Influence of Surface Conditions on Wear and Friction of Hardmetals

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Abstract

Tribological properties of a number of hardmetal grades exhibiting various surface finishing conditions as a result of polishing, grinding and electro-discharge machining (EDM), were investigated by performing comparative dry friction experiments on a small-scale pin-on-plate test rig, according to ASTM G133.

The observed wear was examined by optical microscopy, scanning electron microscopy, energy dispersive X-ray analysis and X-ray diffraction. Wear volumes were derived using surface scanning topography equipment.

Wear damage of cemented carbides, i.e. hardmetals, was found to occur according to a combination of several mechanisms. A correlation between wear volume and coefficient of friction on the one hand and surface conditions and finishing treatment on the other hand (Llanes et al*, 2001) was determined. A significant influence of the binder matrix on wear resistance of hardmetals was proven.*

1. INTRODUCTION

In an industrialized society approximately one third of the gross national product is spent on damages as a consequence of wear and corrosion. Therefore, based on economic reasons but especially today based on ecological reasons as well, there is a rising demand for an adequate limitation of the wear of machines and construction tools with attention to the efficient application of scarce materials and resources, and hence, an obvious industrial need exists for high performance materials, in order to increase the life-time of wear applications such as high speed cutting, milling, drilling, punching and reaming.

Hardmetals could meet this need, as they exhibit an excellent wear resistance in combination with outstanding mechanical properties and chemical inertness. Furthermore, their electrical conductivity allows them to be manufactured, irrespective of their extremely high degree of hardness, by electro-discharge machining (EDM), i.e. an electro-thermal material removal process (Ho & Newman, 2003)

2. EXPERIMENTAL

2.1. Tested Materials

The investigated cemented carbides consisted of very hard tungsten monocarbide (WC) grains, cemented in a binder matrix of tough cobalt (Co) or nickel (Ni) by liquid phase sintering. Three of the examined grades contained a small amount of chromium (Cr) and/or vanadium (V) as well, serving as grain growth inhibitor during the sintering process. Their chemical, microstructural and mechanical properties are summarized in Table 1.

Table 1: Hardmetal grades: average grain size, binder mean free path length, compressive strength, transverse rupture strength, Vickers hardness, indentation fracture toughness, Young's modulus, thermal conductivity

Hardmetal	WC10Co	WC10Co (Cr/V)	WC6Co (Cr/V)	WC8Ni (Cr)
Grain size [µm]	2.165	0.318	0.548	0.808
BMFPL [µm]	0.926	0.136	0.166	0.296
CS [MPa]	4200	6600	7200	5000
TRS [MPa]	3064±91	3509±168	3078±295	2881±303
HV10	1149±10	1685±38	1913±13	1376±17
K_{IC}^{30kg} [MPa.$\sqrt{m}$]	> 20.6	11.1	9.3	15.2
E [MPa]	578±6	541±4	609±4	557±11
K [$W.m^{-1}K^{-1}$]	105	85	90	85

Surface conditions and roughness parameters of the cemented carbides were obtained by applying three finishing techniques:

- a diamond *grinding* wheel (Polymer bonded D46 SW-50-X2 (TechnoDiamond), resulting in Ra-and Rt-values below 0.2 µm and 1 µm respectively;
- a *polishing* ultra-fine grained diamond paste, involving Ra- and Rt-values below 0.01 µm;
- a *wire-EDM* treatment under different consecutively performed *finishing regimes*, leading to Ra- and Rt-values ranging from over 2 µm and 10 µm respectively for the roughest cut, down to below 0.2 µm and 1 µm for the final cut.

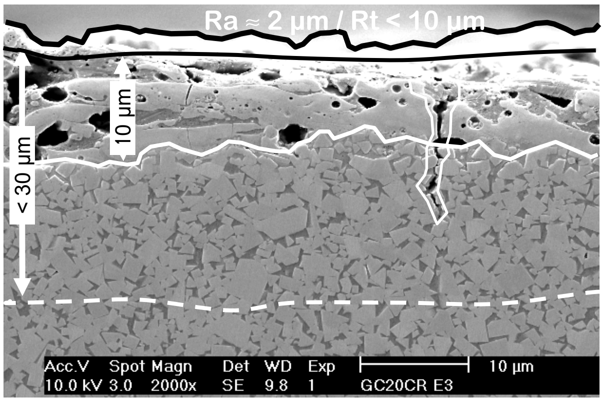
The wire-EDM finishing cuts were performed on a ROBOFIL 2030 (Charmilles Technologies, Switzerland) in demi-water with a dielectric conductivity of 5 µS/cm, using a CuZn37 wire electrode (diameter of 0.25 mm, tensile strength of 500 MPa). The EDM parameters of four EDM regimes are listed in Table 2.

Table 2: applied wire-EDM parameters: one rough cut and three finishing cuts

EDM regime	E3	E8	E21	E23
Ra (µm)	± 2	± 1	<0.4	±0.2
Material removed (µm)	-	12	2	0
Open voltage (V)	80	80	140	140
Pulse Ignition Height (A)	8	16	5	2.5
Pulse duration (µs)	1.2	1	3	1
Pulse interval (µs)	8.3	10	6.6	4
Maximum speed (mm/min)	14.5	14.5	6.1	8
Servo Reference Voltage (V)	50	13.2	7	0
Flushing pressure (bar)	6.5	0	0	0
Wire winding speed (m/min)	8	6.8	6.8	4.8
Wire Tension (N)	11	16	12	10

During the first EDM manufacturing step, a rough surface is created, containing three types of layers, which is illustrated in Figure 1.

Figure 1: Cross-sectional micrograph (SEM) at the surface of a roughly EDM'ed WC/Co hardmetal



The top surface contains a thin layer of spattered *EDM residue* (Cu, Zn) originating from the molten metal and the small amounts of electrode material.

Underneath the easily removable EDM residue a *recast layer* is formed during solidification of molten material (leading to cavities) that has not been expelled and has instead been rapidly quenched by the dielectric. Depending on the base material, its microstructure can be altered to such an extent that it becomes brittle with formation of microcracks. XRD analysis revealed the presence of tungsten subcarbide and η-phase (W_3Co_3C and W_6Co_6C) for the Co-based hardmetal grades. However, this layer can substantially be removed by further finishing EDM-operations.

The *heat-affected zone* especially modifies the binder, exhibiting a lower melting temperature than the WC grains, and may locally alter the performance of the hardmetal. This area is affected by the amount of current applied in the roughing and finishing operations.

2.2. Wear Test rig

Pins (diameter 7.9 mm, length 22 mm) were reciprocally slid, unlubricated, against counter plates (width 38 mm, length 58 mm, thickness 4 mm) using a high frequency tribometer, in an air-conditioned atmosphere of 23 °C and a relative humidity of 60 %, in accordance with ASTM G133. All hardmetal grades were tested as plate material, in combination with the highest hardness grade hardmetal pin, i.e. WC6Co(Cr/V). Contact loads were varied from 15 N up to 100 N. The stroke length of the oscillating motion was 15 mm. A sliding velocity of 0.3 m/s was applied. The test duration was associated with a sliding distance of 10 km, allowing wear volumes to be compared.

2.3. Post mortem analysis

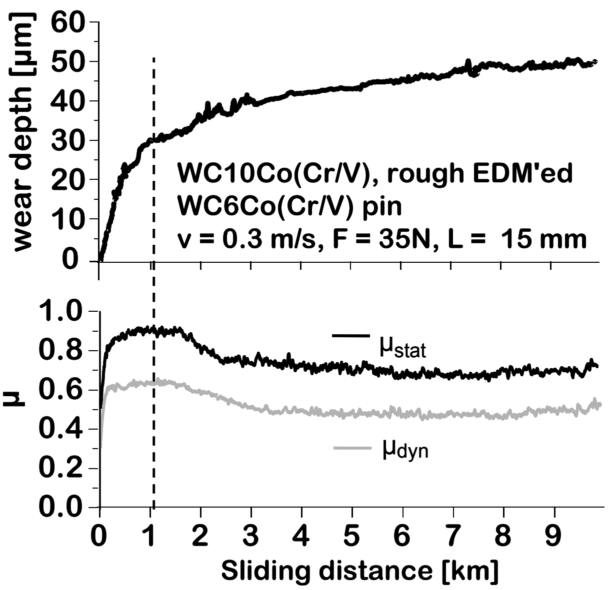
The generated wear was quantified topographically by surface scanning equipment (Somicronic® EMS Surfascan 3D, type SM3, number 380027, needle type ST305). The wear tracks were observed by SEM (Philips XL 30 FEG) and analyzed by EDX.

3. RESULTS AND DISCUSSION

3.1. Coefficient of friction and wear depth

During the online monitoring of friction and wear depth of the hardmetal tribocouples, a typical wear behaviour was observed, Figure 2. The friction coefficient and wear rate were initially high, due to a very restricted pin on plate contact surface, then they decreased, with growing contact surface, and eventually an approximately constant level of wear rate and friction was reached, corresponding to a regime situation. The curves of dynamic friction were similar to those of the static friction, but always exhibited lower values.

Figure 2 combined wear depth and coefficient of friction for a WC6Co(Cr/V) pin sliding at 0.3 m/s, with a 35 N contact load, against a roughly EDM'ed WC10Co(Cr/V) plate

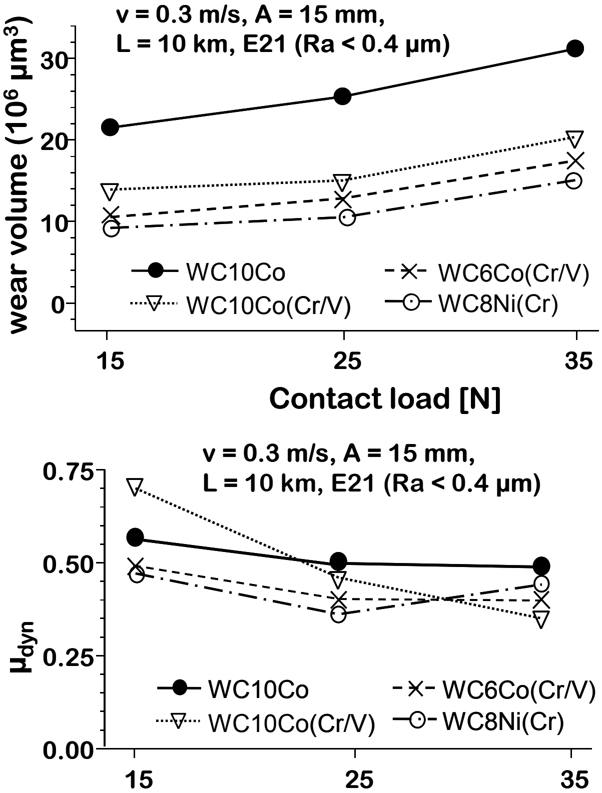


It is worth noting that a relative large scatter was bound to occur between the tests due to the powerful influence of minor factors on the type of wear mechanism which predominates. Therefore, error bars should be included in each data point. However, this did not change the observed trends.

3.2. Influence of contact load

Wear volumes and dynamic coefficients of friction for all investigated hardmetal grades are compared as function of the applied contact load in Figure 3.

Figure 3: wear volume and initial dynamic coefficient of friction as function of contact load for 4 fine-EDM'ed (regime E21) hardmetals



The highest wear level is found with the largest grain size/lowest hardness grade, i.e. WC10Co, whereas the highest wear resistance appears with the nickel based hardmetal grade. Furthermore, wear volume is noticed to increase with higher contact load.

With the one exception of the nickel grade at the highest contact load, friction is noticed to decrease with an increasing contact load, probably attributed to an elastic deformation behaviour (Van Beeck, 2001).

The higher wear volume for higher contact loads can be associated with a more pronounced occurrence of following wear mechanisms which were observed:

- grain cracking and grain fracture (Figure 4),
- polishing of grains (Figure 4),
- pull out of WC-grains (Figure 5),
- thermally induced matrix binder transformation (oxidation) (Hsu & Chen, 1996) (Figures 5, 6).

Figure 4: cross-sectional micrographs (SEM) at the wear surface of a ground Co-based hardmetal after sliding 10 km at 0.3 m/s with a 50 N (a) and 100 N (b) contact load; *grains* are *polished,* wear track (b) shows a higher degree of fractured grains

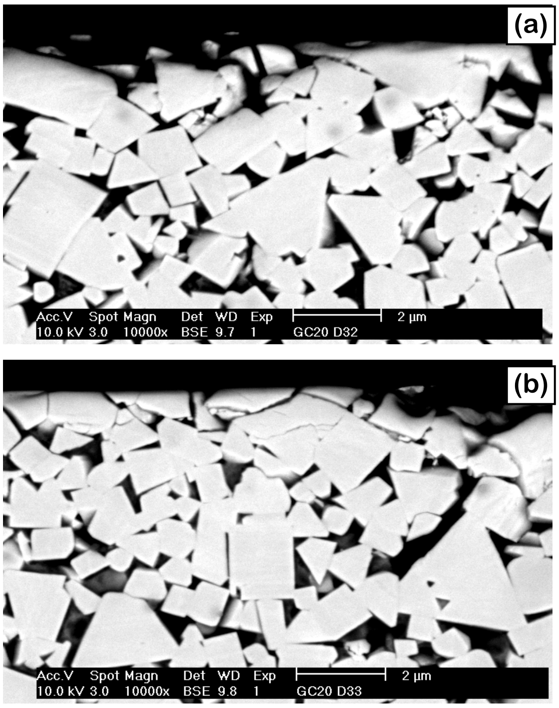
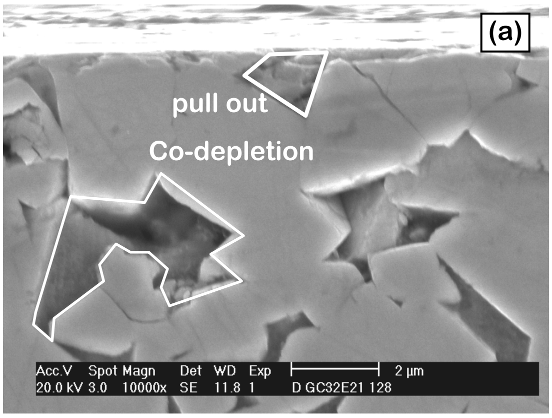


Figure 5: cross-sectional micrographs (SEM) at the wear surface of a fine EDM'ed (regime E21) Co-based hardmetal after sliding 10 km at 0.3 m/s with a 15 N (a) and 35 N (b) contact load; Co-depletion (diffusion) and a higher degree of *grain pull out* in wear track (b)



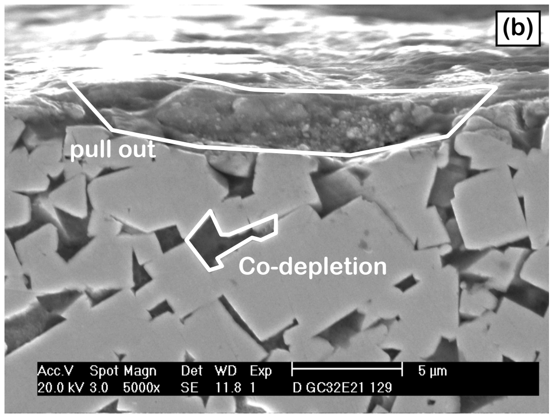
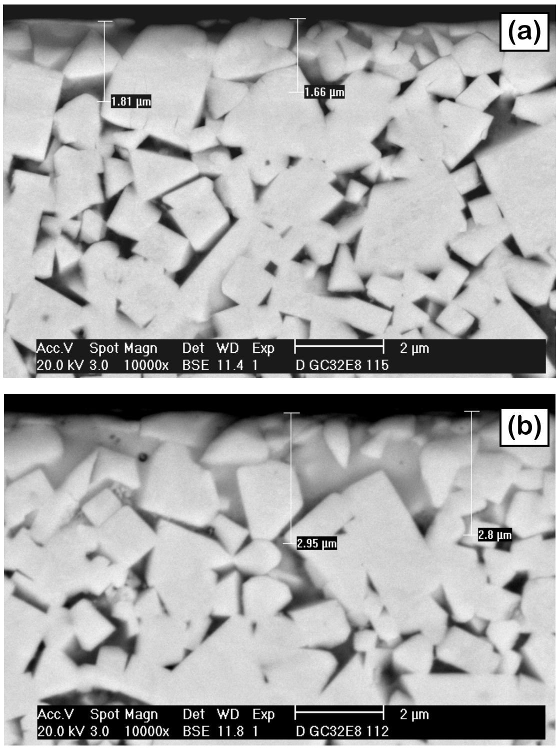


Figure 6: cross-sectional micrographs (SEM) at the wear surface of a roughly EDM'ed (regime E8) Co-based hardmetal after sliding 10 km at 0.3 m/s with a 15N (a) and 35N (b) contact load; deeper *Co-binder transformation* zone (color change) under wear track (b)

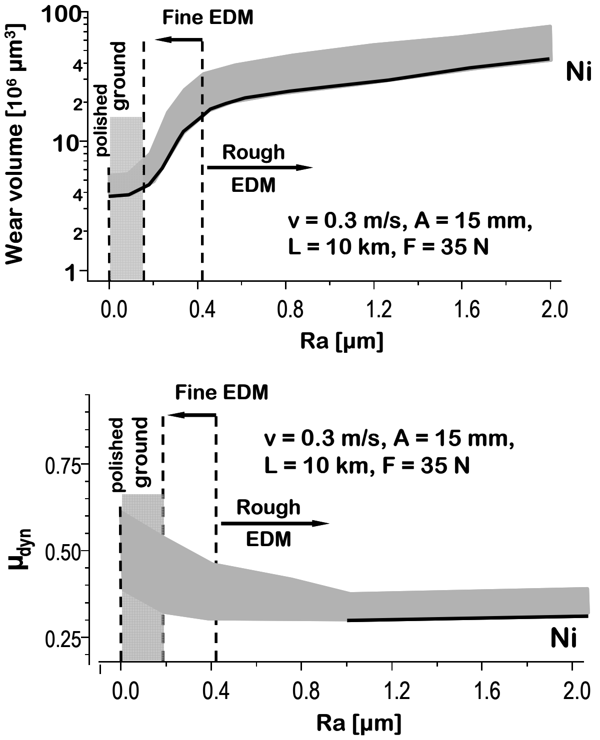


3.3. Influence of surface conditions

Wear volume and initial dynamic coefficient of friction for the investigated hardmetal grades as function of their surface finishing treatment are compared in Figure 7.

These trends confirm the tendency of the nickel based hardmetal exhibiting the most favourable tribological behaviour. Furthermore, wear volume is noticed to decrease with lower surface roughness. The best wear resistance is accomplished with polishing and grinding. The roughly machined hardmetals exhibit the highest wear level, which decreases drastically though by further execution of EDM towards the finest regime.

Figure 7: wear volume and initial dynamic coefficient of friction as function of surface conditions of hardmetal plates, slid 10 km at 0.3 m/s with a 35 N contact load against WC6Co(Cr/V) pins

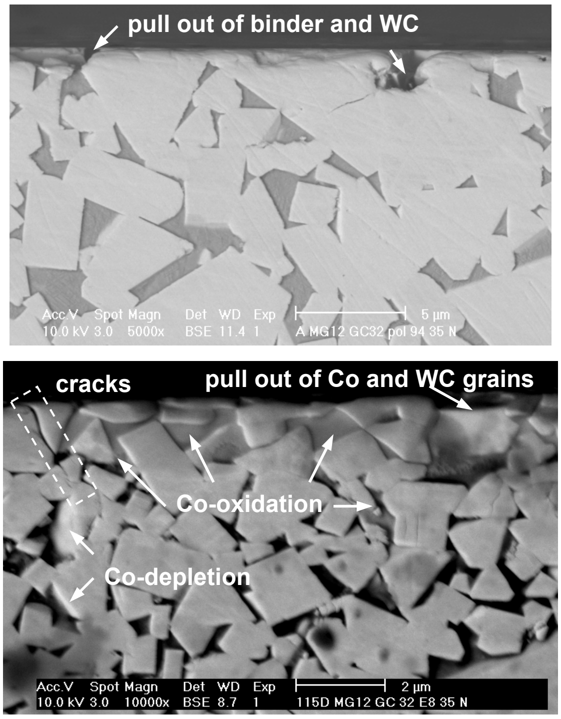


The coefficient of friction is almost constant for EDM'ed surfaces but increases for decreasing Ra-values below 0.4 µm where adhesion becomes more pronounced as a result of a growing real contact area due to higher atomic forces between the sliding surfaces (Jahanmir, 1994).

The lower wear resistance of the roughly EDM'ed cemented carbides compared to their polished and ground equivalents can be attributed to both the microstructural surface modification and a different residual surface stress state (Jiang *et a*l, 2005), and thus the alteration of (the relative importance of emerging) wear mechanisms participating in the global surface damage:

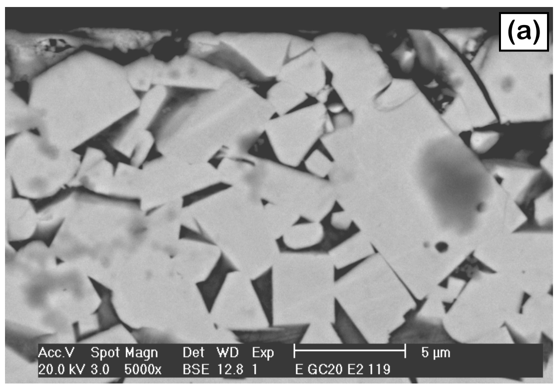
- An increasing probability of *grain fracture* due to crack growth of already existing transgranular and/or intergranular cracks in a brittle surface layer, originating from the EDM process (Figure 1);
- An energetically more favourable situation for thermally induced *transformation* (oxidation) of the *binder* material (Figure 8);
- A more pronounced *abrasion* due to a higher surface roughness.

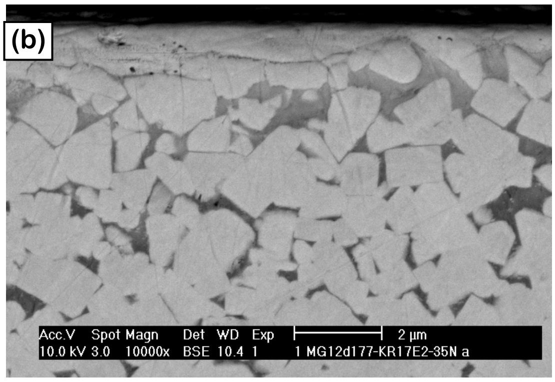
Figure 8: cross-sectional micrographs (SEM) at the wear surface of a polished (a) and roughly EDM'ed (regime E8) Co-based hardmetal, slid 10 km at 0.3 m/s with a 35 N contact load against WC6Co(Cr/V) pins; the EDM'ed surface is much more affected by wear



The influence of the binder metal on wear resistance is illustrated in Figure 9. High contact loads completely remove the recast layer in cobalt-based hardmetal grades, which is not the case for the nickel based hardmetal. However, an elucidation for this phenomenon was not found yet.

Figure 9: cross-sectional micrographs (SEM) at the wear surface of an roughly EDM'ed (regime E2) hardmetal with Co-binder (a) and Ni-binder (b), slid 10 km at 0.3 m/s with a 35 N contact load; recast layer worn out completely for Co-binder, only partially for Ni-binder





4. CONCLUSIONS

Dry friction experiments on polished, ground and electro-eroded cemented carbides revealed several mechanisms involved in their global degradation process caused by wear: thermally induced oxidation and depletion of the binder metal, brittle grain cracking, pull out and polishing of tungsten carbide grains, adhesion and abrasion.

Correlations between their tribological properties, surface conditions and chemical, microstructural and mechanical characteristics were derived. An increasing contact load was found to increase the wear volume and to slightly decrease the coefficient of friction. Wear resistance appeared to be strongly influenced by surface finishing. Polishing and grinding improve wear resistance of hardmetals in a higher degree than electro-discharge machining. However, in comparison with the rough EDM regime, the execution of consecutive EDM finishing steps to the finest surface regime was noticed to considerably enhance the wear resistance.

The significant influence of the binder material in the hardmetals was proven. The most favourable tribological results were obtained for the nickel based hardmetal grade. These promising results with the Ni-binder emphasize the importance of further investigation in this direction.

5. ACKNOWLEDGMENTS

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