High-Precision Micro Cutting of Ceramics with Short-Pulsed Solid-State Lasers

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This contribution will present results for high-precision cutting of technical ceramics with short-pulsed solid-state lasers in fundamental and frequency-doubled wavelength. On the basis of ample experiments, a surprising absorption behaviour of some ceramics in the case of irradiation with high intensity will be discussed. Furthermore, the influence of wavelength and process gas on cutting speed and quality is demonstrated. The investigations resulted in a process strategy with multiple passing over of the kerf suited for remarkably improving process velocity and quality. Finally, structures applicable for nozzles and spinnerets are shown.

Keywords: micro cutting, ceramic, short-pulsed, solid-state laser, laser-machining.

1. Introduction

In the case of ceramics, conventional processes cannot meet the increasing requirements with regard to reduced dimensions and tolerances. Furthermore, there is a demand for non-circular shaped holes which cannot be adequately fulfilled by conventional techniques. For this reason, the interest of industry in precise laser machining of ceramics has constantly grown.

Up to now, CO_2-lasers have almost exclusively been used for laser processing of ceramics in industrial applications. In the case of micro machining, mainly excimer lasers have been taken into account. The wavelengths emitted by both types of lasers are strongly absorbed in ceramics, which is not expected for solid-state lasers.

2. Absorption behaviour of ceramics

Regarding the interaction of laser beam and bulk material, there is an essential distinction between pure and homogeneous ceramics and technical ceramics. Furthermore, there is a difference in absorption phenomena at high and low intensity.

2.1 Low temperature, low intensity absorptivity

In literature, for pure ceramics some data of optical properties can be found [1]. The degree of reflection is lower than in metals and much more of the incident light is penetrating into the bulk material. In metals, penetrating radiation is completely absorbed in a surface layer of a thickness an order of magnitude smaller than the wavelength. Fig. 1 depicts the optical penetration depth in case of some ceramics. It is remarkable that the behaviour of these ceramics is totally different from those of metals in the spectral range between 0,5 and 10 μm. The penetration depth is even up to three orders of magnitude larger than the wavelength in this so-called transmission window.

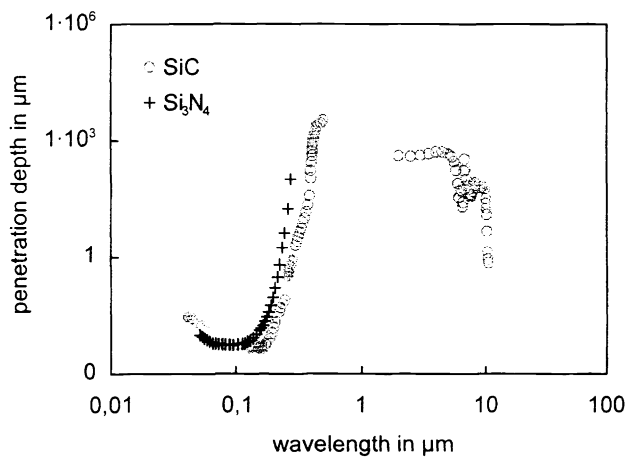

Fig. 1: Absorption length l_α in pure and homogeneous SiC and Si_3N_4 depending on wavelength.

As laser ablation is a thermal process, the penetration depth has a decisive influence. Depending on the incident fluency, a certain maximum of optical penetration should not

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be exceeded to reach temperatures required for laser ablation. Neglecting heat conduction, it is possible to calculate achievable surface temperatures in dependence on optical penetration depth and fluency. In case of pure ceramics only a deficient heating is to be expected because of the optical penetration depth in the range of 1 mm.

2.2 High temperature, high intensity absorptivity

Despite of what could be deduced from Fig. 1 and the calculations, ceramic materials can be machined with Nd:YAG-lasers quite efficiently [2]. An explanation for this surprising observation was found by investigating the high temperature optical behaviour of various ceramics with a calorimetric set-up [3]. Fig. 2 shows results for technical Si_3N_4 and AlN. Besides a more or less pronounced trend of decreasing penetration depth, both materials show a dramatic increase in reflectivity starting at a temperature depending on material composition. In [4], this effect was connected with the high temperature chemistry of these materials causing a decomposition in gaseous and liquid metallic components, mainly. From this we can conclude that in case of energy density values high enough to heat the surface within pulse duration to decomposition temperature, the ceramic material starts to show optical behaviour like metals.

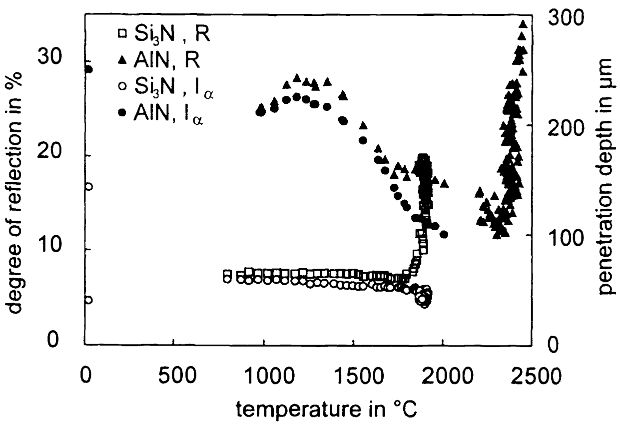

Fig. 2: Reflectivity R and absorption length l_α of technical AlN and Si_3N_4 at high temperature.

3. Ablation behaviour of ceramics

In ceramics, the change to metallic behaviour described above is limited to the hot interaction zone, the surrounding bulk material remains semi-transparent. The change to metallic behaviour however, should not be necessarily permanent as transmission experiments with picosecond laser pulses turned out at the General Physics Institute in Moscow. The results of these experiments are shown in Fig. 3. At first, initial transmission through a thin ceramic plate was measured at an intensity too low for ablation. Afterwards transmission was measured during ablation with an intensity of 10^{12} W/cm^2 and finally with low intensity after ablation. During ablation, a transmission an order of magnitude smaller than the initial value was measured for both ceramics. In case of AlN, the degree of transmission remained at a low level after ablation whereas the value of Al_2O_3 nearly approached the initial value. An explanation for the decrease of transmission during ablation is plasma shielding which was confirmed in further experiments [5]. On the other hand, the permanent decrease of transmission for AlN could not be explained. For this reason, it should be supposed that a highly absorbing layer is formed during irradiation with lasers of high intensity. In case of AlN, this layer kept the optical properties after ablation, but lost them for Al_2O_3.

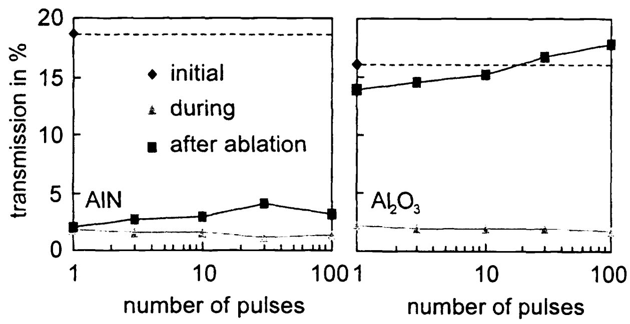

Fig. 3: Transmission of laser light through thin ceramic plates.

According to the Hirschegg Model for drilling with short-pulsed lasers [5] also two tools acting during the cutting process can be assumed for the special process technique described below. The primary one is the laser beam which is responsible mainly for the deepening of the kerf in the direction of its propagation and feed direction. The secondary tool is a laser induced plasma which acts primarily in radial directions, widens the kerf and smooths the cutting edge.

4. Processing technique

As we have shown in several publications [5-7] for drilling, a breaking up of the process in a multitude of ablation steps (the so-called helical drilling) is suitable to enhance accuracy. We adapted this technique to the high-precision micro cutting of complex geometries. In contrast to conventional cutting which is essentially a through drilling followed by the cutting procedure, the so-called laser-machining reaches the breakthrough after multiple passing over of the kerf. While penetrating the workpiece, the focal position, the pulse energy and to some extend the energy per section can be varied. An increase of accuracy is reached by shortening the pulse duration and minimizing the focal diameter which leads to reduction of ablated material per pulse.

The performance data of the diode pumped solid-state laser system used in the investigations are shown in Tab. 1

Table 1 Data of the diode pumped Nd:YAG-laser

wavelength	repetition rate	pulse duration	pulse energy	focal diameter	energy density
1064 nm	1 kHz	12 ns	8 mJ	19 µm	2822 J/cm^2
532 nm	1 kHz	12 ns	5 mJ	11 µm	5261 J/cm^2

4.1 Influence of process strategy

Fig. 4 depicts cutting kerfs and edges in Si_3N_4. The thickness of the sample is 1 mm. To compare the results of the different strategies it is helpful to define the effective feed rate by the ratio of instantaneous feed rate to number of passes. Although the instantaneous feed rate is different (1,2 mm/min for the single pass and 6 mm/min for five passes), the effective feed rate is the same and also the resulting processing time is equal.

In case of the conventional cutting technique, there is a lot of recast material remaining in the kerf. Whereas for the laser-machining nearly no recast material is observed. Furthermore, the cutting edge is even smoother than for a single passing. One possible explanation for this could be the better removal of the ablated material due to the small ablated volume per pulse in laser-machining.

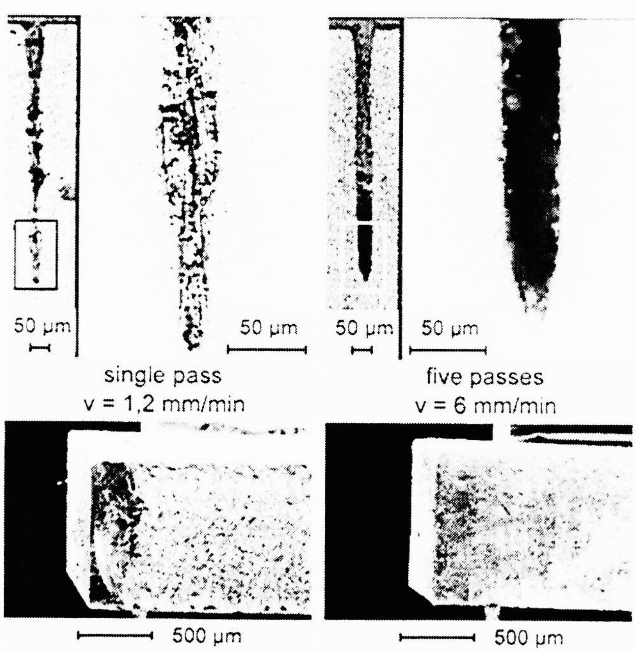

Fig. 4: Kerfs (above) and cutting edges (below) in Si_3N_4 with conventional cutting technique (left) and laser-machining (right) at same effective feed rate (v_{eff} = 1,2 mm/min, λ = 532 nm).

Further on, laser-machining not only offers an improvement in process quality but also in process efficiency as demonstrated in Fig. 5. By all means, the effective feed rate is kept constant for the comparison of the results. For both wavelengths the achievable kerf depth, which corresponds to the cutable material thickness, can be increased by raising the number of passes. This is another advantage of the small ablated volumes per pulse in laser-machining.

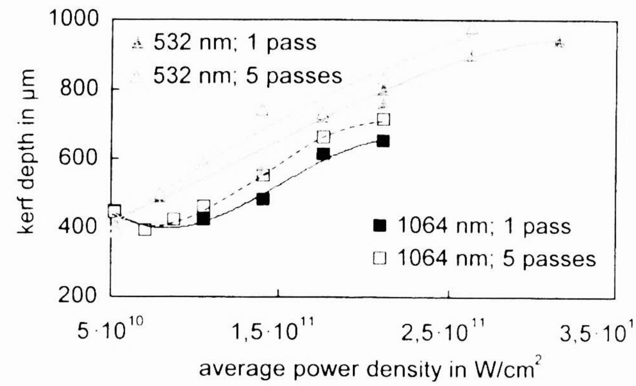

Fig. 5: Influence of process strategy on process efficiency at same effective feed rate (Si_3N_4, v_{eff} = 2,4 mm/min).

The same results have been obtained for oxide ceramics like Al_2O_3 or ZrO_2.

4.2 Influence of wavelength and process gas

The influence of process gas on process efficiency is shown in Fig. 6 for Al_2O_3 and different wavelengths. At 1064 nm and for a material thickness of 800 µm, it is possible to increase the feed rate by 100% from about 1 mm/min to more than 2 mm/min by using helium as process gas. This can be attributed to smaller shielding effects of the laser induced plasma, in comparison to a processing without helium. Due to less plasma interaction at shorter wavelengths it is even possible to achieve a 50% higher feed rate in the second harmonic than in the basic wavelength without gas. No remarkable increase in feed rate at higher material thickness could be attained with helium as process gas for a wavelength of 532 nm.

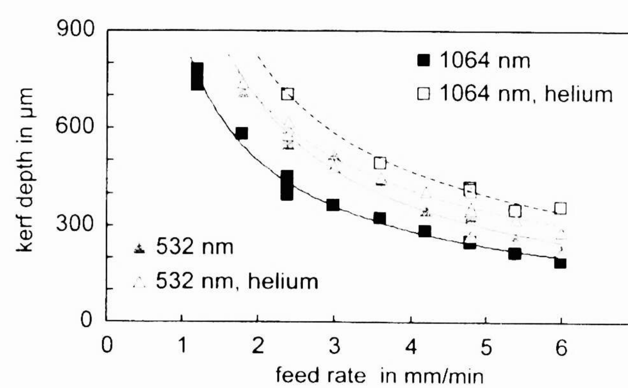

Fig. 6: Influence of wavelength and process gas on cutting speed (Al_2O_3, single pass, E = $2,1 \cdot 10^{11}$ W/cm^2).

Apart from process efficiency it is important to consider the process quality. In Fig. 7 SEM-pictures of typical cutting edges are depicted for Al_2O_3. Best results are obtained by

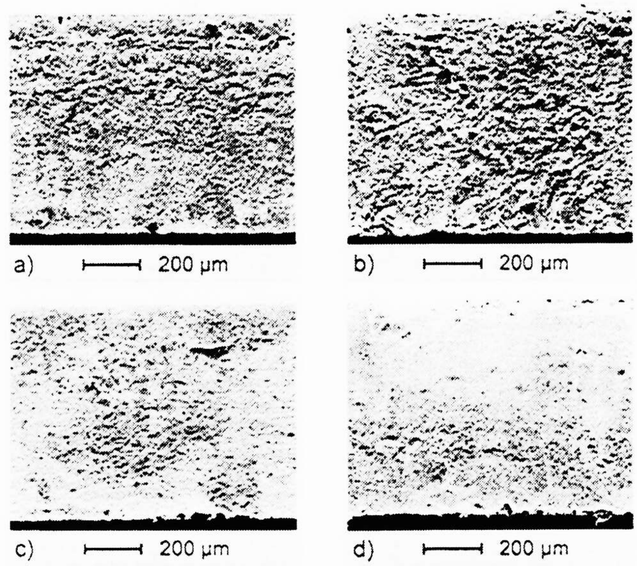

Fig. 7: Typical cutting edges in Al_2O_3 (laser-machined a) λ = 532 nm, b) λ = 532 nm with helium, c) λ = 1064 nm, d) λ = 1064 nm with helium).

laser-machining without process gas at 1064 nm. The flank is quite homogeneous, nearly without any redeposited material on it. Quality gets worse by using helium - a redeposited layer with low roughness is formed which is partly cracking off. In the second harmonic also a good quality of the cutting edge is possible without process gas. The use of helium is not sensible for reasons of quality as well as process efficiency.

4.3 Applications

An application demonstrating the possibilities of laser-machining is presented in Fig. 8. A so-called trilobal geometry in Al_2O_3 with a thickness of 0,4 mm was produced. The width of the legs is 100 µm and the length is about 300 µm. The cast taken from this complex geometry shows a very smooth surface of the flank and good constancy in shape. The detail on the right depicts the sharp edge at the exit.

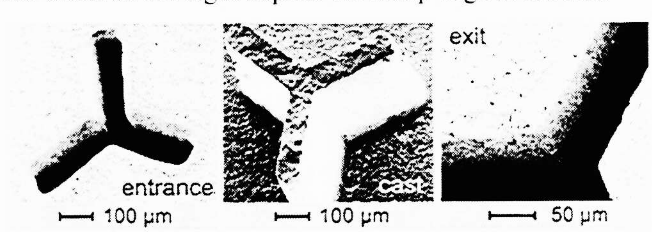

Fig. 8: Laser-machining of a trilobal geometry for spinnerets (under contract of CeramTec AG).

As a matter of principle, nearly any geometry can be produced by laser-machining. For this reason, an application in ceramic nozzles and spinnerets is conceivable. A prototype of a ceramic spinneret in ZrO_2 is depicted in Fig. 9. The dimensions of the star are nearly the same as for the trilobal, the material thickness to be cut is about 600 µm.

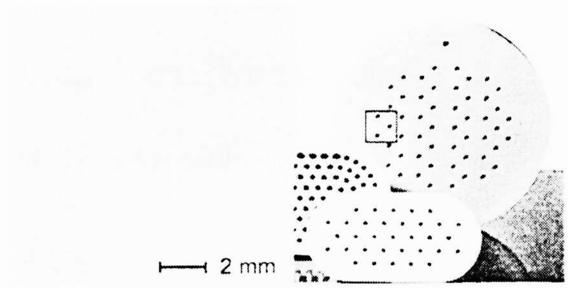

Fig. 9: Prototype of a laser-machined spinneret.

5. Conclusions

Diode pumped solid-state lasers offering pulse energies beyond several mJ at pulse duration near to 10 ns allow to produce complex geometries of high aspect ratio and unprecedented accuracy in combination with the laser-machining process.

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