Joining of Aluminium Alloy (AA6061-T6) to Pre-Threaded Pure Copper by Friction Spot Lap joining (FSpLJ) Process

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Abstract. Objective - The objective of this study is to join Aluminum alloy type (AA6061-T6) of (1.5) mm thickness to pre-threaded pure copper of (2) mm thickness applying the frictional spot lap joining (FSpLJ) technique. Styling - All specimen aluminum and copper was prepared by cutting them by dimensions (100×25) mm, pure copper samples (2) mm thickness were pre-punctured with a diameter of (4) mm and then threaded it with a diameter of (4.8) mm, a tooth step (1) mm, a rotational instrument with a (10) mm diameter was used for the joining operation. Configuration - The threaded copper was put in the mold channel, placing aluminum on top of the copper, putting the fastener over the sample, and placing the top cover of the template and fixation it with three bolts. Approach - The process parameters [rotating speed (RPM), plunging depth (mm), and pre-heating time (sec.)] was optimized by using Taguchi style, there were four levels for each parameter. The influence of the operation parameters on the joint shear strength was analyzed. The tests [Visual examination, shear force, macrostructure, and the microstructure of the joint were applied]. Results – AA6061 was extruded through the pure copper hole and its interlock with the thread slot. As a result, it was obtained mechanical overlap between the extruded aluminum and the copper. The plunging depth parameter had the greatest influence on the shear strength of the joint. Increasing the plunging depth and the rotational speed of the tool was gradually increased the efficiency of the joint. The results showed that the samples failed to test shear in the zone of the lap joint. The highest shear force is (2176) N.

Keywords. Friction spot lap joining, AA6061, Copper, shear force, Microstructure.

1. Introduction
At this time, with the rapid advancement of technology, it was needful to produce instrument components and engineering structures utilize dissimilar materials, which had to be joined. The unusual properties required for most applications, as no single material gives it all, such as [high toughness, high conductivity, high corrosion resistance, high strength, and, lightweight] [1,2]. Surely, it becomes necessary to combine different materials with different properties to obtain all the features of their further properties. This is usually important in the automotive, aviation, medicinal, and biological products, which in the manufacture use materials with particular properties for high execution, but also require lighter structures to reduce fuel consuming [3]. Finding effective welding of dissimilar materials is a task that has caught the attention of engineers and scientists. It is always necessary to improve the parts/machines/systems that equip the reduction in weight, high wear resistance, high strength, and to improve the electrical and thermal properties of the joint interface. Currently. Most components require multiple properties that require different materials to be used in a single component structure [4]. Aluminum and copper have good electrical and thermal conductivity.
and are widely used in electrical and thermal applications. Most of the time, Al to Cu joints are used in a variety of applications, such as [electrical conductors, busbars, capacitor and condenser foil coils, transformer’s foil conductor, refrigeration tubes, tubes of heat exchangers, and tube sheets][5,6]. Modernity in design and in automotive structures requires advance welding techniques, competent in joining dissimilar metals; the material of high importance in such industries are copper and aluminum. Both materials are largely applied to produce effective electric trains. Friction stir welding (FSW) has become a basic procedure for joining dissimilar materials, as this process provided good properties in terms of solid-state joining as it requires minimum energy for bonding process to occur. While in conventional welding it requires high electric currents in automotive and other applications [7]. The joining of aluminum to copper produces a high number of the layers of intermetallic compounds (IMC) in various weld regions, which are brittle, hard, having higher electrical resistance, and having lower strength [4]. Fusion welding processes utilized to joining aluminum to copper are not recommended, due to liquefaction cracking, solidification, and also the tendency to create a brittle and hard zones (IMCs) [6]. The working principle is based on linking dissimilar materials with low temperature, considered local heating during welding is one of the most important problems of welding, the complex thermal stresses take place during welding, while distortion, and residual stress result after welding. Thermal stress, distortion, and residual stress cause mismatching and cracking, high tensile Locked-in stresses in zones near the weld may due to breaking under specific conditions, compressive residual stress, and distortion in the basic plate may decrease buckling strength of structural [8]. In this experiment, the friction spot lap joining process (FSpJ) was used to join the AA6061 aluminum alloy with pure copper. Using a rotary tool, aluminum was extruded through the threaded copper hole. The purpose of the experiment is to join dissimilar materials to a low temperature to avoid defects that occur due to their height, which negatively affects the efficiency of the joint. The copper thread has two benefits, the first is to avoid the pulling of the aluminum extruded into the copper hole, and the second acts as a mechanical lock between the two metals. By using the design of experiments method, the shear strength of the joints was analyzed.

2. Experimental specifics
2.1. Materials and specimens’ dimensions
Aluminium alloy type AA6061-T6 of (1.5) mm thickness and pure copper of (2) mm thickness was used. The chemical composition of the Aluminium alloy is recorded in the table 1 and the mechanical and physical properties of AA6061-T6 and copper are recorded in the table 2. Both metals were cut into sheets with dimensions of (100 ×25) mm thickness, the pure copper samples were holed with a diameter of (4) mm and then threaded with a diameter of (4.8) mm, a tooth step (1) mm. as displayed in figure 1.

| Table 1. Chemical composition of AA6061-T6 |
|------------------------------------------|
| Element wt.%                          | Si       | Fe      | Cu      | Mn      | Mg      | Cr      | Zn      | Ti      | Al      |
|------------------------------------------|----------|---------|---------|---------|---------|---------|---------|---------|---------|
| Standard ASTM                           | 0.4 -    | 0.7     | 0.15-   | 0.15    | 0.8-    | 0.04-   | 0.25    | 0.15    | Rem.    |
| B209[9]                                  | 0.8      | 0.4     |          |         |         | 1.2     | 0.35    |         |         |
| Measured                                 | <.800    | 0.510   | 0.233   | 0.127   | 0.959   | 0.211   | 0.056   | 0.062   | Rem.    |

| Table 2. Mechanical and physical properties of AA6061 and copper |
|---------------------------------------------------------------|
| Material Properties | Yield strength (MPa) | Tensile strength (MPa) | %Elongation | Thermal conductivity W/(m.K) | Density g/cm³ |
|--------------------|----------------------|------------------------|-------------|-----------------------------|---------------|
| AA6061-T6          | 241                  | 289                    | 10          | 167                         | 2.7           |
| Cooper             | 310                  | 358                    | 20          | 401                         | 8.96          |

2.2. Joining operation
Friction spot joining process (FSpJ) was applied by a milling machine which generated a higher application load during the joining operation. The heat produced by the friction between the tool’s
surface and aluminium surface as a result of the pressure applied determines the amount of aluminium extruded through the hole of the threaded copper [10]. The AA6061 and pure copper samples require to be fastened through the installer to avoid specimen slipping because the occurrence of an opposing force during penetration of the join tool as shown in figure 2. The operation of joining was developed in this work, which is established on two successful processes of friction welding, first joining the friction spots, and second joining the friction lap. Figure 3 displayed the specimen arrangement of the lap friction spot joining process by using a vertical milling machine, dimension of the tool, and dimensions of a welded sample. The tool rotates at a certain speed according to the parameters, to touch the aluminum surface for a specified period to soften the inner surface of the alloy, then, by applying the load, the tool doing to flow the aluminum into the copper through the threaded copper to a certain depth [11]. Figure 4 shows the joined samples of the AA6061 to pre-threaded pure copper. Figure 5 shows the top and bottom view of a joining sample, as it shows the trace of the tool on the upper surface of the aluminium and how it extruded inside the copper.

![Figure 1](image1.png)

**Figure 1.** (A) Dimensions of samples, (B) Threaded copper

![Figure 2](image2.png)

**Figure 2.** Stages of fixing the sample, A- Putting the threaded copper in the channel, B- Placing aluminum alloy on top of the pure copper, C- Putting the fixative over the specimen, D- Placing the top cover of the template and fixation it with three bolts.
2.3. Design of the experiments

The designing of the experiments (DOE) parameters was applied utilize statistical software Minitab by a (Taguchi method) to analyze the influence of parameters on the joint efficiency. Table 3 shows the parameter variables of joining the aluminium alloy to pure copper specimens. The purpose of this experience is to study the influence of instrument joining parameters on the force of the joint. The process parameters were, (Rotating speed, plunging depth, and Pre-heating time).
### Table 3. Parameters joining of AA6061 to pure copper

| No | Rotating speed (RPM) | Plunging depth (mm) | Pre-heating time (sec.) |
|----|----------------------|---------------------|-------------------------|
| 1  | 900                  | 0.1                 | 10                      |
| 2  | 900                  | 0.2                 | 15                      |
| 3  | 900                  | 0.3                 | 20                      |
| 4  | 900                  | 0.4                 | 25                      |
| 5  | 1120                 | 0.1                 | 15                      |
| 6  | 1120                 | 0.2                 | 10                      |
| 7  | 1120                 | 0.3                 | 25                      |
| 8  | 1120                 | 0.4                 | 20                      |
| 9  | 1400                 | 0.1                 | 20                      |
| 10 | 1400                 | 0.2                 | 25                      |
| 11 | 1400                 | 0.3                 | 10                      |
| 12 | 1400                 | 0.4                 | 15                      |
| 13 | 1800                 | 0.1                 | 25                      |
| 14 | 1800                 | 0.2                 | 20                      |
| 15 | 1800                 | 0.3                 | 15                      |
| 16 | 1800                 | 0.4                 | 10                      |

### 3. Results and discussion

#### 3.1. Visual inspection

Visual inspection shows that all samples have been joined well without any deformation. Figure 6 shows the circular effect of the tool on the aluminum surface. The basis of joining AA6061 to copper was depended on welding in the solid-state in which pressure occurs and the metals that are joined do not melt except a very thin layer close to the surface to be joined [12], as well as on the mechanical interlocking between aluminum, and threaded copper. The crystal structure Face Centered Cubic Structure (FCC) possessed by aluminum has made it soft, ductile, malleable, and retractable. Although both crystalline composites Hexagonal Close Packed Structure (HCP) and (FCC) have the same Packing Factor (APF) which is (0.74) as displayed in a table 4, however, the stacking sequences (ABCABC) for aluminum are best than materials that own a crystalline structure (HCP) related stacking sequence (ABAB) in terms of the ductility (allow slippage to occur more easily) property as a shown figure 7.

![Figure 6. Top view, the circular effect of the tool](image)

#### Table 4. The most important metals structures

| The Structure of Metals                      | Atomic Packing Factor (APF) |
|---------------------------------------------|-----------------------------|
| Body Centered Cubic Structure (BCC)         | 0.68                        |
| Face Centered Cubic Structure (FCC)         | 0.74                        |
| Hexagonal Close Packed Structure (HCP)      | 0.74                        |
The stacking sequences, A- Face Centered Cubic Structure (FCC), B- Hexagonal Close Packed Structure (HCP)

All the above advantages of aluminum made it well extruded without any deformation or fracture, and the following figure shows aluminum extrusion inside the copper threaded successfully.

3.2. Shear tensile test
The objective of the test is to determine the shear strength of the joint zone. The shear tensile of the friction spot lap joining specimens were examined by a tensile testing device with a maximum capacity of (20) KN. Table 5 and figure 9 show, respectively, the dimensions of the samples for which the shear test was performed, depending on the specification of the American Welding Society (AWS) the resistance of spot welding [13]. Table 6 shows the values of shear strength. The shear force values were between (1216) N and (2176) N.

| Material | Thickness (t) (mm) | Width (W) (mm) | Welded sample Length (mm) | Contact over lap (mm) |
|----------|--------------------|----------------|--------------------------|----------------------|
| Al       | 1.5                | 25             | 175                      | 25                   |
| Cu       | 2                  |                |                          |                      |
Figure 9. Dimensions of joined sample

Table 6. Tensile shear force values of joining AA6061 to threaded pure copper

| No | Rotating speed (RPM) | Plunging depth (mm) | Pre-heating time (sec.) | Tensile shear force (Mean)(N) |
|----|----------------------|---------------------|-------------------------|-----------------------------|
| 1  | 900                  | 0.1                 | 10                      | 1216                        |
| 2  | 900                  | 0.2                 | 15                      | 1230                        |
| 3  | 900                  | 0.3                 | 20                      | 1280                        |
| 4  | 900                  | 0.4                 | 25                      | 1376                        |
| 5  | 1120                 | 0.1                 | 15                      | 1248                        |
| 6  | 1120                 | 0.2                 | 10                      | 1308                        |
| 7  | 1120                 | 0.3                 | 25                      | 1436                        |
| 8  | 1120                 | 0.4                 | 20                      | 1568                        |
| 9  | 1400                 | 0.1                 | 20                      | 1464                        |
| 10 | 1400                 | 0.2                 | 25                      | 1566                        |
| 11 | 1400                 | 0.3                 | 10                      | 1888                        |
| 12 | 1400                 | 0.4                 | 15                      | 2112                        |
| 13 | 1800                 | 0.1                 | 25                      | 1636                        |
| 14 | 1800                 | 0.2                 | 20                      | 1856                        |
| 15 | 1800                 | 0.3                 | 15                      | 2112                        |
| 16 | 1800                 | 0.4                 | 10                      | 2176                        |

Note:
- The yellow color indicates the lowest shear force value.
- The green color indicates the highest shear force value.

Figure 10 shows the experimental shear strength data for the joint for the (16) samples and the different joining parameters. Through the figure, it is possible to observe the behavior of the shear forces of all samples and higher and less shear force. The highest shear forces were observed in samples (12, 15, and 16), respectively, and their values were (2112, 2112, and 2176) Newton's. These samples recorded a high shear force due to the good friction spot zone between the two metals and the good mechanical interlock between them. While samples (1, 2, and 5) respectively recorded the lowest strengths with values of (1216, 1230, and 1248) Newton's due to the low mechanical properties of these samples as a result of their applied parameters.
3.3. Design of experiments (DOE) results

Using the experimental design method, the effect of process parameters on the shear force of the joints was analyzed. Taguchi design was used in Table 3, which includes three main parameters (Rotating speed, Plunging depth, and Preheating time), with four values for each factor, so that the total number of the experiment became (16) cases [14]. Figure 11 shows the main effect plot for these parameters. The plunging depth and rotating speed of the tool had the great effect of increasing or decreasing the shear force on the joint compared to the preheating time. The Pareto diagram in Figure 12 also gives an indication of the degree of efficacy of the join parameters.

Figure 10. Variation shear forces of joining aluminium samples to copper

Figure 11. Main effects plot of joining AA6061 to copper
3.4. The appearance of the fractured surfaces

The following table 7 shows the surface of the fracture samples before and after failure test.

Table 7. Surface of the joined and fractured samples

| No. | Before the shear force test | After the shear force test |
|-----|-----------------------------|---------------------------|
|     | Upper surface of Aluminum   | Extruded surface of Aluminum | Fractured surface of Aluminum | Inner surface of copper |
|     | Depth, mm                    | The contact with the flat back up plate. | Type of failure |
| A   | 0.1                          | A-without contact          | A-at most shear               |
| B   | 0.2                          | B-with small contact       | B-at most pull out            |
| C   | 0.3                          | C-with medium contact      | C-shear and pull out          |
| D   | 0.4                          | D-with large contact       | D-shear at and bead           |

Figure 12. Pareto chart of shear force for the joining aluminium to copper
It was observed that increasing the depth of plunging of the tool and the speed of rotation had a great effect on the extrusion of aluminum into the threaded copper hole, which resulting in a good zone of friction in terms of excellent mechanical interlocking between the two metals, this is shown in figure
13 of samples with numbers (12, 15, and 16) with high shear values were high penetration and rotation speed were applied. As shown in table 7, the breakage occurred in the above samples at the end of the weld bead, due to the excellent mechanical interference and good friction zone as mentioned earlier. The shape of the fracture can be analyzed. Initially, the shear force was resisted by the welding bead that was filled and intertwined with the threaded copper hole. Secondly, due to shear resistance, a bending occurred in the aluminum sample near the joining area, and then the failure occurred at the end of the bead due to the bending where the area became weak as displayed in figure 14. On the other hand, samples (1, 2, and 5) shown in Fig 15, recorded the lowest shear forces due to the depth of penetration and the low rotating speed as shown in table 7.

![Figure 13. High shear force samples](image)

![Figure 15. Low shear force samples](image)

![Figure 14. Samples failed from the end of the bead](image)

3.5. Macro and Microstructure examination

Figure 16-A shows the samples that were prepared for the purpose of a microstructure examination. Figure 16-C: The macro test shows the spot friction zone, the extruded aluminum, and its mechanical interference with the threaded copper hole. An optical microscope equipped with a digital camera was
used to examine the cross-section of the samples. Figure 17 shows the clarity of the weld line between the aluminium alloy and pure copper, mechanical interlock between the two metals, and the spread of different sizes of copper in the aluminum. Due to the application of pressure on the two metal surfaces to be joined, a very light thickness is melt, which results in the formation of a metallic bond between the copper and the aluminum, which contributes to the bonding of the two metals in addition to the design of the mechanical interlock between them, as mentioned above. The following table shows the number and difference of electrons in the two metals and their distribution in orbitals, which contribute to the formation of the bond.

### Table 8. Distribution of electrons in orbitals

| Minerals | No. of electrons | Distribution of electrons in orbitals |
|----------|------------------|---------------------------------------|
| Al       | 13               | 1s^2 2s^2 2p^6 3s^2 3p^1             |
| Cu       | 29               | 1s^2 2s^2 2p^6 3s^2 3p^0 4s^1 3d^{10} |

**Note:** (s, p, d) means shape of orbitals.

![Image 1](image1.png)

**Figure 16.** A- Microstructure test samples, B- Sample form, C- Macro test.
4. Conclusions
Using frictional spot lap joining (FSpLJ) technique for joining the aluminum alloy AA606 to the pure copper pre-threaded, the following conclusions can be drawn by studying the effect of process parameters on joint strength.
1. The crystal structure (Fcc) of the aluminum made it well extruded inside the threaded copper without deformation or fracture.
2. The mechanical interlocking mechanism between the two metals, the good friction zone, and the formation of the metallic bond all contributed to the success and strengthening of the joining process.
3. Increasing the plunging depth and rotating speed of the tool increased the shear strength of the joints.
4. The maximum and minimum shear force values of the joints were recorded at the maximum and minimum plunging depth and rotating speed of the tool.
5. The shear strength test showed four types of failure: most pullout, shear and pullout, most shear, and shear at end bead.
6. The copper hole thread increased the mechanical interlocking force and reduced the extruded aluminum pull-out and thus increased the joint shear strength.
7. The highest shear force value was (2176) N. at the highest plunging depth and rotating speed (0.4 mm, 1800 RPM) respectively, while the lowest shear force was (1216) N. at lowest plunging depth and rotating speed (0.1 mm, 900 RPM) respectively.

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