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Laser-material interaction using pulsed lasers on structural ceramic: Si_3N_4

Babak Soltani[1], Colin Harper[2], Bahman Azarhoushang[1]

[1]*Institute for Precision Machining, Jakob-Kienzle-Str. 17, 78054, Villingen-Schwenningen , Germany*
[2]*School of engineering, the University of Glasgow, James Watt South building, Glasgow, G12 8QQ, UK*

Babak.soltani@hs-furtwangen.de

Abstract

Pulsed laser radiation can be efficiently applied to create precise detail on the material surface through ablation and heat induced modification of the microstructure. Laser assisted machining processes can provide new opportunities to reduce the manufacturing costs of high performance ceramics like Si_3N_4.

This paper researches the laser-material interaction for Si_3N_4 using both nanosecond and picosecond pulsed lasers with ~1000nm wavelength. Power is kept constant, however the laser scanning speed will be varied to demonstrate how the amount of laser input energy incident on the surface, and pulse duration can alter the process' effects. Laser line depths and heat affected zone (HAZ) widths have been measured to analyse the laser cuts. Further analysis is done utilising EDEX to elucidate data on the chemical integrity of the material after laser ablation.

At picosecond laser scanning speeds up to 100mm/s, there is a pile up of displaced material next to the laser line. There is also a HAZ which shrinks as the speed increases and is still present up to 1000mm/s. In comparison with the picosecond laser, the depth of cuts and laser ablation at any scanning speed was less efficient using the nanosecond laser.

Laser-material interaction, Picosecond laser, Nanosecond laser, Silicon nitride

Introduction

Silicon nitride as a ceramic material which has been used in many industries due to its exceptional mechanical, thermal and chemical properties [1]. However, the manufacturing cost dramatically increases due to the mentioned mechanical properties, particularly high hardness. In order to achieve high stock removal rates, laser ablation methods are used as a non-contact, unconventional machining process or as an assisted-machining process for ceramic materials [1]. The properties on the surface of the bulk material can be altered through laser irradiation; this changes depending on the laser parameters: laser input energy, laser pulse duration and laser wavelength [2-5]. The laser–material interaction during ablation depends on the choice of laser as well as the thermal and optical properties of the material [4,6]. This involves both the photo-thermal (vibrational heating, melt expulsion and evaporation) and photo-chemical (bond breaking and generation of new compositions) processes [6].

Understanding of the laser material interaction leads to improvements to the laser treatment's accuracy and efficiency from both physical and chemical aspects. Consequently this leads to more reliable laser ablation processes for practical purposes.

Experimental setup

This study investigates and analyses the laser-material interaction for Si_3N_4. The applied material in this study was gas-pressure sintered Si3N4 SL200B/BG from CeramTec GmbH. Table 1 shows the mechanical and thermal properties of the material.

As shown in table 2, in all tests, the laser power is kept constant (50 watts) however, the laser scanning speed (1 mm/s to 1000 mm/s) and pulse duration are varied to demonstrate how the amount of laser input energy incident on the surface and can alter the process' effectiveness and the laser cut topography. To investigate the effect of pulse duration, two different lasers were used.

Table 1. Material properties of SL200BG CeramTec Silicon nitride [7,8]

Young's Modulus [Gpa]	166-297
Fracture Toughness K_{1C} [Mpa.m$^{1/2}$]	1.8^{-7}
Thermal Expansion [/°C]	3.2×10^{-6}- 4.3×10^{-6}
Melting Point [°C]	2388 - 2500

Table 2. Test parameters

Scan Speed [mm/s]	**Picosecond laser**		**Nanosecond laser**	
	Power [W]	**Repetition Rate [kHz]**	**Power [W]**	**Repetition Rate [kHz]**
1 to 1000	50	400	50	200
2,5 to 225	-	-	50	200

The laser devices used for these experiments are a TRUMPF TruMicro 5050 picosecond laser and a Rofin Powerline F100. Both of them were Nd:YAG solid state lasers which produce laser pulses with a wavelength of 1064 nm. Table 2 illustrates the laser properties of these devices.

Table 3. Laser parameters

Parameters	**Picosecond laser**	**Nanosecond laser**
Average Power [W]	50	Max 100
Pulse energy [µ Joules]	125	Max 500
Pulse Duration [ps]	<10	1000
Repetition Rate [kHz]	400	Max 200

To analyse the surface topography and chemical composition changes of the laser cut lines, confocal microscopy and EDEX (Energy-dispersive X-ray spectroscopy) were utilized.

Results and discussion

Figure 1 shows the topography of laser cut lines as well as the difference in effects due to the laser pulse duration on surface topology. By decreasing pulse duration from 1000 ns to 10 ps, pile up of ablated substrates increased. It can be concluded that with increasing laser pulse duration, the melt expulsion is dominant as an ablation mechanism.

Figure 2 depicts the trends in laser line depths and HAZ widths in the range of laser scanning speeds from 1 to 1000mm/s. Compared to the nanosecond laser, the picosecond laser induces deeper laser cuts and a wider HAZ at the same laser scanning speeds. As shown in figure 2 (a), the cut depth decreases as the scanning speed increases. Additionally, as the speed increases above 10mm/s to 100 and 1000 the pile-up is diminished and laser cuts with smoother edges are produced. Wider and flatter groove bottoms are also produced by higher scanning speeds. Consequently, the depth of the visible laser cuts increased. However, the height of the pile-up and width of the damaged zone of laser treated surface decreased significantly.

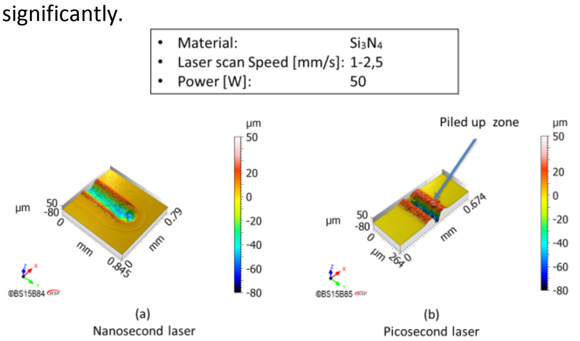

Figure 1. Pulse length effect, confocal microscopy images

Figure 2 (b) clearly indicates that the HAZ width declines sharply with rising laser scanning speeds, from 100 to 1000 mm/s, while there was no pile up zone for laser scanning speeds beyond 300 mm/s. Therefore, it could be concluded that, for laser scanning speeds above 300 mm/s, evaporation of material from the irradiated surface is the dominant ablation mechanism.

Since the experiments were performed in ambient air and the photochemical ablation mechanism can affect the irradiated surface, some EDX analyses have been performed to investigate the oxygen content of the material. Summarized results are depicted in figure 3. The oxygen content in the bulk material was approximately 3-5 atm%, while it was approx. 50 atm% in the laser cuts with 1 mm/s scanning speed. Increasing the laser scanning speeds up to 100 mm/s leads to a decrease in the oxygen content. At 1000 mm/s, there are no visible laser cut lines on the irradiated surface with nanosecond laser. However, on the surface irradiated with the picosecend laser and 1000 mm/s scanning speed, the oxygen content of the laser cut lines decreases to about 2 atm% more than the bulk material.

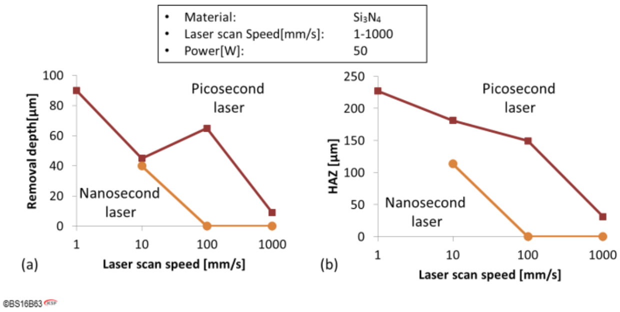

Figure 2. (a) Laser line depth and (b) HAZ width vs laser scan speed

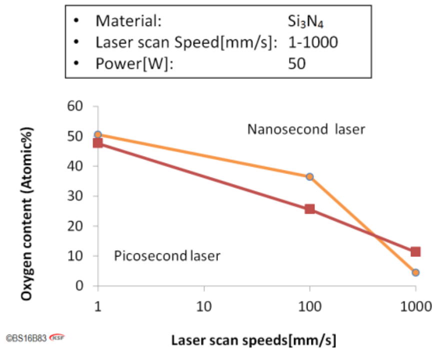

Figure 3. Oxygen content on the laser cuts

Conclusion

The following results can be concluded from this study:

- The melt expulsion dominates as an ablation mechanism with decreased laser pulse duration.
- The laser cut depth decreases as laser scanning speed increases.
- Based on EDX results, at laser scanning speeds more than 700 mm/s, the chemical interaction of the laser cut line with oxygen in the air decreases significantly.
- In all cases, and compared to picosecond laser, the nanosecond laser is less efficient when using the same laser scanning speeds.

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