SiC high-tech ceramics – a comparison of laser processes

Optimizing laser processes for SiC ceramics: focusing on precision, efficiency, and processing quality

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Extensive R&D applied various laser sources – from nanosecond VIS-wavelength to femtosecond IR and water-jet guided lasers – to enhance the quality and efficiency of laser structuring, fine cutting, and drilling of silicon carbide. Tests focused on surface roughness, cutting line precision, and high ablation rates. Challenges due to diverse material compositions, like diamond layers, required combined methods to develop viable approaches. To meet economic constraints, mechanical grinding was integrated with recurring laser processing.

Silicon carbide (SiC) and its variants – sintered SiC (SSiC), silicon infiltrated SiC (SiSiC), diamond SiC, et cetera – is a material that is very popular nowadays. The areas of application range from high-temperature applications such as the lining of steel furnaces and waste incineration plants to composite materials for components in gas turbines [1] and other refractory products. Other areas of application include sealing rings, soot filters and brake disks in the automotive industry as well as structural and functional ceramics [2, 3]. The material owes this wide range of applications to its special properties in combination: very good oxidation and corrosion resistance, low density and a low thermal expansion coefficient meet high thermal conductivity as well as very high hardness and abrasion resistance [3].

One specific example is the components for pumps and other units for subsea applications developed as part of the SubseaSlide R&D project. The environmental conditions make the maintenance of the components used there extremely difficult, which is why materials such as SiC-bonded diamond materials, which are extremely resilient and wear-resistant, are used [4]. However, the properties mentioned pose problems for mechanical manufacturing processes, which is why alternatives such as laser processing come into play here. In laser material processing, for example, technologies such as nanosecond pulsed laser processing [5], pico and femtosecond IR sources [6, 7] and water-jet guided laser beam processing [8] are used.

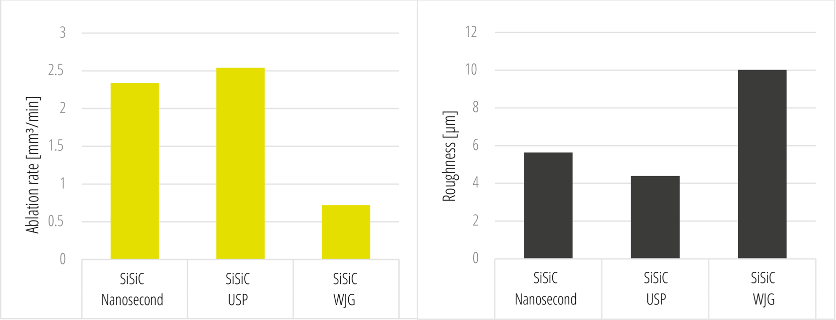

Fig. 1 Comparison of technologies in terms of ablation rate and roughness for structuring

Compared to other mechanical cutting and grinding processes, laser material processing is characterized by tool-free and contact-free processing without mechanical stress on the workpiece. Although the use of conventional, rather long-pulse nanosecond laser sources reduces the energy input and leads to minimal heat conduction effects, the process still belongs to the thermal processes in which the material is melted or directly vaporized in the processing zone [9].

Modern ultrashort-pulse laser material processing uses very short pulses – in the range of femtoseconds and picoseconds – in which the exposure time of the individual pulse in the material is so short that heat conduction effects do not occur or are so small that they can be neglected. It is therefore considered an athermal ablation process. Due to the short pulse durations, the penetration depth and therefore the removal per individual pulse in the material to be processed is less than with thermal processes. However, this increases the accuracy that can be achieved in comparison [9].

The water-jet guided (WJG) laser technology is characterized by the fact that a thin laminar water jet is generated into which a laser beam is threaded. Multiple reflections of the laser beam at the inner edges of the water jet ensure that the intensity distribution of the laser beam is approximately the same over the length of the water jet. In this way, the caustic effect typical of a laser beam is avoided, allowing vertical cutting edges (< 1°) to be produced. Similar to ultrashort-pulse processing, this is an ablative process. The additional cooling of the water jet reduces the thermal input into the material, which means that ceramics such as SiC can also be machined without cracks.

The tests for machining SiC were carried out as part of the funded SubseaSlide, SAPHIR and UKPino R&D projects.

Technology

The SiC laser processing methods that are compared here use nanosecond pulsed (ns), ultrashort-pulsed (USP) and water-jet guided laser radiation, as well as fusion cutting. The ns-pulsed system works with a maximum average power of 100 watts at 1 mJ pulse energy and with a pulse length of 120 ns at a wavelength of 355 nm. The diameter of the laser beam at the focus is 50 µm. The laser beam is positioned by means of scanner optics. The system also has an additional processing head that was used for the fusion cutting experiments. The cutting optics are operated with a solid-state laser (1,070 nm) in cw mode and provide a power of 1 kW. The focus is 60 µm and positioning is carried out using an x-y table.

The laser for ultrashort-pulse processing is characterized by pulses of up to 1 ps at a wavelength of 1,030 nm and a maximum average power of 100 W. The diameter of the laser beam at the focus is 60 µm and positioning is carried out in the same way as with the nanosecond laser using scanner optics.

The water-jet guided system uses a fiber laser with a wavelength of 1,070 nm. The diameter of the water jet and thus also the focus of the laser beam can be adjusted using different nozzles. Nozzles with a diameter of 50 – 80 µm were available for the experiments. As the quality of the water has a decisive influence on the processing result, it is filtered until it has a conductivity value of less than 0.1 µS/cm. An x-y table is used to position the workpiece relative to the water jet, as in the dry processing station.

Evaluation

A direct comparison of test sequences, laser parameters and their optimization makes little sense when comparing the technologies, as their physical modes of action differ too greatly. The processing results are therefore compared with each other.

As ablation processes, nanosecond pulsed, ultrashort-pulse, and water-jet guided technology are able to produce 3-dimensional structures using 2.5D machining. Important target parameters here are the removal rate, which determines how quickly a volume can be processed, and the quality of the processing surface that can be generated, which can be measured using roughness for example.

Laser processes	Minimum pulse duration [µs]	Beam Positioning	Focal diameter [µm]
Fusion cutting	cw	x-y table	60
Water-jet guided (WJG) machining	10	x-y table	50 – 80
Nanosecond (ns) machining	0.12	scanner	50
Ultrashort-pulse machining (USP)	0.000001	scanner	60

Table 1: Overview of technologies with associated systems engineering

Company profile

LCP Laser-Cut-Processing

For more than thirty years, LCP has specialized in the laser fine machining of delicate, geometrically complex and sensitive microprecision components made of special materials. Our technical expertise, our R&D activities as well as the passion and creativity of our team drive us to produce new solutions for high-performance products in demanding high-tech applications. We have a wide range of laser technologies, mechanical machining processes and a network of cooperation partners at our disposal. Advice on technical feasibility and our service along the entire process chain are the basis for the satisfaction of the customers.

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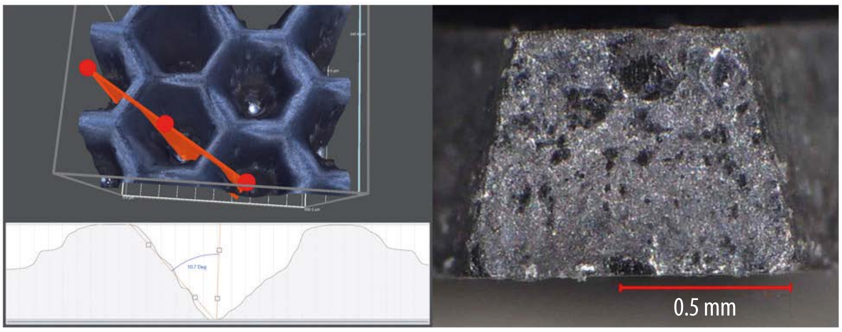

Fig. 2 Taper created during structuring: (a) ultrashort-pulse, (b) water-jet guided laser machining

Fig. 1 shows the comparison of the technologies during structuring in terms of ablation rate (left) and roughness (right). It can be seen that the ablation rate for the nanosecond pulsed and the ultrashort-pulse system is significantly higher than for the water-jet guided technology. The ultrashort-pulse and nanosecond processing systems can provide significantly higher feed rates due to beam positioning using a scanner. In addition, the repetition rates for the machining/preferred parameters are higher – 10 kHz (ns), 400 kHz (USP), 500 Hz (WJG) – which results in a higher ablation rate overall.

A comparison of the roughness of the ablated surface shows the opposite picture. Here, the lowest values are achieved when processing using ultrashort-pulse technology (R_a = 4.4 µm), followed by the ns-pulsed system (R_a = 5.64 µm). The surfaces ablated using a water-jet guided laser beam have a significantly higher value in comparison with an R_a of 10.02 µm. The reason for this lies in the selected track spacing. This is 20 µm for the preferred parameters of ns and ultrashort-pulse machining and 40 µm for water-jet guided technology. The track spacing has a significant influence on the roughness achieved when processing with a pulsed laser: the smaller the track spacing, the lower the roughness [10]. To remove a given geometry, the total processing time increases with reduced track spacing, which has a negative effect on the ablation rate. Fast, scanner-based systems can compensate for this better than the slower systems with an x-y table.

In a comparison of the technologies, structuring using ultrashort pulses achieves the highest ablation rate (2.54 mm^3/min) with the lowest roughness (4.4 µm) within the process parameters considered for this publication. For pure structuring tasks on SiC materials, ultrashort-pulse technology is the preferred variant.

A side effect during removal using ns and ultrashort-pulse technology is the resulting taper. Vertical cuts are possible due to the constant diameter in the working area of the water-jet guided technology [11]. However, the removal of SiC also generates a taper with this process (Fig. 2b).

Fig. 2 shows a comparison of the resulting taper when structuring using ultrashort-pulse and water-jet guided technology. Due to the process, nanosecond and ultrashort-pulse processing requires a widening of the kerf with additional tracks for material thicknesses >100 µm. The tests showed a taper of 11° for the preferred parameters, which would result in a kerf widening of 1.94 mm for a material thickness of 5 mm. Depending on the machining geometry, this is not desired or possible, which is why nanosecond and ultrashort-pulse technology are not considered for the cutting tests.

Several passes are required to cut the SiC for material thicknesses from 0.5 mm (fusion cutting) and 0.2 mm (water-jet guided processing). The required number of passes depends on the material thickness and is ten to fifteen for both processes with a material thickness of 2 mm. An exact number of passes cannot be determined as the number can vary slightly even on the same substrate. One reason for this may be minimal, spatially limited deviations that occur as a result of the material production or as local deviations in the material composition and grain structure.

Fig. 3 shows a comparison of the cutting edge of the water-jet guided technology (3a) and fusion cutting (3b). The measured cutting-edge angle is 0.18° (material thickness t = 5 mm) for the water-jet guided technology and 0.72° (material thickness t = 1 mm) for fusion cutting. A determination of the roughness of the cut edge resulted in an average value of R_a = 1.585 µm (min/max = 0.997 µm / 3.553 µm) for the water-jet guided technology and R_a = 2.952 µm (min/max = 1.585 µm / 4.952 µm) for fusion cutting.

Conclusion

A direct comparison of influencing parameters does not lead to a satisfactory result when comparing the different technologies, as the effects of each differ too greatly. It therefore only makes sense to compare the processing results with each other. Depending on the objectives, each technology has its own purpose, whereby the strengths of the individual processes can be combined.

In terms of material removal, nanosecond pulsed and ultrashort-pulse

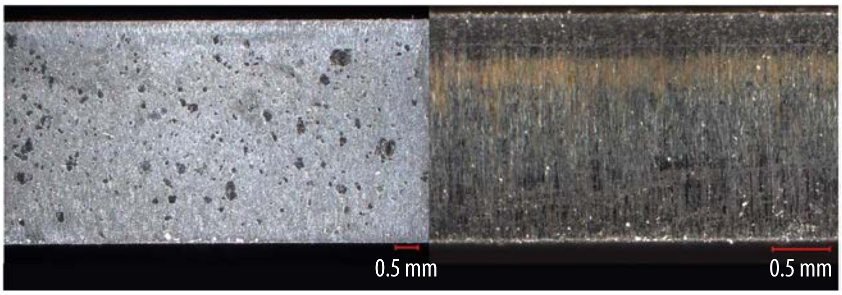

Fig. 3 Comparison image of cutting-edge using (a) water-jet guided technology and (b) fusion cutting

Fig. 4 Combined processing using ultra-short-pulse (trenching) and water-jet guided technology (drilling) from SiC

technologies have an advantage. Due to the high feed rates that can be achieved here thanks to the scanner optics, significantly higher ablation rates are possible with low roughness. For pure cutting geometries, fusion cutting and water-jet guided technology have the advantage, whereby almost vertical cutting edges (< 1°) can be produced. The appropriate process must be selected depending on the geometry to be machined. It is possible to combine different processes in order to achieve the best possible machining result. See Fig. 4 for an example.

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[1] F. W. Zok. Ceramic-matrix composites enable revolutionary gains in turbine engine efficiency, American Ceramic Society Bulletin 95(5), pp. 22-28, 2016

[2] F. Aldinger & W. Böcker: Entwicklung keramischer Hochleistungswerkstoffe. I: Stand der Forschung und Entwicklung, *Keramische Zeitschrift*, pp. 164-172, 1992

[3] W. Kollenberg: Technische Keramik Grundlagen – Werkstoffe – Verfahrenstechnik, Vulkan-Verlag, 2009

[4] BMWK: SubseaSlide – Robuste Gleitlager für Subsea-Pumpen, 4 September 2024. [Online], www.bmwk.de/MAFO/projekte/projekt-03SX508-SubseaSlide.html

[5] Y. Deng, Y. Zhou, Y. Zhang, D. Chen and X. Zhou: Numerical and experimental analysis of nanosecond laser ablation of SiC, *Materials Science in Semiconductor Processing* 151, 15 November 2022

[6] W. Li, R. Zhang, Y. Liu, C. Wang, J. Wang, X. Yang and L. Cheng: Effect of different parameters on machining of SiC/SiC composites via pico-second laser, *Applied Surface Science* 364, pp. 278-287, 28 February 2016.

[7] Y. Huang, Y. Zhou, J. Li and F. Zhu: Femtosecond laser surface modification of 4H-SiC improves machinability, *Applied Surface Science* 615, April 2023

[8] B. Cheng, Y. Ding, Y. Li and L. Yang, „Theoretical and Experimental Investigation on SiC/SiC Ceramic Matrix Composites Machining with Laser Water Jet," *Applied Sciences* 12 (3), 24 January 2022

[9] J. Bliedtner, H. Müller and A. Barz: Lasermaterialbearbeitung: Grundlagen - Verfahren - Anwendungen - Beispiele, Carl Hanser Verlag, 2013

[10] F. A. Sfregola, R. De Palo, C. Gaudiuso, F. P. Mezzapesa, P. Patimisco, A. Ancona and A. Volpe: Influence of working parameters on multi-shot femtosecond laser surface, *Optics and Laser Technol.*, 27 April 2024

[11] N. Shankar: The First Coupling of a Laser Beam to a Water Jet – How a miniature dental hand tool started a revolution in cool laser machining, *Photonics Views* 18(1), pp. 72-76, February 2021, DOI: 10.1002/phvs.202100014

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