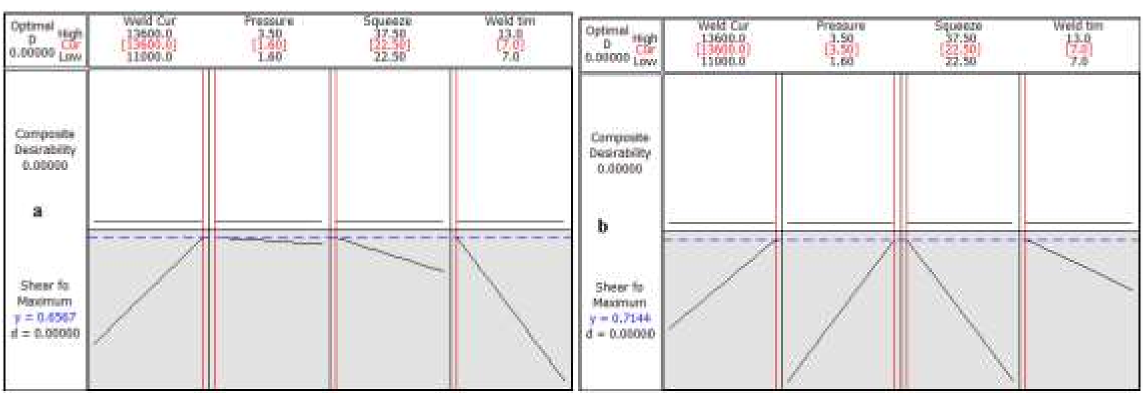


Figure.(18) Response optimizer of similar joints for AA 6061-T6, (a) t = 0.5 mm (b) t = 0.7 mm

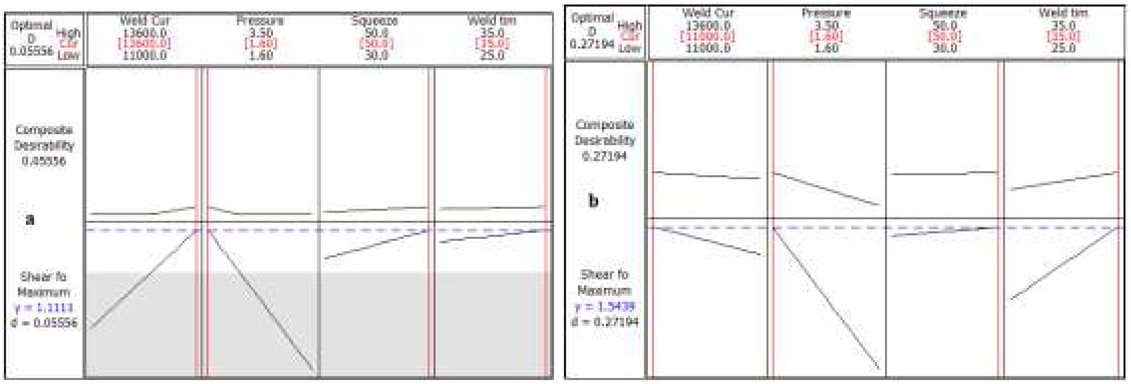


Figure.(19) Response optimizer of dissimilar joints for AISI 304L-AA 6061-T6 , (a) t = 0.5 mm (b) t = 0.7 mm

The Regression Equation

The MINITAB program gives a simple mathematical formula which represents the response as a function of variables. The following shear force formula is concluded using DOE, table (11):

Table (11) Shear force optimizer response

Joint type	Thickness (mm)	The regression equation of shear force
Similar joint for	0.5	$2.21 + 0.000117\ I + 0.151\ X_1 - 0.038\ X_2 - 0.0111\ X_3$
AISI 304L	0.7	$1.52 + 0.000437\ I - 0.425\ X_1 - 0.0318\ X_2 - 0.0228\ X_3$
Similar joint for	0.5	$0.014 + 0.000079\ I - 0.007\ X_1 - 0.0044\ X_2 - 0.0467\ X_3$
AA 6061-T6	0.7	$- 0.001 + 0.000054\ I + 0.118X_1 - 0.0149\ X_2 - 0.0133X_3$
Dissimilar joint for	0.5	$- 0.196 + 0.000097\ I - 0.191\ X_1 + 0.00367\ X_2 +0.003\ X_3$
AISI 304L AA 6061-T6	0.7	$1.41 - 0.000035\ I - 0.246\ X_1 + 0.0015\ X_2 + 0.0237\ X_3$

Where:
I: Welding current (Amp.)
X1: Electrode force (KN)
X2: squeeze time (c)
X3: Welding time (c)

Hardness results

The test was performed on all specimens at (200g) Load by Vickers measurements. The average of all four individual readings varied by no more than ±2 Vickers micro hardness units. Hardness readings were taken using the full-size Vickers diamond indentation method within ±2 Vickers units of the micro-Vickers measurements. An average of 17 readings, 8 on each side of nugget zone was done. Hardness test was achieved across the weld metal and heat affected zone (HAZ) at the weld root for two selected specimens with two thicknesses, Fig. (20, 21 & 22). The hardness profiles shows skewing of the HAZ and peak hardness away from the region adjacent to the fusion boundary.

It has been observed; the peak value of hardness is observed at the center of NZ and reduces slightly until it reaches constant values away from NZ. It is likely that the reason is the difference in cooling rate between the nugget zone and the HAZ, which mainly affects grain size and microstructure. The cooling rate is mainly based on the difference in temperature and other variables such as the type and thickness of metals.

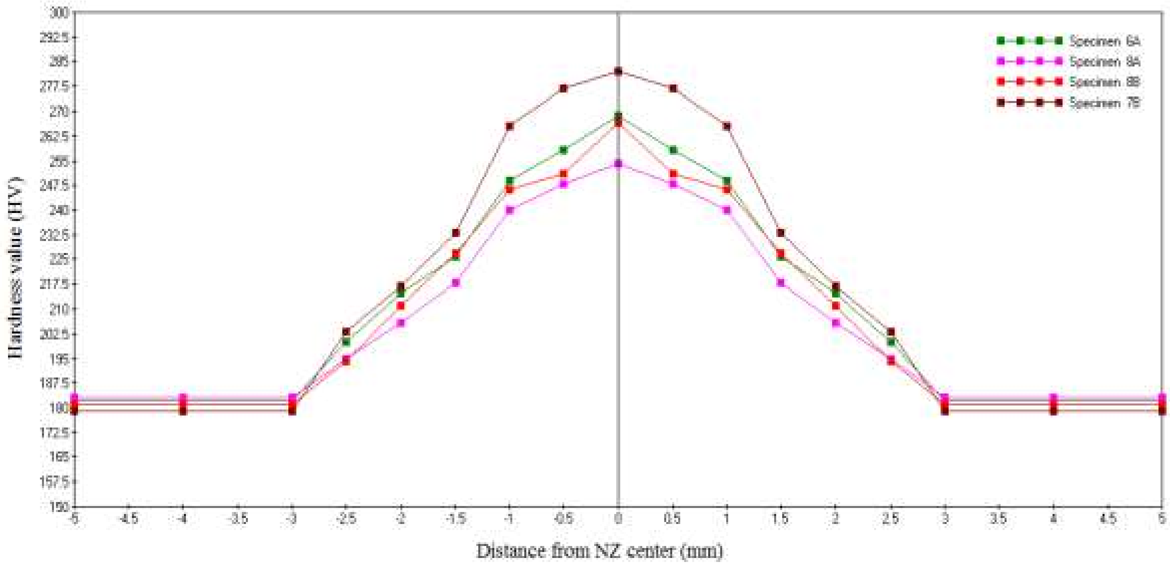


Figure (20) Hardness values of similar joint for AISI 304L

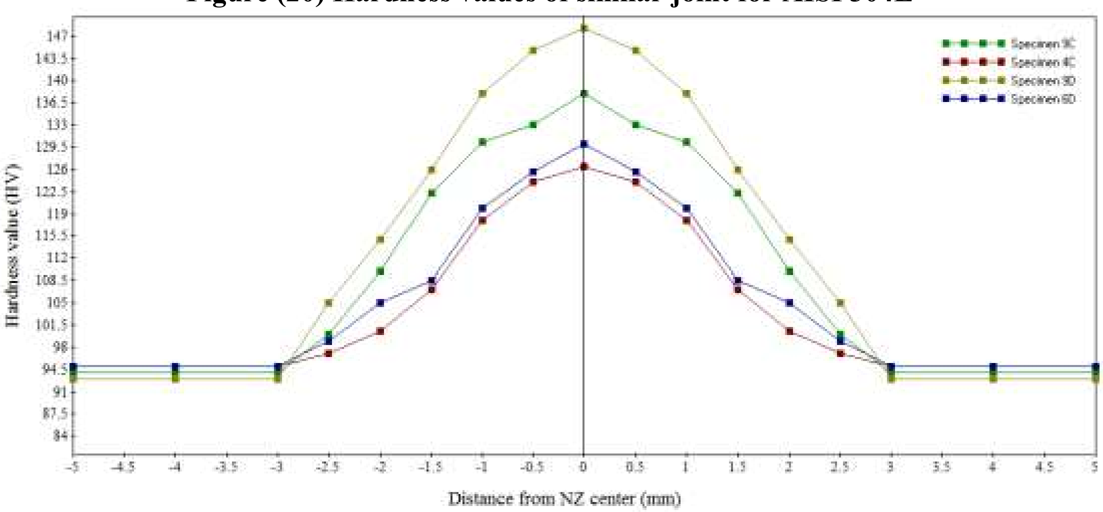


Figure (21) Hardness values of similar joint for AA 6061-T6

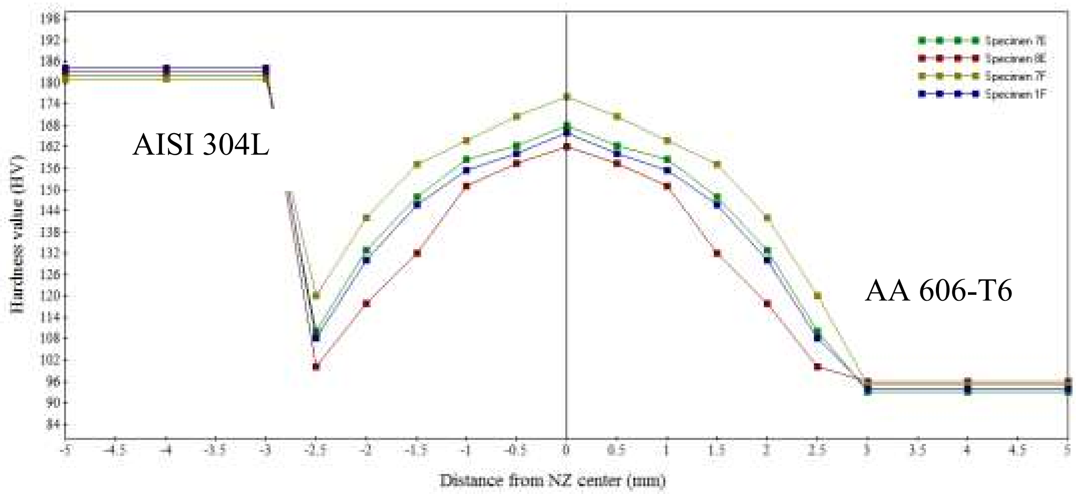


Figure (22) Hardness values of dissimilar joint for (AISI 304L with AA 6060-T6)

Macrostructure Test

After conducting the microstructure test, examination the weld cross-section show that the microstructure of base metal, HAZ and NZ is various from one region to another. The following results have been obtained, fig. (23, 24, and 25):

- When welding similar AISI 304L, it was observed the microstructure consists of austenitic grains showing good shape and columnar dendritic structure, Fig. (23).
- The microstructure of similar AA 6061-T6 in NZ consists of very fine equiaxed grains (smaller size) and uniformly distributed fine precipitates (Mg_2Si), Fig. (24).

In general, welding current and welding time are the most important factors in controlling heat input for resistance spot welding. Spot weld parameters are the reason for the variation of microstructure. The microstructure of all these spot welds structure is influenced by the degree of cooling. The microstructure of dissimilar welding is shown in figure (25).

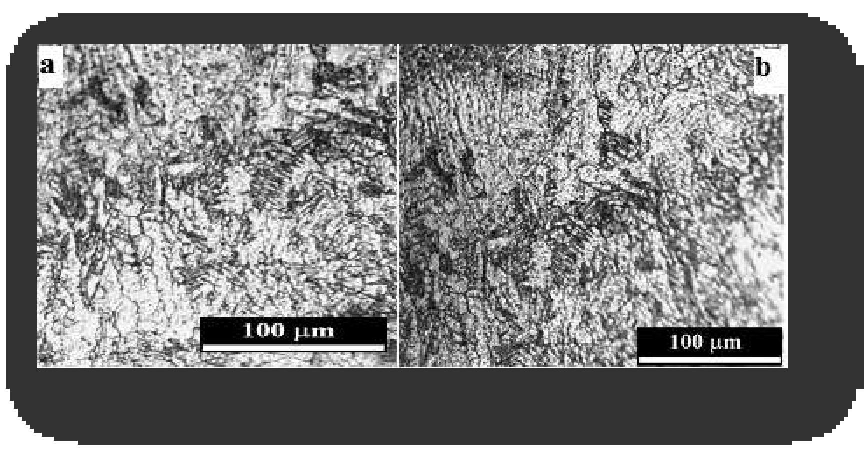


Figure (23) Microstructure of similar joint of AISI 304L, (a) t = 0.5 mm (b) t = 0.7 mm

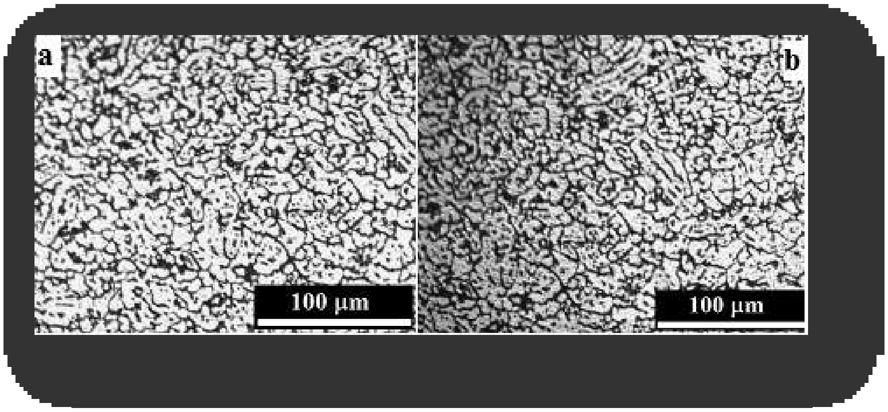


Figure (24) Microstructure of similar joint of AA 6061-T6, (a) t = 0.5 mm (b) t = 0.7 mm

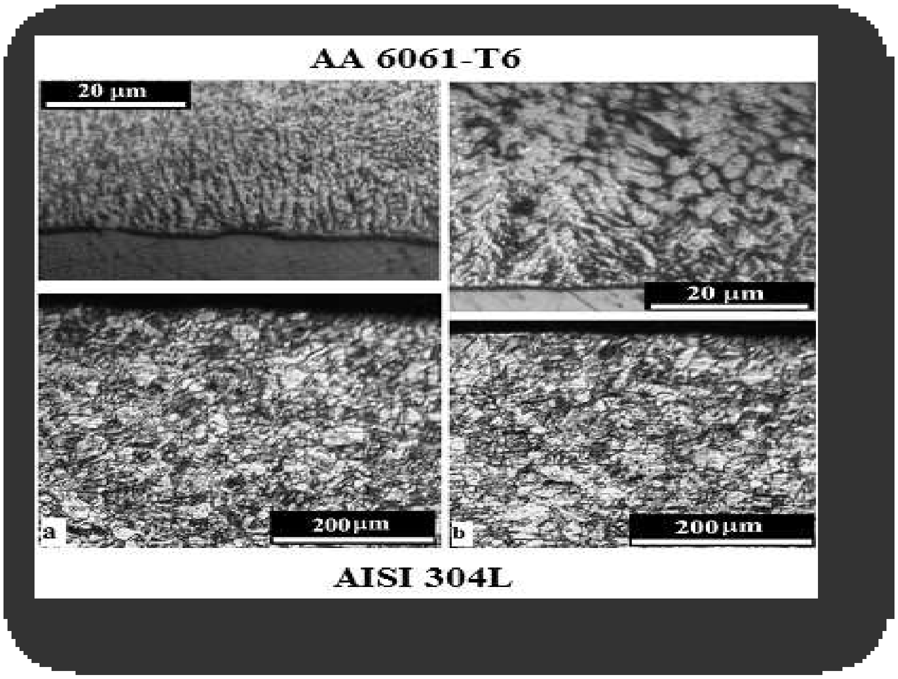


Figure (25) Microstructure of dissimilar joint of AISI 304L with AA 6061-T6, (a) t = 0.5 mm (b) t = 0.7 mm

CONCLUSIONS

1- Increasing the thickness results an increasing in the shear force of spot welding.
2- The higher values of shear force are found in the welding of similar 304L and 6061-T6.
3- The lower values of shear force are obtained in the welding of similar joint of Aluminum specimens.
4- The maximum shear force (F = 4.78 KN) is observed in welding of similar joints of AISI 304L (with thickness = 0.7 mm), while the minimum shear force (F = 0.07 KN) is observed in welding similar joint of AA 6061-T6 (with thickness = 0.5 mm).
5- Using DOE; the maximum shear force (4.78 KN) has been optimized to reach the value (5.13 KN) and the minimum ultimate shear force (0.07 KN) has been optimized to reach the value (0.6567 KN).

6- For dissimilar joint, the maximum shear force (1.42 KN) has been optimized to reach the value (1.54 KN).
7- The center of nugget zone has the maximum value of hardness and then decreases gradually through the HAZ and base metal.
8- The micro hardness value in NZ for similar joint of AISI 304L was higher than that of similar (AA 6061-T6) and dissimilar joint AISI 304L with AA 6061-T6.
9- The NZ microstructure of AA 6061-T6 consists of very fine equiaxed grains uniformly distributed.
10- The NZ microstructure of AISI 1010 consists of austenitic grains showing columnar dendritic structure.

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