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CO_2 laser underwater machining of deep cavities in alumina

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Abstract

A method for crack-free machining of deep cavity in alumina is demonstrated using a low-cost CO_2 continuous wave (CW) laser. CO_2 laser underwater machining has been found to result in reducing substrate defects such as recast layer, dross, cracking and heat damages that are typically found in machining in air. Finite Element (FE) modelling technique and Smooth Particle Hydrodynamic (SPH) modelling technique were employed to understand the effect of water on crack resistance and debris removal during underwater machining. Also the microstructures of machined region were demonstrated to reveal different heating and cooling processes during laser machining in water and in air. The experimental results indicated that the machined kerf width was strongly affected by the water layer thickness, whereas the kerf depth was controlled by both the laser pass number and water layer thickness. The optimal average machining rate was up to 2.95 mm^3/min at a 60 W laser power.

Keywords: Al_2O_3; Milling; Defects; Structural integrity; Laser machining; Finite element modelling (FEM); Smooth particle hydrodynamic (SPH)

1. Introduction

Alumina is one of the most used structural ceramics in a variety of applications ranging from microelectronics to prosthetics due to its desirable properties, such as high hardness, low chemical reactivity, low mass density, low thermal and electrical conductivity and ultra-fine finishing capability.[1] However, these applications require fast processing, tight dimensional tolerance and excellent surface finish. Therefore, processing and manufacturing of alumina with high accuracy become very important. Conventional ceramic machining techniques use diamond grinding to remove the material, which often leads to fracture, tool failure, low surface integrity, high energy consumption, and tool wear.[1,2] Furthermore, the closed and complex cavity machining poses more challenges to traditional machining techniques. As a result of the lacking of techniques for machining high precision and complex shapes for ceramics, laser beam machining techniques have been developed due to the unique advantages of the laser processes, such as high energy density, non-contact machining, high feed rate, high precision, and small heat-affected zone (HAZ).

Although CO_2 lasers and Nd:YAG lasers have been widely used for machining of ceramics, defects such as cracking and recast layers often occurred due to rapid cooling, high thermal gradients and brittleness of the materials. Especially, the continuous wave (CW) lasers were rarely used directly for machining ceramics at room temperatures in air without forced cooling (i.e. assist-gas) due to high stress developments caused by the serious heat generation in ceramics. Nisar et al. studied the effect of continuous and pulsed laser beam modes on thermal-stress developments in diode laser controlled fracture machining of glass. They found that the short pulse lengths can reduce thermal-stresses and arrest the crack propagation.[3] Zeng et al. reported laser carving of 3D structures in alumina substrates using a short pulsed CO_2 laser, by which a 15 mm × 14.27 mm × 2.5 mm cavity was obtained within 50 min. They found the process quality was mainly dependent on the parameters such as pulse repetition rate, scanning speed, pulse energy, interval of scanning lines and slicing thickness.[4] Hand et al. examined the parameters for a nanosecond pulsed (60 ns) Nd:YAG laser crack-free machining of yttria-stabilized tetragonal zirconia polycrstal (Y-TZP) ceramics. They found that the combination of processing

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variables (at an average power of 11.3 W, a repetition rate of 30 kHz and a scan speed of 50 mm/s) provides the optimum material removal rate up to ~2 mm^3/min for machining Y-TZP ceramics. Additionally, it was found that the pulse overlap has a significant influence on the process efficiency and hence the combination of scan speed and repetition rate should be carefully considered. Their experimental results showed that too much pulse overlap or insufficient pulse overlap could create low quality machined surfaces.[5] In order to improve the process efficiency of nanosecond pulsed laser machining, Hand et al. presented a method of nanosecond-laser post-processing of millisecond-laser machined Y-TZP surfaces. A millisecond laser (0.3–5 ms) system was first used to provide a "rough machining" process with a high-speed material removal due to the high average power available, in which the material removal rate was up to 2.5 mm^3/s without significant cracking. However, the quality of the finished surface is limited by recast layer formation and heat-affected zones, in particular surface micro-cracks. A nanosecond laser (50–100 ns) system was then used to finish the "fine machining" process in a relatively short time.[6] The nanosecond laser post-processing of millisecond laser machined surface used two different sets of parameters to combine an optimal material removal rate at 15 kHz for the removal of the recast layers with a lower thermal impact machining at 60 kHz to further reduce the extent of cracking.[7] However, the pulsed laser ablation needed a high power source and machined surface had a relatively high roughness due to the inherent profile of overlapping of the pulses. Moreover, the dual-laser processing technique would be costly for industrial applications. Tsai et al. developed a fracture-machining element technique for the milling of closed cavities in alumina substrates,[8] which was based on the controlled fracture machining technique.[9] It employed crack propagation to achieve material removal and attained a high material removal rate 0.15 mm^3/s with less material melting during process. However, the complicated system consisting of dual lasers (a CO_2 laser and an Nd:YAG laser) was inevitable. Most importantly, the process quality did not satisfy the industrial requirements. A post-process for smoothing the surface was essential before final uses. For a high process quality, picosecond and femtosecond lasers have been applied in previous research, but the material removal rates were very low (2.2 mm^3/min and 0.054 mm^3/min, respectively) and the expensive systems are only suitable for micro-machining.[10,11]

Laser-assisted machining (LAM) is another alternative technique for machining of ceramics. During LAM, the workpiece is heated intensely and locally by a laser beam, and then machined with a conventional cutting tool.[12] Due to the advantage of lowered hardness and brittleness of the material at elevated temperatures, LAM can achieve lower cutting forces, reduced tool wear, higher material removal rates, and better surface quality for various advanced ceramics, such as alumina,[13] silicon nitride,[14] mullite,[15] and magnesia-partially stabilized zirconia.[16] LAM includes laser-assisted turning and laser-assisted milling.[17] Laser-assisted milling has been successfully performed for milling of silicon nitride[18–21] and alumina ceramics.[13] Unfortunately, effective cooling of the cutting tool, optimisation of the machining process and flexible control of the laser source to achieve complex pattern machining are the challenging tasks for laser-assisted milling,[17] which limit LAM for further industrial applications. Until now, laser beam machining is still considered as a desirable technique for machining of hard-to-machine materials due to its unique advantages, such as flexible machining process, compact system structure, controllable process parameters, and high material removal rate.

The main challenge for laser machining in air condition is the heat accumulation and molten material resolidification onto the machined surfaces, which cause serious HAZs and crack initiation. In 1988, Morita et al. first reported the pulsed YAG laser drilling of ceramics in water.[22] They found that the recast layer and cracks that were always formed during machining in air could be avoided in underwater machining. Kruusing further reviewed the advantages and disadvantages of water-assisted laser processing and concluded that the underwater machining techniques can be successfully applied to etching, cutting, surface cleaning, and shock processing.[23,24] In previous studies, the Nd:YAG laser emitted at 1.06 μm was considered as an ideal laser for underwater machining due to the low optical energy absorption of water with respect to this wavelength.[25,26] On the other hand alumina and glass also have a low absorption for a YAG laser compared with a CO_2 laser. Therefore, CO_2 laser underwater machining was developed. The mechanism of CO_2 laser underwater machining is different from that with a YAG laser due to the high absorption of water for the 10.6 μm wavelength CO_2 laser. During CO_2 laser underwater machining, a proportion of the laser energy vaporises the water and forms a conical keyhole in water allowing the laser beam to reach the workpiece. Black et al. found that the thermal load during CO_2 laser underwater cutting of ceramic tile was reduced by the intensive cooling effect of water.[27] Chung et al. employed a CO_2 laser with galvanometer mirrors to achieve crack-free drilling and cutting of Pyrex glass, where the defects of bugle, debris, cracks and scorch often occurred during laser machining in air were eliminated in underwater machining.[28,29] Tsai et al. performed a wide range of experiments on laser drilling and trepanning of thin glass and alumina substrates in air and in water. They found that the underwater drilling quality is much better than that in air. Underwater drilling could prevent the micro-cracking and reduce the HAZ.[30]

Although many investigations focused on the underwater drilling and cutting of thin ceramic or glass substrates, few studies pay attention to the cavity machining for alumina in water, especially machining of mm-deep cavity. Many studies discussed the mechanism of underwater laser processing, but the benefits of the process have not been entirely revealed. Moreover, the machining parameters for CO_2 laser underwater milling of deep cavity in alumina have not been studied before.

In this work, underwater machining of deep cavities in alumina ceramic using a low-cost CO_2 continuous wave (CW) laser was studied. Finite element modelling technique was employed to study the temperature and resulting stress distributions during laser machining in air and in water, in order to understand the mechanism of underwater crack-free machining. The crack formation during machining in air was also predicted based on the FE simulated result and validated via experiments. The effect