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Influence of microstructure on fracture toughness distribution in ceramic–metal functionally graded materials

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ABSTRACT

This paper deals with the influence of microstructure on fracture toughness distribution in functionally graded materials (FGMs) consisting of partially stabilized zirconia (PSZ) and austenitic stainless steel SUS 304. FGMs and non-graded composites (non-FGMs) with fine and coarse microstructures are fabricated by powder metallurgy using PSZ and two kinds of SUS 304 powders. The fracture toughness is determined by conventional tests for several non-FGMs with each material composition and by a method utilizing stable crack growth in FGMs. The obtained results on the fracture toughness are as follows: (1) The fracture toughness increases with an increase in a content of SUS 304 on both FGMs and non-FGMs. (2) On the fracture toughness of the non-FGMs, the influence of microstructure is negligible. (3) On the FGMs, the fracture toughness is higher in the FGM with fine microstructure than in the FGM with coarse microstructure. (4) The fracture toughness of the FGMs is higher than that of the non-FGMs especially in the case of fine microstructure. Finally, the residual stress in the FGMs created in a fabrication process is estimated from the difference in fracture toughness between the FGMs and non-FGMs.

1. Introduction

Functionally graded materials (FGMs) are well known as materials in which a material composition varies gradually in some direction to derive the unique mechanical, thermal and electrical performances different from those of homogeneous or joined dissimilar materials. FGMs consisting of ceramics and metals, for example, can be designed to reduce thermal stress and to take advantages of the heat and corrosion resistance of ceramics and the mechanical strength of metals. Therefore, ceramic–metal FGMs are promising in thermal and structural applications such as thermal barrier coatings, wear and corrosion resistant coatings, ceramic/metal joinings and cutting tools [1,2]. Mechanical performance of FGMs should be made clear to ensure their reliability and to extent their applications.

Ceramic–metal FGMs exhibit complicated fracture behavior due to gradation of mechanical properties and strength. In a ceramic–metal FGM plate, surface cracks emanating at the ceramic side behave in several ways depending on the material gradation and loading condition. Multiple cracks, crack arrest, crack bowing are well observed in ceramic–metal FGMs under thermal shocks or thermal fatigue [3–6]. Crack branching and spallation occurs as a result of crack growth along the interface in multi-layered FGMs [3–7]. In order to analyze the complicated fracture behavior in FGMs and to make clear fracture process and mechanical strength of FGMs, distribution of fracture toughness in FGMs should be known.

For the distribution of fracture toughness or *R*-curve behavior in FGMs, prediction methods based on the crack bridging model or cohesive model were proposed, where the metal phase in ceramic–metal FGMs plays an important role [8–11].

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Nomenclature

P	applied load on a three-point-bending specimen or concentrated force on crack surfaces of an edge crack in a rectangular plate
δ	load-point displacement of a three-point-bending specimen
K, F	mode I stress intensity factor and correction factor
σ_0	bending stress of a three-point-bending specimen
a	length of a crack in a three-point-bending specimen or an edge crack in a rectangular plate
W, B, S, L	width, thickness, span length and height of a three-point-bending specimen or a rectangular plate
b	position of concentrated forces on crack surfaces of an edge crack in a rectangular plate
x	coordinate along a crack line
α	a/W, non-dimensional crack length; x/W, non-dimensional distance from ceramic surface
β	b/a in an edge crack in a rectangular plate subjected to concentrated forces on crack surfaces.
E	Young's modulus
K_R	critical stress intensity factor (fracture toughness) of a FGM
$K_{Res}(x)$	distribution of stress intensity factor due to residual stress
$K_R^{FGM}(x)$	distribution of critical stress intensity factor (fracture toughness) in a FGM
$K_R^{Non-FGM}(x)$	distribution of critical stress intensity factor (fracture toughness) in a FGM estimated from non-FGM and graded material composition
$\sigma_{Res}(x)$	distribution of residual stress in a FGM

The experimental investigations on the fracture behavior of FGMs were relatively limited compared with the theoretical and numerical investigations. Several investigations have been reported using ultraviolet-irradiation-hardened polymer [12] or glass-particle-reinforced epoxy [13], ceramic–metal FGMs [14–19], and ceramic–ceramic FGMs [20]. In these investigations, the distribution of fracture toughness or *R*-curve behavior was discussed for a growing mode I crack parallel to the direction of material gradation [12,14–17,19,20].

In the previous report [19], a method to evaluate the distribution of fracture toughness in FGMs by stable crack growth in three-point-bending FGM specimens was proposed, and it was applied to a FGM consisting of a partially stabilized zirconia (PSZ) and stainless steel (SUS 304). The stable crack growth was realized on three-point-bending tests of the FGM specimens with a very short crack in the ceramic surface and the obtained fracture toughness increased with an increase in a volume fraction of SUS 304 phase.

In the present investigation, the distribution of fracture toughness for a growing mode I crack parallel to the direction of material gradation is evaluated on two kinds of PSZ-SUS 304 FGMs with fine and coarse microstructures. The fracture toughness is determined by conventional tests for several non-graded composites (non-FGMs) with each material composition and by a method using stable crack growth for FGMs. Based on the experimental results, influences of microstructure on the fracture toughness distribution and the relationship between fracture toughness and material composition in FGMs and non-FGMs have been discussed. Finally, the residual stress in FGMs created in a fabrication process is estimated from the difference in fracture toughness between FGMs and non-FGMs. On FGMs of PSZ–metal system, although fracture behavior and strength under thermal shock and thermal fatigue were investigated from a view point of application to thermal barrier coating [3,4], the distribution of fracture toughness was not reported except for the present authors' work [19] as far as it was traced in the literature.

2. Materials and experimental procedure

2.1. Materials

The tested materials were FGMs and non-graded composites (non-FGMs) fabricated by powder metallurgy [19]. Raw materials were commercially available partially stabilized zirconia (ZrO_2–3molY_2O_3, PSZ, manufactured by Atmix Corp.) and austenitic stainless steel (SUS 304, manufactured by KCM Corp.) powders. The mean particle sizes of powders were 0.32 μm for the PSZ and 45 μm and 10 μm for the SUS 304, respectively. The PSZ and SUS 304 powders were mixed in volume ratios of 10–0, 8–2, 6–4, 4–6, 2–8, 1–9 and 0–10, respectively, and each mixture was suspended in isopropyl alcohol, milled for three hours by a vibrational ball mill (Nissin Giken Corp.) and dried. The powder blends were put to form a non-graded composition or were layered so as to form a graded composition in a graphite die with 30 mm in diameter. The powder compacts were pressed up to 14 MPa at room temperature, and then sintered under the condition of 1200 °C and 30 MPa for one hour by a hot-press machine (Shimazu Corp.). Finally, seven kinds of non-FGMs and one FGM for each combination of powders were obtained in the form of disk with 30 mm in diameter and 6 mm in height. These materials are referred to as non-FGM(45 μm), FGM(45 μm), non-FGM(10 μm) and FGM(10 μm) by using the mean particle size of SUS 304 powders, respectively. Fig. 1 shows microstructures of the non-FGM(45 μm) and non-FGM(10 μm). The white and gray regions exhibit the SUS 304 and PSZ phases, respectively. The non-FGM(10 μm) and non-FGM(45 μm) have fine and coarse microstructures,