

## Abrasive Wear of Powder Materials and Coatings

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Abrasive wear resistance of composite powder materials and coatings depends on various factors: on the one hand, on the technological parameters of the production, structure and properties of materials and coatings; on the other hand, on testing and exploitation conditions. Based on the information available on the abrasive wear of the materials and coatings, mostly from the laboratory tests, it is shown that hardmetals and different hardmetal-type coatings and composition behave differently under different conditions of wear. To compare the abrasive wear resistance of powder materials and coatings determined in the case of different abrasive wear conditions, tests of materials and coatings to be studied were carried out at low-speed abrasion wear (2–3 m/s) and high-speed erosion wear (up to 80 m/s) conditions. The wear resistance with the same abrasive – quartz sand and with different test equipment was determined. The difference in wear resistance using different low-speed abrasion methods of studied coatings is small, but in the case of hardmetals and cermets it differs up to ten times; using high-speed erosion methods the wear resistance of materials and coatings is comparable. At impact wear was revealed the superiority of hardmetal.

*Keywords:* abrasive wear, abrasion, erosion, hardmetals, thermal sprayed coatings.

### 1. INTRODUCTION

Most of the information available on the abrasion and erosion wear properties of the tribological materials and coatings has been derived from the laboratory tests. Wear resistance of powder materials and coatings depends to a large extent on structural peculiarities (heterogeneity of the composite structure, porosity of materials, state of stress of surface etc) and qualitative properties (hardness, toughness). On the other hand, abrasive wear of materials depends on testing conditions: properties of abrasive (hardness, particle size and shape), wear parameters (impact velocity, impact angles) and other testing conditions (temperature, testing media etc). It has been demonstrated by different researchers that powder materials – hardmetals and similar coatings of different type and composition behave differently under the conditions of abrasive wear [1–4].

A large number of papers on the abrasive wear of materials has been published. Therefore it is difficult to present an overview of all these studies.

Wear resistance of different conditions of abrasive wear of traditional tungsten carbide-cobalt (WC-Co) based hardmetals has been extensively studied because this material group is widely used. Abrasion of WC-Co hardmetals has been studied under various circumstances. High-velocity erosive wear-related studies have been conducted on WC-Co, the most common hardmetals.

Traditional WC-Co-type hardmetals have been tested in laboratory erosion tests using the grit-blasting, centrifugal-type wear tester and others. A systematic study of the erosion resistance of different hardmetals and cermets was conducted at Tallinn University of Technology. The results confirm that the influence of hardness on the abrasive wear isn't decisive alone, the relationship between hardness and erosion resistance of

hardmetals differs substantially from the linear relationship found for metals. At the same level of hardness, the wear resistance of WC-Co hardmetals may differ by up to 50%. At the same time, an increase in hardness does not always result in an increase of wear resistance. At the same level of hardness, the wear resistance of various TiC-based steel-bonded cermets differs more (up to two time more) than the variation found for the WC-base hardmetals. It has been shown that wear resistance is much more structure sensitive than any single mechanical property. The structure sensitivity of erosive wear is much higher than that of other types of wear, for example, by low velocity abrasion wear, which is related to differences in stress-strain states and fracture mechanisms during erosion [4, 5]. Studies concerning the abrasion of TiC-based cermets are less common and available data on the wear of chromium carbide-based cermets are given in last year's papers [5, 6].

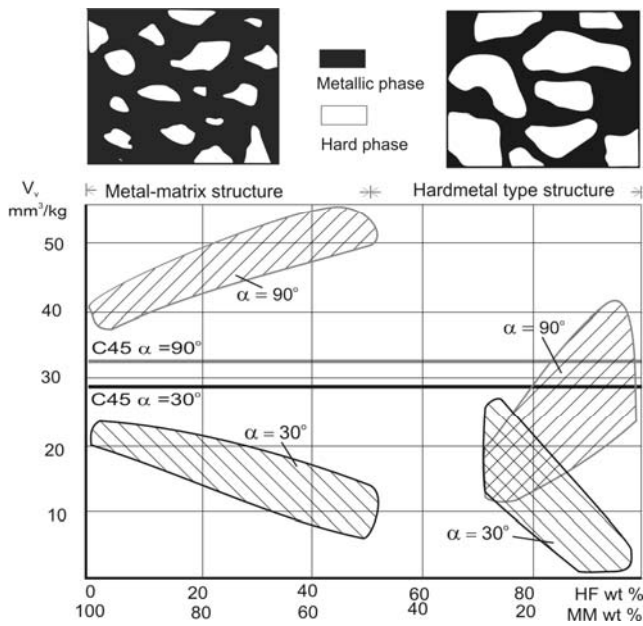
Based on the abrasive-erosion studies of hardmetals, cermets and thermally sprayed coatings with different composition deposited by different methods, the main criteria for their creation and selection can be divided as follows: structural, tribological, qualitative [7, 8].

#### *Microstructure and composition*

For the erosion wear conditions, materials and coatings with composite structure are preferred: very hard phases (carbides, nitrides etc) in a relatively hard metal matrix.

Based on different fracture mechanisms of wear by erosion under different wear conditions, the dependence of the optimal structure of materials and coatings on the conditions of wear is described in [7, 8]. In the case of oblique impact erosion (at small and medium impact angles), where the wear rate decreases with an increase in the hardness and the mechanism of microcutting is dominating, the hardmetal type framed structure is preferred (Fig. 1). The hard phase content must exceed 50%. In the case of normal impact, the matrix structure with hard phase content less than 50% is preferred.

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**Fig. 1.** Recommended structures of materials and coatings in the conditions of different impact erosion [8]

For the mixed erosive wear conditions, multicomponent, preferably “double cemented” WC-Co hardmetal based coating structure, instead of a simple cobalt matrix, containing particles of WC or other carbides, is cobalt (nickel) matrix based structure containing particles of WC-Co agglomerated granules or particles of WC-Co hardmetal [9].

### Hardness of abrasive

The abrasion rate depends on material hardness, more precisely, on the material hardness/abrasive hardness ratio ( $H_m/H_a$ ) – if it is lower than abrasive hardness, microcutting of the surface may take place. If material hardness is higher than abrasive hardness ( $H_m > H_a$ ), clear removal of the material usually does not take place and the entire process has the nature of fatigue.

The hardness of coatings must be maximum and higher than that of the abrasive, depending on the erosion conditions, to guarantee high abrasion-erosion wear resistance at small impact angles; at normal impact, the optimal level of hardness is recommended.

As it was shown by the theory of erosive wear of plastic materials, in material removal due to microcutting, the shape of erodent particles is also of essential importance.

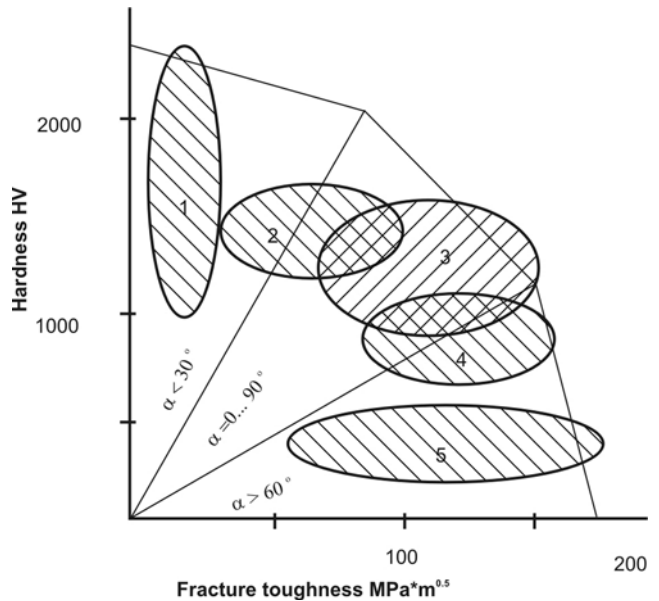
### Hardness and toughness

The effect of the hardness on the relative wear resistance of spray and fused composite coating varies. At small and medium impact angles, the wear resistance of fused coatings increases with an increase in coating hardness ( $\varepsilon > 1$ ). At large impact angles, an increase in coating hardness causes a decrease in their wear resistance ( $\varepsilon < 1$ ).

The toughness of a coating material is an important mechanical characteristic since a fracture determines the wear resistance of impact erosion, like at normal impact, where two different modes of fracture, direct and fatigue, dominate, or like at oblique impact, where microcutting

dominates. In the latter case, as a result of impact, crack nucleation and propagation take place; these cracks will reduce the erosion resistance as they decrease the resistance to shear force present during the impact of a particle at the oblique angle.

When selecting coatings for erosion wear, the following requirements must be taken into account: at oblique impact (at small and medium impact angles), with the mechanism of microcutting dominating, hardness characteristics are important; at normal impact ( $\alpha > 60^\circ$ ) with the direct or low-cyclic fracture mechanism dominating, toughness and fatigue characteristics are important (Fig. 2).



**Fig. 2.** Hardness-toughness criteria of materials and coatings selection: 1 – ceramics and ceramic coatings; 2 – cermets and hardmetal-type coatings; 3 – metal-matrix of high binder ceramics and coatings; 4 – carbide steels and hard alloy coatings; 5 – steels and steel coatings [8]

At high-energy impact of abrasive particles, brittle fracture of the material and detachment of carbide grains or their fragments take place, the toughness characteristics are more important.

From other operating parameters at erosion the corrosion and oxidation must be taken into consideration. The erosion-enhanced corrosion at room temperature and erosion-enhanced oxidation at high temperature increase the wear rate of coating materials substantially. As a result, more erosion-resistant coatings should be developed for reasons of corrosion and intermediate temperatures.

## 2. EXPERIMENTAL

### 2.1. Abrasive wear testing methods

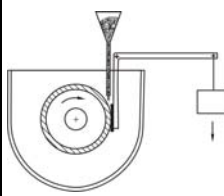
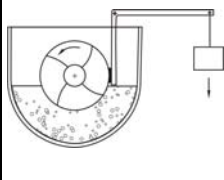
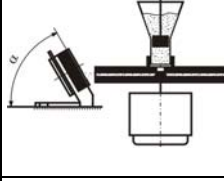

The abrasive wear testing methods used can be roughly divided into two groups:

- 1) low-speed (up to 2 – 3 m/s) wear testing methods
  - wear of materials and coatings against a rubber wheel (block on rubber wheel) with an abrasive,
  - wear of materials and coatings against a steel counter-face (block on steel wheel) in the slurry of an abrasive;

- 2) high-speed (up to 80 m/s) wear testing methods
- solid particle erosion using a centrifugal-type tester CAK-4,
  - abrasive impact wear using tester DESI.

Schemes and parameters of abrasive wear testing methods are given in Table 1. The abrasive used for that work was quartz sand. The steady state erosion was studied as a function of the impact angle at the velocities of 60 m/s (hardmetals and cermets) and 80 m/s (coatings) of abrasive particles. Impact wear was studied at 60 m/s with the particles of granite. Steel of 0.45 % C (normalized, 200 HV) was adopted as a reference material.

**Table 1.** Abrasive wear test methods and parameters of wear

Velocity of particles	Test method and equipment	Scheme	Parameters and abrasive
Low-velocity	Abrasion on rubber wheel. Block-on-ring/rubber wheel tester (ASTM G65-94)		$v = 2.4$ (0.24)* m/s $F = 222$ (140)* N Quartz sand (0.1–0.3) mm
	Abrasion in slurry. Block-on-ring/steel wheel tester (ASTM B611-85)		$v = 2.2$ m/s Quartz sand (0.1–0.3) mm
High-velocity	Abrasive erosion. Centrifugal accelerator CAK-5 (GOST 23.201-78)		$\alpha = 30^0$ $v = 80$ m/s Quartz sand (0.1–0.3) mm
	Impact wear. Centrifugal desintegrator type tester DESI		$v = 60$ m/s Abrasive granite $d = (4 - 6)$ mm

\*By hardmetals and cermets.

Since differences in materials composition would lead to incorrect results because of great differences in carbide density (WC – 15.6, TiC – 4.9, Cr<sub>3</sub>C<sub>2</sub> – 6.7 g/cm<sup>3</sup>), their volume loss was calculated and the volumetric wear rate as the volume loss of the target sample per mass of abrasive (mm<sup>3</sup>/kg) was determined.

The relative wear resistance  $\varepsilon$  was calculated at the ratio of the volumetric wear rates of the studied and the reference material (0.45 % C steel).

## 2.2. Materials and coatings to be tested

The hardmetals and cermets studied can be roughly divided into three groups:

- tungsten carbide-based hardmetals (cobalt content 8 and 15 wt%),

- chromium carbide based cermets (nickel binder content 20 and 30 wt%),
- titanium carbide based cermets (nickel-molybdenum binder content 30 and 50 wt%; Ni: Mo = 2 : 1).

The composition and hardness of the hardmetals and cermets are given in Table 2.

**Table 2.** Composition and hardness of the hardmetals and cermets studied

Type of material	Composition, wt%	Hardness HV10
Hardmetals		
WC-8Co	92WC-8Co	1350
WC-15Co	85WC-15Co	1200
Cermets		
TiC-30NiMo	70TiC-30NiMo	1364
TiC-50NiMo	50TiC-50NiMo	1053
Cr <sub>3</sub> C <sub>2</sub> -20Ni	80Cr <sub>3</sub> C <sub>2</sub> -20 Ni	1180
Cr <sub>3</sub> C <sub>2</sub> -30Ni	70Cr <sub>3</sub> C <sub>2</sub> -30 Ni	780

The coatings studied were fabricated by thermal spray processes – flame spray fusion (FSF) and high-velocity oxy-fuel spray (HVOFS). The coating materials used can be roughly divided into three groups: nickel based self-fluxing alloy (NiCrSiB) powders, tungsten carbide-cobalt (WC-Co) hardmetal powder and composites on the basis of NiCrSiB alloy powder and (WC-15Co) hardmetal powder.

Spray materials for the coatings selected for the abrasive wear tests, their chemical composition and hardness are listed in Table 3.

**Table 3.** Composition and hardness of selected coatings

Type and composition (wt %) of spray material	Method of deposition	Porosity, %	Hardness HV0.2
12495* (NiCr13Si4B3)	FSF	0	560
12495+25 (WC-15Co)	FSF	0	685/1445***
1275H** (NiCr16Si4Fe4B3.5)	HVOFS	1.7	805
1343V** (WC-17Co)	HVOFS	2.9	1300

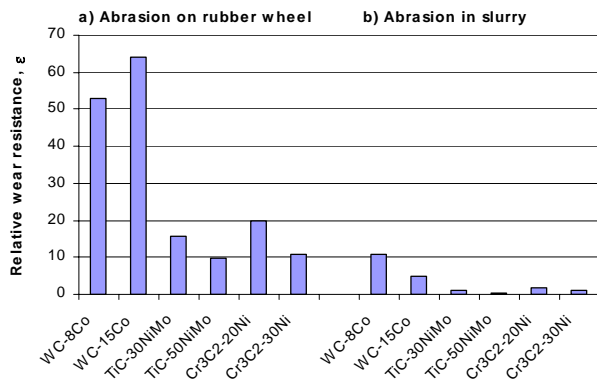
\*Castolin SA; \*\*Tafa Inc; \*\*\*Hardness of metal matrix/hard phase.

## 3. RESULTS AND DISCUSSIONS

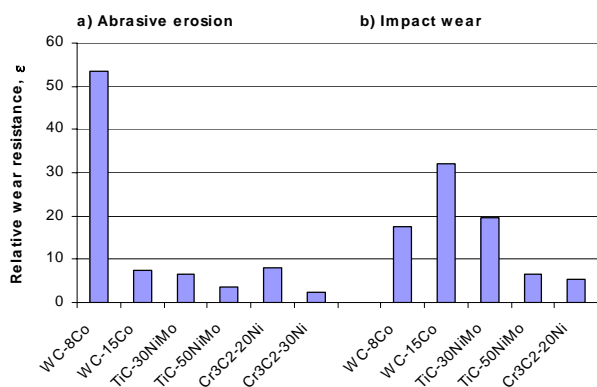
As indicated by the studies of powder materials, hardmetals and cermets of different type and composition behave differently under different conditions of wear. The results of testing – relative wear resistance of the WC-Co hardmetals, TiC-NiMo and Cr<sub>3</sub>C<sub>2</sub>-Ni cermets are given in Fig. 3 and Fig 4.

As can be seen on Fig. 3, at low-speed abrasive wear hardmetals and cermets are more resistant to volumetric wear in the case of abrasion on rubber wheel than abrasion in slurry. The difference of wear resistance under abrasive erosion and abrasive-slurry wear is about 4–6 times. At high speed impact testing methods (Fig. 4) the hardmetals and cermets behave differently. In the case of abrasive erosion more wear resistant is WC-8Co hardmetal (wear

resistance is comparable with it at abrasion on rubber wheel), in case of impact wear – WC-15Co hardmetal.



**Fig. 3.** Relative wear resistance of hardmetals and cermets at low-speed methods



**Fig. 4.** Relative wear resistance of hardmetals and cermets at high-speed methods

At high-energy impact wear conditions the good resistance demonstrated also the high binder content (30 wt%) TiC based cermets. The TiC-based cermets are preferable, especially considering the fact that their density is lower compared to hardmetals and weight wear rate is on the level of hardmetals.

It can be explained at first with the different mechanisms of wear. To compare the wear mechanism of hardmetals of analogous chemical composition by abrasive erosion and abrasion in slurry we can observe the differences in the wear mechanisms:

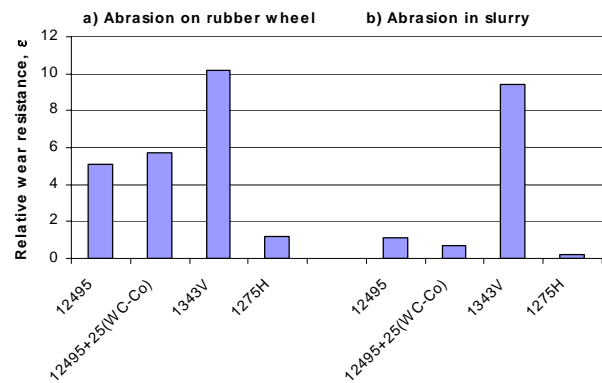
- by abrasion in slurry the removal of binder metal is caused by the microcutting and as a result hard WC-particles will be removed,
- by abrasive erosion at oblique impact due to the tangential component the removal of binder metal also takes place primarily as a result of the microcutting process; at the same time plastic binder metal will work harden due to the multicyclic loading of binder. Direct fracture of carbides may also occur.

The results of comparative testing – relative wear resistance of the powder coatings are given in Fig. 5 and Fig. 6.

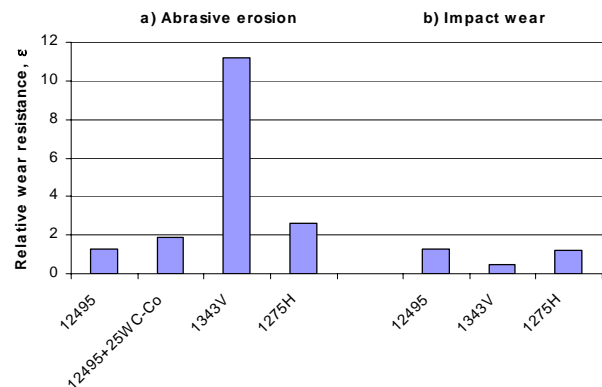
When comparing the wear resistance of different thermally sprayed powder coatings under different abrasive wear conditions (abrasive erosion, abrasion in slurry

and abrasion on rubber wheel), the following tendencies can be observed (Fig. 5 and Fig. 6):

- the abrasive wear resistance of hardmetal-type HVOF-sprayed WC-Co coatings is similar at all studied wear testing methods except of impact wear.
- the spray-fused NiCrSiB-alloy based coatings are more resistant in the condition of abrasion on rubber wheel. The difference in wear resistance comparing with other testing methods is about 3 – 4 times.



**Fig. 5.** Relative wear resistance of powder coatings at low-speed methods



**Fig. 6.** Relative wear resistance of powder coatings at high-speed methods

Comparing wear mechanisms under different wear conditions it can be concluded that HVOF-sprayed coatings behave similar by to hardmetals. Higher wear resistance at abrasive-slurry wear can be explained by the peculiarities of coatings microstructure. From different types of thermal sprayed coatings under different conditions of wear HVOF sprayed WC-Co hardmetal coatings are most resistant (their relative wear resistance is about 10 times higher than that of reference material). Wear resistance of other types of coatings (NiCrSiB based self-fluxing alloy is low – it is on the level of reference materials (steel 0.45 % C) except for abrasion on rubber wheel.

The behaviour of HVOF sprayed coatings at high-energy impact wear is different. The coatings were too thin (about 0.2 – 0.3 mm) to get adequate results in this experiment (in some regions of the specimens the coating

was removed entirely due to the high energy impact and plastic substrate promoting the spalling of coating).

#### 4. CONCLUSIONS

1. The behaviour of powder materials and coatings under different abrasive wear conditions depends on the type and composition of materials, as well as on the conditions of abrasive wear (abrasive particle size and velocity, media of abrasive wear etc):
  - the wear of WC-Co hardmetals and chromium carbide based cermets at low-speed abrasion in slurry is about 4–5 times lower compared to abrasion on rubber wheel,
  - the behaviour of materials and coatings under high-speed erosion is similar to abrasion on rubber wheel,
  - the high-velocity oxy-fuel sprayed coatings behave similarly to analogous WC-Co hardmetals under low and high-speed abrasive wear conditions,
  - NiCrSiB-alloy based coatings with (WC-Co) reinforcement have the highest wear resistance under abrasion on rubber wheel.
2. Under high-energy impact wear TiC based cermets with optimal composition are almost as good as hardmetals. The wear resistance of sprayed coatings at impact wear is low due to their low thickness.
3. To select the powder materials and coatings it is obligatory to consider the structural peculiarities of materials as well as the tribological peculiarities of wear.

#### Acknowledgments

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