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Effect of friction time on the properties of friction welded YSZ-alumina composite and 6061 aluminium alloy

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ABSTRACT

The aim of this work was to study the effect of friction time on the microstructure and mechanical properties of alumina 0, 25, 50 wt% yttria stabilized zirconia (YSZ) composite and 6061 aluminium alloy joints formed by friction welding. The alumina-YSZ composites were prepared through slip casting in plaster of Paris molds (POP) and subsequently sintered at 1600°C, while the aluminium rods were machined down using a lathe machine to the dimension required. The welding process was carried out under different rotational speeds and friction times, while friction force (0.5 ton-force) was kept constant. Scanning electron microscopy was used to characterize the interface of the joints structure. The experimental results showed that the friction time has a significant effect on joint structure and mechanical properties.

Keywords: friction welding, aluminium alloy, alumina-yttria stabilized zirconia, microstructure, bending strength

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1. INTRODUCTION

It has been known for a long time that the mechanical energy generated in overcoming friction is continuously transformed into heat. In most circumstances the thermal energy generated is regarded as undesirable, but under controlled conditions it can be used to join materials, as in the case of friction welding.[1,2]

Friction welding (FW) is a solid state joining method[3] which produces coalescence of materials under compressive force when workpieces rotate or move relative to each other producing heat and plastically displacing the material from the faying interface.[4,5] Heat is generated at the weld interface because of the continuous rubbing of contact surfaces, which in turn, causes a temperature rise and subsequent softening of material.[6] Eventually, the material at the interface starts to flow plastically and forms an upset. When a certain amount of upsetting has occurred, the rotation stops and the compressive force is maintained or slightly increased to consolidate the weld.[7] Friction time, friction pressure and rotational speed are the most important parameters of friction welding.[8,9] These factors must be controlled to obtain a uniform and strong joint.

For a particular application, heating time is determined during the set-up or from previous experience. Excessive heating limits productivity and wastes material. Insufficient time may result in uneven heating as well as entrapped oxides and cause unbonded areas at the interface. Uneven heating is typical of friction welds in a bar stock. Near the centre of a rotating bar, the surface velocity may be too low to generate adequate frictional heating. Hence, thermal diffusion from the outer portion of the faying surface must take place to ensure a sound bond overall. Heating time can be controlled in two ways.[4] First is with a suitable timing device that stops rotation at the end of a preset time. Preheat and forging functions can be incorporated with heating time using a sequence timer. The second method is to stop rotation after a predetermined axial shortening. This method is set to consume a sufficient length to assure adequate heating before upsetting. Variations in surface condition can be accommodated without sacrificing the weld quality.[10]

In the present study, the joining performances of alumina - 0, 25, 50 wt% ceramic composite rods and 6061 aluminum alloy rods by direct drive friction welding machine with constant rotational speed and axial force were investigated. The influence of friction time as the variable parameters on the mechanical properties and welding quality of joints were evaluated.

2. MATERIALS AND METHODS

The test materials used in the present investigations were alumina rods containing 0, 25, 50 wt% yttria stabilized zirconia prepared through slip casting technique with commercial 6061 Aluminium alloy rods, typically used for aerospace application. The starting materials were alumina commercial powder (high purity average particle size 1.04 μm, specific area 8.65 m^2/g), 5.2 mol% yttria stabilized zirconia powder (ZrO_2/5.2 mol % Y_2O_3, average particle size 1.77 μm, specific surface Area = 0.8511 m^2/g, purity 99.95% Zr) from STREM Chemicals, USA. Appropriate quantities of alumina and zirconia powders were slurry mixed in distilled water and mixed for 24 h using ball milling with zirconia ball. The ceramic composite samples were prepared through slip casting in the plaster of Paris molds. Subsequently, the cast alumina- zirconia rods were sintering at 1600°C with a soaking time of 5 hours. The aluminium alloy rods were cut off and machined down using a lathe machine to the diameter required. Tests were conducted on the weld joints, which were produced by friction welding process using 16 mm diameter rods of the sintered alumina and the aluminium alloy. The joints were prepared on a direct drive friction-welding machine modified from an existing lathe machine model: APA TUM-35. The contacting surface of ceramic composite and aluminum alloy were then ground to a smooth surface, as well as removing any sharp edges. They were ultrasonically cleaned using acetone to remove dirt and grease. The two rods were then friction welded.

The friction welded pieces were cut into sections, ground with 400–1200 grit silicon carbide papers and polished with 1 μm Al_2O_3 particulate suspension polishing liquid. The samples were ultrasonically cleaned using acetone to remove dirt and adherent particles. The morphology was observed using the ZEISS SUPRA 35VP Field Emission Scanning Electron Microscopy. After completing the friction welding process for different friction times, the effect of friction time on the joining between alumina - YSZ composite and 6061 aluminum alloy specimen was observed.

The temperature measurements in workpieces were measured by using a digital thermometer (Ebro TFN 520/530, Produktion- u. Vertriebs GmbH, Germany) based on the standard DIN IEC 584-2 for accuracy of probe. The temperature was increased rapidly within the first 5 seconds until it reached the temperature where maximum joining occurs. The temperature measurement in the joining was important as it affects the microstructure developed in the friction welding process.[6]

The bend test has the ability to concentrate the strain in a localized region, like the weld. This test was used as a qualitative test to detect any cracking in the specimens.[11] Bond strength measurements provide information on the mechanical quality and integrity of joints between metal and ceramic components. Bending tests have been used to determine the bond strength of friction welded joints.[12] The experiments were performed using an axial torsion test system (BISS Bi-00-701, GT Instruments Sdn. Bhd., Malaysia) based on the standard BS EN 843-1 for ceramic flexural testing under static loading.

In this study, different friction times of 30, 60 and 90 seconds were used to produce the weld joints. The rotational speed (630, 900, 1250, 1800 and 2500 rpm) and axial force (0.5 ton-force) were kept constant. The specimens were studies using scanning electron microscopy. The mechanical properties of the joints were determined by the four point bending test, and results compared with those produced in previous papers.

3. RESULTS AND DISCUSSION

Previous studies[12–14] have shown there are three main systems apparent in the joining of the friction welded involving different alumina-YSZ composite joined with 6061 aluminium alloy such as pure alumina, alumina-25 wt. % YSZ and alumina-50 wt. % YSZ. The main conclusions[13] from this research is that pure alumina was joined with 6061 aluminum alloy at rotational speeds between 1250 and 2500 rpm, while alumina-25, 50 wt. % YSZ has been joined at lower rotational speeds (630 rpm - 900 rpm).

3.1. Variation of friction temperature with respect to friction time

Figures 1–3 show the variation in friction temperature while keeping friction force and rotational speeds constant, as the friction time increases the temperature peak increases. From these figures it can be seen that the maximum friction temperature obtained when increasing the time to all types of ceramic used, which leads to increased oxidation in the metal surface and then increased brittleness.

The peak temperatures measured for pure alumina/6061 aluminium alloy joints ranged between 102.1°C to 125.4°C in period time 30 seconds, 146°C to 169.3°C in period time 60 seconds and between 189.9°C to 213.2°C in period time 90 seconds for rotational speeds 1250 rpm to 2500 rpm, respectively, shown in Figure 1. For alumina - 25 wt. % YSZ composite/6061 aluminium alloy joints, temperature indications ranging from 129.1°C to 166.1°C in period time 30 seconds, from 173°C to 210°C in period time 60 seconds and higher friction time (90 seconds) were observed, that friction temperature values varied between 216.9°C to 253.9°C for rotational speeds between 630 to 2500 rpm (Figure 2). Moreover, the alumina- 50 wt. % YSZ/6061 aluminium alloy joints experienced temperatures ranging between 157.3°C to 214.7°C in period time 30 seconds, 202.3°C to 259°C in the period time 60 seconds and between 247.3°C to 298°C in the higher friction time (90 seconds), for rotational speeds 900 rpm to 2500 rpm, respectively, shown in Figure 3.

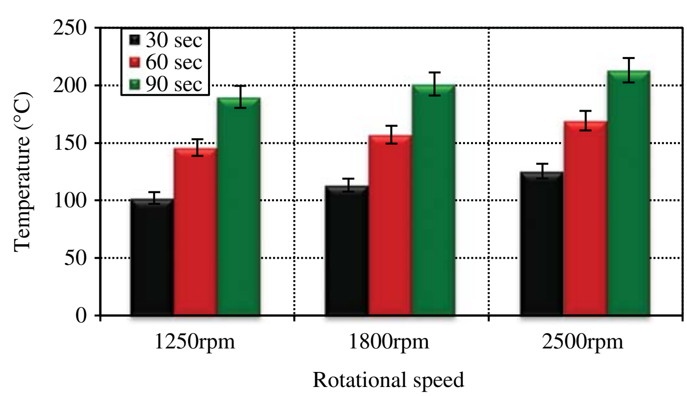

Figure 1. Effect of friction time with the friction temperature of the joining between pure alumina and 6061 Al alloy.

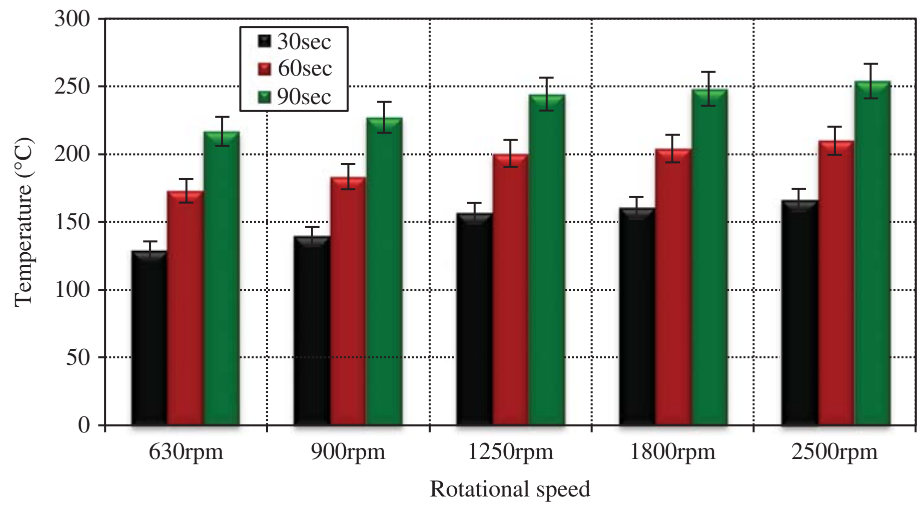

Figure 2. Effect of friction time with the friction temperature of the joining between Al2O3 25% YSZ and 6061 Al alloy.

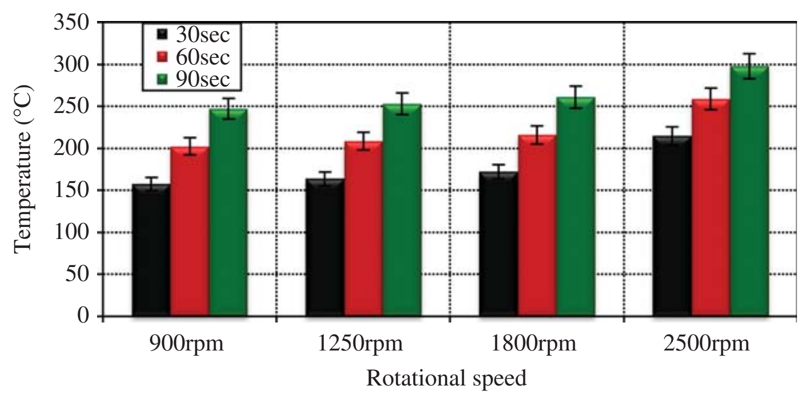

Figure 3. Effect of friction time with the friction temperature of the joining between Al2O3 50% YSZ and 6061 Al alloy.

3.2. Microstructures

After friction welding for different friction times, the effect of friction time on the joining between alumina - YSZ composite and 6061 aluminium alloy specimen has a significant impact on the strength of the joining between these materials. The microstructure analysis showed that this joint was sound, shown in Figures 4–6. The structures were identified an the welding interface of the parent materials based on the presence of cracks after the welding process.

The microstructure of the welded joint between pure alumina and 6061 aluminium alloy under 1250 rpm with friction time of 60 seconds, taken at 3000X using the FESEM, is shown in Figure 4, and the microstructure of alumina - YSZ composite with aluminium alloy with same friction time is presented in Figure 5. These results indicate that the weld has experienced long thermal times.[15] The relatively long heating rate influenced the microstructure of the weld. Specifically, the increased friction time has led to the appearance of cracks in the microstructure of the interface area.

Figures 6 and 7 show the micrographs of pure alumina and alumina - YSZ composite with 6061 aluminium alloy specimens welded for a friction time of 30 seconds at rotational speed of 1250 rpm. It is clear that the microstructure of the joint between two materials is common to clean and there are no cracks at the interface. However, it was observed that the microstructure of the interface in the friction welding process at constant rotational speed with different friction time, lead to increased oxidation in the metal surface, which increases the brittleness. In addition, the thickness of interface depends on the effect of rotational speed, thermal expansion and other parameters as stated in previous papers.[12–14]

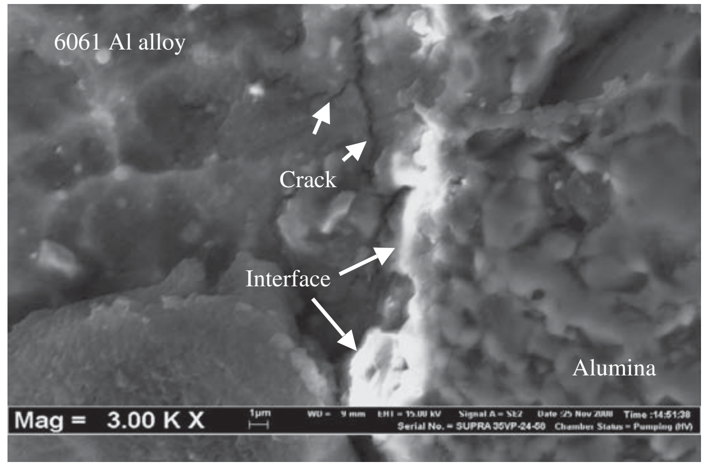

Figure 4. Interface of alumina/6061 Aluminium alloy weld, observed under FESEM at 1250-rpm speed, 60 sec.

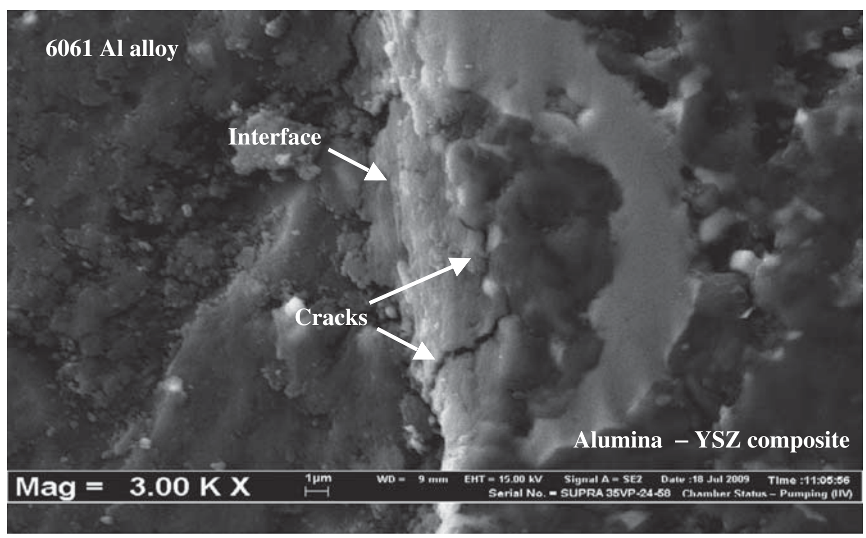

Figure 5. Interface of Al2O3 – YSZ composite/6061 aluminium alloy weld, observed under FESEM at 1250 rpm speed, 60 sec.

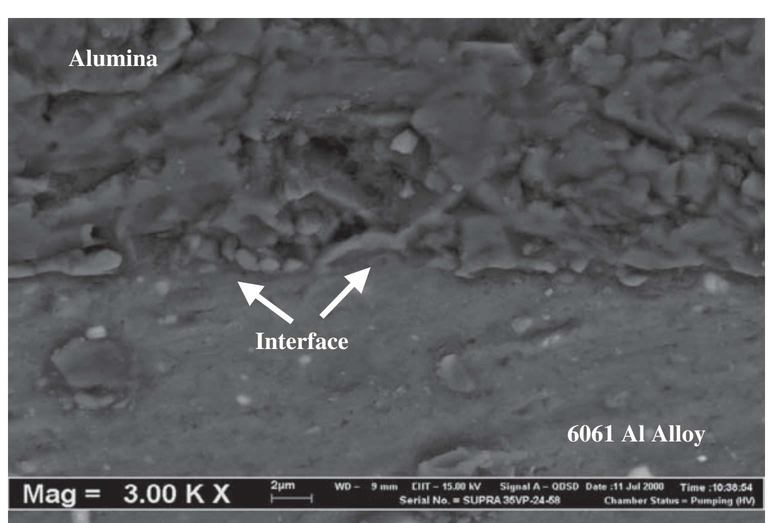

Figure 6. Interface of pure alumina and 6061 aluminium alloy weld, observed under FESEM at friction time 30 sec and rotational speed 1250 rpm.

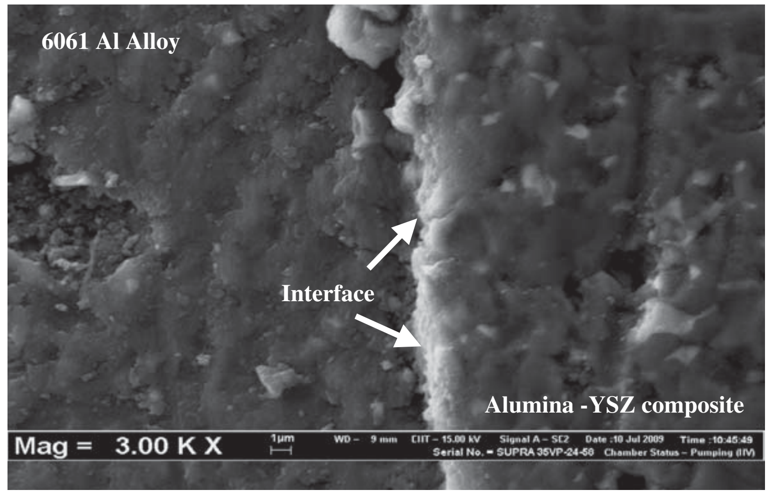

Figure 7. Interface of alumina – YSZ composite with 6061 aluminium alloy weld, observed under FESEM at friction time 30 sec and rotational speed 1250 rpm.

3.3. Four-point bending strength

The bending test has the ability to concentrate the strain in a localized region, like the weld. This test was used as a qualitative test to detect any cracking in the specimens.[11] Bond strength measurements provide information on the mechanical quality and integrity of joints between metal and ceramic components.[16] Bending tests have been used to determine the bond strength of friction welded joints. The results of the four-point bending strength tests with different friction time are shown in Figs. 8–10,

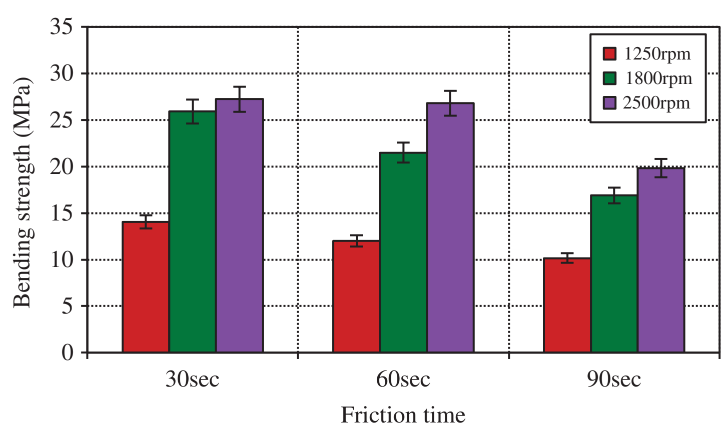

Figure 8. Four point bending strength of pure alumina/6061 Al alloy friction welded joints with different friction times.

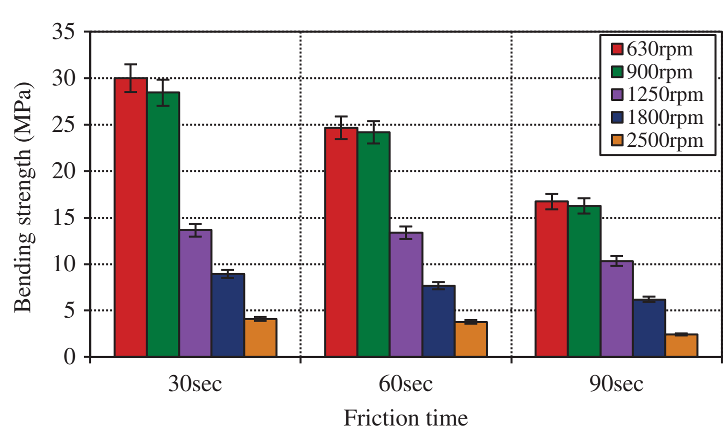

Figure 9. Four point bending strength of Al_2O_3-25 wt%/6061 Al alloy friction welded joints with different friction times.

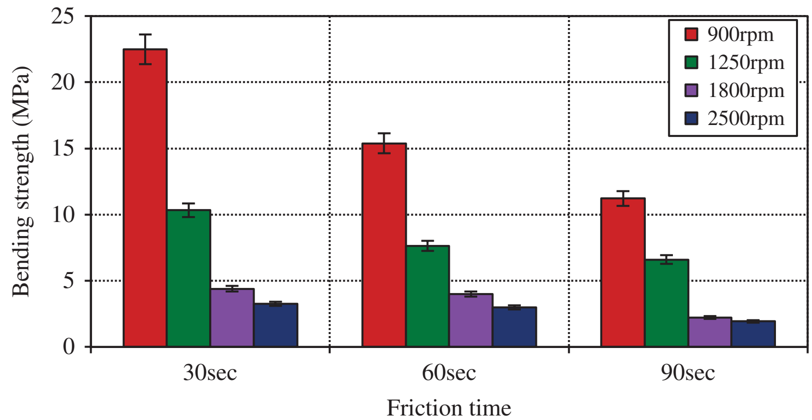

Figure 10. Four point bending strength of Al_2O_3-50 wt%/6061 Al alloy friction welded joints with different friction times.

for the three types of specimens (alumina 0, 25, 50 wt % YSZ composite) prepared using friction welded joints obtained from the five different rotational speeds. The four point bending test results of the pure alumina to metal alloy are summarized in Figure 8, where the bending strengths reported are an average of five tests per processing condition. It has been shown that the pure alumina joint bending strength values were greater at the friction time of 30 seconds than at 90 seconds to all rotational speeds. Meanwhile, it was also found that the bending strength values on joints were smaller in the pure alumina joint at 1250 rpm while it were higher at a higher rotational speed of 2500 rpm at the same friction time. In Figure 9, the bending strength values obtained on alumina- 25 wt % YSZ composite joint with different friction times were greater with rotational speed 630 rpm than with 2500 rpm at the same friction time. In Figure 10, the bending strength values for the alumina- 50 wt. % YSZ composite joint with different friction times were greater with 900 rpm than 2500 rpm. Moreover, the bending strength values were greater at the friction time of 30 seconds than 90 seconds.

From the results of the four point bending test, it was observed that the low bending strength values of pure alumina and Al_2O_3- 25, 50 wt % YSZ friction-welded joints were the result of the increased temperature rather than the lower friction time (30 seconds). The friction temperature at higher friction time (90 seconds) increased the brittle phases between the metal–ceramic interface as well as the thermal expansion between these materials at high temperatures.

4. CONCLUSIONS

The effect of friction time is important, because it not only defines the microstructure at the interface, but also affects the depth of heating in the workpieces by conduction and therefore the width of the HAZ. The relatively long heating rate influences the microstructure of the weld. Specifically, the increased friction time has led to the appearance of cracks in the microstructure of the interface. The friction temperature at a higher friction time (90 seconds) increased the brittle phases between the metal–ceramic interface as well as the thermal expansion between these materials at high temperature. Therefore, the low bending strength values of alumina 0, 25, 50 wt % YSZ friction-welded joints at 90 seconds were the result of the increased temperature rather than the lower friction time (30 seconds).

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