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Evaluation of microstructures and mechanical properties of dissimilar materials by friction welding

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Abstract

The joining dissimilar metals demanding increasing importance in many industrial applications to utilize hybrid structures and reduce the cost and weight of components. The applications of dissimilar metal aluminium – copper alloys are widely involved in defence, aviation, power transmission and automobile industries due to its combinations of properties such as high strength to weight ratio, excellent mechanical properties, high resistance to corrosion and low density. However, the joining of aluminium to copper by conventional fusion welding techniques are not feasible to weld because of the newly formation of brittle intermetallic compounds at the weld pool. Hence, to overcome these problems new welding processes with high reliability and productivity for these combinations of dissimilar materials are demanded. The present work therefore studied the continuous drive friction welding of aluminium to copper for defence applications. As a result, the tensile strength of the joints achieved was 3.8 % higher than base material of the aluminium. The microstructural characterization of the weld interface was analysed by optical and scanning electron microscopy and X-ray diffraction analysis technique. Microhardness profile across the welds was showing the maximum hardness value obtained at weld interface. The joints were examined with X-ray diffraction technique in order to understand the formation of secondary phases at weld interface during welding. Tensile fracture of the welded joint occurred at aluminium side and the fracture morphology characterizing by ductile mode of failure with dimple structure.

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Keywords: Aluminium; copper; dissimilar metals; microstructure; mechanical properties; friction welding.

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1. Introduction

Aluminium and its alloys are characterized by high strength to weight ratio, formability, better weldability, low specific gravity and as well as excellent corrosion resistance in sea water and many corrosive environments. In consideration of its properties aluminium is particular interest in both automobile and aerospace applications Hatch (1984). However, they are not entirely replaced by copper, which has higher strength, good weldability at certain structures. Therefore, it is necessary to join copper to aluminium alloys. In recent years, joining of dissimilar materials was investigated because of its complex functions and several applications in the transportation and manufacturing industries. The joining of dissimilar materials is compulsory in most engineering applications. Typical fusion welding techniques such as gas welding, arc welding, and high energy beam welding are involved in excessive heating can cause deteriorates the welds, including weakening the strength and distortion Weigl et al. (2011) and Murali et al. (2012).

The joining of dissimilar metals such as aluminum to copper by conventional welding processes is result in an unreliable weld due to the occurrence of stress concentration, chemical segregation and formation of brittle intermetallic compounds. It is very difficult to remove of oxide layer from aluminium while during the welding, the difference in melt temperatures of these two materials cause to exhibit high thermal conductivity and tends to form the brittle intermetallics Behcet (2008). A common technique of metallic bond has been accomplished to bond the aluminum plate with another metal that facilitates soldering, but this practice constrained to only small joints and it involves in many steps. Eslami et al. (2011) reported the diffusion bonding of aluminium to copper achieved maximum shear strength and observed that the contact surfaces are poor at bonding. The multiphase diffusion of Cu to Al at diffusion bond lines are caused to formation of Cu-Al intermetallics due to the high bonding temperatures Yajie et al (2011). Abbasi et al. (2001) reported that roll bonding of Al-cu welds are weak in strength with the formation of bulk intermetallics layers. The joints between Cu and Al produced by brazing technique Feng et al. (2012), and found that the difficulties with finding a proper filler metals and problems are associated with ductility of the joints.

Many investigations have researched on the producing of a reliable Cu/Al joints to overcome the problems in welding of these two dissimilar materials. Lee et al., (2005) discussed the intermetallics effect mechanical and electrical properties of the Cu-Al friction welds. Mai et al. (2004) studied the characteristics of Al/Cu joints produced by laser beam welding. Mumin (2010), studied the friction welding of copper to aluminium, excellent mechanical properties observed and found the increase in hardness towards weld interface. Mechanical microstructural evaluations of Cu/Al joints produced by friction stir welding Tan et al. (2013), and investigated that the stir zone contains the formation of Cu-Al intermetallics and inhomogeneous hardness distribution. Though, except friction welding, the discussed other joining methods are all arising various problems with in the welds. Many authors have recently conducted extensive investigation into the friction welding of dissimilar materials. The benefits of joining of dissimilar materials are the combination of low specific weight, good corrosion resistance of one material and good mechanical properties of other material. The major advantage of this process derives from its applicability to join dissimilar materials. Many combinations that can be friction welded cannot be joined by fusion welding process because of the formation of brittle phases which makes the weld joint poor in mechanical properties. Short weld times of friction welding and absence of melting allow many combinations of materials to be joined Muralimohan et al. (2013).

In this work, dissimilar friction welding of 6082-T6 aluminium to commercially pure copper rods was carried out, and assessment of mechanical properties and microstructural characterization of dissimilar joints were investigated. The formation of dissimilar joints produced by friction welding based on the experimental results was discussed.

2. Experimental procedure

The materials used in the present experiment were 6082-T6 aluminium alloy and industrial commercially pure copper in the form of cylindrical rods. The friction welding conducted on the specimen dimensions of 120 mm in length and 20 mm in diameter are used. The chemical composition and mechanical properties of the substrates were showed in Table 1 and 2 respectively. The continuous drive friction welding method was used to perform the friction welding joints. The welds which were made between AA 6082- T6 aluminium and copper by friction welding, each deformation resistance differs greatly, in that the aluminium base metal deforms by plastic deformation during joining. The Al alloy maintained as a rotating part and copper positioned as a stationary part. Resulted welds obtained the circular flash diameter on Al side is larger than the copper side, so that the flash was machined on lathe to required size. In this experiment, the friction welding parameters such as friction time and forging pressure are varied while the rotating speed, forging time and friction pressure are held at constant. Parameters employed in performing the various trails are given in Table 3. After completion of the welding the sample taken out from the machine and tensile sample is prepared as per ASTM-E8 standard. The specimens for V-notch impact of 55x10x10 mm and V-notch is prepared at weld interface of 2 mm depth and 45° angle. The toughness of the resulted welds is recorded at with increase in forging pressure and increase in friction time. The metallographic techniques were applied for all the welds made by different process parameters.

Microstructural observations of the as-received rods and weld interfaces were accomplished via optical metallography technique and scanning electron microscope (SEM) analysis. The transverse sectioned welds were prepared for microstructural observation as per standard metallography procedures. Microhardness survey was performed at the bond interface of the joints and the zones immediate both the copper and aluminium alloy by with a digital microhardness tester. A load of 200 g for 10 s was applied to take the indentation on the specimens. The tensile fracture surfaces of the welded joints were examined using SEM for locates the fracture and mode of failure. The presence of intermetallic compounds in the reaction zone was confirmed by X-ray diffraction (XRD) using a copper target operated at voltage 40 kV and current 30 mA.

Table 1. Chemical composition of base materials (wt%).

Materials	Si	Fe	Mn	Zn	Ni	Ti	Cr	Mg	S	Pb	Sn	Al	Cu
6082 Al alloy	1.1	0.4	0.9	0.2	-	0.1	0.22	1.1	-	-	-	Balance	0.1
Copper	-	0.004	0.05	0.006	0.005	-	18.98	1.83	0.004	0.004	0.003	-	Balance

Table 2. Mechanical properties materials used in the experiment.

Base materials	Tensile strength (MPa)	Elastic Modulus (GPa)	Density ($g.cm^{-3}$)
6082 Al alloy	170	78	2.71
Copper	220	104	8.9

Table 3. Friction welding conditions.

Friction pressure (MPa)	Forging pressure (MPa)	Friction time (s)	Forging time (s)	RPM
110	80-160	1-4	6	1500

3. Results and discussions

3.1. Microstructure of welded joints

The joint shows the formation of higher flash with increasing in forging pressure and friction time. The flash was observed to be from both aluminium and copper materials and the outer diameter of the aluminium flash is little bit more than that of copper, suggesting that Al experienced to more deformation than copper. The microstructural evaluation of welded joints revealed a plastic deformation zone and heat affected zone near to the interface. The difference in physical and thermal properties of the materials to be welded in dissimilar metal welding are resulted in asymmetrical deformation. The formation of more outer flash on aluminium side than the copper side is because of low strength of aluminium. The width of deformation zone is depending on the generation of frictional heat due to the effect of friction time, and the as friction time increases width of deformation increasing and the heat affected zone reveals at the weld interface Yimaz et al (2003) and Muralimohan et al. (2014). With an increase in temperature due to friction the yield strength of copper decreases and the atomic diffusivity increases which results in more interfacial deformation and facilitates the metallurgical bonding. The presence of deformed grains in copper

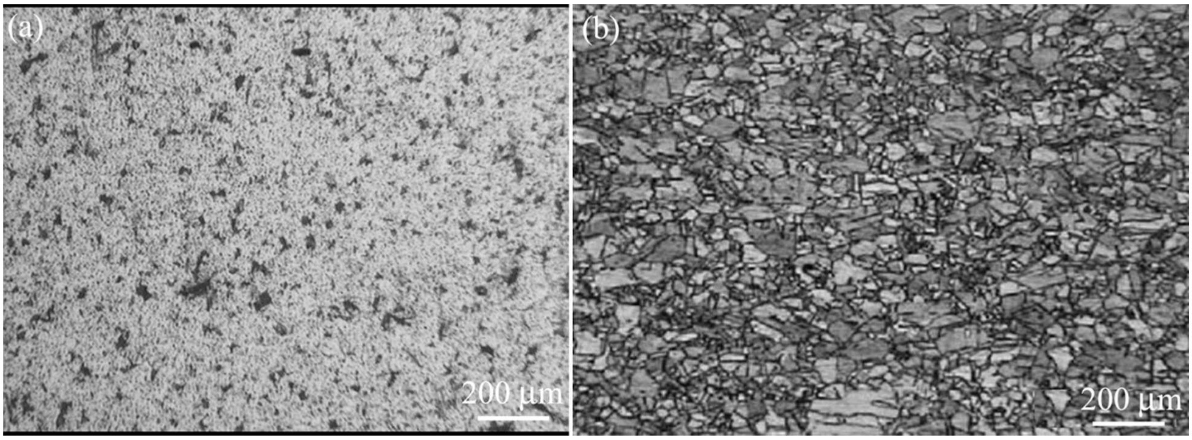

Fig. 1. Optical microstructure shows the HAZ of the joints (a) Al, and (b) Cu side.

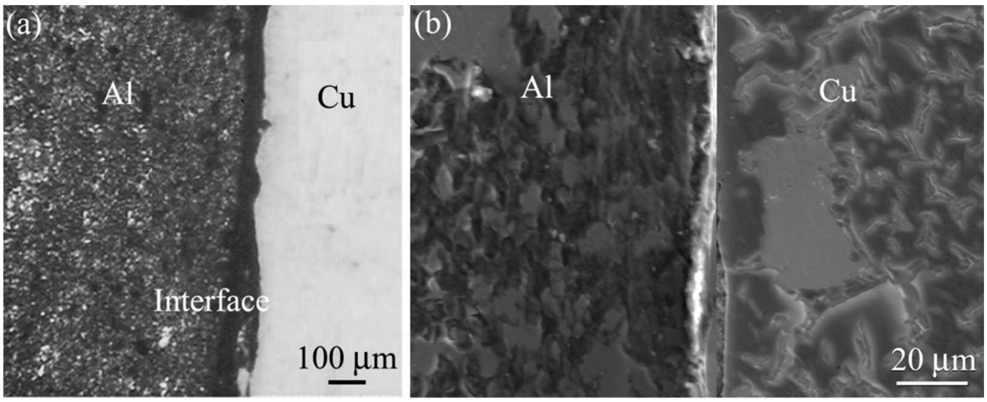

Fig. 2. Microstructure welded at aluminium to copper interface of the joints (a) Optical microscopy, and (b) SEM.

indicates that deformation is not confined to aluminium but copper also subjected to some amount of deformation near to the weld interface. Generally in friction welding method the periphery regions experienced more heat generation than the central region of the weld. Due to this the central region of the welds consists of finer grains are shown in Fig. 1. Fine grain size at centre region is due to the dynamic recrystallization. The microstructure of the Al/Cu weld interface is shown in Fig. 2. The Cu/Al weld interface is characterized by thin diffusion layer revealed at Al side near to the interface. The diffusion layer thickness increases with increasing forging pressure. The weld interface in Fig. 2 (a) shows that thickness of diffusion layer formed in several microns of width and indicates that the movement of atoms through the interface of Cu and Al materials. The SEM microstructure indicating the deformation region on Al side near the weld interface is shown in Fig. 2 (b).

3.2. Microhardness survey

The micro hardness profile of the joints across the weld region is an important factor which decides the mechanical properties of the joints. The hardness survey was conducted across the Al–Cu joint interface covering base material and abutting weld material affected by frictional heat is demonstrates in Fig. 3. It can be envisage from results showing eventually the analogous tendency in hardness distribution away from interface. Whereas, in interface area it deliberates hardness profile slightly strengthens with higher in forging pressure. These changes

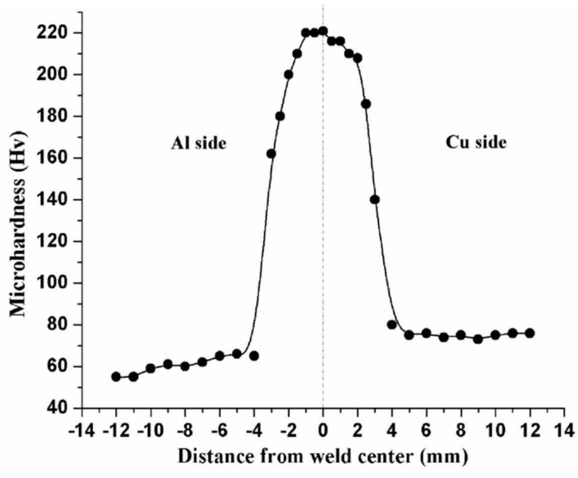

Fig. 3. Hardness profile across the Al/Cu joints

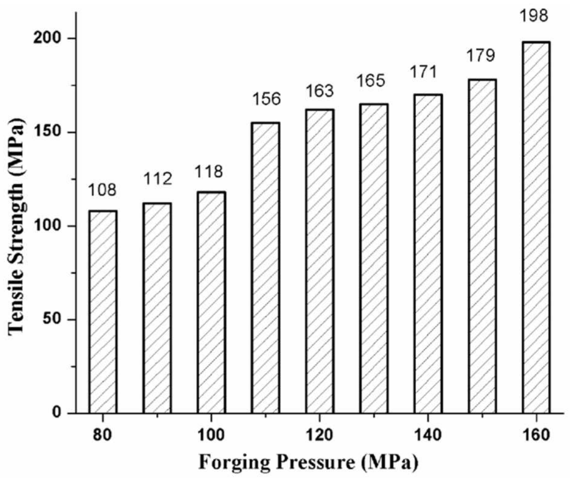

Fig. 4. The correlation between tensile strength and forging pressure

caused due to the slighter frictional heat input accessible at the interior resulting outrageous strain hardening effect. The highest hardness value on aluminium side near the weld lines is directly associated to the microstructure crystallized in the weld as a result of high density dislocations during extensive plastic deformation. However, there is no appreciable increase in hardness in copper side equated to original hardness of the parent material representing that strain hardening is less and the extent of deformation is limited on copper compared to aluminium. The peak hardness recorded at Al/Cu interface can be attributed to the formation of intermetallic compounds of Al–Cu and microstructural formation. Feng et al. (2012) reported that the distinctively the higher hardness values on the Cu and Al side near weld interface are due to the formation of Cu/Al intermetallics compounds. Moreover, the hardness of the diffusion layer structures was measured as high as 220 HV, which one more than that of the deformation area on either Cu or Al materials. Previous experiments indicated that the hardness of the Al–Cu intermetallics was very high as compared to substrates, and the highest hardness value could reach 760 HV, Xue et al. (2011). Therefore, the peak hardness values of the interface originated mainly from the Al–Cu intermetallics.

3.3. Tensile and impact test results

Friction welding of Cu/Al joints was evaluated for their joint efficiency through tensile testing. The correlation between forging pressure tensile strength of the joints was depicted in Fig. 4. It is observed that the resulted tensile strength of the welds enhanced gradually through an increase in forging pressure over the 80 MPa. Therefore, the average tensile strength of the welds is higher than strength of the aluminium base material and the joint efficiency is 3.8 % higher than the aluminium. The longer friction times and higher forging pressure is directly related to the strength of the joints. The selection of optimum friction time is depending on the composition of the materials, friction pressure and rotational speed of the specimens. The required heat for producing the friction welded joints is the duration friction time and the heat is raised to achieve to require softening for metallurgical deformation and solid state welding. Though, in all the joints tensile fracture occurred at aluminum side nearer to weld interface, some joints also failed at weld interface.

Impact strength results confirmed the influence of temperature on welds. The toughness of the welds varying through different welding processes and with varies temperatures. Hence, the toughness is depleting with inappropriate assortment of process parameters. The inflated forging pressure ameliorates in associating the bonding of the joints. The experimental impact test results are increased with forging pressure and the maximum strength of 28 J attained at forging pressure-140 MPa and friction time–3 s. Impact strength is decreasing with enhancement of friction pressure due to the heat development in the weld interface is affected on larger grain size. Toughness and

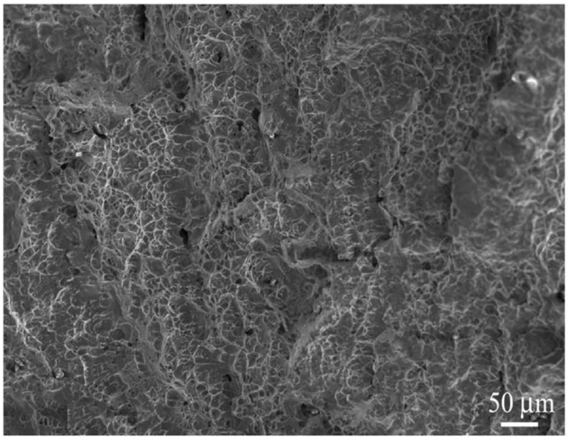

Fig. 5. SEM micrograph of the tensile fracture surface at Al side

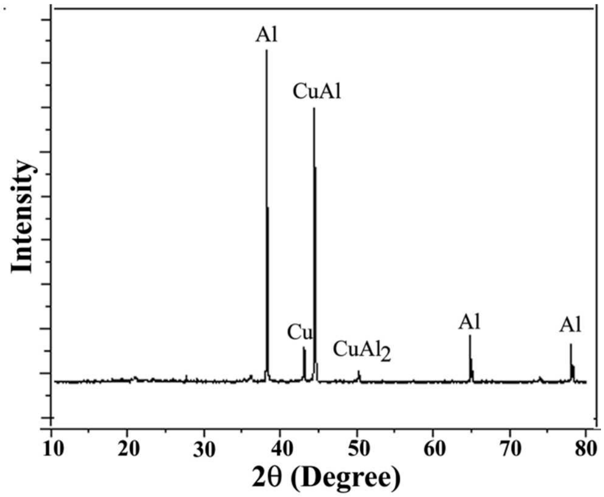

Fig. 6. Result of XRD analysis of tensile fracture surface of the welds

tensile fracture strengths intensifying with amplifying the forging pressure, and this resulting due to equi-axed granulated grain pattern with exorbitant strain hardening effect on heat affected zone and weld interface.

3.4. Fractured surface analysis

The ruptured specimens after the tensile and impact test were observed by SEM to identify the fracture location and mode of failure. Tensile fracture obtained at aluminium base metal is adjacent to the weld interface for majority of joints. The tensile fractured SEM microstructure is presented in Fig. 5. The SEM fractured graphs propounded that the fracture is assorted manner. Some of the fracture morphology depicted that the tensile shearing surface due to the effect of tension test. The mode of failure is purely ductile in nature with formation of dimple structure. The toughness is increasing with the higher forging pressures due to higher deformation and the failure occurred under impact load was near to the weld interface is evidenced that the failure away from weld interface and fracture observed as a ductile failure. This confirms the fact that joints has strong weld interface, which is formed with good toughness.

3.5. XRD analysis

The XRD analysis was utilized to detect the intermetallic phases in the fracture surface after performing the tensile test. XRD patterns from fractured surfaces of the aluminum side of the joints which were failed at weld interface are shown in Fig. 6. The diffraction peaks indicate the presence of CuAl and $CuAl_2$ in the fracture surface. The characteristic diffraction peaks of the CuAl phase could be clearly observed, however the diffraction peaks of the $CuAl_2$ phase were very weak, which was different from the observation in friction welding Cu-Al joints, where the diffraction peaks of both CuAl and $CuAl_2$ phases exhibited same and little higher range of intensities, Bhamji et al. (2012). A good metallurgical bonding between the aluminium alloy and the copper atoms is usually expected when small number of intermetallics formed at the weld interface Xue et al. (2011).

4. Conclusions

In this study, the microstructure of friction welded Cu/Al joint and its weld interface characterization were identified and discussed. Moreover, the correlation between microstructure and mechanical properties was investigated. The following conclusions were made:

1) AA6082-T6 alloy and copper are joined successfully by friction welding with on optimized parameters such as forging pressure of 160 MPa and friction time of 4 s.
2) The friction weld joints have achieved a higher tensile strength compared to their base metal strength. The average tensile strength and elongation of the dissimilar joints are 198 MPa and 3.8 %, respectively.
3) The microhardness value constantly increasing towards the weld interface due to the strain hardening effect. The highest hardness indicated at diffusion layer in the interface of the presence intermetallics.
4) The microstructural characterization shows that the welds between Cu and Al accompanied by the diffusion Al into the Cu.
5) Tensile fracture studies investigates that the fracture is in ductile mode of failure with the presence of dimples structures.
6) XRD studies confirmed the formation of CuAl and $CuAl_2$ intermetallics in the joints failed at interface with low tensile strength.

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