Influence of Electro-discharge machining, microstructural and mechanical properties on wear behaviour of hardmetals

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Summary

A number of tungsten carbide based hardmetal grades were either finished by polishing or by electro-discharge machining under different regimes, corresponding to varying surface roughness levels. Dry friction experiments on these materials were performed according to the ASTM G133 wear test principle, using a small-scale high frequency pin-on-plate test rig, with the goal to characterize their friction and wear behaviour and to investigate the influence of the EDM-regime, their microstructural and mechanical properties on their wear behaviour.

Optical microscopy and scanning electron microscopy (SEM) were used to qualify the generated wear. Energy Dispersive X-ray Analysis (EDX) and Transmission Electron Microscopy (TEM) were used as well in order to analyze wear debris particles formed during the wear experiments. The wear tracks of the hardmetal plates were topographically quantified by means of surface scanning equipment in order to determine wear volumes and wear rates.

Keywords

Hardmetal, tungsten carbide, electro-discharge machining, surface roughness, friction, wear, surface topography

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 need for an adequate limitation of the wear of machines and construction tools with attention to the efficient application of scarce materials and resources (such as energy). In this way there is an obvious industrial need for wear resistant materials to be applied under heavy tribological circumstances and preferably without lubrication as for instance for tools (chisels, cutting tools, metal forming dies, punches, etc.) and various machine parts (bearings, gears, sealings, etc.).

At present, hardened steels or some technical ceramic materials, in bulk or as a surface coating, are often used for these applications. The main purpose of these materials is to extend the lifetime of existing devices and/or components by decreasing their wear rate. A significant disadvantage of these materials is their relatively high friction coefficient in dry contact conditions (heat development and energy loss). Moreover, their high hardness renders them intrinsically difficult to shape and to finish using conventional methods. Today nearly the only suitable manufacturing technique is grinding with super hard grinding grains (diamond, CBN tools), which restricts however seriously the possibilities in geometries that can be realized.

Hardmetals could be an ideal solution, because these ceramic materials display excellent mechanical properties, wear resistance and chemical inertness. Moreover, they are electrical conductive, which allows them to be manufactured by electro-discharge machining (EDM), a thermal process with material removal occurring via the discharge of energy between the work piece and a tool electrode. With the technique of EDM, complex shapes in materials can be accomplished with high accuracy, irrespective of their mechanical properties.

Currently a number of EDM’able ceramic hardmetals are already commercially available. A problem however is the lack of knowledge of the tribological properties of these EDM’ed materials and the insufficient scientific perception of the influence of EDM on their friction and wear resistance. This research was performed with the goal to investigate and compare several hardmetal grades regarding their surface roughness conditions (EDM-regimes or polished) and their microstructural, chemical, mechanical and tribological properties.

2. Experimental

2.1 Test materials

Six CERATIZIT hardmetal grades were investigated. They consist of tungsten carbide as matrix grains with cobalt or nickel as binder material and chromium and/or vanadium as grain growth inhibitor. Their chemical, microstructural and mechanical properties are listed in *TABLE 1*.

*TABLE 1: Chemical, microstructural and mechanical properties of WC-based hardmetals. *Measured on ground samples*

hardmetal grade	WC10Co	WC12Co(V)	WC12Co(Cr)	WC8Ni(Cr)	WC10Co(Cr/V)	WC6Co(Cr/V)
binder material [wt%]	10% Co	12% Co	12% Co	8% Ni	10% Co	6% Co
inhibitor material	none	V	Cr	Cr	Cr/V	Cr/V
average grain size [µm]	2.165	0.849	0.928	0.808	0.318	0.548
density [g/cm^3]	14.33	14.08	14.01	14.47	14.23	14.62
Electrical resistivity [Ω.m]	105	95	95	85	85	90
Thermal conductivity [W.m^{-1}.K^{-1}]	$1,3.10^{-7}$	$1,4.10^{-7}$	$1,3.10^{-7}$	$1,4.10^{-7}$	$1,7.10^{-7}$	$1,4.10^{-7}$
Vickers hardness [HV10]	1149 ± 10	1286 ± 8	1306 ± 5	1376 ± 17	1685 ± 38	1913 ± 13
Fracture toughness K_{IC}(30kg) [MPa$\sqrt{m}$]	> 20.6	20.6	19.9	15.2	11.1	9.3
3-point bending strength [MPa] *	3064 ± 91	4279 ± 61	2919 ± 101	2881 ± 303	3509 ± 168	3078 ± 295
compressive strength [GPa]	4.2	4.9	4.9	5	6.6	7.2
Young's modulus E [GPa]	578 ± 6	563 ± 2	546 ± 2	557 ± 11	541 ± 4	609 ± 4

The surfaces of the hardmetals were either polished or finished by wire-EDM under different regimes, resulting in different roughness levels. 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 5 consecutively performed finish cutting regimes are summarized in *TABLE 2*.

TABLE 2: Applied wire EDM finishing regimes

EDM regime	E3	E8	E13	E21	E23
Surface Roughness Ra (µm)	± 2	± 1	± 0.4	± 0.2	< 0.2
Material removed (µm)	-	12	2	1	0
Open voltage (V)	80	80	140	140	140
Pulse Ignition Height (A)	8	16	5	4.5	2.5
Pulse duration (µs)	1.2	1	3	1	1
Pulse interval (µs)	8.3	10	6.6	4	4
Maximum speed (mm/min)	14.5	14.5	6.1	6.1	8
Servo Reference Voltage (V)	50	13.2	7	6	0
Flushing pressure (bar)	6.5	0	0	0	0
Wire winding speed (m/min)	8	6.8	6.8	6.8	4.8
Wire Tension (N)	11	16	12	10	10

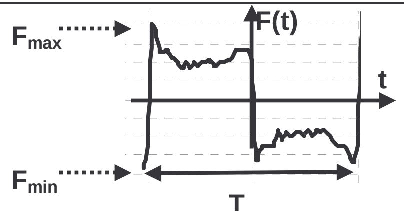
2.2 Test rig

Sliding wear experiments on the hardmetal grades were performed using a small-scale pin-on-plate tribometer, in accordance with the ASTM G133 “Reciprocating Wear Test” principle. The most important features of the test rig are summarized in *TABLE 3*.

TABLE 3: Characteristics of the pin-on-plate test rig

Normal load	10 up to 250 N
Stroke length	0.1 up to 15 mm
Frequency	2.5 up to 40 Hz
Resistance Heating of Test Specimen	20°C up to 400°C
Online measured Parameters	- wear (thickness change) - friction coefficient (both normal and horizontal force)
Controlled Parameters	- sliding velocity (frequency) - (normal) load - temperature and relative humidity - sliding distance (test duration)

The WC6Co(Cr/V) grade was used as pin material because this grade exhibits the highest hardness. The pins have a diameter of 7.9 mm, a length of 22 mm, whereas the plates have a width of 38 mm, a length of 58 mm and a thickness of 4 mm. The horizontal friction force, which is applied by the moving pin to the plate, is measured by a piezo-electric transducer and characterizes the friction coefficient µ. Both the evolution of the friction force as average and minimum/maximum friction force values during each one movement cycle are registered. The real normal load is measured online as well. A static and dynamic friction coefficient can then be calculated as indicated in *figure 1*.



$$F_{stat} = \frac{|F_{\max}| - |F_{\min}|}{2} \Rightarrow \mu_{stat} = \frac{F_{stat}}{N}$$

$$F_{dyn} = \frac{1}{T}\int_0^T F(t).dt \Rightarrow \mu_{dyn} = \frac{F_{dyn}}{N}$$

Figure 1: Definition of static and dynamic friction coefficient

The normal displacement of the pin towards the fixed hardmetal plate is recorded continuously by a contactless proximitor. This measurement gives an indication of the combined wear of both surfaces and is a useful tool in identifying wear transitions.

2.3 Test conditions

For the selection of realistic wear test conditions, the laws of Hertz were used, allowing a mean contact pressure calculation between two sliding surfaces for a given normal load. Based on the compressive strength properties of the hardmetal grades, a maximal appropriate normal load for the dry friction experiments was derived, as shown in *TABLE 4*. From these results it was decided to apply normal contact loads varying from 15 N up to 50 N.

TABLE 4: maximal appropriate normal contact loads for the hardmetal grades in combination with a WC6Co(Cr/V) pin, based on their compressive strength properties

hardmetal grade	WC12Co	WC12Co(V)	WC12Co(Cr)	WC8Ni(Cr)	WC10Co(Cr/V)	WC6Co(Cr/V)
p_{max} [GPa]	4.2	4.9	4.9	5	6.6	7.2
F_{max} [N]	126	208	217	206	491	587

A stroke length of 15 mm was applied. The test duration was chosen in accordance with a constant wear distance of 10 km, allowing wear volumes to be compared afterwards. The sliding velocity was 0.3 m/s. The dry friction tests were performed in a conditioned atmosphere at room temperature (23 °C) and a relative humidity of 60 %.

3. Results

During the online measurement of friction coefficient and wear as a result of WC6Co(Cr/V) pins sliding against hardmetal plates, a typical wear behaviour is observed. The initial friction coefficient and wear rate are high, as pin-on-plate contact surface is very restricted (point contact), then they decrease, as pin penetrates into plate while the contact surface is growing, and eventually an almost constant wear and friction level is reached, corresponding to a regime situation, with only little variations.

It is also worth noting that a relative large scatter is 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 seem to change the observed trends.

Wear volumes are determined by surface scanning after a sliding distance of 10 km. The specific wear rate is defined as the wear volume divided by the normal force and the sliding distance. The friction coefficients are measured online. Similar observations are made for static and dynamic friction, with the only difference that the static component exhibits higher values. Wear tracks and wear debris formed during the wear experiments were observed and analyzed by SEM, EDX and TEM.

A number of correlations with wear and friction were investigated:

- contact pressure (normal load);
- sliding distance (test duration);
- surface roughness (EDM-regime);
- the type of hardmetal and its microstructural and mechanical properties: grain size, binder material, Vickers hardness (HV10) and compressive strength.

3.1 Influence of normal contact force

Wear volume, specific wear rate and dynamic friction coefficient at start and end of wear testing for hardmetal plates with a surface roughness as a result of an E21 EDM-regime are summarized as function of normal force in *figure 2*.

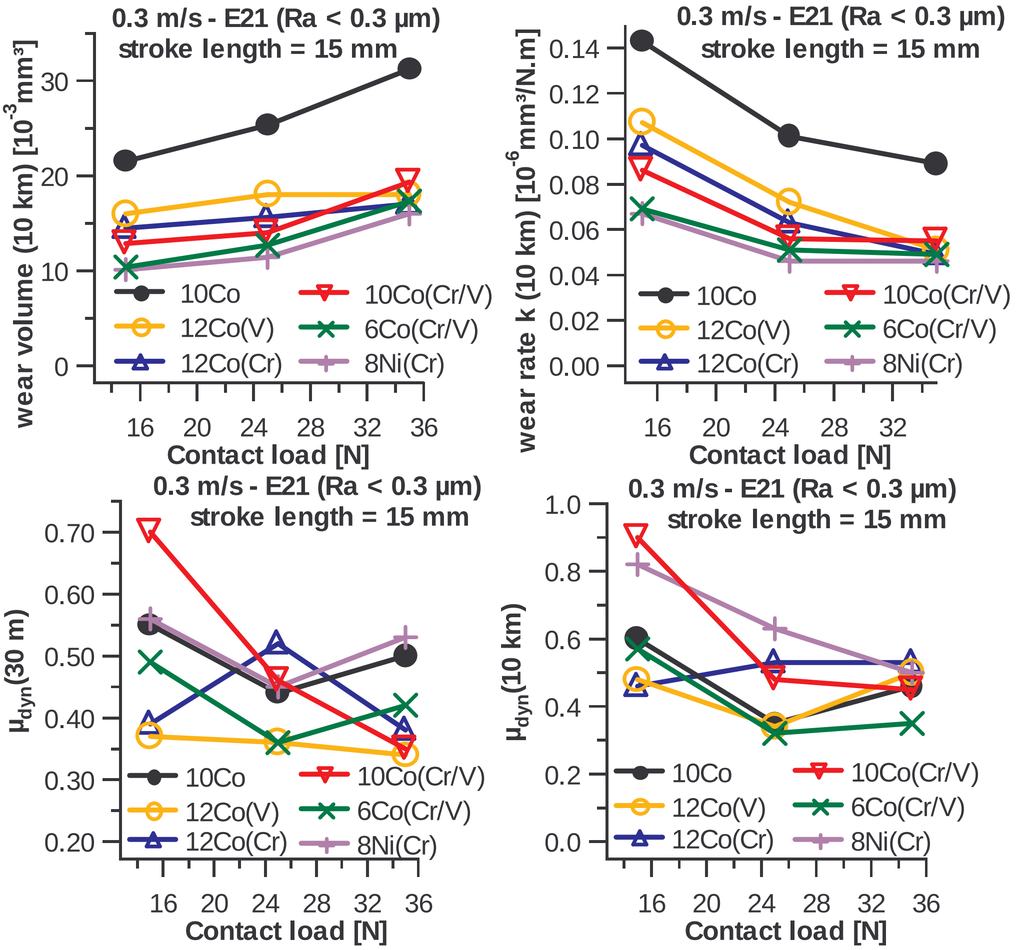


Figure 2: wear volume, specific wear rate, dynamic friction coefficient at start and end of testing as function of normal load for hardmetal grades with surface roughness according to EDM-regime E21

Following correlations between friction, wear and contact pressure can be derived:

- wear volume increases with an increasing normal force;
- specific wear rate decreases with increasing contact pressure, which can be explained by the mainly elastic deformation behaviour of hardmetals;
- the highest wear volume and wear rate are found with the WC10Co grade, exhibiting the largest grain size and the lowest hardness;
- generally the same trends occur for both the initial and regime values of static and dynamic friction coefficient: globally decreasing with an increasing normal contact load, which is explained by the mainly elastic deformation attitude of hardmetals.

3.2 *Influence of sliding distance*

In real-time measured wear depth and friction coefficient curves as function of sliding distance for hardmetal plates with different EDM-regimes are summarized in *figure 3*.

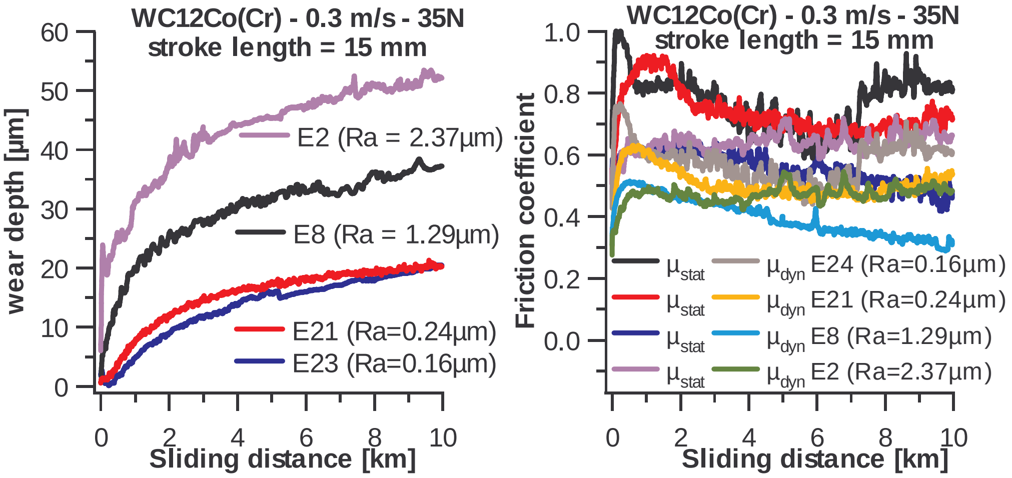


Figure 3: wear depth and friction coefficient as function of sliding distance for WC12Co(Cr) hardmetal with different EDM-regimes, tested with a normal force of 35 N and a sliding velocity of 0.3 m/s

Some correlations between wear, friction, sliding distance and EDM-regime are found:

- initial wear rate and friction coefficient are high as the pin penetrates the counter surface, then they decrease till a nearly constant value is reached, corresponding to a regime situation with wear increasing almost linearly with sliding distance;
- the fluctuations in the friction and wear curves, both in the initial and regime situation, are due to a continuous breaking and regeneration of microjunctions and indicate a more pronounced adhesive wear;
- with increasing Ra, i.e. a decreasing degree of surface finishing by EDM, wear depth and initial wear rate increase whereas friction coefficient globally decreases;
- wear rate in the regime situation seems independent of the EDM-regime.

3.3 *Influence of EDM-regime*

Wear volume and initial dynamic friction coefficient for the investigated hardmetal grades as function of their surface roughness after applying a sliding distance of 10 km, a normal load of 35 N and a sliding velocity of 0.3 m/s are presented in *figure 4*.

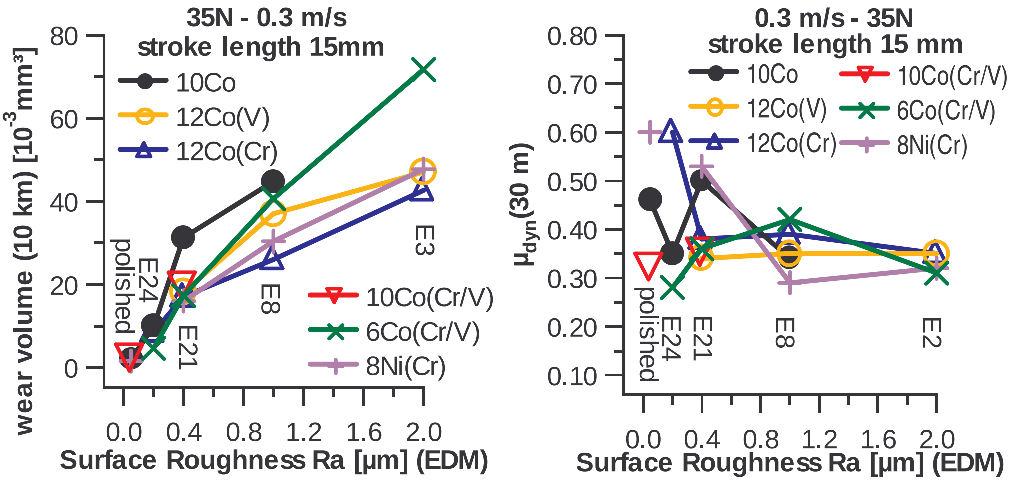


Figure 4: wear volume and initial dynamic friction coefficient at start as function of EDM-regime for several hardmetals, tested with normal force of 35 N, sliding distance of 10 km, sliding velocity of 0.3 m/s

Following correlations between tribological properties and EDM-regimes can be made:

- wear volume increases with increasing roughness Ra, with a bending point at an Ra-value of approximately 0.4;
- the friction coefficient is almost constant for Ra-values above 0.4 µm, but globally increases with decreasing Ra-values below 0.4 µm, with large scattering.

This “bending point” phenomenon is confirmed in literature. The friction coefficient appears to be approximately constant within a certain roughness interval but increases for both higher or lower Ra-values due to an increasing ploughing component (abrasive wear) or an increasing real contact area due to high atomic forces between the surfaces (adhesive wear) respectively.

3.4 Influence of grain size and binder material

Wear volume and initial dynamic friction coefficient for the hardmetal grades with a surface roughness as a result of an E21 EDM-regime, after applying a sliding distance of 10 km, normal loads of 15 up to 35 N and a sliding velocity of 0.3 m/s are presented in *figure 5* as function of their grain size.

The wear volume is noticed to decrease with decreasing grain size. On the other hand, below grain sizes of 0.8 µm, this trend appears to be reversed when the grain size is further reduced, i.e. for WC10Co(Cr/V) and WC6Co(Cr/V) grades. A bending point in this behaviour is found with the WC8Ni(Cr) grade, where nickel was used as binder material instead of cobalt. The higher wear volumes with the WC6Co(Cr/V) grade hardmetals can be attributed to a more pronounced adhesive wear because in this case pin and plate material are identical and thus exhibit high tribological compatibility.

The friction coefficient is noticed to be more or less constant for grain sizes above 0.8 µm, whereas it seems to increase for decreasing grain sizes below 0.8 µm. The largest scattering in the friction coefficient as function of normal load appears for the WC10Co(Cr/V) hardmetal, which exhibits the finest grains.

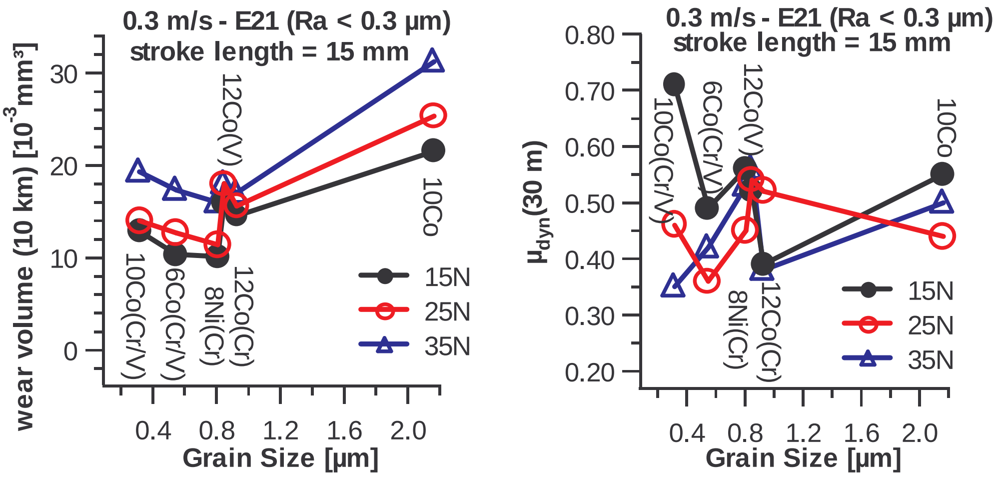


Figure 5: wear volume and dynamic friction coefficient at start as function of grain size for hardmetal grades, tested with normal loads of 15 up to 35 N, sliding distance of 10 km, sliding velocity of 0.3 m/s

3.5 Influence of hardness

Wear volume and initial dynamic friction coefficient for hardmetal grades with a surface roughness corresponding to an E21 EDM-regime, after applying a sliding distance of 10 km, normal loads of 15 up to 35 N, a stroke length of 15 mm and a sliding velocity of 0.3 m/s are presented in *figure 6* as function of their Vickers hardness (HV10).

The wear volume is noticed to decrease with an increasing hardness, with a bending point at the hardness level of the WC8Ni(Cr) grade hardmetal. For the WC10Co(Cr/V) and WC6Co(Cr/V) grades a reversed trend is found as the wear volume increases slightly with hardness. In case of the WC6Co(Cr/V) grade hardmetals, the higher than expected wear volume can be attributed to a more pronounced adhesive wear as pin and plate material are identical, and thus more tribologically compatible.

For low contact pressures, the friction coefficient is noticed to increase for increasing hardness, with the exception of the WC12Co(Cr) and the WC6Co(Cr/V) grade. For higher loads, a reversed behaviour is observed as the friction coefficient slightly decreases for increasing hardness.

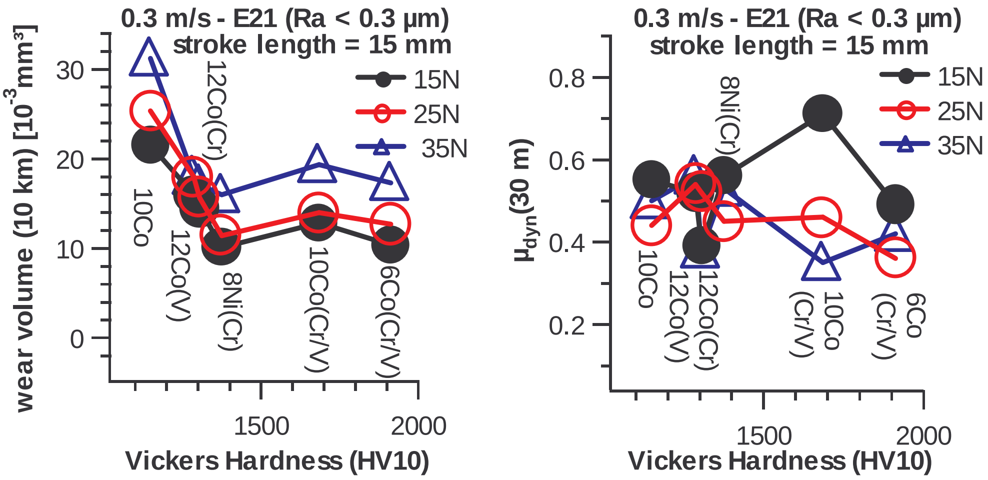


Figure 6: wear volume and initial dynamic friction coefficient as function of Vickers hardness HV10 for hardmetals with finishing regime E21, tested with normal loads of 15 up to 35 N

3.6 Influence of compressive strength

Wear volume and initial dynamic friction coefficient for hardmetal grades with a surface roughness corresponding to an E21 EDM-regime, after applying a sliding distance of 10 km, normal loads of 15 up to 35 N, a stroke length of 15 mm and a sliding velocity of 0.3 m/s are presented in *figure 7* as function of their compressive strength.

The wear volume is noticed to decrease with an increasing compressive strength, with a bending point occurring for the WC8Ni(Cr) hardmetal, which is the only grade with nickel as binder material. For the WC10Co(Cr/V) and WC6Co(Cr/V) grades a reversed trend is found as the wear volume increases slightly with compressive strength. In case of the WC6Co(Cr/V) grade hardmetals, the higher as expected wear volume can be attributed to a more pronounced adhesive wear as pin and plate material are identical, and thus more tribologically compatible.

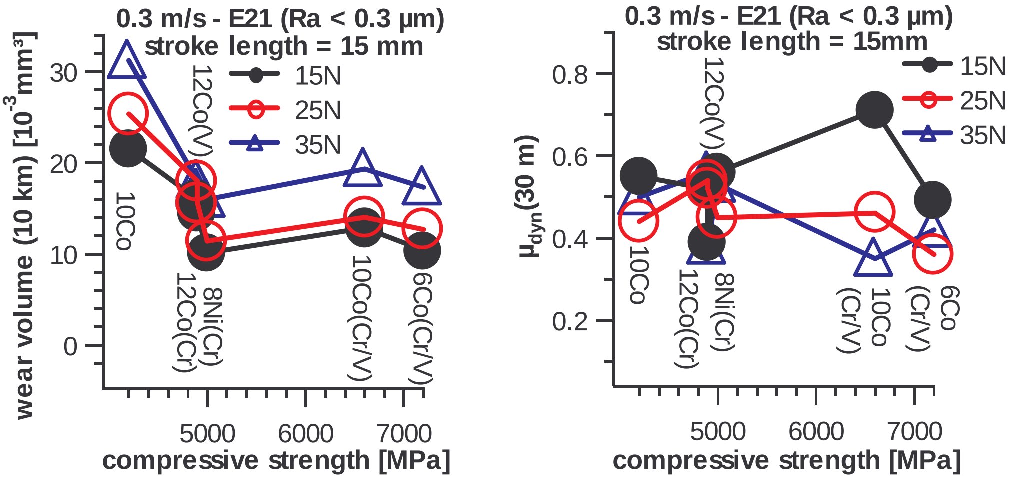


Figure 7: wear volume and dynamic friction coefficient at start as function of compressive strength for hardmetal grades with surface finishing regime E21, tested with normal loads of 15 up to 35 N

For low loads, globally the friction coefficient is noticed to increase with increasing compressive strength, with the exception of the WC6Co(Cr/V) grade. For higher loads, the friction seems to decrease with compressive strength. The optimal situation appears for the WC8Ni(Cr) grade, where nickel was used as binder material.

3.7 Wear debris analysis

In the wear debris originating from WC-based hardmetal grades with cobalt as binder material, two types of particles were observed. A dense population of nano precipitates can be seen in the agglomerate presented in *figure 8 (a)*. The chunk in *figure 8 (b)* is richer in oxygen compared to the particle in *figure 8 (a)*. The information obtained by EDX originates from a volume of about 1 µm^3.

The wear debris of a ground WC6Co(Cr/V) hardmetal plate that was tested at a sliding velocity of 0.45 m/s and with a normal contact force of 100 N, was observed using a Philips CM200 FEG TEM, operating at 200kV. The morphology of an identified elongated WC-grain (single crystal) and corresponding diffraction pattern is shown in *figure 9*. More commonly, very fine clustered nanoparticles were observed, as shown in *figure 10*.

The diffraction pattern originating from a focussed electron beam on such a cluster reveals relatively sharp rings with spots, indicating the presence of nanoparticles most probably together with some amorphous material. Preliminary indexing of the diffraction rings indicates that these particles are most likely $CoWO_4$ oxide.

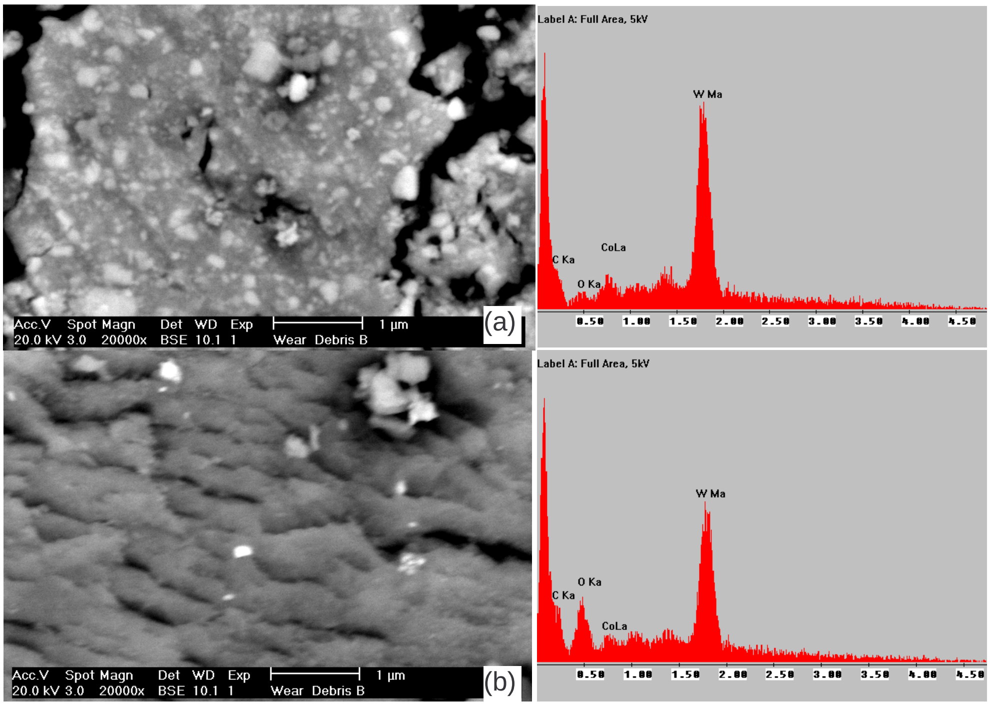


Figure 8: SEM and EDX analysis of wear debris: dense population of nano precipitates

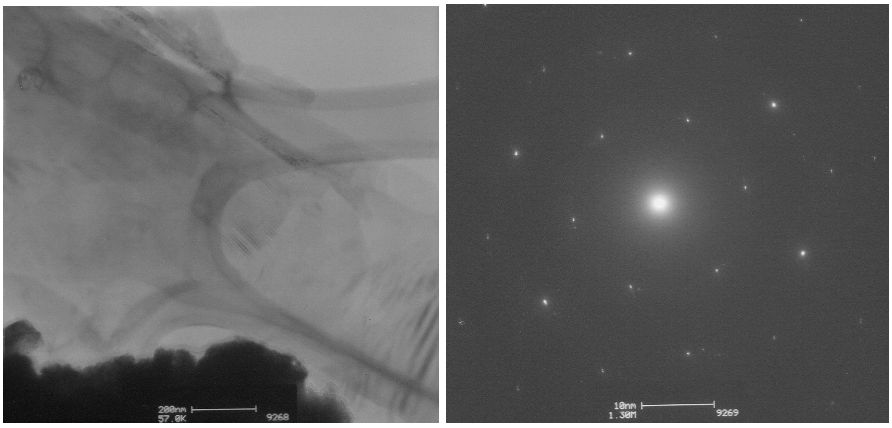


Figure 9: WC-grain and corresponding electron diffraction pattern

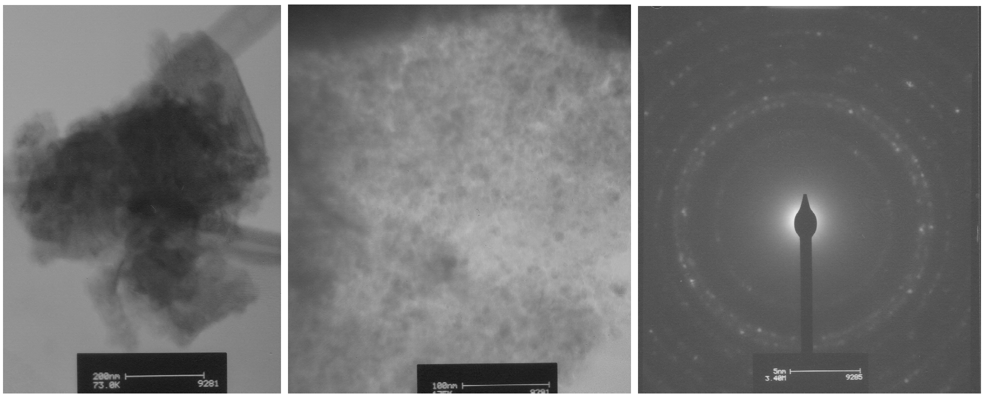


Figure 10: Nanocrystalline wear debris and corresponding diffraction pattern

4. Conclusions

Comparative dry friction experiments under varying contact pressures were performed using WC6Co(Cr/V) hardmetal pins against several hardmetal plates of which the surface was finished by a polishing or EDM treatment. Wear seems to occur according to two main mechanisms: abrasion and adhesion. Moreover, the deformation behaviour appears to be mainly elastic. The specific wear rate k of all investigated grades varies between 0.05 and 0.1 10^{-6} mm^3/N.m. The initial and regime static and dynamic friction coefficient are noticed to vary in a range of 0.3 and 1.2.

Correlations between tribological properties, test parameters, surface conditions (EDM-regime), microstructural properties and mechanical properties of the hardmetal grades were investigated. The results are summarized in next table. The most favourable tribological results were obtained for the hardmetal grade with nickel as binder material: the lowest wear and friction corresponding with intermediate values of mechanical properties and grain size in comparison to hardmetals with cobalt binder. Therefore, a further development of WC-based hardmetals with nickel binder would be of great interest.

SEM and TEM investigation of wear debris originating from WC-based hardmetal grades with cobalt as binder material revealed that this debris has an agglomerated nanoparticle nature. Preliminary determination revealed the presence of most probably $CoWO_4$.

General correlations between tribological properties and test parameters, surface conditions, mechanical and microstructural properties of hardmetal grades

property / parameter	wear	friction
contact load	↑	↓ (*elastic deformation*)
	WC10Co >...> WC12Co(Cr)	WC10Co(Cr/V) >.... > WC12Co(Cr), WC12Co(V)
Ra (EDM)	↓	↑ for Ra ↓ (< 0.4 µm) (*adhesion*)
	WC6Co(Cr/V) >...> WC10Co	WC12Co(Cr) >...> WC8Ni(Cr)
grain size	↑	↑ for ↓ grains < 0.8 µm (WC8Ni(Cr))
	exc. WC10Co(Cr/V), WC6Co(Cr/V)	(large scatter for WC10Co(Cr/V))
hardness HV10	↓	↑ for low load / ↓ for higher load
	exc. WC10Co(Cr/V), WC6Co(Cr/V)	(large scatter for WC10Co(Cr/V))
compressive strength	↓	↑ for low load / ↓ for higher load
	exc. WC10Co(Cr/V), WC6Co(Cr/V)	(large scatter for WC10Co(Cr/V))

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