# Analysis and Optimization of Resistance Spot Welding Parameter of Dissimilar Metals Mild Steel and Aluminum Using Design of Experiment Method

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**Abstract**

This research aims to study the effect of parameters of the resistance spot welding (RSW) on the shear strength of the spot weld for different metals {AA 6061-T6 and AISI 1010} using (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 have been analyzed by Minitab program by design of experiments (DOE) in order to determine and reduce the number of specimens required to achieve the tests. The design of experiment method which used was Taguchi method

The experimental tests that had been done are shear, Microhardness and microstructure tests. It was found that the maximum shear force in welding of dissimilar metals (AA 6061-T6 with AISI 1010) is (F = 1.14 KN for t = 0.7 mm ). This value has been optimized to reach (F =1.24 KN) using DOE. The minimum shear force was (F = 0.25 KN in t = 0.5 mm).

In general, increasing the welding current and sample thickness gave an increase in the shear force, but at the same time the reduction in shear force have occurred during the increasing in electrode force, squeeze time and welding time. From Microhardness tests, the maximum value of hardness is found at the center of nugget zone (NZ) and it reduces slightly until reaching constant values away from NZ.

**Keywords**: resistance spot welding, dissimilar welding, DOE

## تحليل وأمثلة متغيرات لحام المقاومة النقطي للمعادن المختلفة حديد المطاوع والألمنيوم باستخدام طريقة تصميم التجارب

**الخلاصة:**

هذا البحث يهدف لدراسة تأثير متغيرات لحام المقاومة النقطي على مقاومة القص لنقطة اللحام لمواد مختلفة { AA 6061-T6 and AISI 1010} باستخدام سمك (0.5 , 0.7) ملم. استخدمت ثلاث قيم من

متغيرات اللحام ( تيار اللحام , قوة القطب , زمن الضغط وزمن اللحام ).تم تحليل تأثير هذه المتغيرات باستخدام برنامج (Minitab) بطريقة تصميم التجارب (DOE) لغرض حساب وتقليل عدد العينات اللازمة في الاختبارات. طريقة تصميم التجربة التي استخدمت هي طريقة تاكوشي

التجارب العملية المنجزة هي (اختبار الشد القصي , الصلادة الدقيقة وفحص البنية المجهرية ). وجد ان أقصى قوة قص في لحام المواد المختلفة { AA 6061-T6 and AISI 1010 } هي ( F = 1.14 KN بسمك t = 0.7 mm). تم تحسين هذه القيمة الى (F = 1.24 KN ) باستخدام طريقة تصميم التجارب (DOE). اقل قيمة قوة قص كانت ( F = 0.25 KN بسمك t = 0.5 mm).

بصورة عامة , زيادة تيار الحام وسمك المعدن اعطى زيادة في قوة القص , ولكن بنفس الوقت النقصان في قوة القص حصل خلال زيادة قوة القطب وزمن الضغط وزمن اللحام. من خلال تجربة الصلادة (المجهرية) أقصى قيمة للصلادة لوحظت في مركز المنطقة الصلبة وتقل تدريجيا حتى تصل قيمة ثابتة بعيدا عن هذه المنطقة.

## 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 metal 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 metals sheets. These regions have different metals properties. For example, the yield stress in the nugget is up to three time's upper than in the base metals, 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 metals. 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 metals thickness and type, the quantity of flow current, and the area of the cross-sectional for the contact surfaces of welding tip [4].

The high thermal and electrical conductivity of aluminum require higher current and shorter weld time, typically 25% of that used to RSW steel. Accurate control and synchronization of current and electrode force is required due to the narrow weld temperature range [5].

**Experimental work:**

**Metals Properties:-**

Two types of metals were selected for this research, AISI 1010 Dead Mild Steel and AA6061-T6 Aluminum sheets. For each metal, two different thicknesses have been used (0.5 and 0.7 mm). The specific chemical compositions and mechanical properties of each metal are shown below in Tables (1) and (2) respectively.

**Table (1a): Chemical Composition of AISI 1010**

| | Element wt % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Metals** | **C** | **Mn** | **Cr** | **Ni** | **P** | **S** | **Cu** | **Fe** |
| Nominal [6] | 0.08-0.13 | 0.3-0.6 | - | - | 0.04 | 0.05 | - | Remainder |
| Actual | 0.082 | 0.388 | 0.04 | 0.024 | 0.01 | 0.026 | 0.048 | Remainder |

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

| | Element wt % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Metals** | **Si** | **Mn** | **Mg** | **Ti** | **Cr** | **Cu** | **Fe** | **Zn** | **Al** |
| Nominal [7] | 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 | 0.7 | 0.13 | 1.1 | 0.1 | 0.148 | 0.329 | 0.5 | 0.017 | Remainder |

**Table (2): Mechanical Properties of AISI 1010 and AA6061-T6.**

| | | Mechanical Properties | | |
|---|---|---|---|---|
| **Metals** | | Yield Strength (MPa) | Tensile Strength (MPa) | Elongation EL, (%) |
| AISI 1010 | Nominal [6] | 169 | 305 | 10 |
| | Actual | 195 | 325 | 12 |
| AA6061-T6 | Nominal [7] | 240 | 290 | 10 |
| | Actual | 270 | 305 | 12 |

**Specimens Preparation:-**

In order to carry out the necessary tests required for studying the mechanical properties of the RSW for dissimilar metals, two values of thickness were tested (0.5 and 0.7 mm). The Specimens dimensions were selected in accordance with AWS [8]. Each sample is carried out by cutting up the sheet metal into two plates with the dimensions shown in Table (3), Fig. (1).

**Table (3): Dimensions of the sample**

| Thickness (t) mm | Width (W) mm | Length (L) mm | Contacting Overlap mm |
|---|---|---|---|
| 0.7 | 16 | 76 | 16 |
| 0.5 | 16 | 76 | 16 |

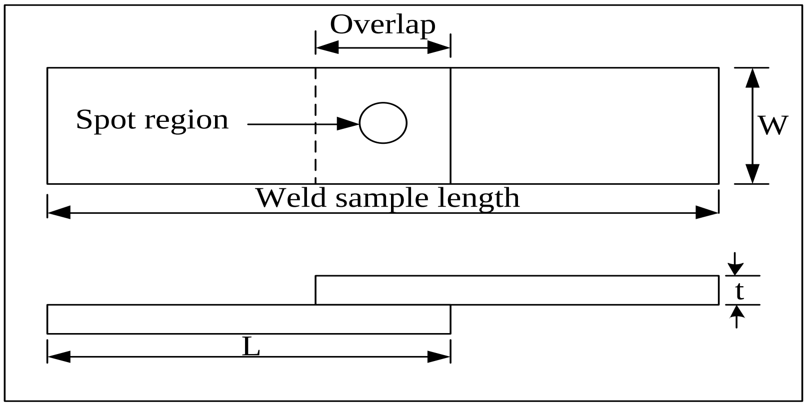



**Figure (1) Overlapping of two welded plates**

## Spot Welding Machine

The welding of the samples was performed on 50Hz power supply. The details of this machine are shown in Table (4). Figure (2) represents the photograph picture of spot welding machine.

**Table (4): Welding Machine Details**

| Manufacturer | DAIDEN(Japan) |
|---|---|
| Type | resistance spot welding machine |
| Transformer Capacity | 30 KVA |
| Electrode Force (max) | 4.5 KN |
| Water Flow Rate | 4 litter / min |
| Cooling Water Temperature | 15 – 25 °c |
| Welding Capacity (sheet metal) | 4+4 mm |
| Welding current(max) | 13600(A) |
| Squeeze Time(max) | 100(c) |
| Welding Time(max) | 99(c) |
| Hold Time(max) | 60(c) |

**Figure (2): Spot Welding Machine**

**Machine Electrode**

There are two types of electrodes which have been used in accordance with AWS based on the welded metals. The electrodes were made of chromium-zirconium-copper alloy by AWS specification with high thermal and electrical conductivity. Each electrode has two different caps and can be classified as follow:

1.The first electrode was a 20˚ truncated conical shape with 5mm circular contacting area RWMA GROUP A class 2 type E was used for AISI 1010 welding.

2.The second electrode was 10mm face diameter RWMA GROUP A class 1 type C was used for AA6061-T6 welding [8].

Dissimilar plates with equal dimensions were welded together by RSW method by placing the plates in between two electrode tips.

**Welding Machine Parameters**

Based on the fact that the weld 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.)
- Pressure electrode force (KN)
- Squeeze time (cycle)
- Welding time (cycle)

Table (5) is refers to the welding parameters that used for welding the dissimilar metals with three levels of welding parameters.

**Table (5): Welding parameters**

| Parameters | Level1 | Level2 | Level3 |
|---|---|---|---|
| Welding current (A) | 11000 | 12300 | 13600 |
| Electrode force (KN) | 1.6 | 2.55 | 3.5 |
| Squeeze Time (c) | 30 | 40 | 50 |
| Welding time (c) | 25 | 30 | 35 |

## Taguchi method

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 weld process modeling is applied for each thickness (0.5 and 0.7 mm).The process variables (and notations) are shown in table (6).

**Table (6): Taguchi Method for Welding Machine Parameters.**

| | Parameters | | | |
|---|---|---|---|---|
| **Specimen No.** | **Welding current (A)** | **Electrode force (KN)** | **Squeeze Time (c)** | **Welding time (c)** |
| 1 | 11000 | 1.6 | 30 | 25 |
| 2 | 11000 | 2.55 | 40 | 30 |
| 3 | 11000 | 3.5 | 50 | 35 |
| 4 | 12300 | 1.6 | 40 | 35 |
| 5 | 12300 | 2.55 | 50 | 25 |
| 6 | 12300 | 3.5 | 30 | 30 |
| 7 | 13600 | 1.6 | 50 | 30 |
| 8 | 13600 | 2.55 | 30 | 35 |
| 9 | 13600 | 3.5 | 40 | 25 |

The welded specimens in this work are shown in Figure (3).

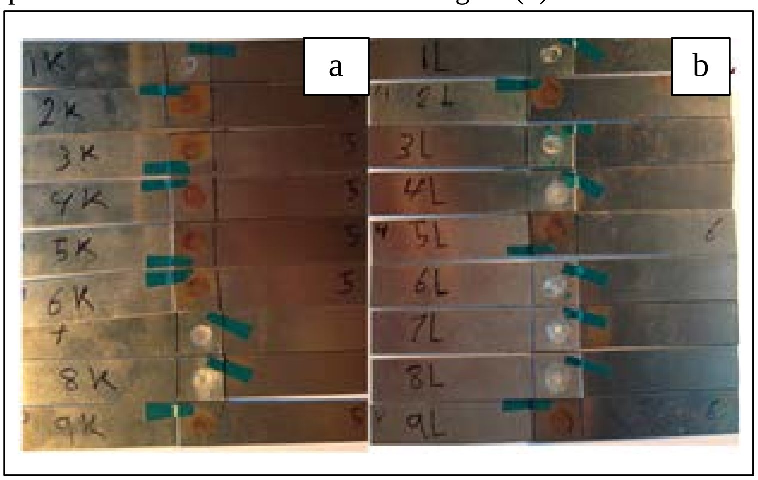



**Figure (3) the welded specimen: (a) t= 0.5 mm (b) t= 0.7 mm**

## Mechanical Tests

### Shear Strength Test

The shear strength test was performed on a rectangular specimen, 76mm in length and 16mm 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 specimens. Figure (5) illustrates the tested shear force specimens.

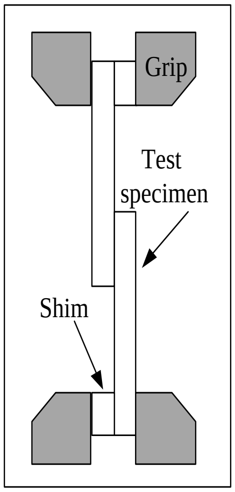



**Figure (4): Schematic of Tensile Strength Test**

**Figure (5) the tested shear force specimens.**

**Microhardness Test**

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

The specimen preparation included grinding and polishing according to ASTM E90-82 [9]. A load of (200 g) was employed and a dwell time was (15sec). Microhardness locations have been taken along straight line starting from the center of spot-weld through HAZ until reaching to unaffected base metal.

**Microstructure Test:-**

To examine the microstructure of base metal, fusion zone and heat affected zone, 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.
- Made cooled 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 respectively) with a rotating speed of 2000 rpm of universal polishing and grinding machine for metallographic specimen preparation. During the grinding process, water was applied as a cooling liquid.
- After the grinding stage was completed, polishing stage started directly, it included using polishing cloth, alumina ($Al_2O_3$), and rotating speed of disc.
- Photo taken stage (etching stage) was started right after the grinding stage, etching stage included immersion specimen in to etching solution by using solution (1-

5mL $HNO_3$ and 100mL ethanol(95%) )for dead mild steel AISI1010 , and solution (2mL HF , 3mL HCL , 5mL $HNO_3$ , and 190mL water) for aluminum AA6061 for few second, then directly specimen was washed with water, also it was directly dried by hot forced air to prevent surface oxidization, according ASTM E 407- 99[10].

## Results analysis

### DOE Results:-

A Minitab program is used to input and analysis the shear strength data. For input variables, uncoded units are used. That means the same data in Table (6) 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 (6):-

The following table (7) represents the ranges of spot welding machine parameters that increase the spot shear force for each thickness:

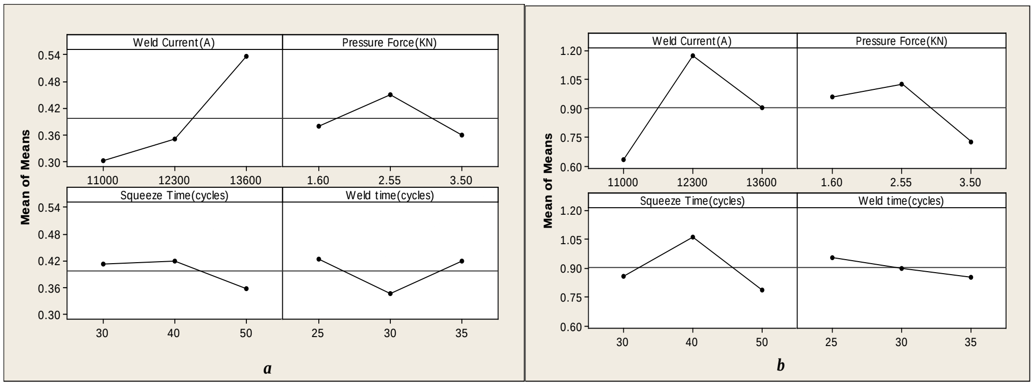
**Table (7) the ranges of spot welding machine parameters that increase the shear force**

| Thickness (mm) | Welding current (Amp.) | Electrode force (KN) | squeeze time (c) | Welding time (c) |
|---|---|---|---|---|
| 0.5 | All range. | 1.6 - 2.55 | 30 - 40 | 30 – 35 |
| 0.7 | 11000 - 12300 | 1.6 - 2.55 | 30 - 40 | - |

Also, table (8) represents the ranges of spot welding machine parameters that decrease the spot shear force for each thickness:

**Table (8) the ranges of spot welding machine parameters that decrease the shear force**

| Thickness (mm) | Welding current (Amp.) | Electrode force (KN) | squeeze time (c) | Welding time (c) |
|---|---|---|---|---|
| 0.5 | - | 2.55 – 3.5 | 40 - 50 | 25 – 30 |
| 0.7 | 12300 - 13600 | 2.55 – 3.5 | 40 - 50 | All ranges |




**Figure(6) Main effects plot for means of shear force [(a) t= 0.5 mm, and (b) t= 0.7 mm]**

## Interactions Plot

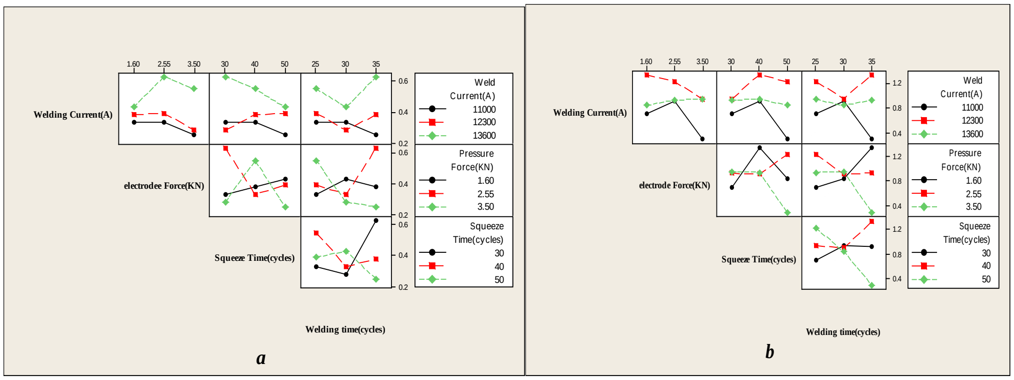
The interactions plot shows the interactions effect of all factor son the response variable (shear force).This method is use to establish which factors having effect of each two welding parameter separately and its impact on the shear, tables (8 and 9) explained those effects for each thickness ( t = 0.5 and 0.7 mm ) respectively:-

**Table (8): parameters that effect on shear force with 0.5mm thickness**

| Welding current | Electrode force | Squeeze Time |
|---|---|---|
| • The (11000 and12300 A) have the same effect on the other welding parameters.<br>• The (13600A) has alternating effect, and gave highest value of shear force. | • The (1.6 KN) nearly has the same effect on the other welding parameters.<br>• The (2.55 and 3.5 KN) give alternating effect. | • The (30, 40 and 50 c) have an alternating behavior with welding time. |

**Table (9): parameters that effect on shear force with 0.7mm thickness**

| Welding current | Electrode force | Squeeze Time |
|---|---|---|
| • The (11000A) has alternating effect, and give lower values of shear force.<br>• The (12300A) has alternating effect, and gave highest values of shear force.<br>• The (13600A) has the same effect on the other welding parameters. | • The (1.6, 2.55 and 3.5 KN) have alternating effect. | • The (30, 40 and 50 c) have an alternating behavior with welding time. |




**Figure(7) Interactions plot of shear force [(a) t= 0.5 mm, and (b) t= 0.7 mm]**

## Pareto Chart

Pareto charts are very helpful for analyzing the parameters requiring interest primarily, since the longer bars at the chart clearly show the variables that have the most significant effect on a given system. In this work, it can be concluded that the welding current has the highest effect on the shear force as comparing with the other parameters for each specimen thicken, figure (8).

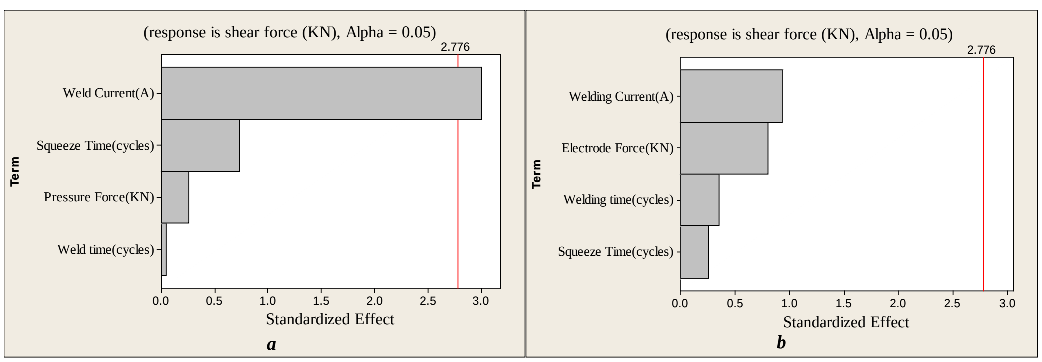



**Figure (8) Pareto chart for shear force, [(a) t= 0.5 mm, and (b) t= 0.7 mm]**

## Response Optimizer

The response optimizer method is used to show which factors have effect on welding parameter separately and their impact on the shear, and which give the best value for the response variable (shear force). Table (10) represents the analysis of optimizer response from (DOE) for shear force, figure (9):-

**Table (10) Shear force optimizer response**

| Thickness mm | Welding current (A) | Electrode force (KN) | squeeze time (c) | Welding time (c) | Shear force (KN) |
|---|---|---|---|---|---|
| 0.5 | 13600 | 1.6 | 30 | 25 | 0.789 |
| 0.7 | 13600 | 1.6 | 30 | 25 | 1.24 |

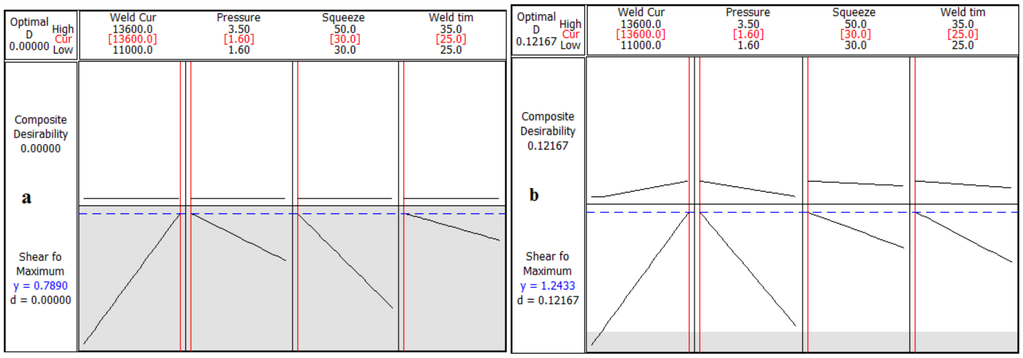



**Figure (9) Response optimizer of shear force, [(a) t= 0.5 mm, and (b) t= 0.7 mm]**

## The Regression Equation

The MINITAB program gives a simple mathematical formula which represents the response as a function of variables. In this work and by using DOE, the following shear force formula is concluded:

- For thickness 0.5 mm

The regression equation is

Shear force = - 0.557 + 0.00009 I - 0.0105$X_1$ - 0.00283$X_2$ - 0.00033$X_3$

- For thickness 0.7 mm

The regression equation is

Shear force = 0.4 + 0.000104 I - 0.123 $X_1$ - 0.0037 $X_2$ - 0.0103 $X_3$

Where:

I: Welding current (Amp.)

X1: Electrode force (KN)

X2: squeeze time (c)

X3: Welding time (c)

From the above results , it has been observed in general that the shear force increases with increasing the specimen thickness under the same boundary conditions. it found any increasing in thickness conduce to increasing in the penetration and the weld nugget diameter and this results lead to increase the shear force.

## Hardness Test

The test was performed on all specimens at (200 g) Load of by Vickers measurements. The average of all four individual readings varied by no more than ±2 Vickers Microhardness 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, Figure (10). The hardness profiles shows skewing of the HAZ and peak hardness away from the region adjacent to the fusion boundary.

As 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.

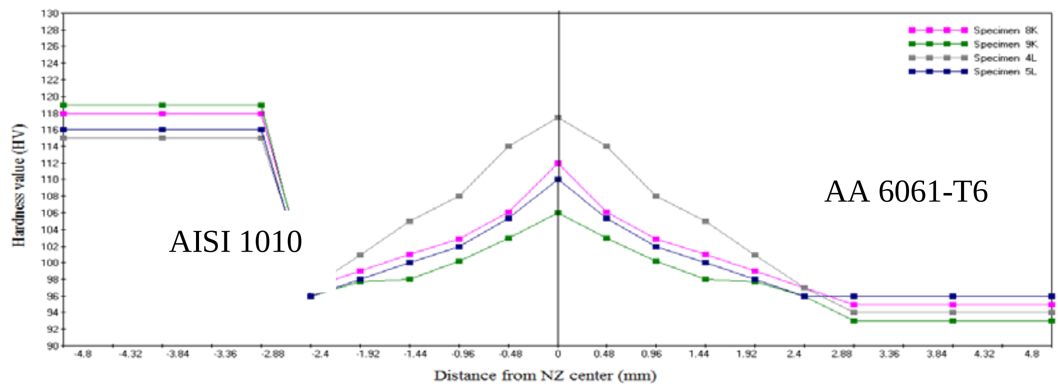



**Figure (10) Hardness values**

## 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, figure (11):

- It was observed that the microstructure of AA 6061-T6 in NZ consists of very fine equiaxed grains (smaller size) and uniformly distributed fine precipitates.
- It was observed the microstructures of AISI 1010 in the NZ and HAZ of the spot welded steel give the mixture of ferrite and binate.

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.

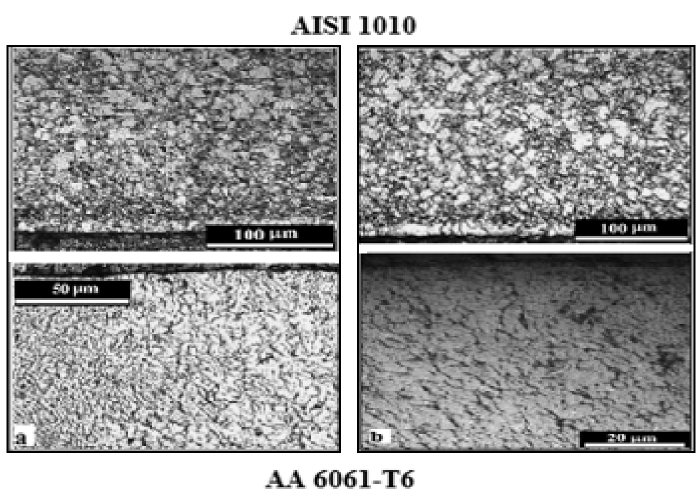



**Figure (11) Microstructure of weld cross section, [(a) t= 0.5 mm, and (b) t= 0.7 mm]**

## Conclusions

1- Increasing the thickness results an increasing in shear force of spot welding.

2- The center of nugget zone has the maximum value of hardness. This decrease gradually through the HAZ.

3- The maximum shear force (1.14 KN) has been optimized to reach the value (1.24 KN) by apply DOE with using welding parameters welding current (13600A), electrode force (1.6 KN), squeeze time (30 c) and welding time (25 c).

4- Due to heat generated, very fine equiaxed grains and uniformly distributed fine precipitates were observed in the NZ of AA 6061-T6.

5- A mixture of ferrite and bainite is observed in the NZ and HAZ of AISI 1010.

6- The nugget diameter is increased when the electrical and thermal coefficients decrease, at the same time the HAZ is decreased when the electrical and thermal coefficients increase.

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