Tribological Properties of Hypersonically Sprayed Carbide Coatings

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Research of the abrasive wear and coefficient of friction research of hypersonically sprayed carbide coating of WC-Co and Cr_3C_2-25%NiCr powders were presented. The coatings were deposited with the use of ultrasonic spraying system TAFA JP-5000 (HVOLF). Microstructure of coatings were investigated with SEM-EDS microscope. Phase composition was evaluated with Brucker D8 Advance diffractometer. To estimate abrasive wear resistance, dry abrasive rubber wheel tester T-01 was applied. Friction coefficient was measured on ball on ring type tribo-tester T-01M. These tests show that chromium carbide coating have got better wear resistance while tungsten carbide coating presents lower coefficient of friction.

Keywords: *HVOLF, carbides, coefficient of friction, abrasion.*

1. INTRODUCTION

Carbide coatings are applied in many branches of industry [1]. This kind of coatings consists of hard phase of carbide grains embedded in tough matrix phase of metal. Their high wear resistance allows them to replace the hard chrome coatings in abrasion, sliding and erosion conditions according to the new environmental regulations [2,3]. Among various types of carbides, tungsten carbide is used at temperatures below 540 ºC, chromium carbide can be applied up to 815 ºC. The carbide coatings have been deposited by atmospheric plasma spraying (APS) or D-gun process. High temperature of APS process causes decarburization of tungsten monocarbide to W_2C, and metallic tungsten occurs as well. The following reactions [4] describe these phenomena:

$$2WC \rightarrow W_2C + C$$
$$W_2C \rightarrow 2W + C$$

A marked carbon loss in the coating associated with its oxidation in the flame occurs according to the following reaction:

$$2C + O2 \rightarrow 2CO \text{ (gas)}$$

All these processes are conditioned by the spraying parameters and significantly influence coatings wear resistance. D-gun process, however, gives coatings with excellent properties, but is a hard accessible process. The high velocity oxy-fuel (HVOF) process is one of the most popular thermal spraying technologies and has been widely adopted by many industries due to its flexibility and the superior quality of produced coatings. Detrimental reactions which occur during APS spraying are limited due to low flame temperature and short dwell time of particles in jet in HVOF process.

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The HVOF process is a relatively new thermal spray process developed by J. Brown in the mid-eighties of the last century as competition to patented D-gun process [1]. HVOF differs from conventional flame spraying by drastically increased velocity of combustion gases. Therefore, also powder particles injected into the flame of HVOF guns are accelerated to much higher velocities, i.e. roughly 650 m/s for modern equipment. Very high kinetic energy of particles striking the substrate surface does not require the particles to be fully molten to form high quality HVOF coatings. This is certainly an advantage for the carbide cermet type of coatings and is where this process really excels. A liquid fuelled form of spraying equipment is called high velocity oxy-liquidfuel (HVOLF) systems, and is a new generation of hypersonic spraying systems where velocity and temperature of the sprayed particles are better controlled (Fig. 1).

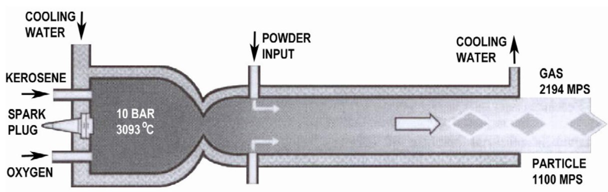

Figure 1. Schematic diagram of HVOLF process

Fuel and oxygen mix is atomized after passing through orifices into the combustion chamber creating stable and uniform combustion. The exit nozzle of combustion chamber is sized and shaped to create a hypersonic over expanded jet and maintains a low-pressure region where the powder is introduced. HVOLF sprayed coatings are widely used to improve the service life of machine components. Properties of HVOLF sprayed coatings cause that the processes of wear are more complex than in the case of monolithic materials. The phenomenon, however, has not been fully explained. Hypersonically sprayed elements are exposed to high loads, variable rotational speeds and high temperatures, which may result in an undesirable lubrication or no lubrication at all. All forms of wear failure can be observed on the surfaces of mating elements. Intensive adhesive or thermal wear due to the occurrence of local grafting and adhesion leads to the shorter life [5-9]. The aim of this study was to investigate process of wear and coefficient of friction for WC17Co and Cr_3C_2-25%NiCr hypersonically sprayed coatings.

2. EXPERIMENTAL

Tungsten carbide, WC17Co, (FST K-674.23) and chromium carbide, Cr_3C_2-25%NiCr, (1375VM) powders were used. The size and shape of powder grains are shown in Figure 2. The both powders are trade materials designated for thermal spraying. Grains of powders are manufactured by agglomeration and sintering of fine grains. Cross-section of the grains of powders is shown in Figure 3. Well seen porosity of grains is result of applied method of powder production.

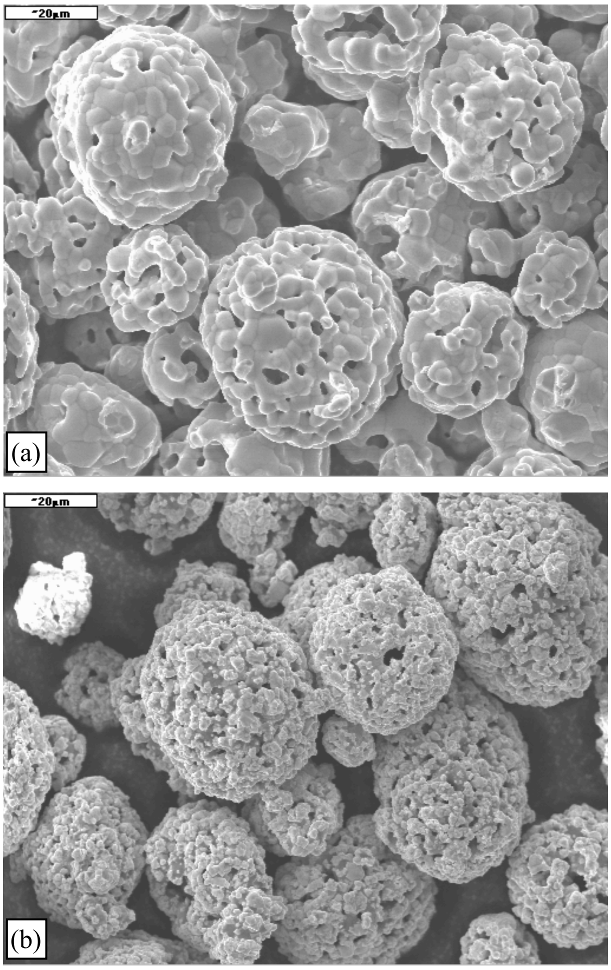

Figure 2. Powder grains: (a) WC17Co and (b) Cr_3C_2-25%NiCr

Powders were sprayed with TAFA JP-5000 system where kerosene is applied as fuel (Table 1).

Table 1. HVOLF spray parameters

Spray parameters	WC17Co	Cr_3C_2-25%NiCr
Barrel length [mm]	150	150
Oxygen pressure [kPa]	890	890
Kerosene mass flow [l/h]	22.7	22.7
Powder feed rate [g/min]	330	200
Feeder gas	argon	argon
Spray distance [mm]	380	380

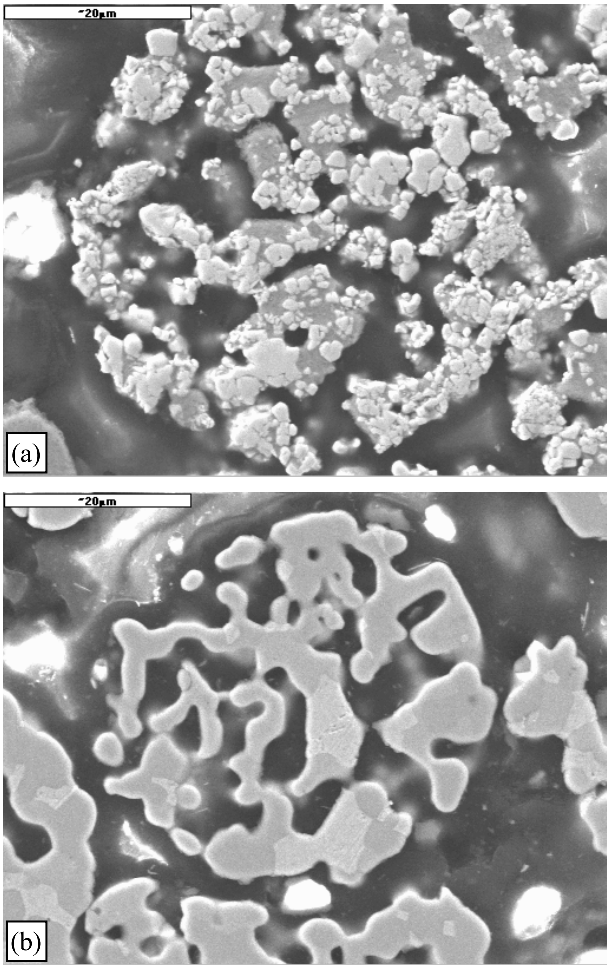

Figure 3. Cross-section of powder grains: (a) WC17Co and (b) Cr_3C_2-25%NiCr

For the metallographic examination, the coatings were deposited on thin flat samples in low-carbon steel with dimensions of 50 mm × 25 mm × 5 mm, whereas for the tribological test the coatings were deposited on ring-shaped samples in low-carbon steel with dimensions of Ø46 mm × Ø25 mm × 6 mm. Before spraying, the substrate had to be degreased and grit blasted with electrocorundum EB-12 at a pressure of 0.5 MPa. The thickness of the coatings after grinding was 0.3 mm. The microstructure of the sprayed coatings was analysed with a scanning electron microscope JOEL JSM-5400, the element distribution with a microprobe ISIS 300 Oxford Instruments and phase composition by BRUKER D8 Advance diffractometer. The roughness of coatings was measured with Talysurf-4, whereas Zwick 3210 was used to study their hardness. Well known dry abrasive rubber wheel tester (T-01) with alumina (grain size 0.5 mm) as abradant was applied to estimate abrasive resistance of sprayed coatings. The T-01M ball-on-ring type tribo-tester was used to determine the coefficient of friction in unlubricated conditions for the sprayed carbide coatings. The ball in bearing steel 100Cr6 had a diameter of 0.635 mm. The testing involved applying a computer to aid in registering and controlling the action of the friction force in the function of time. The parameters for the T-01M tester were as follows: load P = 4.9 N, linear velocity v = 1 m/s, test duration t = 1 h. The schematic diagram of the tester operation is presented in Figure 4.

The coatings of ring samples were sprayed and subsequently ground and polished for one hour. The roughness of the WC-Co coatings was R_a = 0.37 μm, and of the coatings Cr_3C_2-25%NiCr was R_a = 0.44 μm; their microhardness was 1640 HV 0.1 and 1174 HV 0.1 respectively.

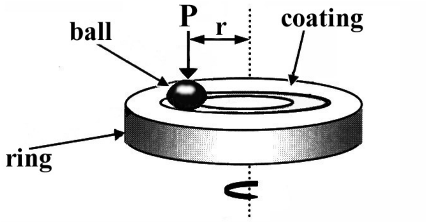

Figure 4. Principle of operating of the tribological tester T-01M (ball-on-ring type)

A series of tests for abrasion resistance included the measurements of mass decrease in samples (3 samples per each coating). 100 g, 200 g and 300 g of the abrasive material were applied in the subsequent stages of the research. The samples were cleaned and weighed on the laboratory scales after each cycle of the research.

3. RESULTS AND DISSCUSSION

Figure 5 shows the microstructure of HVOLF sprayed carbide coatings. Cross-section of WC17Co coating (Fig. 5a) reveals non-deformed grains of WC in the cobalt matrix. Linear analysis (Fig. 5c) proved a diversified composition of the coating in particular zones. In a tungsten carbide coating, the white grains testify the presence of tungsten, whereas the dark matrix appears to be rich in cobalt and contain little tungsten. In the case of cross-section of Cr_3C_2-25%NiCr coating bigger non-deformed dark grains are embedded in light matrix (Fig. 5b). Linear analysis (Fig. 5d) shows that dark grains are a phase with high content of chromium, whereas light matrix is an area with content of nickel. In both sprayed coatings the presence of small pores is visible as the darkest spots.

The presence of different phases in both coatings was investigated by XRD using identical conditions as the corresponding analysis of the powders, i.e. Cu Kα (λ = 1.54 Å). The XRD patterns of powders were compared with recorded patterns for coatings to see if phase transformations had occurred during HVOLF spraying. XRD patterns recorded for both powders and coatings, respectively, were nearly identical in both cases. The research indicates the presence of WC and Co in the WC-Co powder. Tungsten carbide and small quantities of W_2C and Co_6W_6C are present in the sprayed coating (Fig. 6).

Diffractional lines of the phases in coatings are much wider, which indicates a significant level of elastic-plastic deformation, i.e. a significant level of energy stored in the form of network defects. It is particularly characteristic in the case of Co phase. The analysis of the Cr_3C_2-25%NiCr (Fig. 7) revealed the presence of the phases NiCr, Ni, Cr_3Ni_2 and Cr_3C_2 carbide both in the

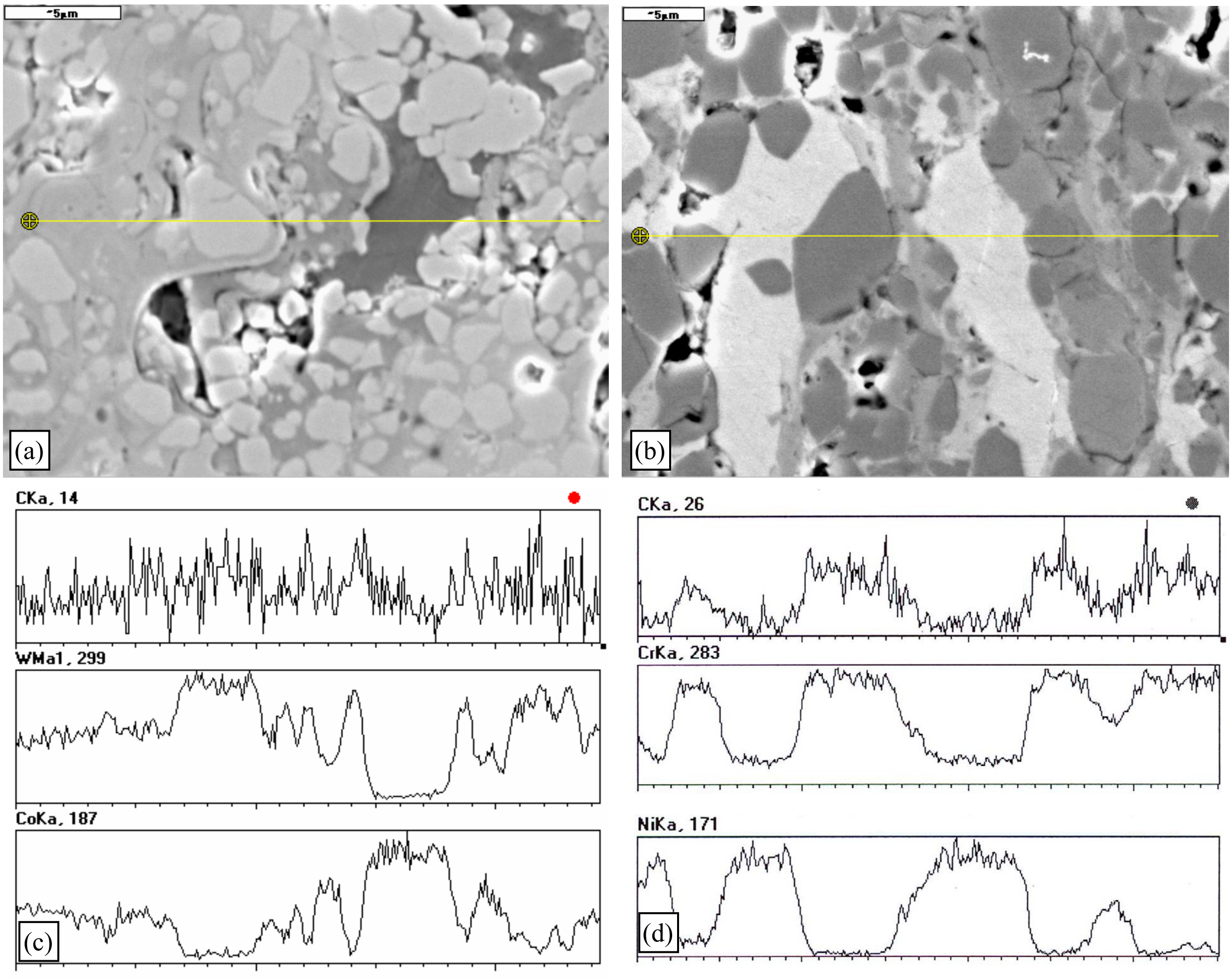

Figure 5. Microstructure and linear analysis of sprayed coatings: (a) and (c) WC17Co and (b) and (d) Cr_3C_2-25%NiCr

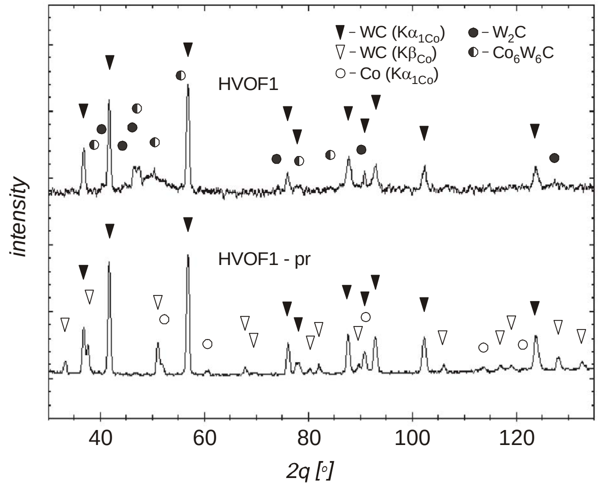

Figure 6. XRD patterns of WC17Co powder and as-sprayed coating

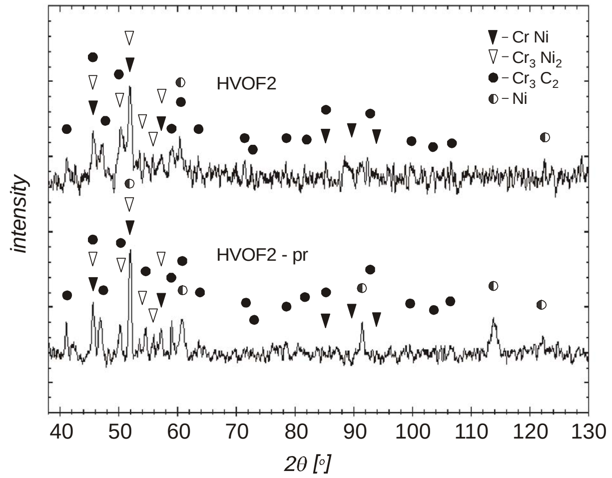

Figure 7. XRD patterns of Cr3C2-25%NiCr powder and as-sprayed coating

powder and the sprayed coating. The sprayed coating contains the same phases; but the metallic phases are characterised by significant deformation indicated by wide differential lines. It is consistent with the previous case. There is also additional occurrence of a very wide pick of diffuse dissipation, which indicates the occurrence of an amorphous phase.

3.1 The coefficient of friction

Figure 8 presents the changes in the coefficient of friction with time for both coatings.

As it is indicated in the two diagrams, a steady course of the coefficient of friction occurs after the first 6 minutes, with a slight growth tendency. The changes of the coefficient of friction for the sprayed WC-Co coating indicate that its value begins to stabilise after 1 h at the level of 0.75. The coefficient of friction changes for the Cr_3C_2-25%NiCr coating reveal much higher oscillations whose amplitude decreases with the duration of the test. The value of the coefficient of friction tends to stabilise after 1 h at the level of 0.85.

3.2 Abrasion resistance of sprayed coatings

The wear of each coating was determined against the function of the abrasive material applied. The results of the research are presented in the Figure 9.

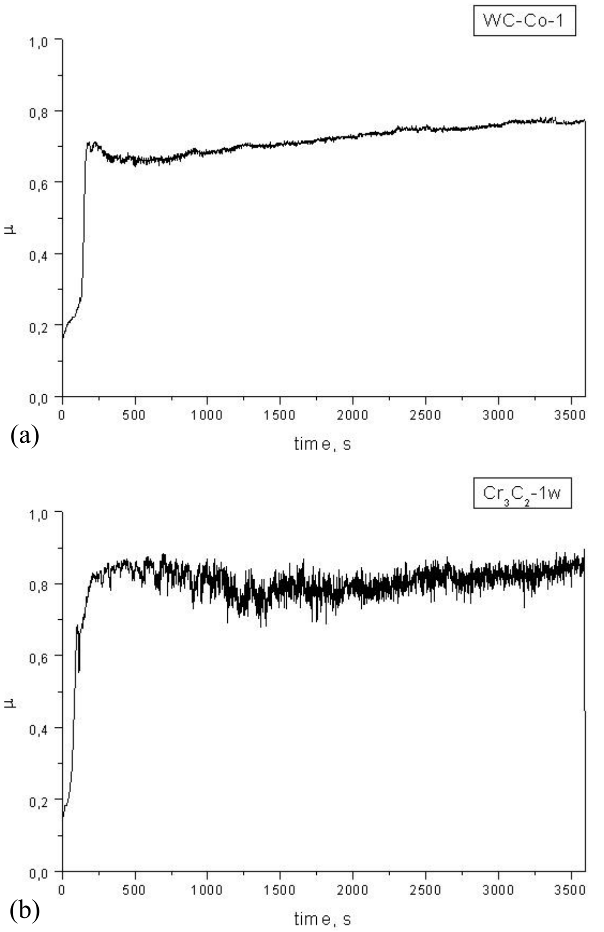

Figure 8. Coefficient of friction for HVOLF sprayed coating: (a) WC17Co and (b) Cr_3C_2-25%NiCr

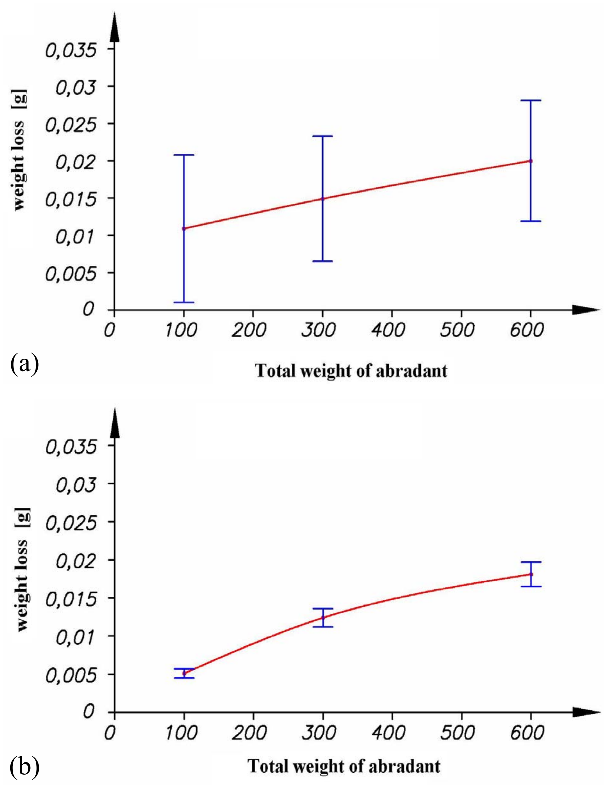

Figure 9. Weight loss for HVOLF sprayed coating: (a) WC17Co and (b) Cr_3C_2-25%NiCr

The research findings indicate that the sprayed WC-Co coating is less abrasion resistant than the sprayed

Cr_3C_2-25%NiCr coating, and the standard deviation of wear is higher for tungsten carbide coating than for chromium carbide coating. WC-Co coatings are harder HV 0.1 = 1218 than Cr_3C_2-25%NiCr coating, whose hardness is HV 0.1 = 945. The analysis of the structure of coatings surfaces and their microstructure reveals that the wolfram carbide coatings are more porous, which facilitates penetration of the surface structure by hard electrocorundum particles. The surfaces analysis of the images of coatings wear also reveals a different mechanism of coatings wear (Fig. 10).

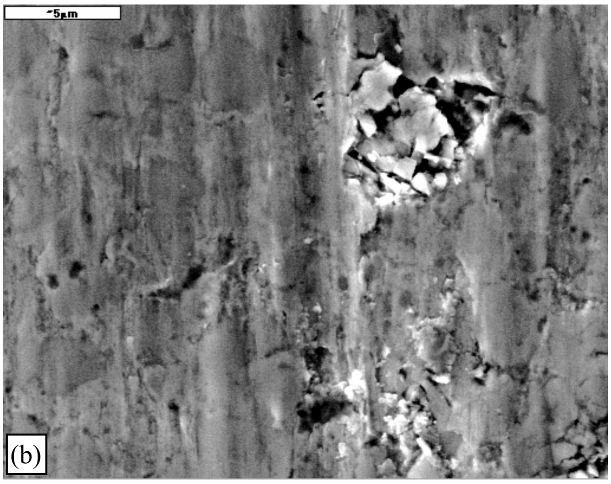

Figure 10. Microstructure of worn surface after abrasion for HVOLF sprayed coating: (a) WC17Co and (b) Cr_3C_2-25%NiCr

The rough worn surface of the WC-Co coating surface reveals traces of the removal of hard carbide grains from the cobalt matrix that had previously been plastically deformed in result of repeated application of abrasive material grains.

The cobalt constitutes a soft phase in comparison with fragile wolfram carbide grains and is more susceptible to plastic deformation. The WC-Co grains are easily removed from the surface of the soft cobalt matrix once it has been removed.

The image of the worn surface of the Cr_3C_2-25%NiCr coating is different. The chromium carbide and the nickel-chromium matrix are micromachined. It is consistent with a more intensive abrasive wear than ridging. Micromachining causes loss of material at the first contact with the abrasive particle. Ridging results mostly in plastic deformation of sprayed particles, and only repeated application of abrasive particles can result in the particle detachment from the coating.

4. CONCLUSION

- HVOLF spraying of algometric and sintered WC-Co and Cr_3C_2-25%NiCr powders produce a coating whose structure consists of undeformed carbide grains imbedded in a matrix.
- The process of supersonic HVOLF spraying does not result in significant changes in the phase composition of the produced WC-Co and Cr_3C_2-25%NiCr coatings.
- HVOLF sprayed WC-Co coatings reveal a steadier course of the coefficient of friction, whose value is lower for the Cr_3C_2-25%NiCr coating.
- HVOLF sprayed WC-Co coatings are less wear resistant than Cr_3C_2-25%NiCr coatings. Still, the mechanism of abrasion wear for the coatings is different. In case of wolfram carbide it is manifested as plastic deformation of the cobalt matrix and removal of hard grains, whereas micromachining was dominant in case of chromium carbide.

REFERENCES

[1] Pawlowski, L.: *The Science and Engineering of Thermal Spray Coatings*, John Willey & Sons, Chichester, 2008.

[2] Flitney, B.: Alternatives to chrome for hydraulic actuators, Sealing Technology, Vol. 2007, No. 10, pp. 8-12, 2007.

[3] Sahraoui, T., Fenineche, N.-E., Montavon, G. and Coddet, C.: Alternative to chromium: characteristics and wear wear behavior of HVOF coatings for gas turbine shafts repair (heavy-duty), Journal of Materials Processing Technology, Vol. 152, No. 1, pp. 43-55, 2004.

[4] Kreye, H.: High velocity flame spraying – process and coating characteristics, in: *Proceedings of 2nd Plasma Technik Symposium*, 05-07.06.1991, Lucerne, pp. 39-47.

[5] Liao, H., Normand, B. and Coddet C.: Influence of coating microstructure on the abrasive wear resistance of WC/Co cermet coatings, Surface and Coatings Technology, Vol. 124, No. 2-3, pp. 235-242, 2000.

[6] Sudaprasert, T., Shipway, P.H. and McCartney, D.G.: Sliding wear behaviour of HVOF sprayed WC–Co coatings deposited with both gas-fuelled and liquid-fuelled systems, Wear, Vol. 255, No. 7-12, pp. 943-949, 2003.

[7] Kong, C.J., Brown, P.D., Horlock, A., Harris, S.J. and McCartney, D.G.: TEM assessment of HVOLF thermally sprayed Al–12 wt.% Sn–1 wt.% Cu alloy, Materials Science and Engineering: A, Vol. 375-377, pp. 595-598, 2004.

[8] Maiti, A.K., Mukhopadhyay, N. and Raman, R.: Effect of adding WC powder to the feedstock of WC–Co–Cr based HVOF coating and its impact on erosion and abrasion resistance, Surface and

Coatings Technology, Vol. 201, No. 18, pp. 7781-7788, 2007.

[9] Żórawski, W., Zdravecka, E., Skrzypek, S. and Trpčevska, J.: Tribological properties of HVOLF coatings, Tribologia, Vol. 36, No. 3, pp. 361-368, 2005 (in Polish).

ТРИБОЛОШКЕ КАРАКТЕРИСТИКЕ КАРБИДНИХ ПРЕВЛАКА НАНЕТИХ ХИПЕРСОНИЧНИМ РАСПРШИВАЊЕМ

Wojciech Żórawski, Stanisław Skrzypek, Jarmila Trpčevska

У раду су представљени резултати испитивања отпорности на абразионо хабање и коефицијената трења две карбидне превлаке нанете хиперсоничним распршивањем прахова WC-Co и Cr_3C_2-25%NiCr. Превлаке су нанете помоћу хиперсоничног спреј система *TAFA JP-5000* ХВОЛФ спреј поступком. Микроструктуре превлака су испитиване помоћу скенирајућег електронског микроскопа са енергодисперзионим спектрометром (СЕМ-ЕДС). Фазни састав превлака је одређиван помоћу ренгенског дифрактометра *Brucker D8 Advance*. За одређивање отпорности на абразионо хабање коришћен је уређај са гуменим точком и сувим абразионим честицама, ознаке Т-01. Коефицијент трења је мерен на трибометру Т-01М, типа „куглица на диску“. Резултати испитивања су показали да хром-карбидна превлака поседује бољу отпорност на абразионо хабање, а да волфрам-карбидна превлака има нижи коефицијент трења.