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High-temperature sliding wear behaviour of thermally sprayed Cr$_3$C$_2$-based coatings

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Abstract

Thermally sprayed Cr$_3$C$_2$-25NiCr coatings are known for their good wear, corrosion and oxidation resistance. Under elevated temperature dry sliding contacts, the coatings are known to form an oxide based tribolayer which significantly decreases the coefficient of friction. Several commercial Cr$_3$C$_2$-based compositions exist that can be seen as alternatives to the conventional Cr$_3$C$_2$-25NiCr composition, e.g. Cr$_3$C$_2$-37WC-18NiCoCrFe and Cr$_3$C$_2$-50NiCrMoNb. These materials can potentially provide improved wear or corrosion protection. However, very limited information about their high temperature performance in sliding contacts can be found. In the current study, four commercial Cr$_3$C$_2$-based powders were used as feedstock materials to spray coatings. All coatings were produced with two spray processes: high velocity oxy-fuel (HVOF) and high velocity air-fuel (HVAF) spraying. The study shows that all coatings exhibit low coefficient of friction against an Al$_2$O$_3$ counterpart (between 0.35 and 0.48), while the Cr$_3$C$_2$-25NiCr coatings provided the lowest wear rate and coefficient of friction. Moreover, the HVAF sprayed Cr$_3$C$_2$-25NiCr provided improved wear resistance at high temperature sliding conditions compared to the HVOF sprayed counterpart. Structural analysis of the coatings revealed extensive carbide precipitation during the high temperature testing and sub-surface cracking of the HVOF sprayed coatings. Similar cracking behaviour was not observed on HVAF sprayed coatings. The coatings formed mainly a smooth and uniform oxide-based tribolayer on the wear surfaces and the collected wear debris consisted of micro- and nanometric crystalline oxide particles.

Keywords: Thermal spraying, sliding wear, Cr$_3$C$_2$, HVOF, HVAF.

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1. INTRODUCTION

Wear of materials is a common problem in many industrial fields causing material loss, which can result in component replacement or need for refurbishment. Many of the wear problems can be controlled by material selection. However, the change of component base material can lead to rapid increase of material costs and bring new challenges, e.g. in the machinability of the material. Surface engineering provides a wide range of techniques that can be used to alter the surface to remarkably improve the component performance [1]. This approach also enables the use of cost-effective materials for the components while improved properties can be provided by modifying only the surface layer. Thermal spraying belongs to the surface engineering techniques and consists of coating processes that can be used to apply thick wear resistant coatings on large surfaces [2]. Feedstock material, typically in powder or wire form, is heated up and accelerated by the spray process. The completely or partially melted particles are projected with high velocity on the component surface where the particles impact and rapidly flatten, solidify and mechanically interlock with the underlying surface. The coating is built-up in layers by continuous impacts of the fine particles until desired coating thickness is achieved, typically in the range of 50-1000 µm. One of the main benefits of thermal spraying is the vast variety of materials, ranging from soft plastics to hard refractory materials, that can be processed to produce functional coatings for numerous environments and applications, e.g. thermal barrier coatings for aviation industry, corrosion resistant coatings for offshore applications, wear resistant coatings for mining industry and corrosion (and oxidation) resistant coatings for power industry [3].

Hardmetal materials consist of hard particles embedded in a ductile metal matrix. In thermal spraying such feedstock materials are most commonly manufactured by agglomeration and sintering processes, which results in spherical and fairly dense particles [4]. The most common compositions of the hardmetals used in
thermal spraying are WC-Co/Ni with optional Cr addition and Cr$_3$C$_2$-25NiCr [5]. The current industrial standard technology to manufacture hardmetal coatings is the high velocity oxy-fuel (HVOF) flame spray process. Good properties of the HVOF coatings are due to the high temperature supersonic gas stream which accelerates the particles to high velocities (500-800 m/s) and produces dense coatings. The combustion takes place between gaseous or liquid fuel and oxygen. Most common fuels are propane, propylene, hydrogen and kerosene. Some of the drawbacks of the HVOF process are related to the deposition rate and overheating of the particles causing carbide dissolution and tensile stresses [6]. One way to control the overheating is to use high velocity air-fuel (HVAF) flame spray process, in which the combustion takes place between gaseous fuel, e.g. propane, propylene or MAPP, and compressed air instead of pure oxygen [7]. This dramatically decreases the flame temperature while producing even higher particle velocities compared to HVOF [8]. As a result, the coatings are even denser and finer particle size distributions can be used to produce coatings with even lower surface roughness. The research on HVAF spraying has been increasing during last years but most of the studies have focused on WC-CoCr materials [9,10]. The information about HVAF Cr$_3$C$_2$-based coatings, on the other hand, is mostly based on the older HVAF torches [11,12]. The early HVAF guns used kerosene and suffered from low particle temperature and deposition efficiency. The ease of operation and the deposition efficiency were significantly improved by later developments of the combustion chamber design allowing effective burning of gaseous fuels [7]. Only recently few publications concerning the modern HVAF process and Cr$_3$C$_2$-based materials have emerged [13,14].

The WC-based coatings are known for their high wear resistance [5]. However, their use at high temperatures (over 500 °C) is limited by the low oxidation resistance of the hard WC particles embedded in the ductile metal matrix [15]. The common Cr$_3$C$_2$-25NiCr composition has lower wear resistance but significantly higher oxidation resistance and it is often used as a wear resistant coating at high temperatures [5]. Several commercial Cr$_3$C$_2$-based powder materials are available, which are designed to provide improved corrosion or wear resistance compared to the standard Cr$_3$C$_2$-25NiCr composition. The corrosion resistance of the Cr$_3$C$_2$-based coatings can be improved closer to that of the metallic materials by increasing the metallic matrix content and by tailoring its composition, e.g. Cr$_3$C$_2$-50NiCrMoNb, while providing also good wear resistance [16]. On the other hand, the wear resistance of typical Cr$_3$C$_2$-25NiCr coatings can be improved by replacing some of the Cr$_3$C$_2$ particles with harder WC particles, e.g. Cr$_3$C$_2$-37WC-18NiCoCrFe [17]. These coating materials have been analysed in our previous study, in which the HVAF sprayed coatings proved to be denser than HVOF sprayed coatings [14]. However, the high temperature sliding behaviour of these alternative coating materials has not been reported and only HVOF sprayed Cr$_3$C$_2$-25NiCr coatings have been studied earlier [18-20]. The material is known to form a Cr$_2$O$_3$ film, i.e. a tribolayer, on the wear surface, which effectively decreases the coefficient of friction [19]. This behaviour has not been studied for the other materials and for HVAF sprayed coatings, which makes it an important topic. Also, the effect of some WC additions on the high temperature sliding behaviour is unknown and should be studied to see if it affects the coating performance. In this work, the high temperature sliding wear behaviour of HVOF and HVAF sprayed novel Cr$_3$C$_2$-based materials was studied and characterisation of the wear tracks was carried out.

2. EXPERIMENTAL

2.1 Coating Materials

Commercial agglomerated and sintered Cr$_3$C$_2$-37WC-18M (M=NiCoCrFe) and Cr$_3$C$_2$-50NiCrMoNb powders were selected as interesting alternatives to conventional Cr$_3$C$_2$-25NiCr. In addition, two powders with the Cr$_3$C$_2$-25NiCr composition were chosen as reference materials. One of the Cr$_3$C$_2$-25NiCr materials was a common agglomerated and sintered powder whereas the other one was plasma densified after the agglomeration and sintering process (marked with (d)). Two particle size distributions were chosen for each of the four powders. Finer particle size (-25+5, -30+5 or -30+10 µm) was used with HVAF spraying and the coarser one (-45+15 or -38+11 µm) for HVOF spraying. The particle size distributions are given as $d_{10}$-$d_{90}$ µm. The details of the powders are listed in Table 1.
### Table 1: Details of the powders, processes and nominal particle size distribution given by manufacturer.

<table>
<thead>
<tr>
<th>Powder composition</th>
<th>Manufacturing process</th>
<th>Spray process</th>
<th>Particle size (µm)</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr₂C₂-50NiCrMoNb</td>
<td>A&amp;S</td>
<td>HVOF</td>
<td>-45+15</td>
<td>H.C. Starck</td>
</tr>
<tr>
<td>Cr₂C₂-50NiCrMoNb</td>
<td>A&amp;S</td>
<td>HVAF</td>
<td>-30+5</td>
<td>H.C. Starck</td>
</tr>
<tr>
<td>Cr₂C₂-25NiCr</td>
<td>A&amp;S</td>
<td>HVOF</td>
<td>-38+11</td>
<td>H.C. Starck</td>
</tr>
<tr>
<td>Cr₂C₂-25NiCr</td>
<td>A&amp;S</td>
<td>HVAF</td>
<td>-30+10</td>
<td>H.C. Starck</td>
</tr>
<tr>
<td>Cr₂C₂-25NiCr (d)</td>
<td>A&amp;S, densified</td>
<td>HVOF</td>
<td>-45+15</td>
<td>Oerlikon Metco</td>
</tr>
<tr>
<td>Cr₂C₂-25NiCr (d)</td>
<td>A&amp;S, densified</td>
<td>HVAF</td>
<td>-30+10</td>
<td>Oerlikon Metco</td>
</tr>
<tr>
<td>Cr₂C₂-37WC-18NiCoCrFe</td>
<td>A&amp;S</td>
<td>HVOF</td>
<td>-45+15</td>
<td>Oerlikon Metco</td>
</tr>
<tr>
<td>Cr₂C₂-37WC-18NiCoCrFe</td>
<td>A&amp;S</td>
<td>HVAF</td>
<td>-30+10</td>
<td>Oerlikon Metco</td>
</tr>
</tbody>
</table>

A&S = Agglomerated and sintered, (d) = densified

### 2.2 Spray Processing

Coatings were produced with commercial HVOF and HVAF guns, DJH2700 (Oerlikon Metco, Wohlen, CH) and M3 (Uniquecoat Technologies LLC, Oilville, US), respectively. The spray parameters are given in Table 2. The flow of process gases in the HVAF process is pressure-controlled and therefore given in bar, while the gas flow rates for HVOF are given in slpm. Coatings were sprayed on 5 mm-thick low carbon steel substrates (S235) measuring 200x50 mm and the substrates were grit-blasted prior to spraying with mesh 36 alumina grit. Long combustion chamber, 4L2 nozzle and injector #1 were used as the M3 hardware and propane as the fuel gas. Target coating thickness was 300 µm.

### Table 2: Spray parameters used in HVAF and HVOF processes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HVOF</th>
<th>HVAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td></td>
<td>240 slpm</td>
</tr>
<tr>
<td>Air</td>
<td>7.4 bar</td>
<td>383 slpm</td>
</tr>
<tr>
<td>Fuel 1</td>
<td>7.0 bar</td>
<td>70 slpm</td>
</tr>
<tr>
<td>Fuel 2</td>
<td>7.3 bar</td>
<td>-</td>
</tr>
<tr>
<td>Spray distance</td>
<td>300 mm</td>
<td>230 mm</td>
</tr>
</tbody>
</table>

### 2.3 High Temperature Sliding Wear

Sliding wear tests were performed with a ball-on-disk configuration on a high temperature tribometer (Anton-Paar Tritec, Peseux, CH). The coated sample disk was induction heated to 700 °C and the temperature was monitored with a thermocouple in contact with the sample. Alumina sphere counterpart with 6 mm diameter was pressed on polished coating surfaces with 10 N normal load. The relative sliding speed was set to 0.10 m/s and wear track radius to 7 mm for a total sliding distance of 5000 m. The coefficient of friction (CoF) was monitored during the test using a load cell. The volume losses of the samples were measured by using an optical confocal profilometer (CHR150, Stil, Aix en Provence, FR) and the ball wear was inspected with an optical microscope. Volume losses were converted to wear rates by normalizing over the sliding distance and normal load.

### 2.4 Characterisation

The surfaces and cross sections of the wear scars were inspected with a field emission gun-scanning electron microscope (FEG-SEM: Nova NanoSEM 450, FEI, Eindhoven, NL). Moreover, Micro-Raman spectroscopy (LabRam, Horiba Jobin-Yvon, Villeneuve D’Ascq, FR) was employed to characterise the structure of the wear debris sticking to the wear tracks and of the oxide scale formed outside the wear track after testing at 700 °C. The laser radiation, having a wavelength of 632.81 nm, was focused onto the samples using a 100x-magnification objective. The microhardness measurements of the as-sprayed coatings from cross sections were carried out with MMT-X7 Vickers microindenter (Matsuzawa, Akita, JP) by using 0.3 kg load to calculate an average hardness value from ten indentations.
3. RESULTS AND DISCUSSION

The microstructures of the feedstock powders and the as-sprayed HVOF and HVAF coatings of the Cr$_3$C$_2$-50NiCrMoNb, Cr$_3$C$_2$-37WC-18NiCoCrFe and the two Cr$_3$C$_2$-25NiCr compositions were studied in our previous work [14]. Small amount of porosity was observed on all coating cross sections. However, the HVAF sprayed coatings proved to be denser compared to the HVOF sprayed coatings in the open circuit potential tests. The results suggested higher density and better cohesion of the HVAF sprayed coatings. The XRD patterns of the sprayed coatings showed similar phase structure as the powders, with Cr$_3$C$_2$ as the main phase. Presence of some Cr$_7$C$_3$ was detected in both alternative materials, Cr$_3$C$_2$-50NiCrMoNb and Cr$_3$C$_2$-37WC-18NiCoCrFe, and in the densified Cr$_3$C$_2$-25NiCr (d).

3.1. Wear Rate and Coefficient of Friction

The same coatings from the previous work were studied for their high temperature sliding wear behaviour. The test results and coating hardness values are summarised in Table 3. Significant differences can be observed between the wear rate results of the coatings. The lowest wear rates were measured for the coatings with the nominal composition of Cr$_3$C$_2$-25NiCr. The HVAF Cr$_3$C$_2$-25NiCr coating experienced the lowest wear rate during the test with 0.68*10$^{-6}$ mm$^3$/Nm). The HVOF Cr$_3$C$_2$-25NiCr and Cr$_3$C$_2$-25NiCr (d) coatings both reached the same wear rate of $\approx$3*10$^{-6}$ mm$^3$/Nm), while higher standard deviation can be observed for the latter. The HVOF Cr$_3$C$_2$-25NiCr (d) coating, on the other hand, experienced the highest wear rate from the group of Cr$_3$C$_2$-25NiCr coatings with 5.9*10$^{-6}$ mm$^3$/Nm due to surface delamination.

The wear rates of both Cr$_3$C$_2$-50NiCrMoNb coatings were significantly higher than those of Cr$_3$C$_2$-25NiCr coatings, reaching $10^5$10$^{-6}$ mm$^3$/Nm). This is attributed to the higher content of the metallic matrix in the coating compared to Cr$_3$C$_2$-25NiCr coatings. However, the wear rates are significantly lower than those measured for iron and nickel based metallic coatings at 700 °C [21]. The measured wear rates for FeNiCrBSi and NiCrFeSiB were approximately 4*10$^{-4}$ mm$^3$/Nm and 8*10$^{-4}$ mm$^3$/Nm, respectively. The wear rates of both HVAF and HVOF Cr$_3$C$_2$-37WC-18NiCoCrFe coatings were comparable with the wear rates of the Cr$_3$C$_2$-50NiCrMoNb coatings.

The measured steady state CoF values are presented in the Table 3. All Cr$_3$C$_2$-25NiCr coatings experienced low CoF values of $\approx$0.35, which is significantly lower than the values measured at room temperature (0.65) [19]. The Cr$_3$C$_2$-50NiCrMoNb coatings experienced slightly higher values of $\approx$0.4, while the HVOF Cr$_3$C$_2$-37WC-18NiCoCrFe coating reached the highest CoF of 0.48. The highest values are in the same range with the iron based metallic coatings tested previously by Boletti et al. [21].

Table 3: Coefficients of friction, wear rates and hardness values of the tested coatings.

<table>
<thead>
<tr>
<th>Powder composition</th>
<th>Spray process</th>
<th>Wear rate [10$^{-6}$ mm$^3$/Nm]</th>
<th>Coefficient of Friction</th>
<th>Hardness (HV$_{0.2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr$_3$C$_2$-50NiCrMoNb</td>
<td>HVOF</td>
<td>24.66 ± 5.07</td>
<td>0.39 ± 0.02</td>
<td>806 (±117)</td>
</tr>
<tr>
<td>Cr$_3$C$_2$-50NiCrMoNb</td>
<td>HVAF</td>
<td>15.73 ± 0.40</td>
<td>0.40 ± 0.01</td>
<td>885 (±58)</td>
</tr>
<tr>
<td>Cr$_3$C$_2$-25NiCr</td>
<td>HVOF</td>
<td>3.13 ± 0.18</td>
<td>0.36 ± 0.01</td>
<td>938 (±79)</td>
</tr>
<tr>
<td>Cr$_3$C$_2$-25NiCr</td>
<td>HVAF</td>
<td>0.68 ± 0.02</td>
<td>0.37 ± 0.06</td>
<td>920 (±51)</td>
</tr>
<tr>
<td>Cr$_3$C$_2$-25NiCr (d)</td>
<td>HVOF</td>
<td>3.20 ± 0.94</td>
<td>0.35 ± 0.01</td>
<td>947 (±144)</td>
</tr>
<tr>
<td>Cr$_3$C$_2$-25NiCr (d)</td>
<td>HVAF</td>
<td>5.86 ± 1.20</td>
<td>0.35 ± 0.01</td>
<td>958 (±69)</td>
</tr>
<tr>
<td>Cr$_3$C$_2$-37WC-18NiCoCrFe</td>
<td>HVOF</td>
<td>23.79 ± 5.86</td>
<td>0.48 ± 0.01</td>
<td>934 (±195)</td>
</tr>
<tr>
<td>Cr$_3$C$_2$-37WC-18NiCoCrFe</td>
<td>HVAF</td>
<td>19.13 ± 4.25</td>
<td>0.40 ± 0.04</td>
<td>1104 (±118)</td>
</tr>
</tbody>
</table>

3.2. Tribolayer and Wear Mechanism

The overall good wear resistance and low CoF values of the HVOF and HVAF sprayed Cr$_3$C$_2$-25NiCr coatings are a result of a tribo-oxidation wear regime shown in Figure 1a. Indeed, a smooth oxide-based tribolayer was formed on the wear track of the conventional Cr$_3$C$_2$-25NiCr coatings. The layer probably forms in the beginning of the test as a result of breaking and smearing of the oxide scale developed on the coating surface. The wear proceeds by a dynamic process, in which the smooth tribolayer breaks out in small
flakes exposing new coating surface to be oxidized. The partial breaking up of the tribolayer can be seen in Figure 1b, where small cracks have formed on the surface and parts of the layer are partially loose. The newly formed wear debris is then removed from the wear track or smeared on the exposed coating surface. The tribolayer is eventually reformed by the combination of smearing of the debris and oxidation of the exposed surface. Smooth smeared areas can be detected in Figure 1c with fine-grained material clusters around the edges. The formation of the smooth oxide layer on the sliding contact is clearly one of the benefits of chromium carbide based coatings compared to metallic coatings. The structure of the metallic coatings is softened and they experience high wear rates [19]. This softened structure does not provide sufficient support for the formation of a uniform oxide layer. The tribolayer and the supporting microstructure underneath protects the coating from the direct contact of the alumina ball. The alumina counterpart did not experience any measurable material loss during the tests. Only some grooving of the ball surface was detected accompanied by the accumulation of wear debris. The collected wear debris from the tested coating surfaces was further analysed with TEM. It can be observed from Figure 2a that the imaged debris cluster consists of fine submicron particles. High resolution image in Figure 2b shows the crystalline structure of the fine particles confirmed by the SAED image in Figure 2c. Dynamic re-crystallisation of these highly deformed and comminuted debris particles is probably due to the high temperature of the system during the sliding wear test.

Figure 1: SEM micrographs of the a) wear track, b) flaking of the tribolayer and c) smearing of the wear debris on the surfaces of the wear scars obtained after ball-on-disk testing at 700 °C on HVOF-sprayed Cr3C2-25NiCr.
Figure 2: TEM images of the wear debris showing a) cluster of debris particles, b) crystalline structure of the fine particles and c) the SAED pattern confirming the crystalline nature of the debris.

The tribolayer formation between the coatings sprayed from the conventional and the densified Cr$_3$C$_2$-25NiCr powders was similar, but analysis of the wear surface shows significant difference in wear mechanism. Both HVOF and HVAF coatings from plasma densified Cr$_3$C$_2$-25NiCr powders were susceptible to large scale delamination of the top surface layer and the tribolayer. The HVOF coating surface in Figure 3a shows large delaminated areas instead of the flaking and small-scale material removal observed in conventional Cr$_3$C$_2$-25NiCr coatings (Figure 1b). More detailed view of the cracking can be seen in Figure 3b. It seems that the tribolayer is not strong enough or strongly enough attached to the underlying coating to withstand the continuous stress cycles.

Figure 3: Cr$_3$C$_2$-25NiCr (d) coating. a) SEM image indicating the delaminated area (red oval) on the wear track and b) more detailed view of the tribolayer delamination.

The Cr$_3$C$_2$-50NiCrMoNb coatings experienced similar wear mechanisms as the coatings with Cr$_3$C$_2$-25NiCr composition. Uniform oxide layers were formed on the wear tracks of both coatings, which enabled the low CoF. However, the steady state CoF values were slightly higher than in the case of the Cr$_3$C$_2$-25NiCr coatings, which might have been caused by different oxide scale composition. Raman spectra were measured to study the compounds present in the oxide scales of the tribolayer and outside the wear track. The results of the analysis are presented in Figure 4 and reveal that the tribolayer of the Cr$_3$C$_2$-50NiCrMoNb coatings indeed composed of Cr$_2$O$_3$ and NiCr$_2$O$_4$ (Figure 4b), while only Cr$_2$O$_3$ was detected in the tribolayer of the conventional compositions (Cr$_3$C$_2$-25NiCr in Figure 4a). This mixed oxide film probably possesses different sliding properties, which is displayed by the slight increase of the CoF compared to the Cr$_3$C$_2$-25NiCr coatings (from 0.35 to 0.40) in Table 3. The Raman spectra include a peak at 790 cm$^{-1}$ that has not been identified. Also, two strong peaks can be observed on the oxide scale spectra that are suspected of belonging to carbon.
The Cr$_3$C$_2$-37WC-18NiCoCrFe coatings exhibit significant degradation of their wear resistance at 700 ℃. The main factor causing the high wear rate is the poor oxidation resistance of the WC particles [19]. At lower temperatures the fine WC particles strengthen the coating structure and provide higher hardness than any of the other tested coatings (Table 3). The wear track of the HVAF coating after the high temperature test in Figure 5a shows protruding oxidised WC particles on the surface while other areas are covered by smooth oxide layer hiding most of the structural details of the wear track surface. It is likely that the higher wear rate of the Cr$_3$C$_2$-37WC-18NiCoCrFe coatings is caused by the fine WC particles as they 1) prevent the formation of uniform tribolayer by protruding from the surface, 2) oxidise and loose their strengthening capability and 3) are more easily removed from the coating surface. The protruding oxidised WC particles demonstrate that the chromium carbides and chromium containing matrix did not protect the WC particles from oxidation, neither did the smearing of the wear debris. The tribolayer on the wear track was proved to consist of WO$_3$ as a result of the direct oxidation of the WC particles and NiWO$_4$ as a result of reaction with the nickel from the metallic matrix (Figure 4c). Even though the extensive oxidation of the WC particles is evident, the high temperature performance and oxidation resistance is remarkably better than those of WC-CoCr or WC-(W,Cr)$_2$C-Ni coatings tested in other studies [22]. This is due to the significantly lower WC content in the currently tested coatings and even distribution of the WC particles within the coating microstructure, seen in Figure 5a. The SEM micrograph in Figure 5b taken from outside the wear track demonstrates the extensive oxidation of the WC particles compared to the Cr$_3$C$_2$ particles and the Cr alloyed matrix. The WC particles grow thick oxide clusters while rest of the coating structure forms a layer of fine oxides. The WC particles evidently loose most of their strengthening capability, but on the other hand, they do not cause catastrophic failure of the coating either.

3.3. Effect of the Spray Process

The results in Sections 3.1. and 3.2. demonstrated the observed differences in performance between the three coating material compositions: Cr$_3$C$_2$-25NiCr, Cr$_3$C$_2$-50NiCrMoNb and Cr$_3$C$_2$-37WC-18NiCoCr. The effect of the spray process was small in the case of the two alternative compositions but the measured difference in the wear rate is marginally in favour of the HVAF sprayed coatings. However, more pronounced difference
was observed in the case of the conventional Cr$_3$C$_2$-25NiCr and significant improvement of wear resistance was measured. One reason for this could be the subsurface cracking of HVOF sprayed Cr$_3$C$_2$-25NiCr and Cr$_3$C$_2$-50NiCrMoNb coatings during the test. This cracking of the top layer of the HVOF Cr$_3$C$_2$-25NiCr coating is evident in Figure 6b. The cracks observed in the structure are probably formed by fatigue fracture caused by the continuous loading cycles during the wear test. Such subsurface cracking probably promotes the removal of the tribolayer. When compared to the HVAF Cr$_3$C$_2$-25NiCr coating with the lowest wear rate, it seems that the uniformity and cohesion of the underlying coating surface plays an important role in the observed behaviour. The HVAF sprayed coatings proved to maintain the dense structure without similar cracking behaviour. This enabled the formation of the thick oxide-based tribolayer seen in Figure 6a. Extensive carbide precipitation can be observed in the microstructure of both coatings indicating substantial carbon content of the metallic matrix in the as-sprayed state. During the high temperature testing the carbon starts to form fine carbide precipitates with chromium [23]. This behaviour demonstrates that extensive particle melting has taken place during the spraying with both processes.

![Figure 6: SEM micrograph of the wear track cross section of a) HVAF and b) HVOF sprayed Cr$_3$C$_2$-25NiCr coatings.](image)

4. CONCLUSIONS

Various Cr$_3$C$_2$-based coatings were produced with HVOF and HVAF high kinetic thermal spray processes: Cr$_3$C$_2$-25NiCr, Cr$_3$C$_2$-50NiCrMoNb and Cr$_3$C$_2$-37WC-18NiCoCr. The sliding wear behaviour was tested at 700 °C by tribometer with ball-on-disk configuration. Alumina ball was used as the counterpart. Following conclusions were made from the presented results:

- Low coefficients of friction were achieved for all the tested coatings as a result of the formation of oxide based tribolayers on the wear tracks. Lowest values of 0.35 were measured for Cr$_3$C$_2$-25NiCr coatings.
- The tribolayers of Cr$_3$C$_2$-25NiCr coatings consisted of Cr$_2$O$_3$ while the tribolayer on Cr$_3$C$_2$-50NiCrMoNb coatings contained also NiCr$_2$O$_4$. The coatings containing WC formed a tribolayer of WO$_3$ and NiWO$_4$.
- Lowest wear rate was measured for the HVAF sprayed Cr$_3$C$_2$-25NiCr coating. Cr$_3$C$_2$-50NiCrMoNb coatings, on the other hand, experienced higher wear rate due to higher matrix content and Cr$_3$C$_2$-37WC-18NiCoCr coatings suffered from the rapid oxidation of WC particles preventing the formation of a uniform tribolayer.
- Subsurface cracking took place in HVOF sprayed coatings of Cr$_3$C$_2$-25NiCr and Cr$_3$C$_2$-50NiCrMoNb during the high temperature sliding tests. The HVAF sprayed counterparts did not show the same behaviour, which is beneficial for maintaining the tribolayer intact and decreasing the wear rate.

5. ACKNOWLEDGEMENTS

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6. REFERENCES


