The Investigation of Parameters on the Microstructure of Friction Stir Welded 1060Al/Cu Butt Joint with 10mm Thickness

Y N Wei 1 *, H Li 1, F Sun 2, X Peng 1 and J T Zou 1

1Department of Materials Science and Engineering, Xi’an University of Technology, 5 South Jinhua Road, Xi’an 710048, P.R. China
2Shaanxi Zhituo Solid-State Additive Manufacturing Technology Co., Ltd., 70 west of chaoyang street, Weinan 714000, P.R. China

Email: weiyanni@xaut.edu.cn

Abstract. T2 pure copper and 1060 aluminium alloy 10mm in thickness were joined by friction stir welding. The influence of fixed position and offset on the microstructure and hardness of joints was analysed. A joint having a good surface formation and a defect-free cross section was obtained when the copper was fixed on the advancing side and the offset was 3 mm. Layered structures, composite-like structures and clear copper side and nugget zone interface can be observed at the weld cross section. Under the combined action of heat and force, copper and aluminium inter-diffused and formed layered IMC at the interface. The layered IMC consists of Al2Cu and Al1Cu6 by EDS and TEM analysis. The hardness of the joint first increases and then decreases from Cu side to Al side, and the hardness of the offset of 3mm is the lowest.

1. Introduction

Modern engineering structures often need to join heterogeneous materials, which are characterized by giving full play to their respective performance advantages and having good economic advantages [1-2]. Al/Cu composites can achieve high conductivity and thermal conductivity with a 40% reduction in mass and a price of only 60% of copper. Therefore, the joints of Al-Cu are often used in power transmission, refrigeration, and hydrometallurgy, and others fields, such as bus-bars, electrical connectors, heat-exchangers tubes, conductive tool, etc [3-5]. However, it is difficult to effectively weld Al and Cu using conventional fusion welding due to huge differences in their physical and chemical properties. And it is easy to form a large number of hard, brittle, high-resistance intermetallic compounds (IMCs) in the weld zone because of the strong chemical affinity between Al and Cu [6-7]. Thus, much attention has been directed towards solid state joining methods. Solid phase method, such as explosion welding [8,9], diffusion welding [10-11], friction stir welding (FSW) [12], etc, has been used for welding Al to Cu in past decades. However, the explosion welding and the diffusion welding are mainly for the lap joint method, and the intermetallic compound layer at the interface is thick. FSW, an innovative solid-state welding technology invented by TWI, is a solid-state process which produces welds of high quality in difficult-to-weld materials such as Al and Cu [13]. In previous study, most of the research focused on the welding between Al and Cu plates below 6 mm. So far, there are few reports about the connection of Al and Cu thick plates. However, in practical industrial applications, joining of Al and Cu sheets of 10 mm or more are often used. In addition to the
tool rotation rate and welding speed, the fixed location and the offset of the stir tip were the important parameters in the friction stir welding of Al/Cu dissimilar materials. In this paper, the effect of fixed location of Al and Cu on the weldability of the joints was investigated and different offset was used to study the appropriate offset for friction stir welding of Al/Cu soft/hard dissimilar materials. The microstructure, phase composition, and bonding strength of the Al/Cu joints were analysed.

2. Experimental procedures
T2 pure Cu and 1060 Al plates 10mm in thickness, 200mm in length, and 70mm width was butt friction stir welded in this paper. The experimental tool adopted taper threaded tool pin profile which had a shoulder 25 mm in diameter and a pin 8 mm in diameter and 9.6 mm in length. The rotation speed is 950-1500 rpm, and the welding speed is 60 mm/min. In this paper, two fixed location of Al and Cu (Cu as the advancing side and Al as the advancing side) was used. The offset is the distance from the centre line of the stir tool to the butt line of Cu and Al. Three different sets of offsets were designed which were 1, 2 and 3mm respectively. The welded joints were cut for section view, of which the structures and compositions were examined by optical microscope and scanning electron microscopy (SEM, JEOL, JSM-6700) equipped with an energy-dispersive spectrum (EDS). The hardness was carried out on a Vickers Hardness Tester.

3. Results and Discussion

3.1. The effect of fixed location on the weldability of the joints
The fixed location is one of the important parameters in the friction stir welding of Al/Cu dissimilar materials \(^{[14-15]}\). Figure 1 shows the macroscopic topography of the surface and cross-sectional at different fixed locations. The welding parameters are a rotation speed of 1500 rpm, a welding speed of 60 mm/min, and an offset of 3mm. As can be seen from Figure 1a and 1b, the weld surface is well formed, and a macroscopic defect-free joint is obtained when Cu plate is fixed on the advancing side. However, when Cu is fixed on the retreating side, the weld surface is poorly formed, and defects such as holes, tunnels, are observed. Figure 1c and 1d is the cross-sectional morphologies of the joint, Similarly, it can be seen from the cross section of the weld that Cu is placed on the advancing side without obvious defects. but when Cu is placed on the retreating side, a large void appears at the top of the weld, and the void extends in the welding direction to form Tunnel defect.

![Figure 1](image)

Figure 1. the surface and cross-section morphologies of the joints at different fixed location. (a)(c) Cu at the advancing side (b)(d) Al at the advancing side.

3.2. The effect of offset on the microstructure of the joints
In the similar materials butt friction stir welding, the tool pin is usually inserted into the centre of the joint line, at this time, the tool pin is 0mm offset. previous Studies shown that the quality of joints is poor at 0 mm offset, and it is difficult to obtain a joint without defects \(^{[14,16-17]}\). Therefore, in order to obtain a joint without defects, the tool pin is generally offset toward the softer material. So, in this
experiment, the stirring needle is biased toward the Al side, and the offset amounts are 1 mm, 2 mm, and 3 mm, respectively. Figure 2 shows the effect of offset on the appearance and cross-section morphologies, it can be seen from Fig. 2a and b that a smaller offset cannot be obtained sound weld, At an offset of 1 mm, voids and cracks are observed on the weld surface and the cross section, and large-sized Cu blocks appear at the edges of the voids. When the offset is 2 mm, the weld surface is good, but there are hole defects inside the weld, the weld nugget zone is mixed with a large amount of Cu pieces and the Al matrix; and when the offset reaches 3 mm, the well-formed weld is obtained.

3.3. Microstructure of FSW joints

Figure 3 is a cross-sectional SEM image of the offset of 2 mm. As seen from Figure 3a and 3b, the weld nugget is formed by mixing a large number of different sizes of Cu fragments with Al matrix to formed a structure similar to an Al matrix composite. However, the presence of holes and cracks is observed near the Cu side at the bottom of the nugget zone. This may be due to the fact that the heat generated by friction stir welding is mainly provided by the shoulder, and the thickness of the sheet used in this paper is large, so the temperature gradient in the thickness direction is higher. The heat transfer and loss on the Cu side will be faster because the thermal conductivity of Cu itself is higher than that of Al. Therefore, the temperature near the Cu side at the bottom of the nugget zone is lower than that of other parts, and the material fluidity is worse, leading to the formation of unfused holes and cracks. On the contrary, as shown in Fig. 3c and 3d, the upper of the nugget zone generated more heat and the material fluidity is better, so that a good metallurgical bond is formed between Cu and Al without the occurrence of voids and cracks.

Figure 4 is a microstructure SEM of different regions. Figure 4a and 4b are the microstructure of the Cu-rich region at different offsets. When the offset is smaller, there are a small number of large-sized Cu blocks in the nugget zone, and the Cu-Al layered stack structure appears on the edges and inside of the Cu blocks, and light grey transition layers appeared in layers and layers (The colour is difference Cu and Al); With the increase of the offset, a large number of shredded and refined small-sized Cu pieces are uniformly dispersed in the Al matrix by the action of the thermo-mechanical coupling, to formed the structure similar to the Al-based composite material, and at the same time, the pieces reacted and generates IMC with Al matrix. By analysing the EDS of intermetallic compounds at different positions, it can be inferred that 1, 2, 3, and 4 points correspond to Al3Cu, Al, Al+Al3Cu, and Al2Cu, respectively (i.e., Table1). Figure 4c and 4d shows that the Cu side and the nugget zone have a distinct interface, and a continuous, uniform IMCs with a thickness of about 1 μm was formed at the interface. This is because the Cu is fixed on the advancing side, and the material softened on the advancing side mostly flows forward along the welding direction, and the shear strain rate is larger. Secondly, due to the offset of the tool pin, the material in the nugget is mainly Al matrix. Therefore, the weld nugget zone forms a distinct interface with the Cu side.
Table 1 EDS results for different locations in figure 4.

| Point | Al(wt%) | Cu(wt%) | Al(at%) | Cu(at%) | Possible phase |
|-------|---------|---------|---------|---------|----------------|
| 1     | 13.73   | 86.27   | 27.27   | 72.73   | Al$_4$Cu$_9$   |
| 2     | 85.76   | 14.24   | 93.41   | 6.59    | Al             |
| 3     | 72.16   | 27.84   | 84.45   | 15.55   | Al+Al$_2$Cu    |
| 4     | 54.49   | 45.51   | 73.82   | 26.18   | Al$_2$Cu      |

3.4. The Performance of joints
Due to the difference in hardness of the material itself, the micro-hardness of the joint shows an asymmetry along the centreline of the weld. Figure 5 is a profile showing the Vickers hardness of the weld cross-section at different offsets, it can be seen that the hardness trends first increases and then decreases from the Cu side to the Al side, the hardness value of the nugget fluctuates between the two base metals, and the maximum hardness value appears near the interface between the Cu side and the nugget. The nuggets hardness value with an offset of 3 mm is smaller than that with the other two offsets. This is due to the occurrence of river-like Cu-Al laminated structure similar to that in figure 4a in the structure of the nugget. Therefore, the hardness value varies with the laminated structure. When the offset is larger, the number of laminated structures in the nugget decreases, and correspondingly,
the hardness value is lower. The contribution to the hardness of the nugget mainly depend on grain refinement.

![Fig 5. microhardness profile for Al–Cu joint at difference offset.](image)

4. Conclusions
In this paper, the effects of fixed position and offset on the microstructure and hardness of FSW Al-Cu joints were discussed. The main conclusions are as follows:
(1) Al/Cu joint with good weld surface and no defect inside the cross section can be obtained when the Cu is fixed on the advancing side and the offset to the Al side is 3 mm.
(2) The Cu fragment which are peeled and shredded by the tool pin formed a layered structure and a composite structure in different regions of the joint. Atomic interdiffusion occurs at the interface between Cu and Al to form intermetallic compounds and these was identified as Al$_2$Cu and Al$_3$Cu$_9$.
(3) The trend of joint hardness is firstly increased and then decreased from Cu to Al, and the maximum value of hardness appears near the interface between the nugget and the Cu side.

References
[1] Huang G Q, Hou W T, Li J P and Shen Y F 2018 Surf. Coat. Technol. 344: 30–42.
[2] Xiong J, Peng Y, Zhang H, Li J and Zhang F 2018 Vacuum 147: 187–193.
[3] Khan H A, Wang K F and Li J J 2018 Mater. Charact. 141: 32–40.
[4] Liu J, Cao B and Yang J W 2017 Metals 7: 471.
[5] Tan C W, Jiang Z G, Li L Q, Chen Y B and Chen X Y 2013 Mater. Des. 51: 466–473.
[6] Mehta K P and Badheka V J 2017 Trans. Nonferrous Met. Soc. China. 27(1): 36–54.
[7] Mehta K P and Badheka V J 2015 Int. J. Adv. Manufact. Technol. 80: 2073–2082.
[8] Behcet G 2008 Mater. Des. 29(1): 275–278.
[9] Yuan Y, Chen P W, An E F and Feng 2018 Mater. Sci. Forum. 910: 52–57.
[10] Guo Y J, Liu G W, Jin H Y, Shi Z Q and Qiao G J 2011 J Mater. Sci. 46: 2467–2473.
[11] Eslami P, Karimi Taheri A and Zebardast M 2013 J Mater. Eng. Perform. 22: 3014–3023.
[12] Kumar R, Pancholi and Bharti R P 2018 J. Mater. Process. Technol. 255: 470–476.
[13] Mishra R S and Ma Z Y 2005 Mater. Sci. Eng. R 50: 1–78.
[14] Xue P, Ni D R, Wang D, Xiao B L and Ma Z Y 2011 Mater. Sci. Eng. A 528: 4683–4689.
[15] Debroy T and Bhadeshia H K D H 2010 Sci. Technol. Weld. Join. 15(4): 266–270.
[16] Singh S H and Mahmeen M 2016. Journal. Int. J. Mod. Trends. Eng. Res.3: 75–80.
[17] Esmaeili A, Besharati Givi M K and Zareie Rajani H R 2012 Mater. Manufact. Process. 27(12): 1402–1408.

Acknowledgments
This work is financially supported by the National Natural Science Foundation of China under Grant no. 51701154, the Key Research and Development Project of Shaanxi Province under Grant no. 2017ZDXM-GY-033 and 2018ZDXM-GY-136.