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Internal friction behavior of an unidirectionally solidified Al_2O_3/YAG eutectic at high temperature

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Abstract

The internal friction behavior of a unidirectionally solidified Al_2O_3/YAG eutectic was examined between room temperature and 1400 °C. No internal friction was observed up to 1200 °C. Above 1200 °C, the internal friction drastically increased with increasing temperature and the number of torsional loading cycles. For the 1400 °C test, the internal friction gradually increased with the number of loading cycles and then saturated after 10^3 cycles.
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1. Introduction

Unidirectionally solidified oxide/oxide eutectic ceramics, the so-called MGC (melt-growth composites) materials, are potential candidates for high temperature structural applications because of their superior bending strength and oxidation resistance up to 1700 °C [1,2]. The steady state creep stress at 1600 °C of a unidirectionally solidified Al_2O_3/YAG ($Y_3Al_5O_{12}$) eutectic is over ten times larger than that of a sintered polycrystalline material with the same composition as the eutectic one [1]. The high temperature excellent mechanical properties of MGC materials are closely related to their unique microstructure. It is reported that a unidirectionally solidified Al_2O_3/YAG eutectic consists of single crystal sapphire and single crystal garnet phases which are tangled each other without boundary phases [1]. The minimum creep rate for this material lies on between single crystal of YAG and sapphire and 100 times smaller than for a sintered polycrystalline bulk [1].

In our previous report, the internal friction of Al_2O_3/YAG eutectic was found to drastically increase above 1200 °C [3]. In that friction test, a constant cyclic torsion pendulum was loaded on the sample. The internal friction tests may be viewed as a cyclic load fatigue test with a small amount of torsional load. In this paper, the internal friction test for Al_2O_3/YAG eutectic was performed at high temperature and the internal friction behavior was discussed associated with the fatigue behavior.

2. Experimental procedures

A unidirectionally solidified Al_2O_3/YAG eutectic sample was prepared using a Bridgman-type apparatus (Japan Ultra-High Temperature Materials Research Institute) [1]. The solidified sample was cut into 2 mm × 2 mm × 60 mm testing piece.

The internal friction test for this sample was performed using the torsion-pendulum-type internal friction equipment (MR-2001C, Rhesca Co. Ltd.) at elevated temperature. The test conditions of the Japan Industrial Standard JIS-K-7213 were followed. The top and bottom of the strip specimen were fixed on the equipment by a jig. The logarithmic attenuation (Δ) and shear modulus (G) for the given torsion pendulum were measured and the internal friction (Q^{-1}) was calculated from the logarithmic attenuation. The logarithmic attenuation (Δ)

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and the internal friction (Q^{-1}) for each torsion pendulum were calculated using Eqs. (1) and (2).

$$\Delta = \ln \frac{V_i/V_{i-n}}{n} \tag{1}$$

$$Q^{-1} = \frac{\Delta}{\pi} \tag{2}$$

where V_i, V_{i-n} and n denote the maximum amplitude, minimum amplitude and the frequency in one cycle, respectively. The torsion angle was fixed to 0.5° during the test.

3. Results and discussion

In our previous report, the internal friction of Al_2O_3/YAG eutectic bulk was examined between room temperature and 1400 °C with a heating rate of 5 °C/min [3]. The Al_2O_3/YAG eutectic and sapphire single crystal showed the same internal friction behavior in the above temperature range, the internal friction of these samples drastically increased above 1200 °C [3]. These results suggested that the internal friction above 1200 °C for the eutectic is dominated by that of the sapphire phase.

The maximum shear stress for each cyclic torsion pendulum τ_{max} can be calculated by Eq. (3):

$$\tau_{max} = G\theta a \frac{f_1}{f_2} \tag{3}$$

where θ, a and f denote the specific torsion angle, the side length of the sample and configuration factors, respectively.

From Eq. (3), τ_{max} for the present test can be calculated to 44 MPa. Since the shear modulus G for this sample did not change between room temperature and 1400 °C [3], τ_{max} showed a fixed value between room temperature and 1400 °C as shown in Fig. 1.

It is well known that a sapphire phase has three slip systems, $(0001)\frac{1}{3}\langle 2\bar{1}\bar{1}0\rangle$ basal slip, $\{\bar{1}2\bar{1}0\}\langle 10\bar{1}0\rangle$ prism plane slip and $\{10\bar{1}1\}\frac{1}{3}\langle \bar{1}101\rangle$ pyramidal slip [4]. Lagerlof et al. [4] measured the yield stress for basal and prism plane slips system at elevated temperatures. In their report, the basal slip system is dominant above 700 °C as shown in Fig. 1 [4]. The slip systems for basal and prism plane slip are schematically drawn in Fig. 2. In Fig. 1, it is seen that the maximum shear stress in the present study intersects with the yield stress for the basal slip system at 1200 °C. The yield stress for the prism plane system between 1200 and 1400 °C is higher than the maximum shear stress in the present study. Thus, it can be considered that the drastic increase of the internal friction of Al_2O_3/YAG eutectic bulk above 1200 °C is caused by the $(0001)\frac{1}{3}\langle 2\bar{1}\bar{1}0\rangle$ basal slip of the sapphire phase.

The internal friction test in the present study corresponds to a kind of cyclic torsion pendulum fatigue test with the maximum shear stress τ_{max} = 44 MPa. Hence, in this work, the internal friction test for the eutectic bulk was performed at 1100 and 1400 °C. Fig. 3(a) and (b) show the internal friction at 1100

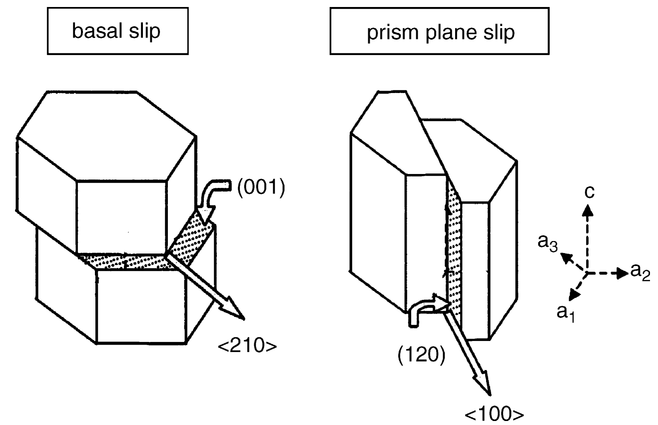

Fig. 2. Slip modes of $(0001)\frac{1}{3}\langle 2\bar{1}\bar{1}0\rangle$ basal slip and $\{\bar{1}2\bar{1}0\}\langle 10\bar{1}0\rangle$ prism plane slip.

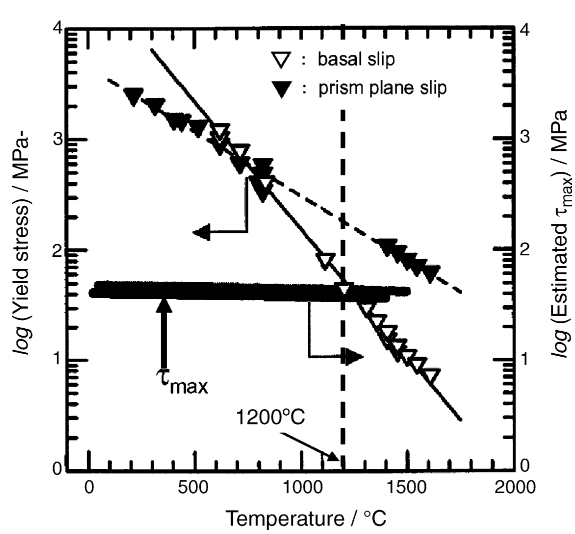

Fig. 1. Maximum shear stress for each cyclic torsion pendulum τ_{max} and yield stress of $(0001)\frac{1}{3}\langle 2\bar{1}\bar{1}0\rangle$ basal slip and $\{\bar{1}2\bar{1}0\}\langle 10\bar{1}0\rangle$ prism plane slip for the sapphire phase [1].

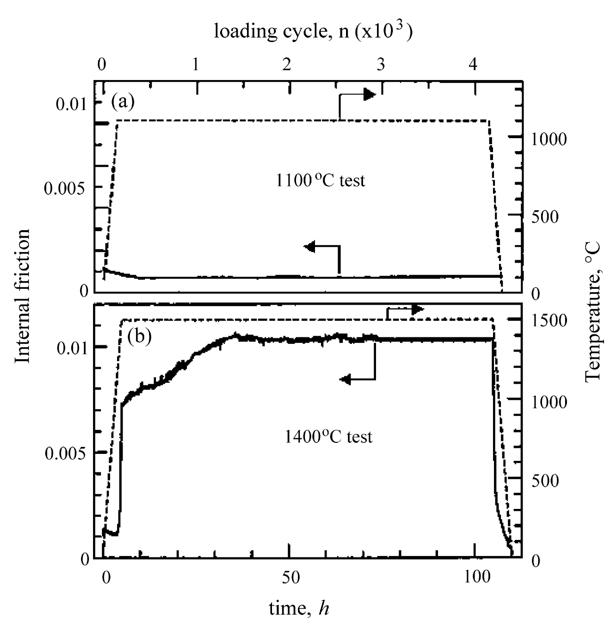

Fig. 3. Internal friction of Al_2O_3/YAG eutectic at (a) 1100 and (b) 1400 °C.

and 1400 °C, respectively. The dashed lines in the figures denote temperature profiles. The sample was heated with an heating rate of 5 °C/min. Since the internal friction of the unidirectionally solidified Al_2O_3/YAG sample did not vary up to 1200 °C [3], no internal friction changes were observed during the 1100 °C test as shown in Fig. 3(a). On the other hand, the internal friction drastically increased above 1200 °C up to 0.007 at 1400 °C as shown in (b). After that, the internal friction gradually increased with the work of cycles. After 35 h, which corresponds to 1500 torsion cycles, the internal friction saturated.

The internal friction at 1400 °C is similar to the work hardening behavior for metals. Commonly, the work hardening of metals is induced by a tangle of dislocations when a secondary slip system is activated. However, in the present study, only the yield stress of $(0001)\frac{1}{3}\langle 2\bar{1}\bar{1}0\rangle$ basal slip at 1400 °C for sapphire phase is lower than the cyclic torsion pendulum τ_{max} at 1400 °C as shown in Fig. 1. Hence, it is difficult to consider the occurrence of a secondary slip system for the eutectic bulk at 1400 °C.

Recently, Matson and Hecht reported the creep mode for a unidirectionally solidified Al_2O_3/YAG eutectic fiber at 1530 °C [5]. In their report, it is predicted that the transition from the lattice diffusion controlled creep in the YAG phase to the dislocation controlled creep as a function of the sample length along the stress axis is caused by the back stress due to the lower creep resistance of Al_2O_3 [5]. This model supports that the creep behavior of the Al_2O_3/YAG eutectic shows a transition in the creep mode with time at high temperature.

In the present study, the internal friction linearly increased with time up to 1500 cyclic torsions at 1400 °C under τ_{max}. From Fig. 1, the yield stress of $(0001)\frac{1}{3}\langle 2\bar{1}\bar{1}0\rangle$ basal slip mode is lower than τ_{max} above 1200 °C. Thus, it is considered that the linear increase of the internal friction observed in Fig. 3(b) is caused by the basal slip. Furthermore, the internal friction was saturated after 1500 torsion cycles. From these results, it is considered that the $(0001)\frac{1}{3}\langle 2\bar{1}\bar{1}0\rangle$ basal slip mode was completely blocked by the other slip modes whose yield stresses are higher than the cyclic torsion pendulum τ_{max}, before the occurrence of the transition slip mode suggested by Matson and Hecht [5].

4. Conclusions

The internal friction of Al_2O_3/YAG eutectic bulk gradually increased with the cyclic torsion pendulum with τ_{max} = 44 MPa due to $(0001)\frac{1}{3}\langle 2\bar{1}\bar{1}0\rangle$ basal slip of sapphire phase at 1400 °C. The increase of internal friction was completely blocked by the other slip mode of sapphire and/or YAG phases when the back stress of the eutectic sample is saturated.

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