ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 18, No. 1. 2012

Wear Resistant Thermal Sprayed Composite Coatings Based on Iron Self-Fluxing Alloy and Recycled Cermet Powders

Heikki SARJAS [1] *, Dmitri GOLJANDIN [1], Priit KULU [1], Valdek MIKLI [2],
Andrei SURŽENKOV [1], Petri VUORISTO [3]

[1] *Department of Materials Engineering, Tallinn University of Technology, Ehitajate tee5, 19086 Tallinn, Estonia*
[2] *Centre for Materials Research, Tallinn University of Technology, Ehitajate 5, 19086 Tallinn, Estonia*
[3] *Tampere University of Technology, Department of Materials Science, FI-33101 Tampere, Finland*

crossref http://dx.doi.org/10.5755/j01.ms.18.1.1338

Received 07 June 2011; accepted 05 September 2011

Thermal spray and WC-Co based coatings are widely used in areas subjected to abrasive wear. Commercial cermet thermal spray powders for HVOF are relatively expensive. Therefore applying these powders in cost-sensitive areas like mining and agriculture are hindered. Nowadays, the use of cheap iron based self-fluxing alloy powders for thermal spray is limited. The aim of this research was to study properties of composite powders based on self-fluxing alloys and recycled cermets and to examine the properties of thermally sprayed (HVOF) coatings from composite powders based on iron self-fluxing alloy and recycled cermet powders (Cr_3C_2-Ni and WC-Co). To estimate the properties of recycled cermet powders, the sieving analysis, laser granulometry and morphology were conducted. For deposition of coatings High Velocity Oxy-Fuel spray was used. The structure and composition of powders and coatings were estimated by SEM and XRD methods. Abrasive wear performance of coatings was determined and compared with wear resistance of coatings from commercial powders. The wear resistance of thermal sprayed coatings from self-fluxing alloy and recycled cermet powders at abrasion is comparable with wear resistance of coatings from commercial expensive spray powders and may be an alternative in tribological applications in cost-sensitive areas.

Keywords: hardmetals, recycling, HVOF, composite coatings, wear resistance.

INTRODUCTION

Thermally sprayed coatings are widely used in areas where high wear and corrosion resistance are required [1]. Hence, thermally sprayed coatings are not the cheapest solution due to relatively expensive equipment and running costs, especially powders [2, 3]. Rapidly increasing raw material prices won't be giving any benefit as well [4]. Therefore, use of HVOF technology is limited due to economical reasons. From that point of view recycling materials for thermal spray powders, especially carbides, could give reasonable results [5, 6].

However, pure carbide based coatings, due to brittleness, do not perform well in impact loading conditions [7]. Therefore, there is a need for a tough matrix material with relatively high hardness and low cost. Only iron based alloys meet all these requirements [8]. Up to date, iron based self-fluxing alloys are relatively less studied than nickel based self-fluxing alloys, but are cheaper and harder.

The aim of this study was (a) to investigate the properties of iron based self-fluxing alloys reinforced with hardmetal/cermet particles in different wear conditions (abrasion and solid particle erosion wear), (b) to investigate the structure and hardness of sprayed coatings.

EXPERIMENTAL DETAILS

As a substrate material carbon steel C45 with dimensions 100 mm × 25 mm × 5 mm was used. The chemical composition and hardness are shown in Table 1.

Table 1. Chemical composition and hardness of steel C45

Grade of steel	Composition, wt %	Hardness	HV1
		as normalised	as hardened
C45	0.45 C; 0.60 Mn; 0.30 Si	200 – 235	300 – 310

Chemical composition of used powders, both self-fluxing alloys and recycled hardmetal are shown in Table 2. From that powders four different powder composities were mixed containing 60 vol% self-fluxing alloys as metallic matrix and 40 vol% hardmetal/cermet particles as reinforcement produced by mechanical milling. WC-Co recycled hardmetal powder produced by mechanical milling, causes high iron content in the powder due to the intensive wear of the grinding media as can be seen from Table 2 [9, 10].

Fig. 1 illustrates the particle shape and size distribution of typical mechanically milled hardmetal. The powder particles of chromium carbide cermet were primarily equiaxed in form. The shape of WC-Co was more angular.

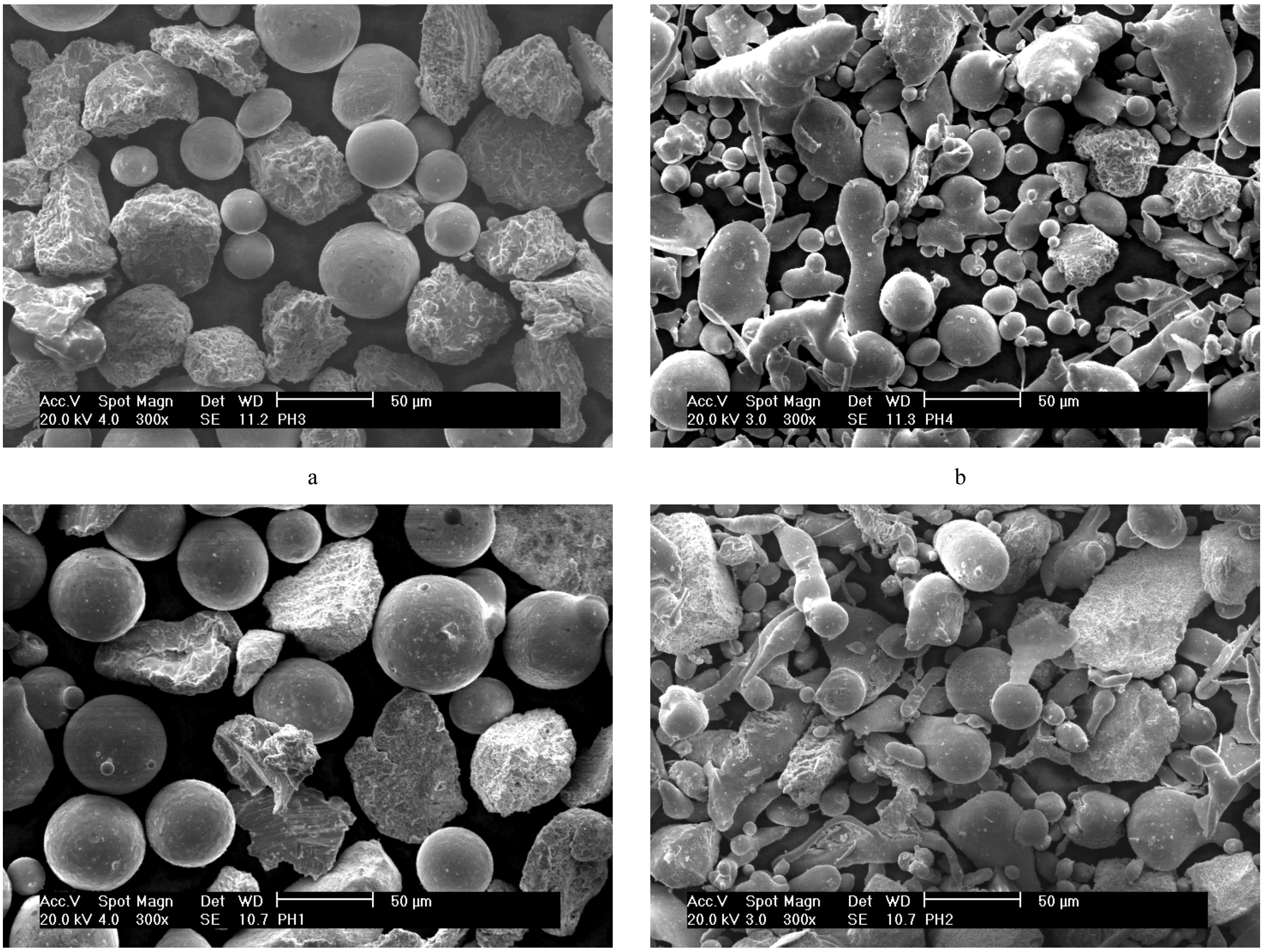
---

[*] Corresponding author. Tel.: +372-620-3470; fax.: +372-620-3196.
E-mail address: *heikki.sarjas@ttu.ee* (H. Sarjas)

Table 2. Chemical composition and particle size of the used self-fluxing alloy and hardmetal/cermet powders

Type of powder	Composition, wt %						Particle size, µm
	Cr	Si	B	C	Ni	Fe	
NiCrSiB*	7.5	3.5	1.6	0.25	bal	2.5	–53 +15
FeCrSiB*	13.7	2.7	3.4	2.1	6	bal	–45 +10
Cr_3C_2-Ni**	78 Cr3C2; 2.5 W				14	3.1	–50 +20
WC-Co**	75.6 WC; 11.5 Co					12.9	–50 +20

* Produced by Höganäs.
** Experimental TUT.



a b

c d

Fig. 1. Micrographs of composite spray powders: a – (Cr_3C_2-Ni)+FeCrSiB; b – (Cr_3C_2-Ni)+NiCrSiB, c – (WC-Co)+FeCrSiB, d – (WC-Co)+NiCrSiB

For deposition of coatings High Velocity OxyFuel (HVOF) spray system Diamond Jet Hybrid 2700 (propane hybrid gun from Sulzer Metco) was used. Parameters of HVOF spray are shown in Table 3.

Polished cross-sections of coatings were observed by light microscope using Omnimet image analysis system and SEM Zeiss EVO MA-15. X-ray analysis (EDS) was performed on Oxford Instruments INCA- Energy system for estimation of the changes in composition of metal matrix.

Surface hardness measurements were performed with universal hardnessmeter Zwick 2.5/TS at load 10 N (1 kgf). Load was selected to obtain the size of indents comparable with sizes of hard phase in the compostie.

For measuring microhardness in cross-section Micromet 2001 was used. The applied load was 2.45 N (300 gf).

Sprayed coatings were tested at two different wear conditions including abrasion (abrasive rubber-wheel wear) and abrasive-erosive wear (AEW).

Table 3. Parameters of HVOF spraying process

Parameter	Value
Propane flow, l/min	68
Oxygen flow, l/min	240
Air flow, l/min	375
Spray distance, mm	250
Surface speed, m/min	120
Distance between passes, mm	6
Powder feed rate, g/min	40
Number of passes	40 30 for (Cr3C2-Ni+FeCrSiB)

Abrasive wear tests were carried out using the block-on-ring rubber wheel (ABRW) scheme (ASTM standard G 65-94) (Fig. 2, a). The diameter of the ring was 228.6 mm, the applied force 130 N, feed rate of abrasives 330 g/min and the speed of rotation 200.8 1/min (linear velocity 2.4 m/s). Testing time was 5 min. The parameters of wear tests are shown in Table 4.

The mass loss of the specimens at ABRW was determined and the wear coefficient calculated as

$$k = \frac{\Delta m}{\rho \cdot F \cdot t \cdot v \cdot r}, \tag{1}$$

where Δm is the mass loss, kg; ρ is the density, kg/m^3; F is the force, N; t is the time of the experiment, s; v is the rotation speed 1/min; r is the radius of the ring, m.

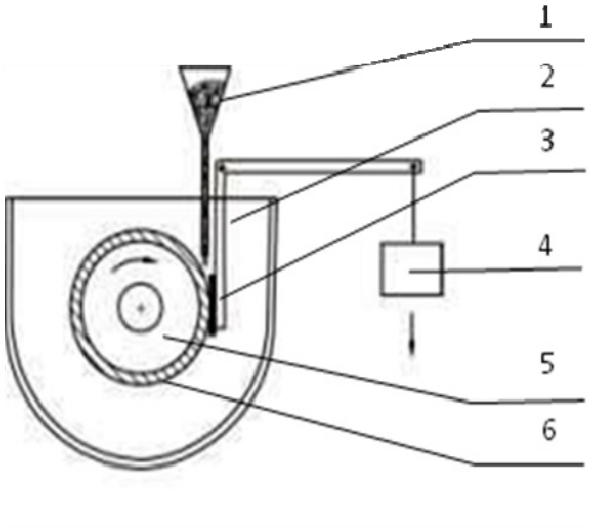


Fig. 2. Principal scheme of block-on-ring wear tester: 1 – abrasive particle vessel; 2 – specimen holder; 3 – specimen; 4 – weights; 5 – steel wheel; 6 – rubber wheel

Abrasive erosive wear (AEW) of coatings was studied by the experimental centrifugal-type wear testers CAK (Fig. 3). The velocity of abrasive particles was 80 m/s, impact angles 30° and 90°. Wear experiments at ABRW and AEW with quartzite sand of fraction 0.1 mm – 0.3 mm were carried out. Hardness of the quartz, measured at the cross-section polishes, was 11.0 HV 0.05 GPa.

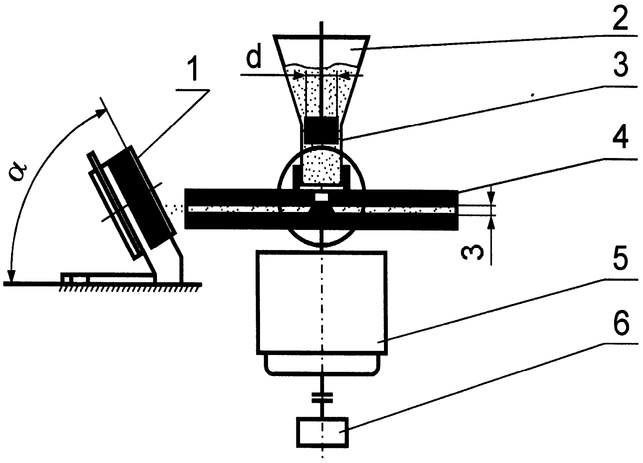


Fig. 3. Principal scheme of block-on-ring wear tester: 1 – specimen; 2 – abrasive particles vessel; 3 – shield; 4 – rotor; 5 – drive motor; 6 – rotation frequency gauge

At AEW the mass loss of the specimens was determined and the volumetric wear rate I_v was calculated, dividing mass loss by abrasive mass per specimen and material density (Eq. (2)).

$$I_v = \frac{\Delta m}{\rho \cdot q}, \tag{2}$$

where Δm is the mass loss in mg; q is the quantity of abrasive per specimen in kg; ρ is the sample density, mg/mm^3.

The relative volumetric wear resistance ε_v was determined on steel C45 by the following equation:

$$\varepsilon_v = I_v / I_v^{C45}, \tag{3}$$

where I_v is the volumetric wear rate of tested coating; I_v^{C45} is the same of reference steel C45.

Table 4. Abrasive wear testing parameters

Type of wear	Velocity, m/s	Abrasive and particles size, mm	Amount of abrasive, kg
Abrasion block-on-ring wear (ABRW)	2.4	Quartz sand 0.1 – 0.3	1.5
Erosion wear (AEW)	80	Quartz sand 0.1 – 0.3	3

RESULTS AND DISCUSSION

Thickness of the coatings determined by SEM cross-section images and presented in Fig. 4 was from 300 μm up to 400 μm. Porosity was between 1 % – 3 %. Coating adhesion with steel substrate was good. Only some small pores and SiO_2 particles were found in the border between steel and coating. As a result of high velocity of deposition the hard phase particles (WC-Co and Cr_3C_2-Ni) were destroyed, elongated in a direction of substrate surface and fractured partially (first of all more brittle particles of Cr_3C_2-Ni). According to EDS analysis (Fig. 4, windows and Table 5) the obtained coatings consist mainly of the initial phases – WC-Co, Cr_3C_2-Ni, FeCrSiB and NiCrSiB respectively. Additionally, some Fe areas were found primarily in coatings consisting of WC-Co formed in hardmetal powder production process.

The hardness measurements of surface hardness as well as microhardness of the coating showed that Fe-based self-fluxing alloy matrix proved to be slightly harder than ones of Ni-based self-fluxing alloys as expected. The relationship of harder matrix–higher abrasive wear resistance was proved (Table 7). Hardness of reinforcement particles was from 7.6 – 9.2 and 8.5 – 12.6 for Cr_3C_2-Ni and WC-Co respectively. Impact of harder reinforcement materials on ABRW wear was moderate (Table 7).

Table 5. Detected phases in coatings (Fig. 4)

Composition of spray powders	Phases by EDS analysis			
	1	2	3	4
Cr_3C_2-Ni+FeCrSiB	Cr_3C_2	Ni	FeCrSiB	–
Cr_3C_2-Ni+ NiCrSiB	Cr_3C_2	Ni-Cr	NiCrSiB	Fe
WC-Co+FeCrSiB	WC	Co	FeCrSiB	Fe
WC-Co+NiCrSiB	WC	Co	NiCrSiB	Fe

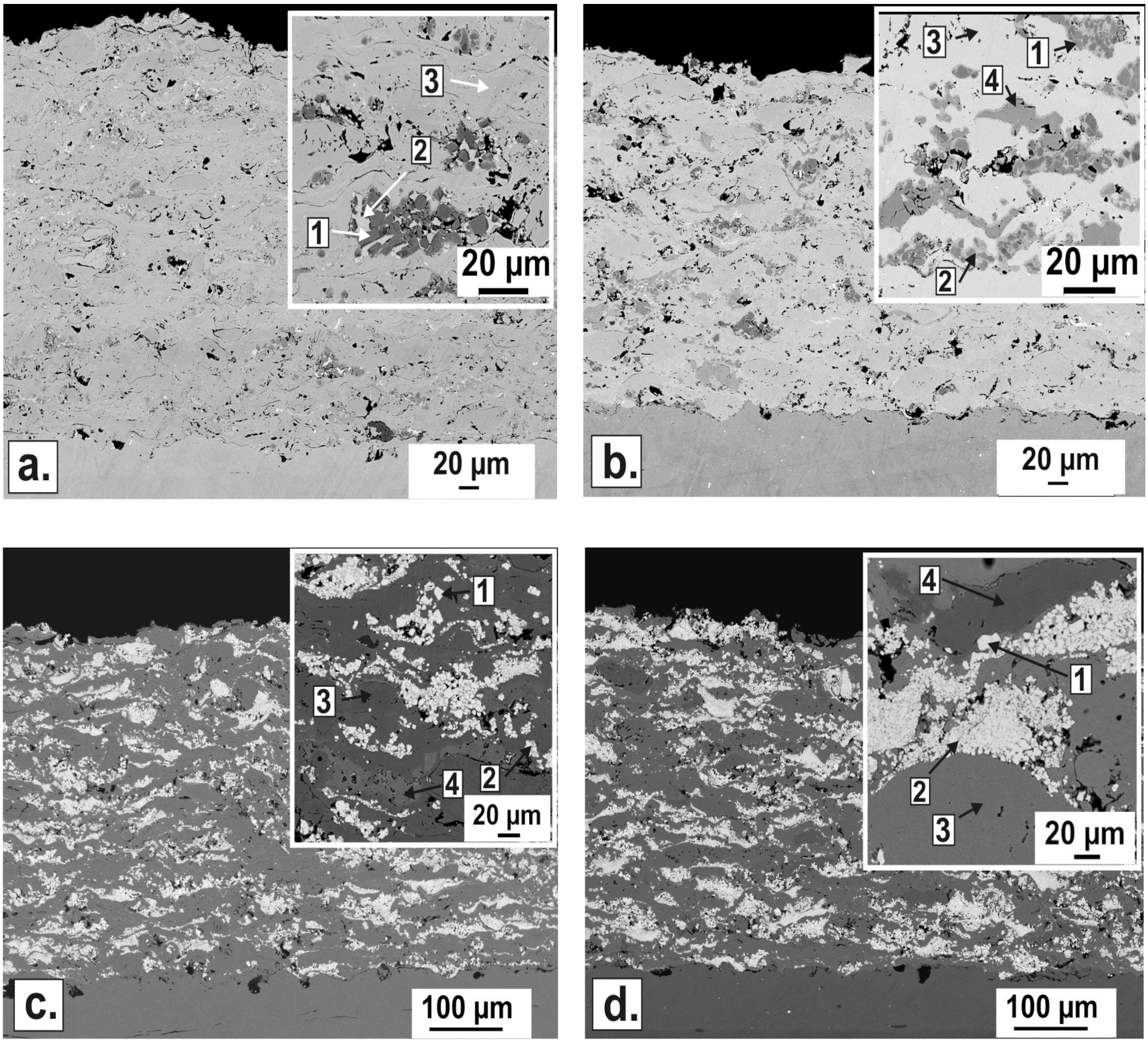


Fig. 4. Coatings cross-sections and EDS phasemaps (window areas): a – (Cr_3C_2-Ni)+FeCrSiB; b – (Cr_3C_2-Ni)+ NiCrSiB; c – (WC-Co)+FeCrSiB; d)– (WC-Co)+NiCrSiB

The predominant wear mechanism at abrasion is the loss of the softer matrix phase and often leads to the loss of hard phase (Fig. 5). Results of abrasion of coatings tested at ABRW showed 1.5 – 2.7 times better wear resistance than reference material steel C45 (Table 7). The relative wear resistance of Fe self-fluxing alloy based and hardmetal/cermet consisting hardphase coatings compared with Ni-based reference coating proved to have slightly higher wear resistance.

Erosion resistance of coatings proved to be quite poor at 30° angle and extremely low at 90° angle (Table 8). It can be explained with fracture of hard phase, first of all Cr_3C_2 particles at high energy spray process as it follows from the structure studies (see Fig. 4). Wear at high and low velocity and at high impact angles from carbide based particles fracture or removal at sprayed matrix metal microparticles due to low-cycle fatique process (see Fig. 5) [11].

Table 6. Hardness of sprayed coatings

Composition of coatings	Thickness, µm	Hardness HV, GPa	
		Surface	Matrix / reinforcement
		HU	HV1
Cr3C2-Ni+ FeCrSiB	300	3.5 – 4.3	4.9 – 5.9/7.6 – 8.3
Cr3C2-Ni+NiCrSiB	400	3.2 – 3.8	4.4 – 5.1/8.0 – 9.2
WC-Co+FeCrSiB	400	4.3 – 5.0	4.7 – 5.6/8.5 – 12.6
WC-Co+NiCrSiB	400	2.9 – 3.5	4.8 – 5.2/8.8 – 12.6

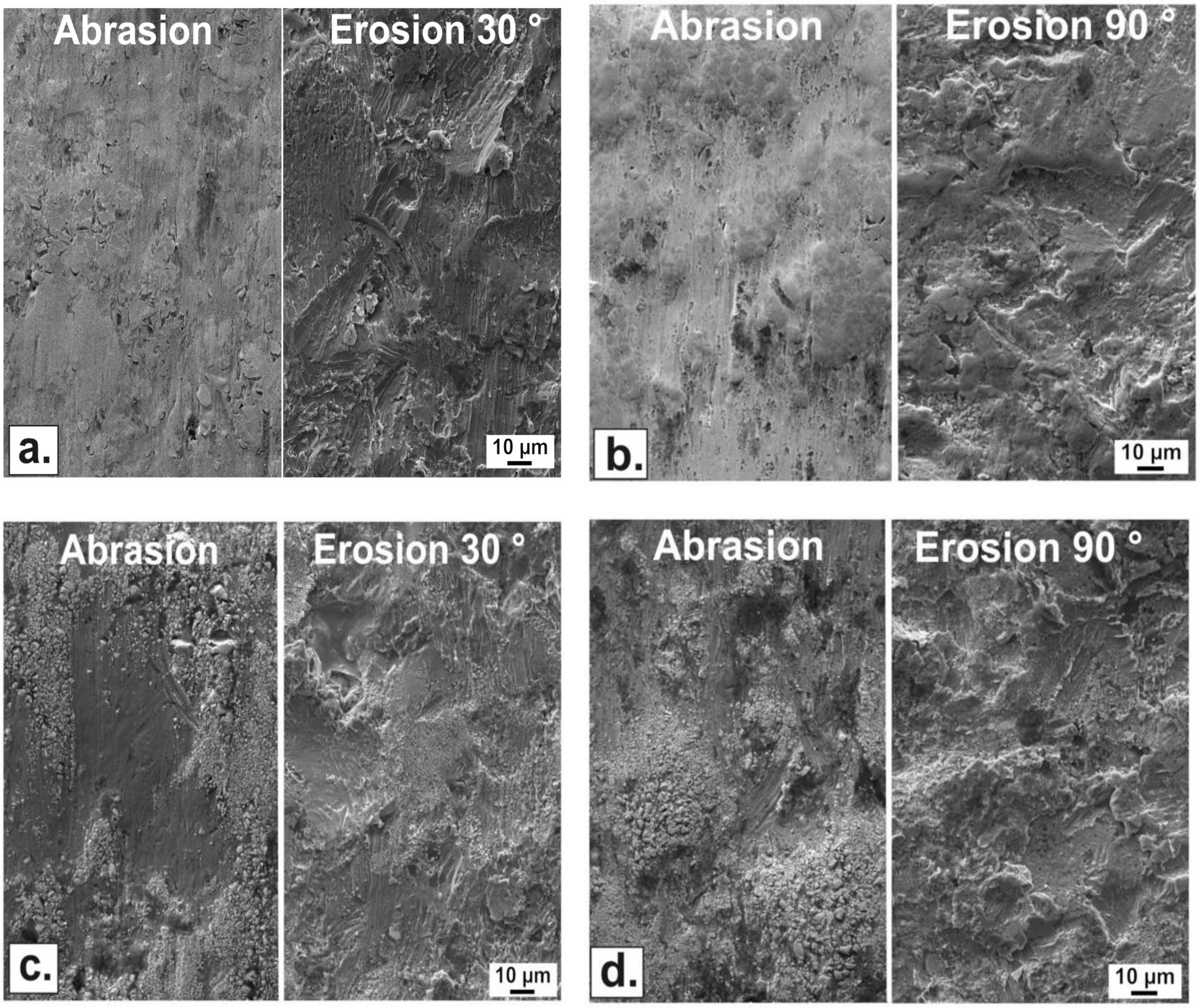


Fig. 5. Worn surfaces of the coatings after abrasive wear: a – (Cr_3C_2-Ni)+ FeCrSiB; b – (Cr_3C_2-Ni)+ NiCrSiB; c – (WC-Co)+ FeCrSiB; d – (WC-Co)+ NiCrSiB

Table 7. Abrasion resistance of tested coatings

Material	Wear coefficient K, mm^3/Nm 10^{-5}	Relative wear resistance to ε_v
Cr3C2-Ni+FeCrSiB	10.0	2.2
Cr3C2-Ni+NiCrSiB	14.0	1.6
WC-Co+FeCrSiB	8.3	2.7
WC-Co+NiCrSiB	11.1	2.0

Table 8. Erosion wear resistance of coatings

Material	Volumetric wear rate I_v, mm^3/kg	Relative wear ε_v resistance
	30°/90°	30°/90°
Cr3C2-Ni+ FeCrSiB	47 / 125	0.8 / 0.2
Cr3C2-Ni+ NiCrSiB	46 / 100	0.8/ 0.2
WC-Co+ FeCrSiB	31 / 78	1.2 / 0.3
WC-Co+ NiCrSiB	34 / 79	1.1 / 0.3

CONCLUSIONS

1. High Velocity deposition of Fe and Ni matrix based hardmetal/cermet hardphase consisting coatings leads to formation of high defective lamellar structure.
2. Wear resistance at abrasion of Fe-based matrix coating with WC-Co reinforcement is three times higher and depends primarily on the microhardness of surface, caused by hardphase content in coating (needs further study).
3. Abrasive impact wear resistance at erosion of studied composite coatings is low due to high defective of the hardphase in coatings and high energy of impact (at velocity of 80 m/s.

Acknowledgments

The authors of the article would like to express their gratitude to Mikko Kylmälahti from Tampere University of Technology. This work was supported by the Estonian Ministry of Education and Research (target-financed project SF 01400091s08) and by European Social Fund's Doctoral Studies and Internationalisation Programme DoRa.

REFERENCES

1. Surface Engineering for Corrosion and Wear Resistance. Ed. by **J. R. Davis**, ASM International, 2001.
2. Handbook of Thermal Spray Technology. Ed. by **J. R. Davis**, ASM International, 2004. 338 lk
3. **Legg, K. O., Sartwell, B.** Alternatives to Functional Hexavalent Chromium Coatings: HVOF Thermal Spray. *Rowan Technology Group.* Presented at *AESF-SURFIN*, June 2004. http://www.hazmat-alternatives.com/Documents/Briefings&Presentations/PEL_session-AESF-SURFIN-6-04.pdf (20 May 2011).
4. **Shedd, K. B.** 2006 Minerals Yearbook, Tungsten. *U.S. Geological Survey,* April 2008. http://minerals.usgs.gov/minerals/pubs/commodity/tungsten/myb1-2006-tungs.pdf (27 May 2011).
5. **Zimakov, S., Pihl, T., Kulu, P., Antonov, M., Mikli, V.** Applications of Recycled Hardmetal Powder *Proceedings of the Estonian Academy of Sciences, Engineering* 9 (4) 2003: pp. 304 – 316.
6. **Zimakov, S.** Novel Wear Reisstant WC-Based Thermal Sprayed Coatings *PhD Thesis* Tallinn, TUT Press, 2004.
7. **Kleis, I., Kulu, P.** Solid Particle Erosion. Occurrence, Prediction and Control. Springer-Verlag London Limited, 2008: 201 p.
8. **Surzenkov, A., Kulu, P., Tarbe, R., Mikli, V., Sarjas, H., Latokartano, J.** Wear Resistance of Laser Remelted Thermally Sprayed Coatings *Estonian Journal of Engineering* 15 (4) 2009: pp. 318 – 328.
9. **Kulu, P., Käerdi, H., Mikli, V.** Retreatment of Used Hardmetals. *In: Proc. TMS 2002 Recycling and Waste Treatment in Mineral and Metal Processing: Technical and Economic Aspects.* Lulea 1 2002: pp. 139 – 146.
10. **Tümanok, A., Kulu, P., Mikli, V., Käerdi, H.** Technology and Equipment for Production of Hardmetal Powders Form Used Hardmetal *In: Proc. 2nd Int. DAAAM Conference*, Tallinn, 2000: pp. 197 – 200.
11. **Veinthal, R., Kulu, P., Kärdi, H.** Microstructural Aspects of Abrasive Wear of Composite Materials and Coating *International Journal of Materials and Product Technology* 40 (1 – 2) 2011: pp. 92 – 119.

Presented at the 20th International Baltic Conference
"Materials Engineering 2011"
(*Kaunas, Lithuania, October 27–28, 2011*)