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Joining partially-sintered alumina ceramics using a mixture slurry of alumina sol and suspension

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Abstract

The joining of advanced ceramics allows the manufacture of components with a range of complex shapes that cannot be achieved in a cost-effective manner using existing techniques, i.e. green state shaping and/or machining. A new technique for joining partially-sintered alumina ceramics was developed by simply using a mixed slurry of Al_2O_3 sol and suspension. The interlayer of the joints had the same composition as the parent bodies, and the mechanical and chemical properties of the joint were comparable to those of the bulk material. This process can be applied to the joining of a variety of advanced ceramics.

Keywords: A. Joining; Ceramics; Partially-sintered; Alumina; Machining

1. Introduction

Joining of ceramic parts, as an effective way to produce large and/or complex shapes of advanced ceramics, has always been a challenge [1,2]. The joining of advanced ceramics that have been extensively studied over many years include the methods of joining by glass-frit bonding [3,4], active metal brazing [5], diffusion bonding [6–9] and green body joining [1,2]. On the other hand, difficulties in the joining of ceramic parts occur because joined components are sometimes required to perform at very high temperatures and/or in corrosive environments. Therefore, no low-melting-temperature phases or easily corroded materials can be tolerated as joining materials, which excludes joining methods, such as frit bonding and metal brazing [1,2]. To avoid the presence of impurities at the joint, many studies have examined diffusion bonding, in which the simultaneous application of high temperatures and pressures are required to induce plastic deformation at the joint region and consequently obtain joints with high-temperature stability and strength [10,11]. However, broad applications of this method are questionable because of the substantially high cost of hot pressing and the limited shapes that can be achieved [1,2].

Alumina is one of the important ceramic materials having excellent high temperature strength and resistance to wear and oxidation. Reliable joining technologies for these materials are required for increasing their applications [12]. Green state joining is commonly used in the clay-based ceramic industry to produce complex parts. The plasticity induced by alkali ions in the layered structures of the clay-based ceramics renders the green body joining of clays relatively easy [13–15]. Advanced ceramics, such as Al_2O_3, do not exhibit plasticity. Hence, the green state joining of Al_2O_3 has been overlooked as a method of fabricating complex shapes. Nevertheless, some recent research has shown that the unique behavior of clay-based ceramics can be approximated by dispersing powders in a carrier medium and pasting this slurry on joint interfaces [2,13,16,17]. Han [13] examined the joining of Al_2O_3 ceramics using an Al_2O_3 slurry paste and reported that green state joining is a potentially viable method.

Although there have been some successes in the green state joining of ceramics, this technique is limited when applying it to the joining of engineering components made of advanced ceramics. To machine green ceramic components, e.g. the principal challenge is to obtain sufficient strength for the component to withstand the stresses generated during

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machining whilst maintaining the advantages of the easy machining of porous ceramics [18]. Partial sintering conducted before machining can provide structural integrity to allow the machining of the ceramic components with metalworking tools. The particles in the green ceramic components form particle–particle bonds (i.e. necks) between them during partial sintering. Although little or no densification occurs during this heat-treatment, the strength and elastic modulus of the partially-sintered bodies increases dramatically. As a result, the alumina bodies impart sufficient mechanical strength to withstand the stresses generated by machining [18]. Therefore, the machining of partially-sintered bodies followed by joining is preferred over machining the green ceramic parts due to the high strength and the fully densified ceramic parts due to the reduced machining time and cost.

The aim of this study was to develop a way of joining partially-sintered Al_2O_3 ceramics using Al_2O_3 sol-suspension mixture slurries as an interlayer. A method was developed for joining partially-sintered Al_2O_3 ceramics by pasting a mixture slurry on the to-be-bonded surfaces followed by co-sintering the parent partially-sintered bodies and interlayer between them without applying external pressure during sintering.

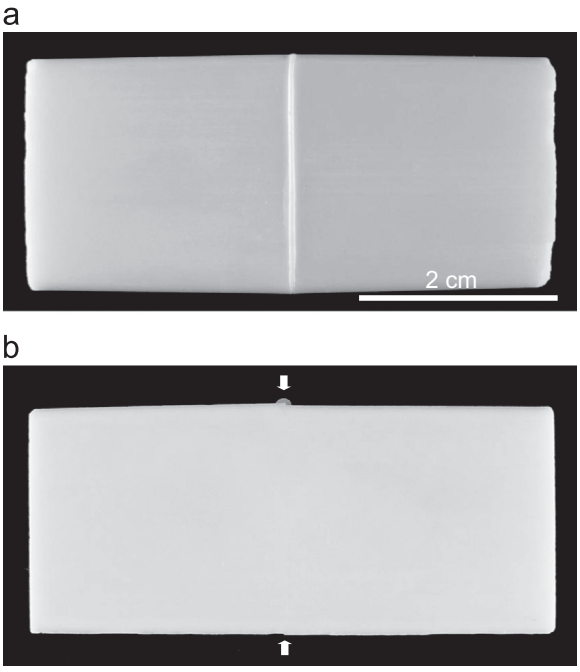

Fig. 1. Photographs showing the (a) as-sintered outer surface and (b) inner cut face of the Al_2O_3 bars.

2. Experimental

The joining paste used in this study was prepared by mixing an Al_2O_3 sol and its suspension. The alumina sol was first prepared using methyl alcohol (CH_3OH, Extra Pure Grade, Duksan Pure Chemicals, Ansan, Korea) as the solvent, $AlCl_3 \cdot 6H_2O$ (Extra Pure, Daejung Chemicals & Metals Co., Ltd., Shiheung, Korea) as the Al^{3+} source and acetyl acetone ($CH_3C(O)CH_2C(O)CH_3$, Extra Pure, Daejung Chemicals & Metals Co., Ltd., Shiheung, Korea) as the chelating agent to form the Al ion-complexes. The methyl alcohol solution, where aluminum chloride was dissolved to a concentration of $[Al^{3+}] = 1.26$ mol/l, was mixed dropwise with the other methyl alcohol solution containing 2.46 mol/l of the chelating agent. The concentrations of the aluminum chloride and acetyl acetone in the resulting sol solution were controlled to 0.62 and 1.24, respectively. The resulting sol solution was stirred for several days to develop the Al ion complexes, during which the solution changed from a colorless clear tone immediately after mixing to a yellowish tone with increasing stirring time. Ethylene glycol ($((CH_2)_2(OH)_2$, Guaranteed Reagent, Junsei Chemical Co., Ltd., Japan) was then added to the solution at a concentration of 50 wt% to prevent drying of the solution. To prepare a mixture slurry of the alumina sol and suspension, 72.2 wt% of Al_2O_3 powder (AES-11, Sumitomo Chemical Co., Ltd., Tokyo, Japan) was mixed with the sol solution and ball milled for 6 h with alumina balls in a polyethylene container. The partially-sintered alumina samples, $2.7 \times 2.7 \times 3$ cm^3 in size, were prepared by uniaxial die pressing, cold-isostatic pressing (CIP) at 135 MPa and pre-sintering at 1150 °C for 0.5 h, and used as the parent parts for joining.

Before joining, the surfaces of the partially-sintered green compacts to be joined were treated by dipping the surface into molten wax to reduce the absorption of the carrier medium when pasting the Al_2O_3 sol-suspension mixture slurry. The capillary pressure exerted by the porous surfaces of the green bodies deprives the mixture slurry of its carrier liquid, thereby hindering the rearrangement of particles in the joint region, which is believed to be essential for joining, due to the rapid consolidation of the paste. After this treatment, the to-be-joined surfaces were ground to a smooth surface with SiC paper (P #500). A paste of the Al_2O_3 sol-suspension mixture slurry was then applied to the to-be-joined surfaces of the parent partially-sintered green parts to form a sandwich assembly. Joining was performed simply by placing two parent parts together and rubbing them face-to-face until the joining paste was almost consolidated. After drying overnight at room temperature, the joined green parts were sintered at 1650 °C for 2 h in air. A low heating rate (1 °C/min) and holding (at 160 °C for 1 h, 350 °C for 1.5 h and 600 °C for 1 h) was applied at temperatures ranging from 25 to 600 °C to burn out the organic additives.

To evaluate the strength of the joints, the joined bodies were cut into $4 \times 3 \times 40$ mm^3 bars, where the joint interface was positioned at the center of the test bar, and their outer surfaces were then polished using diamond pastes with decreasing sizes to 6 μm. The flexural strength of the joint was measured by three-point bending with a 20 mm span on an universal testing machine (Autograph 500, Shimadzu Co., Kyoto, Japan) at a displacement rate of 0.5 mm/min. Six test bars were tested to obtain the mean bond strength of the joints. The microstructures of the joint region were observed by scanning electron microscopy (SEM, S-4200, Hitachi High-technologies Co., Ltd., Tokyo, Japan) after thermal etching of its polished surface at 1550 °C for 0.5 h.