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Friction Spot Joining of AA6061 to Pre-holed Pure Copper Sheets with a Snap Rivet Head Die

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Abstract

This work aims to join AA6061 to Copper sheets using friction spot joining technique without formation of intermetallic compounds (IMCs). Aluminium (Al) sheets were arranged with a lap joint configuration over a pre-holed copper sheet. A snap die was used under the copper specimen. A rotating tool was utilized to carry out the joining technique by friction at the common surface between the tool shoulder and Al surface. Three process parameters were selected to study its influence on the joint quality: rotating speed, pre-heating time, and plunging depth of the tool. Two materials were joined by extruding the Al metal through the copper hole, and forming a rivet head. The results indicated the two materials joined by mechanical interlock at an interface line of a micro-scale, without forming IMCs or presence of defects like cracks, voids or gaps. The extruded aluminium through the rivet head die prevented pull-outing the joint. The plunging depth of the tool exhibited the highest influence on the joint's shear force which recorded a maximum value of 1800N.

Keywords: Friction spot joining; Copper; AA6061; Rivet Head Die

1. Introduction

Nowadays, various industries aim to produce structures and machine parts with a high strength, light weight, low cost and good electrical properties [1]. Structures components that required multiple properties can be achieved by combination of two or more materials into a single part [2]. Welding or joining different materials is the technique of combination of different materials. joints of type aluminium – copper are widely used in several industries applications like automotive, refrigeration and electrical applications due to their excellent electrical and thermal conductivities [3]. Aluminium – copper joints are used in electrical connectors, batteries tab to bus bars, condenser, transformer foil condenser, refrigeration tubes, capacitor foil windings, tube cover and heat exchanger tubing [4]. A mechanical joining method was used to join dissimilar materials such as aluminium and Cu. This method consists drilling and joining materials with the aid of bolts [5] or rivet. The mechanical method requires a cost of drilling the holes and assembling the rivets or bolts. Also, the holes can be considered as a stress concentration regions. The bolts or rivets are additional elements that increase structure weight [6].
Various attempts have been intruded to produce reliable joints from the aluminium and copper. A brazing technology was used to weld Cu C1020 together with AA 1050. Due to higher difference in melting temperature between the aluminium (Tm≈ 660 °C) and copper (Tm≈ 1083 °C), the joints of the two materials had a weak electrical and mechanical properties. Resistance spot welding technology (RSW) was used to weld a copper together with aluminium tabs of battery connections. The results indicated that the higher electrical and thermal conductivity of the copper led to form an oxide layer on aluminium surface at the weld zone which reduced the performance of the joint [7]. A nickel- coated copper was welded with aluminium of 0.3 mm thickness using two different welding techniques: micro-Tungsten inert gas welding and RSW. The micro-Tungsten inert gas welding technique produced a joint of higher strength compared with that of the RSW [8]. Friction stir welding (FSW) technique is a solid-state process that was introduced by the welding institute and used to weld similar and dissimilar materials [9]. A rotating tool of a shoulder and pin was utilized to generate the required heat to weld the materials with the aid of stirring the two materials by the pin of the tool [10].

Nomenclature

AA	Aluminium Alloy	IMCs	Intermetallic Compounds
T_m	Melting Temperature	RSW	Resistance Spot Welding
FSW	Friction Stir Welding	FJ	Friction Joining
HSS	High-Speed Steel	DOE	Design of the Experiments
SEM	Scanning Electron Microscope	XRD	X-Ray Diffraction

FSW of Al to Cu form an intermetallic compounds (IMCs) due to higher difference of metallurgical and physical properties between the two materials. The IMCs is a brittle compound that reduce the strength and electrical performance of the joint [11]. Formation of IMCs of type Al4Cu9 improves the joint strength and increases its hardness [12]. Higher levels of welding speed refine the grain size at the weld zone and form IMCs of type Al2Cu which reduce hardness of the joint. Small levels of welding speed increase number of IMCs at the interface line between the aluminium and copper. The joint strength reduce by formation of voids and cavities at an incomplete weld interface [13]. To reduce or prevent formation of brittle IMCs during the FSW technique, a filler metal was inserted between the two materials [14]. The FSW method was used to weld aluminium of 2 mm thick to copper with the aid of a zinc foil placed between the two materials. The results indicated that the intermediate zinc foil reduced weld defect at the interface line and improved the mechanical properties of the joint [15]. The joint strength of FSW of AA6061/C11000 was improved by applying a cold sprayed of Ni interlayer [16].

To prevent the formation of IMCs, friction joining (FJ) technique was used to join dissimilar material [17]. This technique was achieved by applying a pressure and heat from the rotating tool to join dissimilar materials without stirring at the interface line. AA5052 was AISI 1006 by extruding an aluminium metal through a steel hole using the friction spot joining (FSJ) process. Shear strength of the joint reached 1.25 of the weakest material. The results indicated that the joining occurred between the two materials at an interface line width of 50 µm, without formation IMCs [18].

In this work, The FSJ technique was used to join a pure copper together with aluminium alloy AA6061 without IMCs formation. A rotating tool of a shoulder was utilized to extrude an aluminium metal from the aluminium sheet through a pre-holed of copper sheet. A snap die was manufactured and placed under the copper sheet to form a rivet head die from the extruded aluminium. Three technique parameters were utilized: rotating speed, pre-heating time, and plunging depth of the tool. The experiments were designed according to the design of the experiment method to determine the influence of the technique parameters on the performance of the joints. The joints were tested by a tensile and micro-hardness test. The microstructure, XRD and SEM of the joint's cross-section were examined.

2. The Process Details

2.1. Materials and dimensions

Two dissimilar materials were used to achieve the joining process: pure copper and Aluminum alloy AA6061, with thickness of 2 and 1.5 mm, respectively. The wrought materials were tested using a tensile test. The mechanical properties of those materials are display in Table1. The specimens of the two materials were machined with a rectangular shape of dimensions 100*25 mm2, as shown in Fig. 1a. The copper specimens were machined with a hole of 4 mm diameter at the centre of the lap joint, as shown in Fig. 1b.

Table 1 Mechanical property of AA6061 and pure copper

	Tensile strength (MPa)	Yield strength (MPa)
AA6061	279	236
Copper	254	84

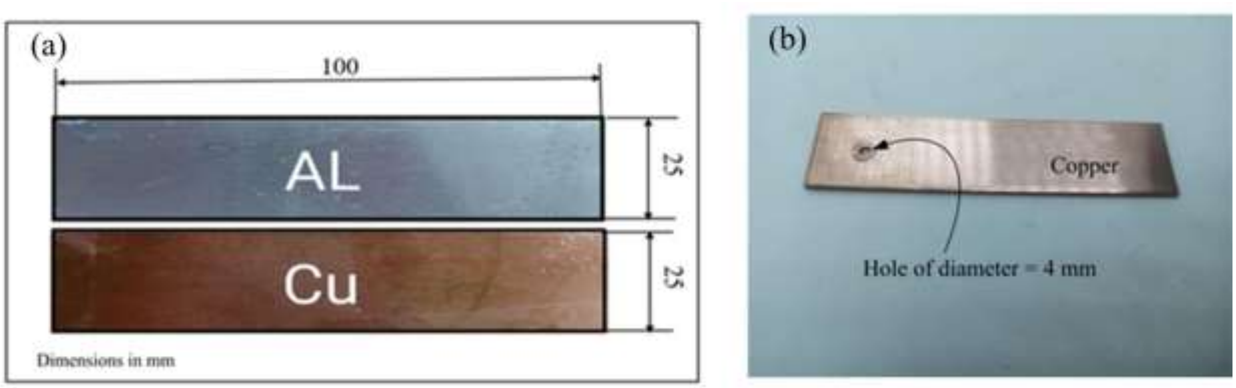
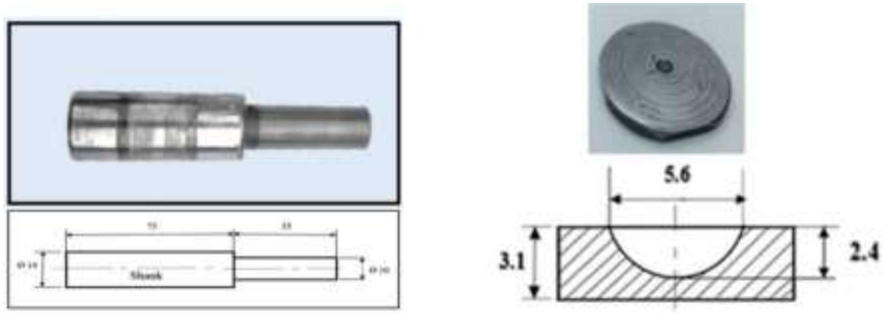


Fig. 1 Specimens dimensions; (a) sheets, (b) copper hole

2.2. Materials and dimensions

The joining technique was accomplished by a rotating friction between lower surface of a tool and the upper surface of the sample. A higher input heat is generated due to the rotating friction. The compound effects of the friction and the generated heat affected the tool and its life during the joining process. So, a special material of the rotating tool is required to maintain the same shape and dimensions of the tool through the joining technique. A suitable non-consumable tool should be carefully selected. A high-speed steel tool (HSS) of 10 mm shoulder diameter was used to achieve the joining technique, as display in Fig. 2a. The main aim of die is to form a rivet head from the extruded Aluminum during the joining process to avoid and\or prevent joint pull-outing. A suitable die material and design are required. A snap rivet head like a semi-spherical was designed and manufactured from a carbon steel material, as shown in Fig.2b.



(a) Tool, dimensions in mm (b) Die, dimensions in mm

Fig. 2 Image and Schematic of tool and die

2.3. Joint setup

A milling machine was utilized to setup and produce the final joints. The specimens of the Aluminum and copper were setup in the base of the milling machine according to following steps, as shown in Fig. 3:

a) Putting the rivet head die at the machine base.
b) Inserting the copper specimen into the machine fixture's slot.
c) Placing the Aluminum specimen on top of a copper specimen (lap joint configuration).
d) Putting the upper cover of the fixtures on the sample, and tightening the fixtures assembly with suitable bolts.

The copper and Aluminum specimens were fixed by a suitable design of fixtures (of carbon steel material) to prevent the slipping of the samples during the joining process. The fixtures consisted of two plates: upper and lower, which consisted of a slot of a width equal to the width of the Aluminum and copper specimens. The sample and the rivet head die are put on the lower plate of the fixture.

Fig. 3 Joint setup steps

2.4. Process parameters

The basic principle of the joining was depend on generation heat required to soften the Aluminum metal and extrude it during the pre-hole of the copper passing through the rivet head die. So, the joining process required two main variables: temperature to generate heat and pressure to extrude the Aluminum. Those variables depend on process parameters which can be considered as: rotating speed, pre-heating time, and plunging depth of the rotating speed. The three parameters were considered to achieve the joining process and study its effect on the joint quality. For each of the three technique parameters, four different levels were utilized. In order to study the influence of compound effect of the technique parameter, the design of the experiments technique (DOE) was used to design the level of each parameter for each experiment of the joining process. Taguchi process was utilized to design the experiments with sixteen experiments, as illustrated in Table 2.

2.5. Joining process

Joining the Aluminum specimen together with the copper based on two steps: pre-heating and plunging. In the pre-heating step, the rotating tool touches the upper surface of the Aluminum specimen. The Aluminum metal under the shoulder surface of the tool heated under effect of temperature rise that generated due to effect of the rotating friction between the tool and the Aluminum specimen. The heated Aluminum softened during a pre-heating time and being ready to the second step. In the plunging step, the rotating tool moves down with a specific depth which, in turn, applies a load on the softened Aluminum. The applied load extrudes the softened Aluminum through the rivet head die passing through the copper hole, as shown in Fig. 4. Fig. 5 illustrates joined samples of aluminium to copper. It clearly observed that the aluminium extruded through the copper hole.

Table 2 Taguchi design of the joining process parameters

No.	Rotating Speed (RPM)	Pre-Heating Time (Sec.)	Plunging Depth (mm)
1	900	15	0.2
2	900	20	0.4
3	900	25	0.6
4	900	30	0.8
5	1120	15	0.4
6	1120	20	0.2
7	1120	25	0.8
8	1120	30	0.6
9	1400	15	0.6
10	1400	20	0.8
11	1400	25	0.2
12	1400	30	0.4
13	1800	15	0.8
14	1800	20	0.6
15	1800	25	0.4
16	1800	30	0.2

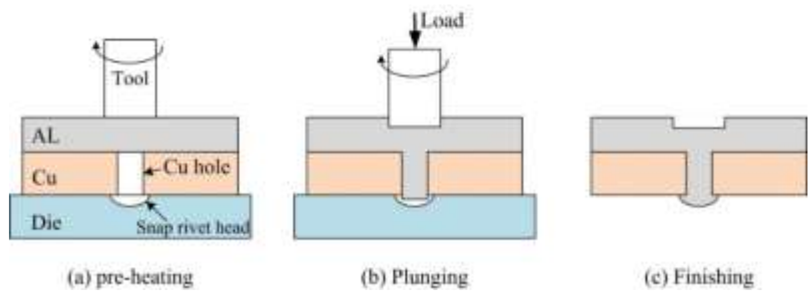


Fig. 4 Schematic of joining process

Fig. 5 Joined samples

2.6. Joining process

To examine the mechanical properties of the joined samples and investigate the influence of technique parameters on the joint quality, a tensile test was carried out. The micro-hardness of the joined samples was carried out at the joint cross-section, with various points along the joint cross-section. To study the microstructure behaviour of the extruded aluminium and investigate the joining mechanism between the two materials, the microscopy, SEM and XRD tests were carried out at the joined samples.

3. Results and Discussion

3.1. Joint shear force

The tensile test was carried out to test the ultimate sheer force of the joined samples. This test was achieved by applying a force at the end of the joined specimens until the samples fail at the joined area by shearing and/or pull-outing the extruded Aluminum. The ultimate (maximum) shear force was recorded and plotted in fig. 6. The shear force ranged between a minimum value of 700 n (in sample no.1) to a maximum value of 1800 n (in sample no. 10). The joined samples (no.1-4) indicated that the sheer force of the samples increased gradually with increasing the pre-heating time and plunging depth of the rotating tool. The main aim of the pre-heating time was to soften the Aluminum metal under the shoulder surface of the rotating tool. While, the main aim of the plunging depth of the tool was to extrude the softened Aluminum during the pre-heating time. Increasing the pre-heating time and the plunging depth increase amount of the extruded Aluminum through the copper hole which increase the ultimate value of the joint's shear force [19].

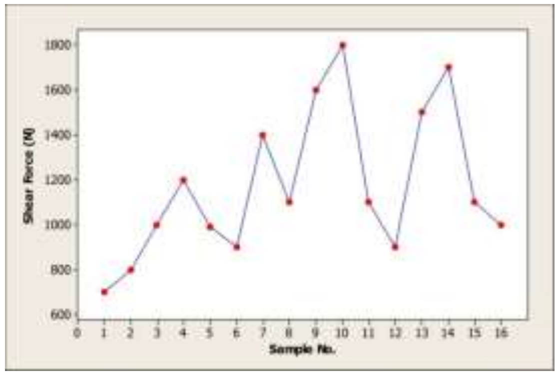


Fig. 6 Shear force of the joined samples

Fig. 7 appears effect of the joining technique parameters on the shear forces. It clearly observed that the joint's shear force increased gradually by increasing the rotating speed of the tool (regardless of the pre-heating time), as shown in fig. 7a. This may be consoled to the fact that the rotating speed generates a higher input heat during the joining process compared with those that generate under effect of the pre-heating time. The input heat can be generated by a rotating friction between the shoulder surface and the Aluminum specimen. Increasing the generated heat (or process temperature) can increase amount of softened Aluminum and/or increase the soften-ability of the Aluminum metal which (in turn) increase amount of the extruded Aluminum through the copper hole [20]. Moreover, fig. 7b indicates that the compound effect of the plunging depth and rotating speed of the tool increased the joint's shear force. Both process parameters contribute in increasing the amount of the extruded Aluminum through the copper hole and snap die.

Effect of joining process parameters on the joint's shear force was analysed by DOE method utilizing Minitab program, as shown in Fig. 8. The main influence plot, Fig. 8a, indicates that the raise in the rotating speed and plunging depth of the tool raised the joint's shear force, while the increase in the pre-heating time reduced the joint's shear force. The Pareto chart, Fig. 8b, showed that the plunging depth of the tool has the maximum influence on the joint's shear force followed by the rotating speed and the pre-heating time.

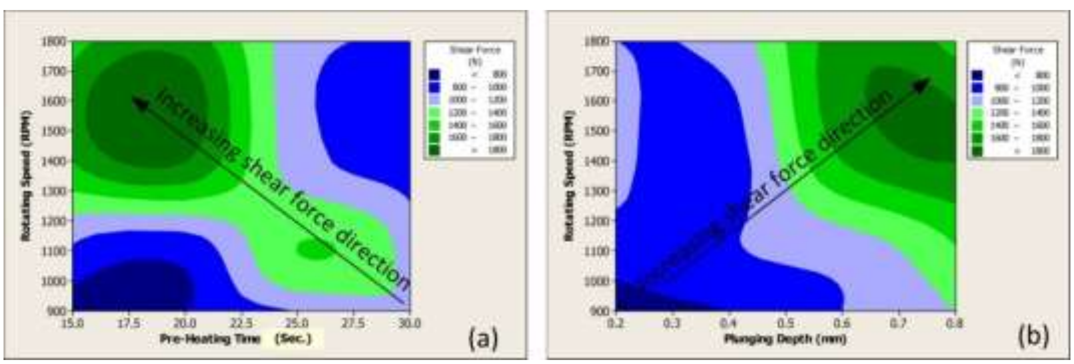


Fig. 7 Variation of shear force with joining process parameters

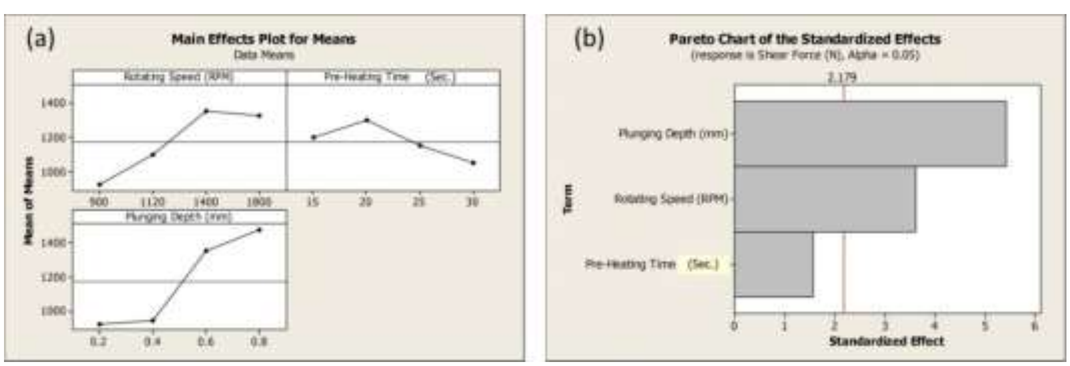


Fig. 8 Influence of technique parameters on joint's shear force, snap die; (a) main influence plot, (b) pareto chart

3.2. Surface features

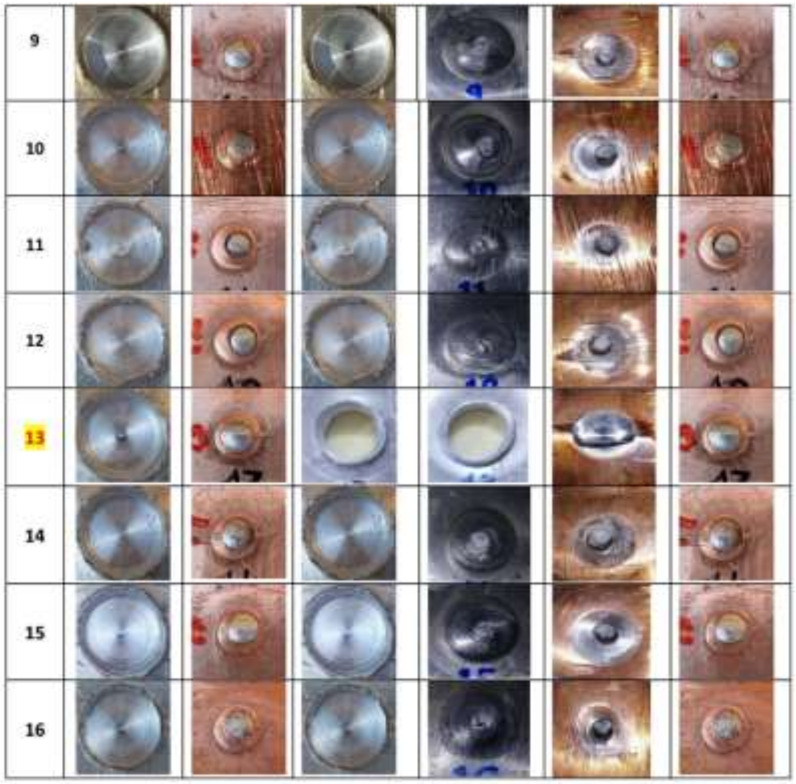
Table 3 illustrate images of the joined and fractured samples. It clearly observed, from the lower surface of the copper specimen, that the Aluminum metal extruded with different amount depending on the joining technique parameters. The first group of the joined samples (No.1, 2, 3 and 4) joined at small rotating speed and exhibited a lower amount of the extruded Aluminum metal. The images of the joined samples indicated that the extruded Aluminum not reach the die surface. So, this group of the joined samples exhibited a minimum shear force.
There are three types of failure that occurred during the tensile test: pull-outing the extruded Aluminum from the copper specimen (as in sample No.1), pull-outing the Aluminum metal from the Aluminum specimen (as in sample No.13) and shearing the extruded Aluminum (as in the other samples). The sample No.1 joined at minimum process parameters which produced a small amount of the extruded Aluminum through the die hole. So, the extruded Aluminum formed with a shape like the copper hole only, and without forming the rivet head by the die hole (which resist the pull-outing). As a result, this sample failed by pull-outing the extruded Aluminum from the copper specimen with minimum shear force compared with the other samples. Although the sample No.13 joined with sufficient process parameters that formed the extruded Aluminum through the snap die, it exhibited pull-outing the Aluminum metal from the Aluminum specimen. This sample joined with a higher rotating speed and plunging depth of the tool, which reduced thickness of the Aluminum specimen, and resulted in make the region of the tool trace as a stress concentration region. So, the Aluminum metal pulled- out from the Aluminum specimen without shearing it from the base material. In the other samples, the mode of failure was shearing the extruded Aluminum at the lap joint, without pull-outing it from the Aluminum and/ or copper specimens. Shearing the extruded Aluminum from the Aluminum specimen indicated that the remaining thickness of the Aluminum specimen was enough to resist the applied load without failing the Aluminum specimen with a stress concentration at the tool trace. Shearing the extruded Aluminum without pulling- out it from the copper specimen indicated that the formed rivet head of the extruded Aluminum through the die had enough thickness to resist the pull-outing.

3.3. Macrostructure and SEM features

The macrostructure and SEM feature of the sample No.10 is appeared in Fig. 9. The macrostructure image, Fig. 9a, indicates that the aluminium metal extruded uniformly through the copper hole and joined with inner surface of the copper hole at an interface line along the common region between the extruded aluminium metal and the copper surface. Moreover, the joining mechanism occurred without presence defects such as cracks, voids or gaps. Fig. 9b shows the SEM at the interface line of the joined sample. It clearly observed that the two materials were joined by a mechanical interlock with an interface line width of 23 μm.

Table 3 Fracture feature of samples

	surface of joined samples		surface of fracture samples			
No	Upper aluminum	Lower copper	Aluminum samples		Copper samples	
			upper	Lower	upper	Lower
1						
2						
3						
4						
5						
6						
7						
8						



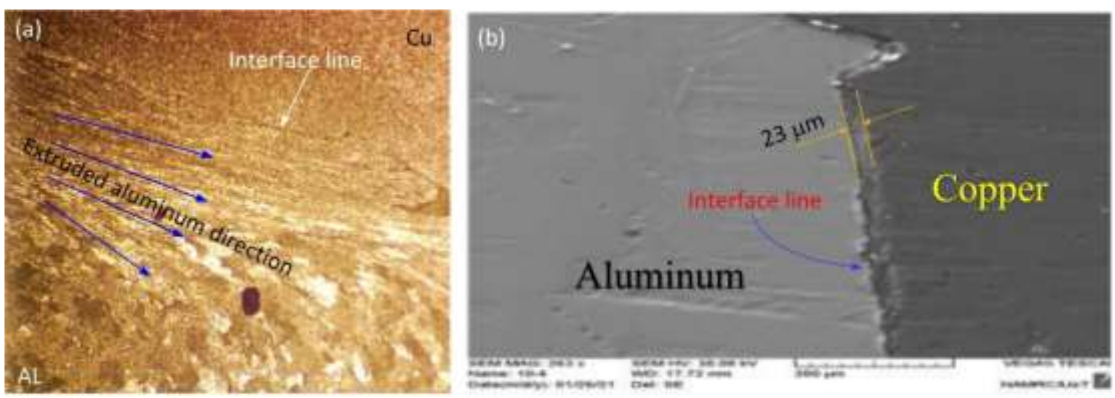


Fig. 9 Sample No.10; (a) macrostructure, (b) SEM

3.4. X-ray diffraction

XRD test was carried out at the interface line to examine presence of elements or phase formation during the joining process. The test indicated that the interface line, at the common region between the joined materials, contained single chemical elements without formation compound phases or intermetallic compounds (IMCs). The peaks were of Al, Cu, Fe, Si and Mg. The elements Al and Cu represent the wrought joined materials, while the other elements represent the chemical compositions of the aluminium alloy AA6061, as shown in fig. 10.

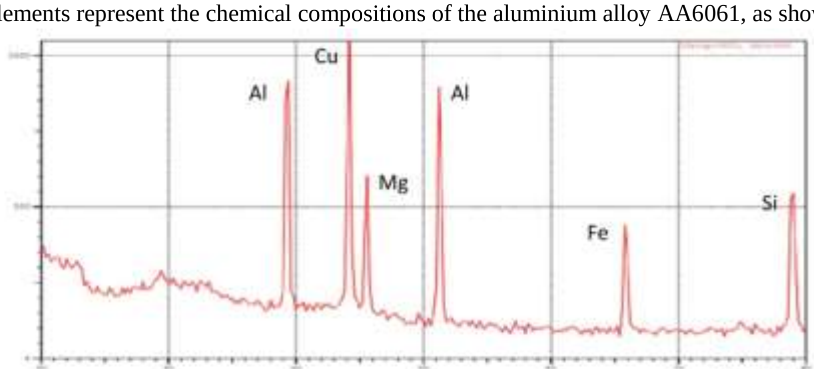


Fig. 10 X-ray diffraction, Sample No.10

4. Conclusions

A FSJ process was utilized to join Al alloy sheets together with a pre-holed pure copper by extruding Al metal during the copper hole. A snap die was used to form a rivet head from the extruded aluminium. The effect joining process parameters were studied. The following conclusion can be drawn:

1. The joined samples recorded a shear force estimates ranged from 700 to 1800 N.
2. The joint's shear force raised by incrementing amount of the extruded Aluminum metal, rotating speed and plunging depth of the tool.
3. The plunging depth of the tool has the highest effect on the joint's shear force followed by the rotating speed and the pre-heating time.
4. The samples of minimum shear force failed by pull-outing the extruded aluminium from the copper specimen.
5. The samples that exhibited a forming of rivet head of the extruded Al failed by shearing the extruded Al.
6. The two materials joined by mechanical interlock at an interface line width of a micron-scale, without formation of IMCs.
7. The joining mechanism occurred without presence of defects like cracks, voids or gaps.

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