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Joint properties of friction welded 6061 aluminum alloy/YSZ–alumina composite at low rotational speed

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ABSTRACT

In this study, a ceramic composite of alumina–yttria stabilized zirconia (YSZ) was friction welded to 6061 aluminum alloy. Alumina rods containing 25 wt.% YSZ were formed using slip casting and subsequently sintered at 1600 °C to form a solid body. The 6061 aluminum alloy sample was cut and polished, and then subjected to friction welding experiments. Both rods were 16 mm in diameter. The results of this study showed that the alumina–25 wt.% YSZ composite was able to be friction welded to 6061 aluminum alloy at a lower rotational speed of 630 rpm compared with high rotational speeds. The friction force was maintained at 5 KN for a frictional time of 30 s. Optical Microscopy (OM) and Field Emission Scanning Electron Microscope (FESEM) were used to analyze the microstructure of the products, particularly at the interface of the joints. The joints were also examined with EDX line and area (energy dispersive X-ray) in order to determine the phases formed during the low speed welding. The mechanical properties including bending strength and Vickers microhardness were measured. The experimental results indicated that the mechanical strength of friction welded alumina–25 wt.% YSZ composite/6061 aluminum alloy components were obviously affected by joining in the low rotational speed (630 rpm), having higher strength as compared to higher rotational speed.

1. Introduction

Ceramic–metal bonding presents huge challenges because of the large differences in the thermal expansion coefficients of the two types of materials. Several techniques have been developed depending on the materials bonded such as solid state welding, direct diffusion bonding, hot isostatic pressing, reactive metal bonding and active metal brazing [1,2]. The degree of success, when two different materials are joined, depends on factors such as the properties of the interface created in the joint and the thermal expansion coefficient mismatch between the joined materials, which results in large residual stresses being generated during cooling from the joining temperature [3]. In order to overcome those problems, friction welding could be the technique for producing high integrity joints. It is one of the most economical and highly productive methods in joining similar and dissimilar metals, but unknown in the metal to ceramics. It is widely used in automotive, aerospace industrial and engineering applications [4].

The friction welding process is a solid state joining process that produces a weld under the compressive force contact of one rotating workpiece to another stationary workpiece [5]. It employs a machine that is designed to convert mechanical energy into heat using relative movement between surfaces of workpieces, without the use of electrical energy or heat from other sources [4,6]. The heat is generated at the welding interface because of the continuous rubbing of contacting surfaces, which, in turn causes a temperature rise and subsequent softening of metal. 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. Friction time, friction pressure and rotation speed are the most important operational parameters in the friction welding process [7].

The relative rotational speed is the most sensitive process parameter. In practice, it may vary over a wide range without influencing the quality of the welding connection. The tendency to increase the rotational speed during friction welding to obtain better mechanical properties is erroneous, and there are certain optimum speeds for each individual material combination and application [8].

From the standpoint of an improvement of the quality of the welded connection (particularly for welding of metals sensitive

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to overheating), it is desirable to use relatively low rotational speeds. The process efficiency is improved as a result of reduced heat losses, which in turn reduces the amount of energy used for welding. This, however, leads to a necessary decrease in the thermal conductivity of the ceramic material and, what is more important, to a more insulator of the ceramic material. The duration of this stage (and for low rotation speeds, throughout the entire welding process) depends on a large degree of the initial condition and the nature of the materials welded on the friction surfaces [8].

At high rotational speeds, deep tearing at the friction surfaces is replaced by a polishing action. As a result, to achieve the conditions for plasticization at the faying surfaces, longer heating times are required. Longer heating times would allow the propagation of thermal energy along the axial direction of the workpieces, and consequently a greater volume of material is heated [8].

In the present study, the joining performances of alumina rods containing 25 wt.% YSZ and 6061 aluminum alloy rods by direct drive friction welding machine with constant friction time and friction force were investigated. The influence of the low rotational speed as the variable parameters on the joint properties and welding quality of joints were evaluated.

2. Materials and methods

The test materials in the present investigations were commercial 6061 aluminum alloy rods (96Al, 2.1Si, 0.95 Mg, 0.33Fe, 0.17Cu, 0.066Cr, 0.04Mn, 0.022Ti, 0,014Zn, 0.014Ni, 0.013 Ga) which is typically used for aerospace application, and alumina rods containing 25 wt.% YSZ were prepared through slip casting technique. 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 5.334 m^2/g, purity 99.95% Zr) from STREM Chemicals, USA. Tests were performed on the welded joints, produced by friction welding using 16 mm diameter rods of the ceramic composite and aluminum alloy.

All the friction welding joints were carried out using a rotational friction welding machine modified from an existing lathe machine model: APA TUM-35. The connection surface of ceramic composite and aluminum alloy were initially ground to a smooth surface to remove any sharp edges. Before welding each sample was cleaned using acetone to ensure grease and dirt-free surfaces. The two surfaces were then contacted and friction welded. Friction welds were obtained under different rotational speeds between (630 and 2500 rpm). The friction force of 5 KN and friction time of 30 s were kept constant. Five welds were performed for every set of test parameters in order to ensure the accuracy and repeatability of results. The temperature changes during the friction welding process were measured by K-type thermocouples attached to the welding joint at the different rotational speeds. The measurements were performed using Digital Thermometer (Ebro TFN 520/530, Produktions- u. Vertriebs GmbH, Germany) based on the standard IEC 584-2 [9] for accuracy of the probe. After friction welding, the welded specimens were cut vertically to the direction of bonded interfaces direction using a low speed diamond saw. Standard grinding and polishing sample preparation procedures used aqueous sodium hydroxide solution (2% NaOH, 10 min time) to etch the samples. The appearances and cross sections of joints were observed by Optical Microscopy (OM) (Olympus BX51 M Microscope). The microstructures and fracture surfaces were analyzed using a Field Emission Scanning Electron Microscope (FESEM) (Zeiss Supra 35VP FESEM) equipped with an EDX. The joints were examined with EDX line and area (energy dispersive X-ray) in order to determine the behavior of element distribution formed during the welding. The Vickers microhardness measurement of the interface was evaluated using a microhardness testing machine (FM-700, Future Tech, 0.3 kg/10 s). The strength of the joints was also determined using four-point bending with an Axial Torsion Test System BISS Bi-00-701.

3. Results and discussion

3.1. Temperature measurements

Friction welding generates steep temperature gradients near the joint process zone [10]. Large scale deformation occurs in the heat-affected zone over a timescale of several seconds. The temperature of the welding zone in this work is recorded with Digital Thermometer (Ebro TFN 520/530). It is evident from Fig. 1 that keeping the frictional force (5 KN) constant while the rotational speed increases would raise the peak temperature. The temperature in the friction interface rises sharply owing to a combination of friction and plastic work. From this figure, it can be seen that the increase friction temperature is obtained when increasing the rotational speed from 630 rpm to 2500 rpm. The operation temperature for alumina–25 wt.% YSZ composite/6061 aluminum alloy joint is around 129 °C at the low rotational speed (630 rpm) while for high rotational speed is around 166 °C. The increase in friction temperature has to be associated with the nature of the materials and the amount of heat generated in this process.

3.2. Microstructure obtained by the Optical Microscopy at the Interface Zone

The optical images (taken at 200× and 500×) of the alumina–25 wt.% YSZ composites with 6061 aluminum alloy which were joined with (630 rpm, 1250 rpm and 2500 rpm) rotational speeds are shown in Figs. 2–4. The two magnifications are used exclusively in order to clarify the size and shape of grains and the layer of deformation occurring in 6061 aluminum alloy with different rotational speeds. It is generally observed that the welded joints are continuous and the deformation zones are different for the different rotational speeds. However, for the different speeds used, there is a clear distinction between the microstructures developed near the interface in the metal alloy part.

In the joint produced at 630 rpm, uniform grains structure is seen on metal side of the weld interface, Fig. 2(a and b). The deformation zone is not visibly seen. However, there is a good interfacial bonding with no visible, excessive cross-over of joining between the two dissimilar materials. The effect of rotational movement of one piece against the other at the welded joint can be clearly seen in this rotational speed. In the welded joints produced at 1250 rpm, a more refined grain structure is produced in the welded

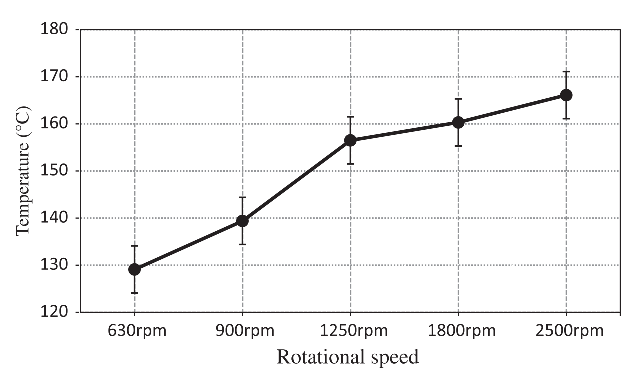

Fig. 1. Effect of rotational speed on the friction temperature of the joining between pure alumina–25 wt.% YSZ and 6061 aluminum alloy.