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Wear resistance of laser remelted thermally sprayed coatings

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Abstract. Advantages of hard coatings and deposition technologies such as HVOF have opened new opportunities for the production of wear parts operating in an abrasive environment. Thermally sprayed hardmetal coatings are widespread in industrial applications for wear, but not usable under impact wear conditions. To widen the scope of thick hard coating applications, powder coatings, produced by plasma spraying and powder spray-fused coatings using laser remelting, were studied. Nickel- and iron-based self-fluxing alloy powders and WC-Co hardmetal powders were used as spray materials. The microstructure of coatings and the influence of heat treatment on the structure and composition of coatings as well as on the composition of the substrate were studied. The duplex-treated surfaces were tested under the conditions of abrasion and abrasive erosion and impact wear and the mechanisms of coating degradation were analysed. Prospects of coatings, containing thermal spray-fused iron-based metal-matrix WC-Co hardmetal for erosive wear conditions, are demonstrated. Based on the comparative studies of abrasive, erosive and impact wear resistance, recommendations for materials and coatings are formulated.

Key words: powder coatings, thermal spray, laser remelting, abrasion, erosion, abrasive impact wear.

1. INTRODUCTION

In terms of product lifetime of engineering materials and machine components, the surface is of prime concern. This involves wear behaviour and mechanical properties such as surface fatigue [1,2]. Thermally sprayed hardmetal coatings, also often called “carbide coatings”, are used widely in many industrial applications for wear, corrosion and high temperature protection [3]. Recent attention has focused on reduced consumption of existing resources and materials recycling. Therefore the application of composite powders, based on used (recycled) hardmetals for thermal spray is topical [4,5].

Wide use of thermally sprayed coatings gives evidence of the cost-effectiveness of self-fluxing alloys containing tungsten carbide (WC) particles, applied by the spray and fusion methods (flame, plasma and laser fusion). Some materials, most notably MCrSiB compositions, where M stands for either Ni, Co or Fe, can be fused by heating them up to the temperature of 1050 °C. Due to the brittleness of tungsten carbide, the impact wear resistance of the coatings is not high [4]. Because of their low porosity and high bond with the basic materials, the spray-fused composite coatings, containing WC-Co hard phase, can resist significant impact loads [6]. It has been shown that abrasive erosive and impact wear resistance of powder materials and coatings are not high [5,7,8]. Usage of the recycled hardmetal powder, produced by mechanical milling, causes high iron content in the powder (up to 20%) due to the intensive wear of the grinding media [9,10]. It is a factor, hindering their use in nickel-based compositions.

Following from the abovementioned, this work focuses on thermal spray-fusion for the production of high-performance surfaces, use of the deposition of hard coatings by thermal spray and subsequent laser treatment of powder composition, based on iron-based spray powder. To improve the impact wear resistance of plasma sprayed coatings, the following laser remelting was studied.

2. EXPERIMENTAL

2.1. Studied materials and coatings

For coatings, as a substrate, specimens of the size $50 \times 25 \times 10$ mm of plain carbon steel C45 were used. The composition and hardness of the steel are given in Table 1.

The composite powders for spray and fused coatings contained nickel- and iron-based powders as basic components. Table 2 shows the chemical composition of the self-fluxing alloy powders of the powder composites. With a spherical shape, their particle size was (+10 –45) and (+15 –53) μm for Fe- and Ni-based powders, respectively.

Table 1. Chemical composition and hardness of the substrate steel

Grade of the steel	Composition, wt%	Hardness HV1	
		Normalized	Hardened
C45	0.45 C; 0.60 Mn; 0.30 Si	200–235	480–515

Table 2. Chemical composition and particle size of the used self-fluxing spray powders

Type of the powder	Trade mark	Composition, wt%						Particle size, μm
		Cr	Si	B	C	Ni	Fe	
NiCrSiB (S)	1640–02*	7.5	3.5	1.6	0.25	bal.	2.5	+15 –53
NiCrSiB (H)	1660–02*	14.8	4.3	3.1	0.75	bal.	3.7	+15 –53
FeCrSiB	Grade 6A*	13.7	2.7	3.4	2.1	6.0	bal.	+10 –45
WC-Co	Rec VK**	WC – 75.6; Co – 11.5					12.9	+20 –63

* Powders of Höganäs AB, Bruksgatan 35, SE-263 83 Höganäs, Sweden; (S) – soft (380 HV), (H) – hard (780 HV).
** Experimental, TUT.

Nickel- and iron-based self-fluxing alloy powder compositions, containing 25 wt% of hardmetal particles, were used. WC-Co hardmetal powder, produced from used hardmetal by disintegrator milling, was employed [9,10]. Chemical composition of the hardmetal powder was the following (in wt%): WC – 75.6, Co – 11.5, Fe – 12.9. Powders had the particle size of (+20 –63) and –63 μm. Figure 1 illustrates the particle shape. Particles were primarily equiaxed in form and their microstructure showed a typical tungsten carbide based hardmetal structure.

2.2. Plasma spray and laser treatment of coatings

To depose a coating, plasma spray equipment RotAloy of Castolin Eutectic was applied. Plasma spraying parameters of the coatings are given in Table 3. Thickness of the coatings was about 0.2 mm. The plasma sprayed coatings were remelted using Nd: YAG laser Haas HL 4006 D of Trumpf with a wavelength of 1064 nm; the cross-section of the laser beam was 8×5 mm, overlapping – 50%. Parameters of laser remelting are provided in Table 3.

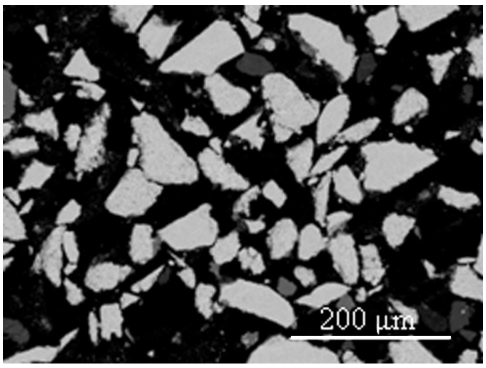

Fig. 1. Micrograph of hardmetal powder particles.

Table 3. Parameters of plasma spraying and laser remelting

Type of the coating	Power	Gas flow rates, l/min	Other parameters
Plasma spraying	–	Ar – 135 H_2 – 90	Spray current – 380 A, voltage – 150 V, powder feed rate – 30 g/min, spray distance – 100 mm
Laser remelting	I series – 1.75 kW for NiCrSiB compositions II series – 1.5 kW for FeCrSiB and NiCrSiB compositions	Ar – 20	Scan speed – 10 mm/s

2.3. Characterization of the coating structure, hardness and wear resistance

2.3.1. Microstructure of coatings

Coatings were characterized both in the sprayed condition and after laser remelting. Polished cross-sections were observed by the optical microscope using an Omnimet image analysis system and SEM. X-ray analysis (EDS) was performed to estimate changes in the composition of the metal matrix.

2.3.2. Determination of hardness

To determine surface hardness, measurements were made with a universal hardnessmeter Zwick 2.5/TS at a load from 1 to 100 N. The load was selected to obtain the size of indents comparable with the size of wear craters, formed by abrasive wear.

Microhardness measurements in the cross-section were carried out using the Micromet 2001 measuring device. The applied load was equal to 0.245 N. Low loads enabled us to measure the hardness of the metallic matrix as well as of the hardmetal particles in the matrix of the coating.

2.3.3. Abrasive wear testing

Abrasive block-on-ring wear (ABRW) abrasion tests were carried out using the block-on-ring rubber wheel scheme (ASTM standard G 65-94) (Fig. 2a). The diameter of the ring was 228.6 mm, the applied force was 222 N and the speed of rotation was 200.8 1/min (linear velocity 2.4 m/s). The parameters of the wear tests are given in Table 4. Abrasive erosive wear (AEW) and abrasive impact wear (AIW) of the coatings were studied with the experimental centrifugal-type wear testers CAK and DESI [7]. At AEW the velocity was 80 m/s, impact angles were 30° and 90°. By AIW tests a one-rotor system was used (Fig. 2c) [7]; the velocity was 80 m/s and the impact angle of abrasive particles with the specimen on the fixed pin surface was about 90°. Wear experiments ABRW and AEW with

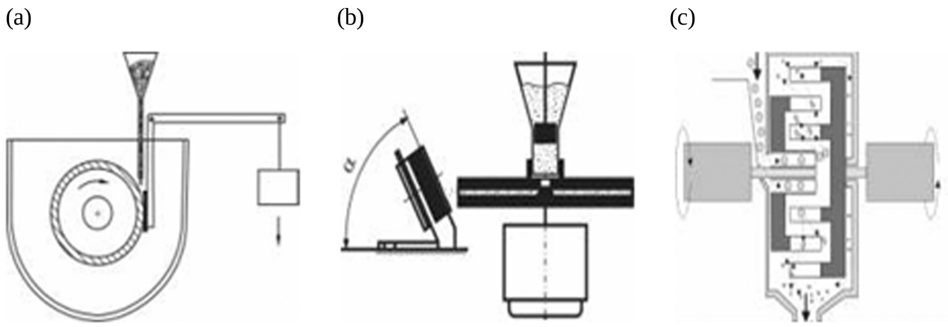

Fig. 2. Principal schemes of the block-on-ring wear tester (a), centrifugal-type erosion tester CAK (b) and disintegrator type impact wear tester DESI (c).

Table 4. Parameters of tribological tests

Type of the test	Velocity, m/s	The abrasive and the particle size, mm	Amount of the abrasive, kg
Abrasive block-on-ring wear (ABRW)	2.4	Quartz sand 0.1–0.3	1.5
Abrasive erosive wear (AEW)	80	Quartz sand 0.1–0.3	3
Abrasive impact wear (AIW)	80	Granite gravel 4–5.6	6

quartzite sand of fraction 0.1–0.3 mm were carried out. AIW tests were conducted with granite gravel of fraction 4.0–5.6 mm. Hardness of the quartzite and granite, measured at the polished cross-section, was 11.0 and 9.28 HV 0.05 GPa, respectively.

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

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

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

At AEW and AIW the mass loss of the specimens was determined and the volumetric wear rate I_v was calculated as

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

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

The relative volumetric wear resistance ε_v was determined for steel C45 as follows:

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

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

3. RESULTS AND DISCUSSION

3.1. Structure, porosity and hardness of the coatings

The cross-sections of laser remelted plasma sprayed coatings are shown in Figs. 3 and 4.

NiCrSiB self-fluxing alloy forms a Ni-based matrix with WC hard particles (WC-Co hardmetal particles are practically dissolved in the Ni-based matrix). This was confirmed by the EDS analysis of the coating – different phase distribution in the coating is shown in Fig. 3b. Retained slag nests in the Ni-based coating were observed.

(a) (b)

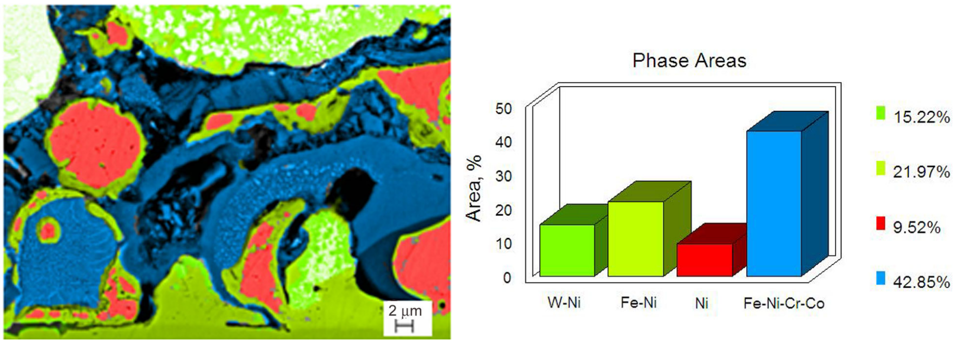

Fig. 3. Micrograph of the cross-section and composition of NiCrSiB(S)-based coating after laser remelting (a) and distribution of the elements (b).

(a) (b)

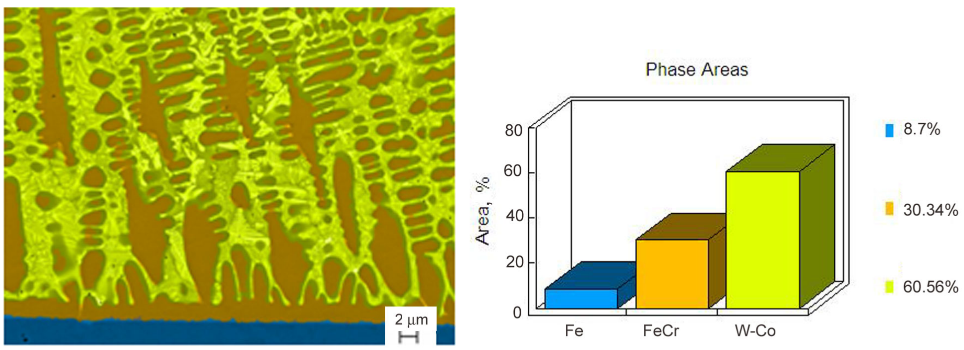

Fig. 4. Micrograph of the cross-section and composition of FeCrSiB-based coating after laser remelting: (a) microstructure; (b) distribution of the elements.

As it follows from Fig. 4, Fe-alloy based coating structure is a typical eutectic structure and more dense than the Ni-alloy based coating, where due to the high content of Fe (about 13%) large Fe-Cr dendrites and smaller W-Co dendrites are formed. The rate of solution of WC-Co in the metal matrix is higher in the Fe-alloy based coating – practically all WC-Co particles are dissolved in the iron-based matrix forming the (Fe-Cr) – (WC-Co) eutectic structure. The results of hardness measurements by both methods are brought in Table 5.

3.2. Wear resistance of spray-fused coatings

Results of abrasive wear tests (abrasion, erosion and impact wear) are given in Tables 6–8.

3.2.1. Abrasive block-on-ring wear resistance

By abrasion, the coatings studied demonstrated low wear resistance, the relative wear resistance is lower than one (0.5–0.9) (Table 6). Because the hardness of the abrasive is higher (about 11 GPa of the quartz sand) than that of the coating (about 3.0–5.6 GPa), intensive wear takes place as a result of microcutting or surface scratching. It was confirmed by the study of the worn surfaces (Fig. 5a).

Table 5. Hardness of spray-fused coatings on steel C45 ((WC-Co) of fraction +20 –63 μm)

Composition of coatings, wt%	Thickness, μm	Hardness HV, GPa	
		Surface HV1	(Metal matrix)/(hardmetal particles) HV 0.1
NiCrSiB(S) + 25 (WC-Co)	200	3.0–3.6	2.7–4.3/5.8–18.8
FeNiCrSiB + 25 (WC-Co)	200	4.4–5.6	4.9–6.8/7.7–9.4

Table 6. Abrasive block-on-ring wear (ABRW) resistance of coatings

Type of the coating and metal matrix	Condition and fraction, μm	Wear coefficient K, $mm^3/Nm \times 10^{-5}$	Relative wear resistance ε_v
NiCrSiB(S) + (WC-Co)	As-sprayed	36.1	0.18
	Laser remelted		
	–63	11.1/8.7*	0.58/0.74*
	+20 –63	13.5	0.48
NiCrSiB(H) + (WC-Co)	–63	8.4	0.76
FeCrSiB + (WC-Co)	As-sprayed	–	–
	Laser remelted		
	–63	8.8	0.73
	+20 –63	7.1	0.88

* I and II series.

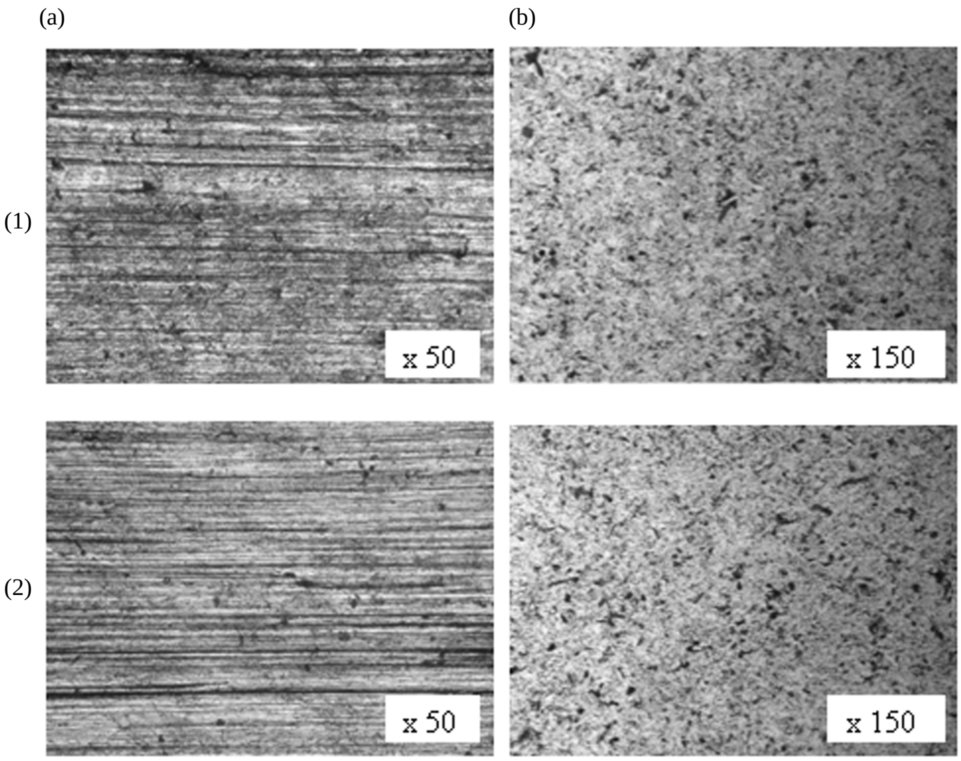

Fig. 5. Worn surfaces, topographigal images of (1) NiCrSiB(S) and (2) FeCrSiB-based coatings after wear: (a) ABRW; (b) AEW ($\alpha = 90°$).

3.2.2. Abrasive erosive wear resistance

Based on the studies of wear rate and wear mechanism of the coatings (Table 7), the wear resistance of Ni-based coatings at low impact angles is lower than the wear resistance of reference steel C45; Fe-based coating showed about 1.2 times higher wear resistance.

The first series (N = 1.75 kw) of the NiCrSiB-based coating demonstrated higher relative wear resistance at straight impact angle ($\alpha = 90°$). It may be explained by the high WC-Co particle solution rate in the Ni-based metal matrix due to different parameters of the laser remelting and the resulting lower brittleness of the composite. Higher erosion resistance of the FeCrSiB-based coatings, in comparison with the NiCrSiB-based coating at low impact angle ($\alpha = 30°$), can be explained by the higher hardness (about 1.5 times) and formation of a eutectic structure.

3.2.3. Abrasive impact wear

Impact wear resistance of the spray-remelted self-fluxing Ni-alloy based coating is practically at the level of the reference material – steel C45 (Table 8). Because of their low impact wear resistance, the HVOF sprayed coatings, based

Table 7. Abrasive erosive wear (AEW) resistance of coatings at different impact angles (hardmetal powder fraction +20 –63 μm) by impact angles of 30° and 90°

Type of the coating and metal matrix	Condition	Wear rate I_v, mm^3/kg		Relative wear resistance ε_v	
		30°	90°	30°	90°
NiCrSiB(S) + (WC-Co)	As-sprayed	447.6	–	0.1	–
	Laser remelted	25.3/33.2	25.7/29.7*	0.7/0.8	1.6/0.7*
NiCrSiB(H) + (WC-Co)	Laser remelted	22.1	25.3	0.8	1.6
FeCrSiB + (WC-Co)	Laser remelted	23.5	28.2	1.2	0.7

* I and II series.

Table 8. Abrasive impact wear (AIW) resistance of coatings

Type of the coating	Hard phase fraction, μm	Wear rate I_v, mm^3/kg	Relative wear resistance ε_v
NiCrSiB(S) + (WC-Co)	–63	55.7	1.03
	+20 –63	54.9	1.04
FeCrSiB + (WC-Co)	+20 –63	43.7	1.31

on a Ni-based alloy, and recycled hardmetal are not suitable for applications under impact wear conditions [7,11,12]. Spray-fused Fe-based coatings may offer an alternative for expensive powder steels and in some cases (under restoration of the working elements of milling devices) for traditional WC-Co hardmetals.

The absence of the correlation between the results of different wear tests can be explained by different wear mechanisms, namely by microcutting of the metal matrix in the case of abrasive wear, microcutting of the metal matrix and direct fracture of hard particles during abrasive erosive wear at low angles, micro-cutting or surface fatigue of the metal matrix and direct fracture of hard particles at the straight impact angle, surface fatigue of the metal matrix and direct fracture of hard particles during abrasive impact wear.

4. CONCLUSIONS

Iron-based self-fluxing alloys are more suitable for producing self-fluxing alloy-based composite coatings containing recycled WC-Co hardmetal powder in comparison with the nickel-based ones. Iron-based spray fusion coatings are of higher density and have a typical eutectic sturcture. Due to the laser remelting, the initial WC-Co hardmetal powder reinforcement is practically dissolved in the iron-based metal matrix. Due to the higher hardness of iron-based coatings they are more wear resistant by abrasion, but the iron-based coatings have lower erosive wear resistance by the straight impact than the Ni-based composite coatings. By abrasive impact wear, Fe-based coatings show better performance.

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Lasersulatatud termopinnete kulumiskindlus

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Kõvapinnete ja kiirleekpihustamismooduste kasutuselevõtt võimaldab valmistada unikaalsete omadustega kuluvosi tööks abrasiivkulumise tingimustes. Termopihustatud kõvasulampinded on leidnud laialdast tööstuslikku kasutamist kulumisvastasel eesmärgil, kuid nimetatud pinded ei sobi tööks löökkulumise tingimustes. Laiendamaks paksude kõvapinnete kasutusvaldkondi, on käesolevas

töös uurimisobjektiks plasmapihustatud ja lasersulatatud pulberpinded. Pihustus-pulbrina kasutati komposiitpulbrit iseräbustuva rauasulami baasil, mis kõva-faasina sisaldas 25 kaaluprotsenti taaskasutatavat WC-Co-kõvasulampulbrit.

Uuriti termotöötluse mõju nii pulberpinnete struktuurile ja koostisele kui ka alusmaterjali struktuurile ning omadustele. Pihustus-sulatuspindeid katsetati abrasiivkulumise (abrasioon ja erosioon) ning löökkulumise tingimustes ja uuriti pinnete kulumiskindlust ning kulumise mehhanismi. Selgitati välja raua baasil metallmaatriksiga ja WC-Co tugevdava faasiga pulberpinnete perspektiivsus abrasiiverosiooni tingimustes. Eri tingimustes (abrasioon, erosioon ja löök-kulumine) läbi viidud pulberpinnete kulumiskindluse katsete tulemusena on esitatud soovitused pinnete valikuks.