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### OPTIMIZATION OF FRICTION STIR SPOT WELDING PARAMETERS OF DISSIMILAR WELDED JOINTS OF ALUMINUM ALLOY (AA2024T3) WITH PURE COPPER SHEETS

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#### ABSTRACT

Friction stir spot welding (FSSW) was performed for welding of an aluminum alloy AA2024T3 sheet to commercial pure copper sheet of 2mm thick. Friction stir spot welding are carried out at different tool rotational speeds ( 800,1000 &1250 ) rpm ,plunging times (30 ,60 &90) sec and tool pin profile or geometry ( Threaded cylindrical with flute, Tapered cylindrical and straight cylindrical). Process parameters were optimized by using Taguchi technique and depending on design of experiment (DOE). The aluminum alloy sheet was overlapped on the copper sheet . It was found that maximum shear force was (1527 N) obtained at optimum welding parameters : 1250 rpm rotation speed ,90 sec plunging time and straight cylindrical pin profile which are obtained from the analysis of response optimizer. Pareto chart the standardized effects of tensile shear results showed that the plunging time was the most effect parameter than other welding parameters( rotation speed and pin profile). From temperatures distributions measurements in three points in nugget zone of spot weld , base aluminum alloy(AA2024T3) and base pure copper, it was found that maximum measured temperature was 383 C° in nugget zone of weld .

**KEYWORDS:** Friction stir spot welding, shear force ,dissimilar metals , Taguchi technique.

#### INTRODUCTION

Friction Stir Welding (FSW) process was invented by The Welding Institute (TWI) in 1991 for joining Aluminum alloys[1-2]. Friction Stir Spot Welding (FSSW) is a recent solid state welding technology and it is a variant of the FSW which is found to be environmental friendly and an efficient process. This welding technique is energy efficient, and versatile. FSSW is a novel derivative of “Friction-Stir Welding” (FSW) which is proving to be a better alternative to “Resistance Spot Welding” (RSW). FSSW technique has been gaining ground when compared to resistance spot welding (RSW) , “TIG spot and Laser spot” and could be used in various industries including, automobiles, ship building, aerospace, electrical and construction. FSSW has been successfully used to join several materials used in the above mentioned industries [3-4].

There are many published researches on friction stir welding and processing [ 3-6 ] but so far there is little detailed review on friction stir spot of similar and dissimilar materials.

Fratini et al. [7] [2007] studied the friction stir spot welding (FSSW) of AA6082-T6. In particular, process mechanics is highlighted and joint strength is considered in relation to varying the most relevant process parameters. Furthermore, the results obtained are compared with those derived from the application of traditional mechanical fastening techniques such as clinching and riveting. In this way the effectiveness of FSSW is highlighted.

Tran et al. (2010)[8] investigated the behavior of friction spot welding between AA 5754-O and AA 7075-T6. They showed that, under cyclic loading conditions, the micrographs show that the 5754/7075 and 7075/5754 welds in cross-tension specimens mainly failed from the fatigue crack along the interfacial surface and from the fracture surface through the upper sheet material. Aval et al. (2011) [9] investigated the microstructures and mechanical properties in dissimilar friction stir welding of AA5086-O and AA6061-T6 using thermomechanical model and experimental observations. They found that the hardness in AA5086 side mainly depends on recrystallization and generation of fine

grains in the weld nugget whereas hardness in the AA6061 side varies with the size, volume fraction and distribution of precipitates in the weld line and adjacent heat affected zone as well as the aging period after welding. the finer grain size distribution is achieved within the AA6061 side where higher strain rates are produced.

Muna Khethier Abbass [10][2012] investigated the effect of aging time on mechanical properties of friction stir spot welding process of aluminum alloy AA2024. FSSW was carried out at different welding parameters such as rotational tool speed ( 650 ,750,1000, 1250 and 1500 rpm) and plunging time ( 30, 60 and 90 sec ) with using special tool steel ( X32 ). Solution heat treatment and aging at 190°C for various times were performed for welded joints at optimum welding conditions which are rotational tool speed of 750 rpm and plunging time of 60 sec. It was also found that the maximum shear force and hardness of spot welded joints reach maximum values when aging times were 3hr and 5hr respectively at 190°C.

Ozdemir et al. [11][2012] produced friction stir spot welds using three different plunge depths ( 2.8, 4 and 5 mm), using a tool with a shoulder diameter of 20 mm and a pin with a diameter of 5 mm with using 1600 rpm rotation speed. They produced free- defects spot welds with resulting grain sizes on the copper side close to the Al/Cu interface were finer than those of copper base metal. This is due to the effect of the rotating pin which deformed the grains close to the interface and the recrystallization of grains in the stir zone of the copper metal due to heat input. Krishna et al. [12][2013] used the Taguchi experimental design technique to determine the optimum friction stir welding parameters for dissimilar Al2024-T6 and Al6351-T6 alloys. Effect of FSW process parameters such as tool rotation speed ,welding speed and axial force on tensile strength was evaluated. A mathematical model based on non-linear regression was developed to establish relation between welding parameters and tensile strength. From ANOVA it's found that the speed of tool rotational, speed of welding and force of axial have 67.31%, 13.7% and 14.5% contribution respectively.

Rathod et al. [13] (2014) studied the FSSW of aluminum alloy 6061-T6 and mild steel sheets of thickness 1.5 mm using circular pin tool. Tool rotation speed, plunge depth and dwell time were varied to determine the effect of individual welding process parameter on lap shear load. Process parameters were optimized by using Taguchi technique. The optimum values for processing parameters were obtained as 2800 rpm rotational speed, 0.9 mm plunge depth and 8 sec dwell time. Maximum lap shear load of about 2250N was obtained.

Mukuna P. Mubiayi et al.[ 2014] [14] focused in their reviews on showing the current status of FSSW between similar and dissimilar materials and suggestions to fill the gaps to expand FSSW industrially. They reviewed on FSSW studies are briefly summarized in terms of the evolving microstructure and mechanical properties between aluminum alloys and other materials such as copper, steel and magnesium.

### The aim of this work

A Little researches and a few published results are available about friction stir spot welding of aluminum alloys and pure copper and studies on temperature distribution history during FSSW process in weld or nugget zone of dissimilar metals .Therefore, it is of importance that more research on FSSW and to optimize the FSSW process parameters of (Al2024T3 and commercial pure copper in this study), using Taguchi technique for design of experiment DOE in this study.

## EXPERIMENTAL WORK

### 1-Materials used:

In this study 2mm thick aluminum alloy AA2024T3 and commercial pure copper sheets ( 99.8%)were used as base materials. Chemical composition analysis of these materials or metals were done using spectrometer instrument ARL in COSQC laborite's are shown in **Table 1**. Tensile test was carried out to determine the mechanical properties of base metals according to ASTM standard E8M -09 for sub size specimen as shown in **Table 2**.

*Table 1. Chemical composition of AA 2024T3 Al-alloy and pure copper*

Element wt%	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Pb	V	Al
Nominal value	0.5	0.5	3.8-4.9	0.3-0.9	1.2-1.8	0.1	0.05	0.25	0.15	0.05	0.05	Bal

Measured value	0.126	0.280	4.37	0.593	1.27	0.0013	0.0099	0.166	0.0167	0.008	0.01	Bal
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Table 2. Mechanical properties of base metals, AA 2024T3 Al-alloy and pure copper

Alloys	Yield strength(Mpa)	Tensile strength (Mpa)	Elongation %
AA2024-T3	345	450	22
Pure copper	141	173	51

**2-FSSW Procedure**

FSSW process was performed by using vertical universal milling machine type (DECKEL FP4M NC-Germany) to fabricate overlap welded joints where the Al2024T3 sheet was upper that placed on top of pure copper which was lower sheet. To order to develop the FSSW process , a properly designed clamping fixtures of carbon steel plates were used to fix the work pieces or metal sheets to be welded. Additionally proper backing sheets were used to obtain the desired lap spot joints. The work pieces have a 25x 25 mm<sup>2</sup> overlap area. During FSSW, the friction between the shoulder pin and the work pieces generates most of the heat energy for joining. The tool used in welding operations were machined from high speed tool steel which has hardness of 54 HRC. Three tools pin profiles (threaded cylindrical with flute, tapered cylindrical and straight cylindrical ) were used to fabricate the joints in this study as shown in

**Figure 1.**

The alignment and dimensions of overlap work pieces to be spot welded indicated in **Figure 2**. FSSW process steps to join the dissimilar metals of Al2024T3 and pure copper are shown in **Figure 3**.

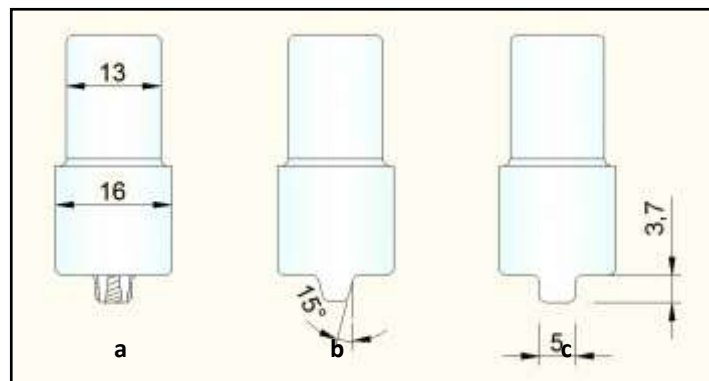
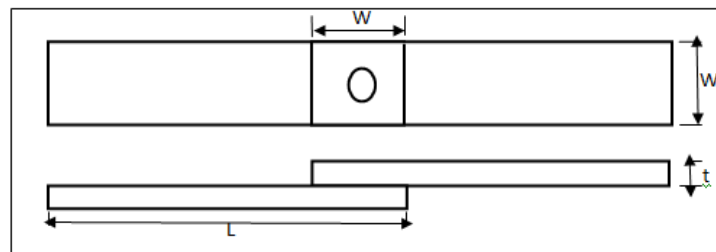


Figure 1 FSSW tool profile and pin size used in this study a) Threaded cylindrical with flute (ThC), b) Tapered cylindrical (TC), Straight cylindrical (SC)



W=25 mm, t=2 mm L=107 mm

Figure 2 Shows the dimensions of overlap work pieces to be spot welded



Figure 3 FSSW process steps to join the dissimilar metals of Al2024T3 and pure copper

(a) Pre heating step ( Dwell time ),(b) Plunging step , (c) Retraction step , (d) Finished spot welded sample  
3-Design of Experiment

FSSW process was carried out at different welding parameters. Taguchi deigns L9 Orthogonal array method was applied as a DOE tool and the FSSW welding parameters were used as variable in the experimental work : rotational tool speed ,plunging time and tool pin profiles and the tilt angle was constant at (0°). Three experiments were carried out on each set of parameters of process. Table 3 shows the parameters and the levels of the process. A total of nine experimental runs were made, a combination of levels was used for each control factor as given in Table 4.

Table 3. Parameters and their levels of FSSW

Parameter	Level 1	Level 2	Level 3
Rotation speed ,RS( rpm)	800	1000	1250
plunging time , PT (sec)	30	60	90
pin profile ,PF	Straight cylindrical (SC)	Tapered Cylindrical (TC)	Threaded cylindrical with flute (ThC)

Table 4. Experimental design of L9 Orthogonal array

Experiment No.	RS(rpm)	PT(sec)	PF
1	800	30	SC
2	800	60	TC
3	800	90	ThC
4	1000	30	TC
5	1000	60	ThC
6	1000	90	SC
7	1250	30	ThC
8	1250	60	SC
9	1250	90	TC

#### ***4-Tensile shear test***

Tensile shear strength was performed on a spot welded specimen with 189 mm length , 25mm width and 2mm thick. Welded lap shear specimens were tested on an Instron machine ,TGM –France machine Model (03M3818.1) at a constant crosshead speed of 5 mm/min with maximum load 100 KN. This machine is available in Metallographic Lab in Institute of Oil Training, Baghdad. For lap shear tensile test, the spot welded specimens of dissimilar metals ( Al2024T3 and pure copper) were gripped with using shims of thickness equal to that of the specimens as shown in **Figure 4**. The maximum shear load was recoded at fracture point during the test for each FSSW specimen.



**Figure 4** Tensile shear test for spot welded specimen with using shims pieces

#### ***5-Microstructure Examination***

Microstructure examination was carried out on cross section of spot welded specimen of dissimilar metals( Al2024T3 and pure copper) and base metals using optical microscope type( OPTIKA -ITALY) provided with computer. A specimens preparation was made including wet grinding process with using SiC paper in different grits of 320,500, 800, 1000 ,1200 and 2000, and then polishing process was performed with using 10  $\mu\text{m}$  diamond past and lubricant and then alumina solution with 3.0  $\mu\text{m}$  with special cloth to obtain polished surface . To examine the microstructure of specimen, etching process was done using etching solution which consists of (1ml HF+99 ml distilled water) for Al2024T3 sheet while it was ferric chloride solution for pure copper sheet. Macrostructure and photographs of cross section were obtained to study welding zones of joint at optimum welding conditions.

#### ***6-Temperatures distributions Measurement***

Thermal and temperatures distributions in spot welded joint and base metals were measured during thermal cycle of FSSW process by inserting three thermocouples type K in three locations or points in nugget (weld)zone, base metal(Al 2024T3) and base metal (pure copper) respectively as shown in **Figure 5**. The first thermocouple was welded in the center of lower sheet ( in center of nugget zone ). Second and third thermo-couples were welded at distance 25 mm from the center of weld in both sides for Al2024T3 and pure copper respectively. These three thermo-couples were welded locally by using thermo-couples magnetic welder device. Temperatures values were recorded in same time using video camera model SONY and photographs of this process were obtained. The thermal cycles and temperatures distributions history were investigated in this study.

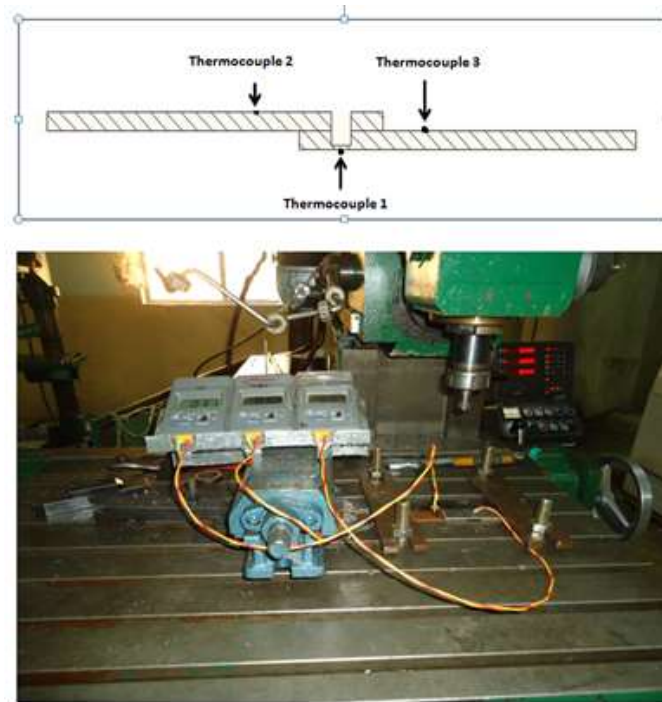


Figure 5 Thermal cycles and temperatures distributions measurement system, a) Three locations or points of thermo-couples , b) Temperatures readers devices

**RESULTS AND DISCUSSION**

**1-DOE Results**

Design of experiment is used to assess the input important factors and interactions that are important to response. In this investigation , a Minitab program 17 is used to input and analysis data. Tensile shear force (shear strength) is an important response property taken into consideration in friction stir spot welding process (FSSW) because it describe the quality of spot welded joints.

**Table 5** shows three levels of welding process parameters as per L9 orthogonal array and means of tensile shear force. **Figure 6** shows the means effect plot for means of dissimilar welded joints of (Al2024T3 and pure copper).

*Table 5. Tensile shear force in experiment*

Experiment No.	RS(rpm)	PT(sec)	PF	Tensile shear force (Mean ) N
1	800	30	SC	1060
2	800	60	TC	960
3	800	90	ThC	760
4	1000	30	TC	1480
5	1000	60	ThC	1440
6	1000	90	SC	1400
7	1250	30	ThC	1360
8	1250	60	SC	1080
9	1250	90	TC	1160

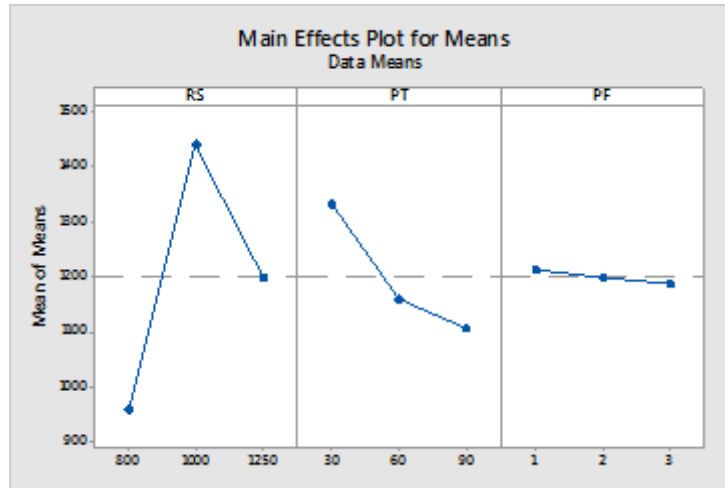


Figure 6 Shows the means effect plot for means of dissimilar welded joints of (Al2024T3 and pure copper)

In this study, Signal to Noise ratio (S/N ) was selected in terms of the standard of the “larger is better” in order to maximize the response. In this study the maximum shear force data were analyzed to know the effect of FSSW parameters. Figure 7 shows the means effect plot for means of tensile shear force and corresponding S/N ratios of dissimilar welded joints of (Al2024T3 and pure copper).

It was found that the maximum tensile shear force is to be largest with tool rotation speed of 1000 rpm ,plunging time of 30 sec and straight cylindrical pin profile (SC) which represents the best results obtained from experimental work.

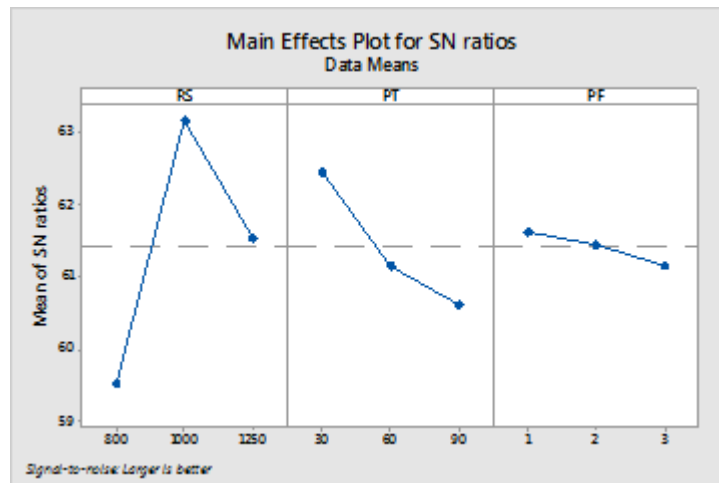


Figure 7 Shows the means effect plot for S/N ratios of dissimilar welded joints of (Al2024T3 and pure copper).

The response optimizer method is used to show welding parameters which have the best value of maximum shear force and their impact on shear force as shown in Figure 8. It was found that maximum tensile shear force was 1527 N at optimum welding conditions with rotation speed of 1250 rpm, plunging time of 90 sec and straight cylindrical pin profile which are obtained from the analysis of optimizer response from DOE for shear force for dissimilar spot joint of (Al2024T3 and pure copper). These results were performed experimentally and it was found that these optimal results are closely to experimental results with errors approximately 1.0%

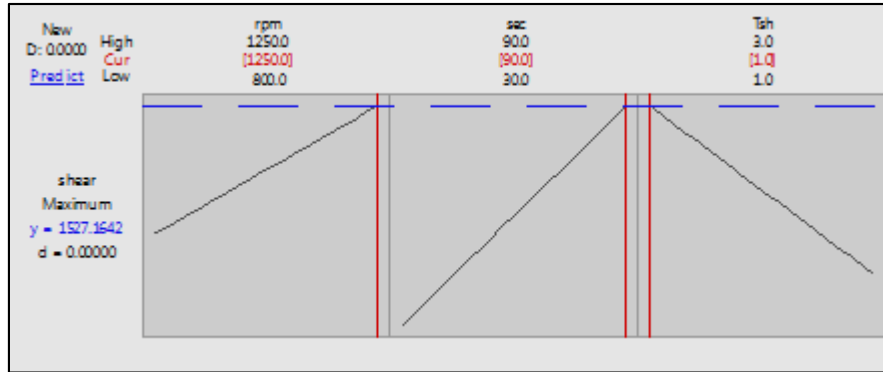


Figure 8 Response optimizer of dissimilar spot welded joints of (Al2024T3 and pure copper)

Pareto Charts are useful and helpful method for analyzing that parameters or variables requiring interest primarily since the longer bars at the chart clearly shows that the variables have the most significant effect on a given system [15]. The chart represents the absolute value to the effects and draws line as the reference at the chart. The method Minitab uses to draw Pareto chart of the effects depend on the freedom degrees for the term of error.

It was seen from Pareto chart the standardized effects of tensile shear results ( in case of effect single factor ) that the plunging time ( factor B ) is the most effect parameter as compared with others ( factors A & C ). It was found that the contribution percentage was 48.61% for plunging time followed by tool rotation speed 45.66 % and the pin profile 5.73% as shown in **Figure 9**. While in case of effect combined two factors , Pareto chart the standardized effects of tensile shear results showed that the plunging time and tool pin profile ( factor BC ) were more effect parameter than others ( factors AB & AC ) as shown in **Figure 10**.

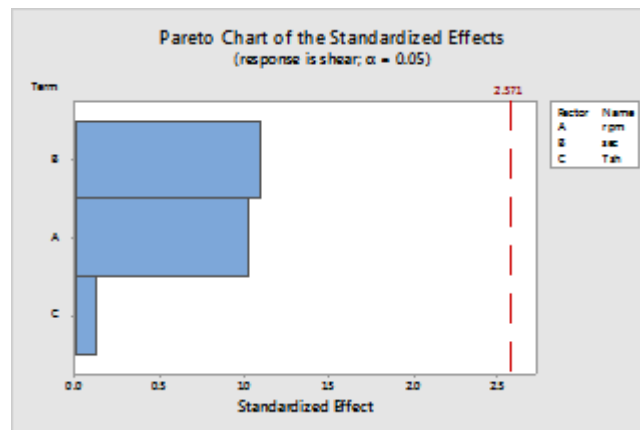


Figure 9 Effect of welding parameters on shear force ( single factor)



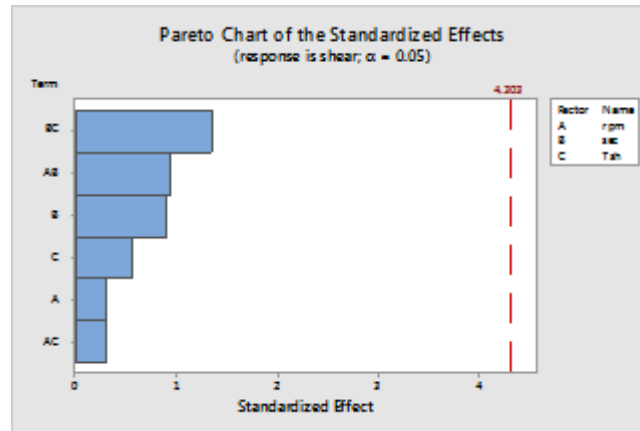


Figure 10 Effect of welding parameters on shear force ( combined two factors)

## 2- Macro and Microstructure Examination

Figure 11 shows macrostructure of the cross section of the spot weld (FSSW) of Al2024T3 and pure copper which was welded at optimum conditions . It was seen there are five zones that have different characteristics including the base Metal (BM), the Heat Affected Zone (HAZ), Thermomechanically Affected Zone (TMAZ), the Stir Zone (SZ) and the Hook on both sides of spot joint.

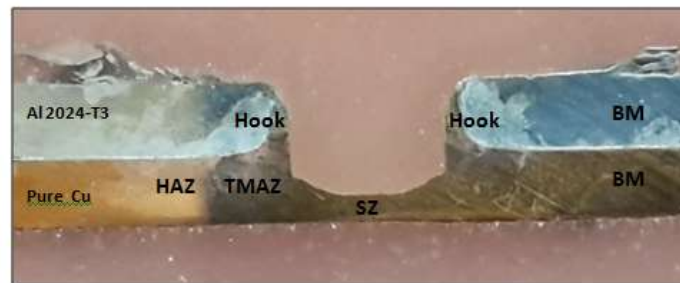


Figure 11 Macrostructure photograph of cross section of dissimilar FSSW joint of Al2024T3 and pure copper

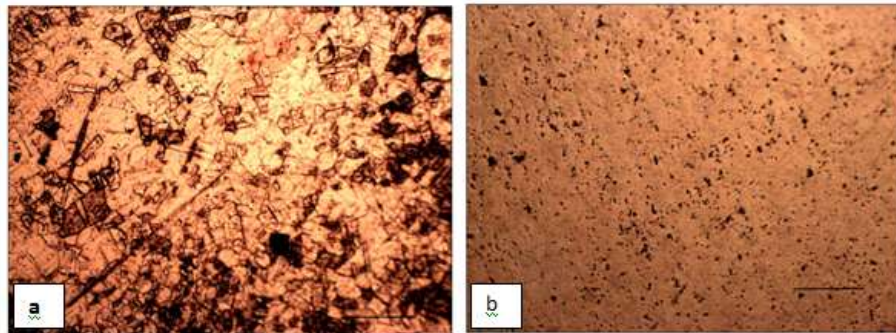
Figure 12 (a & b) shows the microstructures of the base metals of pure copper and Al2024T3 respectively. The microstructure of Al2024T3 sheet contains from matrix of solid solution ( $\alpha$ ) and fine ( $\theta$ ) precipitates distributed uniformly in matrix while in case of copper sheet, the microstructure has one phase of copper twin grains.

The base metal (BM) is the material that is remote from the welded region that has not been deformed; however it may have experienced thermal cycling from the weld. This is not affected by the heat in terms of the microstructure or the mechanical properties. Figure 13 shows the microstructures of the cross section of FSSW joint of (Al2024T3 to pure copper) which was welded at optimum welding parameters .

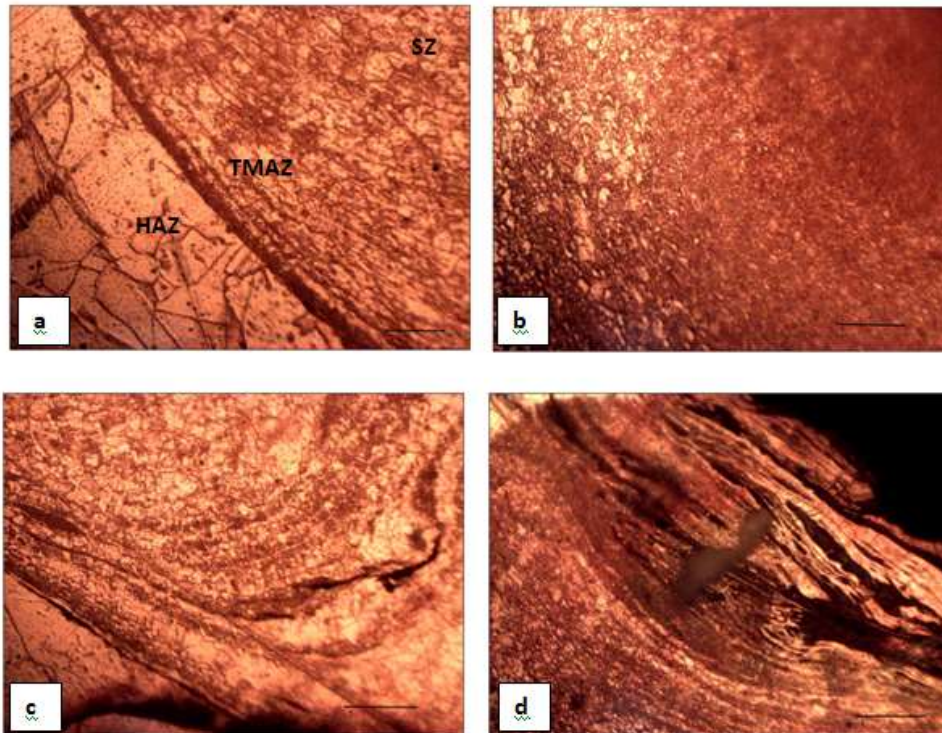
The heat affected zone (HAZ) is the region which lies closer to the weld-center and has experienced a thermal cycle during welding which has modified the microstructure and/or the mechanical property, there is no plastic deformation in this region (Figure 13a). Whereas, the thermomechanically affected zone (TMAZ) is present in the region where the tool has plastically deformed the material. In some metals , it is possible to obtain significant plastic strain without recrystallization in this region. There is a distinct boundary between the recrystallized zone and the TMAZ ( Figure 13a). The weld zone or stir zone (SZ) is the fully recrystallized region that is, in the immediate vicinity of the tool pin. The grains within the stir zone are roughly fine and equiaxed grains and often an order of magnitude smaller than the grains in the base metal (or parent material), This due to higher temperature and severe plastic deformation result in smaller grains in microstructure of stir zone[16] as shown in Figure 13b.

Figure 13c shows the interface between HAZ and TMAZ at high magnification, it was noticed that the union rings are in advancing direction of tool rotation ,while Figure 13d represents the stir zone showing with good mixing and

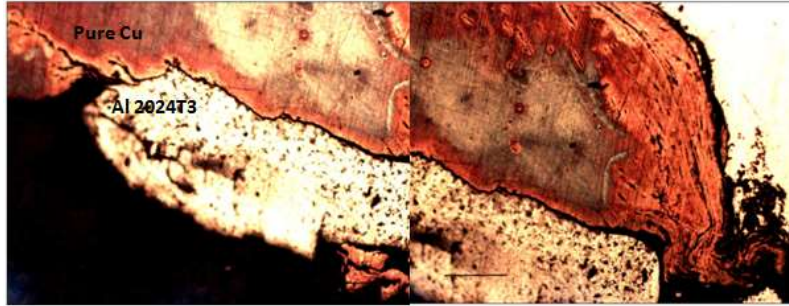
diffusion at Al alloy/ pure Cu interface and also good interference between two metals of Al2024T3 and pure Cu was observed. These results are in agreement with those of researchers [17]. Whereas, the Hook is a characteristic feature of friction stir spot welds in lap configuration where there is a formation of a geometrical defect originating at the interface of the two welded sheets [18], as shown in **Figure 14**.



**Figure 12** Microstructure of base metals at 100x a) Pure copper b) Al2024 T3



**Figure 13** Microstructures of different zones in FSSW joint at 400x  
[1] Interface between HAZ and TMAZ and SZ , b) Stir zone ( SZ)  
c) Interface between HAZ and TMAZ , d) Stir zone showing with good mixing and interference between two metals Al2024T3 and Pure Cu

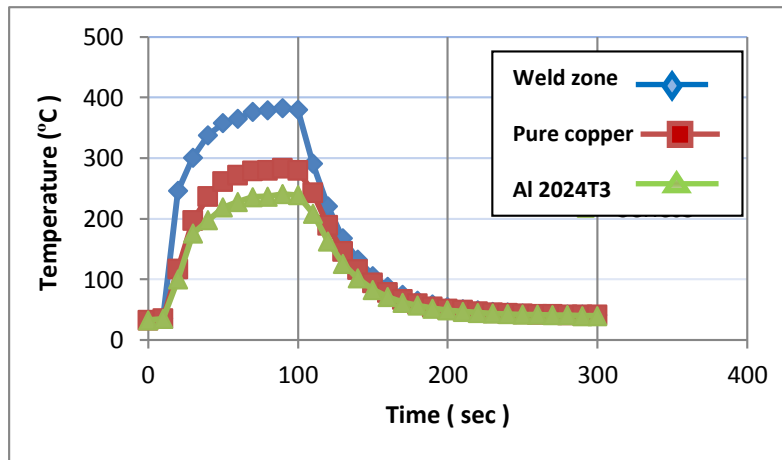


**Figure 14** Microstructure of cross section of FSSW joint showing interface zone between Al 2024T3 and pure Cu and Hook in spot weld at 100x

### 3- Temperatures Distributions and Thermal Cycles Results

During friction stir welding the tool rotates in work pieces without plunging. Frictional is generated in plunging and stirring phase, thus the material adjacent to the tool is heated and softened. The softened upper and lower workpieces of Al2024T3 and pure copper respectively mix together in the stirring phase resulting a weld joint as mentioned above. During FSSW process produces high temperatures and thermal cycles in nugget (weld) zone and base metals as shown in **Figure 15**. The nugget zone exposes to maximum or peak temperature due to rapid heating and cooling cycles during welding, where the temperature may increase to recrystallization temperature because recrystallization requires diffusion and diffusion takes time [19]. Then the temperature decreases toward the TMAZ, HAZ and base metal which becomes the longer the material stays at high temperature, so that grain growth in HAZ and base metal can also be explained with help of thermal cycles as shown in **Figure 15**.

In this study three thermocouples were inserted in nugget (stir) zone and base metals of Al2024T3 and pure copper respectively. Temperatures values measurement was performed as a result of severe deformation, which dislodged the thermocouple ports at the connection points at 25 mm from weld center. It was noticed that maximum actual measured temperature was 383°C in nugget zone of dissimilar spot weld, 241°C and 283°C for base aluminum alloy AA2024T3 and base pure copper respectively. These results are in good agreement with those established in [20].



**Figure 15** Thermal cycles and temperatures distributions in weld zone and base metals

## CONCLUSIONS

- 1-Friction stir spot welding of dissimilar metals of Al2024T3 with pure copper sheets was successfully performed and gave good lap welded joints .
- 2-It was found from experiment work that tensile shear force increases with increasing tool rotational speed up to specific limit and with decreasing plunging time at same tool pin profile.
- 3- The FSSW joints produced with using the straight cylindrical pin profile showed the highest shear force as compared with other pin profiles used in this study.

- 4- The highest tensile shear force was (1527 N) obtained at optimum welding parameters with rotation speed of 1250 rpm, plunging time of 90 sec and straight cylindrical pin profile which are obtained from the analysis of response optimizer.
- 5- Pareto chart the standardized effects of tensile shear results showed that the plunging time was the most effect parameter than other welding parameters( rotation speed and pin profile).
- 6-The macro and microstructural studies revealed that good mixing and high interference between dissimilar metals that had been takes place on the weld joint interface.
- 7- It was found that maximum measured temperature was 383 °C in nugget zone of dissimilar spot weld for base aluminum alloy ( AA2024T3) and base pure copper.

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