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FABRICATION OF Al/Al_2O_3 FGM ROTATING DISC

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ABSTRACT

This study presents a method of fabricating a disc made of Al/Al_2O_3 functionally graded materials (FGM), using a powder metallurgy manufacturing process. The aim is to develop a processing method for a rotating disc made of FGM, by stacking the slurry, layer by layer in a radial direction. A three-layer functionally graded material of Al/Al_2O_3 is fabricated with compositions of 10, 20, 30 vol.% Al_2O_3. The ceramic composition increases from the discs inner (centre) to the outer. The combination of these materials can offer the ability to withstand high temperature conditions whilst maintaining strength in extreme environments.

Keywords: Functionally graded materials, aluminium, alumina, rotating disc

INTRODUCTION

Research on new material concepts to meet the requirements of extreme environments has received worldwide attention in this challenging era. Conventional materials that have been developed may face failure under severe paradigm (Zhu et al., 2001); therefore, materials with unique characteristics need to be derived. Functionally graded materials (FGMs) have been introduced and defined in various aspects (Koizumi, 1997; Kawasaki and Watanabe, 1997; Song et al., 2007; Sun et al., 2008). Feng et al. (2005) defined FGM as a composite material consisting of two or more phases in which the volume fractions of the constituents change, so that the composition, microstructure and properties vary gradually along one direction. The novel concept of FGM is essential in many fields, including: aerospace, automotive, medical, electronic industry, energy industry, etc.

A rotating disc is an essential component in many engineering applications, such as: turbine rotors, gears, internal combustion engines, turbojet engines, ship propellers, etc. In some applications, there is a possibility that external heat transmits to the shaft and from it to the bearings, causing adverse effects on its function and efficiency (Bayat et al., 2008). Normally, rotating discs are fabricated using a single metal or alloy. However, some components cannot withstand extreme mechanical loadings. Furthermore, for some specific applications, such as in high temperature environments, the components have a tendency to fail and cause the discs to crack. Therefore, the concept of an FGM rotating disc, along with a method of its production, was necessary in order to meet this functional performance requirement.

A number of FGM production methods, such as combustion synthesis (Cirakoglu et al., 2002), electrophoretic deposition (Put et al., 2001), centrifugal methods (Watanabe et al., 2006), plasma spraying, laser cladding and powder metallurgy (Zhu et al., 2001) have been successfully developed and reported in recent publications. Among these, the method of powder metallurgy is one of the most viable routes for FGM, in which the composition and microstructure variations, as well as shape forming, can be easily controlled for a wide range of applications (Kawasaki and Watanabe, 1997, Jin et al., 2005). Researchers have developed a variety of material combinations by using powder metallurgy techniques to fabricate FGM products. Some examples include: ZrO_2-NiCr FGMs (Zhu et al., 2001), Al_2O_3-Al_2TiO_5 FGMs (Low et al., 2006; Low and Oo, 2008), Al-Al_2O_3 FGMs (Tao et al., 2001), Al-SiC FGMs (Bhattacharyya et al., 2008), p-$Pb_{1-x}Sn_xTe$ FGMs (Gelbstein et al., 2007). This study presents an FGM rotating disc made by combining Al and Al_2O_3 powders.

PROCESSING METHOD

This section details the fabrication of the FGM rotating disc using the method of powder metallurgy. The development of the manufacturing process begins with the stage of designing the rotating disc and continues up to the characterisation of samples by scanning electron microscopy (SEM). Figure 1 illustrates a flow chart of the proposed fabrication process of the FGM rotating disc.

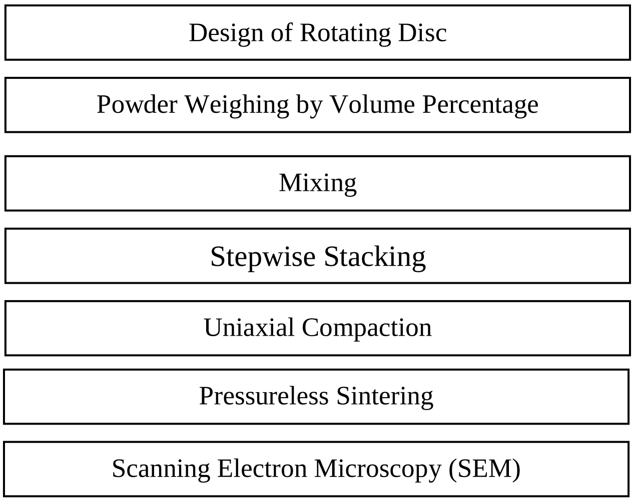

Figure 1. Fabrication process step of FGM rotating disc.

Design Concept of Rotating Disc

The disc is designed in three circular layers each with a different compositional ratio determined by volume percentage, as shown in Figure 2. The three layers form rings with proportions consisting of 90, 80, 70 vol.% Al from the inner (centre) to the outer of the disc. Al powder (99.7% purity, particle size: 63μm) and Al_2O_3 powder (99.7% purity, particle size: 0.7μm) were used as the starting materials. The disc is designed to have a 42 mm diameter for the first layer, 83 mm for the second and 103 mm for the third with all layers 10 mm in depth.

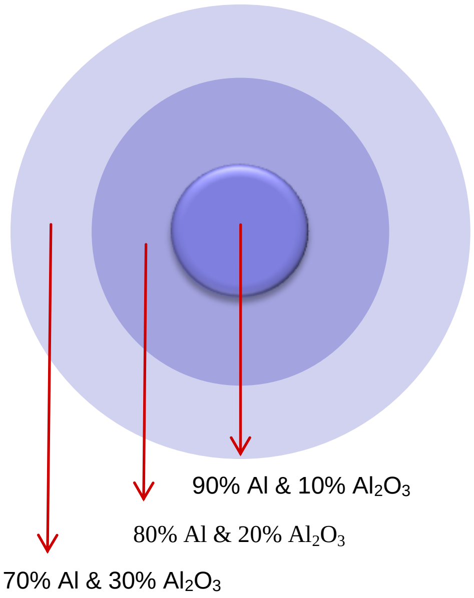

Figure 2. A schematic of layer arrangement and composition.

Mixing Process

The starting powders were mixed in different ratios by using a VT-V Powder Mixer. A special bottle was filled and mixed mechanically in order to facilitate a uniform distribution of the Al/Al_2O_3 powder particles. The mixing was performed with a speed of rotation of 100 rpm for a minimum of 1 hr.

Stacking Process

The inner die, made of material 718, was sprayed with heavy-duty silicone lubricant to ease the discharging process of green compact. A few marks were made on the surface of the bottom base by following the diameter of the two aluminium thin-walled cylinders. The diameters of the cylinder reflect the diameters of layers 1 and 2, which are 42 and 83 mm, respectively. The two cylinders were positioned on the marked points and four pins were used to ensure the cylinders did not move during the stacking of the slurry. The mixtures were sequentially stacked in the die, layer by layer, in a radial direction starting from layer 3 to layer 1. To maintain the correct compositional distribution and to level the height of the mixture among the three layers in the die, a cylindrical rod is used to tap mixtures with low pressure. After levelling the layers, the stacking powders were closed with the top base and the punch. This process is presented schematically in Figure 4.

Figure 3. Stacking powders mixture into die.

Compaction

After the stacking process, the mixed powders were pressed into shapes in the die. The compacted product is called the green component. The purpose of this step is to obtain the required shape, density and particle-to-particle contact, as well as to make the part sufficiently strong. The equipment used was a manual press gang Coleman machine and the pressure exerted on the stacked powders was 44.8 MPa with a holding time of 1 hr.

Sintering Process

The green component was heated in a furnace at a temperature slightly below the lower melting point of the two materials. For the present disc, the melting point of Aluminium (660 °C) is lower than that of alumina (1600 °C). Therefore, the discs must not be heated above 660 °C. The actual temperature used was 640 °C with a holding time of 2 hrs. The heating rate was 5deg/min, taking 2 hrs 8 mins to reach the highest temperature. Then, the product is cooled to room temperature.

RESULTS AND DISCUSSION

The successfully fabricated green component of FGM is shown in Figure 4. It can be seen that the clear circular shape boundary exists on the surface of the rotating disc that divides the region of the ring portion. The bonding of the materials appears to be sound and it can hold its structure perfectly, even when lifted roughly in this state. This confirms that the final product (after sintering) is able to withstand the high stress of centrifugal forces during operation, without breaking at the interlayer of the materials.

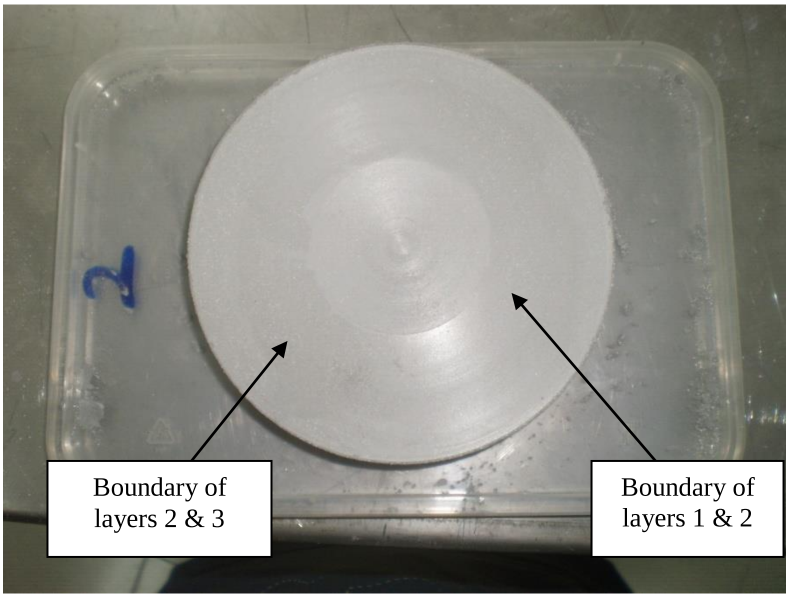

Figure 4. Green compact of rotating disc.

After sintering, the circular shaped boundary can still be clearly seen (Figure 5). This shows that the sintered FGM disc has layers with different compositions arranged in a radial direction. Due to the variation of the composition, the sintered FGM disc experiences very different shrinkage between the adjacent layers during densification, which will remarkably affect its green forming and sintering process (Zhu et al., 2001). During cold compaction, defect formation, such as small cracks and large residual porosity occurred. It is impossible to completely eliminated the porosities, because voids remain after compaction (Kalpakjian and Schmid, 2001). In addition, sintering imbalance occurs in powder compacts with different mixing ratios of metal and ceramics. Consequently, this problem will cause various faults in the sintered disc, such as warping, frustum formation, splitting and cracking (Kawasaki and Watanabe, 1997). Thus, control of a few parameters or processing conditions is necessary in order to produce perfect FGM products; these are optimising the sintering temperature, compaction pressure and the particle size of the raw powders (Jingchuan et al., 2001).

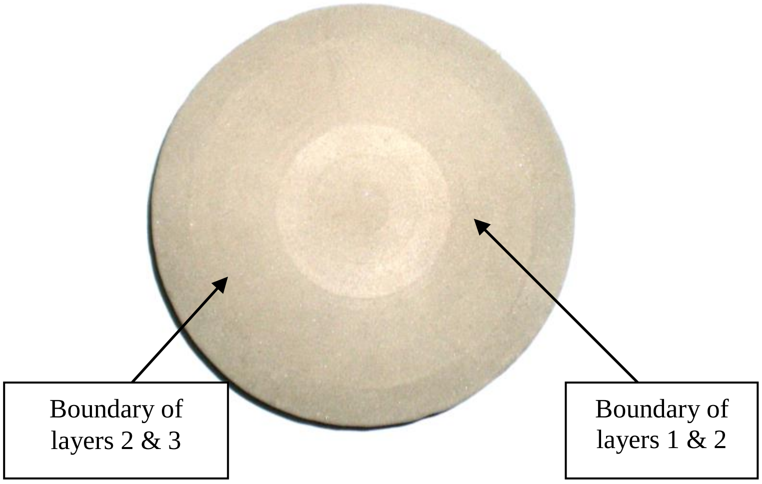

Figure 5. Final product after sintering.

The study of densification of the sintered FGM disc has been conducted using the water-immersion technique. The density of the Al/Al$_2$O$_3$ FGM disc increases with an increase of the Al$_2$O$_3$ content, which changes gradually from 2.437×10^3 kg/m^3 to 2.6978×10^3 kg/m^3 from the inner to the outer of the rotating disc, as shown in Figure 6. However, the real density value of the Al/Al$_2$O$_3$ FGM disc was 2.599×10^3 kg/m^3. The results show that the trend of density increase when the Al$_2$O$_3$ content increases, acts in accordance with the findings of Deng et al. (1995) but the value obtained is lower (Tao et al., 2001).

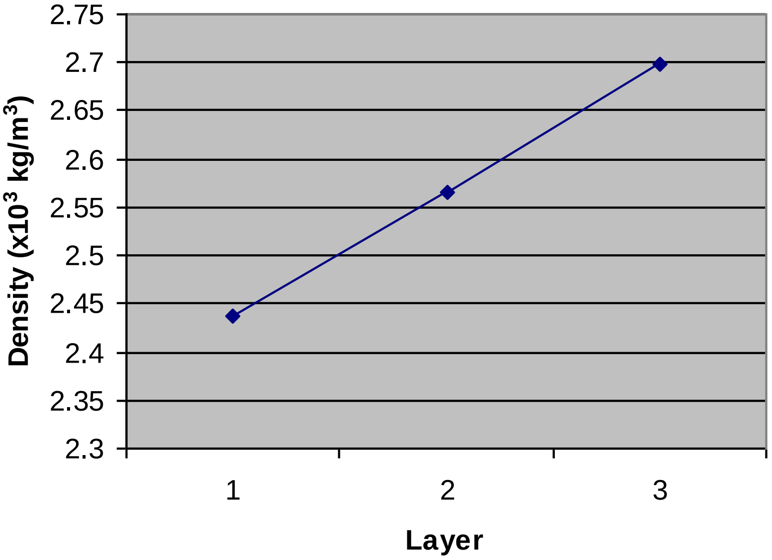

Figure 6. Density of each layer in sintered FGM disc.

In order to obtain the highest density in each layer of the Al/Al$_2$O$_3$ FGM disc, pressure sintering, such as hot-pressing or hot isostatic pressing, may be a more effective method to use, as these processes can enhance the densification of the metal/ceramic FGM, as well as reduce unavoidable porosity. Nevertheless, this work is just the beginning in Malaysia and improvements will guarantee the ability to triumph in the future.

CONCLUSIONS

The Al/Al_2O_3 system of functionally graded materials (FGMs) with various Al_2O_3 fractions has been successfully fabricated by using a powder metallurgy process. A three-layer functionally graded material of Al/Al_2O_3 was fabricated using Al and Al_2O_3 powders, in compositions of 10, 20, 30 vol. % Al_2O_3. A method of fabrication of FGM rotating discs with layers, arranged layer by layer along a radial direction from the inner of the disc (centre) to the outer, was developed and can be applied in producing other FGM-based products.

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