SLIDING FRICTION BEHAVIOR OF HVOF SPRAYED HARDMETAL COATINGS UNDER DIFFERENT LOAD CONDITIONS

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Abstract

The HVOF sprayed hardmetal coatings, thanks to the combination of hard particles and tough matrix, show superior behavior in applications requiring the wear resistance. Among other types of wear, sliding friction and wear behavior is one of the most common. In dependence on application, the working conditions varied in terms of load, velocity, temperature, lubrication etc. In the paper, the influence of load condition on the sliding friction and wear behavior of the WC-based and CrC-based HVOF sprayed hardmetal coating was studied using four different friction and wear tests: ASTM G 99 (Pin-on-disc test), ASTM G 77 (Block –on-ring test), ASTM D5707 (SVR test) and high loaded friction wear test (Pin-on-cylinder test). Several types of lubricants were used to compare the dry and lubricated sliding friction and to study the lubricants influence of the coefficient of friction and wear of selected coatings with respect to the load conditions. Based on the results, the suitability of the WC-based and CrC-based coatings for different application in dependence on working conditions is discussed.

Key words: HVOF, coating, wear, sliding, friction, pin on disc, block on ring, SVR test, pin on cylinder, WC-based coatings, CrC-based coatings

1. EXPERIMENTAL

1.1 Coatings

The 5 commercially available materials for hardmetal coatings were chosen and sprayed by HP/HVOF JP-5000® (TAFA) spraying technology in the VZÚ Plzeň s.r.o., using the standard preparation procedure on the grit blasted substrate of carbon steel (ČSN 11 523) and the previously optimized spraying parameters: Cr3C2-25%NiCr (Amperit 588), Cr3C2-35%NiCr (Amperit 587), Cr3C2-25%CoNiCrAlY (Amperit 594.074), WC-17%Co (FST 674.23) and WC-20%CrC-7%Ni (Amperit 551.074). The WC-17%Co coating is highly wear resistant, the Co content increases its toughness. It is oxidation resistant up to 480° C. The WC-20%CrC-7%Ni coatings offer the combination of both types of carbides. At elevated temperatures it creates the very thin and compact oxidation layer, resulting to coatings oxidation and corrosion resistance up to 750 °C. The CrC-based coatings, thanks to the Cr content, are suitable for high-temperature applications (up to 850°C). The oxidation layer Cr2O3 originating on its surface has also very good frictional properties- low coefficient of friction and high adhesion to the coating. The amount and material of the matrix increase the coatings toughness (35% NiCr) and oxidation resistance (25%CoNiCrAlY) to 1000°C. The resistance to the high temperature and oxidation behavior of coatings were studied in detail previously [1-3]. The coatings microstructures are shown in Fig. 1. From the SEM micrographs the very low porosity and good substrate bonding can be seen as well as the uniform carbides distribution in the matrix. The WC-based and CrC-based coatings phase composition is well described [4-6]. The measured coatings basic mechanical properties are summarized in the Table 1.
Table 1. Coatings mechanical properties

<table>
<thead>
<tr>
<th>Coating</th>
<th>HR15N</th>
<th>HV0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC-17%Co</td>
<td>90.0 ± 0.3</td>
<td>1335 ± 156</td>
</tr>
<tr>
<td>WC-20%CrC-7%Ni</td>
<td>87.0 ± 0.9</td>
<td>829 ± 112</td>
</tr>
<tr>
<td>Cr₃C₂-25%NiCr</td>
<td>84.0 ± 0.5</td>
<td>700 ± 110</td>
</tr>
<tr>
<td>Cr₃C₂-35%NiCr</td>
<td>82.4 ± 0.9</td>
<td>811 ± 33</td>
</tr>
<tr>
<td>Cr₃C₂-25%CoNiCrAlY</td>
<td>85.3 ± 0.9</td>
<td>848 ± 30</td>
</tr>
</tbody>
</table>

1.2 Testing methodology

All the coatings were tested by Pin-on-disc method according to ASTM G-99 at dry and lubricated conditions and at dry conditions with elevated (350°C) temperature, and by Block-on-ring test according to ASTM G-77 at lubricated conditions. The WC-20%CrC-7%Ni and Cr₃C₂-25%CoNiCrAlY coatings were further tested by SVR test according to ASTM D5707 and high loaded Pin-on-cylinder test.

The Pin-on-disc test was realized in the New Technology Research Centre of University of West Bohemia in Plzeň (NTC ZČU), applying ASTM G-99 [7], using the High Temperature Tribometer produced by CSM Instruments SA. The test was performed on the polished coating surface of the roughness Ra 0.07 ± 0.01 for CrC-based and 0.04 ± 0.02 for WC-based coatings. Based on the results of previous studies [8], uniform parameters for all measurements were selected: Al₂O₃ and ČSN 14 109 steel counterpart with Ø 6 mm, Pin load: 10 N, Sliding speed: 0.1 m/s, Number of cycles: 50 000, Wear track diagonal: 2, 3.5 and 5 mm, Temperature: 20°C, 350°C, Lubrication: dry, MOGUL GX X 15W-40, Panolin STREET BIO RACE 4T 10W50. The used Pin-on-disc methodology was described in detail in [9].

The block on disc test was realized in VZÚ Plzeň s.r.o., applying the ASTM G-77 [10], using the home-made testing equipment VRS-3. The coatings were prior grinded by diamond grinding wheel to roughness Ra 0.2. The used test parameters were: ČSN 15 320 steel counterpart, Nominal load: 2.5 MPa, Supply of lubricant: 0.016 dm³/h, Total sliding distance: 250 km, Temperature: 20°C, Lubrication: MOGUL GX 15W-40, Panolin Street Bio Race 4T 10W50, Biodiesel 1 and Biodiesel 2. The lubricants Biodiesel 1 and Biodiesel 2 are new
biodegradable lubricants for 2-stroke diesel engines, developed in KRAFFT (Sp) in the range of project EUREKA E!4504 EQUIMOTOR PLUS [11]. The used Block-on-ring methodology was described in detail in [12,13].

The SVR test according to ASTM D5707 [14] were realized in the KRAFT (Sp) company. The test is intended for evaluation of friction properties of lubricants by high-frequency oscillation movement. The parameters used were as follows: Counterpart: steel, Load: 200N, Stroke: 1 mm, Frequency: 50 Hz, Total time of the test: 2 h, Temperature: 50°C and 80°C, Lubrication: semi-inorganic engine oil 10W-40, inorganic engine oil 5W-30, Biodiesel 1, Biodiesel 2.

The Pin-on-cylinder test was realized in the VCSVT ČVÚT in Praha, using the Amsler A135/275 equipment. The test parameters were as follows: Load: 2 150 N for the first test, than it was decreased to 520-600 N, rotation speed: 193 min⁻¹. The time to coatings wear through, characterized by sudden change of coefficient of friction, was measured and used as a criterion of coatings durability.

2. RESULTS AND DISCUSSION

2.1 Pin-on-Disc Test

The results of Pin-on-Disc test for all measured coatings are summarized in the Figure 2 for Al₂O₃ (a) and steel (b) counterpart. The evolution of CoF in dependence on the number of cycles (sliding distance) is shown in the Figure 3 for Cr₃C₂-25%CoNiCrAlY coating.

![Fig. 2. Coatings average CoF for a) Al₂O₃ counterpart and b) steel counterpart](image)

From the graphs in Fig. 2 it can be said, that the lubrication decrease the CoF of all coatings more then 5-times, regardless the counterpart or type of lubricant. It is also obvious, that in dry friction at elevated temperature and with Al₂O₃ counterpart, the CoF of CrC-based coatings decrease while the CoF of WC-based coatings increase. With steel counterpart the situation is more complicated. The material from the steel counterpart transferred to the coatings surface plays its role. Based on the data measured by Pin-on-disc test it can be concluded, that in dry friction at room temperature and Al₂O₃ counterpart it is favourable to use WC-based coatings, while at the same condition in the contact with steel the CrC-based coatings. Even if their CoF is higher in the running period (which increases the average value of CoF), after creation of oxidic tribofilm it decrease significantly. At elevated temperatures, the higher amount of oxidation can be expected. It manifests in the contact with Al₂O₃ by improved or at least non-deteriorated behaviour of CrC-based coatings, while the WC-based coatings friction properties deteriorate due to the oxidic film with unfavourable properties. In the contact with steel the CoF value are more or less similar for all measured coatings. It can be expected, that the steel material from the counterpart is transferred onto the surface of harder coating, where it participates on the creation of tribofilm. The measured value of CoF is the result of
contact between steel and tribofilm, and with a small scatter it corresponds to 0.6. The differences between results measured at lubricated conditions are very small, probably due to low used load (10 N). The thin film of lubricant separates the friction surfaces. The measured values of CoF than corresponds to a hydrodynamic friction. Nevertheless, some effects can be recognized even in this condition. Using Al₂O₃ as a counterpart, the lubrication with MOGUL 15W-40 led to the lower CoF values at CrC-based compare to WC-based coatings, while the lubrication with Panolin Bio Race led to the opposite rank. Using the steel counterpart, no effect of different types of lubricant was observed.

2.2 Block-on-Ring Test

The results of Block-on-Ring Test are summarized in the Figure 4. The CoF development in dependence on the sliding distance of Cr₃C₂-25%NiCrAlY is shown in the Figure 5.

Based on the Block-on-Ring test results, the profitability of coatings cannot be judged according to their belonging to a group of CrC or WC based coatings. In the average, the highest CoF values were measured for WC-20%CrC-7%Ni coating, followed by Cr₃C₂-35%NiCr coating. On the contrary, the lowest CoF values were recorded for Cr₃C₂-25%NiCr and Cr₃C₂-25%CoNiCrAlY coatings. Nevertheless, CrC-based coatings showed the tendency to decrease CoF with increasing sliding distance. For friction couples steel-WC-based coatings it showed to be more advantageous to use MOGUL 15W-40 lubricant, while for steel-CrC-based coatings couples the Panolin Bio Race lubricant. The values obtained by using the newly developed biodegradable lubricants are comparable with the results of Panolin Bio Race.
From the volume of wear point of view, the harder WC-based coatings are better. From the group of CrC-based coatings, the Cr$_3$C$_2$-25%CoNiCrAlY coating is the best, while Cr$_3$C$_2$-35%CrNi coating, due to the highest volume of soft matrix, showed the highest wear. The influence of different types of lubricants on the volume of worn coatings material is the most significant effect of the performed experiment. From commercially available lubricants, the Panolin Bio Race decrease the wear more distinctively, from experimental oils the Biodiesel 1 is better. With exception of WC-20%CrC-7%Ni, the Biodiesel 1 causes the lowest wear of all measured coatings.

2.3 Pin-on-Cylinder test

The Pin-on-Cylinder test was realized only on two types of coatings: WC-20%CrC-7%Ni and Cr$_3$C$_2$-25%CoNiCrAlY. Based on the result it can be concluded, that the variation of lubricants did not influence the measured values of CoF. Some differences can be observed in the lifetime of the coatings. The Cr$_3$C$_2$-25%CoNiCrAlY showed higher resistance in the majority of tests, compared to WC-20%CrC-7%Ni coating. In pin-on-cylinder test, the Biodiesel 2 increased the lifetime of the coating the most. The coatings failure in this case was caused not by wear through, but by its delamination.

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Dry</th>
<th>MOGUL 15W-40</th>
<th>Panolin Bio Race</th>
<th>Biodiesel 1</th>
<th>Biodiesel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load [N]</td>
<td>2 150</td>
<td>550</td>
<td>580</td>
<td>570</td>
<td>570</td>
</tr>
<tr>
<td>Total time [s]</td>
<td>300</td>
<td>1 000</td>
<td>1 000</td>
<td>1 000</td>
<td>1 500</td>
</tr>
<tr>
<td>Coating lifetime [s]</td>
<td>1</td>
<td>300</td>
<td>100</td>
<td>250</td>
<td>430</td>
</tr>
<tr>
<td>CoF</td>
<td>Not measured</td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 2. Pin-on-Cylinder test results of WC-20%CrC-7%Ni

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Dry</th>
<th>MOGUL 15W-40</th>
<th>Panolin Bio Race</th>
<th>Biodiesel 1</th>
<th>Biodiesel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load [N]</td>
<td>520</td>
<td>590</td>
<td>565</td>
<td>600</td>
<td>570</td>
</tr>
<tr>
<td>Total time [s]</td>
<td>280</td>
<td>1 000</td>
<td>1 000</td>
<td>1 000</td>
<td>1 000</td>
</tr>
<tr>
<td>Coating lifetime [s]</td>
<td>250</td>
<td>170</td>
<td>200</td>
<td>130</td>
<td>300</td>
</tr>
<tr>
<td>CoF</td>
<td>1.2</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 3. Pin-on-Cylinder test results of Cr$_3$C$_2$-25%CoNiCrAlY

2.4 SVR test

Also in the case of SVR test, the influence of various lubricants on the CoF is minimal. The CoF of both coatings are around 0.15. The average CoF values are summarized in the Table 4. The CoF of Cr$_3$C$_2$-25%CoNiCrAlY are slightly higher compare to WC-20%CrC-7%Ni.

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>10W-40</th>
<th>5W-30</th>
<th>Biodiesel 1</th>
<th>Biodiesel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr$_3$C$_2$-25%CoNiCrAlY</td>
<td>0.159</td>
<td>0.157</td>
<td>0.163</td>
<td>0.150</td>
</tr>
<tr>
<td>WC-20%CrC-7%Ni</td>
<td>0.159</td>
<td>0.150</td>
<td>0.158</td>
<td>0.144</td>
</tr>
</tbody>
</table>

Table 4. SVR test results
3. CONCLUSIONS

Based on the results of realized tests, the Cr$_3$C$_2$-25%CoNiCrAlY can be recommended for piston ring application. The Cr$_3$C$_2$-25%CoNiCrAlY coating dispose of beneficial properties of CrC carbides and matrix material, which is harder and more wear resistant compare to NiCr matrix of other two CrC-based coatings. The elevated temperature in the engine prefer the CrC-based coatings, and Cr$_3$C$_2$-25%CoNiCrAlY coating showed stable friction behavior combined with low wear. For other applications, where coatings underlay higher loads, it is necessary to weigh the preference and working conditions. At higher loads, the CrC-based coatings are handicapped by lower wear resistance. In comparison with WC-based coatings, their higher wear can lead to change of friction mechanism from adhesive to abrasive one, increase the CoF value and wear of counterpart. If the working condition does not include the temperature elevated higher than 200°C, it is better to apply the WC-based coatings. From two tested WC-based coatings, the WC-Co coating showed better behavior. The expectation of improvement of friction properties by presence of CrC carbides in WC-CrC-Ni coating was not fulfilled.

LITERATURE


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