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Toughening alumina with nickel aluminide inclusions

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Abstract

Both ceramics and intermetallics are potential materials for high temperature applications. Recent studies indicated that the toughness of ceramics can be improved by adding intermetallics. Among the intermetallics studied, NiAl is an attracting material for its low density and high melting point. In the present study, the toughening behaviour of Al_2O_3–NiAl composites is investigated. In order to determine the contribution from the matrix and reinforcement, the composites containing 0–100 vol% NiAl are prepared by hot-pressing. The toughness of the Al_2O_3–NiAl composites is higher than the values predicted by the rule of mixtures, i.e. the contribution from only the matrix and reinforcement. The toughness enhancement is contributed by the combination of crack deflection and the plastic deformation of NiAl grains. The toughening mechanism for the Al_2O_3-rich composites is mainly crack deflection. The contribution of the plastic deformation of NiAl to toughening effect increases with increasing NiAl content. It is due to the fact that more NiAl grains are interconnected with each other as NiAl content is increased.

Keywords: Al_2O_3; Composites; Intermetallics; NiAl; Toughness and toughening

1. Introduction

The mechanical properties of ceramics can be improved by adding metallic reinforcements, such as Al,[1] Ni,[2] Ag,[3] Cu,[4] Fe,[5] NiAl[6] and Ni_3Al.[7] For example, the toughness of alumina is enhanced by 100 and 180% as 13 vol% Ni[8] and 20 vol% Al[1] are added into Al_2O_3, respectively. Among the metals investigated, NiAl and Ni_3Al are categorized as intermetallics and are the potential materials for high temperature applications. The melting point of NiAl is as high as 1640°C; furthermore, the oxidation and corrosion resistance of NiAl are superior among metals.[9] The chemical inertness of alumina may not degrade significantly as NiAl is added.

For metal-toughened ceramics, the toughening effect is either contributed by the plastic deformation of the metals[1–5,7] or by crack deflection.[5–7] The experimental studies also suggested that the toughening behavior depends strongly on the shape of the metallic reinforcements. The toughening mechanism is mainly crack deflection as the shape of metallic inclusions is particulate.[5–7] However, the plastic deformation of metals is more likely to take place in the composites containing metallic fibers,[10] boundary network[5,11] or foils.[12]

In the present study, NiAl is chosen as the reinforcement material for Al_2O_3. The elastic modulus of NiAl is lower than that of Al_2O_3 (188 GPa vs 380 GPa); however, the toughness of NiAl higher than that of Al_2O_3 (to be shown later, 14 $MPaM^{0.5}$ vs 3.7 $MPam^{0.5}$). As a crack is produced in the composite, the crack tends to propagate through the brittle phase; namely, Al_2O_3. However, the crack will be attracted by NiAl particles for their low elastic modulus. Therefore, the crack can interact with both phases in the Al_2O_3–NiAl composites. Since both phases can interact with the crack, the toughness of composite, $J_{IC,c}$, can be roughly expressed as[13]

$$J_{IC,c} = (1 - F)J_{IC,m} + FJ_{IC,r} + \Delta J_{IC} \quad (1)$$

In the above equation, $J_{IC,m}$ is the toughness of matrix, $J_{IC,r}$ the toughness of the reinforcement, ΔJ_{IC} the toughness increment that depends on the toughening mechanism involved during the fracture process, and F the volume fraction. The J_{IC} can be related to K_{IC} as

$$J_{IC,c} = (EJ_{IC})^{1/2} \quad (2)$$

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where E is the elastic modulus. To model the toughness of composite is a difficult and complicated task. Many assumptions and approximations have been made to obtain Eq. (1).[13] For the difference between the elastic modulus of Al_2O_3 and NiAl is not significant, Eq. (1) can be approximated by the following equation as

$$K_{IC,c} = (1 - F)K_{IC,m} + FK_{IC,r} + \Delta K_{IC} \quad (3)$$

Although the exact relationship between the toughness of composite and the toughness of each component may not be the same as the above equation, the above equation indicates clearly that the toughness of a tough composite contributes by every component in the component and the toughening mechanism involved. The equation can be treated as the basis for comparison.

The first two terms in Eq. (3) show the rule of mixtures. In the previous analyses on the toughening behaviour of the metal-toughened aluminas,[1–8] the toughness of the composite was assumed composing of only matrix toughness and toughness enhancement; namely,

$$\Delta K_{IC} = K_{IC,c} - K_{IC,m} \quad (4)$$

The contribution of the toughness of reinforcement itself, $K_{IC,r}$, to the overall toughness of composite is neglected. It may lead to the over-estimation of toughening effect. In the present study, monolithic Al_2O_3 and monolithic NiAl are also prepared with the same processing technique. The toughness of NiAl is poor among metals.[9] Therefore, the toughness of Al_2O_3, Al_2O_3–NiAl composites and NiAl can be determined with the same measuring technique. The toughening effects of NiAl-toughened Al_2O_3 can thus be evaluated.

2. Experimental procedures

Alumina (TM-DR, Taimei Chem. Co. Ltd., Tokyo, Japan) and various amounts of nickel aluminide (NiAl, Xform Inc., New York, USA) were milled together in ethyl alcohol with an attriator (Model 01-HD, Union Process Inc., USA) for 12 h. The rotation speed of the shaft was 300 rpm. The zirconia balls with diameter of 5 mm were used as grinding media. The particle size distribution of the as-received Al_2O_3 and NiAl powders was determined with a laser particle size analyzer (LS 230, Coulter Co., USA). After milling, the slurry was dried with a rotary evaporator. The dried lumps were crushed and passed through a plastic sieve with aperture size of 74 μm. The sintering was performed by hot pressing at 1450°C with a graphite die for 1 h. The pressure applied was 24.5 MPa. The vapour pressure during hot-pressing was kept below 5×10^{-3} torr. The dimensions of the hot pressed specimen were 50 mm in diameter and roughly 4.5 mm in thickness. The hot-pressed specimens were cut into rectangular bars with a diamond saw. The rectangular specimens were then machined longitudinally with a 44 μm grit resin-bonded diamond wheel at cutting depths of 5 μm/pass. The final dimensions of the specimens were 4×3×34 mm.

The final density was determined by the water displacement method. The phase identification was performed by X-ray powder diffractometry (XRD) with CuK_α radiation. The polished surface was prepared by grinding with diamond slurry to 6 μm and polishing with silica suspension to 0.05 μm. The microstructure was observed with SEM. The size of NiAl grains was determined with the line intercept procedure.[14] The inter-connectivity of NiAl grains in the composites was determined by measuring their electrical resistivity at room temperature. A statistical procedure[15] to determine the aspect ratio of Si_3N_4 grains in the in-situ reinforced silicon nitride was adopted in the present study to evaluate the aspect ratio of NiAl grains. The fracture toughness was determined by the single-edge-notched-beam (SENB) technique. The rate of loading was 0.5 mm/min. The notch was generated by cutting with a diamond saw. The thickness of the blade was 0.33 mm. The width of the notch was 0.4 mm.

3. Results and discussion

The particle size analysis reveals that the median size of the as-received Al_2O_3 and NiAl particles is 0.2 and 5.9 μm, respectively. The XRD analysis indicates that no phases other than α-Al_2O_3 and β-NiAl in composites are produced after hot-pressing. The relative density of the hot-pressed composites is higher than 97.8%. The microstructure of the composite containing 50 vol% NiAl is shown in Fig. 1. The size and aspect ratio of the NiAl grains in the specimens are shown in Fig. 2. The

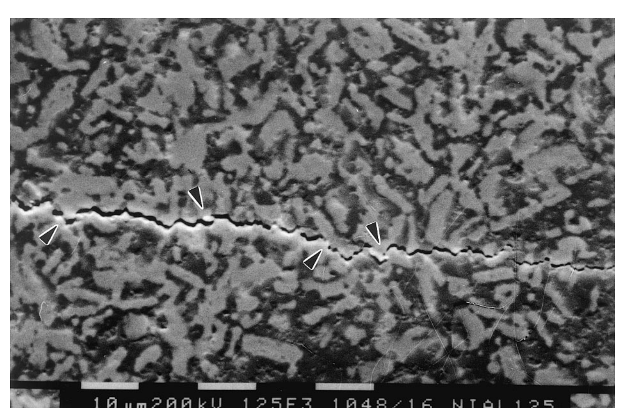

Fig. 1. The SEM micrograph of the composite containing 50 vol% NiAl. The bright phase in the micrograph is NiAl. The interactions between a crack generated by indentation and NiAl grains are also shown. Some stretched NiAl particles which locate between the crack surfaces are indicated with arrows.

shape of the as-received NiAl particles is equiaxed; however, the aspect ratio of the NiAl inclusions in Al_2O_3 matrix varies from 3 to 5.4. The aspect ratio of NiAl inclusions is longer than unity in the hot-pressed composites, it is mainly due to that compressive and shear stresses are applied on the NiAl particles by milling media during attrition milling. The NiAl particles are thus squeezed and elongated during attrition milling. The electrical resistivity of the composites is shown as a function of NiAl content in Fig. 3. It suggests that the NiAl grains are interconnected to each other as more than 20 vol% NiAl is added into alumina.

The toughness of the composites is shown as a function of NiAl content in Fig. 4. The values in the figure indicate the average values of 6–8 specimens being tested. Error bars show the maximum and minimum values measured. The straight line predicted by the rule of mixtures is also shown for comparison. The toughness of the composites is higher than the values predicted by the rule of mixtures, the contribution from only matrix and reinforcement. The toughness enhancement, ΔK_{IC} in Eq. (3), can be estimated, which is shown as a function of NiAl content in Fig. 5.

Previous studies on the ceramic/metal composites showed that the toughening mechanisms are either crack deflection or crack bridging.[1–8] The interactions between a crack and NiAl inclusions are shown in Fig. 1. The crack is either deflected or bridged by NiAl grains. The interface between Al_2O_3 and NiAl is weak.[6] The crack can thus be deflected from the weak interface. The toughness is enhanced as crack deflection takes place.[16] The contribution from crack deflection to toughness enhancement depends strongly on the aspect ratio of inclusions. The toughness enhancement for the composite containing inclusions with the aspect ratio shown in Fig. 2 as predicted by Faber and Evans[16] is shown in Fig. 6. The values for the physical properties, such as elastic modulus and Poisson's ratio, of Al_2O_3 and NiAl are used to calculate the values of toughness enhancement.[2,9] The model predicts that the toughness is increased rapidly as a small amount of inclusion is added. As the volume fraction is higher than 0.2, the toughening increment becomes relatively invariant. However, the toughness enhancement for the Al_2O_3–NiAl composites increases with the increase of NiAl content, Fig. 5. Furthermore, the toughness increase of

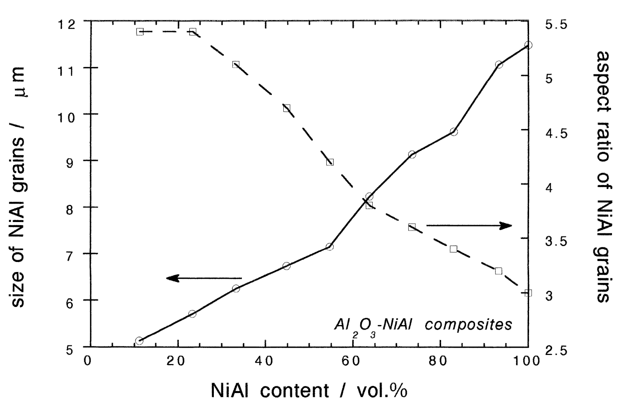

Fig. 2. The size and aspect ratio of NiAl grains as a function of NiAl content.

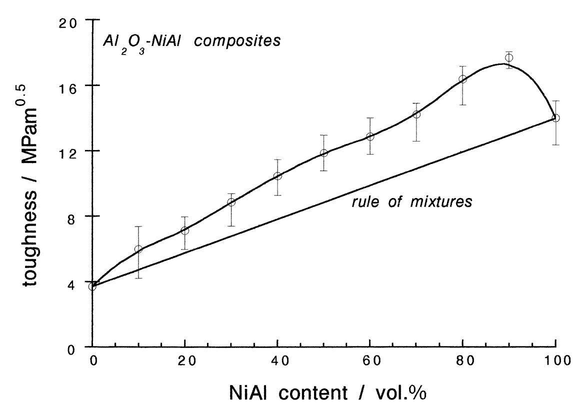

Fig. 4. The fracture toughness of the Al_2O_3–NiAl composites as a function of NiAl content.

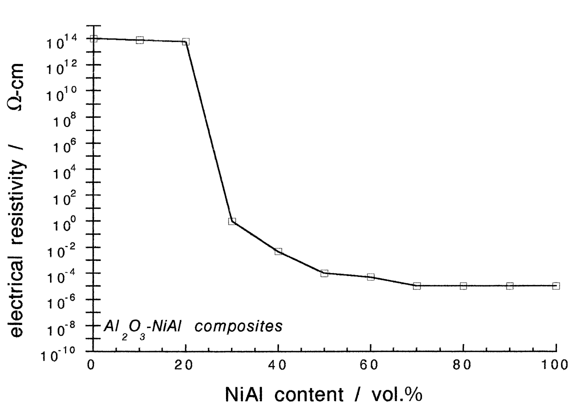

Fig. 3. The electrical resistivity of Al_2O_3–NiAl composites as a function of NiAl content.

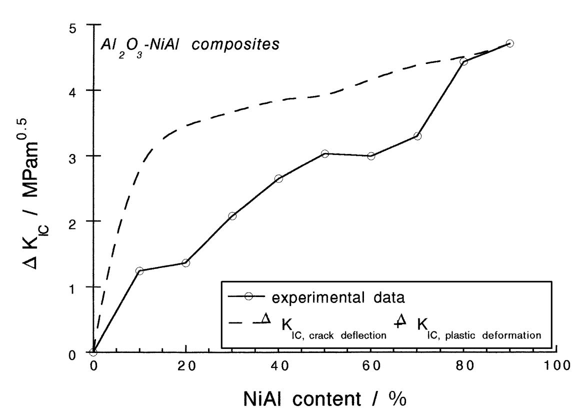

Fig. 5. The toughness enhancement of the Al_2O_3–NiAl composites as a function of NiAl content. The values predicted by adding the contribution from crack deflection and plastic deformation are also shown for comparison.

the composites containing more than 30 vol% NiAl is higher than the values predicted by the prediction solely from crack deflection, Fig. 5 vs Fig. 6. As the NiAl content is higher than 30 vol%, NiAl particles are interconnected to each other, Fig. 3. Despite the weak interface, the crack has to stretch the interconnected NiAl grains to open up the crack surfaces. The contribution of the plastic deformation of NiAl grains to the toughness enhancement, thus, increases with increasing interconnected NiAl grains.

When the toughness increment is resulted from the plastic deformation of the ductile phase, the toughness enhancement is proportional to the square root of the product of volume fraction, F, and the size of inclusion, d, as[17]

$$\Delta K_{\mathrm{IC}} = c(Fd)^{0.5} \tag{5}$$

In the above equation, c is a constant that depends on the physical properties of the ductile phase and the interfacial characteristics.[2,17] Since the value of c in Eq. (5) is not known, it assumes that the crack deflection and plastic deformation mechanisms are independent from each other, the contributions from two mechanisms can thus be added together. In order to compare the experimental results with the theoretical prediction, we force the experimental results to match the theoretical prediction on the composite containing 90% NiAl. The toughness increment of the composite containing 90 vol% NiAl is 4.7 $\mathrm{MPam}^{0.5}$. Since 2.1 $\mathrm{MPam}^{0.5}$ is contributed by the crack deflection, Fig. 6, the contribution from the plastic deformation is 2.6 $\mathrm{MPam}^{0.5}$. The value of c in Eq. (5) can, thus, be determined. The values for the composites containing other NiAl content are determined by using the same value of c. The contribution from the crack deflection, crack bridging and the additive of the two toughening contributions is shown in Fig. 6. For the composites containing a small amount of NiAl, the toughness enhancement is mainly contributed by the crack deflection. The contribution of the plastic deformation is increased with the increase of NiAl content. It can relate to the increase of interconnected NiAl grains. The predicted values are also shown in Fig. 5 for comparison purpose. The experimental values are slightly lower than the theoretical prediction. It may be due to the fact that only part of the inclusions react actively to the propagating cracks.

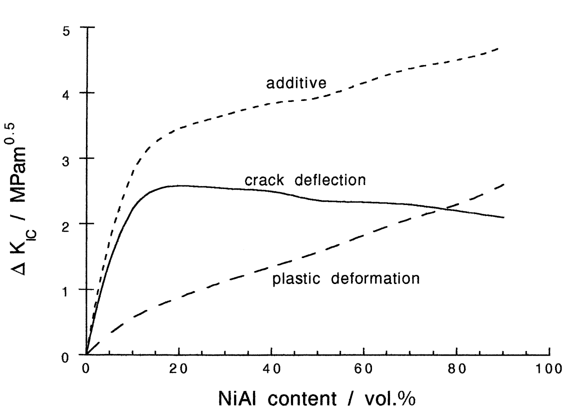

Fig. 6. The predicted values for the toughness enhancement contributed by crack deflection or plastic deformation. The additive of the two toughening increments is also shown. To estimate the toughening increment contributed by the crack deflection, 0.22 is used as the Poisson's ratio for alumina[2] and NiAl.

4. Conclusions and implications

The microstructures of Al_2O_3–NiAl composites are carefully analyzed in the present study. The elongated NiAl particles are produced after attrition milling. As NiAl content is small, NiAl grains are separated from each other. Due to the Al_2O_3–NiAl interface being weak, the crack mainly propagates along the interface. The toughening effect is mainly contributed by the crack deflection. As NiAl grains are interconnected to each other, the crack surfaces can be bridged by the interconnected NiAl grains. The contribution from the plastic deformation thus increases with the increase of NiAl content.

Several assumptions are made in the present study to simplify the complexity involved in the analysis of toughening behaviour of composites. However, the analysis sheds light on the principle for the microstructure design of ceramic/metal composites. The analysis indicates that the toughness the ceramic can be improved by adding the metallic inclusions above a threshold content. As the metallic inclusions are interconnected to each other, the crack surfaces can be bridged by the metallic particles even for the composites with weak interface. The toughness of the composites can, thus, be enhanced significantly.

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