Study of flank wear topography and surface-deformation of cemented carbide tools after turning Alloy 718

Citation for the original published paper (version of record):
Hoier, P., Malakizadi, A., Krajnik, P. et al (2018). Study of flank wear topography and surface-deformation of cemented carbide tools after turning Alloy 718. Procedia CIRP, 77: 537-540. http://dx.doi.org/10.1016/j.procir.2018.08.239

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 77 (2018) 537–540

www.elsevier.com/locate/procedia

8th CIRP Conference on High Performance Cutting (HPC 2018)

Study of flank wear topography and surface-deformation of cemented carbide tools after turning Alloy 718

Philipp Hoier*, Amir Malakizadi, Peter Krajnik, Uta Klement

Department of Industrial and Materials Science, Chalmers University of Technology, Rännvägen 2A, SE-412 96 Gothenburg, Sweden

* Corresponding author. Tel.: +46 31 772 12 71. *E-mail address:* hoierp@chalmers.se

Abstract

An investigation is reported on the characterization of an uncoated tungsten carbide tool used for machining of a Ni-Fe based superalloy (Alloy 718). Scanning electron microscopy (SEM) in combination with white-light interferometry (WLI) was applied to study the flank wear surface topographies both directly after the turning test and when the adhered workpiece material was removed by etching. The obtained results show that the thin layers of adhered workpiece material present on the flank wear land can obscure the wear topography. Removal of adhered workpiece material from the worn areas of interest is therefore necessary to reveal features of worn tool surfaces. SEM observations of worn WC grains revealed that abrasion is an active wear mechanism during cutting. Complementary analysis by the electron backscatter diffraction (EBSD) technique revealed that worn WC grains are additionally characterized by significant strain which suggests the contribution of plastic deformation to the flank wear. Plastic deformation of WC is likely caused by high thermal and mechanical loads acting on the tool during machining.

Keywords: Wear; turning; tribology; scanning electron microscope; electron backscatter diffraction.

1. Introduction

The degradation of tool materials plays a crucial role during many manufacturing processes. During machining operations in particular, changes of the tool geometry due to wear generally cause a deterioration of the machined component's surface quality. Premature tool failures can therefore cause significant costs, e.g. due to process down-times as well as damage to produced components. With respect to metal cutting, significant efforts have been taken to predict tool life. Besides the basic tool life equations, such as Taylor's [1] and Colding's [2], a number of investigations have been dedicated to the development of more comprehensive semi-empirical and physics-based wear models to predict the tool wear evolution rates [3,4]. Such wear models should be able to predict the wear rates, not only in view of tool material changes, but also when its microstructure (e.g. amount of binder, type and size of carbide grains) varies.

Physics-based models, however, require a thorough knowledge of the active wear mechanisms during cutting of different workpiece materials in order to ensure the relevance of the adopted prediction models.

The effort in this study is therefore to provide the fundamental understanding required for developing physics-based wear models. Sandvik Coromant's H13A uncoated cemented carbide grade was used for turning experiments due to its relatively simple composition (WC-Co). Furthermore, this grade is recommended for machining Ni-based superalloys when high bulk toughness is required [5]. The flank wear topography of the WC-Co insert was then investigated using scanning electron microscopy (SEM) and white-light interferometry (WLI) after the machining tests. Additionally, the crystallographic orientation spread within individual WC

10.1016/j.procir.2018.08.239

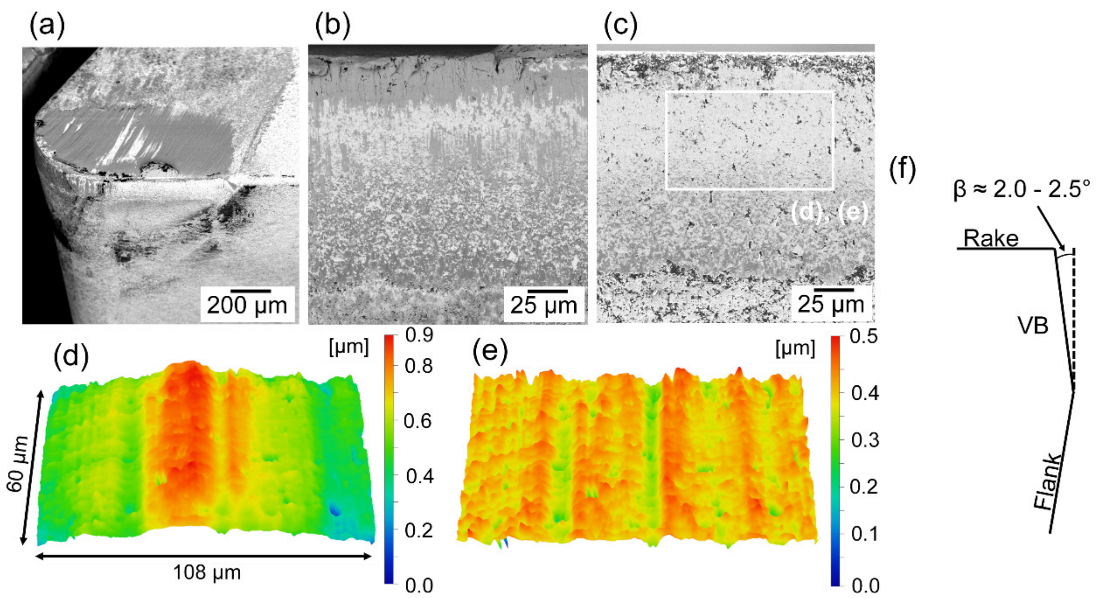

Fig. 1. *Worn cutting edge after the conducted tests: (a) tilted overview; flank wear land at higher magnification (b) before and (c) after etching in HCl; 3D topography of the flank wear land obtained by WLI (d) before and (e) after filtering for removal of waviness; schematic cross-sectional view of the flank wear lank wear land (VB) with its inclination angle (β). The workpiece sliding direction during cutting is from top to bottom.*

grains was examined by electron backscatter diffraction (EBSD) in order to evaluate the contribution of plastic deformation to the flank wear.

2. Experimental

Face turning tests were conducted on an EMCO 365 CNC lathe using uncoated cemented tungsten carbide (WC-Co) inserts in combination with a cutting fluid (6-7% emulsion) which was applied to the rake face of the insert. The experimental details are summarized in Table 1. The test was run under conditions which are close to previous studies concerning tool wear mechanisms when machining Alloy 718 [6,7].

Table 1: Employed tool and cutting parameters

Insert, ISO code	TCMW 16 T3 04
Insert, grade	WC-Co (uncoated, 10 vol.% Co)
Cutting speed, v_c	30 m/min
Depth of cut, a_p	1 mm
Feed rate, f	0.075 mm/rev
Machining time, t	16.2 min
Width of flank wear land, VB	185 µm

The machined workpiece material was age-hardened Alloy 718 with an average grain size and hardness of 27 ± 2 µm and 4.22 ± 0.05 GPa, respectively. The workpiece contained significant amounts of primary NbC carbides as well as TiN inclusions which were measured to have average particle projection areas of around 15 µm^2 and 25 µm^2, respectively. In age hardened condition, Alloy 718 furthermore contains 13-15 vol.% intermetallic γ'' precipitates with a diameter of around 10-20 nm alongside around 4 vol.% intermetallic γ' precipitates (11 nm diameter) [8,9].

The tool's flank wear land was analyzed using WLI (Sensofar S Neox), and SEM (FEI XL-30 and Zeiss Gemini 1550). The adhered workpiece material was removed from the worn tool surface by etching in diluted HCl. Subsequently, the crystallographic orientation of worn WC grains was examined in "top-view" by EBSD without further sample preparation steps. The data was obtained with a HKL Nordlys EBSD detector (Oxford Instruments) using a step-size of 50 nm and an acceleration voltage of 25 kV for the primary electron beam. Post processing of the acquired EBSD data was done with the HKL Channel 5 software (Oxford Instruments). Noise reduction was performed by removal of wild spikes and extrapolation of non-indexed points (5 nearest neighbors required).

3. Results and discussion

Figure 1 shows SEM micrographs of one of the worn tools before (Fig. 1a and b) and after (Fig. 1c) the etching procedure for removal of adhered Alloy 718 from the worn surfaces. As seen in Fig. 1a, the majority of the chip contact-zone on the rake face and parts of the flank wear land are subjected to

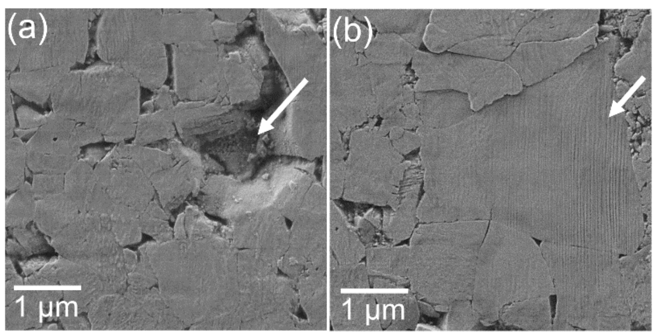

Fig. 2. *Wear topography viewed at high magnification: (a) pit in flank wear land; (b) abrasion marks on WC grain. The sliding direction of the workpiece is from top to bottom.*

adhesion of Alloy 718 (dark contrast). Removal of adhered workpiece material is therefore necessary to reveal the true wear topography. As seen in Fig. 1c, etching in HCl led to removal of the majority of adhered workpiece material from the flank wear land. In Figs. 1d and e, WLI scans of the adhesion free flank wear land are shown. The 3D topography image (Fig. 1d) reveals large-scale waviness, whereas grooves on smaller scale are evident in Fig. 1e together with pits in the worn surface. Note that the grooves are aligned parallel to the workpiece sliding direction. The WLI scan furthermore revealed that the surface of the flank wear land is vertically inclined by around 2 to 2.5 ° (see schematic in Fig. 1f).

Figure 2 shows the flank wear topography imaged at higher magnification. Figure 2a shows a SEM micrograph of a pit which was previously revealed by WLI (Fig. 1). Such pits can be formed due to adhesion and subsequent pull-out of individual WC grains. The WC grains are smoothly worn with occasional presence of nm-sized abrasion marks or grooves (see arrow in Fig. 2b) aligned parallel to the sliding direction.

Smoothly worn WC grains together with presence of grooves at different length scales (see Figs. 1e and 2) indicate that abrasion is an active wear mechanism. This is likely due to presence of different hard, abrasive phases (nm and µm-sized, see section 2) in the superalloy microstructure. However, both the large-scale waviness and inclination of the flank wear land (Figs. 1d and e) indicate that the tool geometry was altered by plastic deformation of the tool material.

EBSD examination was performed to observe whether plastic deformation contributes to the flank wear. Figure 3 shows a SEM micrograph combined with an EBSD orientation map of the same area. The EBSD map is displayed in inverse pole figure (IPF) coloring. For every measured point (pixel), the local crystallographic orientation of the respective worn WC grain is shown according to the provided color code.

Even though the EBSD orientation map in Fig. 3b has a significant fraction of non-indexed (black) areas, many individual WC grains are clearly distinguishable (compare to SEM micrograph). Non-indexed areas can mainly be attributed to the voids present in the worn surface. Additionally some of the WC surfaces could not be indexed. However, the indexed, individual WC grains are characterized by noticeable color variations (see Fig. 3b) which indicate crystallographic orientation spread (misorientation) and hence that the worn grains exhibit intragranular strain. Note that an undeformed grain would be shown with a single color.

A more detailed representation of intragranular strains of some WC grains is provided in Fig. 4. Here, EBSD orientation maps (IPF coloring) of four worn WC grains (Figs. 4a-d) are shown, with lines indicating the locations of misorientation profiles parallel to the sliding direction of the workpiece during cutting. The misorientation profiles plotted versus distance are provided in Fig. 4e. It can be seen that misorientations of about 10 to 30° relative to the first points of the profiles are measured. Similar observations were made on misorientation lines within a total of 15 grains.

Intragranular misorientation is likely to be caused by plastic deformation induced during machining. Even though WC is generally considered brittle, it has been shown to deform plastically during tribological testing by means of scratch

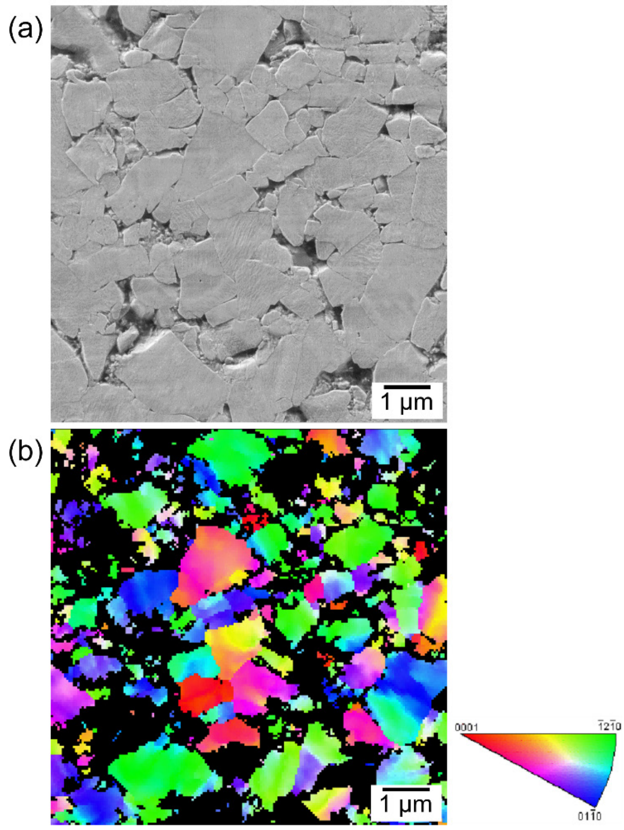

Fig. 3. Characteristics of flank wear land: (a) SEM micrograph of worn WC grains; (b) corresponding EBSD scan presented as inverse pole figure map (non-indexed pixels appear in black). The workpiece sliding direction during cutting was from top to bottom. The inverse pole figure color code is provided on the right.

testing [10–12]. For example, Mingard and Gee [10] have examined the deformation of WC after scratching with a diamond indenter employing 407 mN load. As compared to the present study, they reported lower misorientations of about 5 to 10° within worn WC grains. However, it should be noted that the tribological conditions during scratch testing are significantly different from the conditions occurring at the flank wear land during metal cutting. In particular, the primary shearing zone, which is the source of the majority of the heat generated in metal cutting [13] is not present during scratch testing. Hence, the temperature during metal cutting is expected to be significantly higher as compared with scratch testing.

For example, in case of turning of Alloy 718 under similar conditions as in the present study (30 m/min cutting speed, 0.1 mm/rev feed rate, 1 mm depth of cut), Malakizadi et al. [14] have reported temperatures in the range of 730 to 826 °C. High temperatures in the cutting zone together with the high-temperature strength of Alloy 718 are likely to generate high thermal and mechanical loads on the cutting tool which ultimately lead to larger plastic deformation of WC grains as compared with scratch testing.

The large misorientations in worn WC grains therefore imply that the individual grains as well as the complete network of WC grains on the cutting edge undergo plastic deformation under such machining conditions. The degree of plastic

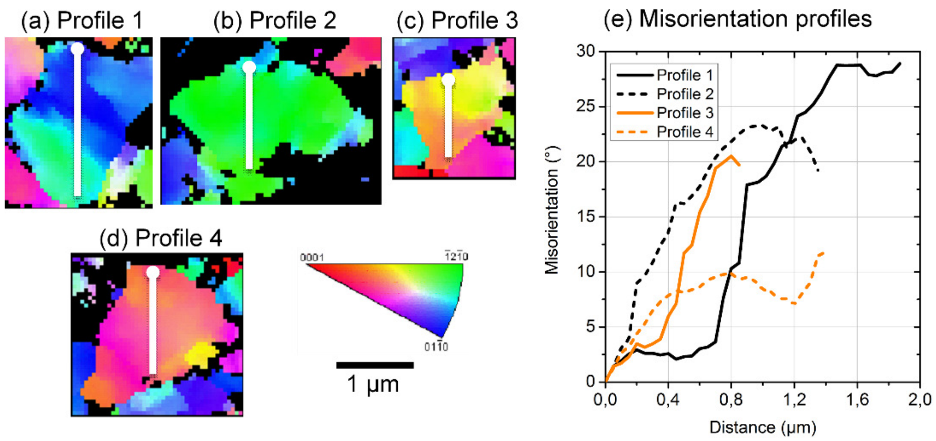

Fig. 4. Examples of intragranular strain present in worn WC grains: (a)-(d) inverse pole figure maps with locations of misorientation profiles indicated; (e) plot of misorientation profiles relative to the first points of the lines (indicated by dot in (a) to (d)).

deformation may vary with the composition/amount of metal binder and WC grain size. This is of vital importance, as a significant plastic deformation of the cutting edge can, for instance, change the thermo-mechanical condition around the edge and thereby the wear rate due to other mechanisms such as abrasion, adhesion and diffusion/dissolution. For example, an investigation by Thomsen et al. [15] indicated a significant increase in thermal and mechanical loads on the flank wear land when a ground tool with 1° flank inclination angle is used. Note here that their flank surface was inclined in the same manner as observed in the present study (see Fig. 1f). If occurring locally, such geometrical changes may explain the previously reported unstable flank wear development when turning Alloy 718 [7].

4. Summary and conclusions

The flank wear surface of a cutting tool used for turning of age-hardened Alloy 718 was characterized using WLI, SEM, and EBSD. In this way, the wear topography as well as the surface-induced plastic deformation were evaluated.

Abrasion marks and grooves on different length-scales indicate that flank wear was mainly caused by abrasion during sliding-contact of the tool with the workpiece. Examination of worn WC grains by means of EBSD proved to be a suitable method to assess the contribution of plastic deformation to tool wear in metal cutting. This is of particular interest for developing a deeper understanding of relative wear rates associated with machining of different workpiece classes and alloys. In the present case, EBSD analysis revealed that worn WC grains are characterized by significant strains leading to about 10 to 30° intragranular misorientation. The measured misorientation is caused by plastic deformation occurring during high thermal and mechanical loads which act on the tool during machining of Alloy 718. Small variations in tool geometry due to plastic deformation can significantly affect tool wear rates. Its quantitative assessment by EBSD can therefore provide valuable information on the relative importance of plastic deformation under the respective cutting condition.

Acknowledgements

Support by the region Västra Götalandsregionen within the PROSAM project, by Chalmersska Forskningsfonden, and by the Area of Advance Production at Chalmers are acknowledged. Jonas Holmberg at Swerea IVF is thanked for his help with the white light interferometry measurements.

References

[1] Taylor FW. On the art of cutting metals. New York: The American Society of Mechanical Engineers; 1907.
[2] Colding B. A wear relationship for turning, milling and grinding. KTH Stockholm; 1959.
[3] Malakizadi A, Gruber H, Sadik I, Nyborg L. An FEM-based approach for tool wear estimation in machining. *Wear* 2016; 368–369:10–24.
[4] Arrazola PJ, Özel T, Umbrello D, Davies M, Jawahir IS. Recent advances in modelling of metal machining processes. *CIRP Ann* 2013; 62:695–718.
[5] Sandvik Coromant. Application Guide - Heat resistant super alloys. Retrieved from https://www.sandvik.coromant.com/
[6] Olovsjö S, Nyborg L. Influence of microstructure on wear behaviour of uncoated WC tools in turning of Alloy 718 and Waspaloy. *Wear* 2012;282–283:12–21.
[7] Hoier P, Malakizadi A, Stuppa P, Cedergren S, Klement U. Microstructural characteristics of Alloy 718 and Waspaloy and their influence on flank wear during turning. *Wear* 2018;400–401:184–93.
[8] Devaux A, Nazé L, Molins R, Pineau A, Organista A, Guédou JY, et al. Gamma double prime precipitation kinetic in Alloy 718. *Mater Sci Eng A* 2008; 486:117–122.
[9] Chaturvedi MC, Han Y. Effect of particle size on the creep rate of superalloy Inconel 718. *Mater Sci Eng* 1987; 89:7–10.
[10] Mingard KP, Gee MG. EBSD examination of worn WC/Co hardmetal surfaces. *Wear* 2007; 263:643–652.
[11] Gee M, Mingard K, Roebuck B. Application of EBSD to the evaluation of plastic deformation in the mechanical testing of WC/Co hardmetal. *Int J Refract Met Hard Mater* 2009; 27:300–312.
[12] Olsson M, Heinrichs J, Yvell K, Jacobson S. Initial degradation of cemented carbides for rock drilling — Model studies of the tribological contact against rock. *Int J Refract Met Hard Mater* 2015; 52:104–113.
[13] Klocke F. Manufacturing Processes 1. Berlin, Heidelberg: Springer Berlin Heidelberg; 2011.
[14] Malakizadi A, Cedergren S, Babu Surreddi K, Nyborg L. A methodology to evaluate the machinability of Alloy 718 by means of FE simulation. *Proc. Int. Conf. Adv. Manuf. Eng. Technol.* 2013, Stockholm: 2013, p. 95-106.
[15] Thomsen EG, Macdonald AG, Kobayashi S. Flank Friction Studies With Carbide Tools Reveal Sublayer Plastic Flow. *J Eng Ind* 1962