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New laser machining technology of Al_2O_3 ceramic with complex shape

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Abstract

A new method was developed for the fabrication of complex-shaped Al_2O_3 ceramic parts by combining laser machining and gelcasting technique. The unwanted ceramic powders parts were selectively removed by laser machining specified by a computer program, and the gelcast Al_2O_3 green bodies were machined to a designed shape by a CO_2 laser at a wavelength of 10.6 μm. The influences of solid loading, laser output power, scanning speed and nitrogen purge on the machining of green Al_2O_3 ceramic bodies were studied. The experimental parameters were optimized, the green Al_2O_3 bodies with solid loading of 40 vol% or below were easier to be machined, while the green bodies with solid loading of 45 vol% or above were hard to be further machined due to the surface sintering. Better machining quality and deeper machining depth could be obtained when the laser power is 30 W. The green Al_2O_3 bodies with complex shape were obtained by the laser machining.

Keywords: Al_2O_3; Gelcasting; Laser machining; Green body; CO_2 laser

1. Introduction

The ceramic machining by laser is an advanced manufacturing method used in many areas such as electronics, aerospace and material processing [1–5]. The machining of ceramics to their final dimensions by conventional methods is extremely laborious and time-consuming. While laser machining is a non-contact, abrasionless technique, which reduces tool wear, machine-tool deflections, vibrations, cutting forces, sub-surface damage, and the limitations of shape formation. However, because of the inherent hardness and brittle nature of ceramic materials, the laser machining progress of sintered ceramics tends to produce spatters and microcracks and has low machining efficiency and high cost, and more and more researchers turns to study the machining of ceramic green bodies [6,7]. Most of the investigations on machining of ceramic green bodies have been focused on one-dimensional and two-dimensional machining so far, and it has been found that a ceramic green bodies with a high-strength is necessary in order to obtain good machinability.

In recent years, gelcasting has received increasing attention for its simple process, low capital equipment cost, low binder content, high green strength and excellent green machinability, etc. Gelcasting is a well-established near-net-shape colloidal processing method for making high-quality, complex-shaped ceramic parts by means of in situ solidification through which a macromolecular network is created to hold the ceramic particles together [8–11]. Gelcasting is one of the most potential for industrial applications because the method is capable of preparing uniform green body with high strength that adapts to be machined.

We proposed a new method of continuous and three-dimensional laser machining for the gelcast green bodies, and this technology combines laser machining and gelcasting technique together to machine complex-shaped ceramic parts. This method builds ceramic parts by selective removal of the unwanted parts of the bodies, layer by layer, as specified by a computer program to generate geometrical objects directly from a three-dimensional computer image without part-specific tooling or human intervention, and then the final three-dimensional ceramic parts with complex shape are obtained. The temperature of the elimination and evaporation of the organic matter is less than 600 °C, much lower than the required temperature as adopted by the regular laser machining on the sintered ceramics, which displays a high machining efficiency and a low cost. Furthermore, the laser machining of green bodies by computer-controlling would be much more precise than the

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conventional machining method, especially for the fabrication of small and complex parts. It is not limited to use with any particular ceramic powder, and it can be quickly adapted for the use of new materials such as metal powder and ceramic powders. Therefore, the laser machining processing method may be applied to the machining of a variety of materials.

In our previous work [12–14], zirconia ceramic parts with complex shape were fabricated successfully by CO_2 laser machining. In this article, the main aim is the investigation on the influences of solid loading, laser output power, scanning speed and nitrogen purge on the machining of Al_2O_3 green bodies with complex shape. The complex shape ceramic parts were fabricated successfully by CO_2 laser machining by the optimization of machining parameters.

2. Experimental procedures

2.1. Materials

Aqueous gelcasting of Al_2O_3 was carried out using acrylamide (AM, $C_2H_3CONH_2$) and *N*,*N*′-methylenebisacrylamide (MBAM, $(C_2H_3CONH)_2(CH_2)$) monomers. Al_2O_3 powders (mean particle size: 0.5 μm, 99.9% purity, Henan Jiyuan Brother Material Co., Ltd., China) employed were commercially available materials. A dispersant (0.2 wt.%, triammonium citrate [$C_6H_{17}N_3O_7$] (TAC)) was added to minimize agglomeration, and potassium persulphate (Merck, $K_2S_2O_8$) was used as initiator. All reagents were chemically pure.

2.2. Procedures

During the gelcasting preparation of Al_2O_3 green body, in the first step, the monomers (AM and MBAM) were completely dissolved in deionized water by mechanical stirring, and the premix solution was served as a dispersing media for the ceramic powders. The next step was to add Al_2O_3 powders into the premix solution, the slurry was degassed for 15–20 min after rolling for 12 h in polyethylene bottles using agate balls, and then the slurry was cast into a nonporous cylindrical glass mold. The slurry was kept at 50–60 °C for 30–40 min to polymerize to form gelled body after casting, and then the gelled part was removed from the mold and dried to remove the solvent system. After polymerization and drying, a green body

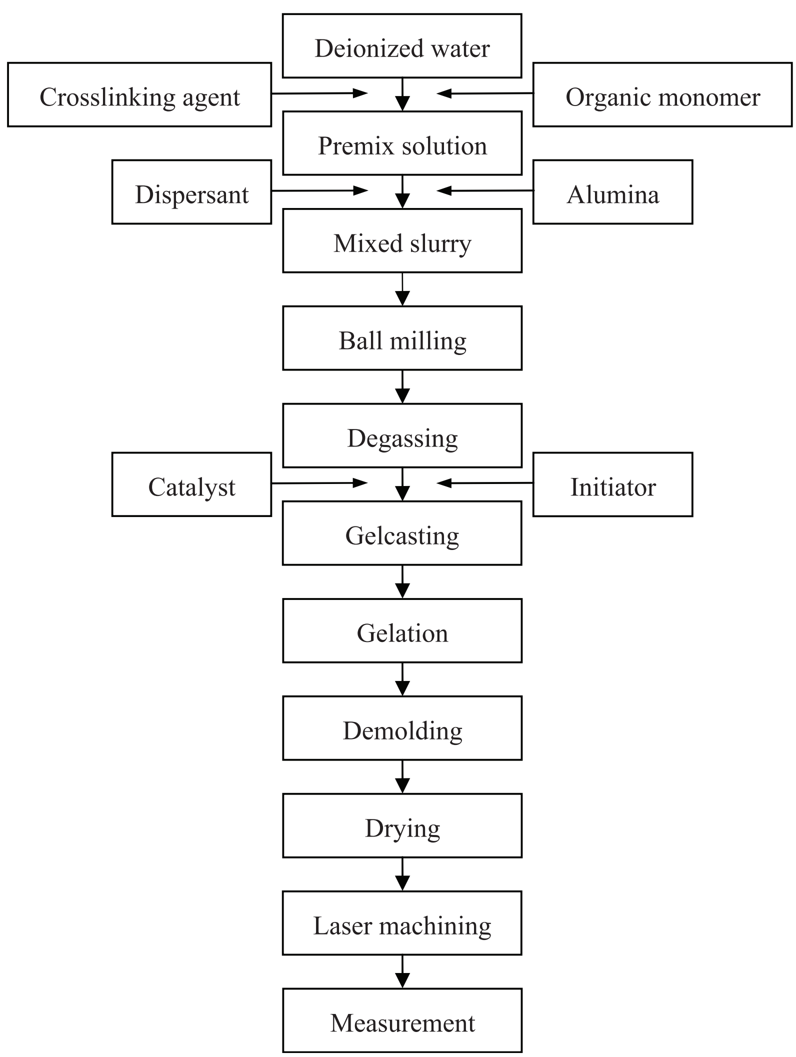

Fig. 1. The detailed flowchart of the gelcasting and laser machining process of the green bodies.

Table 1
Main parameters used in laser machining in the experiment.

Wave length of laser (μm)	Laser power (W)	Focus diameter (mm)	Resolution accuracy (dpi)	Positional accuracy (mm)
10.6	30–40	0.3–0.4	1016	0.025

with high mechanical strength was obtained, and then laser machining was conducted. The detailed flowchart of the gelcasting and laser machining process on the green bodies is shown in Fig. 1.

2.3. Introduction of CO_2 laser machining equipment

The laser machining equipment is a metal RF CO_2 laser (model MC30A) developed by our research group cooperating with Beijing Boao Laser Technology Co., Ltd. It mainly consists of Laser Power Supply System, X,Y Vibrating Mirror System, Optical System, Precision Worktable Orientation System, Blowing Device, Dust Removal Device and Software Operating System, etc. as shown in Fig. 2. The laser beam had a focal spot size of about 100 μm and a wavelength of 10.6 μm by Beam Expander for expanding, the *X*-axis and *Y*-axis two vibrating mirror scanner lens reflex, and the optical focusing lens to the worktable. Vibrating Mirror Scanner under the computer to control in the fast swing, the laser beam can scan in the plane *X* and *Y* two-dimensional direction. The laser beam focuses on the objects surface and forms a micro-burning to machining. After computer-controlled continuous process, advance scheduling characters, graphics, and other contents will be permanently marked on the objects surface. The schematic diagram of the CO_2 laser machining equipment is shown in Fig. 2b, X–Y–Z–ω four-axis simultaneous machining is achieved, and tilt angle θ (the 5th axis) can be adjusted manually by using laser galvanometer with the rotary table.

The controlling of the processing parameters, such as laser output power, output frequency, processing speed, step itinerary and nitrogen purge, is integrated by the software of the three-dimensional laser processing. The data documents of cross sections are formed by the program functions according to the three-dimensional data model. High efficient automated processing is achieved because several layered processing can be completed by adjusting the data and parameters in Software Operating System. The laser parameters are shown in Table 1.

2.4. Characterization

Machining depth was the average of each machining depths measured by a screw micrometer. The particle size distributions were measured by a BI-XDC particle size analyzer (Brookhaven Instrument Corp., USA). The microstructures of the green bodies and machined bodies were observed by a scanning electron microscopy (SEM) (S-450, Hitachi Corp., Japan).

3. Results and discussion

During the laser machining process of the green bodies, high-intensity light excitation energy provided by the laser strikes the materials surface, the photons of the beam are absorbed and converted into thermal energy. The temperature rises locally by various heat transfer processes such as conduction, convection and radiation from the surface into the materials [3]. Under the continual effect of the laser beam, the powder particles is ejected layer by layer by nitrogen purge after the organic decomposition on the surface, and the complex-shaped Al_2O_3 ceramic parts is thus formed. The temperature distribution within the materials as a result of these heat transfer processes depends on the thermophysical properties of the materials (such as density, emissivity, thermal conductivity, specific heat, and thermal diffusivity), dimensions of sample (thickness) and laser processing parameters (absorbed energy, beam cross-sectional area), etc. The heating governs the different physical effects in the material such as melting, sublimation, vaporization, dissociation, plasma formation and ablation responsible for unwanted materials removal/machining. Thus we investigated the influences that the following important experimental parameters such as solid

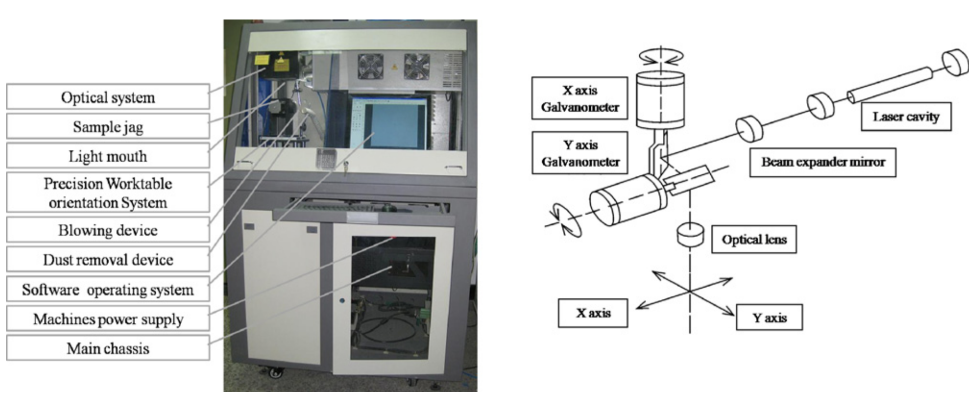

Fig. 2. The photos (a) of the equipment for the three-dimensional laser machining and (b) the schematic diagram of the CO_2 laser machining equipment.

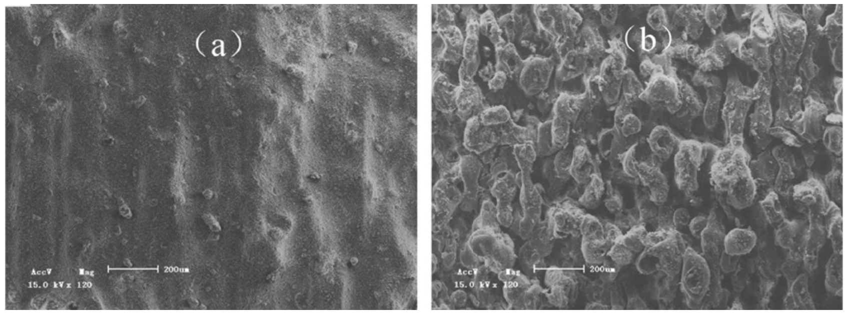

Fig. 3. The surface morphologies of the machined Al_2O_3 green bodies with solid loadings of (a) 40 vol% and (b) 45 vol% at laser power 35 W, scanning speed 6.5 cm s^{-1} and scanning span 0.1 mm.

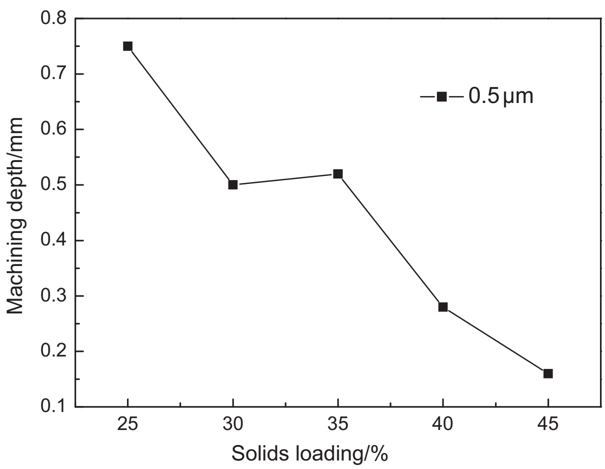

Fig. 4. Relationship between machining depth and solid loading at laser power 35 W, scanning speed 6.5 cm s^{-1} and scanning span 0.1 mm.

loading of the green bodies, laser power, laser scan speed and nitrogen purge on the machining of Al_2O_3 green bodies.

3.1. The influences of solid loading on laser machining

The key role of the laser machining technology is to burn out organic binder with little thermal effects on the ceramic powders [3,12,13]. The dried gelcast green bodies with 55 vol% solid loading contain only 4 wt% binder which is much less than that in most polymer- or wax-based injection molding systems. The relative low content of organic materials indicates a high sensitivity of the green bodies to the radiation of the laser beams.

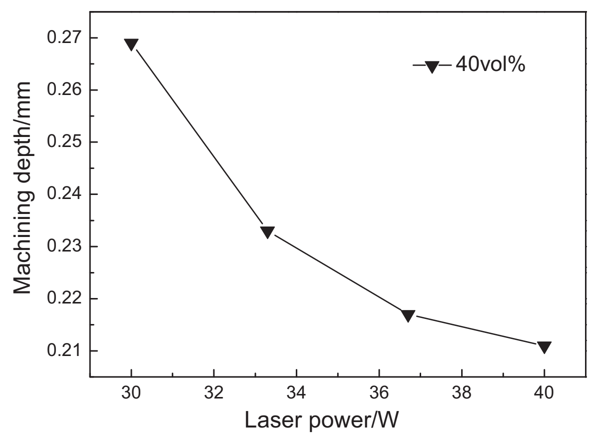

Fig. 6. Relationship between laser power and machining depth with 40 vol% solid loading at scanning speed 6.5 cm s^{-1} and scanning span 0.1 mm.

Fig. 3 shows the surface morphologies of the laser machined Al_2O_3 green bodies with different solid loadings (40 vol% and 45 vol%). The green body with solid loading of 40 vol% (Fig. 3(a)) has visible laser scanning path on the surface and hardly is sintered, while the one with 45 vol% solid loading (Fig. 3(b)) that has a visible sintered powder particles field (50–200 μm) distributed on the whole machined surface. Therefore, the green Al_2O_3 bodies with solid loading of 40 vol% or below were easier to be machined, while the green bodies with a solid loading of 45 vol% or above were hard to be further machined due to the formation of a sintering surface layer.

Fig. 4 shows the relationship between machining depth and solid loading. It indicates that the machining depth decreases with the increase of solid loading, and it means that the green

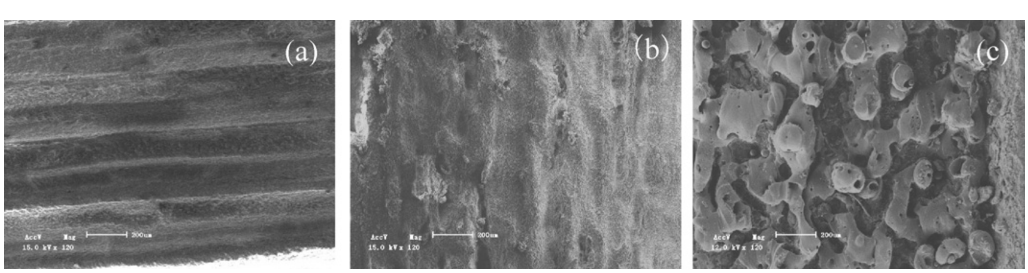

Fig. 5. Machined surface morphologies with laser machining power at (a) 30 W; (b) 35 W; (c) 40 W with 40 vol% solid loading at scanning speed 6.5 cm s^{-1} and scanning span 0.1 mm.

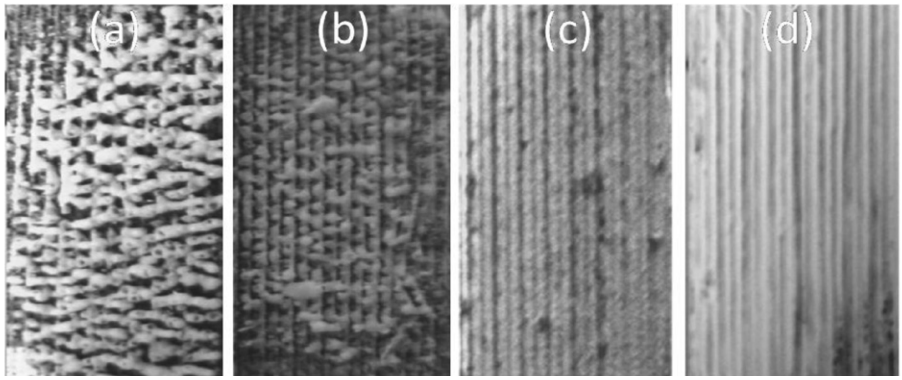

Fig. 7. Machined surface morphologies with different nitrogen flow rate of (a) 0 L min^{-1}; (b) 1 L min^{-1}; (c) 3.2 L min^{-1}; (d) 5 L min^{-1} with 40 vol% solid loading at laser power 35 W, scanning speed 6.5 cm s^{-1} and scanning span 0.1 mm.

Al_2O_3 bodies with relatively low solid loading have more satisfactory effects of machining.

3.2. The influences of laser power on the laser machining

Fig. 5 shows the machined surface morphologies with different laser output power. Smooth machined surface where the unwanted materials is removed using laser machining at laser machining power 30 W is showed in Fig. 5(a), while the green bodies machined at high laser machining power (see Fig. 5(b) and (c)) have a visible sintered powder particles surface.

Fig. 6 shows the relationship between laser power and machining depth. With the increase of laser output power (>30 W), the machining depth decreases. It is because a higher laser power (>30 W) makes the surface temperature of green bodies easily reach the melting point of Al_2O_3 ceramic powder particles, leading to the formation of a sintered surface layer, which deteriorating the further laser machining. The previous results indicated that a low laser power could not supply sufficient heat to remove the organic materials [13,14] resulting in low machining efficiency and the low machining depth. Considering the machining efficiency and machinability, 30 W laser power is preferable in the present study.

3.3. The influences of nitrogen flow rate on the laser machining

It should be noted that, although a green body is machinable under suitable experimental condition, there is still more or less unavoidable residual scattered ceramic powders on the surface after the organic decomposition, and the residual ceramic powders on the surface have harmful effect on deep-processing. Nitrogen purge cannot only take away part of the laser radiation energy (heat convection), but also can blow off the scattered powder and the thin sinters (if exist) from the green body surface, and finally resulting in a better machinability.

Fig. 7 shows the surface morphologies of the green bodies machined by nitrogen purge with different flow rate. The SEM photos reveal that, with the increase of the flow rate of nitrogen purge, the sintering decrease greatly. When nitrogen flow rate is less than 3.2 L min^{-1}, the green body surface is sintered seriously and with poor machinability. Thus nitrogen flow rate less than 3.2 L min^{-1} is insufficient to blow off the scattered powder from the green body surface, and takes away less part of the laser radiation energy. At 3.2 L min^{-1} and 5 L min^{-1}, it is hard to see any sinter on the surface, and this means that the green body surface can be machined at nitrogen flow rate more than 3.2 L min^{-1}.

Fig. 8 shows the relationship between nitrogen flow rate and machining depth with nitrogen flow rate more than 3.2 L min^{-1}. It can be seen that the machining depth nearly has no dependence on the nitrogen flow rate. The converted heat by the laser radiation energy consists of conduction, convection and radiation from the surface into the materials, determining the surface temperature of the ceramic green body. Therefore, when other experimental factors are tolerable where the balance of the heat transfer is sensitive, nitrogen flow rate is effective, while the heat into the surface of the materials is excessive, the effect of nitrogen flow rate is limited.

In this study, Al_2O_3 ceramic bodies with complex shape were successfully fabricated by CO_2 laser machining with the optimization of the parameters, as shown in Fig. 9. Therefore, the new method by combining laser machining and gelcasting

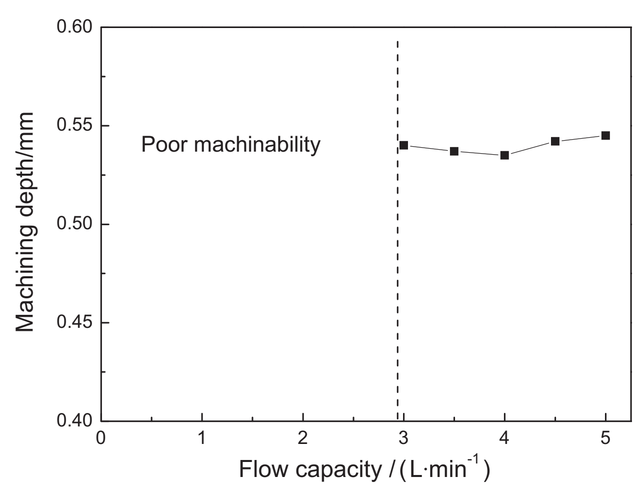

Fig. 8. Relationship between nitrogen flow rate and machining depth with 40 vol% solid loading at laser power 35 W, scanning speed 6.5 cm s^{-1} and scanning span 0.1 mm.

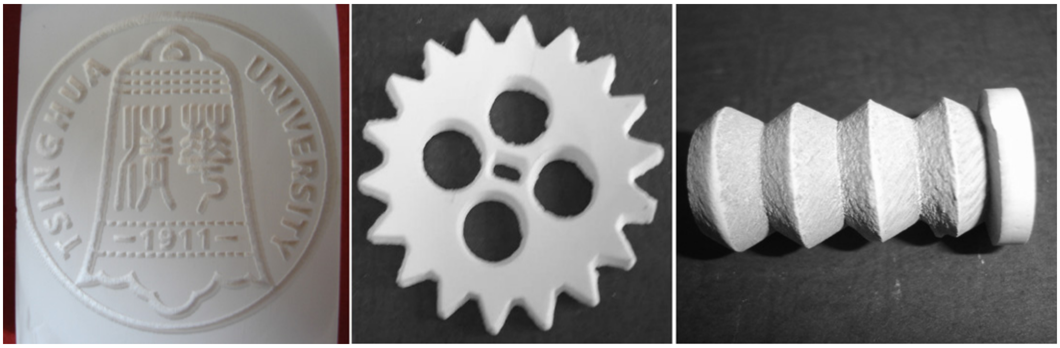

Fig. 9. The complex-shaped sintered Al_2O_3 ceramic parts prepared by laser-machining.

technique has a great theoretical significance and application value, it is quite promising for meeting the market demand of structural ceramics with the characteristic of many varieties of small batch [15].

4. Conclusions

A new machining method was developed for the fabrication of complex-shaped Al_2O_3 ceramic parts by combining laser machining and gelcasting technique. The unwanted parts of gelcast Al_2O_3 green bodies were selectively remove by decomposing polymer binders by laser machining, and the green bodies were machined to a desired shape with a CO_2 laser machining at a wavelength of 10.6 μm. The effects of the parameters such as solid loading, laser power, scanning speed and nitrogen purge on the laser machining of gelcast green Al_2O_3 bodies were investigated. The green Al_2O_3 bodies with solid loading of 40 vol% or below were easier to be machined, but the green bodies with solid loading of 45 vol% or above were hard to be further machined due to the surface sintering. Better machining quality and deeper machining depth could be obtained when the laser power was 30 W. The green Al_2O_3 body could be machined efficiently by applying nitrogen purge more than 3.2 L min^{-1} to bring out excessive heat, scatters powders and sinters. With the optimization of these parameters, Al_2O_3 ceramic bodies with complex shape were successfully fabricated by CO_2 laser machining.

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