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Spatter-free laser drilling of alumina ceramics based on gelcasting technology

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Abstract

Spatter and microcracks are inherent defects commonly associated with holes produced with laser drilling. In order to prevent spatter deposition and formation of microcacks this work reports a novel laser drilling method based on the gelcasting technology. The work presents a new laser drilling method, through which the irregular spatter at the exit of the hole and microcracks produced by the traditional laser drilling method can be effectively prevented by direct laser drilling of gelcast green body and compact micro holes with much more regular shapes without microcracks can be successfully obtained.

Keywords: Al_2O_3; Gelcasting; Laser drilling; Machining

1. Introduction

The machining of ceramics to their final dimensions by conventional methods is extremely laborious and time-consuming. While laser machining is a non-contacting, abrasionless technique, which eliminates tool wear, machine-tool deflections, vibrations and cutting forces, reduces limitations to shape formation and inflicts less sub-surface damage. Therefore laser machining of ceramics is used extensively in the microelectronics industry for scribing and via hole drilling.[1] However, laser drilled holes are inherently associated with spatter deposition due to the incomplete expulsion of ejected material from the drilling site, which subsequently resolidifies and adheres on the material surface around the hole periphery. In addition, the high hardness and brittleness will lead to fracture (microcracks) of the ceramic material during laser machining. In order to prevent spatter deposition and microcracks during laser machining, many techniques based on either chemical or physical mechanisms have been developed,[2–5] but the results were not encouraging.

Gelcasting is an attractive ceramic forming technique for making high-quality ceramic parts. In the process a high solids loading ceramic slurry obtained by dispersing the powders in the pre-mixed monomer solution is cast in a mould of the desired shape. After adding a suitable initiator the entire system polymerized in situ and green bodies of excellent mechanical property but with only a few percents of polymer can be obtained.[6] In the present article a novel spatter and fracture prevention drilling technique based on a gelcasting technique is developed for drilling compact holes on alumina ceramics. Here Nd:YAG laser is used to drill holes directly on gelcast green alumina sheet. Spatter-free holes with more uniform shapes and without microcracks can be easily obtained by this method. This might be attributed to the relatively loose structure of the green body compared with sintered seramics.

2. Experimental

The alumina powder used here is a commercial product An-0.5 provided by China Xinyuan Aluminum Inc., which has a mean particle size of 2.0 μm. In the gelcasting system deionized water is used as the medium.

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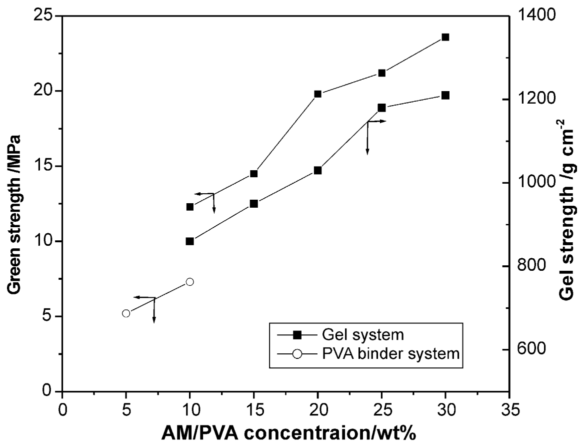

Fig. 1. Influence of AM concentration on the gel strength and green body strength. The mechanical strength of PVA bound green body are also listed for comparison.

Acrylamide ($C_2H_3CONH_2$, AM) and *N*,*N*-methylene-bisacrylamide [$(C_2H_3CONH)_2CH_2$, MBAM] were used as the monomer and crosslinker respectively. *N*,*N*,*N′*,*N′*-tetramethylethylenediamine (TEMED) and $(NH_4)_2S_2O_8$ were used as catalyst and initiator, respectively. Triammonium citrate (TAC) was selected as the dispersant to improve the flowability of the ceramic slurry. The details of how the gelcast polymers were pyrolyzed were determined via thermogravimetric analysis (TGA) in air by using a Dupont Thermal Analyst 2000. The room-temperature mechanical strength of the green body is determined by three-point flexure test. Microstructure of the sample was observed by a Hitachi S-450 scanning electron microscopy (SEM). Hole size was measured through an optical microscopy NEOPHOT21 in combination with SEM photos. A pulsed Nd:YAG laser typical of many in use in industry for drilling and cutting was used for the machining. Some parameters of the laser are listed in Table 1.

Table 1
Some parameters of the laser used in the test

Wave length	Pulse energy	Pulse repetition rate	Pulse duration	Focus diameter
1.064 μm	~10 J	1–30 Hz variable	0.2 ms	~0.1 mm

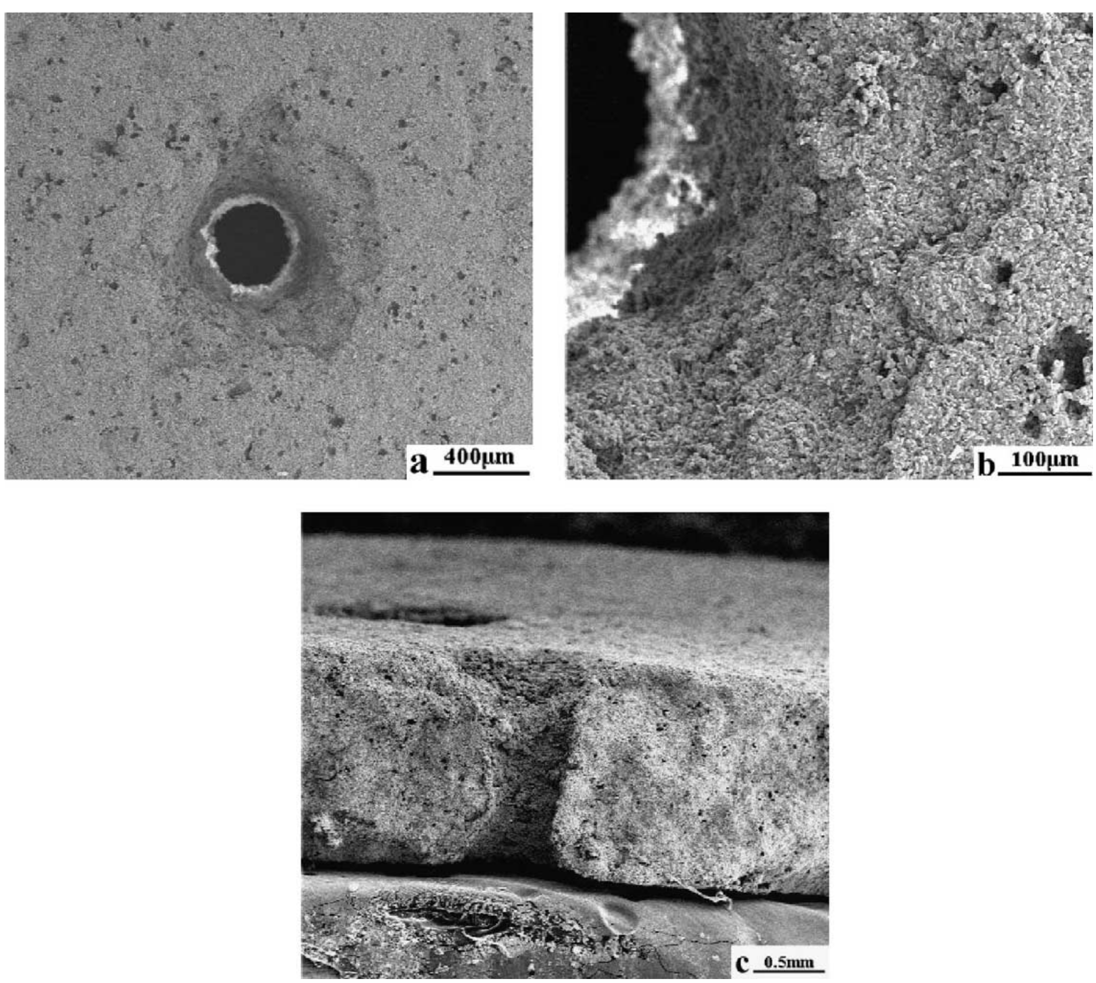

Fig. 2. SEM micrographs of the hole drilled on the conventional green alumina body prepared by using 5 wt.% PVA solution as the binder.

3. Results and discussion

3.1. Mechanical property of gelcast Al_2O_3 green body

The conventional laser drilling of green alumina body containing PVA or PVB as the binders is not a suitable method because the propagation of the shock waves and thermal stresses induced by the laser may cause damage of the alumina body.[7] However, a gelcast body has much higher mechanical strength than the die pressed green body and this is of great advantage for handling of the parts before firing and for being able to produce large castings. Influence of AM content in premix solution on the gel strength and green body strength derived from 50 vol.% alumina slurries are shown in Fig. 1. Here the gel strength was examined by a simple device as that used by Chen et al.[8] We can see that a AM concentration of 20 wt.% can provide a green strength of about 20 MPa. The high strength of the gelcast body is due in large part to both the highly uniform distribution of the binder throughout the casting and the inherent high strength of the crosslinked polymer. Comparatively, die pressed sample by using even 10 wt.% of PVA solution as the binder (ca. 5 wt.% based on the total sample weight) shows a much lower strength of about 7.3 Mpa. Consequently the holes are damaged under the radiation of the laser beams (see Fig. 2).

3.2. Hole microstructure observation

The basic mechanism of laser drilling is based on the thermal action of the light. When a high intensity of light strikes the material surface, the photons of the beam are absorbed and converted into thermal energy. Then the temperature rises locally and a combination of melting and vaporization occurs. Under the continual effect of the laser beam the molten material is ejected by the material vapor thus the hole is formed.[9] SEM mircophotos of the holes drilled on conventional green alumina body pressed by using 5 wt.% PVA solution as the binder are shown in Fig. 2. At the beginning of the drilling the material vapor is inevitably ejected out from a shallow circle molten zone in a wide angle, therefore a

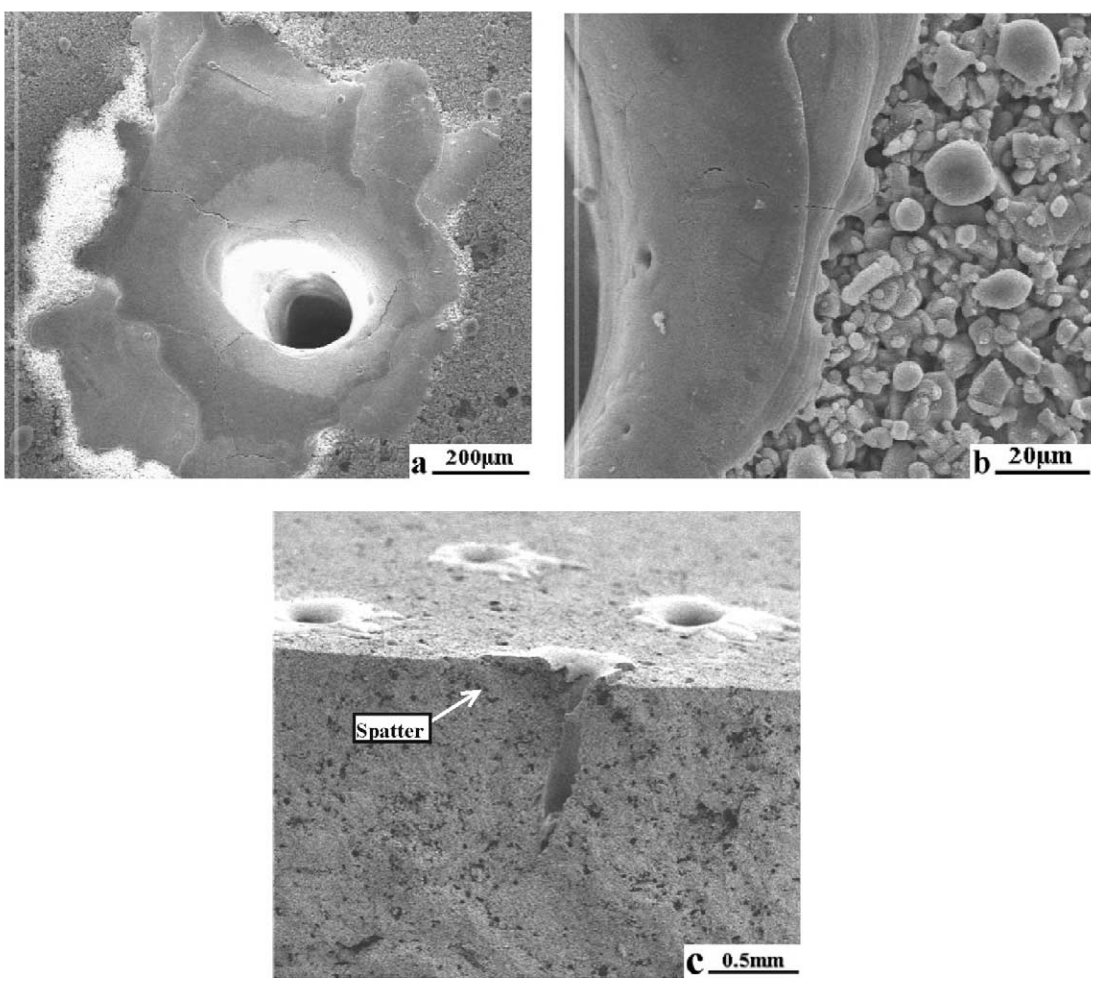

Fig. 3. SEM micrographs of the holes drilled on the sintered alumina body: (a) Top view; (b) Illustration of spatter on the edge of the hole; (c) cross section of the hole.

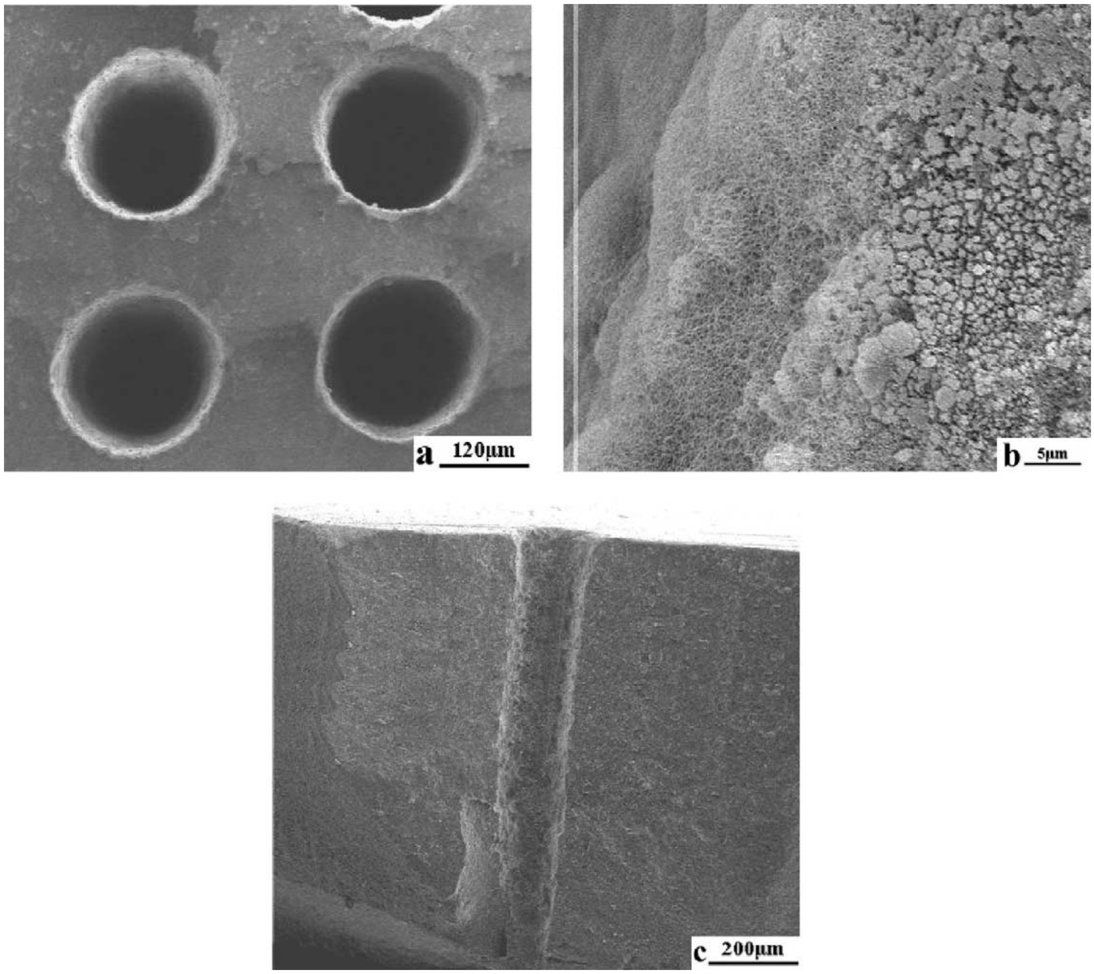

Fig. 4. SEM micrographs of the holes drilled on gelcast green body; (a) Top view; (b) Illustration of the edge of the hole; (c) cross section of the hole.

more or less cone-shaped section of the hole is formed near the material surface. From Fig. 2b we can see that a conical shaped hole with a wide ejection angle was formed during laser drilling. In addition, the hole also exhibits a conical shape near the bottom of the material. Similar phenomena were also reported by Allen et al. in the research of CO_2 laser processing of Al_2O_3.[7] These may be ascribed to the loose binding of the particles and the low mechanical strength of the green body, indicating that the conventional green alumina body containing PVA or PVB as the binder is not suitable for laser machining.

Fig. 3 shows the SEM photos of the laser drilled holes on the sintered gelcast alumina samples obtained from 50 vol.% alumina slurry. When the laser pulse comes to the end, the decrease of the flux density, the blurring of the light spot edges, as well as the power decrease at the pulse trailing edge, all contribute to an increase of resolidified liquid residue in the hole, resulting in recast layers and spatter deposited surface.[9] As can be seen in Fig. 3a, the holes drilled by two pulses on sintered ceramics are encircled with large area of irregular spatter deposits. In contrast, it is clearly evident from Fig. 4a that little spatter is present around the holes drilled on the gelcast green body. Fig. 4a also exhibits an improved surface quality and smooth hole periphery. Figs. 3b and c and 4b and c show further the surface qualities of the holes in Figs. 3a and 4a, respectively. From Fig. 3b we can see that the spatter deposits at the periphery of the hole on the sintered alumina shows a resolidified molten phase characteristics and there exist some microcracks, which may be due to the laser induced thermal shock and stress. While the periphery of the hole on the green body shown in Fig. 4b shows a structure composed of particles and no cracks can be seen. Figs. 3c and 4c compare the cross section features of the holes obtained on the sintered ceramics and on the gelcast green body. It is clearly evident from Fig. 3c that not only the hole entrance but also the upper part of the hole wall are deposited with a large area of spatter. While Fig. 4c indicates that the spatter present on the sintered body does not appear at all.

As a result of the irregular spatter deposition, the consistency of the geometry of the holes on the sintered body are reduced while the drilling of the green body can greatly improve the geometry consistency of the

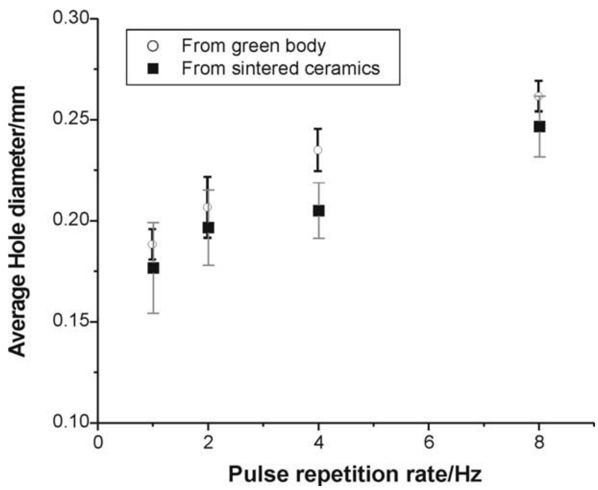

Fig. 5. Average entrance hole diameter with variation in pulse repetition rate.

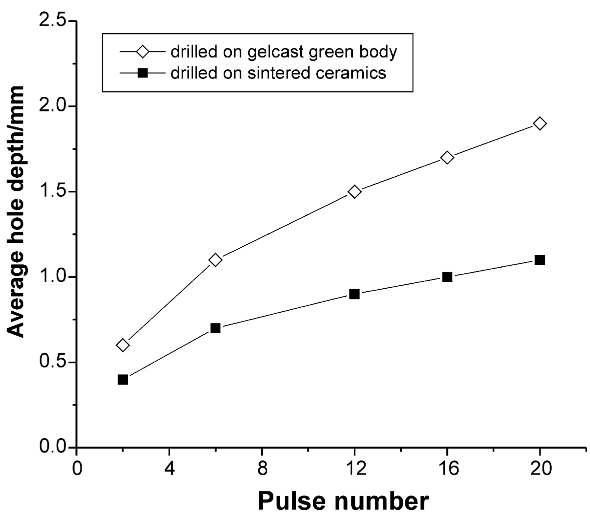

Fig. 6. Hole depth depending on the number of pulses.

process. Fig. 5 compares the average entrance hole diameter values and the errors (standard deviation) on the two samples at different pulse repetition rates. More uniform hole geometry can be obtained on gelcast green samples than on sintered ceramics. Fig. 6 presents the hole depth depending on the number of pulses. Both hole diameter and hole depth drilled on the green body show a higher value than those on the ceramics. It is well known that a lower total heat of evaporation and melting will result in a higher hole depth and hole diameter value,[9] therefore this may indicate a lower evaporation heat of the green bodies. Consequently more intense, wider and volatile material ejection is caused and little material resolidifies on the hole edge. Thus from the thermal nature of the radiation and the microstructure inspection it is reasonable to surmise that the absence of spatter from a gelcast green body may be attributed to the lower evaporation heat and the relatively loose structure of the green body compared with the sintered ceramics.

4. Summary

A new spatter-free laser drilling technique based on the gelcast alumina green body is developed. Dense, strong and homogeneous near-net-shape alumina parts are successfully fabricated. What should be pointed out is that gelcasting is a highly versatile fabrication process. It is not limited to use with any particular ceramic powder. It can be quickly adapted for use with new materials and new applications and it works as well for metal powder forming as for ceramic powders. Therefore the laser processing method used here may be applied to the laser machining of a variety of materials.

Acknowledgements

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