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ScienceDirect

Procedia CIRP 46 (2016) 290 – 293

www.elsevier.com/locate/procedia

7th HPC 2016 – CIRP Conference on High Performance Cutting

Geometry optimization of polycrystalline diamond tools for the milling of sintered ZrO2

Maximilian Warhanek[a,*], Josquin Pfaff[a], Pablo Martin[a], Lukas Schönbächler[a], Jens Boos[b], Konrad Wegener[a,b]

[a]Institute of Machine Tools and Manufacturing (IWF), ETH Zurich, Switzerland
[b]inspire AG for Mechatronic Production Systems and Manufacturing Technology, Switzerland

* Corresponding author. Tel.: +41 44 633 78 40; fax: +41 44 632 11 59. *E-mail address:* warhanek@iwf.mavt.ethz.ch

Abstract

Recent developments on tangential ultrashort-pulsed laser processing enable the generation of solid polycrystalline diamond composite tools with increasing geometric flexibility. To exploit this potential, an experimental study on the influence of the tool geometry on the cutting characteristics and the tool wear while milling sintered Zirconia dioxide is conducted. Three different tool geometries and a variation in rake and flank angles are produced to investigate the effects on processing forces and tool lifetime. The results are applied to the design of an end mill achieving 1.2 mm³/mm s specific material removal rate over a tool lifetime of 8000 mm³/mm.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz

Keywords: Milling; Ceramic; Diamond Tool

1. Introduction

Processing of sintered industrial ceramics is conventionally performed by grinding with electroplated, brazed or vitrified bonded diamond tools. High tool wear, long processing times and the necessity of high-speed grinding spindles are the main challenges for this technology, when applied to geometries that require small diameter tools. High performance grinding processes for sintered Zirconia dioxide (ZrO_2), as presented by Rabiey et al. [1], achieve up to 8 mm³/mm s specific material removal rate using a novel hybrid-bonded diamond grinding tool with a diameter of 6 mm. New manufacturing technologies such as pulsed laser ablation (PLA) and electrical discharge machining (EDM) steadily increase the geometric freedom in the design of solid diamond tools. Accordingly, a number of recent publications investigate the possibility of manufacturing geometrically defined tools, mainly milling tools, from solid diamond materials. Yan et al. [2] use EDM with a rotary electrode for the generation of micro cutting features in polycrystalline diamond composite (PCD) tools. A similar approach is applied by Zhang et al. [3], who use wire EDM to produce micro PCD tools for the machining of tungsten carbide (WC). Cheng et al. [4] demonstrate the applicability of wire EDM to more complex tool geometries, including helical chip spaces and cutting edges. Suzuki et al. [5] produce mono-crystalline diamond tools by PLA. The tools are successfully applied to high-precision milling of WC molds. Butler-Smith et al. [6,7] achieve the production of a solid diamond micro-grinding tool with geometrically defined cutting edges and a PCD micro core drill by PLA.

A different approach to produce milling tools capable of cutting sintered ceramics is diamond coating of WC tools. On the one hand, this method has the drawback of significantly reducing tool lifetime, due to the additional wear mechanism of delamination [8]. On the other hand, it exhibits high geometric flexibility due to the more efficient shape-giving

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doi:10.1016/j.procir.2016.04.003

processes on WC before the diamond coating is applied. Both these tools and similar tools applied in the work of Bian et al. [9] are used for milling sintered ZrO_2, giving insight into the geometric requirements of tools for this process. Based on these findings, this study examines the suitability of three distinctly different milling tool geometries for the processing of sintered ZrO_2 and investigates the influence of flank and clearance angles on the tool performance.

2. Tool design

Regarding the cutting parameters applied in the various studies mentioned in the introduction, chip thicknesses in the range from 0.18 to 5.28 µm are set for the milling of ZrO_2 and WC materials. These low values are chosen to achieve a ductile cutting mode, which according to Bifano et al. [10] requires a cutting depth below a material dependent critical value. Ductile cutting of hard materials is generally associated with better resulting surface quality on the workpiece. Furthermore, preliminary experiments reveal that low cutting depths are necessary while milling ceramic materials in order to limit the occurring process forces to avoid tool failure through overload breakage of the cutting edges or the entire tool shaft. Milling with chip thicknesses in this range does not require large chip spaces. Small chip spaces further have the advantage of allowing the arrangement of more cutting edges on the circumference of the tool, which in turn increases the lifetime of the tool. Based on this insight, the three tools designs, illustrated in Fig. 1, are established. For the sake of comparability, all three designs have a tool diameter of 1.9 mm and a chip space depth of 0.1 mm.

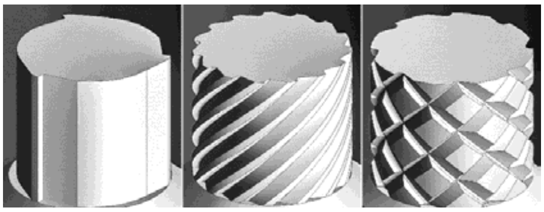

Fig. 1. Milling tool designs:
(left) geometry A; (middle) geometry B; (right) geometry C.

The design of geometry A is chosen for efficient investigation of the influence of rake and clearance angle variation on tool performance. For this purpose, three cutting edges are aligned parallel to the tool axis. This simplifies the manufacturing process and the measurement of the cutting edge geometry. Geometries B and C, are two distinctly different designs with helical cutting edges, generated for the purpose of investigating the influence of continuous and interrupted cutting edges on the tool performance. While geometry B constitutes a standard fluted milling tool, geometry C shall act similar to a micro-grinding tool with defined cutting edge geometries as presented in [6]. The number and size of the chip spaces is adjusted in a way that both tools have the same total cutting edge length. This results in milling tools with 15 helical cutting edges in case of geometry B and 8 rhombical cutting edges around the circumference of geometry C.

3. Experimental setups and test conditions

3.1. Measurement and performance evaluation

The produced tools are measured in the new state and at regular intervals during the milling experiments on an Alicona Infinite Focus 3D microscope. The 3D data allows for evaluation of cutting edge radii, surface roughness, clearance and rake angles as well as radial wear. The milling experiments to evaluate the performance of the different tool geometries are conducted on a high-precision 3-axes Mauser Präzoplan milling centre equipped with an Alfred Jäger type Z100-H536.05 spindle with 35’000 rpm. To investigate the development of the cutting efficiency over the lifetime of the tools, milling force measurements are performed during all experiments with a type 9257A Kistler 3-axes force measurement platform. The ZrO_2 material used for the milling experiments is supplied by METOXIT high tech ceramics. The material type TZP-A is stabilized with < 5 wt% Y_2O_3 and reinforced with < 0.25 wt% Al_2O_3. The hardness is specified as 1200 HV. Roughness measurements on milled surfaces are performed with a Taylor Hobson Form Talysurf 2 machine.

After preliminary experiments, the milling parameters are defined as summarized in Table 1. It is determined that the processing force levels of geometry C are approximately double of those of geometry B, when applied at the same parameters. It is concluded that geometry C acts as a tool with 8 teeth and the feed rate is reduced for this geometry to allow performance comparison with the same feed per tooth. All milling tests are performed without coolant or lubricant.

Table 1. Milling parameters.

Geometry	A	B / C
Cutting speed	50 m/min	50 m/min
Depth of cut (a_e)	0.1 mm	0.1 mm
Width of cut (a_p)	1 mm	1 mm
Feed rate	120 mm/min	720 / 384 mm/min
Spec. material removal rate	0.2 mm³/mm s	1.2 / 0.64 mm³/mm s
Strategy	parallel feed	parallel feed

3.2. Tool manufacturing

The tools are manufactured by ultrashort-pulsed laser ablation on a modified EWAG Laser Line machine tool. The high-precision machine is equipped with three linear stages in X’, Y and Z’ direction, two rotation stages in B’ and C’ configuration and three highly dynamic linear optical axes aligned parallel to the three linear axes. The laser system applied in this machine is a TimeBandwidth Fuego with a pulse duration of $\tau_P < 12$ ps, an average power of $P_{max} = 35$ W and a pulse frequency range from 200 kHz to 8.2 MHz. The chip spaces of geometry A are produced by 2.5D volume ablation as described by Eberle et al. [11]. Supported by the CAM software Samlight SCAPS, this process gives the flexibility of efficient geometry adjustments for the variation of the rake angle. A final pass by tangential laser scanning is applied to set the clearance angle and sharpen the cutting edges while minimizing the circular runout of the tools. Geometries B and