euspen's 16th International Conference &
Exhibition, Nottingham, UK, May 2016
www.euspen.eu

Micro machining of tungsten carbide with geometrically defined cutting edge

F. Böhmermann, O. Riemer

LFM Laboratory for Precision Machining, University of Bremen, Badgasteiner Str. 2, 28359 Bremen, Germany

boehmermann@lfm.uni-bremen.de

Abstract

Tungsten carbides are a promising material for highly wear resistant micro forming dies. However, the machining of tungsten carbides in small geometrical dimensions is challenging. In this work the successful application of CVD-thick-film PCD micro ball-endmills to the machining of tungsten carbide with cobalt binder (WC-Co) resulting in crack free surfaces with a roughness down to Sa = 30 nm is shown. From scanning electron microscopy and metallographic analysis of the workpieces can be concluded, that the material removal mechanism is a mix of ductile inter-crystalline cut through the WC hard grains and an excavation of these grains from the softer cobalt phase. The machining quality, here, is mostly determined by the material composition, not by the hardness. Best results were achieved in WC-Co with a grain size of 0.6 µm.

micro milling, tungsten carbide, forming die manufacture

1. Introduction

Due to excellent wear resistance, cemented carbides are promising forming die materials for dry micro metal forming applications [1]. However, machining of cemented carbides in small geometrical dimensions with features sizes down to 100 µm is challenging, e.g. due to strong geometrical limitations to the application of grinding. Here, micro milling is a promising approach. The first successful ductile machining of tungsten carbide with geometrically defined cutting edge was shown by Liu et al. in various experiments applying CBN tools, however, tools suffered from wear [2, 3]. Arif et al. applied endmills of 5 mm in diameter with polycrystalline diamond (PCD) bits to the machining of cemented carbides. Ductile regime machining was achieved up to a critical feed per tooth $f_{z,crit}$ of 18.5 µm when peripheral milling tungsten carbide samples [4, 5]. Uhlmann et al. showed the successful micro milling of tungsten carbide GXF (88 % WC, 12 % Co) using cutting tools of 1 mm in diameter with binderless PCD bits generated by high-pressure and high-temperature sintering [6]. An alternative approach is the application of novel micro endmills with binderless CVD-thick-film PCD bits to the micro milling of cemented carbides to achieve both, adequate material removal rates and a reliable manufacture of small features with excellent surface finish. Aim of this work is the investigation of the micro milling process of tungsten carbide samples with CVD-thick-film PCD ball-endmills. Machining experiments were carried out into sintered blocks of tungsten carbide with cobalt binder phase exhibiting various grain sizes (0.6 µm, 2.5 µm, and 8.0 µm) and compositions (85 % WC, 15 % Co and 82 % WC, 18 % Co) applying tools of 1 mm in diameter. Tools and samples were investigated by means of scanning electron microscopy (SEM). Furthermore, dye penetrant inspection, roughness measurements, and metallographic inspection were carried out on the machined samples. Depending on the process parameter feed per tooth, crack free machining and an arithmetical mean height down to Sa = 30 nm were achieved.

2. Experimental section

Four sintered blocks (30 x 20 x 10 mm^3) of tungsten carbide with cobalt binder phase (WC-Co) were used as samples. Grain sizes and chemical compositions were varied to allow a correlation of material properties and the machining results. Specifications of the four samples are given in Table 1.

Table 1. Specifications of tungsten carbide sample material.

Material	WC [%]	Co [%]	grain size [µm]	hardness [HV30]
GD30	85	15	2.5	1174
GD40	82	18	2.5	964
GD18F	85	15	0.6	1279
BD40	85	15	8.0	1028

The machining experiments were carried out on a *DMG Sauer US 20 linear* micro milling machine. Six grooves of 10 mm length were machined into each sample using single tooth CVD-thick-film PCD ball-endmills of 1 mm in diameter. A new tool was applied for every sample. The tilt angle of the endmill was $\alpha = 45°$ and machining was carried out in a drawn cut. The spindle speed was kept constant for all experiments at $n = 40\,000$ min^{-1} whilst the feed velocity was increased with every machined groove in 5 mm/min steps starting from $v_f = 5$ mm/min to $v_f = 30$ mm/min. The variation of the feed velocity resulted in six different feed per tooth f_z: 0.125 µm, 0.25 µm, 0.375 µm, 0.5 µm, 0.625 µm, and 0.75 µm.

3. Results and discussion

The cutting edges of a new tool and the applied tools were investigated by means of scanning electron microscopy (SEM).

For none of the applied tools catastrophic wear or breakage of the cutting edge was detected after a feed travel of $l_f = 60$ mm corresponding to a path length due to primary motion of $l_c = 68.25$ m. A correlation of tool wear and material hardness was not detected. The investigations of the machined samples started with dye penetrant testing. Here, no obvious crack formation or damage due to brittle material removal mechanisms could be detected. The machined grooves were investigated with SEM. Besides clean cut surfaces, areas with excavated grains and smeared Co binder were found. These effects were more distinctive for the sample materials exhibiting the coarsest grain (BD40) and the highest content of Co binder (GD40). The best surface finish was achieved for the sample material GD18F exhibiting the finest grain (0.6 µ). The SEM examination of the samples furthermore allowed the identification of smeared sample material at the tool entry and exit zones, leading to the conclusion that a predominant ductile mode machining was achieved. Roughness measurements were carried out using a confocal microscope with a lateral and vertical resolution of 100 nm and 2 nm respectively. The ground of the machined grooves was measured and the raw data evaluated according to the DIN EN ISO 25178 standard (cut-off $\lambda_s = 0.25$ µm, cut-off $\lambda_c = 0.08$ mm) to determine the areal arithmetical mean height Sa. The results of the roughness measurements are shown in Figure 1.

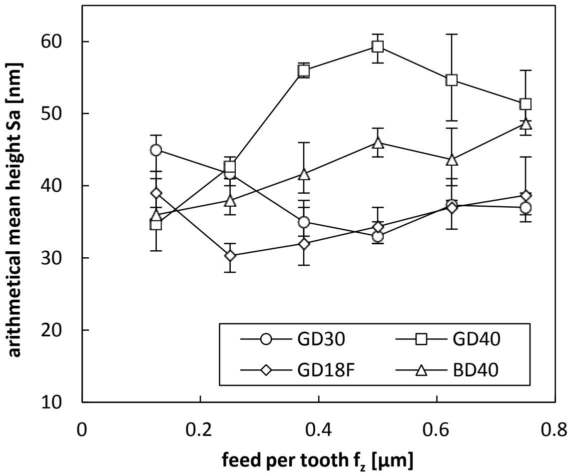

Figure 1. Roughness depending on sample material and feed per tooth.

Lowest roughness values down to Sa = 30 nm were achieved for both the hardest sample materials GD30 and GD18F. For these materials higher feed per tooth f_z appears to be favorable to achieve fine surface finish. For the material GD40 with the highest Co binder content of 18 % a decreasing trend can be observed regarding the roughness after a strong increase for feed per tooth f_z between 0.125 µm and 0.5 µm. This can be explained with an increased excavation of hard grains for larger feed per tooth f_z. The decrease of roughness for even larger f_z can be attributed to an increased smearing of the Co binder onto the generated surfaces leading to a surface smoothening; this corresponds well to the results of the SEM investigations. The investigation of the samples was completed with cross-sectional metallographic analyses of the machined grooves. The results underline the findings of the SEM inspection and the roughness measurements. A mix of predominant ductile inter-crystalline cut, hard grain excavation, and brittle fracture of hard grains can be identified form the metallographic images, compare Figure 2. The distinctiveness of hard grain excavation and brittle fracture is mostly predetermined by the material composition. Fine grained materials exhibit less surface defects after machining and should be favoured for the manufacture of micro forming dies.

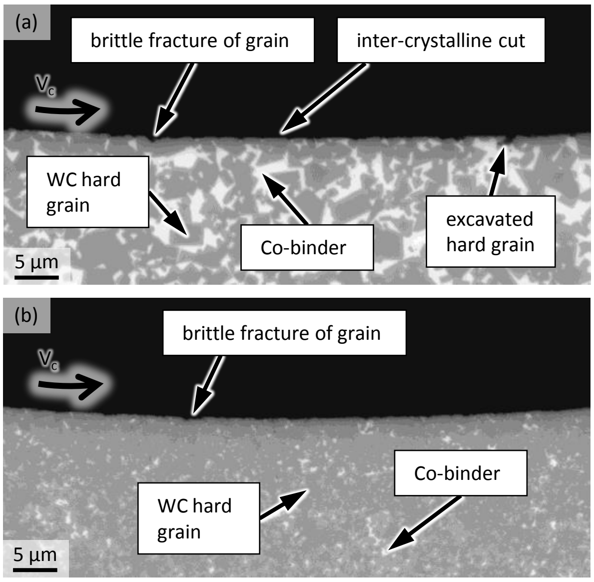

Figure 2. Cross-sectional metallographic images of machined grooves in BD40 (a) and GD18F (b) tungsten carbides.

4. Conclusion

The successful application of micro ball-endmills with binderless CVD-thick-film PCD bits to the micro milling of tungsten carbides was shown in this work. It can be concluded:

- CVD-thick-film PCD micro endmills are suitable for micro milling of cemented carbides
- Machining does not induce crack formation
- Roughness of generated surfaces meet requirements of micro forming tools (< Sa = 200 nm)
- Suitable machining parameters were found
- Ductile inter-crystalline cut is the predominant material removal mechanism
- Best machining results were achieved for the WC-Co sample exhibiting the finest grain (0.6 µm)

Ongoing work is dealing with the definition of adequate tool life criteria for CVD-thick-film PCD micro endmills for the machining of tungsten carbide samples as the next consequent step to the advanced manufacture of micro forming dies.

Acknowledgement

The authors would like to thank the DFG Deutsche Forschungsgemeinschaft for funding this work within sub-project C2 “Surface Optimization” of the Collaborative Research Centre 747 “Micro Cold Forming - Processes, Characterisation, Optimisation” at the University of Bremen.

References

[1] Vollertsen F (Ed.) 2013 Micro Metal Forming, Springer Berlin Heidelberg

[2] Liu K, Li X P 2001 Ductile cutting of tungsten carbide *Journal of Materials Processing Technology* **113(1-3)** 348-354

[3] Liu K, Li X P, Rahman M, Liu X D 2003 CBN tool wear in ductile cutting of tungsten carbide *Wear* **255(7-12)** 1344-1351

[4] Arif M, Rahman M, Wong Y S 2012 Analytical model to determine the critical conditions for the modes of material removal in the milling process of brittle material *Journal of Materials Processing Technology* **212(9)** 1925-1933

[5] Arif M, Rahman M, Wong Y S 2013 A study on the effect of tool-edge radius on critical machining characteristics in ultra-precision milling of tungsten carbide *International Journal of Advanced Manufacturing Technology* **67(5)** 1257-1265

[6] Uhlmann E, Oberschmidt D, Loewenstein A, Polte M, Polte J, Gonia D 2015 Binderless-PCD as cutting material for micro milling of cemented carbide moulds *euspen Conference Proceedings* **15** 299-300