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Fracture morphology and mechanism of a directionally solidified Al_2O_3/$Y_3Al_5O_{12}$ eutectic single crystal

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ABSTRACT

The strength and fracture behavior of a directionally solidified Al_2O_3/$Y_3Al_5O_{12}$ eutectic single-crystal were investigated. To identify and classify the toughening mechanism, fractography of the single-crystal was thoroughly analyzed. It was observed that the interfaces between Al_2O_3 and $Y_3Al_5O_{12}$, which hindered the crack propagation, and nm-sized (111) cleavage planes appearing along the tearing ridge of $Y_3Al_5O_{12}$ markedly improved the Al_2O_3/$Y_3Al_5O_{12}$ eutectic single-crystal toughness. These results could improve understanding of the microstructure design and deformation mechanism of the Al_2O_3/$Y_3Al_5O_{12}$ eutectic crystal.

With a high melting point and excellent high-temperature flexural strength, the directionally solidified Al_2O_3/$Y_3Al_5O_{12}$ (YAG) eutectic crystal has received considerable attentions as one of the most promising structural materials in a new generation of gas turbines operating at 1700 °C [1–3]. However, the applications of the Al_2O_3/YAG eutectic crystal have been limited by its poor ductility [1]. Therefore, it is important to improve the toughness of Al_2O_3/YAG eutectic crystals for use in turbine blades in future aerospace engines and thermal power generation systems. A better understanding of the fracture behavior and crack propagation mechanism in the Al_2O_3/YAG eutectic single-crystal (SX) is scientifically and technologically meaningful.

The directionally solidified Al_2O_3/YAG eutectic crystal has better high-temperature strength retention [4] and creep resistance properties than the SX of the YAG, *c*-axis sapphire and *a*-oriented sapphire because of the interfaces in Al_2O_3/YAG, which block dislocation motion [5]. Additionally, the directionally solidified Al_2O_3/YAG eutectic crystal has higher toughness than either of the constituent materials [6,7], which may be attributed to the interaction between cracks and heterogeneous phase boundaries. Perriere [8] and Song [9] reported that cracks are deflected (rather than penetrated) at the interfaces because of fluctuating residual stress. By contrast, Pastor [10] reported that cracks were straight and did not deflect at the interfaces because of the strong interfacial bonding. Nevertheless, no definitive conclusions have been reached about crack propagation at the interface. The interfacial structure of the Al_2O_3/YAG SX has been reported to be semi-coherent and to have an unusually low strain energy (the misfit is −0.57%) [11].

In this study, we successfully characterized the cleavage plane of the YAG. A series of nanosized cleavage planes are found in the tearing ridge of the YAG. These findings are expected to provide a strong scientific foundation for the future design of an Al_2O_3/YAG eutectic SX with high toughness and presents reliable results for the relationship between the crystallography and mechanics of the directionally solidified Al_2O_3/YAG eutectic SX.

Al_2O_3 and Y_2O_3 powders were mixed and ball milled for 6 h at a mole ratio of 79: 21 according to the eutectic point in the binary phase diagram [12]. Precursors were prepared with a pressure of 40 MPa for 5 min and cold isostatic pressure at 280 MPa for 30 min. Next, the precursors, which were used as the feed bar, were sintered at 1823 K for 2 h. Directional solidification was performed using an optical floating zone (OFZ) furnace with four 3-kW xenon arc lamps as radiation sources in an argon atmosphere with slight overpressure (~1.2 bars). An Al_2O_3/YAG eutectic SX with [110] YAG || $[10\bar{1}0]$ Al_2O_3 and $(2\bar{1}1)$ YAG || (0003) Al_2O_3, which was prepared in previous studies [11,13] was used as the seed crystal. The directional solidification was started with a withdraw rate of 20 mm/h after soaking the liquid ceramic

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Table 1
Fracture toughness of the directionally solidified Al_2O_3/YAG eutectic crystal.

K_{IC} ($MPa \cdot m^{1/2}$)	H_V (GPa)	Reference
5.9 ± 0.3	13.5	Present study
5–6	/	[3]
2–2.5	14–16	[10]
3.6 ± 0.4	17.5 ± 2.0	[7]
2.0	16	[15]
2.0/2.4	/	[16]
2–4	/	RT*-2000K [6]

RT*: room temperature.

zone for 1 min. The as-grown single crystals are approximately ~9 mm in diameter and ~120 mm in length.

The Al_2O_3/YAG eutectic SXs were sectioned perpendicular or parallel to the growth direction by a fixed diamond endless wire saw. The samples were carefully ground with SiC paper until 2000#; then, they were progressively polished down to 2.5-μm diamond paste.

The Vickers hardness (H_V) was measured at a load of 30 N and a dwell time of 15 s. Three-point bending specimens with dimensions of 3 mm × 4 mm × 36 mm were used for the flexural strength measurement. The span is 30 mm, and the crosshead speed is 0.5 mm/min. A series of samples cut from the same single-crystal was used in both the strength and toughness measurements. All eutectic crystals had specific growth directions ([110] for the YAG and $[10\bar{1}0]$ for Al_2O_3). The tests were performed in a universal testing machine, CMT4204 (SANS, Shenzhen, China). Additionally, the fracture toughness (K_{IC}) was calculated based on the indentation method using the following equation [14]:

$$K_{IC} = 0.016 \times (E/Hv)^{1/2}\left(p/c^{3/2}\right) \quad (1)$$

where E is Young's modulus, HV is Vickers hardness, p is the indentation load and c is the half-length indentation diagonal.

The fracture surfaces were observed with scanning electron microscopy (SEM, LEO, SUPRA35, Ammerbuch, Germany). The cleavage planes of the YAG were successfully determined by electron back-scattered diffraction (EBSD, NordlysNano, Oxfordshire, UK).

The flexural strength and fracture toughness of the directionally solidified Al_2O_3/YAG eutectic crystal are 339 MPa and 5.9 ± 0.3 $MPa \cdot m^{1/2}$, respectively. The K_{IC} and H_V are summarized in Table 1 compared with a prior study using the same indentation method. As shown in Table 1, the fracture toughness is slightly higher than that in prior studies.

Fig. 1(a) shows the typical brittle fracture morphology of the directionally solidified Al_2O_3/YAG eutectic crystal. River line patterns (RLPs) are observed on the fracture surface, which is consistent with a study by Yang et al. [16]. The main direction of the RLPs, namely, the direction of crack propagation, is indicated with a black arrow. The cleavage planes of the YAG (the gray) are parallel to each other, as marked by black arrows in Fig. 1(b). However, the cleavages planes of Al_2O_3 (the black) are not paralleled to each other. The different fracture behaviors of Al_2O_3 and the YAG are adequately illustrated in Fig. 1(c).

Fig. 2(a) is the fracture surface of the YAG. Fig. 2(b) shows the EBSD map with a semi-transparency band contrast for the YAG. The YAG cleavage plane is (111).

RLPs are also found in the tearing ridges of the YAG, as shown in Fig. 3. Plane ‘A’ represents the cleavage plane of the YAG, while ‘B’ represents the tearing ridge of the YAG. A series of nanosized cleavage planes, which are marked as ‘a’ in Fig. 3(b), can be observed in the tearing ridge ‘B’. The direction of the main crack propagation (crack #1) is different from that of crack #2.

Fig. 4(a) shows the cracks propagation of the directionally solidified Al_2O_3/YAG eutectic crystal. The interfaces between Al_2O_3 and the YAG are highlighted by white dotted curve lines. The solid white arrow shows the growth direction of the crack. The RLPs of the YAG are discontinuous, and the cracks in the YAG are hindered by the interfaces. Fig. 4(b) shows the crack deflection and bifurcation at the interfaces. As shown by the black arrows, the main crack bifurcates at the interface

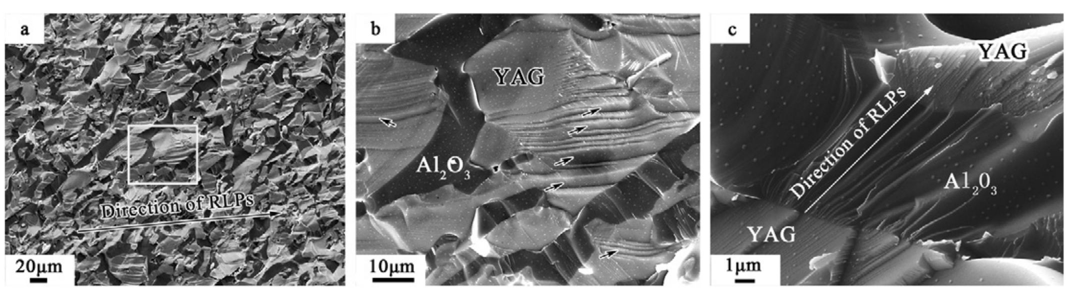

Fig. 1. Typical fracture morphology of a directionally solidified Al_2O_3/YAG eutectic crystal (a); (b) magnified microstructure of the area marked in (a); and (c) the cleavage fracture of Al_2O_3.

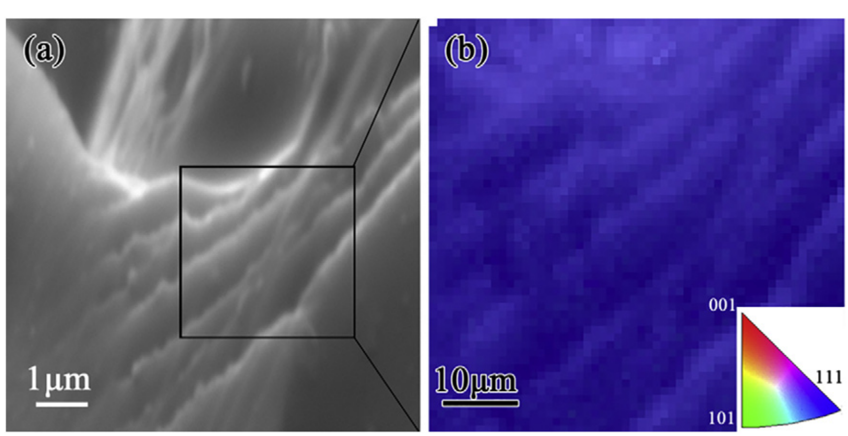

Fig. 2. Fracture morphology of the YAG (a) and (b) the corresponding EBSD map of the YAG fracture surface.