Mechanical and Microstructural Properties of Friction Stir Welded Dissimilar Aluminum Alloys and Pure Copper Joints

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Abstract. Joining dissimilar metal alloys such as aluminum and copper is very difficult to be done because of alterations in chemical, metallurgical and physical behavior. Friction Stir Welding (FSW) is a solid-state welding technique which is one of the new methods used for joining the dissimilar metal. The material used is aluminum alloy 5052 and pure copper plates. The welding parameters were carried out with variable geometry shape of pin tools: taper and threaded cylindrical pin tools. Also preheating were performed on the part of copper plates with temperatures at both 25°C and 200°C. The friction stir welding of dissimilar joints was carried out at the rotary tool speed of 2800 rpm with the angle of 1 degree and the welding travel speed of 2 mm/sec. All welds were then carried out to several mechanical testing and microscopic observation. The results show that the variable geometry shape of pin tools and pre-heating on the copper part affect the microstructure grain size and the formation of Al-Cu inter-metallic phases. The creation of different structures influences the mechanical properties of the friction stir welds. The hardness of welds using threaded pin tools is higher than the taper one. However, the tensile strength of dissimilar welds using the threaded cylindrical pin tools is lower than the taper one. The fracture location commonly occurs at the part of aluminum plates having a brittle intermetallic phase.

1 Introduction

Joining dissimilar metal is unavoidable in fabricating and erecting modern engineering materials for machinery. Different types of metals used have different physical, chemical, and metallurgical properties. Hence, welding dissimilar metals are to combine different properties of metals provides reducing the costs of metals and simultaneously optimizing the performance of components. [1] Copper (Cu) and aluminum (Al) are two engineering materials commonly applied in electric power, transportation, and aerospace industries. The dissimilar joint of Al/Cu is of great interest in electrical contacts because it can reduce the costs and weight as well as extending the service life [2].

Welding method was the main priority for manufacturing of dissimilar joint. However, arc fusion welding is not applicable for joining Cu to Al due to their alterations in chemical and metallurgical features [3]. Also, the dissimilar metal joining by fusion welding can produce the formation of crack and brittle intermetallic compounds (IMCs) which severely decreased the tensile properties of welds. Hence, many types of welding method such as FSW have developed a substitute welding process for joining Al to Cu. [4]

Friction stir welding (FSW) was developed in 1991 by TWI in Britain and has been applied broadly in many industries nowadays [5]. There are commonly several regions of friction stir joints as explained by Threadgill [5] such as parent metal, the thermomechanical affected zone (TMAZ) and the heat-affected zone (HAZ) and the nugget of weld. Not only for joining, but friction stir technology has also been settled for processing metallic alloys to increase their significant properties [6]. This FSW method is very potential for the process of different materials and alloys [7].

Mukuna et al. [8] show that the friction stir welding technique provides more efficiency especially on joining the dissimilar Al/Cu. When the pin tools of FSW were improved, the welds can be produced at the high-quality [8]. However, in most of the study conducted on FSW between aluminum and copper, the design of tool shape is commonly not fully stated. The geometry of tools is a critical factor for creating the sound welds of dissimilar joints.

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2 Experimental Method

The FSW process used for joining between the aluminum alloy 5052 plates and the pure copper plates. The chemical compositions of both plates can be seen in Table 1 and Table 2. The welding configuration used was a square butt joint of $50 \times 120 \times 6 \text{ mm}^3$. The FSW parameters used for producing dissimilar joints were shown in Table 3. All the other settings were kept constant. The pin tools used are made of high-speed steel (HSS) type with a cylindrical shape and a threaded cylindrical taper, as shown in Figure 1. The pre-heating is on the part of the copper side by using the gas burner. Heating is carried out at temperatures up to 200°C .

Table 1. The elemental composition of AA5052 (wt. %)

Al	Fe	Si	Zn	Mg	Mn	Cu	Others
97.7	0.4	0.25	0.1	0.15	0.1	0.1	0.15

Table 2. The elemental composition of pure Cu (wt. %)

Cu	Fe	Pb	Zn	P	Si	Mg	Mn	Al
99.95	0.01	0.00	0.001	0.014	0.00	0.00	0.00	0.00

Fig 1. Tools geometry with (a) Threaded. (b) Tapered cylindrical

The welds joint was manufactured using a milling machine as seen in Figure 2. The weld specimens were prepared for metallography analysis for the various location of the weld joint by using an optical microscope. The metallograph observation was used for analyzing the microstructure and the feature of material flow on the dissimilar joints. The polished mirror specimens were prepared by using a Keller's reagent to observe the microstructural welds. The inter-metallic compounds were analyzed using scanning electron microscope (SEM), and microchemical was determined by using EDS to evaluate the thickness, size, and distribution of it.

Table 3. Friction stir welding parameters

Type of Pin Tools	Parameters	Units
Taper Cylindrical	Rotational speed	2800 rpm
	Tilting angle	1 deg
Threaded Cylindrical	Welding speed	2 mm/sec

Fig 2. The dissimilar FSW process

Fig 3. Dissimilar FSW process with pre-heating

Mechanical properties are examined using a micro Vickers hardness test and tensile strength test. Micro Vickers test performed on a 7-point weld area with a load of 300 kgf for 10 seconds. The tensile test samples are prepared by using ASTM standard E8M-04 and carried out at a speed of 1mm/sec.

3 Results and Discussion

3.1. Metallographic Structures of FSW Weld

The effect of dissimilar FSW Al and Cu and macrostructure is shown in Figure 4. The surface appearance on welds without preheating seems to be rough on weld bead surface compared to the preheating one. Welds using threaded cylindrical pin tools have more significant stirring zone structure (black color) than the weld using taper cylindrical pin tools. It is due to the mixture of Al-Cu metals increased with using the threaded cylindrical pin tools.

Fig 4. The macro-structure of Al - Cu dissimilar FSW with pin tools of: (a) taper cylindrical (b) threaded cylindrical (c) taper cylindrical with pre-heating (d) threaded cylindrical with pre-heating

Fig 5. Microstructure of stir weld zone with the pin tools of: (a) taper cylindrical; (b) threaded cylindrical; (c) taper cylindrical with pre-heating; (d) threaded cylindrical with pre-heating

Using the higher magnification of the microscope as seen in Figure 5, it shows that the part stir zone/nugget zone between Al and Cu are shown. The observation of an optical microscope showing the microstructure of Al-Cu mixed phase has a somewhat yellowish color, in contrast with the color of the base metal of Cu and Al. According to Liu et al. [9], the boundary between copper and aluminum was ostensible, and a plastic combination of materials at the border occurred. The formation of good material flow indicated by a circular ring occurred between the copper and aluminum interface.

The microstructure on the weld interface between aluminum and copper was taken by scanning electron microscope (SEM) and included the chemical composition test by using Energy Dispersive Spectrometry (EDS) as can be seen from Figure 6 to Figure 9. The thin layer of the interface is formed in the FSW dissimilar joint of Al-Cu. The average thickness is the range of 5-10 μm on the section between Al and regional base metal stir zone. This thin layer contained the compound around large copper particles and small copper particles, and it is called intermetallic compounds (IMCs). The results of chemical composition test by using EDS showed that the chemical composition is almost balanced between Al and Cu, so that suggests the formation of intermetallic phases formed between aluminum and copper at temperatures approaching the melting of IMCs.

According to Xue et al [10], aluminum reacted with copper creating some compounds near large copper particles and small copper particles. Hence copper gets converted into the intermetallic compound.

There are found a crack in the Al-Cu interface of dissimilar weld especially at the TMZ Aluminum as seen in Figure 6 and Figure 7. Also, there are also found the weld defects in the form of voids (porosity). This void appears in the weld using the threaded cylindrical pin tools as seen in Figure 7 and Figure 9. According to Bisadi et al., some weld defects were a presence when welding was performed at a low temperature. However, when welding was carried out at a very high temperature, some voids (cavities) were formed at the interface [11]. Also, Xue et al. found that in the weld interface had a good metallurgical bonding observed in the dissimilar Al-Cu welds joined by FSW [12].

The results of chemical composition test by using EDS showed that the chemical composition is almost balanced between Al and Cu, so that suggests the formation of intermetallic phases formed between Al and Cu at temperatures approaching the melting.

Fig 6. Microstructure dissimilar FSW pin tools taper cylindrical and no-preheat observed by SEM-EDS; (1) interface/TMAZ Al (2) stir zone/nugget (3) interface/TMAZ Cu

Fig 7. Microstructure dissimilar FSW pin tools taper cylindrical and no-preheat observed by SEM-EDS; (1) interface/TMAZ Al (2) stir zone/nugget (3) interface/TMAZ Cu

Fig 8. Microstructure dissimilar FSW pin tools threaded cylindrical with pre-heating observed by SEM-EDS; (1) interface/TMAZ Al (2) stir zone/nugget (3) interface/TMAZ Cu

Fig 9. Microstructure dissimilar FSW pin tools threaded cylindrical with pre-heating observed by SEM-EDS; (1) interface/TMAZ Al (2) stir zone/nugget (3) interface/TMAZ Cu

3.1. Mechanical Properties of FSW Welds

The indented location of micro-hardness Vickers on the weld specimen can be seen in Fig. 10. The result of the hardness test can be shown in Fig. 11, then the result of the tensile test can be seen in Fig. 12. The location of the fracture after the tension testing can be seen in Table 4.

Fig 10. Indentation mapping of micro Vickers hardness test on FSW weld samples

Fig 11. Micro-hardness distribution test on welds with no preheat using the pin tool of (a) taper (b) threaded

Fig 12. Micro-hardness distribution test on welds with preheat using the pin tool of (a) taper (b) threaded

Hardness test results in Fig. 11 shows that an increase in mechanical properties such as hardness in the weld area when compared with both base metal Al and Cu. An increase in the average hardness value of about 60%. Factors Increasing the hardness value is influenced by the stirring process that causes the phase of Al and Cu split into fine grains and mixed that is spread on the weld area as composite particles of Al-Cu and Al-Cu intermetallic phase. At welding with pre-heating area base metal, HAZ, and TMAZ hardness value is much higher than in welding without pre-heating, the part most likely exposed to the effects of pre-heating process is performed on Cu so that the properties of hardness increases.

Fig 13. The tensile strength of the base metal & the dissimilar welds and compared with parameters

The results of the tensile test on FSW dissimilar weld joints as seen in Figure 13 showed that the FSW weld produced by using taper cylindrical pin tools have the higher tensile strength of 165 MPa compared with the welds using threaded cylindrical pin tools of 52 MPa without any preheating. The low UTS on the threaded cylindrical pin tools is due to the presence of weld defects such as cracks and void (porosity) with considerable amounts in the weld stirring zone. According to Akinlabi et al. [13], the increasing weld microhardness value at the interface because of the presence of strain hardening.

Table 4. The tensile strength of dissimilar welds and fracture

FSW variable	UTS (MPa)	Fracture Location	Picture of The fracture area
Pin tools taper cylindrical	165	HAZ Al	
Pin tools threaded cylindrical	52	HAZ Al	
Pin tools taper cylindrical pre-heating	91	Nugget/ stir zone	
Pin tools threaded cylindrical pre-heating	82	HAZ Al	

The effect of preheating on the mechanical properties of dissimilar weld joints as seen in Figure 13 showed that the ultimate tensile test of welds decreased when the preheating applied during welding. It is because the effect of pre-heating process on Cu base metal may cause extremely high temperatures which would then affect the aluminum which tends to form brittle structures at the HAZ Aluminum. According to several researchers [14-19], it shows that the dramatic changes in the mechanical properties of the weld joint because of the inter-metallic layer at the interface and the formation of cavities (void)

4. Conclusion

The variable geometry shape of pin tools and pre-heating on the copper part affect the microstructure grain size and the formation of Al-Cu inter-metallic phases. The use of taper cylindrical pin tools produces an excellent weld structure with few weld defects and hence have good mechanical properties for FSW dissimilar Al-Cu joints. The hardness of welds is mostly higher in the area of the weldment. The tensile strength of dissimilar welds using the taper cylindrical pin tools is higher than the threaded cylindrical one. The effect of the pre-heating process on Cu base metal may cause extremely high temperatures which would then affect the aluminum to form brittle structures at the HAZ Aluminum. Therefore, the fracture location of a tensile test commonly occurs at the part of aluminum plates having a brittle intermetallic phase.

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