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Sliding wear of TiC-NiMo and Cr_3C_2-Ni cermet particles reinforced FeCrSiB matrix HVOF sprayed coatings

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Abstract. In the current article, high-velocity oxy-fuel (HVOF) sprayed composite powder TiC-NiMo and Cr_3C_2-Ni cermet particles reinforced self-fluxing alloy matrix (FeCrSiB) coatings were studied. The actual content of the reinforcement in the sprayed coatings was smaller in comparison with the feedstock powders. Cermet particles were deformed at the impact with the substrate, deformation was more remarkable in the case of the TiC-NiMo particles. Sprayed coatings exhibited a structure with a number of defects, like voids and cracks, whereas the latter were more pronounced in reinforced coatings. Despite the bigger number of defects, cermet particles reinforced coatings had up to 1.2 times higher surface hardness than the unreinforced coating. TiC-NiMo particles reinforced coating demonstrated 1.8 times higher sliding wear resistance than the unreinforced coating. Cr_3C_2-Ni particles reinforced coating showed 1.3–2.8 times higher sliding wear resistance in comparison with the unreinforced coating, depending on the series of tests. Addition of cermet particles allowed to increase the resistance of the FeCrSiB matrix to deformation and scuffing.

Key words: composite, HVOF spraying, cermet, FeCrSiB, coating.

1. INTRODUCTION

Metal matrix composites (MMCs) are highly attractive due to their relatively high hardness and wear resistance in comparison with metal alloys, which are provided by the combination of hard reinforcement and ductile metal matrix.

However, it is not always reasonable and sometimes not possible to manufacture bulk MMCs. Therefore, the application of a MMC coating instead can be a promising alternative [1].

MMC coatings may be produced by a number of technologies, such as self-propagating high temperature synthesis [2], hot isostatic pressing, thermal spraying [3], etc. Among thermal spraying processes, high velocity oxy-fuel spraying (HVOFS) is one of the most advantageous, as it allows to obtain denser coatings with lower oxide content and higher adhesion [4]. For HVOFS MMC coatings, Ni-based self-fluxing alloys (NiCrSiB) were found to be an optimal choice as the matrix material [5]. In this case, tungsten carbide-cobalt hardmetals (WC-Co) are commonly used as reinforcement [6]. However, WC-Co is prone to loss of carbon with the formation of brittle W_2C phase during the spraying process [7] that worsens the performance of sprayed coatings. Therefore, potential substitutes, such as TiC-NiMo and Cr_3C_2-Ni cermets, are currently being studied [8,9]. On the other hand, Fe-based self-fluxing alloy (FeCrSiB) matrix coatings showed better wear properties than NiCrSiB matrix ones [9–11]. Despite that, so far little research has been conducted on FeCrSiB matrix cermet particles reinforced coatings. For example, to the authors' best knowledge, sliding wear of FeCrSiB matrix cermet particles reinforced coatings has not been studied yet. On the basis of these considerations, the current research concentrates on sliding wear behaviour of HVOFS FeCrSiB matrix TiC-NiMo and Cr_3C_2-Ni cermet particles reinforced coatings.

2. EXPERIMENTAL

2.1. Substrate preparation

Specimens, onto which coatings were sprayed, were machined from carbon steel C45 (0.43 wt% C, 0.75 wt% Mn, 0.035 wt% P, 0.035 wt% S, ≤0.40 wt% Cr, ≤0.10 wt% Mo, ≤0.40 wt% Ni) to dimensions of 50 × 25 × 10 mm. Prior to spraying process they were grit blasted with Al_2O_3 to the surface roughness of Ra = 10.0±1.0 μm.

2.2. High-velocity oxy-fuel spraying process

The studied HVOFS MMC powder coatings had three compositions: pure FeCrSiB (reference), 70 vol% FeCrSiB + 30 vol% TiC-NiMo and 75 vol% FeCrSiB + 25 vol% Cr_3C_2-Ni. The grades, manufacturers, particle sizes and chemical compositions of powders are presented in Table 1. Prior to spraying, FeCrSiB powder was dried at 200 °C and cermet powders – at 150 °C for 6 h.

Coatings were sprayed, using the Tafa JP-5000 (Praxair Inc.) high-velocity oxy-fuel spraying device. The spraying parameters are presented in Table 2. Instantly before spraying, the substrate was dried by the gun flame for 5 s to remove moisture from the surface asperities.

Table 1. Parameters of sprayed powders

Alloy	Type	Particle size, µm	Chemical composition, wt%
FeCrSiB	Commercial, 6AB[1]	+10 –45	6.04 Ni, 13.72 Cr, 2.67 Si, 3.40 B, 0.32 Mn, 2.07 C, 0.02 S, bal. Fe
TiC-NiMo	Experimental[2]	+20 –63	70 TiC, 20 Ni, 10 Mo
Cr_3C_2-Ni	Experimental[2]	+20 –63	70 Cr_3C_2, 30 Ni

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Table 2. Parameters of HVOF spraying

Oxygen supply pressure	1.45 MPa
Oxygen flow pressure	0.97 MPa
Oxygen flow	55.22 m^3/h
Kerosene supply pressure	1.17 MPa
Kerosene work pressure	0.83 MPa
Kerosene flow	0.02 m^3/h
Combustion pressure	0.71 MPa
Nitrogen pressure	0.50 MPa
Nitrogen flow	1.62 m^3/h
Spraying distance	380 mm

2.3. Microstructure studies

Polished cross-sections of the coatings were studied using the scanning electron microscope (SEM) EVO MA-15 (Carl Zeiss). Distribution of chemical elements was studied by the energy dispersive spectroscopy (EDS) method.

2.4. Hardness measurements

Universal hardness (HU) was measured according to the standard DIN 50359 "Testing of metallic materials – Universal hardness test", using the universal hardnessmeter Zwick 2.5/TS, applying the optimal load of 50 N and indentation depth of 35 µm.

2.5. Sliding wear testing

Standard ball-on-plate sliding wear tests were conducted, applying the Al_2O_3 Ø 3 mm ball as the counterbody with the load of 7.85 N (0.8 kgf) and the frequency of 2 Hz. The amplitude was 1 mm, the total duration of the test was 3600 s, relative humidity about 50%. Unreinforced FeCrSiB coating and hardened (850 °C, water) and tempered (550 °C, 1.5 h) carbon steel C45 were used as reference materials (steel C45 specimen was tested for 1800 s, as it exhibited relatively high wear). Each coating was tested three times. After the tests, the cross-sections of the wear scars were studied applying the Mahr profilometer, and the respective wear volumes were calculated as a product of the cross-section area of the wear scar by its length; average wear volumes were calculated afterwards. Wear scars were studied under EVO MA-15 (Carl Zeiss) SEM to inspect the wear mechanisms.

3. RESULTS AND DISCUSSION

3.1. Microstructure studies

The actual content of the cermet reinforcement in the sprayed coatings is lower than in the feedstock powders before spraying, being approximately 15 vol% in the case of the TiC-NiMo and 20 vol% in the case of the Cr_3C_2-Ni cermet (Fig. 1a,b). Such a reduction of the reinforcement's volume was most probably caused by the phenomenon of the loss of the coarser part of the feedstock powder during the HVOF spraying process [4]. As the coarsest cermet particles have larger sizes than the coarsest self-fluxing alloy ones, the loss of the cermet particles must be higher.

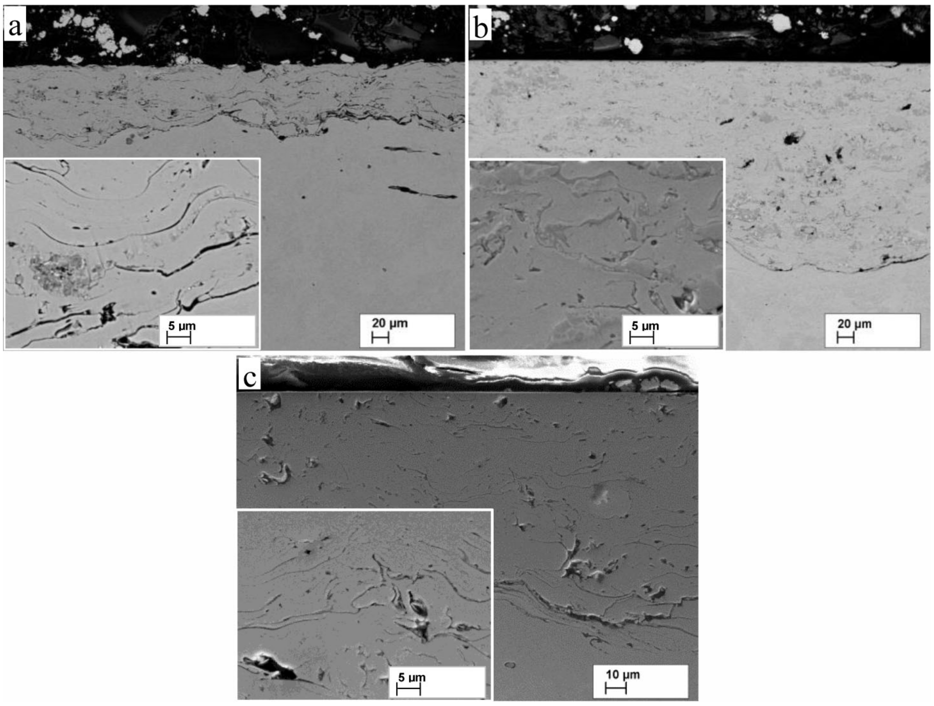

Fig. 1. Microstructure of HVOFS coatings: a – FeCrSiB + TiC-NiMo, b – FeCrSiB + Cr_3C_2-Ni, c – pure FeCrSiB (reference).

All sprayed coatings have a number of defects in the structure, such as voids and cracks. The latter seem to be more obvious in the cermet particles reinforced coatings, especially the TiC-NiMo particles reinforced one. Cermet particles are elongated (fractured) in the direction, perpendicular to the direction of spraying, which happens due to their high kinetic energy during spraying, leading to their deformation at the moment of impact with the substrate [9]. No destruction of the carbide phases was observed, thus the elongation of the cermet particles occurs due to deformation of the metal matrix. The more remarkable deformation of TiC-NiMo particles may be explained by the smaller size of the carbide phase, what eases a more extensive deformation of the metal matrix at the moment of the impact. No dissolution of the reinforcement in the matrix could be found, what is in correspondence with former results [9,10].

3.2. Hardness measurements

Cermet particles reinforced coatings have 1.2–1.3 times higher surface hardness in comparison with the unreinforced coating (Table 3; Vickers microhardness values from [10] were added for comparison), what generally corresponds with the contents of the reinforcement in the composite coatings. Values, obtained by both methods, must be related to as correspondent with a composite structure, as the sizes of the indentation marks exceeded the sizes of the reinforcement and matrix areas in both cases. The more remarkable effect of hardness increment in the case of TiC-NiMo particles reinforced coating in comparison with Cr_3C_2-Ni reinforced one can be induced by a higher hardness of the TiC-NiMo cermet (1415 HV [12]) in comparison with the Cr_3C_2-Ni one (980 HV [13]).

3.3. Sliding wear study

Cermet particles reinforced coatings demonstrated somewhat controversial results at sliding wear tests in comparison with the reference materials (Fig. 2). TiC-NiMo particles reinforced coating had a 1.8 times lower wear in comparison with the unreinforced coating and 2.2 times lower wear in comparison with steel

Table 3. Hardness of sprayed coatings

Substrate	Hardness, GPa	
	HU (surface)	HV0.1 (cross-section)
FeCrSiB + TiC-NiMo	4.9 ± 0.2	8.5 ± 1.2
FeCrSiB + Cr_3C_2-Ni	4.4 ± 0.2	8.5 ± 2.0
FeCrSiB (reference)	3.8 ± 0.4	7.7 ± 1.0
Hardened and tempered steel C45 (reference)	3.3 ± 0.2	3.1 ± 0.1

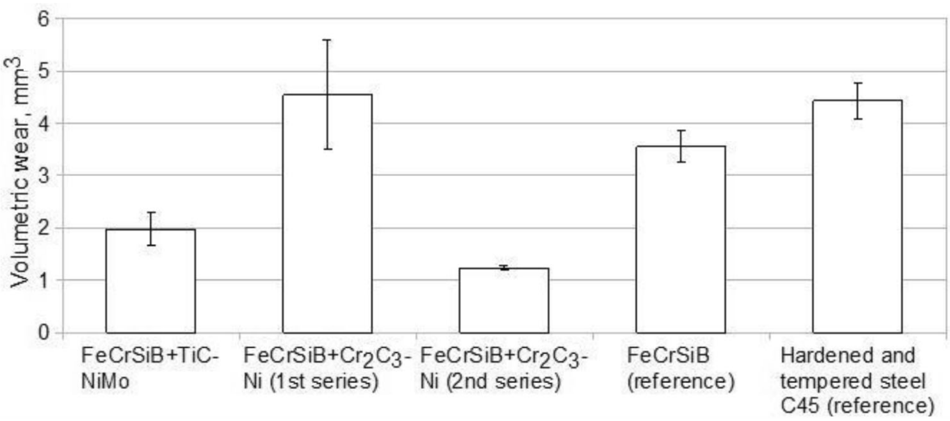

Fig. 2. Sliding wear of sprayed coatings.

C45. In contrast to that, during the first series of tests, Cr_3C_2-Ni particles reinforced coating showed wear values, comparable to those of steel C45, and 1.3 times higher in comparison with the pure FeCrSiB alloy coating. Considering the relatively large deviations in the wear values, the same Cr_3C_2-Ni particles reinforced coating was tested for the second time. During the second series of tests, wear of this coating was respectively 2.8 times and 3.6 times lower in comparison with those of the unreinforced coating and the steel specimen.

Wear mechanism of the pure FeCrSiB coating had a fatigue character, similar to that described in [14] (Fig. 3d): circular cracks, initiated by the coating's deformation, developed until formation, development and spalling of the particles from the coating. In addition to that, a relatively remarkable abrasive wear occurred.

Addition of cermet particles obviously helped to decrease the deformation of the FeCrSiB alloy matrix, thus reducing cracking (Fig. 3a–c). Wear of reinforcement inside the coating started with the loss of the binder phase, followed by consequent spallation of unbound carbide particles.

The wear mechanism of FeCrSiB matrix was similar to that of the unreinforced coating, but on a smaller scale, except for the Cr_3C_2-Ni particles reinforced coating during the 1st series of tests. In the latter case, extensive spallation of the matrix occurred (Fig. 3b), leading to relatively high wear. However, in the case of the 2nd series, spallation was less evident (Fig. 3c), thus lowering the wear. The reason for such a result is not clear and needs further research. Currently an uneven distribution of residual stresses in the coating [15] may be suggested as one of the causes of different results of wear tests. It should also be noted that abrasive wear of reinforced coatings had a milder character in comparison with unreinforced coating.

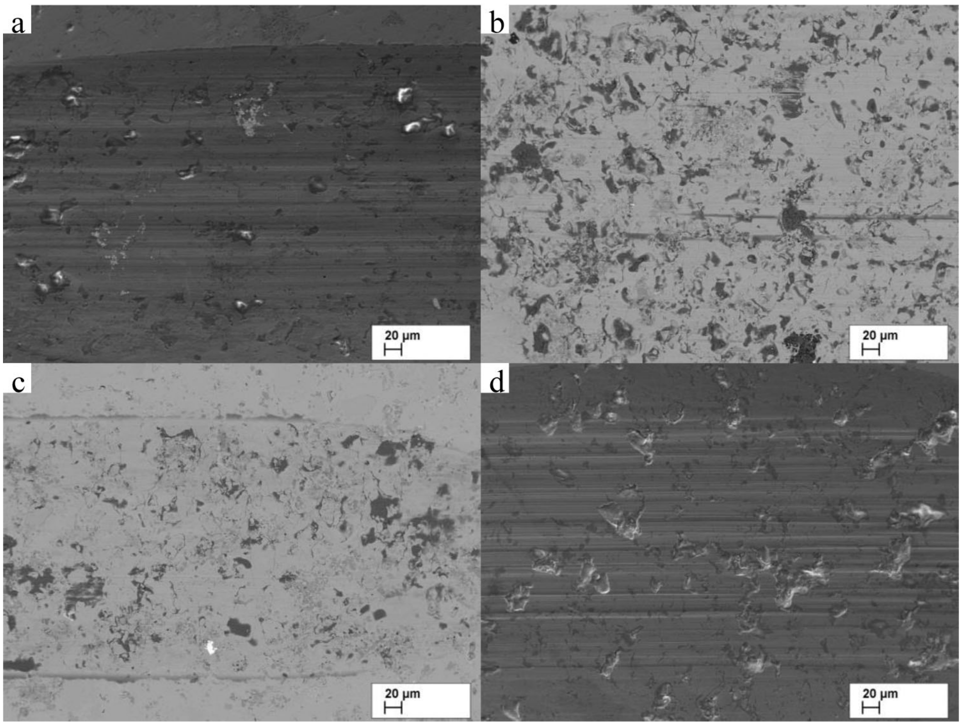

Fig. 3. Wear scars of the sprayed coatings: a – FeCrSiB + TiC-NiMo, b – FeCrSiB + Cr_3C_2-Ni (1st series), c – FeCrSiB + Cr_3C_2-Ni (2nd series), d – pure FeCrSiB (reference).

4. CONCLUSIONS

1. TiC-NiMo and Cr_3C_2-Ni cermet particles reinforced coatings exhibit more defect structure in comparison with unreinforced coating.
2. Cermet particles reinforced coatings have about 20% higher surface hardness in comparison with the unreinforced coating.
3. TiC-NiMo particles reinforced coating had 1.8 times higher and Cr_3C_2-Ni particles reinforced coating in the best case – 2.8 times higher sliding wear resistance in comparison with unreinforced coating.
4. Addition of cermet particles to the FeCrSiB self-fluxing alloy allows to diminish its spallation and to decrease abrasive wear of the coating.

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REFERENCES

1. Yan, H., Zhang, P., Yu, Z., Li, C. and Li, R. Development and characterization of laser surface cladding (Ti,W)C reinforced Ni-30Cu alloy composite coating on copper. *Optics Laser Technol.*, 2012, **44**, 1351–1358.
2. Yuan, X., Liu, G., Jin, H. and Chen, K. In situ synthesis of TiC reinforced metal matrix composite (MMC) coating by self-propagating high temperature synthesis. *J. Alloys Compounds*, 2011, **529**, L301–L303.
3. Kiliç, F., Gül, H., Aslan, S., Alp, A. and Akbulut, H. Effect of CTAB concentration in the electrolyte on the tribological properties of nanoparticle SiC reinforced Ni metal matrix composite (MMC) coatings produced by electrodeposition. *Colloids and Surfaces A: Physicochem. Eng. Aspects*, 2013, **419**, 53–60.
4. Davis, J. R. *Handbook of Thermal Spray Technology*. ASM International, Materials Park, 2004.
5. Määttä, A., Kanerva, U. and Vuoristo, P. Structure and tribological characteristics of HVOF coatings sprayed from powder blends of Cr_3C_2-25NiCr and NiCrSiB alloy. *J. Thermal Spray Technol.*, 2011, **20**, 366–371.
6. Chen, H., Xu, C., Qu, J., Hutchings, J. M. and Shipway, P. H. Sliding wear behaviour of laser clad coatings based upon a nickel-based self-fluxing alloy co-deposited with conventional and nanostructured tungsten carbide-cobalt hardmetals. *Wear*, 2005, **259**, 801–806.
7. Kim, H.-J., Hwang, S.-Y., Lee, C.-H. and Juvanon, P. Assessment of wear performance of flame sprayed and fused Ni-based coatings. *Surf. Coat. Technol.*, 2003, **172**, 262–269.
8. Zikin, A., Antonov, M., Hussainova, I., Katona, L. and Gavrilović, A. High temperature wear of cermet particle reinforced NiCrBSi hardfacings. *Tribol. Int*. Forthcoming.
9. Sarjas, H., Goljandin, D., Kulu, P., Mikli, V., Surženkov, A. and Vuoristo, P. Wear resistant thermal sprayed composite coatings based on iron self-fluxing alloy and recycled cermet powders. *Medžiagotyra (Materials Science)*, 2012, **18**, 34–39.
10. Surzhenkov, A., Vallikivi, A., Mikli, V., Viljus, M., Vilgo, T. and Kulu, P. Wear resistant self-fluxing alloy based TiC-NiMo and Cr_3C_2-Ni hardmetal particles reinforced composite coatings. In *Proc. 2nd Int. Conference INDUSTRIAL ENGINEERING & MANAGEMENT*. Prešov, Slovak Republic, 2012, 34–37.
11. Surzhenkov, A., Kulu, P., Tarbe, R., Mikli, V., Sarjas, H. and Latokartano, J. Wear resistance of laser-cladded thermal sprayed coatings. *Estonian J. Eng.*, 2009, **15**, 318–328.
12. Pirso, J., Viljus, M., Juhani, K. and Kuningas, M. Three-body abrasive wear of TiC-NiMo cermets. *Tribol. Int.*, 2012, **43**, 340–346.
13. Hussainova, I. Some aspects of solid particle erosion of cermets. *Tribol. Int.*, 2001, **34**, 89–93.
14. Zhang, Z. Q., Li, G. L., Wang, H. D., Xu, B. and Piao, Z. Monitoring fatigue wear of the coating based on acoustic emission. *Tribology*, 2012, **32**, 89–95.
15. Ryabchikov, A., Lille, H., Toropov, S., Reitsnik, R., Surženkov, A. and Kulu, P. Investigation of residual stresses in flame sprayed Ni-based wear resistant coatings by the hole-drilling and X-ray methods. *Mater. Sci. Forum*. Forthcoming.

TiC-NiMo ja Cr_3C_2-Ni kermiste osakestega armeeritud FeCrSiB maatriksiga kiirleekpihustatud pinnete liugekulumine

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Artiklis on uuritud kiirleekpihustatud TiC-NiMo ja Cr_3C_2-Ni kermiste osakestega armeeritud iseräbustuvast sulamist (FeCrSiB) maatriksiga komposiitpulberpindeid. Tegelik armatuurisisaldus pihustatud pinnetes osutus pihustatavate

pulbritega võrreldes väiksemaks. Kokkupõrkel alusmaterjaliga olid kermiste osakesed deformeerunud, deformatsiooniaste oli suurem TiC-NiMo-osakeste puhul. Pihustatud pinnete struktuur sisaldas mitmeid defekte, sh tühimikke ja pragusid, kusjuures viimased olid silmapaistvamad armeeritud pinnetes. Armeerimata pindega võrreldes, vaatamata suuremale defektide arvule, näitasid kermiste osakestega armeeritud pinded kuni 1,2 korda suuremat pinnakõvadust, TiC-NiMo-osakestega armeeritud pinne 1,8 korda ja Cr_3C_2-Ni-osakestega armeeritud pinne 1,3–2,8 korda suuremat liuglemiskindlust. Kermiste osakeste lisamine aitas suurendada FeCrSiB maatriksi vastupanu deformatsioonile ja kriipele.