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CERAMICS-METAL FUNCTIONALLY GRADED MATERIALS FOR ADVANCED APPLICATIONS

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ABSTRACT

In the present work, ceramics-metal functionally graded materials (FGM) with improved mechanical properties compared to monolithic materials was designed and fabricated using powder metallurgy approach. The microstructure of the FGM has shown uniform transition of the two materials system. Mechanical properties of the FGM such as fracture energy and flexural strength were characterized. Toughening effect of the layered system was also studied and crack deflection mechanism is reckoned to be the operating mechanism for enhanced mechanical properties. The experimental studies are also shown to be consistent with the experimental findings. It is hence shown that FGM could provide a superior material system for many advanced applications.

KEYWORDS

FGM, fracture energy, crack deflection

INTRODUCTION

Functionally graded materials (FGMs) provide a combination of properties and have attracted huge attention in many advanced applications. The characteristic of FGMs lies in their continuously varying compositions or volume fractions of the constituent materials built in a layered form, hence providing optimum thermal and mechanical properties without discrete interface within the component. FGMs have also found their potential applications in many areas including structural [1-4] and biomedical applications [5-7].

A number of techniques have been reported in the literature on the fabrication of FGMs [8-11]. It is, however, reported that powder metallurgy method is the most commonly employed technique due to its flexibility in compositional and microstructural control [12]. In the present work, Alumina-Iron (Al_2O_3-Fe) system is fabricated using the powder metallurgy route, where Fe is the pure metal layer at one end and 100% Al_2O_3 is the full

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ceramic layer at the other end, with mixed composition in-between the two faces. The intermediate mixture layers, other than providing a smooth transition in microstructure, could also provide toughness enhancement effect via crack deflection toughening mechanisms in the system when a difference in fracture energy is present between the adjacent layers [13-15].

EXPERIMENTAL PROCEDURE

The materials used were 99.99% pure alumina powders (AKP30 Sumitomo Chemical, Japan) with average size of 0.3 μm, and 99.5% pure Iron powder (Aldrich Chemical Company, Inc., USA) with average size of 5 μm.

The FGM includes totally of 5 layers. In addition to the metallic Fe and ceramic alumina layers at the two ends, the intermediate structure consists of 3 layers with different ratios of the two constituent materials, i.e., 70wt%Fe-30wt% Al_2O_3, 50wt%Fe-50wt% Al_2O_3, and 30wt%Fe-70wt% Al_2O_3, respectively. The layers are termed as Layer 1 to Layer 5 from pure metal end to pure ceramic end in the present work as shown in Table 1.

During processing, the raw powders were first weighed according to the ratio designed. Mixing was done by milling using a planetary ball miller (Restch, USA) with agate balls and isopropanol as solvent. The ball : powder : isopropanol weight ratio was 1 : 1 : 0.5 and the rotation speed was set at 130 rpm. After milling, the slurry was transferred onto a plastic tray to be air dried for 48 hours.

The powders were sieved using a 250 micron steel mesh to remove any agglomerates. During the stacking of the layers, the respective compositional powders were filled in sequence into a 50 mm graphite die. A pressure of 20 MPa was used to compact the powder layers into the initial form. The layered compact obtained was then subjected to hot pressing in a hot press furnace (Centorr, USA) at 1373 K and 40 MPa for 210 minutes. The heating and cooling rates were both maintained at 17 ^{o}C/min.

After hot pressing, the component was cut using a diamond cutter (Microactive USA) to reveal the cross-sectional view of the sample. Metallographic examination of the sample was carried out using a SEM (JSM-5310, JEOL, Japan). The samples were finally cut into 3 × 3 × 45 mm rectangular bars to investigate the fracture properties using 3-point bend test.

RESULTS AND DISCUSSIONS

Figure 1 shows the cross-sectional SEM image of the FGM component. It can be seen that the microstructure of the system gradually transits from Al_2O_3 to Fe. The interface between the layers are continuous and without any delamination. It is noted that a good integration between the layers has been achieved.

Table 2 shows the fracture toughness of the FGM fabricated measured using 3-point bending test, and its comparison to that of pure alumina. The standard 3-point bending test (ASTM E 855) was used in this work. The size of the sample is not standard because of their small size. The length of support span is 20mm.

It can be seen that the FGM system has demonstrated tremendous improvement in fracture toughness compared with the pure alumina material. The enhancement of toughness in FGM is mainly due to its combination of properties. Not only it combines the properties of both Fe metal and Al_2O_3 ceramics, the variation of properties in the system has also contributed to the toughness improvement by crack deflection.

Figure 2 shows the crack propagation path in the FGM system during the bending test. It is worth noting that the failure crack was deflected between the full ceramics layer and its adjacent layer.

Theories proposed in the literature have indicated that the most important parameter that affects the crack deflection ability is the fracture energy difference between the adjacent layers [16, 17]. He et al. [18] have shown that when the ratio of the interfacial energy R_x, to that of the adjacent layer, R_{x+1}, is less than 0.64, crack deflection could occur. Ma et al. [19] have also verified this with their experimental work using $Ti\text{-}TiB_2$ FGM systems. To investigate into the above discussed theories, monolithic samples of the individual compositional layers in the FGM were formed using the same fabrication procedure described earlier. The fracture energies of these samples were then measured and it is found that the ratio of these adjacent layers was 0.38, and hence crack deflection was strongly favored to occur when the crack was propagating from the full ceramics layer to the next layer.

CONCLUSIONS

Al_2O_3-Fe FGM sample was successfully fabricated by powder metallurgy route. A smooth transition was achieved and toughness enhancement effect was shown to be able possible via crack deflection toughening mechanism. The crack deflection mechanism was also verified with the theoretical predictions proposed in the literature.

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Table 1

100%wtAl2O3 , t=1.36mm
30wt%Fe-70%wtAl2O3 , t=0.91mm
50wt%Fe-50%wtAl2O3 , t=0.80mm
70wt%Fe-30wt%Al2O3 , t=0.80mm
100wt%Fe , t=0.68mm

Table 2

	FGM	**Pure alumina**
Fracture work (J/M^2)	**1,900.0**	**62.0 [19]**

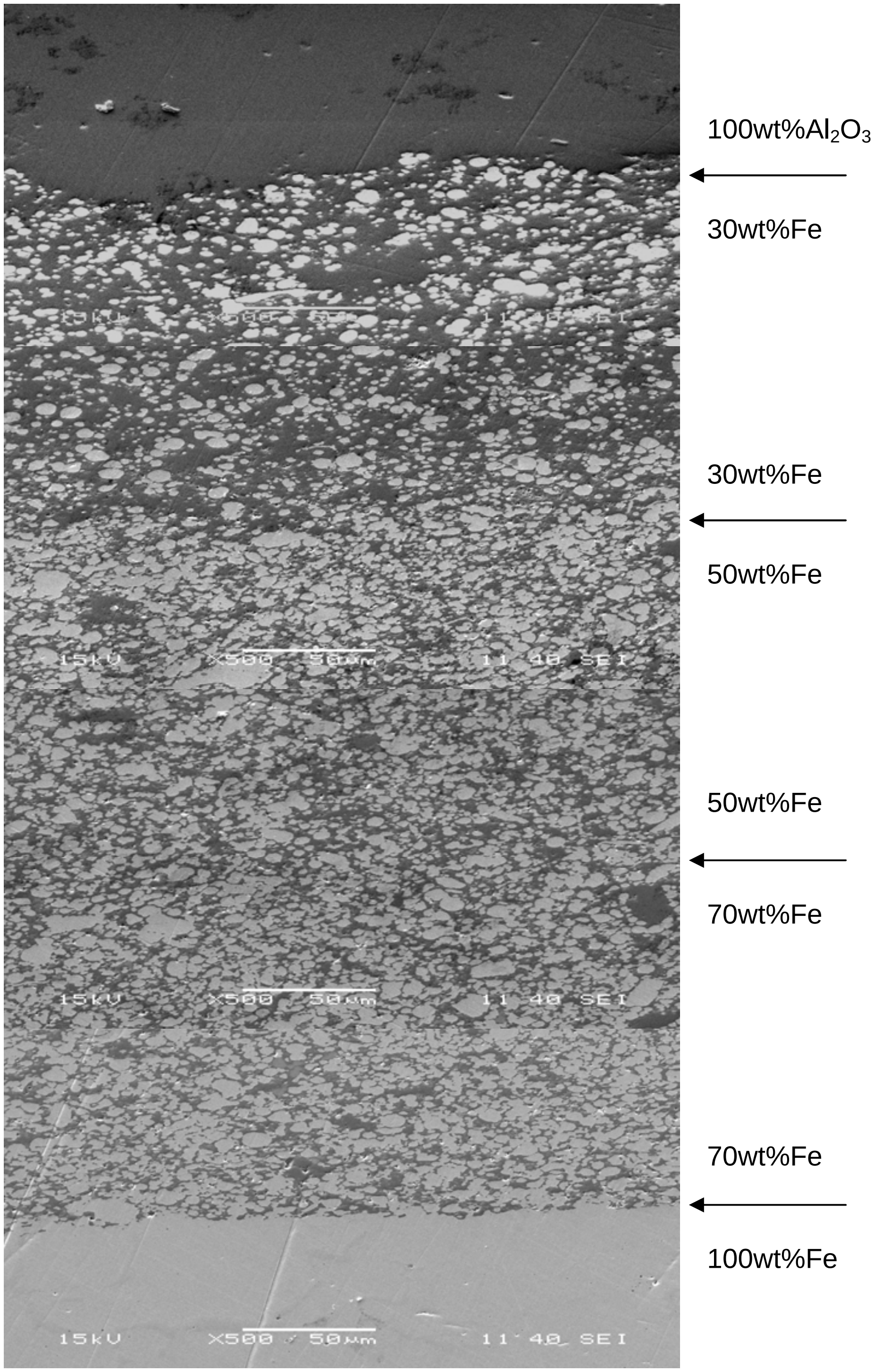
100wt%Al_2O_3
30wt%Fe
30wt%Fe
50wt%Fe
50wt%Fe
70wt%Fe
70wt%Fe
100wt%Fe

Fig.1

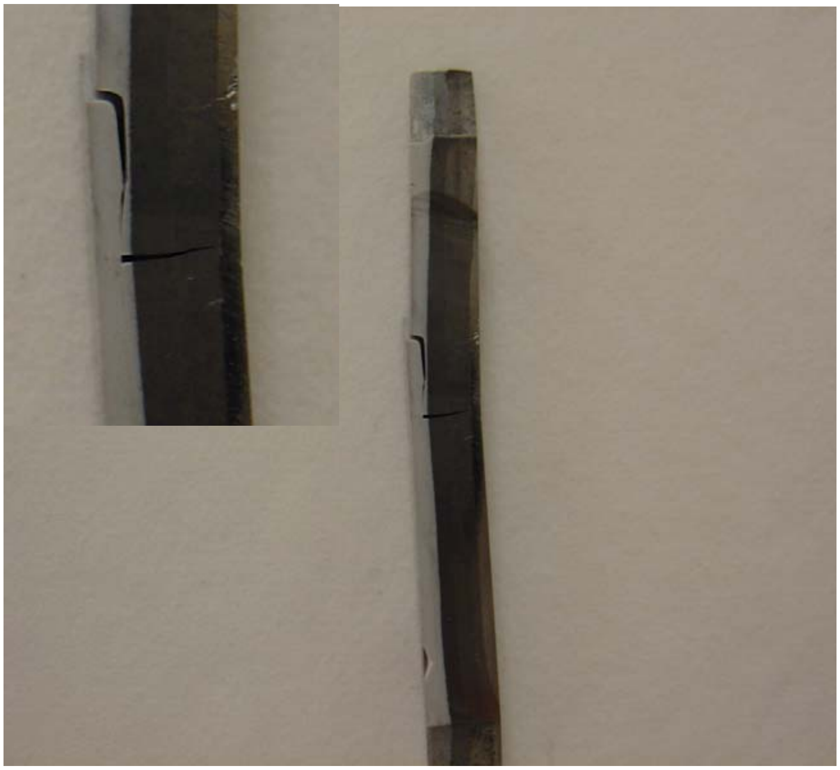

Fig. 2 (X 1.88)