Metallurgical investigation and mechanical properties of dissimilar friction crush welded Cu-Al sheets with flanged edge

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Abstract. Welding of dissimilar metals is one of the most substantial requirements of industries and extensively used in engineering applications. Dissimilar friction crush welding between oxygen-free copper (C1020) and aluminum (1145-H1) sheets with a thickness of 1 mm was investigated in this work using different flange edge heights (2, 2.5 and 3 mm) and gaps (0.5 and 1 mm) between Cu-Al sheets. Tool rotational speed of 1500 rpm and feed rate of 120 mm/min were used in all welding experiments. Evaluation of Cu-Al joints was performed successfully using optical microscope, SEM, XRD, EDS, hardness and tensile tests. Several FCW experiments were carried out to obtain the optimum properties by adjusting the flanged edge height and gap between dissimilar sheets. Cracks are the main defect encountered in Cu-Al joints. The XRD results showed that no new reaction phases were formed in the Cu-Al joints. EDS results showed no pronounce diffusion of elements in the crush zone and mechanical coalescence was responsible for welding. The results also indicated that the FCW parameters has a significant effect on the hardness and tensile strength of Cu-Al joints.

1. Introduction

Generally, copper and aluminum replace steel in electrical supply systems due to the higher level of electrical conductivity. However, welding copper and aluminum using conventional fusion welding processes is usually difficult due to their high thermal conductivity [1]. Copper and aluminum have many applications as engineering structural materials due to their wide and good properties such as excellent electrical and heat conductivities, ductility and corrosion resistance. Welding of dissimilar materials such as copper and aluminum is of great importance in engineering applications due to its technical and
beneficial advantages. The structure of copper and aluminum will contribute to cost and mass reduction by lowering the amount of strategic metals usage [2]. Various welding methods, including fusion welding, braze welding and pressure welding, have been applied to joining of Al–Cu dissimilar metals in spite of many problems encountered such as oxidation, cavities and cracks [3, 4]. Solid-state welding processes that limit extent of intermixing are generally employed in such situations. Friction welding is one of solid-state welding processes that widely employed in engineering applications. It uses in welding of tubes, pipelines, fuel tanks, as well as in engines, electronic packages and in other several applications [5, 6]. These wide applications go back to the past investigating showed that fusion welding caused many problems in the welding zone of light metals such as aluminum alloys [7]. The principle of friction welding depends on two main factors, compressive forces and friction heat. The compressive forces are used for bonding while the frictional heat produced as a result of mechanical energy due to relative motion of the tool or relative motion of the workpieces [8]. In friction welding, the relative motion of the tool usually used for joining thin sheets that are difficult to weld by other friction welding techniques. The relative motion of the tool during friction welding determines two main welding techniques; friction stir welding (FSW) and friction crush welding (FCW). Friction crush welding FCW can be used for welding of thin sheets. In friction crush welding, a non-consumable tool having a specific profile rotates around the horizontal axis and workpieces with flanged edges are placed against each other with specific gap, where a frictional contact is made between tool and workpieces during welding. The tool with a disk geometry was used to crush a certain volume of base metal into the gap between two sheets [9]. Several researchers studied the influence of friction crush welding parameters on the properties of similar welded joints such as aluminum [10], copper [11,12], and steel [13,14]. However, a limited attempt has been made to investigate the mechanical properties of FCWed joints such as welding 6061 T-6 aluminum alloy to AISI 304 stainless steel [15].

Many applications in the fields of construction and industrial manufacturing require welding of dissimilar materials. However, from the literatures survey, no literature was found regarding the joining of Cu-Al sheets using friction crush welding. Therefore, this work was performed to characterize the microstructure of Cu-Al joints. An analysis of mechanical properties and failure mechanism is also included in this work.

2. Experimental work

FCW experiments were carried out on horizontal milling machine type IWASHITA, Japan figure 1. The tool in the form of disk is set on milling machine with different rotational and linear speeds to weld sheets of oxygen-free copper (C1020) to aluminum (1145-H1) sheets with dimensions of 150 mm x 75 mm x 1mm. The workpieces were fixed to the machine table adjacent to each other with the help of clamping device. The tool was manufactured from high-strength low alloy steel (A514 R) with chemical composition illustrated in Table 1. The chemical composition of oxygen-free copper (C1020) and aluminum (1145-H1) sheets were illustrated in Table 2. Different flanged edge heights and gaps between Cu-Al sheets were used in welding experiments as illustrated in Table 3. After several experiments, welding was achieved using tool rotational speed of 1500 rpm and feed rate of 120 mm/min. The copper-aluminum sheets, friction crush welding tool and tool schematic diagram are illustrated in figure 2.
Figure 1. Horizontal milling machine used in FCW experiments

Table 1. Chemical composition of friction crush welding tool (A514 R)

| Element wt.% | C   | Si  | Mn  | Ni  | W   | Co  | Cr  | Al  | Mo  | V   | Cu  | Fe  |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| A514 R       | 0.234 | 0.253 | 0.894 | 0.390 | 0.025 | 0.018 | 0.567 | 0.028 | 0.167 | 0.007 | 0.114 | Balance |

Table 2. Chemical compositions of oxygen-free copper and aluminum

| Element wt.% | Al  | Fe  | Sn  | Mn  | Mg  | Cr  | Ni  | Zn  | Ag  | Pb  | Si  | Cu  |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| C1020(Copper) | 0.001 | 0.003 | 0.002 | 0.003 | 0.001 | 0.001 | 0.005 | 0.02 | 0.002 | 0.010 | 0.004 | Balance |
| 1145-H1(Aluminum) | Balance | 0.379 | 0.005 | 0.04 | 0.007 | 0.001 | 0.007 | 0.04 | 0.002 | 0.005 | 0.116 | 0.05 |
Table 3. Flanged edge heights and gaps between Cu-Al sheets used in FCW experiments

| Specimen Symbol | Gap between Cu-Al sheets (g), mm | Flanged edge height (h), mm |
|-----------------|----------------------------------|----------------------------|
| G               | 0.5                              | 2.5                        |
| H               | 0.5                              | 2                          |
| I               | 0.5                              | 3                          |
| J               | 1                                | 2.5                        |
| K               | 1                                | 2                          |
| L               | 1                                | 3                          |

Figure 2. (a) Cu-Al sheets prepared for welding, (b) FCW tool and (c) schematic diagram of FCW tool in mm

The gap between copper-aluminum sheets that filled by flanged edge material during welding was determined accurately after several experiments achieved. Figure 3 schematically shows the position of dissimilar Cu-Al sheets with flanged edge before welding. The formulas used to calculate the height of a flanged edge (A) and the total height of a flange (F) were illustrated elsewhere [10]. Tensile tests were performed for various FCWed Cu-Al joints to express the relationship between the welding strength and the FCW parameters used. Tensile test specimens for dissimilar Cu-Al joints are illustrated in figure 4.
All tensile test specimens were performed in accordance with EN ISO 4136 standard using universal testing machine model WDW-200E.

![Figure 3. Schematic diagram of Cu-Al sheets prepared for welding](image)

**Figure 3.** Schematic diagram of Cu-Al sheets prepared for welding

Vickers Hardness Tester type (HVS-1000) was used to measure the hardness values at several points on the welding line across the welded joint. A 500 g load was applied during hardness test on the cross section of the welded joint for 15 s. The cross-section of the welded joint surface was prepared using grinding, polishing and etching, respectively, in order to reveal the microstructure. The etching was achieved using etching solutions of (5 g FeCl₃, 50 ml HCl, 100 ml distilled water) for the copper side and (95ml H₂O, 2.5ml HNO₃, 1.5ml HCL, 1 ml HF) for the aluminum side of the Cu-Al joints. Optical microscope model Optika-Italy and scanning electron microscopy (SEM) model (FEI 9922650) with high-resolution were used to characterize the microstructure. Energy dispersive spectroscopy (EDS) model (BRUKER) which was combined with SEM was used for elemental analysis. X-ray diffraction analysis was carried out using X-ray device type (XRD6000-Shimadzu).

![Figure 4. Dissimilar Cu-Al tensile test specimens](image)

**Figure 4.** Dissimilar Cu-Al tensile test specimens
3. Results and discussion

Figure 5 shows the microstructure of the cross-section of the FCWed Cu-Al joint. In the crush zone (CZ), mechanical coalescence is formed between cooper and aluminum due to severe plastic deformation and heat generation as a result of the relative motion of the disk with the workpiece figure 5(a). In contrast, the material in the thermomechanical affected zone (TMAZ) has been affected by heat and plastic deformation only. Dynamic recrystallization can be clearly seen in TMAZ zone of both sides of Cu-Al joint figure 5(b, e). On the contrary, a material in the heat affected zone (HAZ) is affected by heat and does not experience significant plastic deformation. Coarsening of the α-Al and β-Cu grains in this zone occurs due to the release of heat through the crush zone to TMAZ adjacent to the HAZ zone during welding figure 5(c, f). Finally, the base matrix of either copper or aluminum can be clearly distinguished as the unaffected zone by plastic deformation or heat figure 5(d, g). All these zones are presented in both sides of the Cu-Al joint. The formation and characteristics of each zone depend on the parameters of the FCW as well as the addition or absence of filler material in the crush zone [13]. In all of the FCW experiments achieved no filler was added.

Figure 5. Microstructure of cross section of FCWed Cu-Al joint using 2 mm flanged edge height and 1 mm gap between Cu-Al sheets
The microstructure of crush zone of Cu-Al joints is illustrated in figure 6. Figure 6(G) indicated that the microstructure is defect free and with complete gap filling between Cu-Al sheets. It is clearly that narrow area mixed zone between Cu and Al can be recognized along the crush zone due to limitations of welding parameters used. Figure 6(H) shows decreasing the mixed zone thickness along the crush zone between the Cu-Al sheets and the crack can be recognized. The reason for defects formation may be related to poor mechanical coalescence of materials and an incomplete filled gap. The microcrack can be clearly distinguished which is one of the causes of deterioration in mechanical properties figure 6 (I). The large gap between Cu-Al sheets and insufficient metal to fill the gap led to cracks formation figure 6 (J, K). The excessive gap between the Cu-Al sheets resulted in several welding defects such as cracks, cavity and unsound joint formation figure 6 (L). It is clear from microstructural investigation that mechanical coalescence between copper and aluminum in the crush zone and weld properties were based on FCW parameters used as flanged edge height and gap between Cu-Al sheets.

Figure 6. Microstructure of crush zones at different flanged edge heights and gaps between Cu-Al sheets (G) 2.5 mm and 0.5 mm, (H) 2 mm and 0.5 mm, (I) 3 mm and 0.5 mm, (J) 2.5 mm and 1 mm, (K) 2 mm and 1 mm gap and (L) 3 mm and 1 mm
Figure 7 shows XRD of the crush zone of FCWed Cu-Al joint. Two phases can be recognized from the XRD chart. These two phases are $\alpha$-Al and $\beta$-Cu. Both phases have FCC crystal structure. The formation of these two phases related to mechanical coalescence of Cu and Al in the crush zone during welding. No intermetallic compound can be identified from the XRD. This means that the generated heat and/or heat survival in the crush zone is not enough for intermetallic compounds formation.

![XRD chart showing two peaks for $\alpha$-Al and $\beta$-Cu phases.](image)

Figure 7. XRD of crush zone of Cu-Al joint using 2.5 mm flanged edge height and 0.5 mm gap between Cu-Al sheets

Figure 8 shows SEM image of secondary electron with EDS mapping of a specified location in the crush zone of FCWed Cu-Al joint using 2 mm flanged edge height and 0.5 mm gap between Cu-Al sheets. It is clear that mechanical coalescence in the crush zone play a significant role in bonding. Some of copper was incorporated within aluminum figure 8 (a). Furthermore, mixed zone due to mechanical coalescence can also be identified figure 8 (b). Interface can be clearly showed between aluminum and mixed zone. This interface is enriched with aluminum despite the interface between copper and aluminum that enriched with copper. The welding parameters used were not encourage to form another new phase in the mixed zone figure 8 (c).
Figure 8. (a) SEM image, (b) EDS mapping and (c) elemental analysis of crush zone of FCWed Cu-Al joint using 2 mm flanged edge height and 0.5 mm gap between Cu-Al sheets.

Increasing the flanged edge height to 2.5 mm with 0.5 mm gap between Cu-Al sheets changed the crush zone characteristics as shown in figure 9. It is obvious that mixed zone can be identified in the crush zone. Certainly, these mixed zones not cover the whole interface between Cu and Al figure 9 (a). Covering the mixed zone along the interface depends on the FCW parameters used. Fully mechanical coalescence between Cu and Al can be recognized in these zones figure 9 (b). No new phases were formed in these zones due to insufficient temperature formation and/or rapid releases the heat during welding figure 9 (c). Therefore, β-Cu and α-Al remain the two phases presented in the crush zone regardless mechanical coalescence zones formation and the same FCC crystal structures of both phases.
Figure 9. (a) SEM image, (b) EDS mapping and (c) elemental analysis of crush zone of FCWed Cu-Al using 2.5 mm flanged edge height and 0.5 mm gap between Cu-Al sheets

Figure 10 shows the vickers hardness vs. the distance along the cross section of the welded joint under the influence of using different flanged edge heights and gaps between the Cu-Al sheets. The hardness of the crush zone of the aluminum side is greater than the hardness of the aluminum base matrix. This is due to the mechanical coalescence between aluminum and copper as the hardness of copper (80 Hv) increases the hardness of the crush zone compared to the lower hardness of aluminum (29 Hv). In contrast, the hardness of the crush zone of the copper side is lower than that of the copper matrix due to the lower hardness of aluminum which coalescence mechanically with the copper. For the six welds performed, the weld (G) had the highest hardness of 65 HV in the copper side and 20 HV in the aluminum side. The weld hardness values of specimens (H) to (L) on both sides, copper and aluminum, were (64, 18 HV), (63, 16 HV), (61, 14 HV), (60, 13 HV) and (59, 12 HV), respectively. Obviously, the total hardness gradually decreases from 80 HV of the base metal in the copper side and 30 HV in the aluminum side to a certain value in the crush zone. It should be noted that the fluctuation of hardness values is influenced by the welding parameters used and the defects created in the crush zone. As explained before, the main defects are the incomplete filled gaps and cracks. It is evident that the insufficient gap and the reduced height of the flanged edge resulted in insufficient metal to fill the gap between the Cu-Al sheets resulting...
in the formation of defects and thus decreased hardness. Therefore, it is important to adjust the gap and the height of flanged edge to obtain the desired characteristics.

![Hardness distribution along cross-sectional area of FCWeld Cu-Al joints at various flanged edge heights and gaps between Cu-Al sheets](image.png)

**Figure 10.** The hardness distribution along cross-sectional area of FCWeld Cu-Al joints at various flanged edge heights and gaps between Cu-Al sheets: (G) 2.5 mm and 0.5 mm, (H) 2 mm and 0.5 mm, (I) 3 mm and 0.5 mm, (J) 2.5 mm and 1 mm, (K) 2 mm and 1 mm gap and (L) 3 mm and 1 mm

Figure 11 shows the σ-ε curves of copper, aluminum sheets as well as FCWeld Cu-Al joints. It is obvious that copper sheet has the highest tensile strength of 180 MPa and elongation of 15% compared with 85 MPa tensile strength and 4% elongation for aluminum sheet. All Cu-Al joints have lower tensile strength than copper and aluminum sheets. The reduction in the tensile strength may be related to the straining of the crush zone which led to the formation of cracks which accelerated the failure. Failure to fill the gap completely between Cu-Al sheets depending on FCW parameters may also reduce the tensile strength of welded joints. The highest tensile strength of Cu-Al welded joints is specimen (G) having about 73 MPa, and this value corresponds to 85% of the tensile strength of AA1145-H1 aluminum with 3% elongation. This is related to the crush zone which showing an almost complete filled gap between Cu-Al sheets and defect free as showed in figure 6. The tensile strength of the specimen (H) is about 70 MPa and the elongation is 2.8%. The decrease in tensile strength and elongation compared to specimen G may be due to poor mechanical coalescence with some cracks formed in the crush zone, as well as an incomplete filled gap between the Cu-Al sheets. Greater decrease in tensile strength of specimen (I) which is about 68 MPa and elongation 2.5%. This decrease in tensile strength and elongation is related to the cracks and high gap between Cu-Al sheets which leads to deterioration of the weld joint resulting in lower tensile strength. The further decreased tensile strength and elongation for the specimens (J) and (K) to be 65 MPa and 46 MPa, 2.3% and 2.2%, respectively, are related to cracks formation and insufficient metal to fill the Cu-Al sheets gap. Greater reduction in the tensile strength and elongation of the specimen (L) is developed to be 45 MPa and 2%, respectively, due to the large gap between the Cu-Al sheets, the formation of cracks and the insufficiency of the metal to fill the gap between the Cu-Al sheets.
Figure 11. \(\sigma-\epsilon\) curves of copper, aluminum and FCWed Cu-Al joints at various flanged edge heights and gaps between Cu-Al sheets: (G) 2.5 mm and 0.5 mm, (H) 2 mm and 0.5 mm, (I) 3 mm and 0.5 mm, (J) 2.5 mm and 1 mm, (K) 2 mm and 1 mm gap and (L) 3 mm and 1 mm

Figure 12 shows SEM of the fracture surface of FCWed Cu-Al joint using 2.5 mm flanged edge height and 0.5 mm gap between Cu-Al sheets. It is clear that at aluminum side the ductile fracture can be clearly noticed figure 12 (a). Channel can be seen distinctly in the fracture surface. The formation of channel may be related to insufficient metal to fill the gap in distinct locations in the crush zone. Crack can also be recognized and its formation may be attributed to straining the crush zone during welding. Cavities can be identified on the fracture surface and their formation may be related to the separation of copper that coalescences mechanically with aluminum from the surface during tensile testing. A ductile fracture can also be seen in the copper side of the FCWed Cu-Al joint figure 12 (b). Ductile dimples can be identified on the fracture surface. Each dimple on the fracture surface corresponds to the void. Responsibility of voids nucleation is related to inclusions within copper wherein void nucleation, growth and coalescence is mechanism of ductile facture [2].

Figure 12. SEM images of fracture surface of tensile tested Cu-Al joint using 2.5 mm flanged edge height and 0.5 mm gap between Cu-Al sheets: (a) aluminum side, (b) copper side
4. Conclusion
Oxygen-free copper (C1020) and aluminum (AA1145-H1) sheets were welded successfully by friction crush welding. Microstructural characterization using optical and SEM of the FCWed Cu-Al joints showed that the joint characteristics were dependent on FCW parameters used. X-ray diffraction analysis of FCWed Cu-Al joints showed no reaction phases were formed. EDS mapping of FCWed Cu-Al joints of the crush zone showed that mechanical coalescence between copper and aluminum had a critical role in bonding copper with aluminum although there was no apparent diffusion of the elements. The hardness and tensile strength of FCWed joints decreased as the gap between the Cu-Al sheets increased and the flanged edge height changed. The highest hardness of FCWed Cu-Al joints were 65 HV at copper side and 20 HV at aluminum side, respectively, obtained using flanged edge height of 2.5 mm and 0.5 mm gap between the Cu-Al sheets. The maximum tensile strength of FCWed joints was 73 MPa obtained using flanged edge height of 2.5 mm and 0.5 mm gap between the Cu-Al sheets. Analysis of the FCWed joint fracture surface revealed a ductile fracture type.

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