Optimization and Characterization of Friction Stir Spot Welding of Aluminum Alloy (AA 5754-H114) with Pure Copper Sheet

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Abstract. Friction stir spot welding (FSSW) was conducted to weld a sheet of an aluminum alloy (AA5754-H114) to a commercial sheet of pure copper (Cu) having (2 mm) thickness. It was performed at various tool rotating speeds (800, 1000, and 1250 rpm), times of plunging (30, 60, and 90 sec) using a tool pin geometry or profile (straight cylindrical, threaded cylindrical with the flute, and tapered cylindrical). The welding process parameters were optimized based on the Taguchi method relying upon the design of experiment (DOE). The used sheet is made of "aluminum alloy" overlapped upon copper sheets. The results manifested that the "maximum" shear forces were found at the best or optimum parameters of welding: (1000 rpm) rotational speed and (90 sec) plunging time when using the straight cylindrical pin profile. The Pareto chart of standardize influences of the tensile-shear outcomes elucidated that the time of plunging was the higher influential parameter than the other welding parameters, such as the speed of rotation and the profile of the pin.

Keywords. Aluminum alloy, Copper sheet, FSSW, Microstructure, Optimization.

1. Introduction
In 1990, The Welding Institute (TWI) invented friction stir welding to join Aluminum alloys [1-2]. Friction stir spot welding (FSSW) is a modern solid-state welding technique, and it is a variation of FSW that establish an ecological and efficacious process. This welding procedure is multipurpose and derived initially from Friction-Stir Welding, which is evidencing to be improved substitute energy efficient, to Resistance Spot Welding (RSW). The friction stir spot welding process has been acquiring ground in comparison with the RSW. TIG spot and Laser spot could be employed in different applications, such as aerospace, building ships, automobiles, construction, and electrical fields. Friction stir spot welding has been positively implemented for joining numerous materials utilized in these industries [3-4]. Ozdemir et al. [2012] [5] made "friction stir spot welds" utilizing three various depths (2.8, 4, and 5 mm) of plunge, a (200 mm) diameter of tool shoulder, and a 5 mm diameter of the pin using a rotational speed (1600 rpm). They made sound spot welds with the resulting more sufficient grain sizes upon the copper side near the
Aluminum/Copper interface than those of the copper base metal. This is due to revolving pin effects that deformed the grains near the interface and the grains re-crystallization within the Cu metal stir zone (SZ) because of heat input. Shen et al. [2013] [6] investigated the mechanical properties as well as the mechanisms of failure of the (FSS) welds for (AA6061-T4) sheets having a thickness of 2 mm and utilizing a high-speed tool steel H13 (JIS, SKD61) ( DIN 1.2344). The tool was manufactured with a 10 mm shoulder diameter and concave profile.

The weld microstructures were divided into (4) zones, SZ, TMAZ, HAZ, and BM; there are dynamic recrystallization and precipitate dissolution inside the weld. It was observed that the spot weld hook geometries change considerably, relying upon the dwell time and the rotating speed. It was also found that the profile of Vickers hardness across the spot weld section showed an upside-down V-shaped or W-shaped look. Due to the effects of the strain-hardening, the lowest hardness reached (46.7 HV) in both (TMAZ) and (HAZ) zones. Rathod et al. [2014] [7] investigated the friction stir spot welding of mild steel and aluminum alloy AA 6061-T6 sheets having a thickness of (1.5 mm) and using a circular tool pin. Plunge depth, dwell time, and tool rotation speed were changed to determine individual welding parameters' effects upon the lap shear force. The parameters of the welding process were optimized via implementing the Taguchi method. The optimum values of these parameters were determined as (0.9 mm) plunge depth, (2800 rpm) rotational speed, and (8 sec) dwell time. About (2250 N) maximum lap shear force was obtained. Mukuna P. Mubiayi [2015] [8] conducted the friction stir spot welding of (copper C11000) and (aluminum alloy Al1060) with 3 mm thickness. FSSW was performed via employing two various kinds of tool geometries (a flat shoulder-flat pin and concave shoulder-conical pin), with a shoulder diameter of (15 mm). Two rotational speeds (800 and 1200 rpm) were used with two plunging depths (0.5 mm) and (1 mm) of the shoulder. Results indicated that in most spot welds made, the accomplished mixing of the material was good. In the whole spot welds, a copper ring existed. Also, the length rose with the plunging depth of the shoulder.

FSS welds made at a rotational speed of (1200 rpm) for both geometries of tool displayed a reduction and a small increment in the Cu ring length utilizing these geometries. Muna et al. [2016][9] performed the (FSSW) for the dissimilar sheets of materials (AlA024-T3 and AA5754-H114) having 2 mm thickness at various speeds of rotation (800, 1000 & 1250 rpm) of tool and (30, 60 & 90 sec) times of plunging using a pin profile or a geometry of tool (straight cylindrical, tapered cylindrical, and threaded cylindrical with flute). The process parameters were optimized via employing the Taguchi method based upon DOE. The analysis of data depended upon the Taguchi technique was conducted via Minitab 17 for estimating the (FSSW) important parameters and principal influences, utilizing only a few experimental runs. The "Pareto" charts of "standardized" influences of the "tensile-shear" outcomes revealed that the geometry of the pin was the higher influential factor than the other factors of welding (the speed of rotation as well as the plunging time).

Muna and Kareem [2018] [10] made welded joints by friction stir lap process for the similar and dissimilar sheets of materials (AA1100 with AA6061-T6) having (3 mm) thickness using a new technique and changing the parameters of welding; the speeds of rotation (1000, 1250 and 1600 rpm) of the tool, the speeds of welding (35, 75 and 100 mm/min), and the length of pin (2.8, 5.4 and 5.7 mm) utilizing a tool of a cylindrical-threaded pin profile. The obtained results manifested that the ultimate tensile shear force was (4.93 KN), and the efficiency of the joint was (93%) when the process of welding was achieved via a novel method with utilizing friction stir diffusion welding procedure at 75 mm/min welding speed, 1250 rpm tool rotational speed and employing a 2.8 mm length of the pin. Limited researches studied the effect of the (FSSW) process parameters of dissimilar materials of AA5754-H114 to the pure commercial copper sheets; thus, in the present investigation, more information is introduced. The current study aims to optimize the friction stir spot welding process parameters depending upon the mechanical properties, including the tensile shear force and the microhardness of the FSS welded joints, via employing the Taguchi method based upon the (DOE) of the dissimilar joints.
2. Experimental work

2.1. Materials
A 2 mm thickness of AA 5754-H114 with a commercial pure copper 99.8% was used in the present work. Chemical composition analyses of the nominal and used material were conducted employing spectrometer device (ARL) in the (COSQC) Laboratories, as is displayed in Table (1). The tensile test was done for obtaining the mechanical properties of AA574-H114 and pure copper based upon the ASTM standard E8M-09 for a sub sized sample, as listed in Table (2).

Table 1. The chemical composition of nominal and measured values of used AA5754-H114 alloy.

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Ni  | Zn  | Ti  | Ga  | V   | Other | Al   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|------|
| Nominal | 0.4 | 0.4 | 0.1 | 0.5 | 2.6-3.6 | 0.3 | -   | 0.2 | 0.15 | -   | -    | 0.15  | Bal. |
| Measured| 0.0005 | 0.280 | 0.038 | 0.358 | 2.97 | 0.046 | 0.005 | 0.016 | 0.015 | 0.011 | 0.013 | 0.0327 | Bal. |

Table 2. The mechanical properties of AA5754-H114 and pure copper.

| Alloys     | Yield strength (Mpa) | Tensile strength (Mpa) | Elongation % |
|------------|----------------------|------------------------|--------------|
| AA5754-H114| 191                  | 248                    | 18           |
| Pure copper| 185                  | 228                    | 51           |

2.2. Friction stir spot welding procedure
The friction stir spot welding process (FSSW) was performed using a vertical universal milling machine type ( Deckel FP4M NC) to fabricate the overlapped welds or joints, where the aluminum sheet of AA5754-H114 was placed on the top of the lower sheet of pure copper. In order to improve the FSSW process, properly designed clamping fixtures made of carbon steel plates were used to fix the workpieces or metallic sheets to be welded. Also, appropriate backing sheets were utilized for obtaining the required lap spot joints. The workpieces possess an overlap area of (25 x 25 mm²). Through the FSSW, the friction between workpieces and the shoulder's pin creates most of the heat energy for welding. The utilized tool in the welding processes was made from tool steel with (54 HRC) hardness. Three types of tool pin shapes or profiles (straight cylindrical (SC), tapered cylindrical (TC), and threaded cylindrical with flute ThC) were employed for fabricating the joints in the present investigation as viewed in Figure (1). The dimensions and alignment of the overlapped workpieces required for the FSSW are illustrated in Figure (2). The FSSW process stages to weld the dissimilar metals, such as AA5754-H114 with pure copper, are manifested in Figure (3).

Figure 1. Types of (FSSW) tool profile and size of pin utilized in the present investigation, where (a): Threaded cylindrical having flute (ThC), (b): Tapered cylindrical (TC), and (c): Straight cylindrical (SC).
2.3. Design of experiment

FSSW process was performed at various parameters of the welding process. Taguchi designs L9 Orthogonal array method was used as a DOE tool. The considered FSSW welding parameters in the experimental work are speed of tool rotation, plunging time, tool pin profiles, or shapes. The used tilt angle was constant at (0°). Three tests or "experiments" were done for each set of process parameters. Table (3) shows the parameters and their levels of the process. In total, 9 experiment runs were completed; a grouping of levels was used for every control factor, as given in Table (4).
Table 3. FSSW process parameters with their levels.

| Parameter               | Level 1 | Level 2 | Level 3                  |
|-------------------------|---------|---------|--------------------------|
| Rotation speed, N (rpm) | 800     | 1000    | 1250                     |
| Plunging time, t (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 | Rotation speed, N (rpm) | Plunging time, t (sec) | Pin profile, 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              |

2.4. Tensile shear test

Tensile shear tests of the FSSW samples were done by tensile test instrument type (TGM) with a (100 KN) maximum capacity approved by COSQC in Baghdad. This instrument is available in the "Metallographic Lab/Institute of Oil Training/Baghdad." The overlapped spot-welded sample has dimensions of 25 mm wide and 175 mm in length. To prevent slipping and bending during the tensile shear test, shims from the same materials and thickness were used. The linear velocity of the tensile shear test is 1 mm/min.

2.5. The examination of the microstructure

This examination was achieved upon the cross-section of the FSS welded sample of the dissimilar materials (AA5754-H114 to pure copper) and the base materials employing an optical microscope type (Opitika) connected to a computer. The specimen was prepared by the process of wet grinding utilizing (SiC) paper in various grits (320, 500, 800, 1000, 1200, and 2000), the process of polishing was done utilizing a 10 μm size of diamond past with lubricant. Finally, alumina's solution having a 3.0 μm size with a particular cloth, was used to obtain the polished surface. For examining the specimen’s microstructure, a process of etching was conducted employing an etching solution that contains (99 ml distilled water + 1 ml HF) for the Al Alloy sheet, while it was a ferric chloride solution for the pure copper sheet. Macrostructure and photos of the cross-section were determined to study the joint's welding regions at the optimal welding states.

3. Results and discussion

3.1. Results of the tensile-shear test

Values of the tensile shear force for the samples are evinced in Table (5), and the maximum tensile shear force was obtained in specimen no; (2290 N) at 1000 rpm, 90 sec, and straight cylinder tool (SC). Figures (4) and (5) describe the effects of rotational speed (N) and plunging time (t) on the shear force with different pin shapes, respectively. Figure (4) shows that the maximum shear force was at 1000 rpm,
and the minimum shear force was at (1250 rpm). The straight cylinder tool (SC) with 1000 rpm yielded a maximum tensile-shear force, and the threaded cylinder with flute (ThC) with (1250 rpm) gave a minimum tensile-shear force. From Figure (5), the maximum tensile-shear force was (90 sec.), the minimum tensile-shear force was in (30 sec), the straight cylinder tool (SC) with (90 sec) yielded a maximum tensile-shear force, and the threaded cylinder with flute (ThC) with (30 sec) gave a minimum tensile-shear force. Figure (6) shows the failure of specimens after the tensile-shear test.

Table 5. Values of the tensile-shear force of dissimilar weld (AA5754-H114 to pure copper).

| Run no. | N (rpm) | t (sec) | Pf | Mean Tensile-Shear Force (N) |
|---------|---------|---------|----|-------------------------------|
| 1       | 800     | 30      | SC | 860                           |
| 2       | 800     | 60      | TC | 1450                          |
| 3       | 800     | 90      | ThC | 1480                          |
| 4       | 1000    | 30      | TC | 1790                          |
| 5       | 1000    | 60      | ThC | 2130                          |
| 6       | 1000    | 90      | SC | 2290                          |
| 7       | 1250    | 30      | ThC | 560                           |
| 8       | 1250    | 60      | SC | 1840                          |
| 9       | 1250    | 90      | TC | 1300                          |

Figure 4. Rotational speeds effect on the tensile-shear force.

Figure 5. Plunging time effect on the tensile-shear force.
3.2. Vicker microhardness results

Figure (7) represents the locations of microhardness values for the dissimilar welded specimens.

Figure (8) shows the profile of Vickers hardness across the section of the (FSS) dissimilar weld (AA5754-H114 with pure copper) that was welded at the optimum conditions, at different positions of base metals, (SZ), (TMAZ), and (HAZ). Vickers hardness gradually decreases in the (HAZ) region towards the keyhole, attaining a min value in the perimeter of (TMAZ) and (HAZ). The (SZ) and (TMAZ) hardness increased dramatically, whereas, in the hook, the hardness attains a max value. The discrepancy in the Vickers hardness values in every weld section is due to the complete influences of strain hardening, discrepancies in the dimensions of grain, and the strengthening phase dissolution. Such outcomes agree with the results of previous research [11]. Muna et al. [12,13,14] used the FSW process in butt welding similar and dissimilar aluminum alloys or metals under different conditions. It has been found that the maximum value of hardness was at the stir zone center of the weld and started to decrease away from it. The results demonstrate the intermetallic compound's development in the interface between the dissimilar materials of joints from the X-ray diffraction analysis test. Such compounds are (Mg2Si) and (Al3Mg2) developed upon the substrate of (AA5754-H114) alloy.
3.3. Macro- and microstructure tests

After conducting the macro-and microstructure tests, FSSW cross-sections were examined. The microstructures of BM, HAZ, TMAZ, and SZ are different from one region to another. The following results have been obtained. Figure (9) elucidates the macrostructure of the cross-section of the dissimilar (FSS) weld (AA5754-H114 with pure copper). They were welded at the optimum conditions. There exist (5) zones that possess various features, comprising the base BM, HAZ, TMAZ, (SZ), and the hook on the two sides of the FSS joint.

Figure (10) displays the microstructures of the cross-section of the FSS weld joint (AA5754-H114 with pure copper) that was welded at the best conditions. "HAZ is the region" that lies nearer the center of the weld and has undergone a thermal cycle throughout the process of welding, which has adapted the microstructure and/or the mechanical property; there is no plastic deformation in such zone, as shown in Figure (10a). The (TMAZ) presents a region where the tool has plastically deformed the metal. Certain metals are likely to determine the considerable plastic strain with no re-crystallization inside such a zone. There exists a different boundary between (TMAZ) and recrystallized region, as shown in Figure (10a). The weld zone or SZ is the completely recrystallized zone at an instant neighborhood of the tool's pin. The grains inside SZ are approximately" fine and equiaxed" ones and frequently have an order of value lesser than those grains in base metal; this is owing to the higher temperature and the severe plastic deformation outcome in smaller grains in the microstructure of the stir zone [15], as depicted in Figure (10b).
(10c) exhibits the boundary between HAZ and TMAZ at high magnification; it was noticed that the onion rings are in the advancing direction of tool rotation, while Figure (10d) denotes the stir zone showing a good mixing and diffusion at the Al alloy/pure Cu interface, and also a good interfering between the two metals of dissimilar joint (AA5754-H114 to pure Cu) was observed. Such outcomes agree with the results of other investigators [16,17].

Figure 10. Microstructures of different zones in the FSSW joint of (AA5754-H114 to pure copper).

The hook indicates a geometric imperfection, lessening the (FSS) welds integrity, since if the weld is exposed to exterior loading, the crack can spread alongside the hook. While, the hook is a distinctive aspect of (FSS) welds in the lap shape where there is a creation of a geometric imperfection that originates at the both joined sheets interface [18], as illustrated in Figure (11). Zhang et al. [19] and Yang et al. [20] indicated that the hook instigated first from the zone between the overlapping metallic sheets, after that it is propagated in a dramatic way rising toward the weld, and eventually, it is detained with a plateau in the SZ periphery. Also, the hook manifested a toothed interface. Meaning that the material that flowed into the top sheet is more than the bottom sheet.

Figure 11. Microstructure of the cross section of FSSW joint showing the interface zone between Al alloy and pure Copper and Hook at 100x.
3.4. Main effect plot of (AA5754-H114 to pure copper)

Figure (12) shows the main effect of rotational speed (N), plunging time (t), and pin profile (Pf) for the specimens of the dissimilar FSSW welded joints from (AA5754-H114 to pure copper). From this figure, the following can be stated:

- The tensile-shear force increased if the speed of rotation increased from (800 rpm) to (1000 rpm).
- The tensile-shear force decreased if the rotating speed increased from (1000 rpm) to (1250 rpm).
- The tensile-shear force increased when plunging time increased from (30 sec) to (60 sec).
- The tensile-shear force decreased when plunging time increased from (60 sec) to (90 sec).
- The tensile-shear force decreased from the (SC) pin profile toward the (ThC) pin profile, and the (SC) gave the higher-tensile shear force.

![Main Effects Plot for Means](image)

**Figure 12.** The main effects for the tensile-shear force means for the dissimilar friction stir spot welded joints (AA5754-H114 with pure copper).

It can be seen from Figure (12) that the tensile-shear force attains an ultimate value of (2290 N) at the optimal values of such experimental factors of (1000 rpm) speed of rotation, (60 sec) time of plunging as well as a straight cylindrical pin.

3.5. Response optimizer

The response optimizer technique is utilized to show which factors possess upon the welding parameter individually their influence upon the shear force that yields the best shear strength value. Figure (13) reveals the response optimizer of the FSS welded joints of the dissimilar materials for (AA5754-H114 to pure copper). It was obtained that the optimal input parameters for FSS welded joints are (1250 rpm) speed of rotation, (90 sec) time of plunging, (10 sec) fixed dwell time, (3.7 mm) depth of plunge, and straight cylindrical pin for all welded joints in this study.
Figure 13. Response optimizer of the FSS welded joints for the dissimilar material (AA5754-H114 with pure copper).

3.6. Pareto chart results of AA5754-H114 to pure copper

Pareto charts are a beneficial and supportive technique to analyze the variables or parameters that require consideration initially because the lengthier bars in the chart display that these variables possess the most significant considerable influence upon a particular system [21]. The chart denotes the total value of influences and plots a line as a place in the chart. Minitab is used for plotting the Pareto chart of the effects depending upon the degrees of freedom for the error term. It has been observed from the Pareto chart of standardized effects of the tensile-shear outcomes (in the state of a one-factor effect) that the plunge time (t) (factor B) being the highly effective parameter in comparison with the other factors (A and C). Moreover, it was obtained that the percentage of contribution was (63%) for the plunging time pursued via the pin profile (27.77%) and the rotational tool speed (9.2%), as evinced in Figure (14). While in the state of a combined two factors effect, the Pareto chart of standardized effects of the tensile-shear outcomes elucidated that both the rotational speed and the tool pin geometry (the factor AC) being the higher effective parameter than the other factors (BC and AB). The percentages of contribution are (AC=28.54%), (BC=25.47%), (A=20.40%), (AB=16.66%), (B=4.97%) and (C=3.96%), as shown in Figure (15).

Figure 14. Welding parameters effect upon the shear force  (in case of a one-factor effect).

Figure 15. Welding parameters effect upon the shear force  (in case of a combined two factor effect).
The interaction plot manifests the influence of the whole (FSSW) parameters upon the tensile-shear force of the dissimilar FSS welded joints (AA5754-H114 with pure copper), as shown in Figure (16).

4. Conclusions
1- It was obtained that the tensile-shear force of the dissimilar FSS welded joint of (AA5754 to pure copper) sheet attained a max value of (2290 N) at the optimum welding parameters of (1000 rpm) rotating speed, (90 sec) time of plunging, and a straight cylindrical pin respectively, which are found from the response optimizer analysis.
2- It has shown from the Pareto chart of standardized effects of the tensile-shear outcomes (in the state of a one-factor effect) that the plunging time being a highly influential factor in comparison with the other factors. Also, it was obtained that the percentage of contribution was (63%) for the plunging time pursued via the pin profile (27.77%) and the tool rotation speed (9.2%).
3- The microhardness profile results of the dissimilar lapped FSS welded joints of (AA5754 to pure copper) sheets demonstrated the lower values of hardness that seemed in the (TMAZ) and (HAZ).

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