Erosion resistance comparison of alternative surface treatments

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Abstract. Erosion is a process characterized by the particle separation and the damage of component functional surfaces. Thermal spraying technology HP/HVOF (High Pressure / High Velocity Oxygen Fuel) is commonly used for protection of component surfaces against erosive wear. Alloy as well as cermet based coatings meet the requirements for high erosion resistance. Wear resistance is in many cases the determining property of required component functioning. The application suitability of coating materials is particularly influenced by different hardness. This paper therefore presents an erosion resistance comparison of alloy and cermet based coatings. The coatings were applied on steel substrates and were subjected to the erosive test using the device for evaluation of material erosion resistance working on the principle of centrifugal erodent flow. Abrasive sand Al_2O_3 with grain size 212-250 µm was selected as an erosive material. For this purpose, the specimens were prepared by thermal spraying technology HP/HVOF using commercially available powders Stellite 6, NiCrBSi, Cr_3C_2-25%NiCr, Cr_3C_2-25%CoNiCrAlY, Hastelloy C-276 and experimental coating TiMoCN-29% Ni. Erosion resistance of evaluated coatings was compared with erosive resistance of 1.4923 high alloyed steel without nitridation and in nitrided state and further with surface treatment using technology PVD. According to the evaluation, the resulting erosive resistance depends not only on the selected erodent and surface protection, but also on the erodent impact angle.

1. Introduction

Erosion is a process characterized by separation of particles and functional surface damage. Erosive wear occurs e.g. in machine parts transporting abrasive suspension (pump components, water turbines, pipes, fittings, nozzles), is caused by particles dispersed in air or gas stream (fan, cyclone, blaster, pipe components) or is generated by fluid, steam, droplets and gas flow (steam fittings, steam and gas turbine components). Regarding the erosive wear caused by particles, there can occur several ways in which particles impact on the material surface. If a particle moving askew to the surface has sufficient impact energy, it penetrates into the exposed surface resulting in material dislodge or segregation. If a particle has small impact energy or moves almost parallel with the surface, it can load only within the limits of elastic deformation, and therefore without any damage. Another case is perpendicular impact of particles on the surface resulting in elastic or plastic surface deformation. After the perpendicular impact on the surface, the particle is usually reflected back [1].

Two main methods of erosive wear evaluation are based on particle flow. Particles are moved by air or gas, or on the basis of centrifuge. In the first case, the particles are under a certain pressure accelerated by the air flow towards a specimen and impinge the surface perpendicularly or under a specific angle thanks to adjusted specimen positioning. In the second case, the centrifugal force is introduced by the rotation and acceleration of abrasive particles from channels in the rotating disk. Deng et al. [2] investigated differences between two above mentioned methods, particularly with regard to size, shape, concentration and velocity of abrasive particles. In terms of velocity, they found that the relationship between air pressure and particles velocity is in the gas equipment almost linear for all shapes, sizes and concentrations of abrasive particles. Identical dependency was proved also for the centrifugal equipment, precisely the relationship between the angular velocity of rotating disk and the velocity of particles leaving from channels. In case of gas equipment, it was found that smaller and sharper particles are accelerated to higher velocities. Regarding the dependency between concentration and particle velocity, they found that higher concentrations reduce particles velocity as a result of increased collisions leading to slower particles with lower kinetic energy. On the contrary, the dependence between particle properties and their velocity is minimal by the centrifugal device. An important effect occurring only in gas equipments is an extension of particle flow after leaving an acceleration tube. This effect increases with increasing velocity and concentration of particles. This phenomenon was attributed to the aerodynamic clustering between particles and air stream carrying them, mutual interaction of particles and interaction between particles and acceleration tube wall. The gas stream expansion further results in the generation the so-called "dead zone" in the middle of particle flow. Moreover, smaller particles have greater tendency to copy the gas flow compared to bigger abrasive grains. Furthermore, the effect of abrasive particles properties on material erosive wear was mentioned. The shape of abrasive particles is an important factor. Angular particles cause higher wear in the form of surface cutting, especially at lower impact angles. On the other hand, oval particles cause material removal as a result of plastic deformation and scratching.

Moreover, measurements at elevated temperatures can be performing using centrifugal device, as indicated e.g. Hayashi et al. [3]. In that case, the circumferentially attached specimens are provided with a heating spiral and the entire working part is installed in a tightly sealed chamber, in which the pressure is regulated by means of a vacuum pump. From this reason, erosive tests may be performed in inert or corrosive atmosphere.

2. Experiment

Five commercially available powders were used to prepare the samples. These powders were Amperit 588.074 (Cr_3C_2-25%NiCr) with particle size distribution for HVOF (-45+15 mm), Amperit 594.074 (Cr_3C_2-25%CoNiCrAlY) with particle size distribution for HVOF (-45+15 mm), Stellite 6 - M-484.33 (CoCrWC) with particle size distribution for HVOF (-53+20 mm), M-341.33 (Hastelloy C-276) with particle size distribution for HVOF (-53+20 mm), M-771.33 (NiCrBSi) with particle size distribution for HVOF (-53+20 mm) and one experimental powder labeled T10 (TiMoCN-29%Ni). All coatings were deposited by HP/HVOF (High Pressure/High Velocity Oxygen Fuel) technology with JP-5000 torch from the company TAFA Incorporated. Already optimized spray parameters were used for preparation of each coating. Nitrided stainless steel 1.4923 (P91) was used as a competing surface treatment technology. We were also evaluated surface treatment using PVD technology. Deposited coating was TiAlN.

Construct steel 1.0421 (DIN 11 523) was used as the base material. The substrate surface was degreased and grit blasted before spraying. Brown corundum F22 with grain size (0.8 to 1.0) mm was used as abrasive medium. Before coating deposition, all specimens were blasted in order to achieve proper adhesion of coating on the substrate material. The coating thickness was in the range of 250-400 μm.

2.1. Erosion – Equipment description

The used equipment for evaluation of material erosive wear operates as follows. A given constant amount of abrasive media is led from the feeder in the upper part of the equipment through the "choke valve" and replaceable cross-sectional iris. The abrasive media continues between two firmly connected, rotating discs with four channels resulting in acceleration caused by centrifugal force. As the abrasive media leave channels, it impinges on specimens attached to the disc circumference.

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Specimens are placed on predefined positions, towards both the axis of disc rotation and the axis of channels. Material weight loss of specimen was evaluated. If we know the density of test material the weight loss can be converted to volume loss, which allows quantitative comparisons.

The equipment consists of three main parts shown in Figure 1. The first part is an erodent feeder. The cover with scale to regulate erodent consumption is placed on the feeder, shown in Figure 2b. Erodent particle flow through the choke valve is regulated by a control cone, which is secured against loosening on a bar using a nut. Then the erodent continues into the second, so-called working part, through replaceable cross-sectional iris. After passing through the iris, the particles are ejected through radial rotor channels towards the specimens fixed in desired angle. The longitudinal specimen positioning correlates with the trajectory of particle flow from the rotor. The impact angle can be adjusted by tilting around the horizontal axis. This ensures that the contact area of specimen remains constant even with the different setting of impact angle. Specimens are attached using retractable plates and compression springs in a way that ensures easy attachment and removal. Erodent further falls through the middle part of the equipment, where an electric motor is placed. High speeds could lead to motor overheating and for this reason, the motor is cooled by compressed air which is regulated by mechanical valve. Engine revolutions and thus also erodent speed are controlled by frequency converter. After passing through the middle part, the erodent continues to the bottom of the equipment, into the so-called gripper (tray for abrasive). A sealing (rubber sleeve) to prevent dust particles leakage is placed between the central part and the gripper.

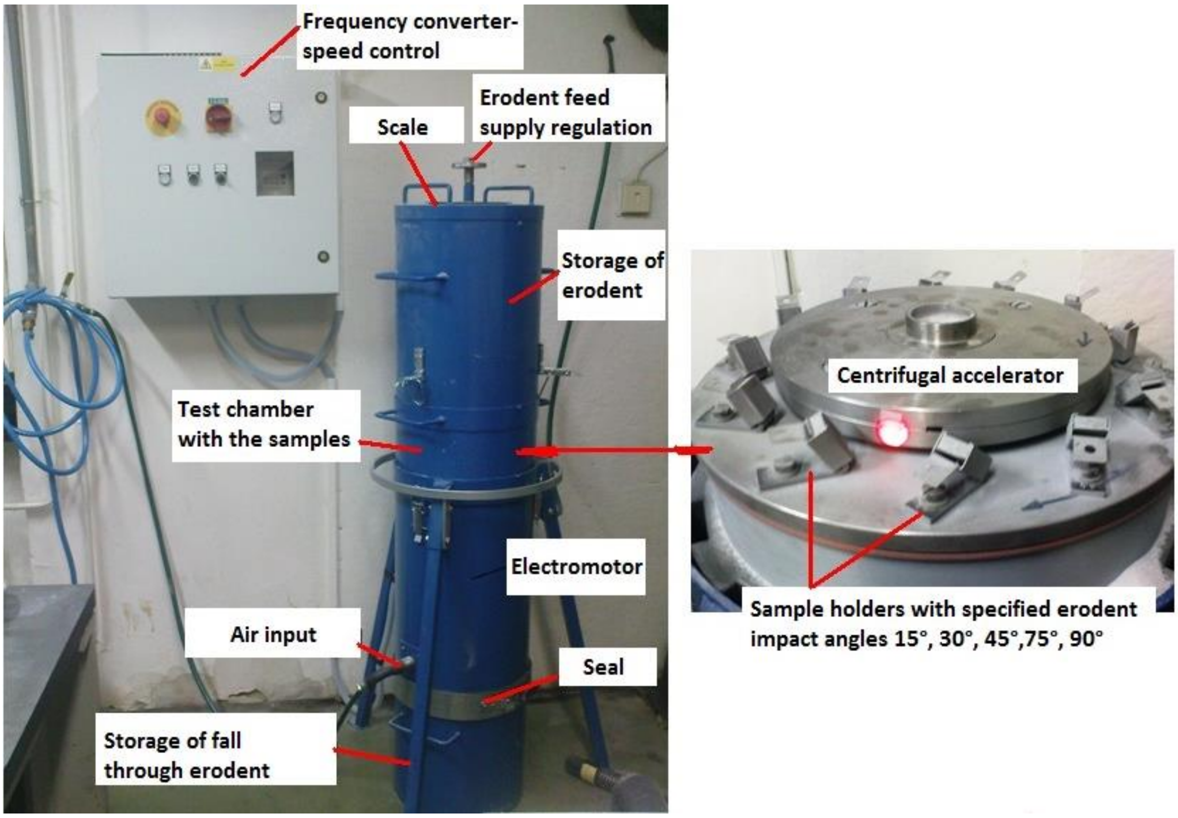

Figure 1. Equipment for evaluation of material erosion resistance working on the principle of centrifugal erodent flow.

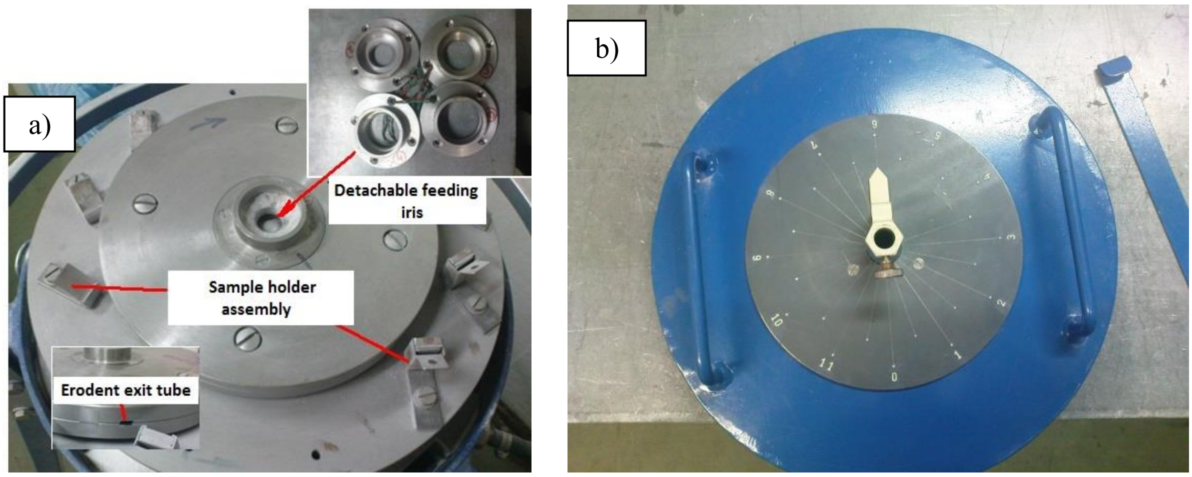

Figure 2. a) Working part of the equipment, b) Cover with scale for regulation of abrasive flow.

2.2 Measurement description

It is necessary to establish some basic parameters before starting the measurement itself. The parameters are the rotational speed of rotating disk and the amount of abrasive media depending on cone rotation (reading on the cover scale). After the finalization of these experiments, other parameters important for repeatable equipment operations were set – the dependence of erodent impact velocity and abrasive media amount on the erosive wear of tested materials.

After equipment tuning and determination of basic parameters, the evaluation of erosive wear resistance by selected thermally sprayed coatings using HVOF technology high was conducted. Optimized parameters were used for coating application. Parameters of erosive tests were following:

- Impact erodent angle - 90 °, 60 °, 30 ° and 15 °
- Evaluation time - 2 min
- Speed of rotating disc - 4500 rev / min
- Iris - 20 mm diameter
- Abrasive flow - cone rotation of 0.5 revolutions (180°)

3. Results

The resulting weight losses were converted using material density to volume losses in order to compare tested materials. Two specimens were used for each angle and the weight losses were measured three times for each specimen. Densities of evaluated materials are shown in Table 1.

Table 1. Densities of evaluated coatings.

Material	Powder indication	Density at 24.5 °C (g/cm^3)
Cr_3C_2-25% NiCr	588.074	6,685
Stellite 6	484.33	8,296
Hastelloy C-276	341.33	8,611
Cr_3C_2-25% CoNiCrAlY	594.074	6,479
NiCrBSi	771.33	7,176
TiMoCN-29% Ni	T10	5,894
Wr.Nr. 1.4923	X22 (P91)	7,7
TiAlN (PVD)		8,000 (estimation)

Weight loss measurement results of evaluated coatings under four erodent impact angles are summarized in the graph in Figure 3 and 4. Volume loss measurement results of evaluated coatings under four erodent impact angles are summarized in the graphs in Figure 5 and 6.

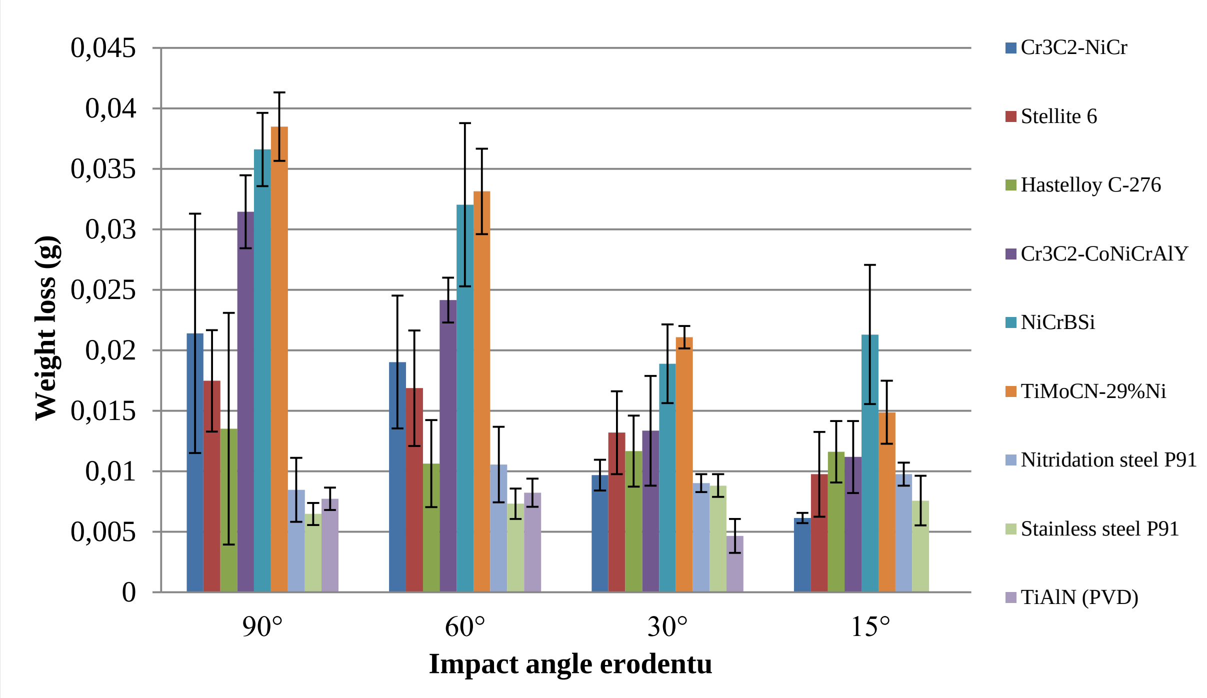

Figure 3. Weight loss of evaluated coatings under all erodent impact angles.

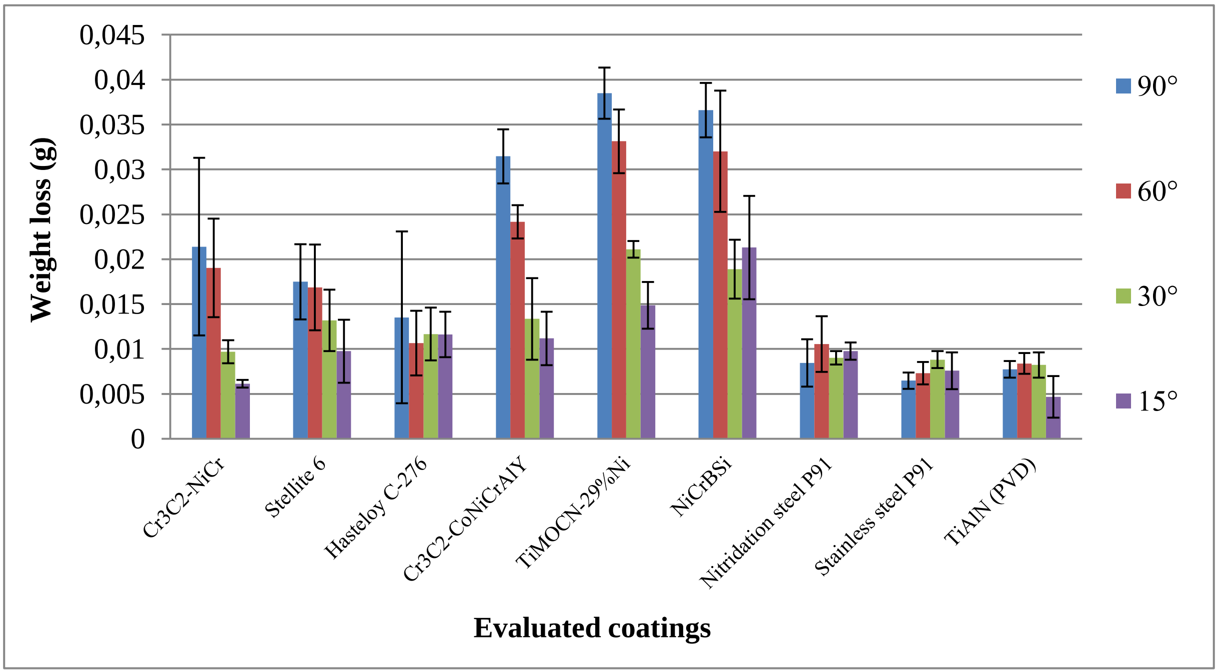

Figure 4. Weight loss of all evaluated coatings.

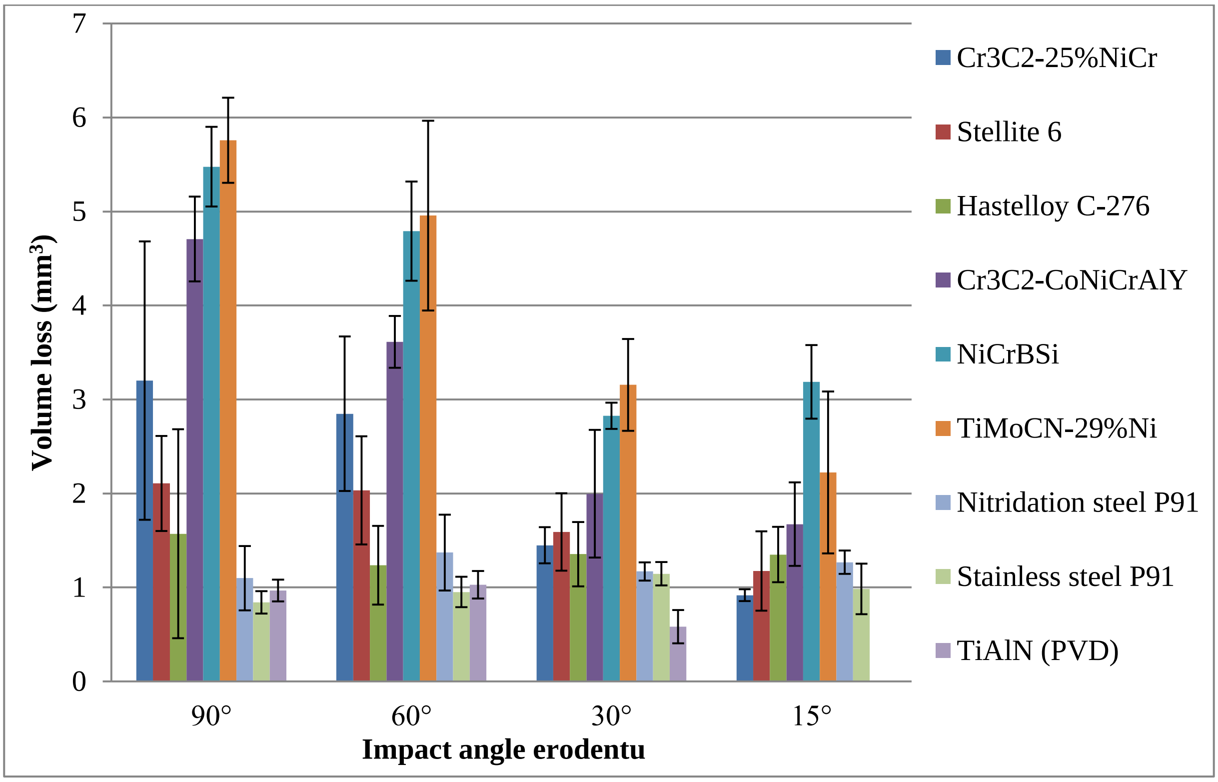

Figure 5. Volume loss of evaluated coatings under all erodent impact angles.

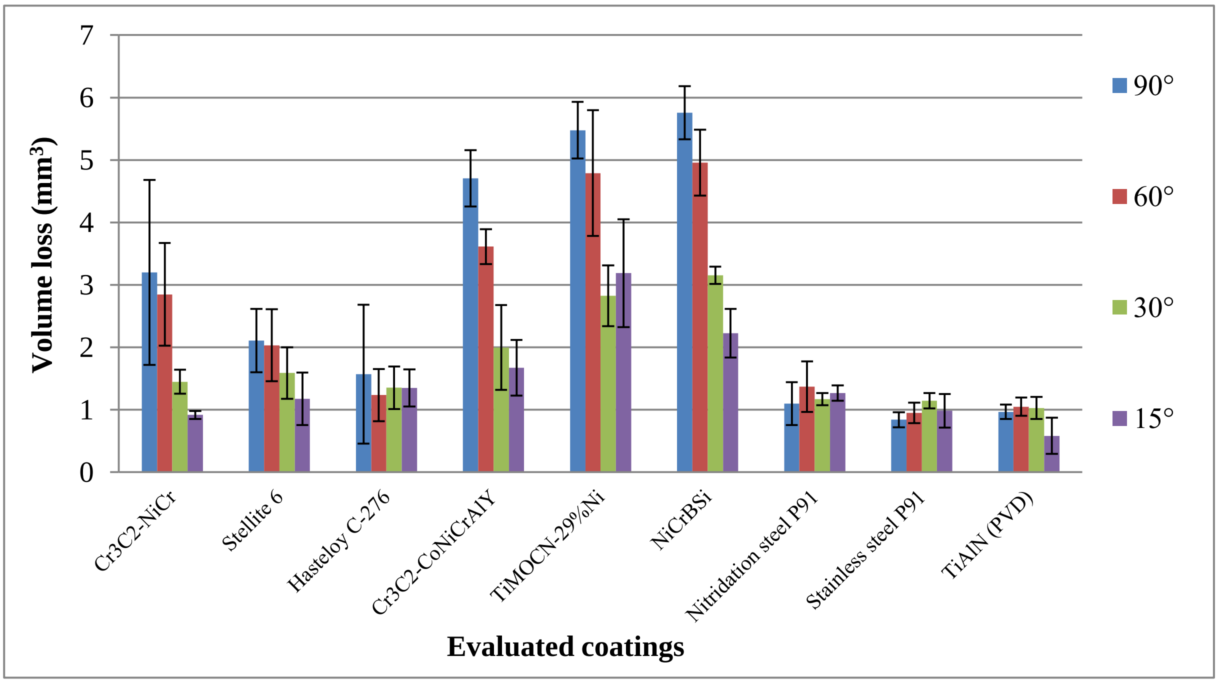

Figure 6. Volume loss of all evaluated coatings.

The wear mechanism under the erodent impact angle of 90 ° and 15 ° for Cr3C2-25%NiCr coating is illustrated in the Figure 7. Surface appearance after the erosive wear test varies significantly depending on the erodent impact angle. In case of perpendicular erodent impact angle, the traces of Al_2O_3 adhesion are visible on the surface. In case of 15 ° impact angle no erodent adhesion occurred.

On the other hand, there occurred significantly noticeable impact direction and the wear mechanism is a combination of plastic deformation and release of bigger coating parts [6], [7], [8]. Furthermore, previous splats are visible on some places. Figures 8 to 15 show traces of erosive wear for other evaluated coatings. Erosion mechanism will be further evaluated in the chapter Discussion.

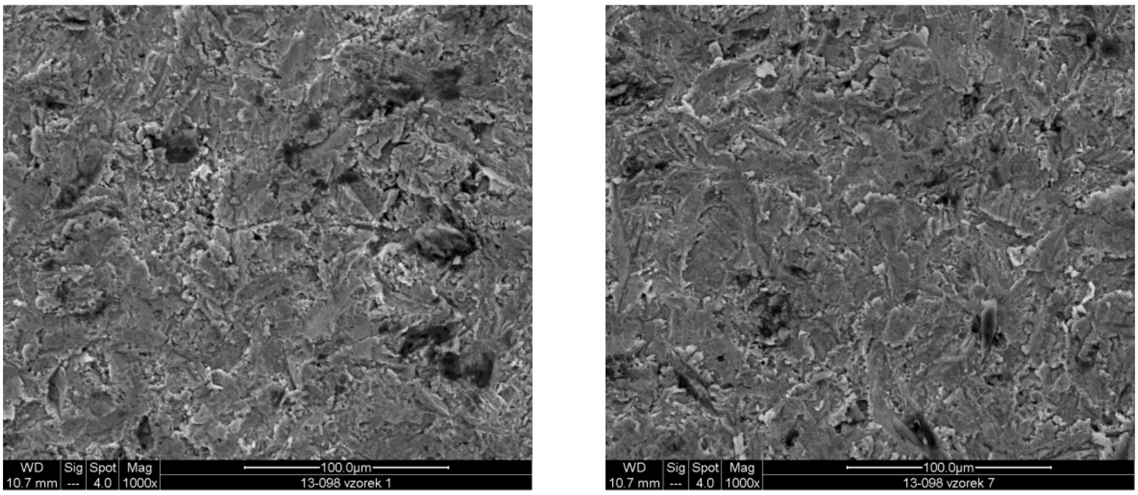

Figure 7. Erosive wear of Cr_3C_2-25% NiCr coating under 90 ° and 15 ° erodent impact angle in MIX mode (1000x magnification).

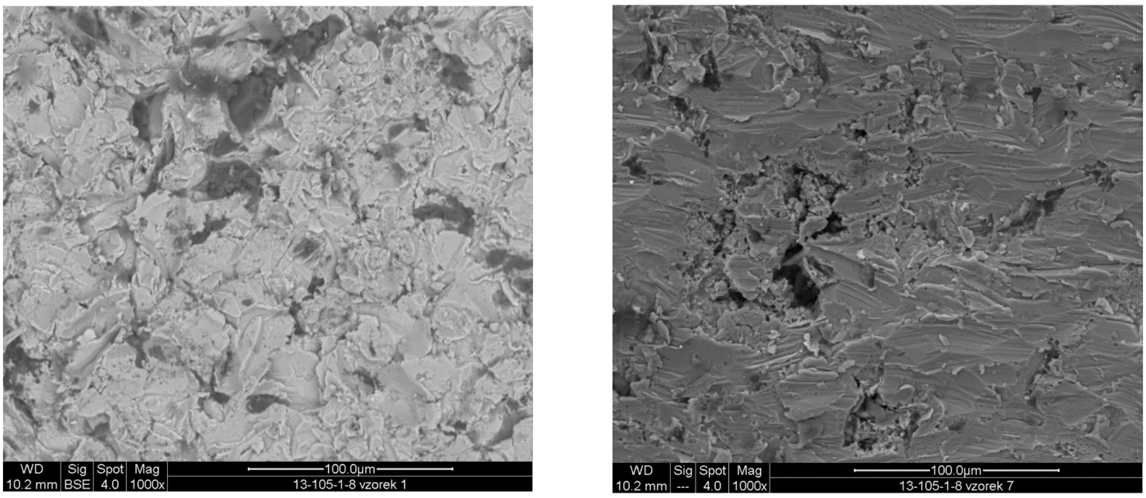

Figure 8. Erosive wear of Stellite 6 coating under 90 ° and 15 ° erodent impact angle in MIX mode (1000x magnification).

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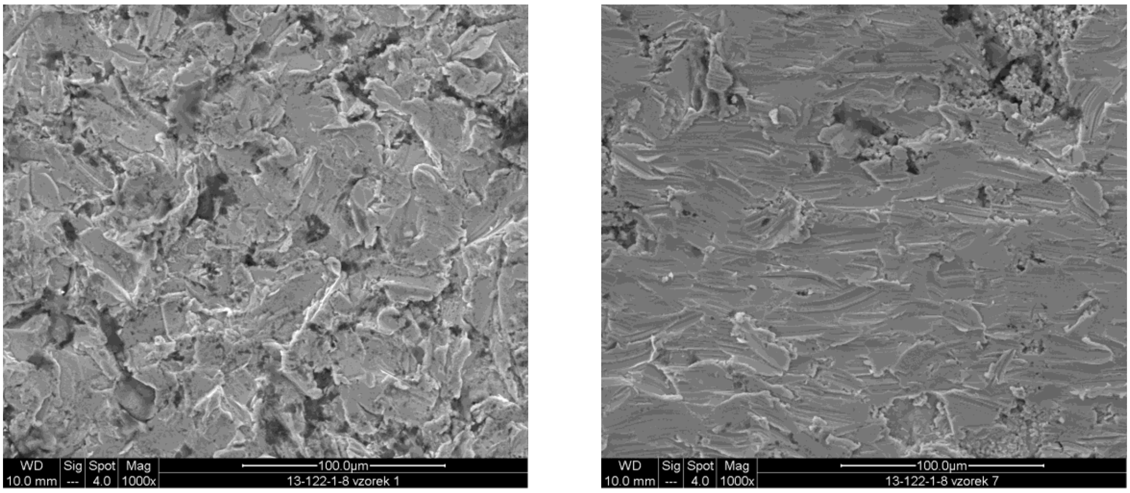

Figure 9. Erosive wear of Hastelloy C-276 coating under 90 ° and 15 ° erodent impact angle in MIX mode (1000x magnification).

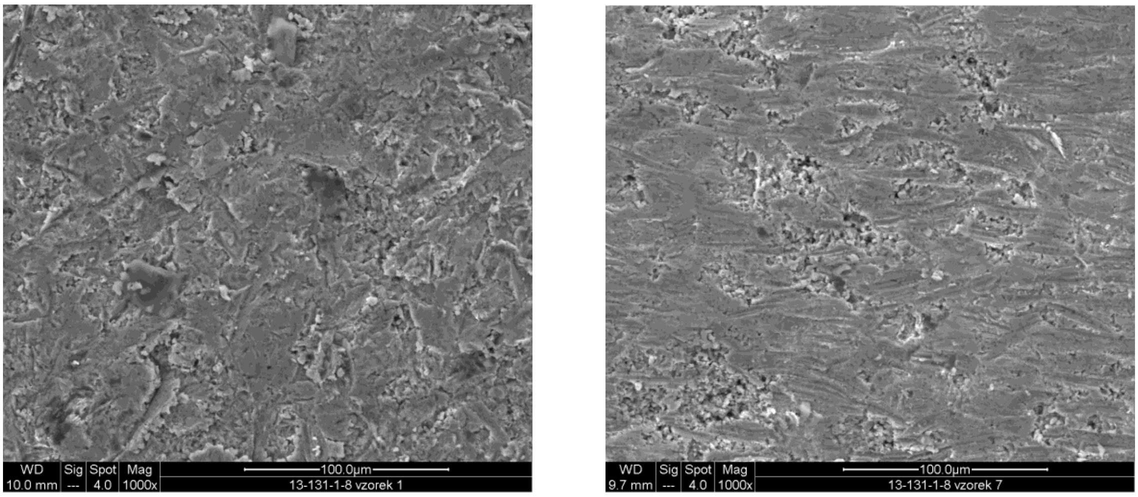

Figure 10. Erosive wear of Cr_3C_2-25% CoNiCrAlY coating under 90 ° and 15 ° erodent impact angle in MIX mode (1000x magnification).

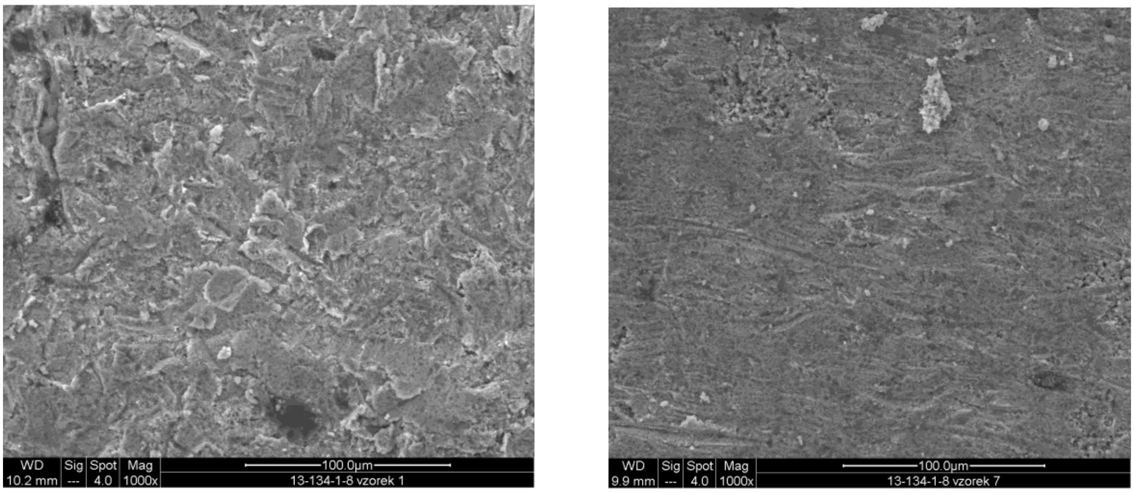

Figure 11. Erosive wear of TiMoCN-29 %Ni coating under 90 ° and 15 ° erodent impact angle in MIX mode (1000x magnification).

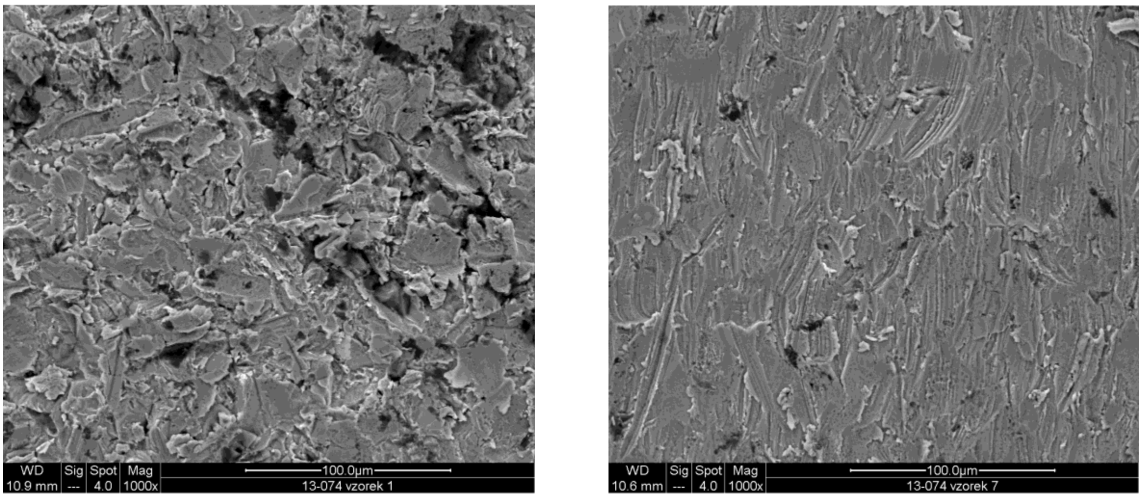

Figure 12. Erosive wear of NiCrBSi coating under 90 ° and 15 ° erodent impact angle in MIX mode (1000x magnification).

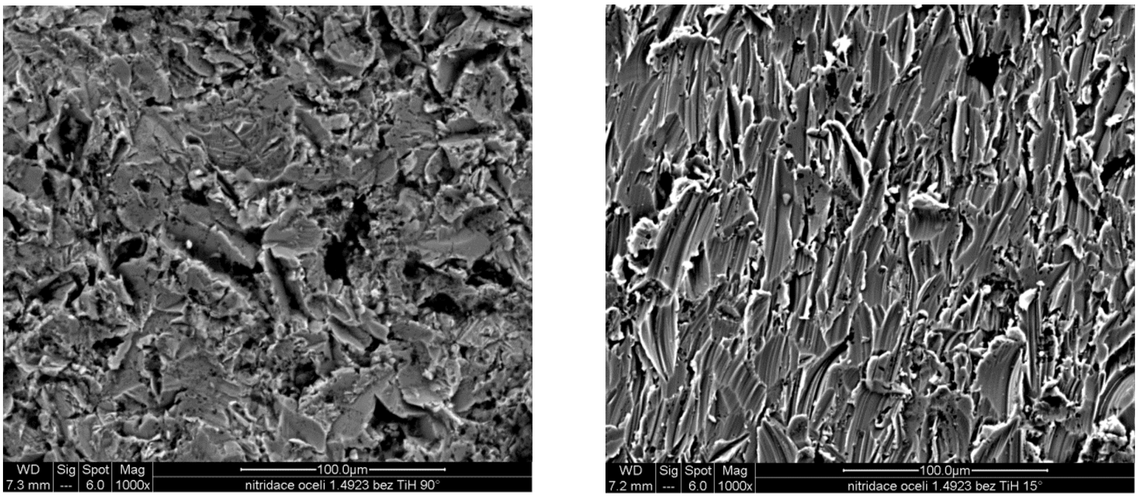

Figure 13. Erosive wear of nitrided steel P91 under 90 ° and 15 ° erodent impact angle in MIX mode (1000x magnification).

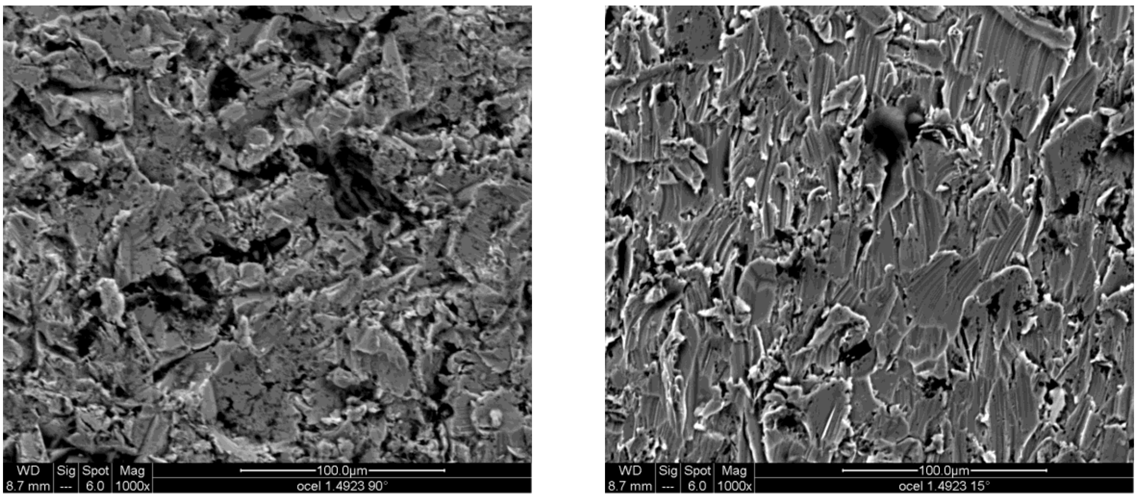

Figure 14. Erosive wear of steel P91 under 90 ° and 15 ° erodent impact angle in MIX mode (1000x magnification).

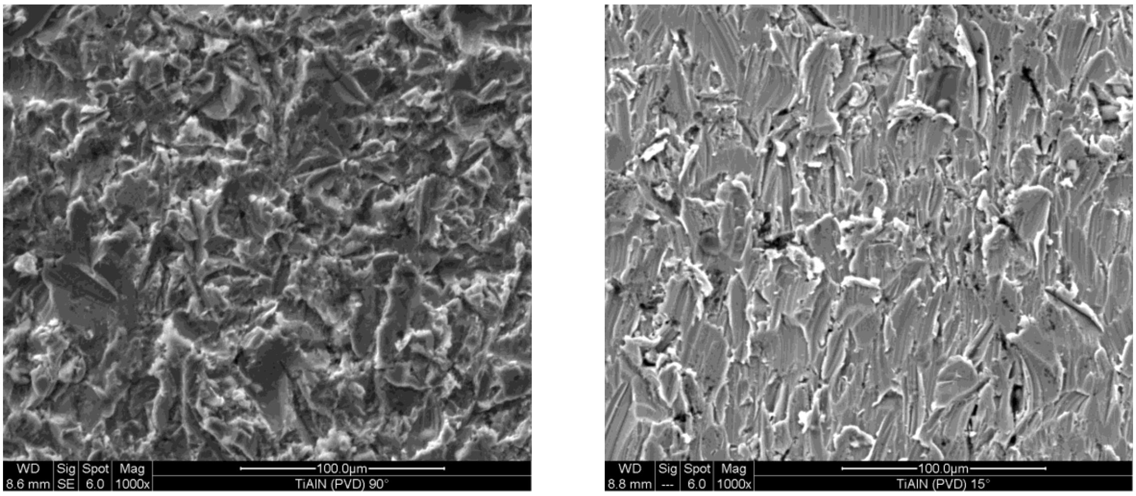

Figure 15. Erosive wear of TiAlN (PVD) coating under 90 ° and 15 ° erodent impact angle in MIX mode (1000x magnification).

4. Discussion

Cr_3C_2-25% NiCr coating exhibited significant dependence on the erodent impact angle. Under the perpendicular impact angle, its wear resistance is lower in comparison with alloy based coatings Hastelloy C-276 and Stellite 6. The wear resistance gradually increases with decreasing erodent impact angle. On the other hand, regarding the erosive wear resistance under 15 ° erodent impact angle, Cr_3C_2-25% NiCr coating shows one of the best results. A similar trend, although to lower extent, shows Stellite 6 coating. On the contrary, alloy based Hastelloy C-276 coating appears to be independent on the erodent impact angle, similarly also nitrided steels P91, TiAlN (PVD) coating and steel P91 without surface treatments.

The results can be interpreted with regard to the presumed material hardness and toughness (brittleness). While hard and abrasion-resistant Cr_3C_2-25% NiCr coating benefits under low erodent impact angle from its high hardness and its erosion wear resistance is similar to abrasive wear resistance; perpendicular erodent impact angle leads to brittle damage, release of carbide particles and overall higher weight loss. Alloy based coatings with lower hardness but higher toughness and plastic deformation ability are less dependent on impact angle. Similar results were achieved during the evaluation of erosion resistance by cermet and alloy based coatings within the project COST 523 [4] and in the publication [5].

Cr_3C_2-25% CoNiCrAlY, TiMoCN-29% Ni and NiCrBSi coatings seems to be very inappropriate as protective coatings against erosive wear for functional surfaces of components.

5. Conclusions

The aim of this study was to evaluate and compare coatings applied using thermal spraying HP/HVOF technology in terms of their erosive wear resistance with competing surface treatments. Figure 5 and Figure 6 evidently show that under the erodent impact angles of 90° and 60°, there occurred the highest erosive wear by Cr_3C_2-25% NiCr, Cr_3C_2-25% CoNiCrAlY, TiMoCN-29% Ni and NiCrBSi coating; somewhat better erosive wear resistance exhibited alloy based coating Stellite 6 and the best results among thermal sprayed coatings exhibited alloy based coating Hastelloy C-276.

Regarding the erosive wear under the erodent impact angle of 30 °, Cr_3C_2-25% NiCr, Hastelloy C-276 and Stellite 6 coatings proved to have very similar resistance. However, the situation changes under the erodent impact angle of 15 °. Due to the different wear mechanism dependent on the impact angle, there were obtained completely different results in comparison with 90° impact angle. In case of perpendicular erodent impact angle, the traces of Al_2O_3 adhesion are visible on the surface. In case of 15 ° impact angle no erodent adhesion occurred. On the other hand, there occurred significantly noticeable impact direction and the wear mechanism is a combination of plastic deformation and

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release of bigger coating parts. Under this impact angle, the best erosive wear resistance showed cermet based coating Cr_3C_2-25% NiCr and the worst NiCrBSi coating.
Cr_3C_2-25% CoNiCrAlY, TiMoCN-29% Ni and NiCrBSi coatings seems to be very inappropriate as protective coatings against erosive wear for functional surfaces of components.

Wear resistance of nitridation, TiAlN (PVD) and P91 steel does not seem to be influenced by any erodent impact angle and they appear to be the most appropriate out of all evaluated surface treatments. From the economical point of view, the best solution would be the base material (steel P91), as it surprisingly showed the highest erosion wear resistance.

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