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An insight into microstructural evolution during plastic deformation in AA6061 alloy after friction welding with alumina-YSZ composite

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ABSTRACT

The microstructural studies of friction welding help in understanding microstructural changes occurred during friction welding. The effect of plastic deformation on microstructural changes in AA6061 alloys is the subject of the considerable practical interest. The development of this subject is remarkable, but a more detailed study could lead us to have a better understanding of the phenomenon. In the present study, Optical Microscopy (OM), Field Emission Scanning Electron Microscopy (FESEM), microhardness and X-ray diffraction (XRD) were used to study the effect of plastic deformation on the grain structure and dislocation density of AA6061 alloy when there was a joint, with the ceramic. The effect of rotation speed and the degree of deformation appeared to be higher on the AA6061 alloy than on the ceramic part. Results showed different deformation mechanisms at different rotational speeds and confirmed unambiguously the change in grain size, microhardness, crystalline grain and dislocation density as a result of changing the distances from the interface.

1. Introduction

Friction welding is reported to be one of the most economical and highly productive methods in joining similar and dissimilar metals, although it is relatively unknown in joining of metal to ceramics. It is widely used in automotive, aerospace industry and engineering applications (Sathiya et al., 2007). The friction welding of dissimilar materials is more complicated than similar materials due to difference in the physical, thermal, chemical and mechanical properties of base materials (Khan, 2012). The weld strength and its interface properties are extremely important. The failure of these welded parts may lead to huge losses. Therefore, the quality of weld is extremely important. In friction welding of dissimilar materials combinations such as AA6061 alloy – Stainless steel 304, 5052 Al alloy – stainless steel 304, the weld strength and its interface properties are degraded due to formation of intermetallic compounds. These compounds strongly depend on the local temperature attained during the welding process and they are responsible for brittle failure of the components. However, there is possibly non-uniform heat generation across the weld interface as the rotational speed of inner region is less than outer region, and thus heat generated in the inner region is less than outer region.

The new methods of friction welding are becoming more widely implemented in the manufacture of aero engines, because these solid phase joining processes provide high weld quality and economic benefits (Kallee et al., 2003). High-strength metal alloys are of interest for

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structures requiring minimum weight, especially in the aerospace industry. Along with the interest in high-strength metal alloys, there is a growing requirement to join ceramic composite components. For high-performance applications an improved strength / toughness combination is needed, and for this reason the solid phase friction welding processes have been developed, as they are likely to have a good balance of properties in the materials. Friction welding processes also permit the joining of dissimilar materials, thus making best use of specific material properties at the operating location.

Therefore, the joining of AA6061 alloy and alumina – YSZ composites explained in this study. The AA6061 alloy was selected for this study because of the cheaper cost as compared to other aluminum alloys. This alloy is widely used in aerospace and automobile industries. Meanwhile, the alumina - YSZ ceramic composite samples were prepared using most cost effective slip casting technique. YSZ reported to be ceramic material having good toughness properties (Cesari et al., 2006) than pure alumina, therefore making a composite with alumina leads to a more durable ceramic material for many applications. The other reason for these selected materials was to produce a novel metal alloy-ceramic composite joining by friction welding technique, which also provides a new data analysis system for future researchers.

Friction welding is a solid state joining that produces a bond under the compressive force of one rotating workpiece to another stationary workpiece (Akbarimousavi and GohariKia, 2011). Heat is generated at the weld interface during friction welding because of the continuous rubbing of contact surfaces, which, subsequently results in softening of the metal. Eventually, the material at the interface starts to flow plastically and forms an upset (Mousavi and Kelishami, 2008). When certain amount of forging had occurred, the rotation stops and the compressive force is maintained or slightly increased to consolidate the weld. Some of the important operational parameters in friction welding are friction time, friction pressure and rotation speed (Özdemir et al., 2007).

In this process, the base dissimilar materials are contacted with a rotation and an applied load so that frictional heat evolves at the interface. After the adequate increase of temperature, an upset stress is additionally applied to obtain the sound joint (Ueji et al., 2013). The heat of welding originates from direct conversion of the mechanical energy of the moving parts to thermal energy and strain energy. The application of an axial force maintains an intimate contact of the parts and causes plastic deformation of the material near the interface during welding (Sathiya et al., 2007). More than 90% of the energy consumed in plastic deformation is transformed into heat, although a small fraction of the energy is stored in the material as strain energy (Kapoor and Nemat-Nasser, 1998). Plastic deformation raises the internally stored energy in the material, mostly due to the creation and rearrangement of dislocations (Hallberg et al., 2010). Grain boundaries pose obstacles to dislocate motion and dislocation accumulation will take place at the grain boundaries, contributing to the macroscopic deformation hardening of the material (Gil Sevillano and Aernoudt, 1987).

Plastic deformation is related to the movement of defects of the atomic lattice (e.g. dislocations), which results in slipping of atoms on favoured planes of the crystal. Hence, the dislocation movement has to be hindered to allow high yield strengths (Schempp, 2013). This can be achieved by many small and hard precipitates (precipitation hardening) or grain boundaries (grain size hardening): the smaller the grains, the more grain boundary area forms a barrier against the propagation of slipping from one to another grain. Furthermore, the dislocations repel each other and each dislocation needs a certain amount of energy to start moving, from which it follows that a high dislocation density also increases the yield stress. This strain hardening mechanism is applied to cold working of metals. In addition, a high dislocation density allows a higher degree of plastic deformation and provides a further important advantage: high ductility. It is known that an increase in dislocation density can also be achieved with grain refinement during plastic deformation (solid state grain refinement) (Qiao et al., 2012).

Polycrystalline ceramics are usually considered to be completely brittle at low temperature and to exhibit permanent deformation before failure only at elevated temperatures. This view is correct in an engineering sense for practical purposes, although considerable plastic deformation is possible in individual ceramic single crystals depending on the ceramic involved and the stress system. The lack of significant plasticity in polycrystalline ceramics is the result of limitations on the number of slip systems leading to a yield strength much higher than the fracture strength (Wachtman et al., 2009).

X-ray diffraction peak profile analysis is a well-established technique for the determination of microstructure in terms of dislocation density and crystallite size in crystalline materials (Woo et al., 2008). The X-ray diffraction line profiles are broadened due to the smallness of crystallites and the lattice distortions. The two effects can be separated on the basis of the different diffraction-order dependence of peak broadening. Williamson-Hall peak analysis method suggests that diffraction peak profiles are broaden when crystallite sizes are small or if the crystal lattice is distorted by lattice defects, especially by dislocations (David, 2006). The size and strain effects on the diffraction peak broadening can be evaluated separately on the basis of their different $h\,k\,l$ dependencies (Ungár and Borbély, 1996; Ungár et al., 1999; Woo et al., 2010). Consequently, better understanding of the grain structure of friction welding, i.e., detailed information on the dislocation density and crystallite size, is necessary since the grain structure can significantly affect the plastic deformation behavior such as strain hardening rate and hardening capacity of the friction welding (Woo et al., 2008). The quantitative analysis of the grain structure in terms of the dislocation density and crystallite size in the metal - ceramic joining is not available in the literature to date.

The objective of the present research was to conduct OM, FESEM, microhardness and XRD for the different experimental parameters used in the joining between the AA6061 alloy and alumina – YSZ composite. The analysis of the aluminum alloy surface after bending test was