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Intermetallic formation in dissimilar friction welds with a silver interlayer

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The present work investigates the formation of an intermetallic during friction welding of two dissimilar joints one made of aluminum alloy 6061(T6) metal matrix composite (MMC) and AISI 304 stainless steel and the other one made of MMC, AISI 304 stainless steel and a silver interlayer. The microstructures of the friction welded samples were analyzed by scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and conventional transmission electron microscopy (TEM). The results show the formation of brittle FeAl and Fe_2Al_5 intermetallics on dissimilar MMC/AISI 304 stainless steel friction welds. In the case of dissimilar MMC/Ag/AISI 304 stainless steel friction welds, circular silver nanoparticles with dimensions ranging from 10 to 20 nm and Ag_3Al intermetallic were obtained.

Keywords: Intermetallics; friction welding; 304 stainless steel; silver nanoparticles; transmission electron microscopy.

El presente trabajo investiga la formación de intermetálicos durante la soldadura por fricción de dos uniones disimiles, una hecha de un material compuesto con matriz metálica (MMC) de aleación de aluminio 6061(T6) y acero inoxidable AISI 304 y otra hecha de MMC, acero inoxidable AISI 304 más una intercapa de plata. La caracterización de la microestructura de las muestras soldadas por fricción, fue realizada por microscopía electrónica de barrido (SEM), espectroscopía de energía dispersiva (EDS) y microscopía electrónica de transmisión convencional (TEM). Los resultados obtenidos mostraron que sobre la unión disímil de MMC/acero inoxidable AISI 304 existió la formación de frágiles intermetálicos de FeAl y Fe_2Al_5 y en la unión disímil de MMC/Ag/acero inoxidable AISI 304 se formó el intermetálico Ag_3Al y se observó la presencia de nanopartículas circulares de plata con dimensiones en el rango de 10 a 20 nm.

Descriptores: Intermetalicos; soldadura por fricción; acero inoxidable 304; nano partículas de plata; microscopía electrónica de transmisión.

PACS: 81.40.-Pq; 81.20.Vj; 81.07.-b

1. Introduction

In order to increase aluminum consumption and especially the application of aluminum MMCs in the automotive and aeronautic industries is necessary to learn how to weld these alloys to other engineering materials, such as steel. Arc welding of dissimilar aluminum/steel joints has several problems: preferential melting of the aluminum alloy and formation of brittle iron-aluminum intermetallics. One possible solution for this type of problems is friction welding. However, intermetallic formation is still of concern, one technique that may reduce this problem is the use of an interlayer. In this research work the effect of silver interlayer is examined. In past studies the effect of interlayer materials on the friction joining mechanism and on intermetallic phase formation at the bondline region has received limited emphasis. Silver interlayers have been applied with the specific objective of preventing intermetallic phase formation and weld cracking during aluminium/stainless steel friction joining [1-2]. By instance, the poor mechanical properties observed in dissimilar friction welds have been associated to the presence of brittle $FeAl_3$, FeAl, and Fe_2Al_5 intermetallics. Also, Pan *et al.* [3] suggested that the poor joint mechanical properties of MMC/AISI 304 stainless steel friction welds resulted from the retention of a mixture of intermetallic ($FeAl_3$) and oxide Fe(Al, $Cr)_2O_4$ or FeO(Al,$Cr)_2O_3$ films at the bondline. Although intermetallic phases do not form in Ag-Fe binary alloys, the Ag-Al binary equilibrium phase diagram does indicate the formation of intermediate phases. Ag_3Al and Ag_2Al phase formation has been observed in 1100 aluminum/stainless steel and 6061 aluminum/stainless steel diffusion welds [4]. During friction welding of aluminum alloy substrates, the contact zone is at high temperature (around 550°C), the strain rate is extremely high (up to 10^4 s^{-1}) [5-6], mechanical mixing occurs and flow of fully-plasticized material redistributes material from the stationary to the rotating boundary of the welded joint [7-8]. The present work investigates the influence of a silver interlayer on intermetallic formation during MMC/Ag/AISI 304 stainless steel friction welding compared with the intermetallic produced without silver interlayer during MMC/AISI 304 stainless friction welding.

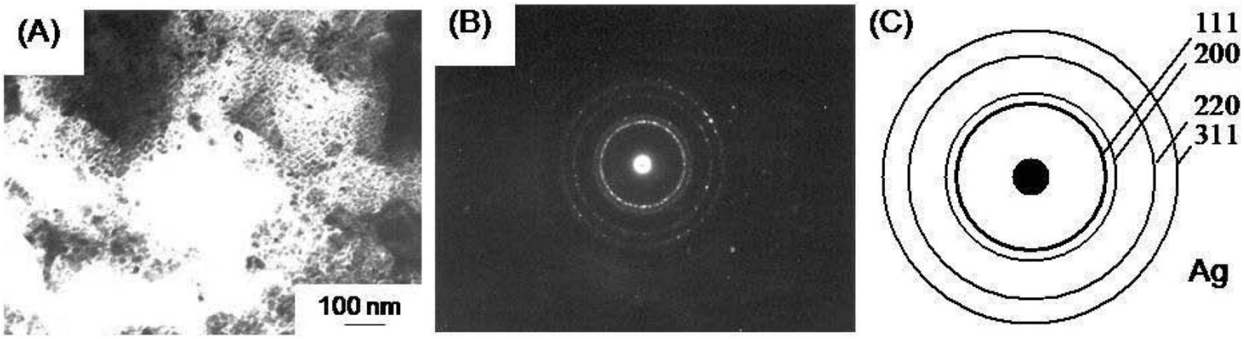

FIGURE 1. (a) TEM micrograph of silver nanoparticles (b) and (c) ring diffraction pattern and key diagram with the main planes marked respectively.

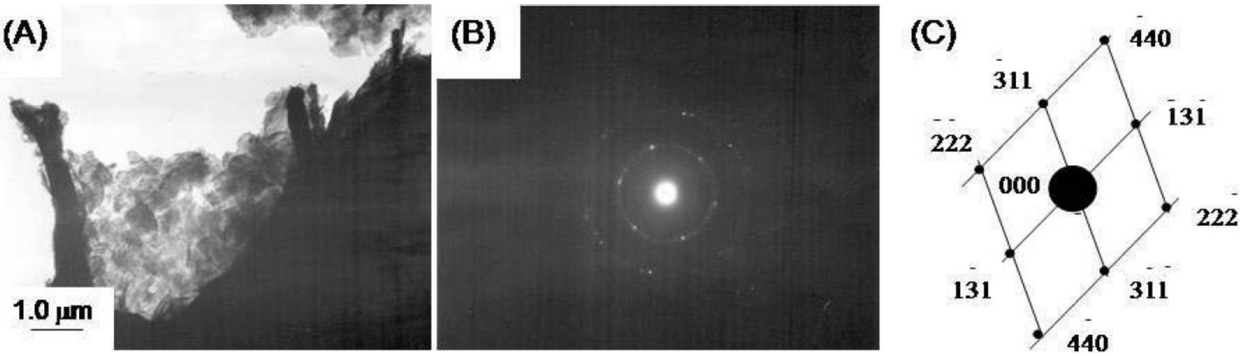

FIGURE 2. (a) TEM micrographs of the Ag_3Al intermetallic (b) and (c) ring diffraction pattern and key diagram along the [112] axis.

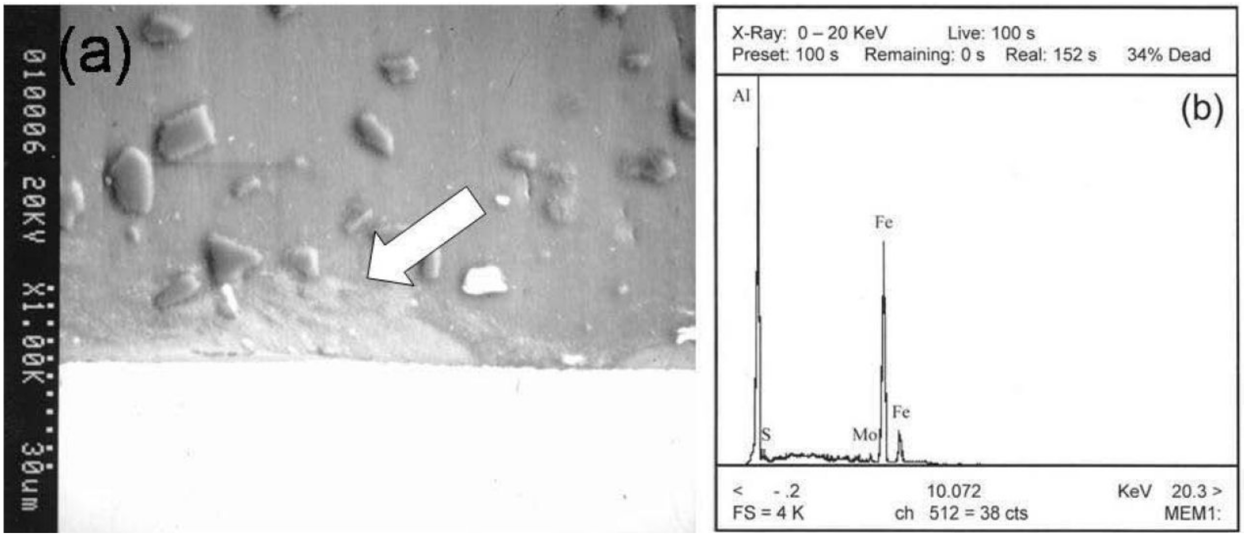

FIGURE 3. a) Micrograph of a dissimilar MMC/AISI 304 stainless steel friction joint showing the transition layer. b) EDS analysis of the transition layer.

2. Experimental procedure

All dissimilar friction welds were made using 19-mm bars of Al 6061 (W6.A.10A-T6) base material containing 10 vol% of reinforcing Al_2O_3 particles (metal matrix composite, MMC). The MMC was produced using a combination of conventional aluminum casting, stirring and melt extrusion at 640°C. This material was supplied by ALCAN LTD of Kingston, Ontario. A 20 μm-thick silver interlayer is electrodeposited on the stainless steel substrate, which has been previously coated with a 5-μm thick nickel layer. A 20 μm-thick silver interlayer was selected because in previous experimental trials thinner silver interlayer (5 and 10 μm) were wiped out during friction welding. The nickel layer serves as a base for subsequent coatings and it has been used when coating stainless steel [8]. The electroplating procedure ap-

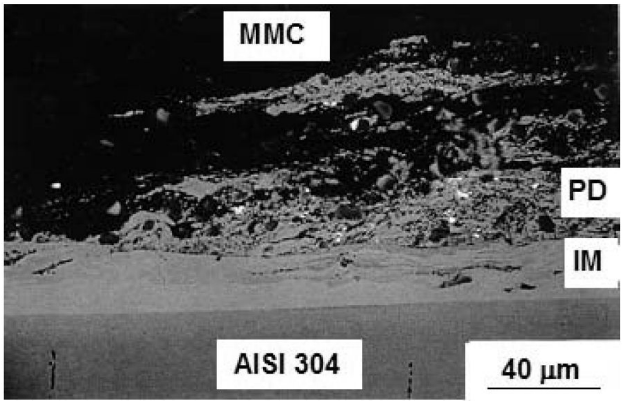

FIGURE 4. Micrograph of dissimilar MMC/Ag/AISI 304 stainless steel friction joints produced with a friction pressure of 30 MPa.

plied was detailed elsewhere [8-9]. All stainless steel and MMC substrates test samples were subsequently polished using 1 μm diamond particles prior to friction joining. Adhesion between the nickel barrier layer and the stainless steel substrate was improved via vacuum heat treatment of the electroplated stainless steel samples at 650°C for 1 hour and at 800°C for 15 minutes. All welds were produced using a continuous-drive machine rated at 15 kW transmission power with a maximum axial thrust of 110 KN and rotational speed held constant at 1500 rpm. During the welding of MMC/AISI 304 stainless steel the friction pressure (P1) was varied from 30 to 240 MPa, the forging pressure equal to 240 MPa. A friction time of 4.0 s and a forging time of 1.0 s. During short-term welding of dissimilar MMC/Ag/AISI 304 welds were produced using friction times ranging from 0.2 s to 1.2 s. The friction pressure was varied from to 30 to 90 MPa, the forging pressure was 15 MPa. For SEM analysis the samples welding were prepared by sectioning off the welding zone. The samples were polished and etched using conventional technique. For TEM microscopy analysis, the samples were prepared as follows: a section of the dissimilar joint was cut into slices and polished to a thickness of 0.120 mm. A perforation was made in the sample using an ion beam milling machine with the specimen rotated during bombardment at incident angles of 15 degrees.

3. Results and discussion

Figure 1 shows TEM image of silver nanoparticles in dissimilar MMC/Ag/AISI 304 joints produced by using a low friction pressure (30 MPa) and a friction time of 4s. Figures 1a, 1b, and 1c corresponds to the original image, ring diffraction pattern and key diagram with the main planes market respectively. This nanocrystalline microstructure was observed in the IM region close to the component centreline and had grain dimensions ranging from 10 to 20 nm. It is suggested that the nanoparticle formed in the silver interlayer may result from the formation of a *transfer layer* early in the welding process resulting from wear or mechanical alloying.

Figure 2 shows a bright field TEM image of the IM region in a dissimilar MMC/Ag/AISI 304 stainless steel friction welds produced by using a friction pressure of 30 MPa and a forging pressure of 240 Mpa. Figures 2a, 2b, 2c and 2d correspond to the Ag_3Al intermetallic, ring diffraction pattern and key diagram with the main planes along of the [112] axis respectively. The size of the grains in the transfer layer depend on the sliding speed, *e.g.*, Rigney *et al*. [10] observed that the dimensions of the crystallites were larger when faster speeds were applied. It is associated the increased size with higher temperature being produced during the wear process and also indicated the microstructure of the transfer layer was similar to the produced during mechanical alloying of oxygen-free high conductivity (OFHC) copper and M2 tool steel balls. The temperature at contact interface had an important influence on nanoparticles formation and on the size of the crystals formed during the wear process.

Figure 3 shows an image of detailed examination of dissimilar MMC/AISI 304 stainless steel friction welds obtained with a friction pressure, 30 MPa, friction time, 4 s, forging pressure, 30 MPa and a forging time, 1.0 s. Figure 3a shows the presence of a discontinuous transition layer along the length of the joint interface. Figure 3b shows the EDS chemical analysis of the transition layer indicating peaks of aluminium and iron. During friction welding, material is transferred from the stationary side of the joint to the rotating side during Stage I of the friction welding process. A transition layer was formed because of the movement of the viscous region close to the bondline. This particular area is subjected to a higher friction pressure and a temperature resulting of the formation of a plasticised region [7,16]. However, in this case, growth of the intermetallic layer is not determined by diffusion across a completely stagnant region in the MMC base material since it has been confirmed that *dynamicallly-quiescent* regions form in MMC/AISI 304 stainless steel welds produced by using a low friction pressure [11]. This *dynamically-quiescent* terminology is employed because the fluid flow occurs in this region, although it is only of the order of a few micrometers per second. The *dynamically-quiescent* regions are the widest at half radius location where the peak temperatures occur during dissimilar friction welding.

Figure 4 shows an image of detailed examination of dissimilar MMC/Ag/AISI 304 stainless steel friction welds obtained with a friction pressure, 30 MPa, friction time, 4 s, forging pressure, 30 MPa and a forging time, 1.0 s. Figure 4 shows the presence of a discontinuous silver layer along the length of the joint interface, a partial dispersed (PD) zone formed by aluminum, silver particle and Ag_3Al and an intermixed (IM) region composed by silver and Ag_3Al zones. The PD and IM regions are the equivalent to the transition layer in dissimilar MMC/AISI 304 stainless steel friction welds.

Figures 5 and 6 show the formation of FeAl and Fe_2Al_5 intermetallic in dissimilar MMC/AISI 304 stainless steel friction welds produced by using a friction pressure of 240 MPa, a forging pressure of 240 MPa, a friction time of 4 s and rotational speed 1500 rpm respectively. Fig. 5(a) shows a TEM

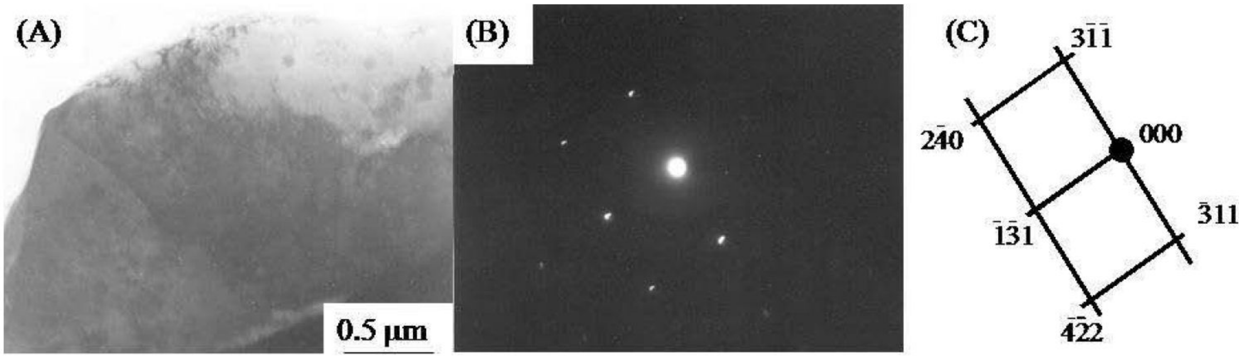

FIGURE 5. (a) TEM micrograph of the FeAl intermetallic (b) and (c) diffraction pattern and a key diagram along the [215] axis respectively.

FIGURE 6. (a) TEM micrograph of the Fe_2Al_5 intermetallic (b) and (c) diffraction pattern and a key diagram along the [110] axis respectively.

image of the FeAl intermetallic, (b) and (c) a diffraction pattern and a key diagram with the main planes market along of the [215] axis respectively. Figure 6a shows a TEM image of the Fe_2Al_5 intermetallic, 6b and 6c a diffraction pattern and a key diagram with the main planes along of the [110] axis respectively. Although, it is generally assumed that intermetallic layer formation in dissimilar friction welds results from an interdiffusion and/or mechanical mixing during the welding process, the exact manner in which this phenomenon occurs is unclear. Fukumoto *et al.* [12] suggested that FeAl, Fe_3Al and Fe_2Al, formation in 1060 aluminium/ AISI 304 stainless steel friction joint resulted from an interdiffusion during the joining process. Since the aluminium diffused 450 μm into the steel, the joint interface temperature was calculated at 911 K (638°C). They assumed that intermetallic formation occurred following completion of the steady-state period in friction joining when the fabricated component was cooling down to room temperature. This assumption is not supported by the results presented in a several research works indicating that the intermetallic thickness and joint mechanical properties are essentially determined by the friction pressure and friction time during the joining operation. Assuming that all the deformation occurs in the dissimilar substrate, which has the lowest flow stress at high temperature, the contacting interface of the other (higher flow stress) substrate will be essentially stationary during the welding operation. When this occurs, intermetallic growth at the dissimilar joint interface may be visualised as occurring along a planar boundary and the width of the intermetallic layer will depend on the time available for interdiffusion and on the temperature at the bondline. This shape of intermetallic growth explains the numerous references [12-13] indicating that thin intermetallic layers and optimum joint mechanical properties are produced when the friction time is as short as possible and the average temperature at the joint interface is lowered via selection of high friction pressure values.

4. Conclusions

It is suggested that the beneficial influence of friction pressure and friction time in minimizing Ag_3Al retention in MMC/Ag/AISI 304 stainless steel friction joints depends on wearing away of material at the joint interface. In contrast, in dissimilar MMC/AISI 304 stainless steel welds, growth of the intermetallic layer depends on interdiffusion and its thickness increases as friction time increases. In dissimilar MMC/Ag/AISI 304 stainless steel friction welds produced using a low friction pressure (30 MPa), the presence of silver nanoparticles and Ag_3Al intermetallics was detected at the joint interface. However, in joints produced with high friction pressure (240 MPa) and long friction time (4 s), the presence of nanoparticles was not observed. Also the formation of FeAl and Fe_2Al_5 intermetallics was observed. In these welds, the application of high friction pressures (240 MPa) promoted the formation of thin brittle intermetallic layers at the dissimilar joint interface.

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