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Polarization toughening of $LiTaO_3$ particles dispersed Al_2O_3 ceramic composite

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Abstract

Effect of polarization treatment on the mechanical properties of 15 vol.% $LiTaO_3/Al_2O_3$ ceramic composite (denoted 15LTA) hot pressed at 1300 °C was investigated and discussed. It was found that polarization treated along the width of bending specimens, both improved the flexural strength and the fracture toughness of the composite. The mechanical properties of polarization treated 15LTA ceramic composite almost returned to the original state after inverse polarization treatment. The changes in mechanical properties of 15LTA composite were related to the residual polarization in $LiTaO_3$ particles. Crack detour around $LiTaO_3$ particles, crack deflection and branching caused by domains and domain switching induced by propagating crack were the three main factors for the improvement of the mechanical properties of LTA ceramic composite polarization treated along the width.

Keywords: D. Al_2O_3; Polarization; Toughening; $LiTaO_3$; Ceramic composite

1. Introduction

High electric field may cause changes in mechanical and electrical properties for monolithic ferroelectric materials [1–8]. For example, Vickers' indents on polarization treated ferroelectrics revealed the anisotropy of fracture toughness. The crack propagating along the polarization direction has a shorter length and an apparently higher fracture toughness. The crack propagating normal to the polarization direction has a longer length and an apparently lower fracture toughness. Structural ceramics containing dispersed ferroelectric particles have been found to exhibit improved mechanical properties. In our previous study [9], Al_2O_3 matrix ceramic composite with a dispersion of $LiTaO_3$ piezoelectric ceramic particles (denoted as LTA) was prepared by hot pressing at 1300 °C. It was found that the mechanical properties of the composite containing 15 vol.% $LiTaO_3$ particles (denoted as 15LTA) were greatly improved relative to those of monolithic Al_2O_3. In this paper, we attempted to investigate the influence of polarization treatment on the mechanical properties of 15LTA ceramic composite. The toughening mechanisms in polarization treated LTA ceramic composite were also discussed.

2. Experimental procedure

Commercially available alumina, Al_2O_3, powder (High Tech Ceramic Institute, Beijing, China) and lithium tantalate, $LiTaO_3$, powder (Dongfang Tantalum Joint-stock Corporation, Ningxia, China) were used as starting powders. The average particle sizes of Al_2O_3 and $LiTaO_3$ powders were ~0.3 and 3.0 μm, respectively. They were mixed in a predetermined ratio ($LiTaO_3/Al_2O_3 = 15$ vol.%) by ball-milling with ethanol for 24 h. The dried powder mixture was hot pressed with a graphite die into a disc with the dimension of ϕ 55 × 4.5 mm^3 at 1300 °C for 90 min under a pressure of 25 MPa in vacuum.

The disc was cut into rectangular bars of 4 mm × 3 mm × 36 mm and 4 mm × 2 mm × 20 mm for flexural strength

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and fracture toughness tests, respectively. Silver electrodes were vapor-deposited on both sides of the bars for the specimens which were treated with polarization before bending test. Polarization treatment was performed at 500 °C and 500 V/mm for 1 h in vacuum. The polarization directions were along the width (w) and the height (h) of the specimens for three-point bending test, respectively. The strength was evaluated by three-point bending technique. The fracture toughness was determined by single-edge-notched-beam (SENB) test. Three to five specimens were tested to determine the flexural strength and fracture toughness for each condition. Vickers' indentation crack was introduced on the polished surface of the specimens under a load of 147 N with a dwell time of 10 s. The crack propagation paths were observed by SEM.

3. Results and discussion

The average flexural strength and fracture toughness of 15LTA ceramic composite before and after polarization treatment are given in Table 1. The minimum and maximum data are shown as errors. To eliminate the effect of heating during polarization treatment, some of the untreated specimens were only heated at 500 °C for 1 h without applying an electric field and cooled down to room temperature. The mechanical properties of them are also given in Table 1. It can be seen that polarization treatment along different directions had different effects on the mechanical properties of 15LTA ceramic composite. Polarization along the width, both improved the strength and the toughness of 15LTA ceramic composite. But polarization along the height, both decreased them. It was found that heating treatment alone had no evident effect on the mechanical properties of 15LTA ceramic composite. Therefore, it can be concluded that changes in mechanical properties of LTA ceramic composite after polarization treatment should have no relations with heating and cooling process. It should be caused by the applied electric field. The changes in mechanical properties of LTA ceramic composite after polarization treatment should be related to the residual polarization in $LiTaO_3$ particles.

If the improvement in mechanical properties of LTA ceramic composite after polarization treatment is really due to the residual polarization in $LiTaO_3$ particles under electric field application, the flexural strength and fracture toughness are thought to return to the original state by removing the residual polarization. Therefore, the specimens polarization treated along the width were heated to 760 °C (above the paraelectric ↔ ferroelectric phase transition temperature ~630 °C of $LiTaO_3$) and kept for 3 h and then cooled down to room temperature to remove the residual polarization. This process was referred to inverse polarization treatment. The mechanical properties of specimens after inverse polarization treatment were compared with those before and after polarization, as also shown in Table 1. It can be seen that the mechanical properties of polarization treated 15LTA ceramic composite almost returned to the original state after inverse polarization treatment. To get rid of the effect of heating during inverse polarization, some polarization untreated specimens were heated to 760 °C and kept for 3 h under the same condition. Such treated specimens were also compared to the original ones, as also shown in Table 1. It was found that there were no evident changes in the mechanical properties of the heated and the original specimens. Therefore, the recovery of mechanical properties of 15LTA ceramic composite after inverse polarization treatment is really related to the elimination of residual polarization. These results provide further evidence that the residual deformation due to residual polarization would be the origin of the improvement in mechanical properties of LTA ceramic composite. The flexural strength and fracture toughness did not perfectly return to the original state by simply removing the residual polarization (Table 1). It is probable that some irreversible change would occur on long time polarization treatment. Similar results have been reported for $BaTiO_3/ZrO_2$ composite [10].

SEM observations on indentation crack propagation paths are shown in Fig. 1. According to our previous study [9], no crack detour around $LiTaO_3$ particles was detected for LTA ceramic composite before polarization treatment. Instead, crack detour occurred in $LiTaO_3$ particles. But a different case appeared for the polarization treated specimens. Crack

Table 1
Flexural strength and fracture toughness of 15LTA ceramic composite before and after polarization treatment and after inverse polarization treatment

Specimens	Flexural strength (MPa)	Fracture toughness ($MPa{\cdot}m^{1/2}$)
Before polarization treatment	450.0 ± 33.5	4.50 ± 0.53
Polarization treated along w	457.2 ± 30.3	4.80 ± 0.74
Polarization treated along h	431.3 ± 71.2	4.20 ± 0.13
Only heated at 500 °C for 1 h	446.0 ± 38.5	4.55 ± 0.18
After inverse polarization treatment	450.6 ± 47.3	4.60 ± 0.11
Heated at 760 °C for 3 h	452.0 ± 56.2	4.58 ± 0.37

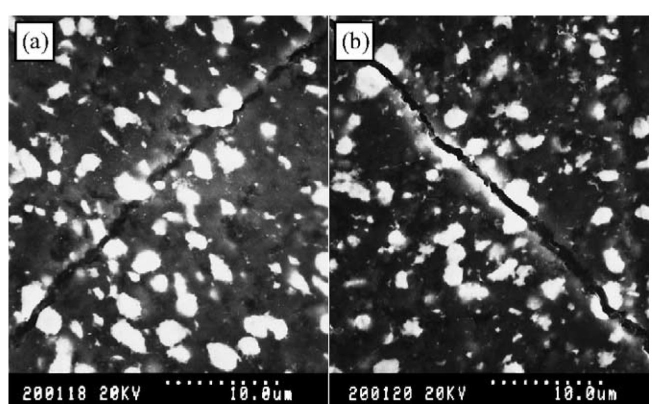

Fig. 1. SEM micrographs of crack propagation paths in 15LTA after polarization treatment. (a) Crack parallel to the polarization direction, (b) crack perpendicular to the polarization direction.

propagating parallel to the polarization direction produced detour around $LiTaO_3$ particles, as shown in Fig. 1(a). But crack propagating perpendicular to the polarization direction still got through $LiTaO_3$ particles and no detour around them was observed, as shown in Fig. 1(b). In addition, less crack detour in $LiTaO_3$ particles was observed in the polarization treated specimens. Detour of cracks around $LiTaO_3$ particles in LTA ceramic composite after inverse polarization treatment was no longer observed.

It has been proposed that domain switching is a new toughening mechanism in structural ceramic composite containing a dispersion of ferroelectric particles [9]. According to the literature [11,12], when domains arrange perpendicular to the crack, the I-type stress field ahead the crack tip can hardly cause domain switching. Only the vertical stress field behind the crack tip may induce some domain switching. When domains arrange parallel to the crack, large amount of domain switching can be induced before and behind the crack except for the region right before the crack. That is to say, the crack parallel to polarization direction can cause much domain switching. Whereas that perpendicular to polarization direction induces only little domain switching. For LTA ceramic composite polarization treated along the width, domains arranged almost along the width. At the same time, the crack plane propagated along the height when the specimen produced fracture during bending test. Thus, the improvement of mechanical properties of LTA ceramic composite polarization treated along the width mainly lied in three aspects: (i) crack detour around $LiTaO_3$ particles along the width due to internal stresses induced by residual polarization, (ii) crack deflection and branching along the height caused by domains in $LiTaO_3$ particles and (iii) large amount of domain switching induced by the propagating crack along the width also enhanced the mechanical properties. For LTA ceramic composite polarization treated along the height, domains tended to arrange along the height. Accordingly, domain boundaries were parallel to the propagating direction of the crack plane. Because domain boundaries were weak, they would promote the growing of crack. At the same time, no crack detour around $LiTaO_3$ particles produced and less domain switching was induced along the width. As a result, the mechanical properties of LTA ceramic composite polarization treated along the height decreased. But because the content of dispersed $LiTaO_3$ particles was low, effect of polarization treatment on the mechanical properties of LTA ceramic composite was small.

4. Conclusions

Al_2O_3 matrix ceramic composite containing 15 vol.% $LiTaO_3$ ferroelectric ceramic particles hot-pressed at 1300 °C was polarization treated along different directions. Polarization treated along the width of bending specimens, both improved the flexural strength and the fracture toughness of the composite. Whereas polarization treated along the height, decreased both of them. The mechanical properties of polarization treated 15LTA ceramic composite almost returned to the original state after inverse polarization treatment. The changes in mechanical properties of 15LTA ceramic composite after polarization treatment were related to the residual polarization in $LiTaO_3$ particles. Crack detour around $LiTaO_3$ particles, crack deflection and branching caused by domains and domain switching induced by propagating crack were the three main factors for the improvement of the mechanical properties of LTA ceramic composite polarization treated along the width.

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