ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 14, No. 4. 2008

Abrasive Wear Resistance of Powder Composites at Abrasive Erosion and Abrasive Impact Wear

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Received 01 July 2008; accepted 02 September 2008

Composite materials produced by powder metallurgy provide solution to many engineering applications where materials with high abrasive wear resistance are required. The actual wear behaviour of the material is associated with many external factors (the abrasive particle size, velocity and angularity) and the intrinsic material properties of wear (hardness, toughness, Young modulus, etc.). The hardness and toughness properties of wear resistant materials are highly dependent on the content of the reinforcing phase, its size and on the mechanical properties of the constituent phase. This study makes an attempt to model abrasive wear (solid particle erosion and impact wear) by using the centrifugal erosive and impact wear devices. Powder materials (cermets, metal-matrix composites and powder HSS) were under the study. The abrasive wear resistance at solid particle erosion (AEW) and the impact wear (AIW) of materials were researched and the mechanisms of surface degradation were studied and compared with the wear mechanisms of commercial steels. Different abrasive materials (quartzite and granite) with the average particle size of 5.6 mm and 0.1 mm – 0.6 mm were under the study. The behaviour patterns of powder composite materials at AEW and AIW were compared. Based on the research into abrasive wear resistance, the wear maps, such as wear resistance versus hardness and toughness of materials, were compiled. According to the study of wear mechanisms, a wear map proceeding from toughness and hardness was created. The following parameters were found necessary for materials selection: hardness (preferably dynamic) characterizing the material removed at plastic deformation, fracture toughness characterizing the brittle fracture mechanism and the fracture probability.

Keywords: abrasive wear, erosion, impact wear, wear resistance, wear mechanisms.

1. INTRODUCTION

Solid particle erosion causes serious problems for industrial equipment, e. g. in milling and mixing [1]. In erosion wear involving solid particle impact against the surface, plastic deformation, brittle fracture or combined mechanisms dominate depending on the properties of the target material surface.

The results of the laboratory erosion tests of steels in the centrifugal accelerator with different erodents have shown that the wear resistance of materials does not directly depend on the hardness of erodents [1]. The tests performed in the erosion tester with soft steels (up to 200 HV) and glass grit having the hardness of about two times lower than that of quartz sand, had the wear rates 1.6 – 2.4 times higher at the impact angles of 30° and 90° correspondingly [1].

The same results were obtained from different milling experiments – the relative wear resistance of different materials used in the grinding device, a disintegrator mill, does not directly influence from the hardness of the material to be ground [1, 2]. The milling experiments with glass and quartz sand in the disintegrator have shown that the wear of working elements – pins from steels in the disintegrator DESI – was higher while milling by glass of lower hardness (3.5 GPa, HV 0.05) than by quartz sand (8.15 GPa, HV 0.05) [1].

The similar results were obtained from the milling experiments of different mineral ores – the wear resistance of the studied steels did not directly depend on the hardness of the studied ores [2].

The abrasive erosion (AEW) and abrasive impact wear (AIW) resistance of the metal-matrix powder composites (MMC) and conventional steels researched by P. Kulu et al. [3] have shown that the results of abrasive erosion and impact wear do not correlate with powder materials and conventional wear resistant steels. For MMC and Weartec,® the relative wear resistance at AEW and AIW differ up to two times. First, it can be explained by the use of abrasives of different particle size and hardness in the above mentioned test: the quartz sand of fraction 0.1 mm – 0.3 mm at erosion wear (1100 HV – 1200 HV) and the granite sand of fraction 4 mm – 5.6 mm (about 930 HV) at impact wear but also by the use of abrasives of different particle shapes.

The results of erosive wear obtained from the quartz sand demonstrated that there is a strong correlation between the particle angularity and the erosion rates [4]. Higher erosion rates obtained from the angular quartz sand (SPQ = 0.614, the angularity parameter or the "spike parameter – quadratic fit" according to [5]) exhibited sharper peaks than those of the round one (SPQ = 0.352). That can cause wear damage to steels. By the ratio of angularity parameters of about 1.75, the erosion rates differ from 1.26 to 1.52 times.

It follows from the erosion tests of Cr_3C_2-Ni cermets with the binder content from 20 wt% to 50 wt% that a higher erosion rate occurs by an angular abrasive only at a low impact angle and a higher binder content (30 wt% and more) [4]. With the cermet of a low binder content

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(20 wt% Ni), no difference occurred in the erosion rates with the abrasive particles of different shapes.

It is well known that there is a dramatic difference between ductile and brittle materials when the weight loss in erosion is measured as a function of the impact angle [1]. Cermets and hard ceramic coatings have been considered sufficient to reduce the scratching and micromachining surface damage exposed to low-angle impacting particles because of their high hardness and stiffness. At a high angle of impact, the exposed surface should be able to withstand repeated deformation. More ductile materials, such as steels, are usually preferred to ceramics and ceramic coatings in which cracks propagate rapidly and lead to the material removal. Based on the mechanisms of erosive wear, the models of plastic deformation and brittle fracture are developed for predicting the erosion of powder composite materials [6].

Besides the angularity of abrasive particles, an important role is played by the spinning of particles. Hutchings [7, 8] proposed three possible kinds of mechanisms of removing material during the erosion of ductile metals. He suggested that the particle rotation occurring after the impact should have a significant effect on the mechanism in operation. The quantitative model by Papini and Spelt was developed [9, 10] to predict the erosion rate involving the particle spin effect – a rigid plastic model of impact to predict the crater volume in case the symmetric angular particles were developed. Indirect evidence that particle spin during flight could have significant effects on the subsequent erosion rate was presented by Burnet et al. [11].

Despite a widespread use of erosion tests for assessment and the fact that the hardness of abrasives is playing an important role in wear resistance of materials and coatings, there is some difference in wear resistance, when using different abrasives of the same hardness and size. There is no systematic study on the effect of the abrasive particle size on the wear behaviour of different materials used as wear resistant materials.

In this research the erosion behaviour of powder composite materials in different wear conditions with two different abrasives and particle sizes is assessed in order to find the basis for understanding the mechanisms of the micro- and macro-scale erosion behaviour and the wear resistance of powder composite materials.

2. EXPERIMENTAL: MATERIALS AND METHODS

2.1. Abrasive wear tests

Abrasive erosion wear (AEW) tests were performed in a conventional centrifugal-type four-channel erosion tester – Fig. 1 [1], that enables up to 15 specimens to be treated under the identical testing conditions. The abrasive particles size used in this work was 0.1 mm – 0.6 mm. The investigation of the erosion rate was carried out at the abrasive particle velocity of 80 m/s and the impact angle of 90°.

Abrasive impact wear (AIW) of materials with the abrasives of particle size 4 mm – 5.6 mm was studied by the experimental disintegrator-based impact wear tester DESI (Fig. 2) at the collision velocity of about 60 m/s. The impact angle of abrasive particles with specimens of the fixed pin surface determined by the calculations and graphical method was about 90°.

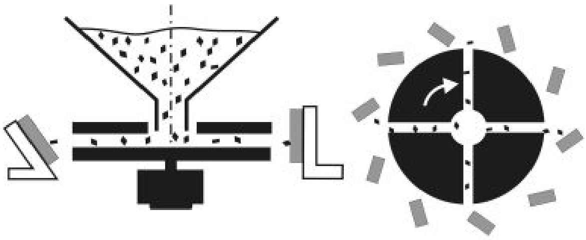

Fig. 1. Principal scheme of AEW tester

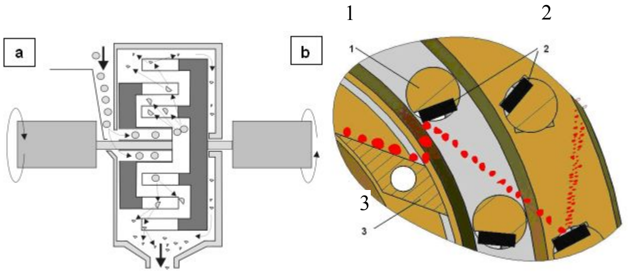

Fig. 2. The principal scheme (a) of disintegrator based AIW tester DESI and simplified scheme of particles moving (b): 1 – pin (specimen holder), 2 – specimen, 3 – impeller

The volumetric wear rate I_v in (mm^3/kg) was determined as the mass loss of the target sample per mass of the abrasive particles divided by sample density. The target mass loss was measured by weighing with the accuracy of 0.01 mg.

2.2. Abrasives

Wear tests were conducted with different abrasives (granite and quartzite) to study the influence of the abrasives particle size, hardness and angularity on the wear rate and mechanism of the materials. Granite and quartzite of fraction 0.1 mm – 0.6 mm were obtained from granite and quartzite gravel after the disintegrator milling of gravel by separating the needed sieves The SEM images of erodent particles, of both fine and coarse abrasives are given in Fig. 3. Their particles empirical frequency polygons $f(x)$ (estimator of the theoretical probability density function) and empirical cumulative frequency polygons $F(x)$ (estimator of the theoretical cumulative probability function) are presented in Fig. 4.

Hardness of the abrasive was measured at the cross-section polishes of the used abrasive particles. The properties of abrasives are given in Table 1.

2.3. Target materials

The studied materials included high-speed steels (HSS) and cermets produced by powder metallurgy (PM) (Table 2). These materials are commonly used in many applications where resistance to abrasive wear is required. The conventional non-alloy and low-alloy steels were studied for comparison. The microstructure of powder materials is presented in Fig. 5.

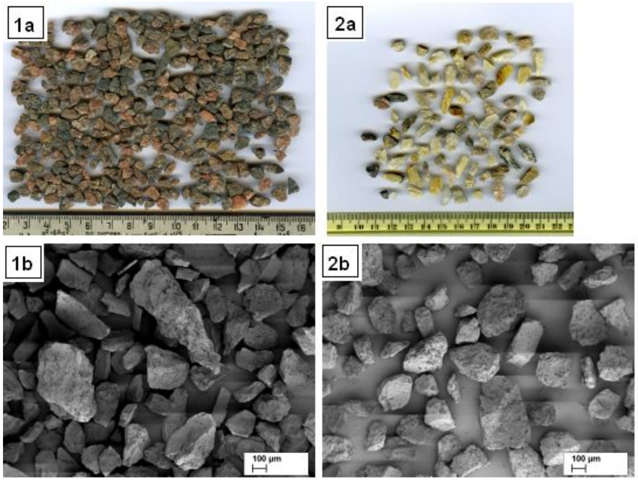

Fig. 3. SEM pictures of studied abrasives: 1 – granite and 2 – quartzite of fractions a – 4 mm – 5.6 mm, and b – 0.1 mm – 0.6 mm

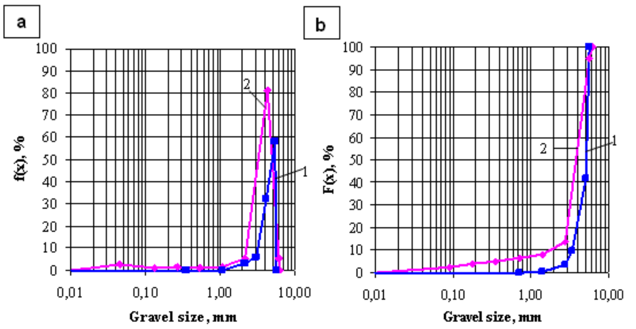

Fig. 4. Particle size distribution of used abrasives: a – frequency polygons $f(x)$; b – cumulative frequency polygons $F(x)$: (1 – granite, 2 – quartzite)

Table 1. Properties of the abrasives used in AEW and AIW tests

Type of abrasive	HV 0.05 GPa	Particle size, mm	E, GPa	K_{1c}, MPa·m$^{0.5}$	Angularity parameter SPQ
Granite	9.28	gravel 4 – 5.6	70	0.7	0.611
		sand 0.1 – 0.6			0.686
Quartzite	11.0	gravel 4 – 5.6	70	0.7	0.543
		sand 0.1 – 0.6			0.680

Table 2. Designation and properties of the materials tested

Group of material	Designation	Composition, wt%	Hardness HV 30
Conventional steels	St 37	0.19 – 0.23 C	140 – 150
	C 45	0.45 C	200
Hardened steels	Hardox 400	0.25 C; 1.60 Mn; 1 Cr; 0.7 Ni; 0.8 Mo	395
	Hardox 600	0.48 C; 1 Mn; 1.2 Cr; 2.5 Ni; 0.8 Mo	540
Powder steels	Vanadis 6	2.1 C; 1.0 Si; 0.4 Mn; 6.8 Cr; 1.5 Mo; 5.4 V	784
	Weartec ®	2.8 C; 0.8 Si; 0.7 Mn; 7.0 Cr; 2.3 Mo; 8.9 V	834
Cermets	VK15	WC – 15 Co	1203 HV1
	J20	Cr_3C_2 – 20 Ni	1148 HV1

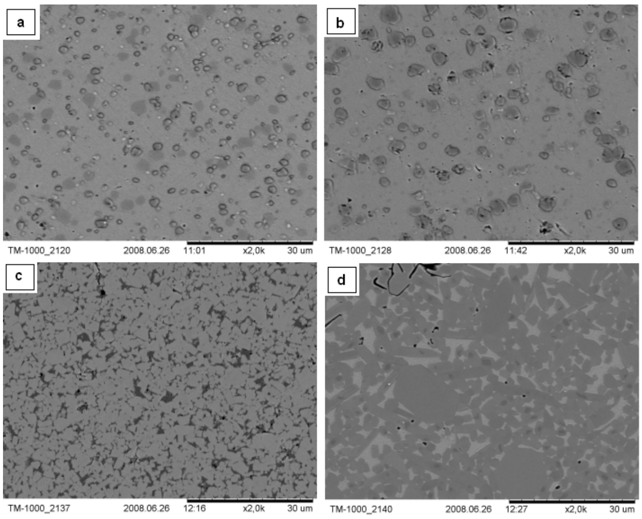

Fig. 5. Microstructure of studied PM materials: a – HSS Vanadis 6, b – Weartec®, c – VK15, d – J20

2.4. Study of wear resistance and wear mechanism

In order to compare the materials, the relative wear resistance ε_v was calculated as the ratio of the volumetric wear rates of the studied powder materials to steels C45 or Hardox 400. To reveal the material behaviour in the conditions of AEW and AIW a SEM study was conducted by using the tabletop scanning electron microscope Hitachi TM-1000. The topography of worn surfaces was analyzed.

3. RESULTS AND DISCUSSION

3.1. Abrasive erosive wear (AEW)

The AEW resistance of the studied PM materials and conventional steels with abrasives – granite and quartzite of particles size 0.1 mm – 0.6 mm at $v = 80$ m/s are given in Tables 3 and 4. The AEW resistance of the studied powder steels was low, lower than 1.0 when compared with steel C45 (Table 3).

Table 3. The AEW rates of steels by different abrasives (particle size $d = 0.1$ mm – 0.6 mm, $v = 80$ m/s, $\alpha = 90°$)

Steel	Granite gravel		Quartzite	
	I_v, mm^3/kg	ε_v $^{1)}$	I_v, mm^3/kg	ε_v $^{1)}$
C45	22.2	1.0	24.2	1.00
Hardox 400	21.6	1.03	23.3	1.04
Vanadis 6	25.7	0.86	25.5	0.95
Weartec®	23.6	0.94	31.5	0.77

$^{1)}$ the reference material C45.

To reveal the material behaviour in the conditions of AEW a SEM study was conducted. The wear surfaces of the PM materials and conventional steels are presented in Fig. 6.

From carbide based powder materials, WC-15Co hard metal (structure is presented in Fig. 3) has the highest AEW resistance (about 4 – 6 times higher when compared with the reference material – steel C45 in granite and quartzite respectively – Table 4).

Table 4. AEW rates of hard metals and cermets by different abrasives (particle size $d = 0.1$ mm – 0.6 mm, $v = 80$ m/s, $\alpha = 90°$)

Material	Granite gravel		Quartzite	
	I_v, mm^3/kg	ε_v 1)	I_v, mm^3/kg	ε_v 1)
VK15	3.7	6.04/ 5.80	6.03	4.01/ 3.87
J20	11.5	1.93/ 1.80	18.7	1.29/ 1.25

1) the reference material C45/Hardox 400.

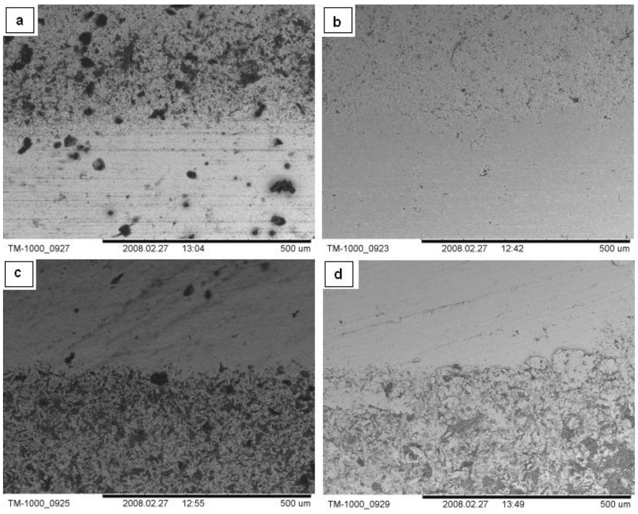

Fig. 6. The surfaces of eroded materials after AEW with quartzite sand ($d = 0.1$ mm – 0.6 mm, $v = 80$ m/s, $\alpha = 90°$): a – VK15, b – J20, c – Weartec®, d – Hardox 400

As it follows from the study of the topography of worn surfaces at AEW of the powder materials (WC-15Co, Cr_3C_2-Ni, Weartec®), the erodent particles of quartzite produce craters (Fig. 10, a – c). In case of steel (Hardox 400), the plastic deformation of the surface is visible (Fig. 10, d). At the same time there is no difference between the wear mechanisms by quartzite or granite due to the similar hardness and particle angularity of the studied abrasives (Table 1).

3.2. Abrasive impact wear (AIW)

The AIW resistance of the studied PM materials and conventional steels with the abrasive – the granite and quartzite gravel of particle size 4 mm – 5.6 mm at velocity 60 m/s are given in Tables 5 and 6.

Table 5. AIW rates of steels by different abrasives ($d = 4 – 5.6$ mm, $v = 60$ m/s)

Material	Granite gravel		Quartzite	
	I_v, mm^3/kg	ε_v^{45}	I_v, mm^3/kg	ε_v 1)
C45	26.6	1.00	38.4	1.00
Hardox 400 $v = 60$	31.8	0.84	39.2	0.98
Vanadis $v = 80$		2.0	20.0	1.92
Weartec	11.4	2.33	17.7	2.17

1) the reference material C45.

At AIW with granite gravel powder HSS Weartec®, consisting of fine carbide particles embedded into relatively soft matrix of Cr-Mo-V, the steels have the highest wear resistance (about 2.3 times higher than reference steel C45). AIW resistance as the traditional tungsten carbide based WC-Co hard metal as well chromium carbide based low binder cermet (Cr_3C_2-20Ni) was high (more than 5 – 18 times higher depending on the abrasive and reference material).

Table 6. AIW rates of cermets by different abrasives ($d = 4 –$ 5.6 mm, $v = 60$ m/s)

Material	Granite gravel		Quartzite gravel	
	I_v, mm^3/kg	ε_v 1)	I_v, mm^3/kg	ε_v^{400} 1)
VK15	2.5	10.64/12.72	2.1	18.20/18.70
J20	2.6	10.23/12.23	7.4	5.19/5.30

1) the reference material C45/Hardox 400.

The wear rates of conventional steels at AIW are comparable with those at AEW but the relative wear resistance of powder steels is about two times higher when compared to conventional steels; it is the same with the wear resistance of cermets: the relative wear resistance of the carbide based materials (VK15, J20) is about 4 – 5 times higher than the wear resistance at AEW. From the study of topography of worn surfaces after AIW (Fig. 7), the following conclusions may be drawn.

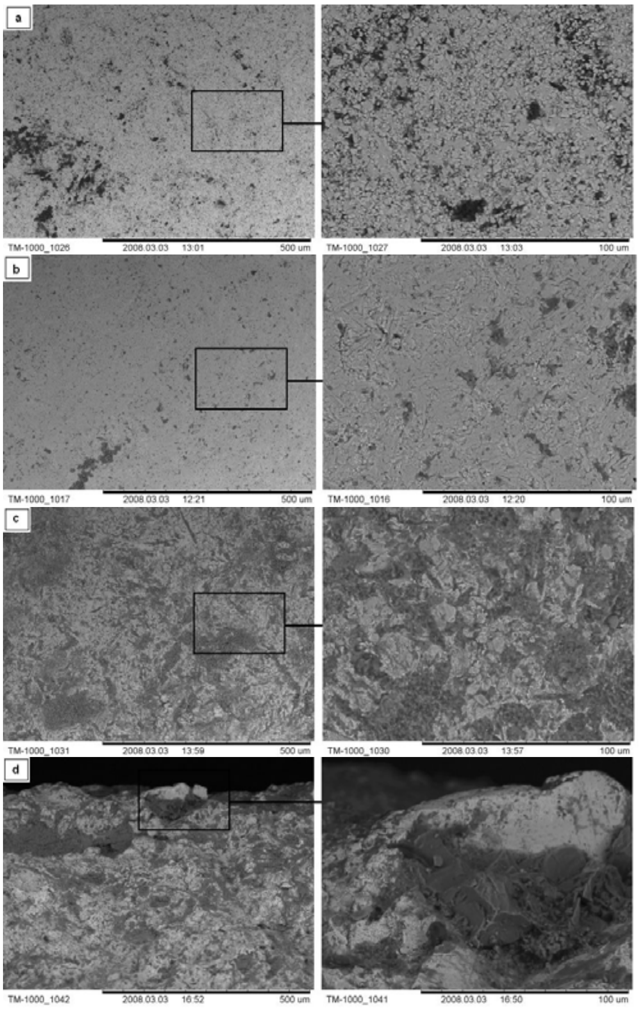

Fig. 7. Wear surfaces of studied materials after AIW with quartzite gravel ($d = 4$ mm – 5.6 mm, $v = 60$ m/s): a – VK15, b – J20, c – Weartec®, d – Hardox 400

Besides the volume fraction of hard particles, the spacing between hard particles seems to be more crucial than the size of hard particles. Spacing between the particles implies that the more homogeneous the composite is in relation to the wear environment, the more wear resistant it is, i. e. that the smallest spacing between hard particles gives the best results. The spacing between particles has an important role from the physical point of view: it determines the free paths for grooving the matrix by abrasive particles.

In the present case, the abrasive particles were angular and of the size ranging from 4 mm to 6 mm; however, a sharp grooving edges of the abrasive particles are much smaller (0.2 mm – 0.4 mm).

4. CONCLUSIONS

1. The relative wear resistance and wear resistance of conventional steels (soft annealed and hardened) as well as the wear resistance of powder steels at AEW do not differ notably. The wear resistance of carbide-based materials exceeds up to 6 times that of reference materials – steels.
   The relative wear resistance of powder steels at AIW is about 2 times higher and of carbide based materials it is 15 – 18 times higher when compared with conventional steels.
2. When comparing the wear rates and relative wear resistance of the studied materials at AEW and AIW by the same abrasives, the wear is much higher at AEW. The difference in wear rates is about 1.2 – 2 times by powder steels and about 2.5 – 4 times by carbide based materials.
3. Remarkable materials sensitivity to the test conditions regarding the differences in materials behaviour at AIW and AEW tests refers that the final material selection should be based on laboratory tests where the conditions are as close as possible to the ones in the real application.

Acknowledgments

The authors are grateful to Peeter De Bakker, the technician, and Dimitri Goljandin, the researcher. SSAB Oxelösund is acknowledged for providing some of the applied test materials. This work was supported by the Estonian Science Foundation (grant No. 7227) and Estonian Ministry of Education and Research (targeted finance project No. SF01400091).

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Presented at the 17th International Conference
"Materials Engineering'2008"
(*Kaunas, Lithuania, November 06 – 07, 2008*)