Picosecond Laser Surface/Deep Patterning of Alumina Ceramics

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Abstract. Traditional machining techniques pose significant drawbacks when applied to ceramics due to the material's inherent brittleness. Specialized laser machining has been known to solve these issues through higher precision and micrometer-scale feature control. In this study, a picosecond fiber laser has been used as a material removal system for different engineering applications of industrial-grade alumina ceramics with a variety of thicknesses and feature dimensions. This work explored picosecond laser process parameters such as focal position, linear speed, and wobble amplitude in order to control the cut depth and optimize cut quality in terms of kerf width, kerf taper, and surface cleanness while avoiding crack formation. The surface roughness was assessed to determine the quality of the cuts. The optimal process parameters between the surface finish and material removal rate were introduced. Using a circular wobble laser pattern, it was determined that a greater cut depth can be achieved at lower linear speeds and wobble frequencies due to the higher linear energy density. It has also been found that the kerf taper is dependent on the cut depth and wobble amplitude, where the measured cuts follow the geometric relation between these parameters accurately.

Keywords: Laser cutting · Alumina ceramics · Ablation · Surface profile · Picosecond laser

1 Introduction

Ceramics are known for their high compressive strength, stiffness, and thermal and chemical resistance. As a result, these properties have increased the use of ceramics in different applications [1]. However, one of the main challenges with ceramic processing is the machinability of ceramics for producing complex parts. Ceramic cuts using mechanical methods induce microcracks along the cut interface which results in crack initiation sites as well as residual stresses [2–6]. This is due to the inherent brittleness of ceramics and is the reason for the low fracture toughness of monolithic components. With laser processing, the material is no longer subject to vibration or cutting forces (shear forces) and instead is exposed to a high-energy beam which results in rapid ablation of the material [7].

Proceedings of the 61st Conference of Metallurgists, COM 2022,
https://doi.org/10.1007/978-3-031-17425-4_15

There are different types of laser cutting/engraving systems applied for several varieties of materials where complex shapes demand precise, fast, and force-free processing. For example, traditional CO2 lasers offer high-beam quality but are rarely used for ultra-short processing applications [8]. Nd:YAG lasers are capable of producing higher peak power than gas lasers in the form of extremely short bursts, but suffer from poor energy efficiency and beam quality [1, 9]. Nanosecond lasers are preferable for material removal or ablation [10, 11]; however, there is risk of forming a significant heat-affected zone and microcrack formations in ceramics, which would affect the ultimate quality of cut geometries [12, 13]. In order to minimize the heat-affected zone and induced microcracks [14], pico-femtosecond lasers were utilized to engrave/cut alumina ceramics [15, 16]. Picosecond (short pulse duration) and femtosecond lasers (ultra-short pulse duration) yield high-quality results, appropriate for the production of high-precision micro- and nanomachining [17].

In this study, a systematic approach was developed to predict the cut profile (i.e., kerf taper and cut depth) of the ablated, smooth, and defect-free laser cuts on industrial grade alumina ceramics. The approach was based on the various input process parameters including wobble amplitude, wobble frequency, linear speed, and number of passes of the picosecond laser system.

2 Experimental Procedure

The laser used in this study is an Ytterbium Picosecond fiber laser (YLPP-25-3-50-R, IPG Photonics, USA) with a maximum average power of 50 W and a laser beam waist diameter of 17 μm. It produces a Gaussian spatial profile beam with 3 ps long 25 μJ pulses of 1030 nm wavelength and is capable of a repetition rate of up to 1.83 MHz. Following the results obtained from the previous study [18], it was determined that optimal cut quality could be achieved by using a circular wobble pattern. Wobble is the optional beam oscillation pattern drawn perpendicular to the laser trajectory. It is defined by pattern shape in the laser software (line, circle, eight (8), and infinity (∞)), repetition frequency (Hz), and wobble amplitude (mm). This scheme directs the laser to produce circles parallel to the substrate surface, as shown by the schematic in Fig. 1a along with a true visualization of the wobble pitch using a 1 mm amplitude. The ceramics used are 1.016, 1.524, and 2.540 mm (0.04, 0.06, and 0.1 in, respectively) thick industrial nonporous 96% alumina tiles (McMaster-Carr, CA) with a density and porosity of 3875 kg/m^3 and 0%, respectively. Cuts of 10 mm in length were generated to study the effect of laser process parameters on the quality of the cuts. The cut depth, kerf taper, and kerf width were then measured using a KEYENCETM 3D Laser Scanning Confocal Microscope, the results of which are represented in the diagram in Fig. 1b, c for different cut profiles (i.e., deep and shallow).

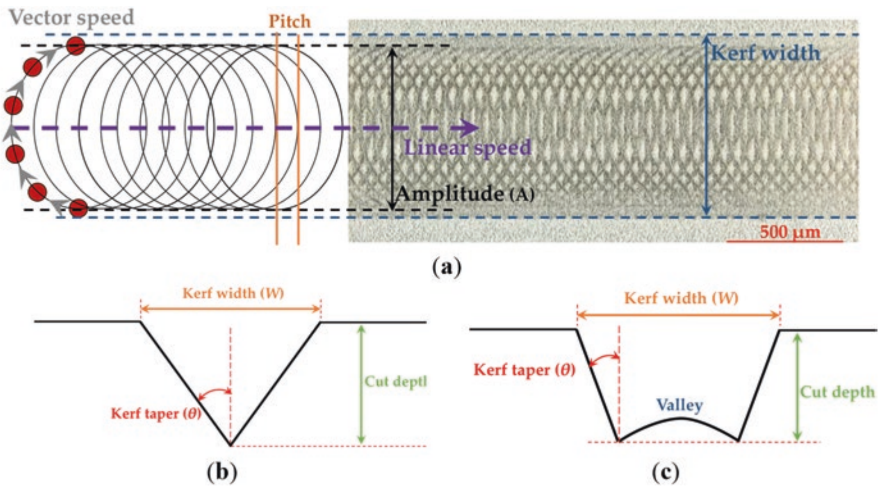

Fig. 1. (**a**) Schematic and microscope image of the circular wobble pattern illustrating the laser pulses and direction, wobble amplitude, wobble pitch, kerf width, linear speed, and vector speed. Schematics of the cut measurement nomenclature of (**b**) Deep, developed cut profiles (>40 passes) and (**c**) Shallow cut profiles (<40 passes).

3 Results

The kerf taper of ablated cuts with developed "V-shape" can be determined using $\theta = \arctan(W/2D)$ (where θ, W, and D are the kerf taper, kerf width, and cut depth, respectively), which is a function of the cut depth and wobble amplitude. Data gathered from various ablation cut experiments are plotted against the geometric approximation, as shown in Fig. 2. Plotted experimental data shows a strong correlation with the theoretical formulation. Here, the kerf taper is primarily controlled by the wobble amplitude if a through-cut is required for the sample. By modifying this input, the theoretical kerf taper range can be predicted using this approach. Making a through cut on a 2.54-mm-thick alumina tile can produce 3.4–21.5° kerf tapers using a 0.3–2.0 mm range of wobble amplitudes. However, there exist a physical limitation of manufacturing through cuts on the 2.54 mm samples for the smaller amplitudes up to 1.0 mm. To achieve this depth using the 0.5 mm wobble amplitude, the power-law relationship estimated the cut time to be in the order of 10^7 s, thus limiting its practical feasibility. This result is due to clipping of the incident laser spots by the tapered surfaces of the cuts, thereby decreasing the energy density on the cut area. For smaller amplitudes, this phenomenon is more significant, which hinders the effectiveness of the laser to ablate material within the cut region. Therefore, the long processing times, which is a result of the decreasing efficiency does not make the kerf taper predicted by the 0.3 mm and 0.5 mm wobble amplitudes viable for ablating depths greater than 1.2 mm. However, it is important to note that this limitation may be addressed by lowering the focal position during the cutting process as preliminary investigations have shown. Finally, as the amplitude of the circular wobble increases, the beam clipping decreases due to the wider cut geometry. Therefore, deeper cuts can be achieved for the larger wobble amplitudes over the 220

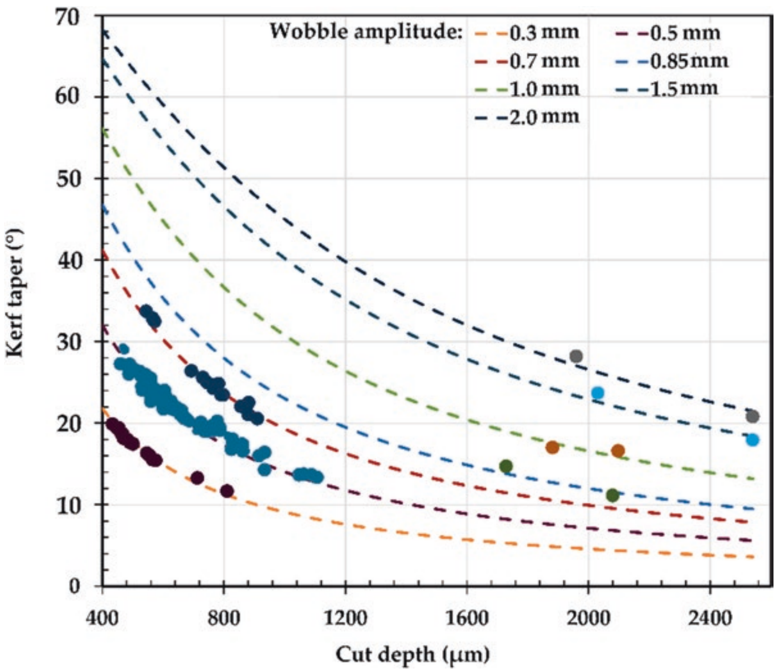

Fig. 2. Geometric dependence of kerf taper to the cut depth for the V-shaped cut profiles.

passes that were required to cut through the 2.54-mm-thick alumina ceramic tile using the 1.5 mm wobble amplitude.

Finding a metric to evaluate the viability of each of these processing schemes was the final step toward implementing the circular wobble pattern for manufacturing near-net geometries. The quality of ablated cuts deteriorates significantly with wobble pitches above the 30-μm threshold as was illustrated by the large increase in surface roughness in Fig. 3. A visually noticeable decrease in cut quality is determined for wobble pitches above 30 μm. This value is in agreement with the laser spot size at the chosen focal position of 400 μm below the surface of the ceramic. At wobble pitches above the laser spot diameter, the lack of spot over-lap results in a decrease of total incident energy, particularly at the center of the cut. This creates the large peaks and valleys where the edges of the cuts experience large overlap due to the nature of the circular cut pattern. Significantly larger pitches (e.g., 70 μm) result in shallow circular cuts due to the least spot overlap of the tested pitches.

Furthermore, the viability of the process is determined by the material removal rate after a set number of passes. The data in Fig. 4 illustrate this evaluation using the 1 mm wobble amplitude after 20 passes. An optimal balance between the quality of the cut and material removal rate was found at Number 1 (300 Hz wobble frequency, 8 mm/s linear speed and 26.67 μm wobble pitch), which was the scheme used later to manufacture various architectured geometries. The proposed approach to predict an ablated high-quality cut geometry (i.e., kerf taper and cut depth) was based on the wobble amplitudes, wobble frequency, linear speed, and the number of passes. First, by

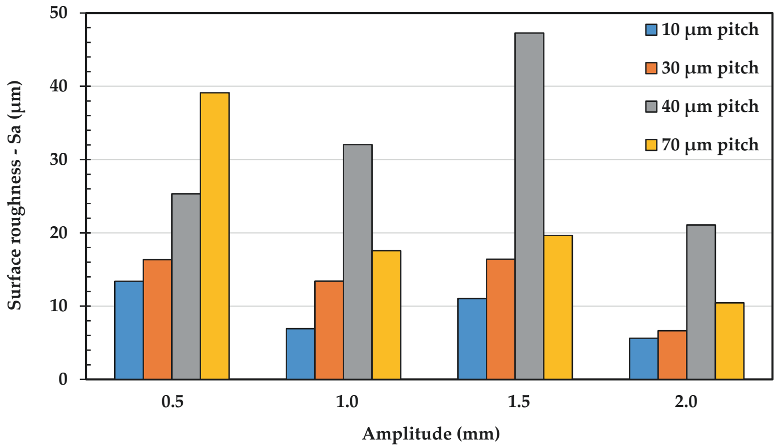

Fig. 3. Surface roughness of laser-cut profiles comparing the cut quality for different wobble pitches and amplitudes.

choosing a kerf taper or cut depth, a set of practically feasible wobble amplitudes can be calculated based on $E_L \propto \frac{P}{\omega} = \frac{E_p \cdot f_p}{\pi A f_w}$ (see Fig. 2). The desired depth can either be a through cut based on the thickness of the ceramic tile or a partial cut to create a net-shaped cavity. To prioritize material removal rate over processing time, a set of low wobble frequencies are chosen, and corresponding linear speeds such that the wobble pitch is less than or equal to 30 µm to maintain acceptable cut quality (see Fig. 4). The specific number of passes is then determined based on the amplitude to obtain the final cut depth and kerf taper. Finally, the experimental cut depth and kerf taper can be compared with the initial inputs to adjust the wobble amplitude or number of passes.

The present work delineates that high precision, deep ablated cuts can be achieved on alumina ceramics through the implementation of low wobble frequencies and linear speeds. Since other types of ceramics have similar characteristics (e.g., material removal by melting vs. ablation), the developed methodology for deep and angle cutting can be applied with similar trends; however, different energy densities should be applied.

I. Lower values of wobble frequencies and linear speeds increase the linear energy density of the picosecond laser that results in a higher material removal rate. This is an important consideration for upscaling the deep cutting process.
II. Both depth and wobble amplitude measurements as functions of wobble frequency were in agreement with the power-law relationship of these parameters with the linear energy density formulation.
III. By setting a maximum wobble pitch (in this study 30 µm), the wobble frequency and linear speed should be optimized for each specific ceramic.
IV. In addition, larger wobble amplitudes can deliver deeper cuts due to decreased beam clipping which is caused by the kerf edges of the cut geometry. However, an important consideration is that higher wobble amplitudes have lower linear energy densities and, when set large enough, may not yield efficient cuts (partial melting

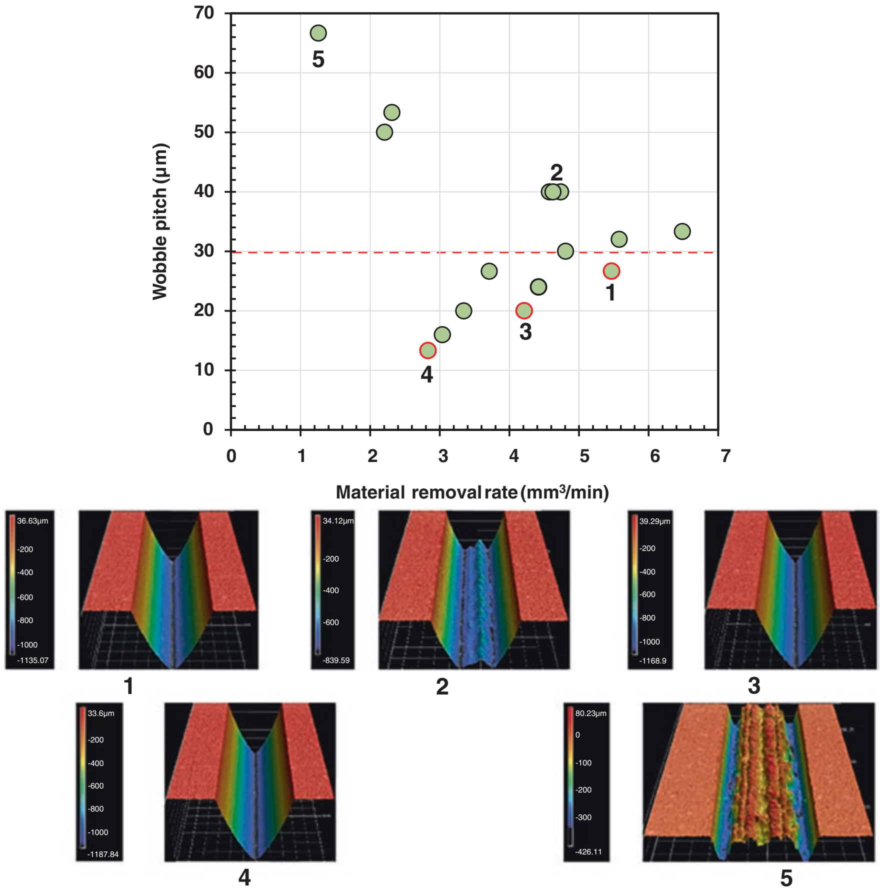

Fig. 4. Evaluation of the wobble pitch and the material removal rate for the 1-mm wobble amplitude cuts to assess the trade-off with low processing time while maintaining high cut quality.

and ablation instead of full ablation). In contrast, low wobble amplitudes (i.e., 0.1 mm) have significantly larger linear energy densities initiating melting mechanisms during manufacturing. There is high variability of the measured cut depth geometry which also demonstrates a visible recast layer causing the initiation of cracks.

V. A non-linear relationship was observed between the material removal rate and the number of passes. There are a plethora of reasons for this outcome, a few of which are: the beam is increasingly out of focus as ablation occurs at deeper regions in the sample, the V shape created by the beam spreads the laser spot over a larger region, clipping of the beam incurred by cut wall shadowing reducing the fluence, increased dust and fume interactions with the laser beam.

VI. In addition to cut depth and kerf width, cut quality is an important parameter to consider. Processing time and cut quality are mutually exclusive with respect to wobble pitch. As the wobble pitch increases, the overall cutting time decreases since a higher linear speed is used for the same input wobble frequency.

VII. By increasing the wobble pitch, the distance between the wobble circles increases and the subsequent overlap of laser pulses decreases, resulting in the "valley and hill" patterns at the center of the cuts.

4 Conclusions

This paper presented a novel method to control the final cut depth and kerf taper to produce cavities and through cuts by implementing a circular wobble scanning pattern with a picosecond laser. Using a range of input process parameters to control the linear energy density and geometry of this pattern (i.e., wobble amplitude, wobble frequency, wobble pitch, and linear speed), smooth, deep and defect-free cuts of desired geometries were obtained with a high degree of precision. It was found that the smaller wobble amplitudes and lower frequencies produce deeper cuts and smaller kerf tapers. Lower wobble frequencies are preferential when considering the processing time, as a greater cut depth can generally be achieved for the same linear speed but 100 Hz must be considered as the lower threshold since significant melting of the ceramic and large heat-affected zones was observed at this frequency. In addition, control of the wobble pitch can be achieved by modifying the linear speed for a chosen wobble frequency. The surface roughness, which is used to determine cut quality, increased significantly for wobble pitches above 30 μm. A 70 μm wobble pitch limits the ablation to a shallow cut profile and can be used for applications that require specific surface roughness's. The developed approach accurately defines the kerf taper as a function of the cut depth for cut profiles that have a developed "V-shape." This approach allows the design of different advanced engineering applications such as manufacturing of topologically interlocked ceramics.

Acknowledgments The authors would like to thank the security, materials, and technologies (SMT) program at National Research Council Canada (NRC).

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