Dissimilar friction stir welding between AA2024-T3 and copper with threaded tool pin

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Abstract: Dissimilar friction stir welding between AA2024-T3 and pure copper was attempted with threaded tool pin. After annealing of copper, the flowability, joint appearance, material sticking with tool was reduced and maximum tensile strength of the joint was achieved for the joint prepared at 470 rev/min tool rotation and 63 mm/min weld speed as compared to the other tested conditions. In the weld stir zone of this joint, presence of copper in dispersion was noticed. Joint failure was observed beyond the weld nugget from the annealed copper side and presence of numerous fine dimples on fracture surface was observed.

1. INTRODUCTION

Joining of similar and dissimilar alloys by friction stir welding has gained immense importance for different industrial applications [1]. However, joining of dissimilar materials are often challenging and requires special attention because of their differences in mechanical, thermal properties as well as possibility of formation of brittle intermetallic compounds. Microstructure evolution and presence of intermetallic compounds during dissimilar FSW between AA6061-T6 and copper [2], copper powder addition in dissimilar FSW of AA60611-AA7075 [3] was studied. Dynamic intercalation microstructures consisting of vortex-like and swirl features were observed during Cu- AA6061, AA2024-AA6061 dissimilar FSW [4]. Microstructure, material movement during FSW of AA5754-Cu with different tool pin profiles were studied [5]. Material flow during dissimilar FSW between AA5083-H111 and Cu-DHP, R240 thin sheets was studied using conical and scrolled shoulder geometry [6]. AA1060 and pure copper was friction stir welded by offsetting tool into Al side and the formation, role of intermetallic compound (IMC) on enhancing the tensile strength was reported [7]. Laser-assisted FSW of AA6061-T6 and pure copper varying tool offset distance was performed by Fei et al. [8]. Material flow during dissimilar FSW between 6061 aluminum alloy and Cu-B370 copper alloy was numerically studied by Kadian and Biswas [9]. Material flow and defects were studied during FSW of AA1050 and brass [10].

The joint morphology, flow/mixing, microstructure influences the joint strength. Therefore, the present study experimentally investigates the tensile strength and failure behaviour of FSW joint between AA2024-T3 and copper in non-annealed and annealed condition. The weld joint microstructural studies and fractographic studies were also performed.

2. MATERIALS AND METHODS

Aluminum alloy AA2024-T3 and copper plates of dimension 100 mm × 50 mm × 3 mm were friction stir welded placing AA2024-T3 on advancing side (AS) and copper on retreating side (RS) as shown
schematically in Figure 1a. Threaded tool pin of 5.5 mm diameter and 2.8 mm length with metric right-hand thread of 1 mm pitch made from H13 die steel was used (Figure 1b). The face of the tool shoulder was provided 3° concave taper. For all welding after tool pin plunging of 2.8 mm length, shoulder plunging of 0.1-0.2 mm was applied.

![Figure 1(a)](image_url_1a)

![Figure 1(b)](image_url_1b)

![Figure 1(c)](image_url_1c)

**Figure 1.** (a) Schematic arrangement of FSW between AA2024-T3 and Cu plates, (b) tool geometry and (c) tensile sample

First, FSW between AA2024-T3 and non-annealed copper was attempted at few parametric combinations of tool rotational speed (rpm) and weld speed (mm/min), however improper mixing, visible tunnel was noted in addition to significant material sticking below tool shoulder and around the tool pin. To improve the material flowability especially for the copper, secondary heating by flame using butane gas torch was provided on Cu plates. Joint appearance of such a trial (referring as W1) at 660 rpm, 63 mm/min with preheating is shown in Figure 2a. The preheating resulted in improvement of flowability of copper thus mixing of material in the stir zone (SZ) and better joint appearance but the joint was improper and unacceptable with presence of tunnels. Thus, to improve the flowability and mixing the Cu plates were annealed by heating in a furnace at temperature of 650 °C for 2.5 hours followed by furnace cooling to room temperature (~24 hours duration). Observing the better flowability and good joint appearance using annealed Cu, finally the FSW joints were prepared with different parametric settings (samples W2 to W5). AA2024-T3 and annealed Cu was joined at 1200 rpm, 63 mm/min applying preheat (W2) but joint was improper (Figure 2a). Since majority of preheat conducted through the copper plates due to high conductivity seemingly leaving less heat accumulated near weld zone, no preheating was used further. Finally, FSW joint between AA2024-T3 and annealed Cu was performed at 660 rpm, 36 mm/min and 470 rpm, 63 mm/min without application of preheating and without any offset (sample W3 and W4 respectively). Later, another joint at 470 rpm tool rotation and 63 mm/min weld speed was performed applying 1 mm offset of tool towards A2024-T3 side. Joint tensile strength, metallurgical characterization, fractographic studies were later appraised for the three good joints i.e. samples W3, W4 and W5. Their joint appearances are also shown in Figure 2a.

After FSW, samples for tensile testing (transverse to weld, dimensions shown in Figure 1c) were cut using wire electric discharge machining. Uniaxial tensile testing was performed on Zwick/Roell (Z50, 50 kN capacity) universal testing machine at cross-head speed of 1 mm/min (strain rate = 0.66×10⁻³/s) at room temperature. Contact type extensometer (25 mm gauge length) was used to measure the strain.

For microstructural observations, transverse samples were cut, cold mounted and polished using emery papers and finally with abrasive paste. After polishing, samples were etched with modified Poulton’s reagents in the Al side and HNO₃+H₂O (1:1) for Cu side. Microstructural observations were carried out using optical microscope (Axio Imager.M2m, Zeiss) and fractographic studies were performed with field emission scanning electron microscope (FE-SEM) (GeminiSEM 500, Zeiss) equipped with energy dispersive spectroscopy (EDS) (Elite Plus, Edax) and electron back scatter diffraction (EBSD).
3. RESULTS AND DISCUSSION

The comparison of ultimate tensile strength (UTS) of the AA2024-Cu (annealed) FSW samples W3, W4 and W5 are shown in Figure 2b. Maximum UTS of the joint (204.3 MPa) has been achieved for the sample W4 as compared to samples W3 and W5. The UTS achieved for the FSW sample W4 was thus recorded about 92.25% of the UTS of the annealed Cu (219.8 MPa) and 47.4% of AA2024-T3 (430.9 MPa) base materials. The tensile stress-strain plot of the base materials and sample W4 are presented in Figure 2c and Figure 2d respectively.

A significant variation in tensile properties like yield strength (YS) (at 0.2% offset strain), UTS and strain at failure for both base materials AA2024-T3 and annealed Cu can be noted from Figure 2c. Due to the variations in mechanical properties, thermal conductivity, melting point of AA2024-T3 and annealed Cu, asymmetric deformation during FSW is observed. The difference in density of the two materials also influences the material transport from AS to RS or the vice-versa. Weld joint cross-sectional morphology for the samples W3–W5 are shown in Figure 3.

![Figure 2](image_url)

**Figure 2.** (a) Appearances of FSW joints under different conditions, (b) comparison of UTS of joints, tensile stress-strain plot of (c) base materials and (d) FSW sample W4

For sample W3 at relatively higher tool rotational speed (660 rpm) and low weld speed (36 mm/min), the temperature in the nugget zone possibly remained high for a very short time that led to instantaneous flow of the plasticized materials due to stirring action. Relatively higher amount of shoulder driven flow towards the upper side compared to the pin driven flow generated a taper shaped stir zone (Figure 3a). Presence of bulk amount of copper can be noticed from Figure 3a. For sample W4, fine dispersion of copper within the stir zone was observed (Figure 3b). On contrary to presence of large chunks, fine distribution of copper within the stir zone appeared beneficial and sample W4
exhibited higher tensile strength of the joint. Finer grains were noted in the SZ owing to high strain and temperature induced dynamic recrystallization. Adjoining to the SZ, thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) can be noticed. TMAZ undergoes moderate strain, thermal induced recrystallization whereas recrystallization in HAZ happened due to thermal induced cycle only. Presence of copper in the SZ is also noticed in sample W5, however tunnel and void defects are also observed in the weld nugget SZ (Figure 3c). Due to tool offset towards AA2024 side, nugget region mostly consisted of stirred AA2024 material.

Electron back scatter diffraction (EBSD) results of one location in SZ of sample W4 are shown in Figure 4a. The material in the SZ underwent dynamic recrystallization resulting in finer grain size as can be seen in inverse pole figure (IPF), grain orientation spread (GOS) in Figure 4a. The phase distribution indicates uniform proportionate distribution of both materials in the SZ. The IPF, GOS and pole figures (PF) of copper adjacent to the SZ are shown in Figure 4b. PF shows presence of shear texture components $A_1^*$, $A$, $\bar{A}$ in {001} where as $B$, $\bar{B}$ and $C$ are noted in {101} and {111}. Presence of $B$, $\bar{B}$ and $C$ textures in the PF indicates a higher degree of shear strain induced deformation during FSW.

![Figure 3. Optical microscopic images of weld cross sections of samples (a) W3, (b) W4 and (c) W5](image-url)
Failure of the sample under tensile testing was noted from the copper material side for W4 whereas for samples W3 and W5 failure took place from the weld region. FE-SEM images of fracture surfaces and EDS analysis at few locations on the fracture surfaces for are presented in Figure 5. Fractographs of sample W3 (Figure 5a) showed cleavage facets/steps indicating brittle dominated failure. EDS analysis indicated higher amount of oxygen presence indicating the oxide formation moreover the intermetallic compound. For sample W4, the failure took place beyond the weld nugget from the softer material side (annealed copper). A cup-cone type of failure was observed and SEM observation showed dimples throughout the fracture surface (Figure 5b). Presence of numerous dimples, generated from the decohesion of metal matrix around inclusions/particles present leading to formation of micro-voids, void growth through plastic flow followed by void coalescence, indicates the ductile mode of failure. EDS results also showed significantly low amount of oxygen presence. Quasi-cleavage failure, cleavage facets, some shear marks were observed on the fracture surfaces of sample W5 and brittle dominated fracture of the joint was observed (Figure 5c).

Figure 4. (a) EBSD IPF, GOS, phases of a region from SZ and (b) IPF, GOS and PF from Cu side on SZ boundary of FSW Sample W4
Figure 5. FE-SEM images of fracture surfaces of samples (a) W3, (b) W4 and (c) W5

4. CONCLUSIONS

Dissimilar FSW using threaded tool pin was attempted between AA2024-T3 and copper. After annealing, the flowability of copper was improved. The maximum tensile UTS was achieved for the AA2024-Cu (annealed) joint prepared at 470 rpm tool rotation, 63 mm/min weld speed than the other tested conditions. In this joint, dispersive presence of copper was noticed within the weld SZ and fracture took place beyond the SZ from the softer annealed copper side leaving weld nugget unharmed. Presence of numerous fine dimples observed in the fracture surface after tensile testing of the joint thereby indicated ductile failure behavior.

REFERENCES

[1]. Lohwasser D and Chen Z 2010 Friction stir welding: From basics to applicationused D Lohwasser and Z Chen (Woodhead Publishing Ltd., Cambridge) chapter 1 pp 1–41
[2]. Ouyang J, Yarrapareddy E and Kovacevic R 2006 Microstructural evolution in the friction stir welded 6061 aluminum alloy (T6-temper condition) to copper J. Mater. Process. Technol.172 110
[3]. Garg A and Bhattacharya A 2019 Influence of Cu powder on strength, failure and metallurgical characterization of single, double pass friction stir welded AA6061-AA7075 joints Mater. Sci. Eng. A759 661
[4]. Murr LE, Li Y, Flores RD, Trillo EA and McClure JC 1998 Intercalation vortices and related microstructural features in the friction-stir welding of dissimilar metals Mater. Res. Innov. 2 150

[5]. Sharma N, Siddiquee AN, Khan ZA and Mohammed MT 2018 Material stirring during FSW of Al–Cu: Effect of pin profile Mater. Manuf. Process. 33 786

[6]. Galvão I, Leal RM, Loureiro A and Rodrigues DM 2010 Material flow in heterogeneous friction stir welding of aluminium and copper thin sheets Sci. Technol. Weld. Join. 15 654

[7]. Xue P, Xiao BL, Ni DR Ma ZY 2010 Enhanced mechanical properties of friction stir welded dissimilar Al–Cu joint by intermetallic compounds Mater. Sci. Eng. A 527 5723

[8]. Fei X, Ye Y, Jin L, Wang H and Lv S 2018 Special welding parameters study on Cu/Al joint in laser-heated friction stir welding J. Mater. Process. Technol. 256 160

[9]. Kadian AK and Biswas P 2018 The study of material flow behaviour in dissimilar material FSW of AA6061 and Cu-B370 alloys plates J. Manuf. Process. 34 96

[10]. Esmaeili A, Givi MKB and Rajani HRZ 2012 Experimental investigation of material flow and welding defects in friction stir welding of aluminum to brass Mater. Manuf. Process. 27 1402