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Effects of processing parameters on corrosion properties of dissimilar friction stir welds of aluminium and copper

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Abstract: The influence of friction stir welding processing parameters on dissimilar joints conducted between aluminium alloy (AA5754) and commercially pure copper (C11000) was studied. The welds were produced by varying the rotational speed from 600 to 1200 r/min and the feed rate from 50 to 300 mm/min. The resulting microstructure and the corrosion properties of the welds produced were studied. It was found that the joint interfacial regions of the welds were characterized by interlayers of aluminium and copper. The corrosion tests revealed that the corrosion resistance of the welds was improved as the rotational speed was increased. The corrosion rates of the welds compared to the base metals were improved compared with Cu and decreased slightly compared with the aluminium alloy. The lowest corrosion rate was obtained at welds produced at rotational speed of 950 r/min and feed rate of 300 mm/min which corresponds to a weld produced at a low heat input.

Key words: aluminium alloy; copper; corrosion; friction stir weld; processing parameters

1 Introduction

It is estimated that corrosion destroys one quarter of the world's annual steel production, which corresponds to about 150 million tons per year, or 5 tons per second [1]. Corrosion is not limited to steel but affects other materials used in various applications especially in welded joints. Corrosion is known to destroy a material or degrade its functional properties, rendering it unsuitable for the intended use [1]. Generally, the durability and the life time of welds, installations, machines and devices are critically dependent on their corrosion rate and wear resistance. Welded joints are specifically susceptible to corrosion when exposed to the environment and most especially dissimilar welds.

Friction stir welding (FSW) process is a solid state welding technique invented by Dr W. THOMAS of The Welding Institute (TWI), United Kingdom in 1991 [2]. FSW is a continuous process that involves plunging a portion of a specially shaped rotating tool between the butting faces of the joint. A schematic of the process is presented in Fig. 1. The relative motion between the tool and the substrate generates frictional heat that creates a plasticized region around the immersed portion of the tool. The tool is moved relatively along the joint line, forcing the plasticized material to coalesce behind the tool to form a solid-phase joint [3].

The resulting microstructures of friction stir welds are described by the different zones as follows: 1) the base metal (BM), which is the material remote from the weld that has not been deformed, and is not affected by the heat in terms of microstructure or the mechanical properties; 2) the heat affected zone (HAZ) which is a region that lies closer to the weld centre and has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties, however, no plastic deformation has occurred in this area; 3) the thermo mechanically affected zone (TMAZ) which is a region where the FSW tool has plastically deformed the material at the weld interface; and 4) the weld nugget (WN) which is the fully recrystallized area,

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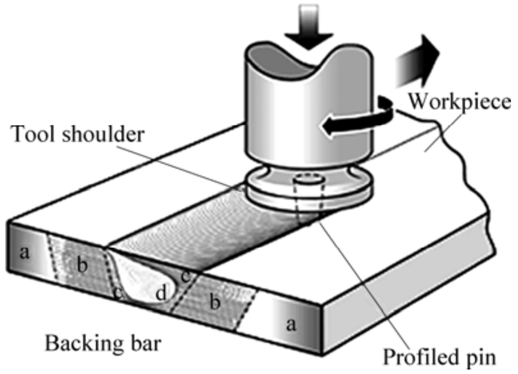

Fig. 1 Schematic diagram of FSW process [3]

sometimes called the stir zone (SZ) or the stir nugget (SN), and refers to the zone previously occupied by the tool pin during FSW [4].

The benefits of this technology include: low distortion, greater weld strength compared with the fusion welding process, little or no porosity, no filler metals, little or no post-weld repair, no solidification cracking, no welding fumes or gases, improved corrosion resistance, and lower cost in production applications [5,6]. Because of the many demonstrated advantages of FSW over the fusion welding techniques, the commercialization of FSW is proceeding at a rapid pace. The FSW of aluminium and its alloys has been commercialized [7,8]; and recent research interest is focused on joining dissimilar materials such as aluminium and copper. Components consisting of aluminium and copper possess the beneficial properties of both. Aluminium is mainly required for its low cost, high corrosion resistance and high specific strength, while copper is mainly used for its superior electrical conductivity and its high thermal expansion. Such applications include bus-bars, switchgears and heat sinks, and many other applications are currently being developed. By successfully joining these metals with superior corrosion resistance, the superior properties of both materials can be utilized in many applications requiring a combination of these properties. Friction stir weld of aluminium and copper being a dissimilar joint is susceptible to galvanic or bimetallic corrosion. Corrosion in these joints can result from the formation of an electrochemical cell between the two metals joined and the corrosion of the less noble metal is thus accelerated. Published literatures in this regard include research by SUREKHA et al [9] on the effect of processing parameters on the corrosion behavior of friction stir processed AA 2219 aluminium alloy. It was found that the resistance to corrosion increases as the rotational speed increases in the processed aluminium samples. This is due to the dissolution of the $CuAl_2$ particles during the friction stir processing which reduces the number of sites available for galvanic coupling and hence increases the corrosion resistance. Further study was conducted by RAO et al [10] on the effect of friction stir processing on the corrosion resistance of aluminium–copper alloy gas tungsten arc welds. It was found that the friction stir processing improved the corrosion resistance of the welds. Fusion welds of this grade of aluminium alloy are known to suffer from poor corrosion resistance due to the uneven distribution of copper in the welds, which produces large differences in the electrochemical potentials [11]. $AlCu_2$ was the major intermetallic compound found, which imparts greater strength in this alloy but decreases the corrosion resistance. This is due to the formation of galvanic cells between the noble $AlCu_2$ and the aluminium matrix [10]. To improve the corrosion resistance, it is necessary to create a uniform level of copper in the weld. Other studies on corrosion properties of friction stir welds include a report by PAGLIA and BUCHHEIT [12] on the corrosion properties of friction stir welds of 7075-O aluminium alloy. They found that the welds are susceptible to intergranular corrosion. However, they suggested that short-term post-weld heat treatments with temperatures similar to the welding temperatures can be used to modify the microstructure and improve the corrosion resistance of the welds. The effect of welding parameters on the corrosion behavior of friction stir welded AA2024–T351 was also conducted by JARIYABOON et al [8]. They found that the rotational speed has the greatest influence on the corrosion sensitivity on the weld cross sections. It was concluded that for low rotational speeds, the corrosion attack is in the nugget region due to the significant increase in the anodic reactivity in this region. For higher rotational speeds, the corrosion attack was in the HAZ region owing to the presence of sensitized grain boundaries in this region. BOUSQUET et al [13] conducted a research on the relationship among the microstructure, microhardness and corrosion sensitivity of friction stir welded joints of AA 2024-T3. They found that the HAZ close to the TMAZ is the region most sensitive to intergranular corrosion because of the presence of the continuous lines of intergranular precipitates at the grain boundaries and the pitting corrosion observed was due to the presence of intermetallic particles at such regions. However, the majority of these studies are limited to joining similar materials especially aluminium and its alloys.

In view of the foregoing, concerted efforts are geared towards optimizing the processing parameters to produce metallurgically sound joints of aluminium and copper using FSW [14−17] which will ultimately lead to its commercialization. It is very important to have an insight into the corrosion properties of such joints in order to produce joints that will meet the service requirements and be guided accordingly. To the authors' knowledge, there is no published literature on the corrosion properties of friction stir welds of aluminium and copper. The main objective of this work therefore is to study the corrosion properties of dissimilar friction stir welds of aluminium and copper produced at different process parameter combinations.

2 Experimental

2.1 Materials preparation

Friction stir welds between aluminium alloy (AA5754) and commercially pure copper (C11000) having 3.175 mm thickness were produced using an intelligent stir welding for industry and research process development system (I-STIR PDS) platform. The chemical compositions of the alloys used are provided in Table 1. The welds were produced using an 18 mm shoulder diameter tool with a tool pin diameter of 5 mm. The copper sheet was placed at the advancing side while the tool pin was plunged in the aluminium alloy and made to touch copper during the welding process. This is an optimized tool displacement setting as reported by AKINLABI et al [18]. Rotational speeds of 600, 950 and 1200 r/min were employed which represented low, medium and high speed settings, respectively. Transverse speeds of 50, 150 and 300 mm/min were employed which also represented low, medium and high feed rate settings, respectively. The weld matrix is presented in Table 2.

Table 1 Chemical composition of Al and Cu materials

Material	w(Si)/%	w(Pb)/%	w(Mg)/%	w(Cr)/%
AA5754	0.40	0.80	3.50	0.30
C11000	0.0005	0.0005	0.0001	0.0003
Material	w(Ti)/%	w(Zn)/%	w(Al)/%	w(Cu)/%
AA5754	0.15	0.50	96.10	0.03
C11000	0.0002	0.009	0.001	99.859

Table 2 Weld matrix of investigated materials

Sample No.	Rotational speed/(r·min^{-1})	Feed rate/(mm·min^{-1})
A1	600	50
A2	600	150
A4	600	300
C1	950	50
C2	950	150
C4	950	300
L1	1200	50
L2	1200	150
L4	1200	300

An optical microscope (Olympus BX51M) and a scanning electron microscope (VEGA 3) were used for the microstructural evaluation of the joint interfaces. A weld length of 160 mm was produced for each setting. The samples for microstructure were taken at 50 mm while the samples for corrosion testing were taken at 75 mm length from the weld start in a transverse direction. The aluminium alloy samples were etched with Flicks reagent and the copper was etched with a solution of 25 mL distilled water, 25 mL ammonia water and 15 mL hydrogen peroxide. Vickers microhardness profiles were measured along the cross sections of the welds with a load of 1.96 N and a dwell time of 10 s, using an MH3 microhardness indenter.

2.2 Electrochemical corrosion testing

Potentiodynamic polarization techniques were used to study the corrosion behavior of the welded joints. The corrosion experiments were carried out using AUTOLAB PGSTAT30 with GPES electrochemical software. All the experiments were carried out using a three-electrode corrosion cell set-up with saturated Ag/AgCl as reference electrode and platinum rod as the counter electrode. The corrosion tests were conducted on both the top surface and the cross-sectional areas of the welds. The samples were cold mounted in polyester resin. The areas exposed to the electrolyte were 2.25 cm^2 for the weld surface and 0.45 cm^2 for the cross-sections of the welded zone. All the tests were conducted at room temperature (25±2) °C. The electrolyte used was 3.5% NaCl solution. Potentiodynamic polarization measurements were carried out using a scan rate of 0.167 mV/s at a potential initiated at −150 mV to +1500 mV versus corrosion potential. Before starting the polarization scan, the specimens were cathodically polarized at −1000 mV for 5 min followed by stabilization for about 1 h. In all cases, triplicate experiments were carried out to ensure reproducibility. Corroded surfaces were observed using ultra high resolution scanning electron microscope (FE-SEM JSM 7600F).

3 Results and discussion

3.1 Structure of welded samples

Figure 2 shows the optical micrographs of the parent materials — aluminium alloy (AA5754) and commercially available copper (C11000). The microstructure of the aluminium alloy consisted of fairly elongated grains resulting from the hot rolling condition, while the grains of the copper sheet were equiaxed resulting from the high rolling temperatures. Figure 3 shows the surface appearances of the friction stir welded samples at 950 r/min as taken from 75 mm of the welded length. The weld appearances were typical of friction stir

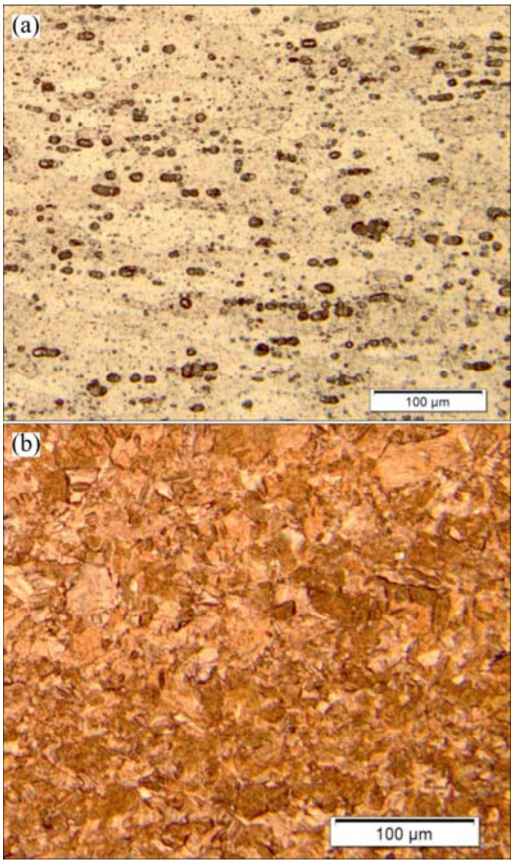

Fig. 2 Optical micrographs of AA5754 aluminium alloy (a) and C11000 copper alloy (b)

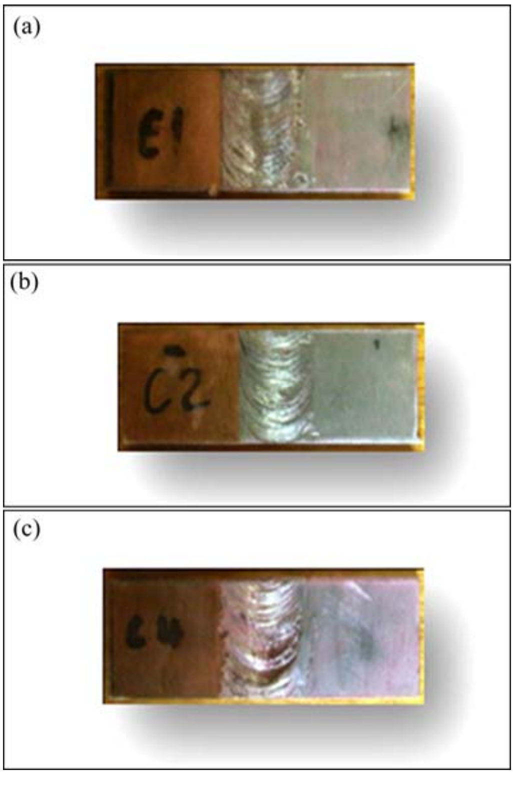

Fig. 3 Surface appearances of friction stir welded samples: (a) Sample C1 (950 r/min, 50 mm/min); (b) Sample C2 (950 r/min, 150 mm/min); (c) Sample C4 (950 r/min, 300 mm/min)

welds and without visual defects. The micrographs of an interfacial region of welds produced at 950 r/min and at varying feed rates are presented in Fig. 4. It was observed that the joint interface of the weld was characterized with an onion ring structure indicating good material flow and good mixing of both materials joined [19]. It can be inferred that this region has undergone dynamic recrystallization during the FSW process.

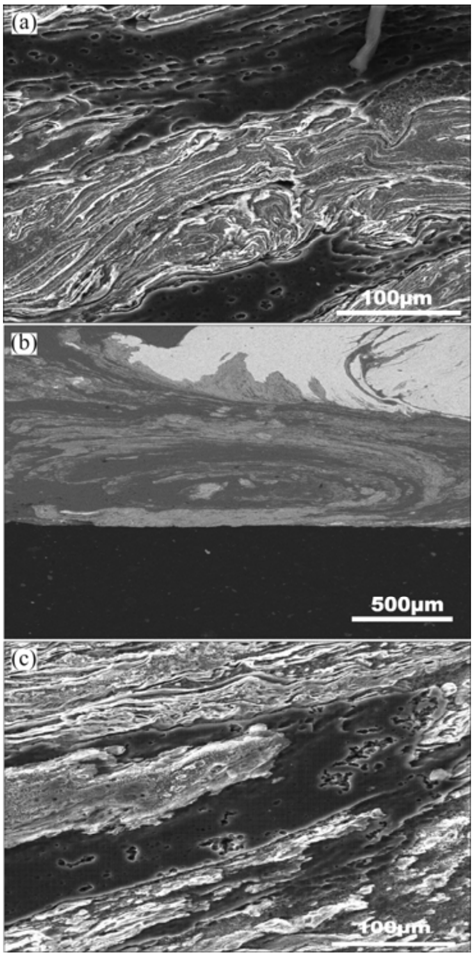

Fig. 4 SEM images of interfacial regions of welds produced at 950 r/min and at different feed rates: (a) 50 mm/min; (b) 150 mm/min; (c) 300 mm/min

The microhardness profile of the weld produced at 950 r/min and 150 mm/min super imposed on the micrograph is presented in Fig. 5. The average microhardness values of the aluminium and copper parent materials used in this study were HV 70 and HV 85, respectively. A constant hardness of approximately HV 70 was observed in the aluminium side until 1 mm to the centre where the hardness increased sharply to a peak of about HV 180. This is due to the transition from aluminium material to an intermetallic (Al_2Cu) present in the copper material. The high hardness value of HV 271 measured at 3 mm into the copper corresponds to the presence of an intermetallic compound (Al_4Cu_9) in the weld as confirmed by the XRD results reported by AKINLABI [14].

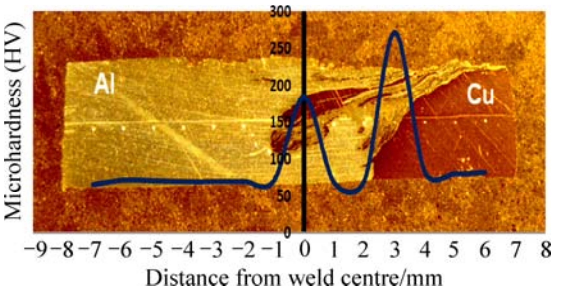

Fig. 5 Microhardness profile of weld produced at 950 r/min and 150 mm/min

3.2 Effects of friction stir welding parameters on electrochemical corrosion behavior

Typical electrochemical corrosion behaviors of FSW of aluminium alloy and copper in 3.5% NaCl solution are shown in Fig. 6. Figure 6(a) shows the corrosion behavior of the sample surface and Fig. 6(b) shows the cross section. Both the surface and the cross section samples indicated similar polarization curves with no stable passivity features. At a potential of about 0.9 V versus Ag/AgCl, the current density of the surface samples first decreased as the applied potential was increased, indicating the formation of surface film on the sample surface, and then increased sharply with a slight increase in the applied potential (Fig. 6(a)). The decrease in the current density was absent in the cross section samples (Fig. 6(b)). The reason could be due to the presence of high concentration of aluminium in the surface samples compared with the cross section samples resulting from the fact that the tool pin was plunged in the aluminium alloy and only made to touch the copper during the welding process. Aluminium with a lower melting point in this regard became plasticized and then got mixed with the copper due to the stirring action of the tool during the FSW. The corrosion potentials of the surface samples were almost the same (−1.017 V vs Ag/AgCl) whereas the corrosion potentials of the cross section samples varied slightly from −1.031 to −0.704 V vs Ag/AgCl. The current densities of both the surface and cross section samples after the corrosion potential increased sharply indicate the possibility of pitting corrosion occurring. The relatively high corrosion rate of surface sample produced at 950 r/min and 50 mm/min could be as a result of the high concentration of Cu present on the surface of this sample, which increased the galvanic interaction. The high concentration of Cu at the welded joint was confirmed by XRD results indicating the presence of both Al_2Cu and Al_4Cu_9. At higher feed rate (300 mm/min), only Al_2Cu was present [20].

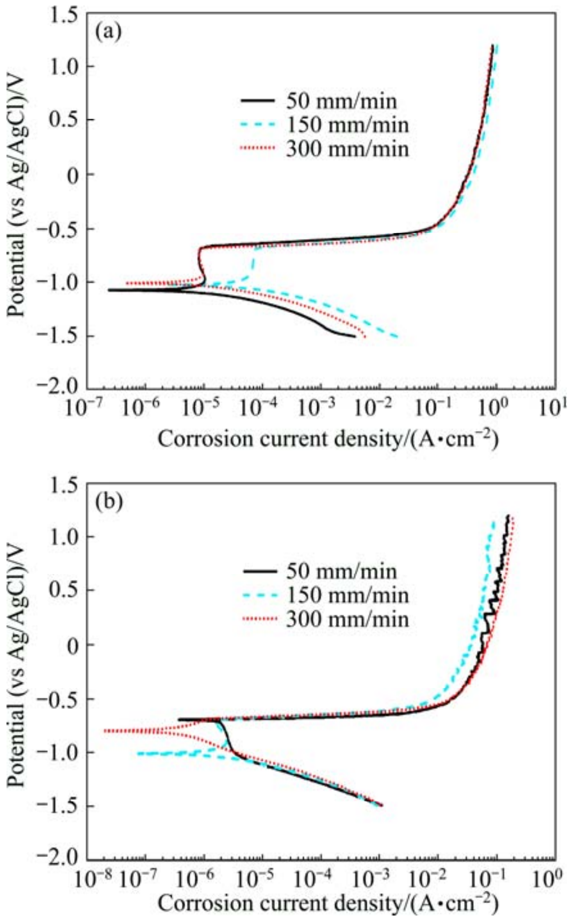

Fig. 6 Effect of feed rate on surface (a) and cross section (b) corrosion behaviour of FSW Al−Cu alloys produced at 950 r/min in 3.5% NaCl solution

The corrosion rates of both the surface and the cross section of the samples were calculated and the results are presented in Fig. 7. In the calculation of the corrosion rate, the equivalent mass of the specimen was used by determining the chemical compositions of the welded zones. It was observed that as the rotational speed increased, the corrosion rate decreased for both the surface and the cross section of the samples. Thus, the rotational speed has a direct relationship with the corrosion rate. In all the instances, there is a significant reduction in the corrosion rate when the rotational speed was increased from 600 r/min to 950 r/min. From 950 to 1200 r/min, the reduction in the corrosion rate was minimal. There was no strong correlation between the feed rate and the corrosion rate. It is interesting to note that for a specific rotational speed, the lowest corrosion rate was observed at the maximum feed rate employed (i.e. 300 mm/min) for most of the samples. This can be attributed to the fact that the welds produced at the highest feed rate of 300 mm/min were conducted with less heat input which resulted in the less mixing of both materials joined compared with the welds produced at the 50 and 150 mm/min feed rates. Hence, in this regard, less heat input into the welds resulting in excellent characteristics of the joint interface is desired. Additionally, at high rotational speed, Al_2Cu phase was mainly identified in the welded zones, whereas at low rotational speed Al_4Cu_9 was identified. It was reported by CHEN and HWANG [21] that the activation energy of Al_4Cu_9 is higher than that of Al_2Cu. This implies that the galvanic interaction between these intermetallics and the base metals would be higher for Al_4Cu_9 than for Al_2Cu; hence the corrosion behavior observed.

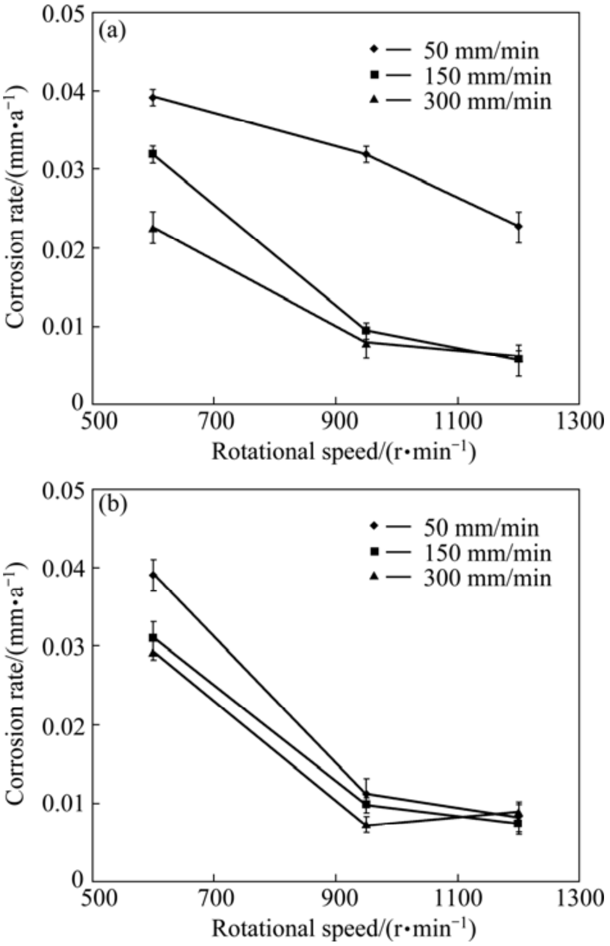

Fig. 7 Effect of rotational speed on corrosion rate of surface (a) and cross section (b) of FSW of Al and Cu alloys in 3.5% NaCl solution

The surface corrosion rates of the aluminium alloy and pure copper were calculated to be 0.00112 mm/a and 0.0367 mm/a, respectively; the corresponding corrosion rates of the cross sectional samples were 0.00129 mm/a and 0.048 mm/a, respectively. It can be observed that the corrosion resistance of copper in 3.5% NaCl was enhanced. This behavior has been reported by WHARTON and STOKES [22] where Al forms a film of hydrated oxide/hydroxide.

Figures 8 and 9 show the microstructures of the surface and cross section of the FSW samples after corrosion, respectively. Localized corrosion was observed on the corroded samples after the corrosion testing in 3.5% NaCl. It was reported [12] that the chemistry of Al alloy solution has a significant effect on the corrosion behavior of the welded piece. Stress corrosion cracking was more intense on the surfaces compared with the cross sectional sample. This is because of the presence of high concentration of Al on the surface samples. Aluminium alloy is susceptible to

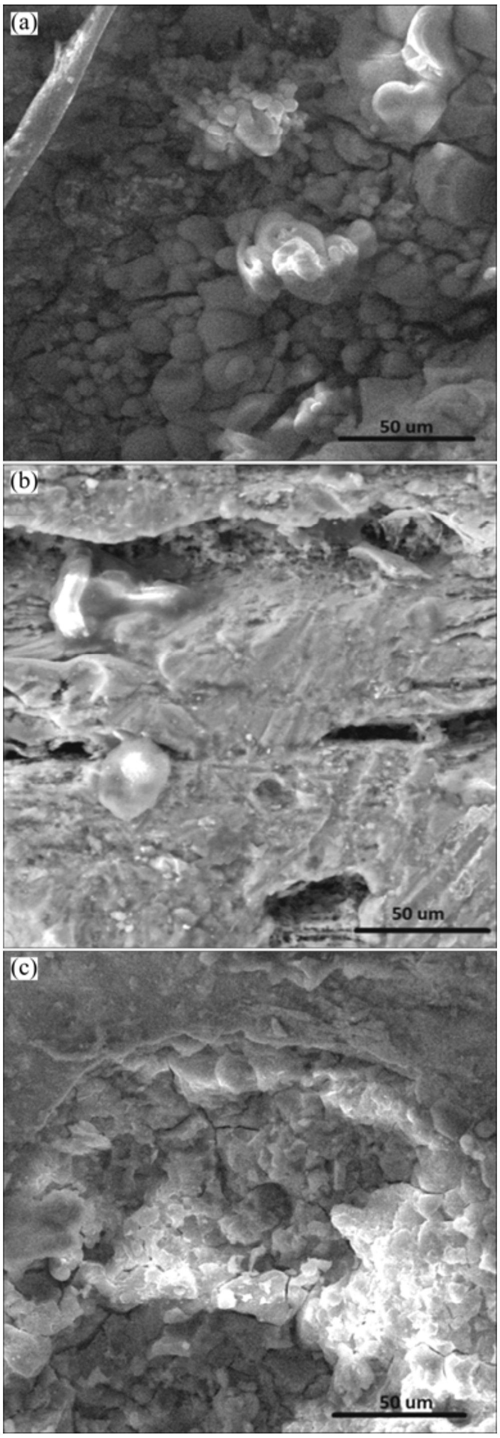

Fig. 8 SEM images of surface of FSW samples after corrosion in 3.5% NaCl solution: (a) A4 (600 r/min, 300 mm/min); (b) C4 (950 r/min, 300 mm/min); (c) L4 (1200 r/min, 300 mm/min)

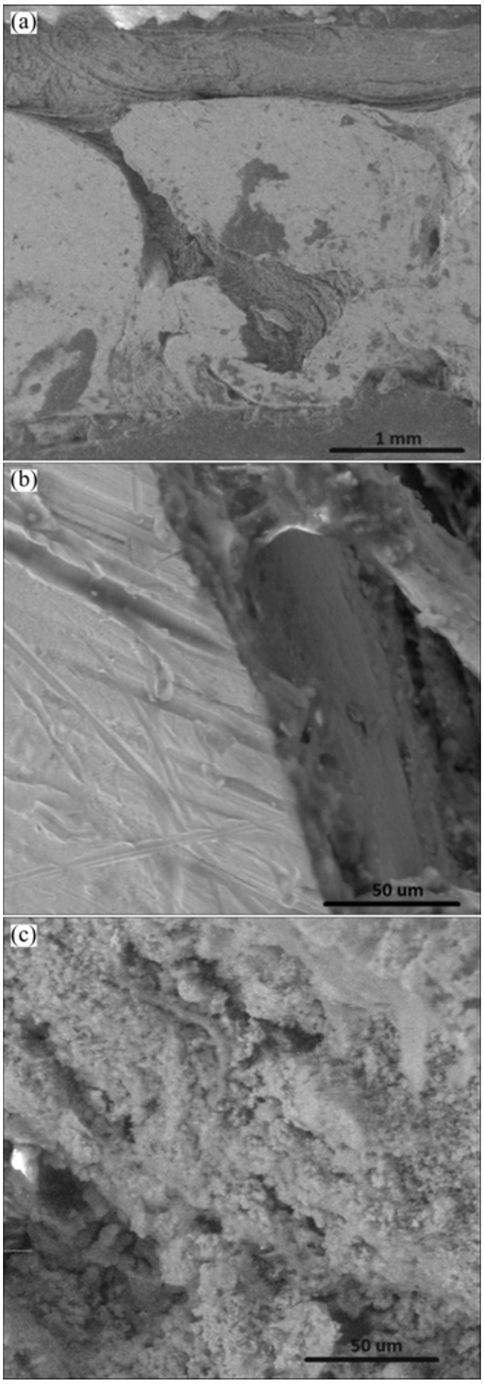

Fig. 9 SEM images of cross section of FSW samples after corrosion in 3.5% NaCl solution: (a) A4 (600 r/min, 300 mm/min); (b) C4 (950 r/min, 300 mm/min); (c) L4 (1200 r/min, 300 mm/min)

stress corrosion cracking; pitting and intergranular corrosion after the alloy microstructure has been sensitized. It can be said that the attack on the friction stir welded samples initiates as pits and propagate as stress corrosion cracking. This agrees with the polarization results presented in Fig. 6. On the cross sections (Fig. 9), intergranular attack was observed at the nuggets.

4 Conclusions

The corrosion behaviors of friction stir welds of Al−Cu joints were characterized and presented. Rotational speeds and feed rates were varied to produce the welds and the corrosion behavior was studied. Microstructural evaluation of the interface revealed the formation of onion rings which are an excellent characteristic of friction stir welds. The corrosion results indicated that the transverse feed rate has little or no effect on the rate of corrosion. However, the corrosion resistance of the welded Al−Cu alloys was enhanced as the rotational speed was increased. This is due to the presence of Al_2Cu intermetallic phase at higher rotational speed compared with Al_4Cu_9 which formed at lower rotational speed. Optimum corrosion resistance was obtained for welds produced at 950 r/min and 300 mm/min, which was correlated to the low heat input in these welds.

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焊接工艺参数对铝和铜异种搅拌摩擦焊接头腐蚀性能的影响

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摘　要：报道了焊接工艺参数对铝(AA5754)和铜(C11000)异种搅拌摩擦焊接头腐蚀性能的影响。研究了在旋转速度 600~1200 r/min、进料速度 50~300 mm/min 下焊接头的显微组织和腐蚀性能。结果表明，在接头界面区域存在铝和铜的金属间化合物层；焊接头的耐蚀性随着旋转速度的加快而增强；焊接头的耐蚀性比基体铜有改善，但比铝略有降低。在旋转速度 950 r/min、进料速度 300 mm/min 的条件下得到的焊接头的耐蚀性最好。

关键词：铝合金；铜；腐蚀；搅拌摩擦焊；工艺参数

(Edited by Hua YANG)