Effect of friction speed on the properties of friction welded Alumina-Mullite Composite to 6061 Aluminum alloy

Marjan Safarzadeh¹, Ahmad Fauzi Mohd Noor¹* and Uday M. Basheer¹

1) School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia.

Email: srafauzi@usm.my

Available online at: www.austceram.com/ACS-Journal

Abstract
The study of mechanical properties and microstructure of friction welded Alumina-Mullite Composite with 6061 aluminum alloy is presented. The welding process was carried out under different speeds (1250 and 1800 rpm) while force and time were kept constant. Field emission scanning electron microscopy (FESEM) was used to investigate the morphology of the fractured surface and welding interface that had taken place during the friction welding. Studying the microstructure of the welding zone is important to investigate the relationship between microstructure and mechanical properties. It was found that in the friction welding of the ceramic composite to the aluminum alloy, the fracture proceeds mainly through the cleavage planes at a low speed while the fracture was occurred through the dimples at a high speed. The experimental results showed that a higher speed had a significant effect on the structure of the joint and also it had improved microhardness and bending strength.

Keywords: Alumina-Mullite Composite; Aluminum Alloy; Friction Welding; Fracture; Microstructure; Mechanical characterization

INTRODUCTION
Ceramic-metal joints have become more significant in modern technology, which are resulted from the combination of the properties of metals like ductility, high electrical and thermal conductivity and the properties of ceramics such as high hardness, corrosion and wear resistance [1, 2]

In the past two decades, an extensive attention was paid to high performing ceramics or fine ceramics such as silicon nitride, silicon carbide, zirconia and alumina, because of their excellent properties such as high temperature strength, wear resistance and high chemical stability. In order to the fine ceramics to function as structural components, they would be often joined to other ceramics or metals at some points with a high strength [3]. For that reason, the joining of ceramic and metals can be performed by different techniques such as ultrasonic joining, brazing, transient liquid phase diffusion bonding, and friction welding [4, 5]. Friction welding of two similar or dissimilar materials has been used widely in many manufacturing processes, which have high production rates. Friction Welding is a solid-state joining that produces coalescence at the faying surfaces under a compressive force involving one rotating and one stationary component. The coalescence of the materials will be obtained through the combination of a mechanically induced pressure and the rubbing friction motion of the two components[6, 5]. As reported by the American Welding Society (AWS), friction welding is the perfect process for joining metals, which are not necessarily similar.

Many researchers have conducted extensive examinations on the friction welding of dissimilar materials. The combination of good mechanical properties, good corrosion resistance, and good electrical properties of two materials are the main reasons for dissimilar joining. Friction welding of dissimilar materials is an economical process as compared to expensive forgings and castings [7, 8]. Some researchers had investigated the friction welding of aluminum alloys with ceramics. Essa and Bahrani [4] had investigated the direct friction welding of an aluminum alloy to 94 % alumina without using any interlayer or an aluminum tube surrounding the ceramic. A high bonding strength was achieved from the joining of the aluminum alloy and alumina but cracking of the alumina during friction welding was the biggest problem. They reported that friction welding of mild steel to alumina and copper to alumina is not possible.
Zimmerman et al. [9] carried out a research concerning the modelling of thermo-mechanical and diffusion effects in the process of friction welding of corundum ceramics and aluminum as well as in the same ceramic and electrolytic copper. From the finite element method (FEM), it was observed that during friction welding of ceramics with aluminum there were uneven distributions of temperature, deformation and pressure occurred near the contacting surface, which then cause inhomogeneity of the bond and affected its strength.

We had studied the quality of bonding at the interface of ceramic/metal alloy friction welded at different rotational speeds [10]. In order to join the alumina to 6061 Al-alloy samples the rotational speed was varied, while the friction pressure and friction time were kept constant. It was found that, the thickness of full plastic deformed zone (FPDZ) at the interface was increased by increasing the rotational speed. It was also reported that the rotational speed of 2500 rpm showed a good joint and microstructure with a higher microhardness in comparison with the other lower rotational speeds.

Uday et al. [11] investigated the ceramic composite of YSZ–Al₂O₃ friction welded to 6061 Al-alloy. Alumina rods with 25 wt% yttria stabilized zirconia were fabricated by slip casting process and were subsequently sintered at 1600°C. They observed that the mechanical strength of friction welded ceramic composite/6061 Al-alloy components was affected by the joining rotational speeds. As opposed to alumina join to aluminum, the addition of 25 % YSZ had allowed the joining to be performed at a much lower speed of 630 rpm than at 2500 rpm with an improved bending strength values on joints (30 Mpa) at the speed of 630 rpm and (4 Mpa) at 2500 rpm.

This paper is an extension of the experiment, which was presented in Materials & Design 31 (2010) 670–676 by the authors. Hence, the same equipments and materials were used. However, in the current study, Alumina-Mullite Composite rods were used. The joining performances of these welded materials were carried out by direct drive friction welding which were welded under various conditions. The aim of this study was to investigate the effect of friction speed on the micro-structural and mechanical properties of the friction welded Alumina-Mullite Composite and 6061 aluminum alloy. Moreover, we would like to take a closer look into the failure phenomena and plastic deformation at the friction welding of Alumina-Mullite Composite and 6061 Al-alloy. As such, FESEM, EDX, XRD and XRF techniques were used additionally.

**MATERIALS AND METHODS**

Elemental contents of the raw materials (6061 Al-alloy, alumina powder and mullite powder) were determined by X-ray Fluorescence (XRF) technique. As shown in Table 1 and 2, the 6061 Al-alloy contains 96 % Al of with the presence of the other typical alloying elements such as Si, Mg, Fe, Mn, Cu and Zn to form 6061 Al-alloy. It was supplied by a local supplier (Heap Sing Huat Metal and Machinery Sdn Bhd, Malaysia). It can also be observed that Alumina powder (which was supplied by Maju Santifik Sdn Bhd, Malaysia), has an average powder size of 0.7 µm and a high purity of 99.7 %. Mullite with 55.8 % of Al₂O₃, 41.4 % of SiO₂ and average particle size of 35.38 µm was supplied by Yanshi City Guangming High-Tech Refractories Products Co, Ltd, China. A high purity was necessary for this work to enhance and produce good ceramic rods which would be suitable for joining.

The Alumina-Mullite Composite rods (16 mm diameter and 50 mm length, containing 30wt % mullite) were prepared through slip casting in plaster of Paris molds. The green cast Alumina-Mullite rods were initially pre-sintered at 1200°C and were then sintered at 1600°C for 2hrs soaking time with a heating and cooling rate of 5°Cmin⁻¹. In order to have uniform shrinkage after pre-sintering rods, samples were inverted upside-down for the final sintering (1600°C). The average rod density of alumina sample was 3.4 g/cm³. The 6061 Al-alloy rods with a diameter of 16 mm, on the other hand, were cut into 60 mm length specimens, using a horizontal band saw machine. Then the rods were ground with SiC papers and polished by 1 µm alumina powder to remove sharp edges. The polished samples were cleaned in an ultrasonic bath with acetone for 10 min to remove grease and dirt. The process of joining was carried out on the Continuous Drive Friction Welding (CDFW) of a lathe machine (model APA TUM-35) equipped with an axial pressure and 2KW power which was modified to operate a rotary friction welding [10]. The friction speed used in the experiment was in the range of (1250 and 1800 rpm). Friction pressure (100 MPa) and friction time (30 sec) were kept constant all through the experiment.

Table 1: Chemical composition of the 6061 Al-alloy (wt%) by XRF technique.

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Si</th>
<th>Mg</th>
<th>Fe</th>
<th>Mn</th>
<th>Cu</th>
<th>Zn</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>96.1</td>
<td>2.7</td>
<td>0.5</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 2: Chemical composition of raw powders (wt%) by XRF technique

<table>
<thead>
<tr>
<th>Materials</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>K₂O</th>
<th>MgO</th>
<th>ZrO₂</th>
<th>NiO</th>
<th>ZnO</th>
<th>Ga₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mullite</td>
<td>55.83</td>
<td>41.45</td>
<td>1.08</td>
<td>0.58</td>
<td>0.21</td>
<td>0.42</td>
<td>0.14</td>
<td>0.09</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alumina</td>
<td>99.69</td>
<td>0.18</td>
<td>-</td>
<td>0.06</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The welded specimens were then sectioned at the weld joint to study the microstructure of the welding zone (Fig.1). The microstructure of the joints was examined, using both optical microscope (Olympus-metallurgical) and field emission scanning electron microscopy (FESEM). A ZEISS SUPRA 35VP field emission scanning electron microscopy was used in this study. Energy Dispersive X-Ray (EDX) analysis consisted of spectra showed peaks of elements which made up the composition of the materials. The phase formation of the sintered ceramic samples and raw materials was determined by X-ray diffraction (XRD) analysis. The XRD instrument used in this work was D8-ADVANCE X-ray diffractometer (Bruker Analytical X-Ray systems). The Future tech (FV-700) Vickers tester, using the 0.3kg load and 10sec holding time, was applied for the hardness measurements, according to standard ASTM: E384-10.

Furthermore, four point bending strength was used to measure the joints, ability to resist deformation under load. The experiments were carried out at room temperature with a crosshead speed of 0.5mm.min⁻¹. In this work, an axial torsion test system (BISS Bi-00-701, GT Instruments Sdn Bhd Malaysia), was used according to ASTM C1684-08 (standard for flexural strength of advanced ceramics-cylindrical rod strength).

2. RESULTS AND DISCUSSION
2.1 Optical Microscopy (OM) at the interface zone

The optical images (50× and 100×) of the welded joints of 6061 Al-alloy with Alumina-Mullite Composite at 1250 rpm to 1800 rpm are shown in Fig. 2 and Fig. 3. It is observed that deformation zone in the interface joint is different with increasing rotational speed. At the speed of 1250 rpm, there is a small deformation observed on both sides of the welded interface (Fig.2 (a and b)). On the other hand, with 1800 rpm speed a thicker plastic deformation in Al-alloy side has occurred (Fig. 3 (a and b)).
This indicates that a higher temperature is experienced by the joints during the welding of the two materials. Although, there is a difference in heat generation between friction welding and conventional welding process, some kinds of similarities exist in the temperature distribution at the welding joints. This would lead to the formation of a fine-grained interface which is flanked by a relatively coarser grained structure. Dissipated frictional heat through the parent material, would result in the temperature gradient which causes zones with different microstructures [10, 12].

2.2 Field Emission Scanning Electron Microscopy (FESEM)

The FESEM was used to observe the microstructure and morphology of the base materials, welding interface and to evaluate the changes in grain size across the joint. Studying the microstructure of the welding zone is important to investigate the relationship between microstructure and mechanical properties.

The FESEM images of the interface region of friction weld taken from the welded joint of Alumina-Mullite Composite with 6061 Al-alloy at 1250 and 1800 rpm are shown in Figure 4 and Figure 5. The interface between the Al-alloy and ceramic composite components at a rotational speed of 1250 rpm is very narrow and can be seen as a thin strip along the boundary on the metal side (Figure 4).

The effect of increasing the rotational speed on the microstructure of the joint interface is observed at the higher rotational speed of 1800 rpm (Figure 5). The side of Al-alloy shows a larger plastic deformation and the effect of frictional heat near the welded zone.

When the rotational speed is increased, the temperature of joints will be higher and this will raise the heat flow. As a result of that, there is a large gradient of temperature difference during cooling due to heat absorption by the welding zone, and this has been similarly discussed by (Ahmad Fauzi et al., 2010). This causes changes to the
microstructure in the full plastic deformed zone (FPDZ). A high rotational speed in FW, results in a clear deformation zone while at a low speed, the deformation zone is not clearly recognised. Moreover, as shown in Figure 5, the welding interface is clear while cracks, pores and unjoined regions are not observed in this joint. On the other hand, the thickness of the FPDZ region is also increased with increasing rotational speeds. The formation of these structures which are formed in the interface zone of friction-welded joint is the result of the heat input and high plastic deformation.

Fig. 5: FESEM of the welded interface of Alumina-Mullite (Al-M) Composite /6061 Al-alloy at 1800 rpm after etching in 1 % NaOH, time: 15min [magnification a) 1000×, b) 3000×]

2.3 Energy Dispersive X-Ray Analysis (EDX)
EDX was carried out on both sides of the Alumina-Mullite Composite and 6061 Al-alloy which were joined at the speed of 1250 and 1800 rpm. EDX was performed in order to determine the composition of the elemental concentration near the welded zone of the joint. As shown in Fig. 6(B), the intermixing of elements and elemental concentration are found to be large in welding zone. This indicates that the FW joint had resulted in diffusion of elements between the two dissimilar materials, forming a new phase. Further away from the joint (>10 µm) the base materials (i.e. the alloy and the composite) still remain unreacted (points A and C) on Fig. 6. This would suggest that 1250 rpm welding speed enables only a short diffusion between the two dissimilar materials. This also suggests that a higher speed leads to more diffusion of the elements from the opposing materials.

Increasing speed of the rotation leads to an increase in heat of the interface, which in turn will change the thickness of the interface layer dramatically. It is noted that the interface between 6061 Al-alloy and Alumina-Mullite Composite begins to spread inside the aluminum metal, revealing diffusion of eutectic components in the aluminum alloy. Fig. 7 shows the oxidized Mg near the interface region with presence of a small amount of silicon (point B).

The formation of intermetallic compounds at the interface of the weld would cause a serious reduction of the joint's strength. It is suggested that the addition of Mg to the aluminum alloy enhances the growth of the IMC layer and reduces the strength of the joint, whilst Si addition retards the growth of the IMC layer and thus improves the strength of the joint. IMC layer has to be controlled to stay within certain limits. Although the presence of a small amount of intermetallic components seem to be favourable for the quality of the weld, the thickness of the IMC layer must not exceed the proposed thickness of 1 µm [13].

2.4 Fractography at the interface zone of Alumina-Mullite Composite
FESEM photographs of friction welded Alumina-Mullite Composite with 6061 Al-alloy (at the speed of 1250 and 1800 rpm) were taken from the fractured surface which were obtained after four point bending test. Fig. 8 shows the morphology of the fractured surface of the welded interface of Alumina-Mullite Composite sample and 6061 Al-alloy at the speed of 1250 rpm. In the ploughing mode, material is displaced from the groove to the sides without the removal material. However due to repeated ploughing during friction between two surfaces, material removal is occurred [14, 15]. The formation of flakes and grooves takes place at the joint surface of the Alumina-Mullite Composite with 6061 Al-alloy (Fig. 8).

The flaking and grooving would be decreased with the increasing plastic deformation during joining process. Therefore, when the rotation speed is increased, the grooves shape in the periphery region turns into dimple shape. This is shown in the fractured surface of Alumina-Mullite Composite and 6061 Al-alloy at the rotational speed of 1800 rpm (Fig. 9). The brittle and ductile fracture can also be observed from the Fig.9. The metal surface consists of dimples with varying sizes and shapes which indicate a ductile fracture. On the other hand, a large ductile area at the peripheral region shows the plastic deformation.
Fig. 6: EDX of the welded interface of Alumina-Mullite (Al-M) Composite with 6061 Al-alloy at 1250 rpm after etching in 1 % NaOH, time: 15min at points A, B, C

Fig. 7: EDX of the welded interface of Alumina-Mullite Composite with 6061 Al-alloy at 1800 rpm after etching in 1 % NaOH, time: 15min at points A, B, C
In this study, a high rotational speed led to an increase in the temperature at the joint surface and a deeper penetration of Al-alloy into the ceramic composite. This resulted in an improved bending strength of the ceramic composite and Al-alloy.

2.5 Mechanical Properties of Friction welded Alumina-Mullite Composite with 6061 Al-alloy

The mechanical properties of friction welded 6061 Al-alloy with Alumina-Mullite Composite (using commercial mullite), were evaluated using Vickers microhardness and four point bending strength tests.

2.5.1 Vickers Microhardness Test

The variation of hardness across the joint zone is a significant factor that identifies the mechanical properties of the joints. According to the variation of hardness across the joint zone, the mechanical properties will vary [16]. As shown in Fig. 10 and Fig. 11, Vickers hardness values of 6061 Al-alloy are lower (<100 Hv) than that of Alumina-Mullite Composite ceramic (>500 Hv). The Hv in 6061 Al-alloy also shows a small scatter. This result is similar to the prior result, which reflects the uniformity and zero defect of aluminum alloy [10]. The result also shows a higher hardness in the interface region (400 to 800 Hv).

On the other hand, the hardness values of ceramic vary with distance from interface, with a wide scatter. This is attributed to the volume fraction of flaws as well to the flaw distribution typically present in the sintered ceramic rods. With increasing rotational speeds, the hardness at the interface is increased from ~800Hv at the speed of 1250 rpm to ~1000Hv at the speed of 1800 rpm. As explained by Özdemir et al. [17] and our own paper [10], an increasing rotational speed led to the increasing heat input and resulted in plastic deformation at the welding interface. This led to a...
decrease in the grain size and subsequently hardening of the FPDZ and DZ region. The hardness value at the interface of Alumina-Mullite Composite/6061 Al-alloy at the speed of 1250 rpm, is reduced to ~800 Hv while in alumina/6061 Al-alloy is ~1200 Hv. This may indicate a lower plastic deformation of the interfaces. It leads to a slight decrease in grain size and hardening at the 6061 Al-alloy side in the region of the interface.

### 2.5.2 Four Point Bending Strength Test

The Bending Strength test can concentrate the strain in a localised region, like the weld. This test could be used as a qualitative test to detect defects such as cracks in the specimens [18]. Bending tests have been used to determine the bond strength of friction welded joints. The results of four point bending strength result of friction welded Alumina-Mullite Composite and 6061 Al-alloy at the speed of 1250 rpm, at room temperature is determined to be 6.18 MPa (Fig. 12). It is found that the bending strength value of pure alumina joint (15.16) is greater by a factor of more than two when compared to Alumina-Mullite Composite at the same rotational speed.

The results show deterioration in the joining properties when adding mullite into alumina, although the joining is successful. The increase in bending strength of the composite to 6061-Al alloy at higher speed (~8MPa) is related to the heat input, high plastic deformation as well as shearing of the grains which occurred at the welded interfaces of the materials [17, 19].

Maximum bending strength values of the friction welding joints of alumina/6061Al-alloy were achieved with 2500 rpm rotational speed while in Alumina-Mullite Composite/6061Al-alloy were 1800 rpm. Alumina-Mullite Composite were not able to join at 2500rpm and had broken at the beginning of the friction welding. This was thought to be due to the low fracture toughness of Alumina-Mullite Composite in comparison with alumina/6061 Al-alloy.

It was also found earlier that the ceramic composite part tended to break when it was joined to Al-alloy at a low speed of 900 rpm. This is due to the lower strength of bonded parts, thus limiting the lower speed to be used. This may be attributed to a narrow width of FPDZ. At the welding interface, the width of the FPDZ would be narrow, due to the smaller heat input and low plastic deformation. Thus, higher rotational speed is required for this joining of Alumina-Mullite Composite to 6061 Al-alloy, in order to avoid the formation of intermetallic compounds, which lead to have brittleness at the interface of the joint, and also to enhance the bonding strength and ductility.

![Vickers microhardness traverse of friction welded Alumina-Mullite Composite/6061 Al-alloy at 1800 rpm](image1)

**Fig. 11:** Vickers microhardness traverse of friction welded Alumina-Mullite Composite/6061 Al-alloy at 1800 rpm

![Four point bending strength test of friction welded Alumina-Mullite Composite / 6061 Al-alloy](image2)

**Fig. 12:** Four point bending strength test of friction welded Alumina-Mullite Composite / 6061 Al-alloy

In contrary, Uday et al. [11] had previously shown that 25 % of YSZ-Alumina composite was successfully friction welded to alumina at a lower speed of 630 rpm while achieving a high bending strength (30 MPa). On the other hand, at a higher rotation, the joining properties were deteriorated. The higher temperature developed at the joining interface at a higher rotational speed resulted in an increase of intermediate brittle phase, and thus affecting the mechanical properties significantly with a lower bend strength of 4 MPa.

As was mentioned earlier, the speed of the welding can be correlated to the microstructure of the joints and it would affect the microhardness and bending strength of the resultant joint. This would result in formation of a fine-grained interface which is flanked by a relatively smaller grained structure. Sathiya et al. [16] also reported a similar observation.

### CONCLUSION

The Alumina-Mullite Composite was joined successfully with 6061 Al-alloy by friction welding at rotation speeds of 1250 and 1800 rpm. The
higher rotational speed of 1800 rpm revealed a higher microhardness and bending strength. Microstructural analysis of the joint exhibited an improved interface of Alumina-Mullite Composite and 6061 Al-alloy. High rotating speeds resulted in a high heat input sufficiently and led to change the thickness of the interlayer significantly as well as the width of the HAZ. The study of the fractured surfaces for different rotational speeds revealed that the fracture between the ductile and brittle fractures was different depending on the heat input at the interface. The higher rotational speeds improved the quality of the joints between the Alumina-Mullite Composite to 6061 Al-alloy.

ACKNOWLEDGMENTS
Authors appreciate the financial support from the Graduate Research Assistant, Universiti Sains Malaysia, under grant (RUI/1001/PBAHAN/814196) to carry out this research. We would like to thank all those who have either directly or indirectly extended their help in carrying out the studies.

REFERENCES: