Materials and Design 31 (2010) 670–676

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Microstructure and mechanical properties of alumina-6061 aluminum alloy joined by friction welding

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A R T I C L E I N F O

Article history:
Received 11 June 2009
Accepted 12 August 2009
Available online 18 August 2009

Keywords:
Friction welding
6061 aluminum alloy
Alumina
Microstructure
Bending strength

A B S T R A C T

The study of the interface of ceramic/metal alloy friction welded components is essential for understanding of the quality of bonding between two dissimilar materials. In the present study, optical and electron microscopy as well as four-point bending strength and microhardness measurements were used to evaluate the quality of bonding of alumina and 6061 aluminum alloy joints produced by friction welding. The joints were also examined with EDX (energy dispersive X-ray) in order to determine the phases formed during welding. The bonded alumina-6061 aluminum samples were produced by varying the rotational speed but keeping constant the friction pressure and friction time. The experimental results showed that the effect of rotation speed and degree of deformation appears to be high on the 6061 Al alloy than on the alumina part. It is discovered that the weld interface formed included three different regions: unaffected zone (UZ), deformed zone (DZ), as well as transformed and recrystallized fully deformed zone (FPDZ). Therefore, when rotational speed increases, the thickness of full plastic deformed zone (FPDZ) at the interface increases as a result of more mass discarded from the welding interface. It was also observed that rotational speed of 2500 rpm can produce a very good joint and microhardness with good microstructure as compared to the other experimental rotational speeds.

1. Introduction

In recent years, significant attention has been paid to fine ceramics or high performance ceramics such as silicon nitride, silicon carbide, zirconia and alumina, because of their excellent properties such as high temperature strength, high wear resistance and chemical stability [1,2]. In order for the fine ceramics to be used as structural components, they must be sometimes joined to metals at some points. For joining metals to ceramics, ultra-high pressure technique and gas–metal eutectic methods have been used. However, these methods have lower efficiency when compared to friction welding method [1].

Friction welding has gained importance in the fabrication industry. The advantages of this process include high reproducibility, short production time and low energy input [3]. This unique method of joining materials is achieved by rotating one component at high revolutions per minute (rpm) in contact with a second motionless component. By applying axial pressure during rotation, the temperature at the interface is increased until the materials reach the plastic state. A simple set up of the friction welding machine is shown in Fig. 1. At a precise moment, the rotation is stopped and axial forging force is then applied between the two components. The combination of pressure and heat forges a solid state bond at the interface of the two joining parts [3]. The process can be carried out using conventional friction welding apparatus but under a protective atmosphere to avoid metal oxidation. The components to be joined (especially the ceramic) must be planar and parallel to avoid crack formation and crack propagation as well as joining imperfections [4].

Many factors affect the quality of friction welds, which among others are friction time, friction pressure and rotational speed [3]. The quality and the strength of the welds depend on the correct choice of these parameters. For example, Ozdemir [3] has joined AISI304L austenitic stainless steel and AISI4340 steel by friction welding using different rotational speeds in their studies. He found that the tensile strength of joints was markedly affected by joining rotational speed selected. Ozdemir et al. [4] have also studied the effect of rotational speed on the interface properties of friction welded of different kind of steel. They observed that the width of the full plastic deformed zone (FPDZ) has an important effect on the strength of friction welded samples and the strength increases with increase of the rotational speed. Mohamed et al. [5] joined alumina with mild steel by friction welding using aluminum sheet as an interlayer. The strength of alumina–steel bonding is much depending on the wettabillity of the alumina surface by the partially molten aluminum interlayer with constant rotational speed. Avinash et al. [6] studied the microstructure

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doi:10.1016/j.matdes.2009.08.019

and mechanical behavior of rotary friction welded titanium alloys. They found that a medium rotational speed can produce a very good weld, with other parameter kept constant.

In this study, friction welding was applied to join sintered alumina bars to a commercial 6061 aluminum alloy bars. The joining performances of this welded material were carried out by direct-drive friction welding welder under various conditions. This paper also aims to demonstrate the influence of increasing in rotational speed on the interface phenomena, microstructure variation near the weld zone and the mechanical properties.

2. Experimental

The test materials used in the present investigations were commercial 6061 Aluminum alloy rods which are typically used for aerospace application, and alumina rods prepared in-house through slip casting technique. The elemental compositions of these materials determined by X-ray fluorescence (XRF) technique are shown in Tables 1 and 2. Tests were conducted on the weld joints, which were produced by friction welding of 15 mm diameter rods of the sintered alumina and the aluminum alloy. The joints were prepared on a direct drive friction welding machine modified from an existing lathe machine model: APA TUM-35. The dimensions of the specimens used for friction welding are shown in Fig. 2.

The alumina rods were prepared by using commercially available alumina powders. The alumina powder was supplied by Maju Santifik Sdn Bhd Malaysia (specific surface area of 8.65 m^2/g (BET) with average particle size of 1.04 μm). The alumina rods were prepared through slip casting in plaster of Paris molds. The green cast alumina rods were sintered at 1600 °C with soaking time of 4 h. The average bulk density of alumina sample is 3.7961 g/cm^3. On the other hand, the large 6061 Al alloy blocks were supplied by a local supplier (Butterworth Motorworks Sdn Bhd Malaysia). The aluminum rods samples were cut off from a large 6061 Al alloy block, and were then machined down to the diameter required using a lathe machine. The end surfaces of alumina and aluminum alloy rods were then smoothened, as well as removing any sharp edges. They were then ultrasonically cleaned using acetone to remove dirt and grease. The two rods were then friction welded.

In the present work, rotational speeds of 1250 rpm, 1800 rpm and 2500 rpm were used to produce the weld joints. Friction pressure of 7 MPa and friction time of 20 s was kept constant. Four welds were performed for every set of test parameters in order to ensure the accuracy and repeatability of results. The welded specimens were then sectioned at the weld joint to study the microstructure of the welding zone. It was observed by optical microscope, scanning electron microscopy and energy dispersive X-ray (EDX) analysis. The microhardness and four-point bending strength test across the interface was also investigated.

3. Results and discussion

3.1. Microstructure characteristics at the interface zone

The microstructures of the welded joints, taken at 100× and 200× using the optical microscope, are shown in Fig. 3, while Figs. 4 and 6–8 show the microstructure observed with a Field Emission Scanning Electron Microscope FESEM for the three rotational speeds applied during the welding. The weld joints are seen to be continuous and the deformation zone being very different. However, there is a distinction between the microstructures developed near the interface in the two parts joined.

In the joint produced at 1250 rpm, uniform grains structure is seen on both side of the weld interface, Fig. 3a and b. The deformation zone itself is not visibly seen. However, it can be seen a dark zone near the interface, which indicates the beginning of the formation of the deformation zone between two materials. This effect of rotational movement of one piece against the other at the welded joint is distinctly shown. In the welded joints produced at 1800 rpm, a more refined grain structure was produced at the welded joints. The deformation zone had also clearly formed between the two pieces welded as shown in Fig. 3c and d. The effect of rotation of the specimen can be seen in this zone, as the grains are pulled in the direction of rotation which was subjected to torque at high temperature. The degree of deformation appears to be high in the metal, similar to that reported by Avinash et al. [6]. In the welded structure produced at 2500 rpm, the deformation zone is distinctly observed between two parts of joining. The effect of the rotation speed and degree of deformation appears to be high on the 6061 Al alloy as compared to alumina as shown in Fig. 3e and f.

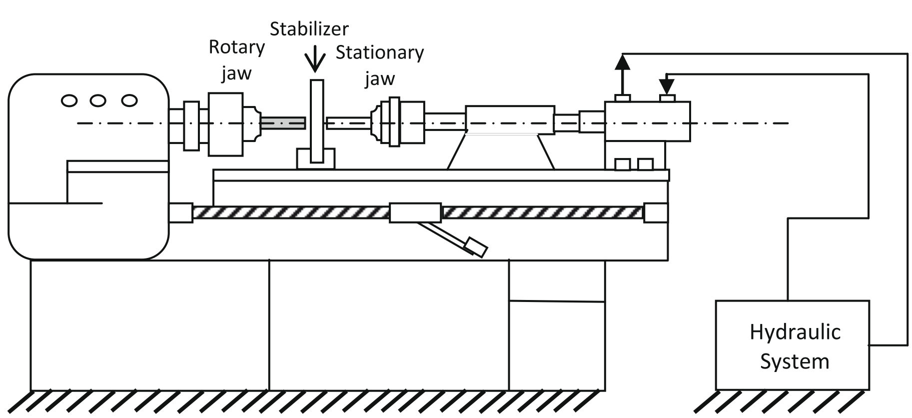

Fig. 1. A set up of a Friction Welding Machine.

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

Al	Si	Mg	Fe	Cu	Cr	Mn	Ti	Zn	Ni	Ga	Bal
96.0	2.1	0.95	0.33	0.17	0.066	0.04	0.022	0.014	0.014	0.013	<0.01

Table 2
Chemical composition of the alumina (wt%) by XRF technique.

Al_2O_3	SiO_2	Na_2O	CaO	Fe_2O_3	NiO	CuO	ZnO	Ga_2O_3
99.4	0.33	0.11	0.024	0.081	0.014	0.001	0.001	0.001

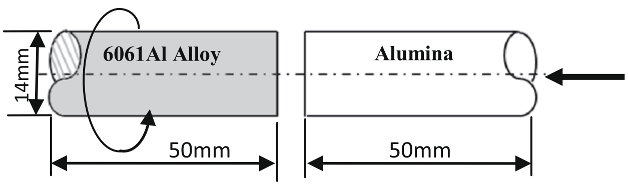

Fig. 2. Shapes and dimensions of specimens used for friction welding.

Previous works [3–7] have shown that there are three main regions apparent in the interface zone of all the friction – welded joints involving metal to metal contacts: the fully plastic deformed zone (Z_{pl}) around the welding line, partial deformed zone (Z_{pd}) and the unaffected zone (Z_{ud}). The microstructures of 6061 aluminum alloy base material and sintered alumina material in the welded zone observed under electron microscopy in this work are shown in Figs. 6 and 7. Unlike the metal–metal contacts, it can be seen here that the base material in the welding zone revealed three different regions at the weld interface, i.e. the unaffected zone (UZ), deformed zone (DZ) as well as the transformed and recrystallized fully deformed zone (FPDZ). This is in agreement with that reported by Sahin [8].

As observed under FESEM, the width and geometry of these regions changed as a function of rotational speed. The large changes in microstructure took place in the FPDZ and DZ regions. Therefore in the welded structure produced at 1250 rpm, the welding interface did not clearly appear and cracks in the unjoined regions are observed (Fig. 4). The effect of increasing rotational speed over the friction welding joint is that both the temperature gradient and axial shortening [5] increased as a result of more mass being transferred out of the welding interface (Fig. 5).

The FESEM micrograph taken at the weld interface of 1800 rpm shows that the microstructure in the interface of this joint consists of three regions at the weld interface Fig. 6. The effect of severe plastic deformation on the grain morphology in the FPDZ and DZ can be seen clearly. It reveals that the interface of this joint (1800 rpm) consists of non-excavation DZ near the welding interface (metal side), grain refinement FPDZ and unaffected parent material (see Fig. 7). Generally, the welding interface is clear while cracks and unjoined regions are not observed in this joint.

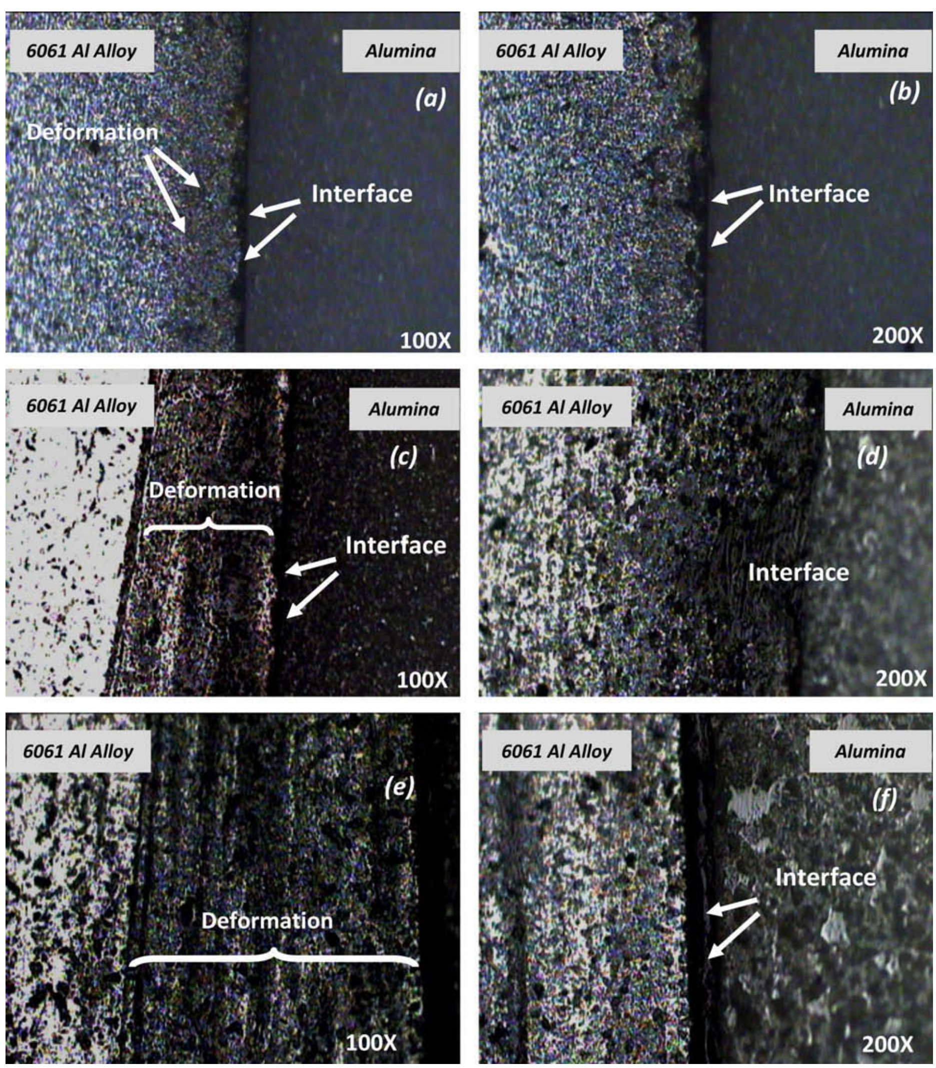

Fig. 3. Optical images of interface properties of specimens welded at (a, b) 1250 rpm, (c, d) 1800 rpm, (e, f) 2500 rpm magnification 100×, 200×.

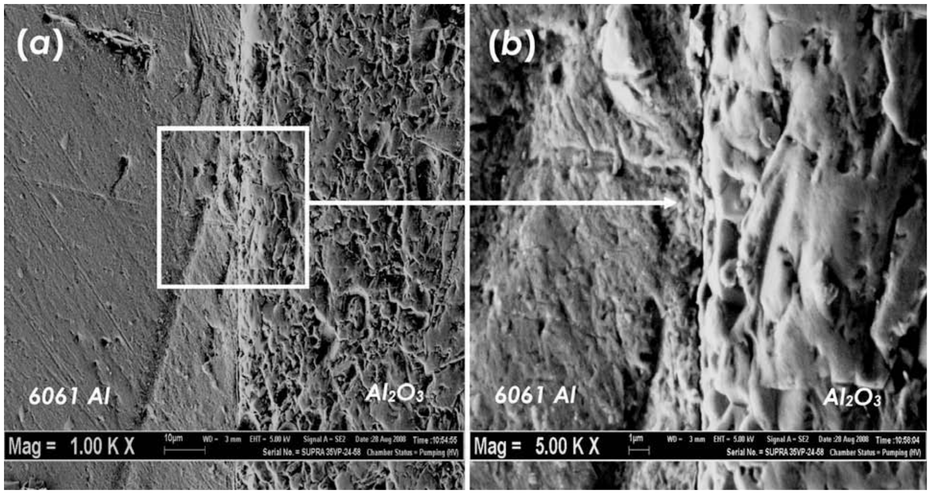

Fig. 4. Interface of specimen welded observed under FESEM at 1250 rpm (a) 1000× and (b) 5000×.

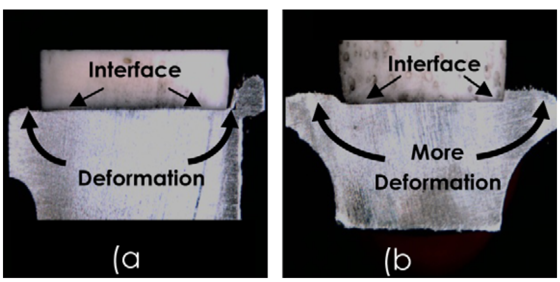

Fig. 5. Shapes of Burrs in the joining between alumina-6061 Al alloy (a) 1250 rpm and (b) 2500 rpm.

The effect of the increase in rotational speed on the microstructure, which formed in the interface during and after friction welding process, can be observed in the high rotational speed 2500 rpm (Fig. 8). The aluminum alloy side was greatly deformed by severe plastic deformation and frictional heat near the weld zone. This observation is similar to that reported by Ozdemir et al. [4]. High rotational speed 2500 rpm can cause local heating at the interface and thus, could reach a high temperature in a short time. This condition causes lower cooling rates and a wider heat affected zone

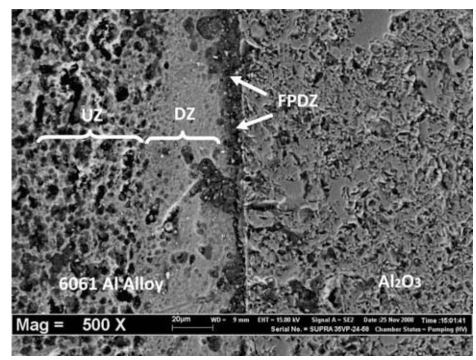

Fig. 7. Interface of specimen welded observed under FESEM at 1800 rpm after etching in 1%NaOH. Time = 15 min.

(HAZ), as a consequence of a greater volume of viscous material transferred out of the interface [3]. However, the alumina grains cracked and break during the very high rotational speed. The FPDZ appears as composite components of both alumina and aluminum alloy, revealing diffusion of eutectic components in the aluminum alloy into alumina.

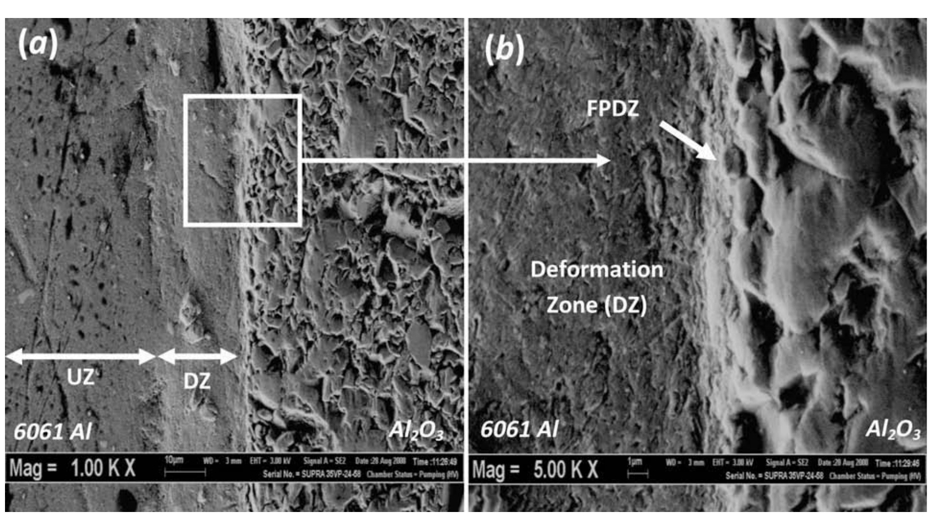

Fig. 6. Interface of specimen welded observed under FESEM at 1800 rpm (a) 1000× and (b) 5000×.

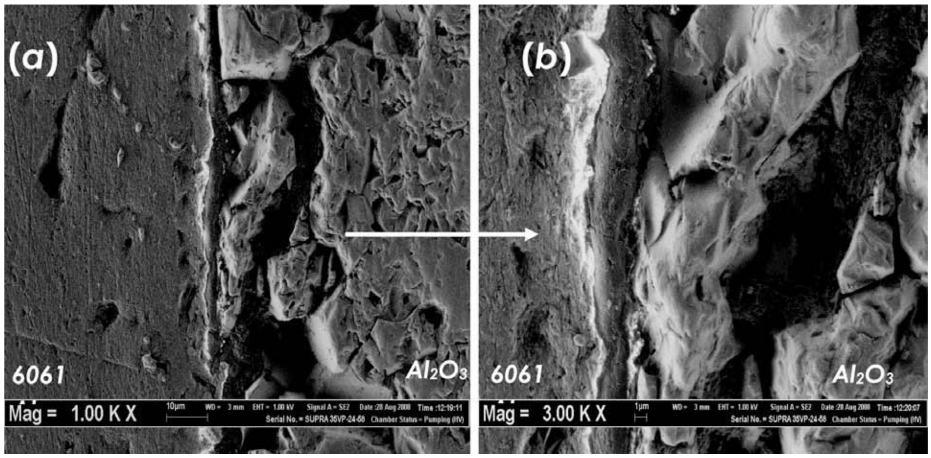

Fig. 8. Interface of specimen welded observed under FESEM at 2500 rpm (a) 1000× and (b) 3000×.

An energy dispersive X-ray (EDX) analysis was performed in order to investigate the phases that formed at the welding interface. Fig. 9a shows the EDX analysis of the points on the microstructure of the interface region of the friction welded alumina-6061 aluminum alloy joints. Fig. 9b–d illustrate the EDX analysis results taken from the point A, B and C corresponding to ceramic/metal joint at 1250 rpm, respectively. From the EDX analysis, the formation of aggregation compounds of Al, Si, Mg, and Cu. The formation of brittle intermetallic compounds has a tendency to degrade the strength of the joints [8].

3.2. Deformation zone and grain size

Though the generation of heat in friction welding is different from the conventionally available fusion process, some kind of similarity exists in the temperature distribution from weldment

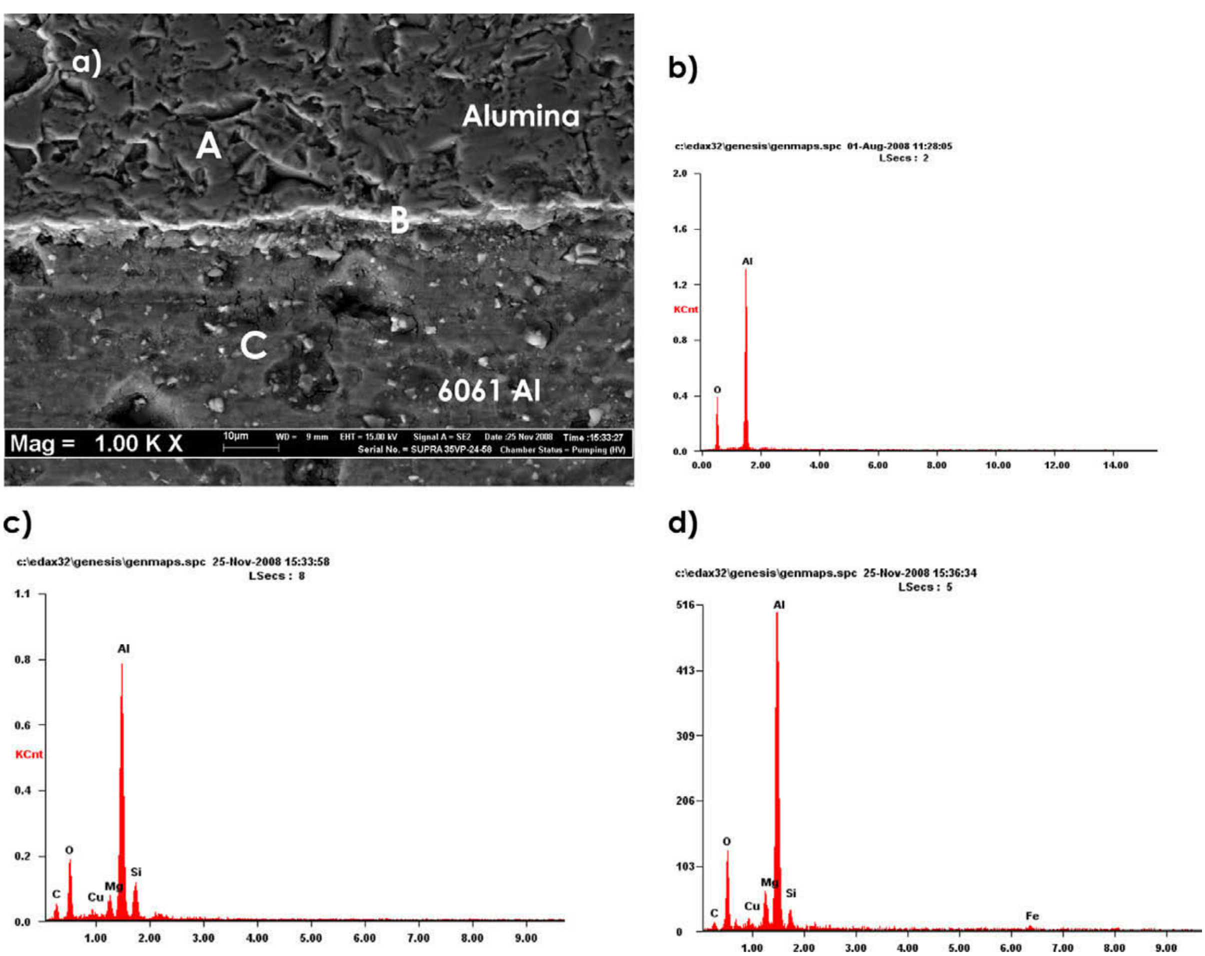

Fig. 9. (a) Micrograph of joining compound, (b) EDX analysis at A, (c) EDX analysis at B and (d) EDX analysis at C.

to parent material. This would result in a fine grained interface flanked by relatively coarser grain. The frictional heat at the interface when dissipated through the parent material would result in a temperature gradient causing zones of material with different microstructure [9].

In the optical microscope observation of all welded specimens, due to the effect of rotational speeds, the grain size reduction has been observed at the deformation zone of the metal side [10–12]. The grains were warped in the deformation zone, and became non-equated in shape and size owing to a strong plastic flow outwards during the friction processes. The grain size became increasingly smaller towards the weld interface. The grain size of the deformation zone was ~5 μm; while the grains adjacent to the weld interface was ~9 μm measured.

3.3. Vickers microhardness tests

Vickers microhardness results in the welding zone are given in Fig. 10. It can be seen that the microhardness values of 6061 aluminum alloy is much lower that the alumina ceramic by a factor of 9 M. The hardness in aluminum alloy is consistently uniform throughout the whole length of the rod. On the other hand, it can clearly be seen that the hardness of alumina varies a lot, i.e. wide scatter. This is probably due to the flaws present on the sintered rods, typically large pores.

This scatter due to the porosity might affect the size of the indentations [13]. At the interface, however, a rotational speed of 2500 rpm gave maximum hardness values. The increasing hardness in the welding interface is associated with microstructure formed in the welding interface as a result of the degree of heat input and plastic deformation [14]. The plastic deformation causes a decrease in the grain size which leads to increase the microhardness in the region of the welding interface [3].

3.4. Four-point bending strength

Bond strength measurements provide information on the mechanical quality and integrity of joints between metal and ceramic components [15]. Bending tests have been used to determine the bond strength of friction welded joints. The results of the four-point bending strength tests are shown in Fig. 11 for the three types of specimens prepared using friction welded joints obtained

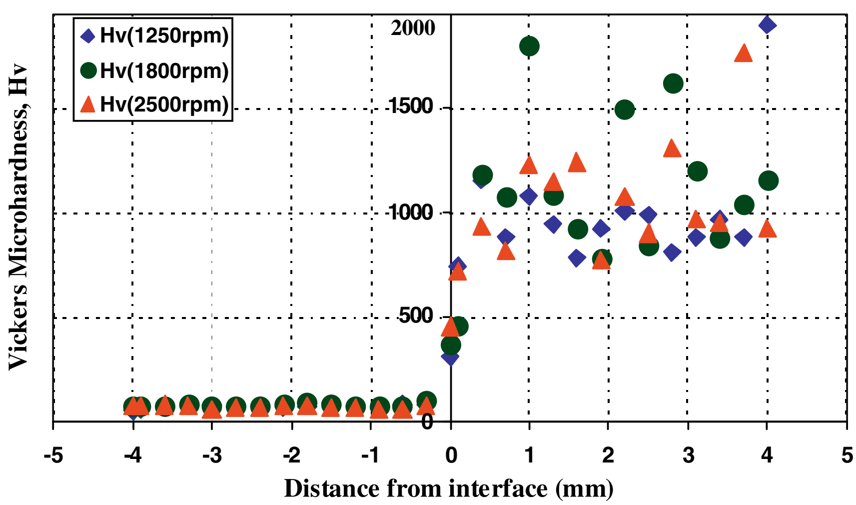

Fig. 10. Microhardness traverse of 6061 Al alloy-alumina friction welded joints.

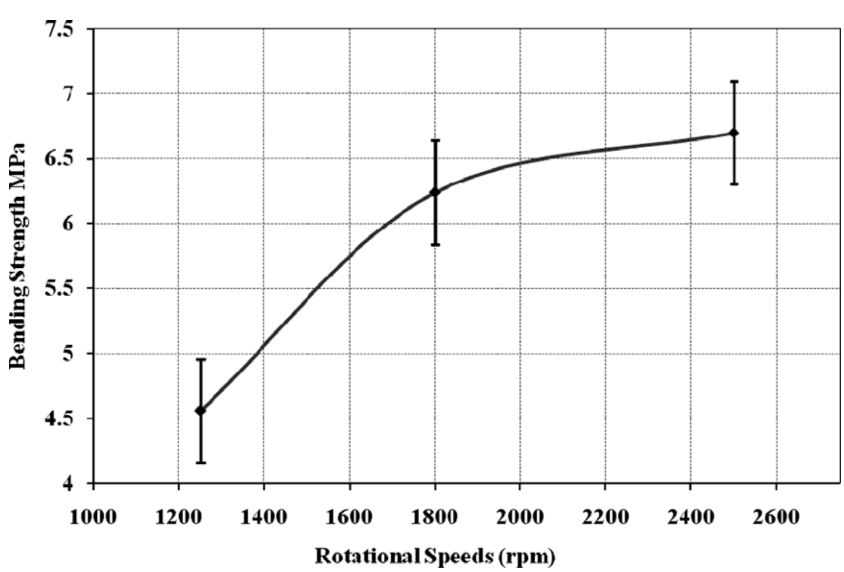

Fig. 11. Four point bending strength of 6061 Al alloy-alumina friction welded joints.

from the three different rotational speeds. Maximum bending strength values of the friction welding joints were achieved with 2500 rpm rotational speed. The increased in bending strength is related to the heat input, high plastic deformation and shearing of the grains that occurred at the components interface as a result of the increased rotational speed and axial pressure.

From the results of the four point bending test, it can be seen that the minimum bending strength values of friction welded joints at 1250 rpm was a result of the narrower width of FPDZ as compared to the higher welding speeds. The narrow width FPDZ at the welding interface is a result of short heat input and low plastic deformation. With increasing rotational speed, the time necessary to attain the temperature required for plastic deformation decreases in the aluminum alloy side.

4. Conclusion

In this study, alumina-6061 aluminum alloy joints were welded successfully by friction welding. Some interesting developments of microstructure and properties were observed in the welding area. The HAZ is very narrow, if not non-existent, in the case of 1250 rpm. But when the speed was increased, the HAZ is more visible on the aluminum alloy part, especially with rotational speed 2500 rpm. The effect of rotation speed and degree of deformation appears to be high on the 6061 Al alloy than on the alumina part. Microstructure studies of alumina-aluminum alloy friction welded joints revealed three different regions at the weld interface, i.e. unaffected zone (UZ), deformed zone (DZ), as well as transformed and recrystallized fully deformed zone (FPDZ).

Most of the microstructural changes took place in the FPDZ and DZ region. The width of FPDZ region is mainly affected by the rotational speed. The microhardness traverses could not adequately describe the properties of the alumina in the joints. This was attributed to flaws in the sintered alumina. The rotational speed of 2500 rpm gave maximum microhardness values in the welding interface.

The bending strength values obtained were greater in joint using rotational speed of 2500 rpm than with 1250 rpm. The use of higher rotational speed with constant friction time and pressure increases the bending strength of friction welded as a result of heat input, high plastic deformation and shearing of grains at the interface.

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