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Wear

2018, vol. 412-413, October 2018, pp. 49-59

ISSN: 0043-1648

DOI: <https://doi.org/10.1016/j.wear.2018.05.016>

Accepted manuscript

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<https://doi.org/10.1016/j.wear.2018.05.016>

Final version available from

<https://www.sciencedirect.com/science/article/pii/S0043164818303193>

Author's Accepted Manuscript

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www.elsevier.com/locate/wear

PII: S0043-1648(18)30319-3
DOI: <https://doi.org/10.1016/j.wear.2018.05.016>
Reference: WEA102427

To appear in: *Wear*

Received date: 8 March 2018
Revised date: 22 May 2018
Accepted date: 25 May 2018

Cite this article as: Serhii Tkachenko, Karel Dvořák, David Jech, Karel Slámečka, Lenka Klakurkova, David Paloušek and Ladislav Čelko, Wear of grinding rotors with thermally-sprayed coatings in a high-speed mill, *Wear*, <https://doi.org/10.1016/j.wear.2018.05.016>

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Wear of grinding rotors with thermally-sprayed coatings in a high-speed mill

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Abstract

In this paper, the erosion behavior of three types of protective thermally-sprayed coatings and non-coated substrate steel was investigated under semi-industrial test conditions using a laboratory high-speed pin mill DESI-11. The grinding in the mill was performed by two counter rotors, on which protective coatings were deposited either by atmospheric plasma spraying (APS) ($\text{Cr}_3\text{C}_2\text{-NiCr}$ and NiCrBSi coatings) or by high velocity oxy-fuel (HVOF) process (WC-CoCr coating). The grinding rotors with deposited coatings were used for milling of the Portland cement, and rotors' weight loss was monitored after milling of 1, 3, 5, 10, and 15 kg of this material. The lowest weight loss in the mixed impact erosion conditions was exhibited by WC-CoCr coating, which was followed by $\text{Cr}_3\text{C}_2\text{-NiCr}$ and NiCrBSi coatings. The greatest material removal on the anterior and the right lateral faces of rotor pins was

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a result of erosion damage at high impact angles through surface fatigue wear and the following failure of protective coatings down to the substrate. In contrast, the top and the left lateral faces of the pins were subjected mostly to the ploughing and microcutting at oblique impact angles that resulted in significant erosive damage only if hardness of the pin was lower than that of the Portland cement (Cr_3C_2 -NiCr-coated and non-coated steel pins). The study also found a significant disproportion between the volumetric wear losses of various rows of pins of grinding rotors. The central part of the grinding tool consisting of two counter rotors (both rows of 2-row rotor and a middle row of 3-row rotor) suffered more intensive erosion wear than the external part (outer rows of 3-row rotor). The design of the mill and the resulting variability in parameters of milled powder particles at different sites of the grinding tool (such as particle size, particle flux and particle velocity) were considered as main reasons of this phenomena.

Keywords:

high-speed milling, solid particle erosion, thermal spray coatings, surface morphology

1. Introduction

Milling by collision is one of the most widely spread methods of refining of various powder feedstock (like minerals, ceramics and intermetallics) used for powder technologies. It is typically performed in high-speed milling equipment, so-called “high-speed disintegrators” [1]. Milling occurs as a result of collisions of treated material particles with grinding elements, such as pins or blades of grinding rotors, when a large stresses generated during a large

8 number of high-frequency collisions lead to fracture of material. Besides the
9 particle refinement, the treated material is also subjected to mechanochem-
10 ical activation. This phenomenon can be explained as the change in the
11 reactivity and physico-chemical properties of the final powder product re-
12 sulting from its bulk and surface structural changes under the influence of
13 mechanical energy supplied by milling [2–5]. Both milling and mechanical
14 activation are considered promising technologies for the enhancement of the
15 reactivity of blended Portland cement constituents (*e.g.*, fly ash) [6–8], and
16 is often used also commercially (Fig. 1). Due to the enhanced reactivity, the
17 resulting cement exhibits improved strength and setting properties. How-
18 ever, a serious problem associated with the use of high-speed disintegrators
19 for fine grinding of construction materials is considerable wear of the working
20 parts of grinding rotors because of erosive action of processed highly-abrasive
21 powders. Wear of working parts leads to a significant reduction in the grind-
22 ing efficiency of milled materials [9], as well as to the additional expenses for
23 equipment repairs.

24 An attractive cost-effective solution is the application of protective thermally-
25 sprayed wear-resistant coatings, which have already shown their high effec-
26 tiveness in reducing abrasive/erosive wear in various industrial applications
27 [10–13]. Moreover, the excellent wear resistance of thermally-sprayed hard-
28 metal coatings (based on tungsten or chromium carbide) has been confirmed
29 by some previous laboratory studies in solid particle erosion tests performed
30 under fixed experimental parameters (particle size, particles' velocities, im-
31 pact angle) [14–18]. However, real milling situations in high-speed mills
32 represent a complex impact erosion phenomena, where material loss of work-

Figure 1: Industrial high-speed disintegrator DESI-18 used for fine grinding of fly ash (courtesy Dastit Technology).

ing parts occurs as a result of combined action of microcutting, ploughing, brittle fracture and fatigue wear mechanisms. In this context, semi-industrial wear evaluation of thermally-sprayed coatings is needed in addition to laboratory model tests, however, it is scarcely reported in the available literature [14, 19].

In the present study, the evaluation of erosion resistance of several types of protective thermally-sprayed coatings in a laboratory high-speed disintegrator was performed, using the Portland cement as an abrasive medium. The studied protective coatings belonged to three materials groups, i.e. (i) chromium carbide (Cr_3C_2) nickel-based hardmetal coating, (ii) the coating based on self-fluxing NiCrSiB alloy, and (iii) tungsten carbide (WC) cobalt-

based hardmetal coating. These materials are frequently used to improve the resistance to sliding, abrasive and erosive wear in various high-temperature applications (such as gas and steam turbines, aircraft engine parts) [20, 21] as well as in aggressive environments involving medium temperatures, abrasion, erosion and corrosion [11, 22, 23]. Since high impact erosion resistance of these coatings has been mainly proved in model experiments under fixed conditions [14, 18, 24–26], the evaluation of their real application performance is therefore of the high importance. Used disintegrator DESI-11 (Desintegrator Tootmise OÜ, Republic of Estonia) represents a commercial solution developed for grinding and mechanical activation of different dry powdered materials with the hardness by Mohs up to 6 (~ 700 HV) in laboratory and small-industry scales. Portland cement was of interest to the present study because it is well-described and extensively used building binder material among, whose mechanical activation by high-energy milling brings obvious benefits, such as an improvement of the mechanical properties due to mechanical activation of the cement particles and the generation of a favorable particle size distribution [6, 27]. Furthermore, Portland cement is abrasive enough due to its hardness between 5-6 according to the Mohs scale [28] and it also has relatively homogeneous component distribution. Therefore, the employed grinding equipment and chosen abrasive powder allow to estimate the performance of used protective coatings under semi-industrial milling conditions. Another subject of this study was the analysis of the wear mechanisms acting on the working parts of grinding rotors, as well as the intensity and uniformity of wear of these parts, which was mostly behind the research scope of up-to-date research literature on the topic except for few attempts

69 [14, 19].

70 2. Experimental

71 2.1. Fabrication of thermally-sprayed coatings

72 Initial powders used for the preparation of powder mixtures suitable
 73 for thermal spraying were commercially available powders (i) $\text{Cr}_3\text{C}_2\text{-NiCr}$
 74 (Praxair 1375VM/CRC-300-1, $-53+16\ \mu\text{m}$), (ii) NiCrBSi (Hoganas 1660-02,
 75 $-53+20\ \mu\text{m}$), and (iii) WC-CoCr (GTV 80.76.1, $-45+15\ \mu\text{m}$). The nominal
 76 composition of the $\text{Cr}_3\text{C}_2\text{-NiCr}$ powder was 20 Cr, 20 C, Ni balance (wt%).
 77 The NiCrBSi alloy powder contained Cr 14.8, Fe 3.7, B 3.1, Si 4.3, C 0.75,
 78 Ni balance (wt%). The nominal composition of the WC-CoCr hardmetal
 79 powder was Co 10, C 5.4, Cr 4 and W balance (wt%).

80 The $\text{Cr}_3\text{C}_2\text{-NiCr}$ and NiCrBSi coatings were prepared from as-received
 81 powder feedstock by means of atmospheric plasma spraying (APS) using
 82 F4MB-XL gun (Oerlicon Metco, Switzerland). WC-CoCr coating was de-
 83 posited via the high-velocity oxygen fuel (HVOF) process using the GLC5
 84 gun (GTV, Germany). The spraying parameters are summarised in Table 1.
 85 For both processes, the industrial 6-axes robot (IRB2600; ABB, Switzerland)
 86 was employed for precise and reproducible deposition. The substrates were
 87 grinding rotors for a high-speed mill (shown in Fig. 2a-b and described in
 88 detail in the following section) made of the medium carbon steel C45. For
 89 each material, a pair of grinding rotors with two rows and three rows of pins
 90 were used. Prior to spraying, all rotors were grit-blasted using pure alumina
 91 angular particles with the size of about 1 mm. Grit-blasting was conducted
 92 at a pressure of 5 atm, using a blasting distance of 100 mm and an incidence

angle of 90° . After blasting, the rotors were cleaned in an ultrasonic bath for 10 min and subsequently dried with compressed air. During spraying, rotation of the coated rotors was ensured by a turning machine at a constant speed of 1100 rpm. The deposition process was performed until the desired coating thickness of $220 \pm 30 \mu\text{m}$ was reached.

Table 1: Deposition parameters of the coatings studied.

Coating designation	Process	Gas supply (slpm)	Current (A)	Spray distance (mm)
$\text{Cr}_3\text{C}_2\text{-NiCr}$	APS	Ar - 65; H_2 - 3	600	130
NiCrBSi	APS	Ar - 57; H_2 - 5	560	150
WC-CoCr	HVOF	O_2 - 200; C_2H_4 - 60	-	200

2.2. Wear testing

Dry erosion testing has been performed in a laboratory high-speed mill (DESI-11; Desintegraator Tootmise OÜ, Republic of Estonia) (Fig. 2a), in which milling of grindable material was accomplished by a pair of counter-rotating grinding rotors (designed and manufactured by FF servis company, Czech Republic) (Fig. 2b). Both rotors were made of the medium carbon steel C45 and had the external diameter of 147 mm. This steel grade was chosen due to its moderate hardness ($\sim 270\text{-}280 \text{ HV}$) with the aim of facilitating the evaluation of wear of milling rotor substrates as compared to the wear of harder protective coatings. According to the scheme shown in Fig. 2c, the left rotor has two rows of pins on a ring-shaped base, while the right rotor has three rows that form concentric circles of various diameters relative to each other. The pins have rectangular shape with dimensions of $2.5 \times 3 \times 3 \text{ mm}$. During milling, the grindable material is delivered to the

112 grinding chamber through the middle of the two-row rotor by a continuous
 113 feeder, collides with the first row of pins of 2-row rotor and disintegrates while
 114 successively passing through posterior rows of pins (Fig. 2c). For compar-
 115 ison with the studied protective coatings, a pair of non-coated 2-row/3-row
 116 rotors made of C45 steel was adopted as a reference sample. The rotors'
 117 rotation frequency used in the experiment was 12000 rpm, which resulted
 118 in the maximum impact speed of 92.4 m/s. The abrasant used for erosion
 119 testing was the Portland cement with the particle size being in the range of
 120 1-48 μm (Fig. 3). The typical chemical composition of this material can be
 121 found elsewhere [29]. Weight loss due to erosion was determined as a ratio
 122 between the weight of the eroded rotors after the milling of 1, 3, 5, 10 and
 123 15 kg of abrasant and the initial weight of the rotors. An accuracy of 0.01
 124 mg was achieved for the weight loss measurements.

Figure 2: (a) General appearance of the high-speed mill DESI-11, (b) a pair of grinding rotors, and (c) the principal scheme of milling process.

125 The evaluation of volumetric wear of individual rows of rotor pins was
 126 performed using 3D optical scanner (ATOS Triple Scan; GOM, Germany)

Figure 3: SEM appearance of Portland cement particles used for erosion testing.

127 equipped with a two-axis rotary table. The evaluation process included (i)
 128 3D digitization of the as-received surfaces of grinding rotors prior to wear
 129 testing, (ii) 3D digitization of the abraded surfaces of the grinding rotors
 130 after wear testing, and (iii) the comparison of the two measurements using
 131 the a specialized software. The measurements were done with MV170 lenses
 132 ($170 \times 130 \times 130$ mm) calibrated in a small objects arrangement. The mea-
 133 suring point distance was 0.055 mm (*i.e.*, 18 points/mm), the recommended
 134 reference points diameter was 0.8 mm, the measuring distance was 490 mm,
 135 the camera angle was 28° , the focal length of camera lenses was 40 mm, and
 136 the focal length of projector lens was 60 mm. The final evaluation of digi-
 137 tized profiles of rotor surfaces was performed in the analysis software (ATOS
 138 Professional; GOM, Germany), by means of which the relative volume loss
 139 of each rotor pin row was calculated as a ratio of its volume change resulted
 140 from erosion testing and its initial volume before wear test (Fig. 4).

Figure 4: Superposition of initial and worn rotor profiles using 3D optical scanner.

141 2.3. Microstructural characterization and evaluation of mechanical properties

142 The microstructure of as-received coatings and eroded surfaces of the ro-
 143 tors was analyzed using a scanning electron microscope (SEM) (Lyra3; Tes-
 144 can, Czech Republic), equipped with an energy-dispersive X-ray spectrome-
 145 ter (EDX) for chemical analyses and elemental mapping. The microstructure
 146 preparation included cross-sectioning of the samples, placing the obtained
 147 cross-sections into resin molds, grinding with #90-2000 SiC papers, and fi-
 148 nal polishing with a 1 μm diamond paste. Chemical analysis of as-received
 149 coatings was performed using X-ray powder diffractometer (X-ray Smartlab
 150 diffractometer; Rigaku, Japan) set up in the Bragg-Brentano geometry with
 151 Cu K α radiation ($\lambda = 0.154 \text{ nm}$) and operated at the current of 30 mA and
 152 voltage of 40 kV. The diffraction pattern was collected from 20° to 100° with
 153 the step size of 0.02° and the scanning speed of $0.4^\circ/\text{min}$. Coating porosity
 154 was calculated using the image analysis with the help of a light microscope
 155 (DSX-510; Olympus, Japan) and an image analysis software (ImageJ 1.51j8;
 156 USA).

The microhardness measurements were performed on the samples' cross-sections using microhardness tester DuraScan-70 (Struers, Austria) under a load of 4.9 N. At least 15 measurements were made for each coating, and average values with their standard deviation are reported in the following text.

3. Results

3.1. Microstructural characterization of as-sprayed coatings and their hardness

XRD patterns of as-sprayed coatings are shown in Fig. 5. The major phases identified in the Cr_3C_2 -NiCr coating were Cr_3C_2 carbide and two Ni phases, both with cubic lattices, however, of slightly different lattice parameters. The XRD pattern of the composite NiCrBSi coating showed a considerable number of different phases, which belonged to either hard phases (Cr_3C_2 , Ni_3B , Ni_3Si , BN, W_2C) or matrix solid solutions (Ni and Cr). In the WC-CoCr coating, both WC and W_2C hard phases were detected, along with peaks of W.

The microstructural examinations of the cross-sections showed that the as-sprayed Cr_3C_2 -NiCr, NiCrBSi and WC-CoCr coatings had a thickness between 200 and 230 μm (Fig. 6a, d, g). All coatings showed well-discernible lamellar microstructure with elongated splats and pores located on inter-splat boundaries. The total areal porosity of the Cr_3C_2 -NiCr, NiCrBSi and WC-CoCr coatings estimated from SEM images was around 8.9 %, 4.6 % and 5.4 %, respectively. The as-received APS Cr_3C_2 -NiCr coating contained isolated Cr_3C_2 carbides grains homogeneously distributed in Ni-based matrix, which

Figure 5: X-ray diffraction patterns of as-sprayed coatings (a) $\text{Cr}_3\text{C}_2\text{-NiCr}$, (b) NiCrBSi , and (c) WC-CoCr .

showed both regions with higher (of dark grey colour) and lower (of light grey colour) Cr dissolution (Fig. 6b-c). The APS NiCrBSi coating showed the Ni-based matrix with embedded micron-sized and submicron hard phases (carbides, silicides and borides) (Fig. 6d-f). The WC-CoCr coating exhibited fine tungsten-based carbides homogeneously distributed throughout CoCr matrix (Fig. 6i).

The microhardness of the as-sprayed coatings increased in the following order: $\text{Cr}_3\text{C}_2\text{-NiCr}$, NiCrBSi and WC-CoCr , being, respectively, 1.7, 2.5 and 4.0 times higher than that of the substrate steel (Fig. 7). Furthermore, studied coatings showed an order of magnitude greater variation in hardness

Figure 6: SEM micrographs of as-sprayed (a-c) $\text{Cr}_3\text{C}_2\text{-NiCr}$, (d-f) NiCrBSi , and (g-i) WC-CoCr coatings, with the EDX elemental mapping of regions shown in middle-column images.

191 than the reference steel, probably because of higher microstructural variation.

192 3.2. Weight loss

193 Wear test results revealed a significant difference between the weight loss
 194 of 2-row and 3-row rotors. For all studied materials, 2-row rotors showed
 195 noticeably greater weight loss as compared to 3-row rotors (Fig. 8a-b). De-

Figure 7: Vickers' hardness of studied coatings and the reference steel.

196 spite this difference, the trend of weight loss was similar between different
 197 thermally-sprayed coatings for each rotor type, i.e. the lowest weight loss was
 198 shown by the WC-CoCr coating, followed by the Cr₃C₂-NiCr and NiCrBSi
 199 coatings. The reference steel generally experienced the highest weight loss,
 200 although it was slightly less than that of the NiCrBSi coating in the case of
 201 2-row rotors until reaching 10 kg of milled cement.

Figure 8: Weight loss of (a) 2-row rotors and (b) 3-row rotors with studied protective coatings with respect to the amount of milled Portland cement.

3.3. Volumetric wear of rotor pins and their morphology

The evaluation of the volume change of grinding rotors due to erosion wear carried out with a 3D scanner revealed that the volume change occurred on the rotor pins, while the rings remained practically intact (the volume change was less than 1%). The data of the relative volumetric loss of individual rows of pins for the different types of rotors (2-row and 3-row rotors) after milling of 15 kg of Portland cement are shown in Fig. 9b, where rows of pins are marked in accordance to the scheme provided in Fig. 9a. For all the materials studied, much larger relative volumetric wear was observed for 2-row rotors as compared to 3-row ones, thus corroborating the mass loss data. The overall trend in the volumetric wear of individual rows of pins is that the outer (2A and 3A) and central (3B) rows suffered more extensive wear than the inner ones (2C and 3C).

Figure 9: (a) Scheme showing the designation of rows of grinding rotor pins and (b) the relative volumetric loss after the milling of 15 kg of the Portland cement of the individual rows of 2-row and 3-row rotor pins.

A 3D optical analysis of worn 2-row rotors (Fig. 10) showed that the front,

216 the right lateral and the upper faces of the pins of both rows were severely
217 worn out. Regardless of the used coating, it was completely removed from
218 these faces, along with a substantial amount of substrate steel, resulting in
219 a prismatic shape of pins. There was no significant difference in appearance
220 between the two rows of pins (2A and 2C) in the 2-row rotors. In contrast,
221 the pins of the 3-row rotors were less damaged, though still noticeably worn,
222 and this was distinctly different for the three rows. Pins of the outer 3A
223 row retained their initial rectangular shape to a greater extent than those
224 from the inner 3B and 3C rows. The faces of the pins that suffered the most
225 intense erosive damage were the same as in the case of 2-row rotor pins, *i.e.*
226 the front, the right lateral and the upper faces.

227 The character of the erosion damage was additionally analyzed by exam-
228 ining the representative cross-sections of the pins after the wear test (Fig.
229 11). As can be seen, in the places of the most severe erosion attack (the right
230 lateral side of the pin), the coating was completely removed together with a
231 significant portion of the steel substrate. Correlating these images with the
232 mass loss of rotors, it can be concluded that a significant amount of mass
233 loss is related to the removed substrate material rather than the coatings.

234 SEM examinations of the damaged surface of the pins after the erosion
235 test revealed several distinctive morphologies shown in Figure 12. In case
236 of the rotor with Cr_3C_2 -NiCr coating, which was completely removed during
237 the test, and the rotor from the reference steel, their surface in the site #1
238 mainly exhibited both mild and deep multiple scratches, and the presence of
239 shallow impact craters. On the other hand, NiCrBSi and WC-CoCr coatings
240 have rather non-scratched appearance, though with some traces of spallation

Figure 10: 3D visualization of worn rotor pins after the milling of 15 kg of the Portland cement as compared to their initial profiles (indicated as translucent outlines) in rotors coated with thermally-sprayed coatings and non-coated rotors. Areas with preserved coatings are indicated with dashed lines.

241 or microcracking. In contrast, the surface in the zone #2, in which none of
 242 the studied coatings survived the experiment, contained mostly deep impact
 243 craters and plastically deformed ridges of material extruded by impacting

Figure 11: Micrographs of the lateral cross-sections of worn grinding rotor pins from the 2-row rotor (inner row 2C) with (a) $\text{Cr}_3\text{C}_2\text{-NiCr}$, (b) NiCrBSi and (c) WC-CoCr coatings (the profiles of non-worn pins are indicated with the dashed lines) after the milling of 15 kg of the Portland cement.

particles.

As shown in Fig. 10 and 12, $\text{Cr}_3\text{C}_2\text{-NiCr}$ and NiCrBSi coatings were completely removed in the anterior faces of the pins, however, WC-CoCr coating has been partially preserved in the anterior bottom part of the pins in 3-row rotor (Fig. 13a). SEM morphology of the eroded WC-CoCr coating surface exhibited numerous areas with characteristics of gross spalling of the coating mostly along the intersplat boundaries, material pull-out and the evidence of surface cracking (Fig. 13b).

4. Discussion

In this work, semi-industrial erosion tests of several thermally-sprayed coatings intended for the protection of working pins of grinding rotors of the laboratory high-speed mill were performed. The relevance of the present

Figure 12: SEM micrographs of worn pins of 2-row rotors (inner row 2C) with (a) Cr_3C_2 -NiCr, (b) NiCrBSi, (c) WC-CoCr coatings, and (d) of non-coated 2-row rotor after the milling of 15 kg of the Portland cement. Areas with preserved coatings are indicated with the dashed lines.

256 study is determined by the complexity of erosion wear processes occurring in
 257 the real operating conditions of a high-speed mill, in contrast to the model

Figure 13: (a) General overview of worn pin of 3-row rotor (inner row 2C) with WC-CoCr coating after the milling of 15 kg of Portland cement, and (b) the appearance of preserved WC-CoCr coating from site#1 in (a).

experiments with well-controlled testing conditions, such as those reported in [17, 18]. The complex nature of erosion wear puts forwards special demands on protective materials, which should possess both optimal microstructure and the balanced set of mechanical properties. As it is known, various parameters of thermally-sprayed coating, such as the chosen material system, the spraying parameters, intrinsic microstructural features (reinforcement content, distribution of individual phases, bonding strength between constituents, porosity, etc.) and resulting mechanical properties (most importantly, the hardness and the fracture toughness) have strong impact on coating's performance under impact erosion conditions [30, 31]. Though, the microstructure and phase composition of the coatings produced in this study were typical representatives of their microstructural classes, and they were similar to those obtained elsewhere [24, 32, 33], several specific features were detected by XRD and SEM analyses. The occurrence of two Ni-based phases with the cubic lattice in the $\text{Cr}_3\text{C}_2\text{-NiCr}$ coating was due to partial disso-

lution of Cr and C in the Ni binder phase around carbide particles during APS deposition process. The WC-CoCr coating showed partial decarburisation of WC to W_2C phase that probably occurred during the deposition process, and it has been observed in some previous studies on the HVOF WC-CoCr coatings [26]. Distinct Co peak from the binder phase was not detected in WC-CoCr coating, however, the occurrence of W peak indicates its possible precipitation from the melt during particle quenching following the deposition process, as reported by Stewart et al. [34].

The obtained microstructure of the thermally-sprayed coatings determines their hardness, which represent the composite hardness of hard phases and the binder phase. Apparently, a high content of submicron hard tungsten carbides in WC-CoCr coating, or Ni-based matrix reinforced with disperse carbides, borides and silicides in NiCrBSi coating provide a higher hardness than do large Cr_3C_2 carbides embedded to ductile Ni-based matrix in the case of the Cr_3C_2 -NiCr coating. The previous findings on the erosive resistance of these types of coatings showed that under fixed experimental conditions (fixed impact angle and particle speed) the WC-CoCr coatings have lower abrasive/erosive wear rates due to higher hardness of WC particles, hardness and fatigue strength of the Co-based binder, and fracture toughness as compared to Ni-based Cr_3C_2 -NiCr and NiCrSiB coatings [18, 26]. In general, high hardness is advantageous for the conditions of erosion wear at low impact angles, where material is removed from the surface by the mechanisms of plastic deformation by abrasive particles and microcutting (provided that the hardness of abrasive material, H_A , is larger than that of the abraded target, H_T ; $H_A/H_T > 1.2$ [35]). However, for the conditions of

298 mixed erosion, when damage involves the brittle fracture and surface fatigue
 299 wear mechanisms, the wear resistance of a coating is more dependent on
 300 size, shape, and distribution of hard phases than on their hardness [36]. The
 301 weight loss data corroborated this, showing no direct correlation between
 302 the hardness of studied coatings and their weight loss. Rotors coated with
 303 WC-CoCr and Cr_3C_2 -NiCr protective coatings, which have lower and higher
 304 hardness than that of the NiCrBSi coating, showed lower weight loss. In this
 305 case, the resulting wear resistance is determined by the set of various char-
 306 acteristics (hardness, fracture toughness, porosity, adhesion between coating
 307 microstructural features, etc.) rather than by the hardness alone. Also, it
 308 should be kept in mind that the weight loss here is a cumulative characteris-
 309 tic, which comprises the wear loss from both the coating and the substrate.
 310 Due to the relatively small thickness of the coatings ($\sim 200\text{-}230\ \mu\text{m}$), the
 311 weight loss of the pins is mainly contributed by the wear of steel substrate,
 312 as shown by the microstructural analysis presented in Fig. 11 and 12. In
 313 this context, the coating can be considered more erosion-resistant if it better
 314 protects the substrate against material removal and volume change by ero-
 315 sion, which is the main reason for the reduction of the grinding efficiency
 316 [9]. For this reason, NiCrBSi coating can be considered less erosion-resistant
 317 than Cr_3C_2 -NiCr, even though it has been better preserved top of the pins.
 318 Such a wear behavior is determined by the different wear mechanisms acting
 319 in different pin faces.

320 The predominant wear mechanisms operating on various surfaces of rotor
 321 pins (Figure 14) were determined using 3D optical scanner, light microscope,
 322 and SEM examinations. Regardless of the protective coating used, the an-

323 terior and the right lateral faces of pins (area I in Fig. 14) experienced
 324 almost complete failure of the coating that was followed by loss of a great
 325 amount of steel substrate (Fig. 11-13). These faces were obviously subjected
 326 to the impingement with cement particles traveling at rather high angles,
 327 as evidenced by the appearance of numerous impact craters with plastically
 328 deformed flakes at their corners. Under such conditions, the material re-
 329 moval from the eroded surface can occur by either one or by a combination
 330 of (i) brittle fracture of carbide particles and the development of inter-splat
 331 cracks that lead to extensive spalling of the coating, or (ii) repeated surface
 332 deformation of ductile binder phase or steel substrate and following gen-
 333 eration of surface and subsurface cracks, which is accompanied by carbide
 334 particle pull-outs, making the surface fatigue a dominating wear mechanism
 335 [14, 37]. Combination of these wear mechanisms are typically observed in
 336 thermally-sprayed coatings eroded at high impact angles [38]. SEM analysis
 337 of the partially preserved WC-CoCr coating in the bottom anterior part of
 338 the 3-row pins (Fig. 13) made it possible to establish wear mechanism, which
 339 mainly included plastic deformation of binder phase with impinging cement
 340 particles followed with material detachment and crack generation in the inter-
 341 carbide areas. The intersplat boundaries, interface between the binder and
 342 carbides, and porosity represent potential sites for crack nucleation due to
 343 higher stress concentration [18]. As for Cr_3C_2 -NiCr and NiCrBSi coatings,
 344 since they were completely removed from these faces of pins, it was impossi-
 345 ble to establish directly the operating wear mechanisms. Nevertheless, given
 346 the microstructural condition of all coatings (*i.e.*, disperse carbide grains in
 347 the ductile binder phase), it can be concluded that the erosion of these ma-

348 terials at high impact angles occurs in a similar manner, as earlier observed
 349 in model experiments [18, 26, 37, 38]. Due to the relatively low hardness
 350 of the cement particles compared with carbides and relatively small carbide
 351 size, direct fracture or microchipping of carbide phases seems unlikely.

352 In contrast, the impacts on the top and left-side faces of pins (zone II
 353 in Fig. 14) occurs mostly at low impact angles, as confirmed by abrasive
 354 scratches and grooves (Fig. 12). Material in these areas is removed due to
 355 ploughing and cutting by cement particles travelling along the tangent trajec-
 356 tories, and the dominating wear mechanism here is abrasion. In accordance
 357 with Hutchings [35], the wear degree of pin faces subjected to oblique impact
 358 could be explained by the ratio between the hardness of Portland cement
 359 particles and the hardness of the coating, *i.e.* the higher the hardness of
 360 the coating over that of the milled cement, the less intense is abrasive wear.
 361 Hence, the Cr_3C_2 -25NiCr coating, which has lower hardness than of the ce-
 362 ment particles (~ 600 -650 HV), was totally worn out in the zone II due to
 363 abrasion. At the same time, the NiCrBSi and WC-CoCr coatings with higher
 364 hardness were partially preserved, hence, representing an evident advantage
 365 over the Cr_3C_2 -25NiCr coating (and other more ductile coatings) and the
 366 steel substrate.

367 An additional important information on the character of erosion processes
 368 occurring in the milling system was provided by the evaluation of uniformity
 369 of wear of grinding rotors by means of 3D optical scanner. Obtained data
 370 provide a possibility to properly adjust the coating deposition parameters in
 371 order to achieve longer lifetime of the grinding system. The disproportion of
 372 the amount of material removed by erosion between 2-row rotors and 3-row

Figure 14: Operating wear mechanisms on different surfaces of a typical grinding rotor's pin.

rotors, as well as occurrence of the most intensive erosive damage in 2A, 2C, and 3B rows can be primarily explained by the design of the mill and resulting variability of milling process parameters at different sites of the milling system. According to previous studies on erosion by liquid/gas-borne particle streams [39–41], the most important parameters relevant to our case are the cement particle size, particle flux (*i.e.*, the number of impinging particles per unit area), particle velocity, and the impact angle. According to the scheme in Fig. 2c, the material to be milled enters the milling chamber through the inlet in the center of the 2-row rotor and makes the first contact with the first row of pins on the 3-row rotor. Apparently, this first contact at this row of pins occurs at relatively low speeds and at high impact angles and, therefore, erosion damage occurs mostly at the anterior faces of the pins (inner row 3C in Fig. 10) and the resulting volumetric loss is relatively small. After that, these pins propel the cement particles to the first row of pins of the 2-row rotor (inner row 2C in Fig. 10), where the impact is carried out by still quite large particles traveling at much higher velocities

and at different angles (both low and high). The same situation is repeated between the second row of the 3-row rotor and the second row of the 2-row rotor (middle row 3B and outer row 2A in Fig. 10, respectively). Since it is generally accepted that higher impact velocity increase the erosion rate [39, 41], abrasive particles located between the 2A, 2C, and 3B rows, which are still relatively large massive and have high impact velocities, have enough kinetic energy at impact to produce high erosive damage of pins. Hence, extensive erosion wear occurs not only on the anterior, but also at the side surfaces of the rotor pins.

Further decrease in volumetric wear of the third row of pins (outer row 3A in Fig. 10) may be caused by two main reasons, including (i) the mass reduction of initial rough particles, and (ii) increase in particle flux, both due to fragmentation of the initial coarse particles. The mass reduction of particles due to their fragmentation during previous milling stages apparently results in the decrease of their kinetic energy at impact. This is in accordance with generally accepted consideration that smaller particles cause lower mass loss by erosion than the same mass of larger particles [39]. As for the particle–particle interactions, it has been shown that higher particle flux may reduce the erosion rate by increasing the collision frequency of particles released into the milling system. Incident particles collide with rebounding particles, diverting a portion of incident particles away from the target surface and reducing kinetic energy [39, 41]. In our case, the fragmentation of initial cement particles leads to the production of high number of smaller particles, thus increasing the particle flux and probability of interactions between the incident and rebounding particles.

414 5. Conclusions

415 In the present work, the erosion resistance of several types of protective
416 coatings under semi-industrial conditions was evaluated using a laboratory
417 high-speed mill. The most wear resistant was the HVOF-sprayed WC-CoCr
418 coating, followed by the APS-sprayed Cr_3C_2 -25NiCr and NiCrBSi coatings.
419 WC-CoCr has both the lowest weight loss and minimal topographical changes
420 of the working pins on the grinding rotors after erosion test. Responsible wear
421 mechanisms have been established that act on different faces of the rotor pins.
422 The surface fatigue wear caused the greatest loss of material and complete
423 failure of all protective coatings on the anterior and the right lateral faces of
424 the pins. Ploughing and microcutting were acting on the top and left lateral
425 faces of the pins and resulted in noticeable damage of the protective coatings
426 when their hardness was lower than that of incident cement particles. Fur-
427 thermore, this study also revealed a significant disproportion of wear between
428 various rows of grinding rotors. The central rows of pins of the milling sys-
429 tem comprising two counter rotors (both rows of 2-row rotor and the middle
430 row of 3-row rotor) suffered more intensive erosion wear than the external
431 ones (outer rows of 3-row rotor). The design of the mill and the resulting
432 variability in milled powder parameters (such as particle size, particle flux
433 and particle velocity) at different sites of the milling system were considered
434 as main reasons for this effect. These conclusions indicate a further need to
435 optimize the coating deposition process to better tailor its microstructural
436 parameters in order to protect the most critical parts of the milling system
437 (and perhaps, to further optimize the design of working parts the mill).

438 Acknowledgement

439 This study was carried out with the financial support from the Ministry of
 440 Education, Youth and Sports of Czech Republic under the projects CEITEC
 441 2020 (LQ1601; under National Sustainability Program II) and AdMaS UP
 442 (LO1408; under National Sustainability Programme I), and from the Czech
 443 Science Foundation under the project "Study of the effects of samples prepa-
 444 ration on the final properties of inorganic binders" (15-08755S). The authors
 445 acknowledge Dr. Zdeněk Spotz for technical assistance during sample char-
 446 acterization. Part of the work was carried out with the support of core
 447 facilities of research infrastructure CEITEC Nano of CEITEC-BUT (MEYS
 448 CR, 2016–2019).

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