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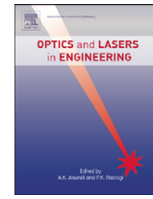

Crack-free cutting of thick and dense ceramics with CO_2 laser by single-pass process

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ABSTRACT

This paper presents a laser crack-free cutting method of Al_2O_3 ceramics by single-pass process in internal straight and curve profiles. The thickness and theoretical density of the ceramics are up to 10 mm and about 99%, respectively. The effective cutting speed is about 0.23–0.42 mm/s corresponding to the laser head moving speed of 3 mm/s. The cutting process based on close-piercing lapping of piercing time of 0.1–0.5 s and piercing pitch of 0.03–0.05 mm is divided into two continuous stages. Appropriate time slot for each piercing, high peak power of 3500 W and low cycle duty ($<30\%$) achieve crack-free cuts. Optimal cut quality parameters are analyzed and characterized. These results demonstrate that the laser crack-free cutting method is a promising method to achieve complex profiles of ceramic cuts.

1. Introduction

Due to their outstanding thermomechanical and thermochemical properties, ceramics have been found to be extensively used in mechanical, electrical and engineering applications. However, their inherent hard and brittle properties lead to slow, noisy, and unproductive mechanical machining processes. The laser cut technique as a promising and alternative method to the conventional mechanical machining of glass or vitro crystalline bodies was first developed by Lambert et al. [1]. Laser cutting properties are high energy density, non-contact machining, high cutting speed, low cost and accurate computer numerical control (CNC). During laser cutting of ceramics, the high energy density thermal nature causes acute thermal-shock damage to the work-piece. Remedial studies attempted to solve this flaw, which appears to be the cause for underutilization of the laser cutting technique of ceramics [2–14]. The main approaches are: (1) the Black and Chua multi-pass cutting of partial cuts during each pass [3], (2) the Garibotti and Lumley controlled-fracture cutting combined laser scribing and laser guiding stress separation [13,14]. The former method is inherently time consuming. Moreover, the heat and resulting stress accumulation due to laser multi-pass irradiation induces many cracks and burnout and reduces the cut quality. The latter method has attracted more and more attention in the recent years for the controllability in the symmetrical straight profile cutting process of thicker ceramics. The method includes controlling separation of fracture with a single laser system or controlling the thermal gradients/cooling rates with a dual-beam laser system consisting of two simultaneous laser sources. The method has been developed for cutting of thick ceramics with thickness of up to 10 mm by synchronously applying a focused Nd: YAG laser, which is used to scribe a groove-crack, while a defocused CO_2 laser is used to drive a crack [6]. Such a sophisticated system consisting of two laser subsystems has inherent deviation of the actual fracture trajectory from the desired angle or curve profiles. Observed numerical simulations suggested that the thermal gradients associated with cutting were so severe that it resulted in the loss of control of thermal stresses added by the unfocused second beam [10,11,15]. Crack damage is the most serious problem during laser cutting of ceramic process, especially for the ceramics of thickness >2 mm or density $\sim 99\%$ and the cutting in curve or asymmetrical path.

In this paper, we reported a laser crack-free cutting method for dense Al_2O_3 ceramics ($\geqslant 99\%$ theoretical density) with a range of thickness (from 1 to 10 mm). Using a slab CO_2 laser, the crack-free cutting of the ceramics in arbitrary curve and angular paths by single pass were obtained. The effective crack-free cutting speed of 0.23 mm/s of 10 mm ceramics corresponding to the laser head moving speed of 3 mm/s was achieved. The cut quality of the ceramics correlated with the optimized process parameters was characterized and analyzed.

2. Experimental

2.1. Experimental procedure

The experimental Al_2O_3 ceramics were of 1, 4, 6, 10 mm thickness, titled, respectively, as samples A, B, C, and D in Table 1,

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within which are listed the physical properties. According to the previous research results [3], the crack-free internal profile cutting is more difficult to be obtained than the external profile cutting. So the internal profile cutting experiments were conducted in our research in order to explore the great potential of the laser which can be easily cut in all profiles. The internal cutting included straight line testing, curvilinear testing, and angular testing. It was performed by means of a CAD–CAM controlling on the cutting paths. Because of the high absorption coefficient of Al_2O_3 to 10.6 μm wavelength laser beam, a slab CO_2 (Rofin–Sinar) laser in pulsed mode with a maximum peak power of 3500 W and pulse frequency of 50 Hz was used to perform the trials. The laser was delivered to the specimen surface through a 127 mm focal length lens for the ceramics with thickness below 4 mm and a 290 mm focal length lens for those with thickness over 4 mm, respectively. The focal plane of CO_2 laser was placed at a defocused distance of 3 mm. The focused laser beam with a diameter of 0.1 mm was irradiated underneath the top surface of the ceramic work-piece. Nitrogen was used as an assist gas and injected by using a coaxial conical nozzle with an exit diameter of 1.5 mm. The nozzle stand-off distance was 1 mm. The trials were carried out with assist gas pressures of up to 5 bar. All the experiments were repeated several times for each test according to a designed matrix on the principle of orthogonal trials. After the experiments, the top surface

Table 1
Physical properties of the Al_2O_3 ceramics used in the trials

Sample	A	B	C	D
Thickness (mm)	1	4	6	10
Density (g/cm^3)	3.77	3.73	3.74	3.75
Hardness (kg/mm^2)	1506	1497	1500	1498
Young's modulus (GPa)	313	310	315	310
Fracture toughness (MPa$^{1/2}$)	4.50	4.50	4.50	4.50

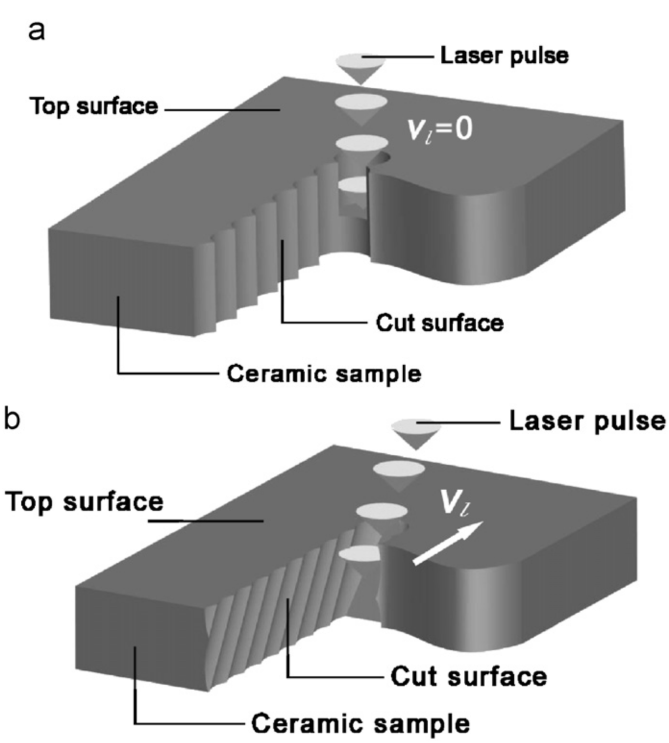

Fig. 1. Conceptualization of two different laser cutting techniques: (a) close-piercing lapping (CPL) laser cutting method and (b) ordinary pulse (OP) laser cutting method.

Table 2
Optimized laser parameters of the CPL laser cutting method for crack-free single-pass cutting of Al_2O_3 ceramics with different thickness

Sample	B	C	D
The first piercing			
Peak power (W)	3500	3500	3500
Duty cycle (%)	15	20	30
Frequency (Hz)	50	50	50
Gas pressure (bar)	2	2	2
Piercing time (t)	0.1	0.2	0.5
The latter piercing			
Peak power (W)	3500	3500	3500
Duty cycle (%)	15	20	30
Frequency (Hz)	50	50	50
Gas pressure (bar)	2	3	5
Piercing time (t)	0.10	0.10	0.20
Piercing pitch (mm)	0.05	0.05	0.05
Effective cutting speed (mm/s)	0.42	0.42	0.23

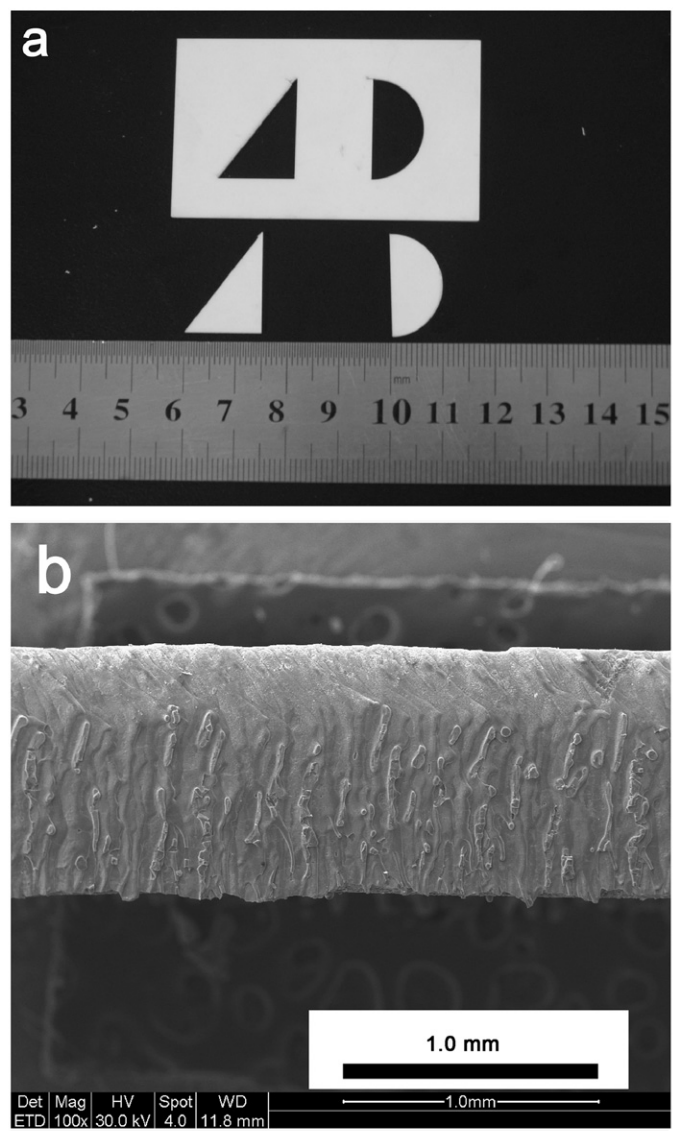

Fig. 2. The cutting results of the 1-mm thick Al_2O_3 ceramic samples processed by OP laser cutting method: (a) photograph of the cuts of the sample and (b) the SEM view of the cut surface of the sample.