High-speed high-efficient grinding of CMCs with structured grinding wheels

Bahman Azarhoushang[1, a *], Mohammadali Kadivar[1,2, b], Robert Bösinger[1, c], Sergey Shamray[1, d], Ali Zahedi[1, e], and Amir Daneshi[1, f]

[1] Institute for Precision Machining (KSF), Furtwangen University of Applied Sciences, Jakob-Kienzle-Strasse 17, D-78054 Villingen-Schwenningen, Germany

[2] Department of Materials & Manufacturing Technology, Chalmers University of Technology, Hörsalsvägen 7B, 412 96 Gothenburg, Sweden

[a] aza@hs-furtwangen, [b]kamo@hs-furtwangen.de, [c] bert@hs-furtwangen.de, [d] shas@hs-furtwangen.de, [e] ali.zahedi@hs-furtwangen.de, [f] dam@hs-furtwangen.de

Keywords: High speed high efficiency grinding; CMCs; Segmented wheel; laser-structure

Abstract. Ceramic Matrix Composites (CMCs) are counted as new materials which their implantation is limited due to their high machining costs as a result of high grinding forces and tool wear. To overcome mentioned problems, modified grinding wheels, one macro-structured by segmenting and another micro-structured (half lasered structured and half non-structured) were used in this study. The grinding tests were carried out at different material removal rates and cutting speeds. The grinding forces, generated surface roughness, and induced residual stress by means of grinding with the structured and non-structured wheels were compared. Reduction in the static cutting edges via wheel structuring resulted in a better performance of the grinding wheel through the reduction of rubbing and ploughing regimes. The grinding forces were respectively 30% and 20% lower in the case of segmented wheel and laser-structured wheel in comparison with the conventional grinding. In addition, the tensile residual stress can be reduced as a negative output of the grinding process via structuring. Moreover, a high-speed high-efficient grinding of CMCs without presence of surface damage was achieved by optimizing the process parameters. The material removal rate can be elevated without changing the grinding forces with application of the structured wheel.

Introduction

One of the new and promising material for high-technological engineering applications is Ceramic Matrix Composites (CMCs). Their superior properties provide the possibility to be utilized in many harsh and severe environments with high lifetime [1]. However, their implantation is expensive due to their high machining costs. To overcome this problem in grinding CMCs, the reduction of grinding forces and tool wear are highly recommended. Using either the structured grinding wheels or ultrasonic vibrations as an assistance to the grinding process are two promising methods to economically and reproducibly grind CMCs [2]. The number of investigations regarding grinding of CMCs is limited. It was reported that the grinding of such materials is generally characterized with excessive grinding forces and temperature [3–5]. Liu et al. [6] studied the machinability of 2D C/SiC composite with 0°/90° woven carbon fibers using a resin bond diamond grinding wheel. They showed that the grinding force and surface roughness decrease with the increase of wheel speed.

By segmented grinding wheel (T-Tool profile), developed by Tawakoli [7–9], the higher wheel life, lower grinding temperatures and a significant reduction in grinding forces were achieved. Lower grinding power, tool wear, thermal damage and thermal stress as well as better finished surface have also been stated by using the intermittent grinding [10,11]. Tawakoli and Azarhoushang [2] developed a segmented grinding wheel to grind CMCs and showed that the grinding process is influenced by macro-topography of the grinding wheel. Zahedi and Azarhoushang [12] used a laser structured grinding wheel in the grinding process and reported that the structured wheel enhances the coolant flow in the wheel-workpiece contact zone and reduces the grinding temperature.

This paper is allocated to study the feasibility of laser structured grinding wheel (LS) and Segmented grinding wheel as intermittent grinding process (IG) on CMC material. Grinding forces, surface roughness, surface topography, and tool wear are compared for grinding of CMC with structured and non-structured wheel. The effect of the grinding parameters like cutting speed and material removal rate under three different grinding strategies are also systematically studied.

Experimental set-up and procedures

In this paper LS represents Laser Structured grinding wheel, IG indicates the segmented grinding wheel as Intermittent Grinding process, and CG donates to Conventional Grinding. Fig. 1 shows the experimental set-up. A Kistler dynamometer (Kistler 9275B), mounted on an ELB Micro-Cut AC8 CNC surface grinding machine was used to measure the grinding forces. The surface roughness was measured by a profile tester Hommel-Werke model T-8000. Three different grinding wheels have been used in this study. A hybrid bonded diamond grinding wheel (D151 C150) in the case of laser structured wheel, which was half laser-structured and half non-structured (Fig.1-b) and two metal bonded diamond grinding wheels with the diameter of 400 mm and width of 15 mm (D151 C118) one for the conventional grinding (CG) and one for intermittent grinding (Fig.1-a). The grinding wheels were dressed using a SiC rotating wheel and sharped by an aluminum oxide stick. Table 1 summarizes the main cutting parameters. In this study, C/SiC with a hardness of 1900 HV0.1 was utilized as workpiece material. The material has a relatively low amount of carbon matrix and high amount of SiC.

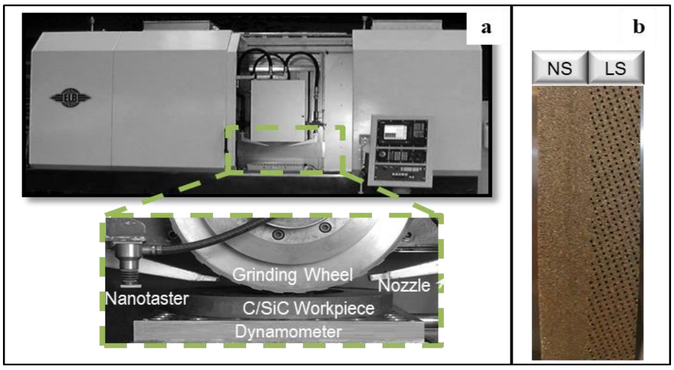

Fig. 1. a) The experimental setup; b) Laser structured wheel

Table 1. Process Parameters

Parameters	Values
Cutting Speed v_c [m/s]	30; 60; 90 and 120
Feed Rate v_w [m/min]	1; 2; 3 and 5
Depth of Cut a_e [µm]	200; 300; 500 and 700
Lubricant	5% emulsion

Results and discussion

The effect of the cutting speed on the specific normal grinding force has been shown in Fig. 2 for the conventional and intermittent grinding (with the segmented wheel) processes. It can be clearly seen that increasing the cutting speed decreases the specific normal grinding forces for both CG and IG. The number of kinematic cutting edges reduces with increasing the cutting speed, which may reduce the fraction of rubbing and plowing. Moreover, Increasing the cutting speed causes thinner uncut chip thickness and lower number of kinematic cutting edges. Hence, the grinding forces acting on each active grain are lower which result in lower total grinding force with increasing the cutting speed [13].

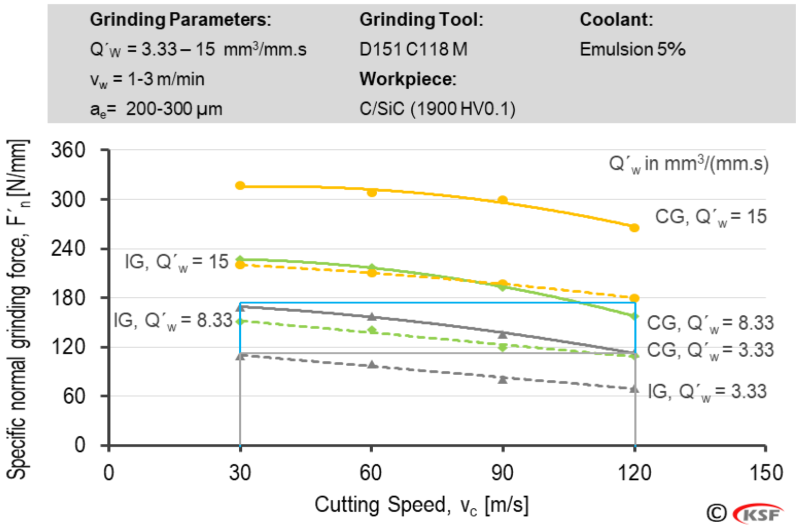

Fig. 2. The effect of the cutting speed and material removal rate on the specific normal force

It is well-known that the lateral extension of cracks in ceramics occurs during indenter unloading [14]. A residual elastic/plastic mismatch stress field drive this kind of cracks. The intermittent grinding may allow the lateral cracks propagation, causing more micro-cracking in the cutting zone. Additionally, segmenting the tool reduces the number of the cutting edges Hence, the grinding forces are lower in the case of using segmented grinding wheel. To investigate the effect of micro structuring on the grinding process, a hybrid bonded grinding wheel has been with a picosecond laser machine half laser-structured.

The corresponding grinding forces of laser-structured and non-structured wheels are shown in Fig. 3. Accordingly, the more reduction in both normal and tangential grinding forces can be observed for the laser-structured wheel in comparison with non-structured wheel. The 20% reduction of grinding force is achieved by only 10% structuring of the wheel. This is due to the reduction in the number of active grains. Which, as already mentioned above, is almost the same reason for the grinding forces reduction for the segmented grinding wheel.

The trend of the changes for the surface roughness with the cutting speed in the case of structured and non-structured wheels is shown in Fig. 4. Structuring the wheel improves the surface roughness in terms of R_Z. The induced grinding forces by the laser structured wheel are smaller than those induced by non-structured wheel. Lower forces lead to lower vibration and also probably fewer pullout grains from the surface of the grinding wheel, generating a uniform surface. Since the material is brittle, the material removal mechanism follows the brittle behavior and crack propagation. Since the grinding forces are higher in the case of the non-structured wheel, the induced stresses on the surface of the workpiece are higher, which may lead to more brittle fracture during the machining process and micro-cracks over the surface of the workpiece, affecting the surface roughness of the ground surface. The lower grinding forces may also reduce the number of pullout grains which affect the surface roughness.

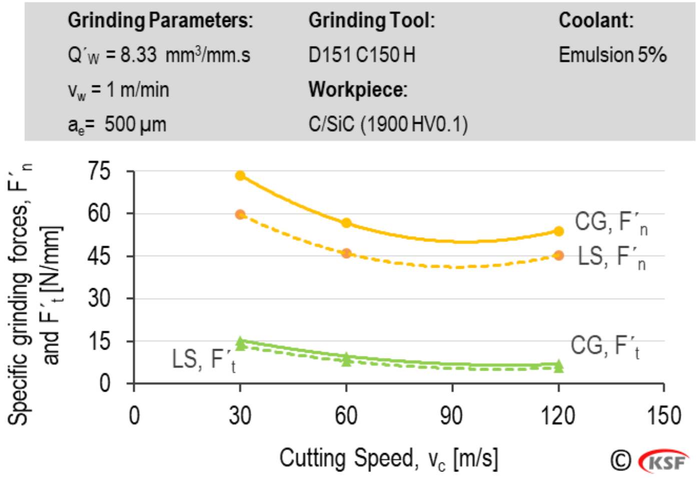

Fig. 3. The effect of laser structuring on the specific grinding forces

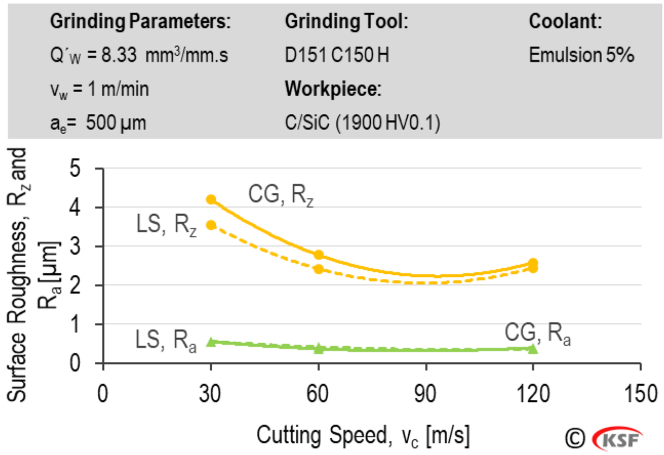

Fig. 4. The effect of the laser structuring on the surface roughness

To prove the aforementioned claim, a long-term grinding test (material removal volume = 3600 mm^3) has been carried out and the grinding wheel surface has been observed with the confocal microscope. The results are presented in Fig. 5. It is clear that the number of the grains which are pulled-out in the case of non-structured wheel are relatively higher than those in the structured wheel which can influence the surface roughness of the workpiece and causes higher grinding forces. Moreover, the grains protrusion height of the non-structured wheel after grinding of 3600 mm^3 material is smaller than that in the structured wheel, meaning higher wear-flat in the case of the non-structured wheel compared to the structured wheel.

After the grinding tests, the residual stress of the ground surfaces has been measured via XRD method for different grinding methods (CG, IG, and LS) as well as for the reference workpiece (which is not ground) using widely accepted sin2ψ technique. The results are presented in Fig. 6. The residual stresses in all cases are tensile which is undesired. However, conventional grinding process induced more tensile residual stress compared to the macro and micro-structured wheels.

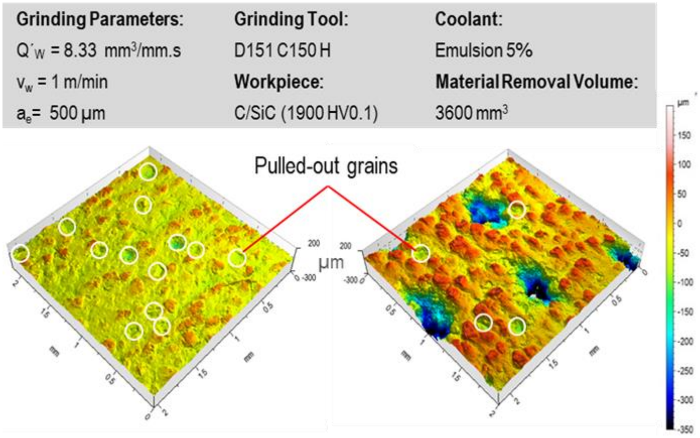

Fig. 5. Confocal pictures from the structured and non-structured wheel after grinding

The induced residual stress by the grinding process occurred as a result of the thermo-mechanical effects on the material. The residual stress initiate either because of the thermal or mechanical mechanisms or their combination. It was evidently verified from these results that the structuring of the wheel can remarkably reduce the thermal effects on the workpiece by reducing the grinding process temperature. Therefore, the lower the temperature, the lower the tensile residual stress.

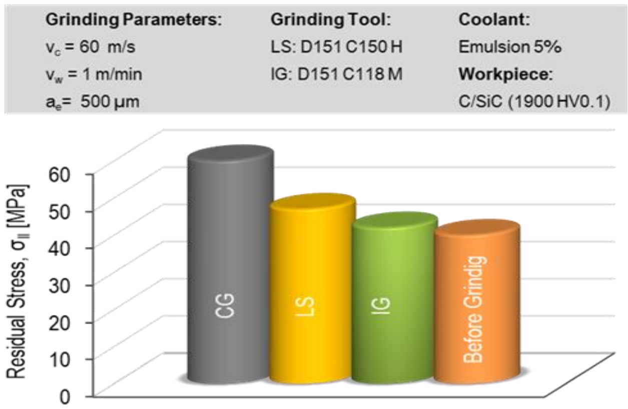

Fig. 6. Grinding residual stress after grinding for different methods

The grinding forces in the case of the metal bonded grinding wheel (non-segmented, CG, and segmented wheel, IG) are much higher than those with the hybrid bonded grinding wheel (laser structured wheel), the residual stress induced by the segmented wheel (metal bound grinding wheel) is smaller than that by laser structured wheel (hybrid bonded grinding wheel) after the grinding process. It can be because of either lower temperature by segmented wheel or better lubrication during the process. In the case of the residual stress, since the tensile residual stress is not desirable, using the segmented wheel is much more desirable, since it did not noticeably change the residual stress after the grinding process.

Conclusion:

Achieving high material removal rate, low tool wear, and low machining forces is one of the biggest challenges in machining of CMCs. The presented experimental study investigated the effects of macro and micro-structuring in high speed high efficient grinding (HEDG) of the CMCs. The following conclusions are drawn from this study:

- The material removal rate can be increased significantly (more than 4 times) at a constant cutting forces and without any surface damages using the segmented grinding wheel compared to the conventional grinding.
- Using the structured wheels improved the cutting mechanism of the CMC by decreasing the plowing and rubbing effect during the cutting process via enhancing the cooling process and reducing the uncut chip thickness. Hence, the grinding forces in both macro and micro structured could be reduced up to 30 and 20%, respectively, compared to conventional grinding.
- The generated surface after grinding process was also influenced by the wheel structuring and was improved by laser micro structuring.

References

[1] Krenkel W (ed.). Ceramic matrix composites: Fiber reinforced ceramics and their applications. Weinheim: Wiley-VCH; 2008.

[2] Tawakoli T, Azarhoushang B. Intermittent grinding of ceramic matrix composites (CMCs) utilizing a developed segmented wheel. International Journal of Machine Tools and Manufacture 2011;51(2):112–9.

[3] Tashiro et al. Towards Synthesis of Micro-/Nano-systems. Springer London; 2007.

[4] Weinert K, Jansen T. Machining Aspects for the Drilling of C/C-SiC Materials. In: Krenkel W, editor. Ceramic Matrix Composites. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA; 2008, p. 287–301.

[5] Li ZC, Jiao Y, Deines TW, Pei ZJ, Treadwell C. Rotary ultrasonic machining of ceramic matrix composites: Feasibility study and designed experiments. International Journal of Machine Tools and Manufacture 2005;45(12-13):1402–11.

[6] Liu Q, Huang G, Xu X, Fang C, Cui C. A study on the surface grinding of 2D C/SiC composites. Int J Adv Manuf Technol 2017;93(5-8):1595–603.

[7] T. Tawakoli. Minimal quantity lubrication in grinding with T-Tool profile wheel (in German),. in: Proceedings of the Fourth Seminar of Modern Grinding 2002:48–54.

[8] T. Tawakoli. Innovative tools for grinding, dressing and milling (in German). Industrie Diamanten Rundschau, IDR, 2001(1):48–54.

[9] T. Tawakoli. Innovative tooling systems for grinding and dressing (in German),. in: Proceedings of the Third Seminar of Modern Grinding 2000(4):1–15.

[10] Gordeev AV. Wear resistance of segmental diamond wheels. Machines & Tooling (English translation of Stanki i Instrument) 1997;48(2):21–2.

[11] Degtyarenko SM. Contact area between the component and the intermittent working surface of the grinding wheel. Soviet Engineering Research(UK) 1989;9(11):54–60.

[12] Zahedi A, Azarhoushang B. Microstructuring strategies of cBN grinding wheels. Int J Adv Manuf Technol 2017;91(9-12):3925–32.

[13] Kadivar M, Azarhoushang B, Shamray S, Krajnik P. The effect of dressing parameters on micro-grinding of titanium alloy. Precision Engineering 2018;51:176–85.

[14] LAWN BR, EVANS AG, MARSHALL DB. Elastic/Plastic Indentation Damage in Ceramics: The Median/Radial Crack System. J American Ceramic Society 1980;63(9-10):574–81.