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Technical Paper

Comparative analysis of tangentially laser-processed fluted polycrystalline diamond drilling tools

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ABSTRACT

Ultrashort-pulsed laser ablation is increasingly applied in various fields of science and technology. For the purpose of processing ultra-hard materials, such as diamond and cubic boron nitride (CBN) composites, lasers have the decisive advantage of wear-free material removal. The availability of high-powered ultrashort-pulsed laser sources enables the efficient applications of tangential processing strategies to generate complex 3D geometries. Compared to the conventionally applied 2.5D volume ablation strategy, the resulting workpiece form tolerance, repeatability, and surface quality is increased significantly and does not depend on the quality of the initial surface. This makes tangential processing an ideal choice for high-precision finishing processes.

This paper presents a set of processes for the tangential ablation of characteristic twist drill features, such as helical grooves, flank faces and notches at the chisel edge. The processes have been implemented using a pulse duration of 12 ps, infrared laser source with an average power of 35 W average power for generating PCD tools. A comparative drilling study in zirconium dioxide (ZrO_2) with diamond-coated tungsten carbide tools and solid PCD tools processed by electrical discharge machining is conducted to assess the performance of the laser-processed PCD tools.

1. Introduction

Ongoing industrial developments towards the applications of hard materials, such as tungsten carbide (WC) and ceramics, automated production, and tighter tolerance create a demand for ultra-hard tool materials, such as diamond and cubic boron nitride (CBN), for increased dimensional stability and tool lifetime. The properties of these materials force conventional tool production technologies, especially grinding, to their limits. Due to its wear-free nature, pulsed laser ablation offers the advantage of highly flexible and precise machining, independent of the mechanical properties of the processed material. This enables the development of new processes for generating ultra-hard tools in a wide range of industrial applications.

This paper demonstrates the applicability of high-powered ultrashort-pulsed laser ablation for the manufacturing of fluted cutting tools. This is achieved by applications of a novel tangential laser process that combines the flexibility of 5-axes CNC machines with the dynamics of galvanometer scanning systems, allowing the efficient laser ablation of complex geometries. The process is applied to produce composite polycrystalline diamond (PCD) drilling tools with a number of characteristic features, such as the flank face, notches at the chisel edge and the secondary cutting edge. The tools are compared to commercially available chemical vapour deposited diamond (CVD-D) coated tools and electrical discharge machined (EDM) PCD tools with respect to surface quality, cutting edge radii, cutting performance and tool life time while drilling zirconium dioxide.

The outstanding properties of zirconium dioxide, such as hardness, wear resistance, chemical and thermal stability, light-weight and biocompatibility, cause their increasing application as technical elements in various fields including biomedicine, metal forming, turbine construction, bearing technology, jet nozzles, etc. The introduction of laser-processed solid PCD tools with defined cutting edges, as presented in this paper, may significantly impact the use of these materials by enabling efficient and precise processing of

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small geometries, such as bores which cannot be ground due to limited accessibility.

2. Literature review

Fluted cutting tools are conventionally manufactured by grinding. The helical groove constitutes the most challenging feature both for the design and for the manufacturing of this tool geometry and is topic of extensive research efforts. Various models are introduced to support this process. Li et al. [1] applied a geometrical approach to determine the shape of the helical groove based on the machine kinematics and the grinding wheel profile. A method to optimise the helical groove geometry with regards to multiple parameters, such as chip evacuation, torque and coolant flow, while considering geometric constraints of the grinding process kinematics and achievable wheel geometries was introduced by Abele and Fujara [2].

However, conventional grinding processes suffer from geometric limitations, wear, long processing times and high mechanical loads when applied to ultra-hard materials. For this reason, a number of recent studies investigated the capability of other manufacturing processes, such as electrical discharge machining (EDM), to generate tool geometries and prepare cutting edges in PCD and composite polycrystalline CBN (PCBN). Zhang et al. [3] produced highly precise microstructures in PCD by EDM. The process was applied to the fabrication of an end mill and evaluated on WC. Yan et al. [4] created microfeatures in PCD samples with a rotary cupronickel electrode. The geometries achieved are comparable to those of cutting tool features and exhibit submicron accuracy. Wire EDM is a process with similar geometrical constraints as tangential laser processing and is applied for the generation of helical tool geometries. Cheng et al. [5] presented a comprehensive CAM system to support these processes. Furthermore, a simulation model for helical tool features produced by wire EDM was introduced by Cheng et al. [6]. By considering the traces of the EDM wire, the tool surfaces are calculated. While simulation results show that positive radial rake angles can be processed by this method, it is pointed out that no concave helix surfaces were achieved due to the linear EDM wire.

Another manufacturing process increasingly applied to ultra-hard materials is pulsed laser ablation. Chong et al. [7] emphasised the unique advantages of laser as manufacturing tool, especially when applied with short and ultrashort pulses to limit the formation of a heat-affected zone. Timmer [8] first described laser processing of profiled rotary tools. Walter et al. [9] further applied the method to dress and true diamond and CBN grinding tools. In both cases, a tangential configuration of the optical axis to the tool surface was chosen to achieve highest dimensional definition of the produced abrasive surfaces. Dold et al. [10] introduced a tangential laser process for ablative cutting and finishing of PCD cutting inserts, identifying ultrashort-pulsed laser ablation as viable alternative to grinding of these materials in terms of processing time and resulting tool quality. Furthermore, more complex geometries of micro-cutting tools with defined cutting edges are processed in diamond materials by pulsed laser ablation with promising results. Butler-Smith et al. [11,12] described the advantageous characteristics of laser-generated diamond abrasive surfaces applied both on planar microarrays and on rotary grinding tools. Suzuki et al. [13] presented a laser process for the generation of monocrystalline diamond micro-milling tools applied for ceramic cutting. A PCD micro core drill was produced through pulsed laser ablation by Butler-Smith et al. [14], demonstrating the unique ability of this manufacturing process to produce microgeometries with difficult accessibility conditions. However, the increased geometric complexity of these tools is hitherto achieved by 2.5D volume ablation. This processing strategy exhibits the advantage of efficient use of the laser power, due to the orthogonal incidence of the beam on the workpiece surface, and high geometrical flexibility, which is limited only by undercuts and the dimension of the laser spot. Tangential processing, as discussed in the following section, requires a target geometry that allows the tangential passage of the beam in at least one direction at each point of the surface. Helical tool geometries fulfil this geometrical constraint, because of similar requirements present in conventional grinding processes with large wheel diameters.

A number of recent studies investigated the suitability of grinding and milling processes with diamond tools on ceramic materials in general and zirconium dioxide in particular. Bian et al. [15] achieve mirror-quality surface roughness by micromilling of zirconium dioxide with diamond-coated WC tools. Delamination of the diamond coating and exposure of the underlying WC substrate were identified as the main tool wear and failure mechanisms. Romanus et al. [16] compared a number of different ultra-hard coating materials to mill zirconium dioxide. This research also determined delamination as the limiting factor for the tool lifetime of coated tools. The high surface loads and the differing mechanical as well as thermal properties of the coating and substrate materials were identified as the main causes for the delamination. Some research was published on the causes for brittle and ductile material removal mechanisms during the machining of ceramic materials, which strongly influence the workpiece surface quality and may have an impact on tool wear. Bifano et al. [17] introduced a much-cited equation describing the brittle–ductile transition at a critical cutting depth depending on certain material properties. Liu et al. [18] determined a linear relationship between the cutting edge radius and the critical cutting depth during precision turning experiments on silicon wafers. The advantages of processing in the ductile regime concerning the resulting surface quality and the minimisation of surface fracturing were emphasised. Jochum [19] determined a dependency of the critical cutting depth on cutting speed during grinding experiments on zirconium dioxide. Thus, workpiece material properties, tool properties and processing parameters were identified as influencing factors for the ductile–brittle chipping mode transition.

3. Laser manufacturing process

3.1. Tangential laser processing

Compared to 2.5D volume ablation, the tangential laser process has the decisive advantage that the material removal takes place orthogonally to the beam direction with a comparatively well-defined and stable dimensional limit. Consequently, the resulting geometry is defined mainly by the relative motion between laser beam and workpiece. Timmer [8] described this characteristic as the ability for *true profiling*. After the target geometry is reached, the contour generated is independent of ablation speed and irradiation time. 2.5D volume ablation, on the other hand, removes material in the optical axis of the laser beam, a direction in which no limit exists within the constraints of the laser–material interaction zone. Therefore, the ablated volume depends on the ablation speed, varying with irregular material composition and laser power, and on the irradiation time, which is difficult to control at a high precision for high pulse frequency and high scanning speed. Furthermore, any defects on the raw material surface or within the ablated workpiece material are projected onto the final contour. Tangential laser processing is applicable to rough and geometrically undefined raw material without loss of accuracy and surface quality of the final contour. This opens the possibility of roughing by conventional means or by high-powered laser preliminary to a tangential laser finishing process. Additionally, a polishing effect of the finished