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Abrasive and Erosion Wear of Composite NiCrSiB Coatings Inflicted with Subsonic Flammable Structure through a Cold Process

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Abstract. Ni-Cr-B-Si alloys are commonly used in the thermal spraying of steels. Despite their widespread use, their role in protecting metal surfaces from wear is not yet fully clarified. In order to obtain data and understanding of the wear and wear resistance of these coatings, the present work is studied the characteristics of the abrasive and erosive wear of new Ni-Cr-B-Si composite coatings applied by means of a sonic flame jet when heating the substrate to 180 °C (cold process). The powdered compositions used contain particles with an average size of 40 µm and a different percentage of the chemical elements. The abrasion wear is investigated using the thumb-disc pattern for dry surface friction with rigidly attached abrasive particles. Erosion wear is investigated by the interaction of air-jet coatings carrying abrasion particles. All samples in abrasion and erosion are tested under the same contact conditions. The mechanism, speed, and intensity of wear, and wear resistance of coatings at different normal load and slip speeds were obtained.

1. Introduction

The protection of the environment from pollution and the exhaustion of natural resources and the saving of energy are top-priority tasks of the scientific research and engineering practice during the last decade. These activities have direct connection with the tribology as a contemporary interdisciplinary science and technology for such contact processes as friction, wear, lubrication in technical systems. The decrease in the wear degree leads to reduction of the expenses for materials and consumables and in this way it decreases the extraction of raw materials from the natural environment, which results in changes in the equilibrium in ecological systems [1-3].

The abrasive and erosive wearing processes are among the most often met kinds of wear in various branches of the industry, especially in ore-mining and processing, foodstuffs producing industry, agricultural technics, energy production, road-construction technics, transportation, aircraft building, space technics and others. More than 50% of all the observed failures, connected with the wearing of industrial details, are due to abrasive wear. The expenses on a world-wide scale, caused by abrasive wear, amount to 1 – 4% of the gross domestic product of the industrially developed countries in the world [4-5].

There are several main tendencies to be outlined in the tribology, aimed at solving the problems, connected with wear [6]:

- The elaboration of new construction and lubrication materials having enhanced tribological characteristics;
- The designing of new production technologies, which ensure qualitatively new tribological properties of the conventional materials;
- The invention of new tribological coatings and modification of surface layers;
- Upgrading of the already existing constructions of the tribosystems and efficient lubricating and filtering systems;
- The discovering of new effects of self-organization in tribological systems, which lead to lowering of the entropy, expressed in minimization of friction and wear, as well as realization of such conditions of no wearing off process.

During the last 15 years there appeared many promising research results in the field of highly resistant to wear composite coatings and surface layers, containing micro- and nano-modifiers of different materials, obtained by different methods [7-10]. It is of special interest to study composite coatings, deposited by the method of thermal spraying by flame stream. The subsonic flame spraying can be realized by two different methods – a cold process and a hot process, which differ in the temperature of heating of the substrate. In the case of hot process the surface is heated in advance to 600-800ºC, while the temperature in the cold process is from 50ºC up to 200ºC depending on the nature and on the quantity of the powder particles and the substrate.

The aim of the present research work was to investigate the characteristics of wearing of composite Ni-Cr-B-Si coatings in both regimes of interaction: dry friction along the surface by solid fixed abrasive particles and interaction with the air stream, carrying the abrasive particles.

2. Materials and technology

Four types of coatings have been studied, obtained by cold thermal spraying upon the substrate of steel having chemical composition: C – 0.15%; S - 0.025%; Mn – 0.8%; P – 0.011%; Si – 0.21%; Cr – 0.3%; Ni – 0.3% and hardness 210.5 HV2. Composite mixtures on the basis of nickel have been used having different percentage of Si, B and Cr in their composition (table 1).

Table 1. Chemical composition, hardness, thickness and roughness of the studied coatings

Sample	Coating designation	Chemical composition (wt. %)	Hardness	Thickness (μm)
1	FS-CP-1 (1355-20)	**Cr**:16; **Si**:4; **B**:3.4; **Fe**:2.7; **C**:0.6; **Mo**:3; **Cu**:3; **Ni** Balance	57 HRC	450
2	FS-CP-2 (80M60)	**Cr**:14; **Si**:4.2; **B**:2,9; **Fe**:4,6; **C**:0.6; **Mo**:2,5; **Cu**:2,4; **Ni** Balance	58 HRC	450
3	FS-CP-3 (72M40)	**Cr**:9,9; **Si**:3.1; **B**:1.7; **Fe**:3.2; **C**:0.35; **Mo**:3; **Cu**:3; **Ni** Balance	57 HRC	450
4	FS-CP-4 (HN40)	**Cr**: 20%; **Ni**: 80%	54 HRC	450
5	Substrate Steel	**Cr**:0.3; **Si**:0.21; **S**:0.025; **Mn**:0.8; **P**:0.01; **C**:0.21; **Ni**:0.3; Fe Balance	215.5 HV	-

The powder particles have average size of 45 ± 2.5 μm. Before the deposition of the coating the surface of the work piece has been treated in three stages: cleaning, blasting and mechanical processing. The cleaning was done using a solvent, which removes mechanical components, moisture, organic molecules, adsorbed on the surface. The blasting was carried out using abrasive material „Grit" in accordance with the requirements of ISO 11126.

The coatings were deposited using the system MICROJET+Hybrid, whereupon a combustion mixture of acetylene and oxygen was applied at a ratio 1:1. The velocity of the flame stream was 100 m/s, while the preliminary heating up of the substrate was done at a temperature 200˚C. The coatings have equal thickness of 450 µm, which was measured by means of the device Pocket Leptoskop 2021 Fe. After polishing and finishing all the surfaces of the coatings have equal ruggedness Ra=0,430÷0,435 µm, measured by profile-metering device „TESA Rugosurf 10-10G". The hardness of the coatings was measured by hardness-metering device "Bambino" on the basis of the scale of Rockwell (HRC).

3. Abrasive wear

3.1. Experimental procedures

The methodology consists in measurement of the mass wearing off degree of the coatings after a certain number of cycles of friction and calculation of the wear rate, the absolute and the relative wear resistance. The abrasive wear resistance is represented as the reciprocal value of the rate of the wearing off process, while the relative wear resistance is the ratio between the wear resistance of the tested specimen and the wear resistance of a sample, accepted as a standard under identical conditions of friction. The abrasive wear was studied by means of the device „Thumb-disk". The samples have cylindrical form of diameter 15 mm. The investigation was carried out under the following conditions: loading of 4.5 N; nominal pressure 2.0 N/cm^2, rate of sliding 0.155 m/s; abrasive surface - Corundum P 320, temperature of the environment 21˚C.

3.2. Experimental results and discussion

The experimental results on the mass wear, the rate of wearing off and the wear resistance are represented in the figures 1, 2 3 and 4.

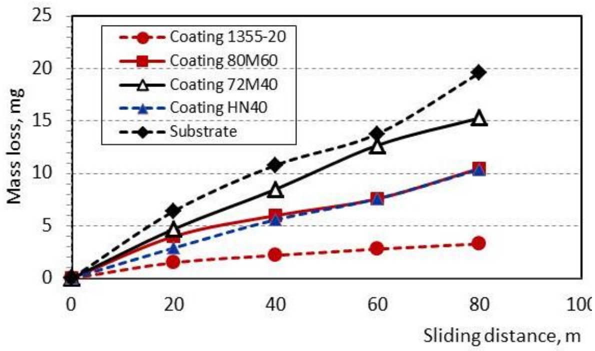

Figure 1. Mass loss vs. sliding distance for tested coatings and substrate.

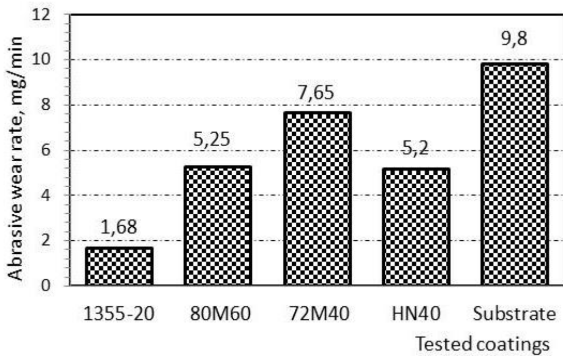

Figure 2. Abrasive wear rate for tested coatings and substrate in the friction path 80m.

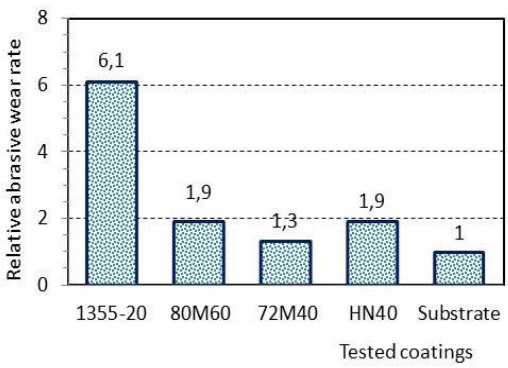

Figure 3. Diagram of relative wear rate to wear rate of substrate.

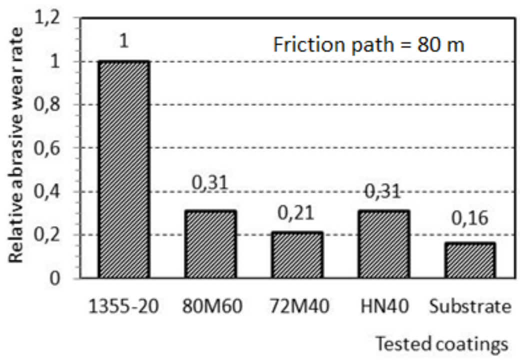

Figure 4. Diagram of relative wear rate to wear rate of coating with minimal wear rate (1355-20).

Based on the plotted kinetic curves of mass loss in Figure 1 one can see that the lowest wearing off degree is manifested by the coating 1355-20, which contains the highest amount of additional components: Cr-16%, B – 3.4%; Si – 4%. The greatest wear was manifested by the coating 72M40 having the lowest content of these elements (table 1). The wear rate value for the coating 72M40 is 4.55 greater than the wear rate of of the coating 1355-20 for one and the same length of the friction path of 80 m. The other two coatings 80M60 and HN40 have the same wear rate along the entire friction path length and values between those of the coatings 1355-20 and 72M40. The kinetic curves of mass wear rates of all the coatings have linear character, which is most distinctly expressed in the case of the coating 1355-20. The obtained results on the abrasive wear rate of the coatings cannot be explained on the basis of their hardness, there exists no correlation between the wear rate and the hardness (table 1).

4. Erosive wear

4.1. Experimental procedures

Erosive wear tests were carried out on jet nozzle type of erosion equipment (figure 5) in the ambient air, at room temperature [6]. This testing utilizes repeated gas-entrained solid particle impingement erosion, and involves a small nozzle delivering a stream of gas containing solid particles, which impacts the surface of a test specimen. Erosive wear tests were carried out on jet nozzle type erosion equipment in the ambient air, at room temperature. This testing utilizes repeated gas-entrained solid particle impingement erosion, and involves a small nozzle delivering a stream of gas containing solid particles, which impacts the surface of a test specimen. Solid particles are poured from the reservoir (1) by freefalling to the nozzle tube (2). Length of the nozzle is 200 mm, diameter is 8 mm, and exit diameter is 6 mm. Before the tests, solid particles material was sieved through a set of sieves and dried in an oven for removal of moisture from the particles. The air stream is provided by the compressed air at controlled pressure, purified from particles and moisture (3). Air stream also enters the nozzle tube (2), where the formation of two-phase (particle-air) working stream takes place. The test sample (4), in the rectangular shape (20×25 mm) and 3 mm thickness, is fixed in a holder (5) attached to the reversing mechanism (6). With reversing mechanism (6), two working parameters are controlled: (a) distance of the sample from the nozzle, and (b) impact angle of the particles. Parameters used in the erosive wear testing (solid particles material, maximum size of the particles, air stream pressure, particles flow, particles impact angle, distance between the sample and the nozzle and duration of the test) were the same for all tested coatings (table 1).

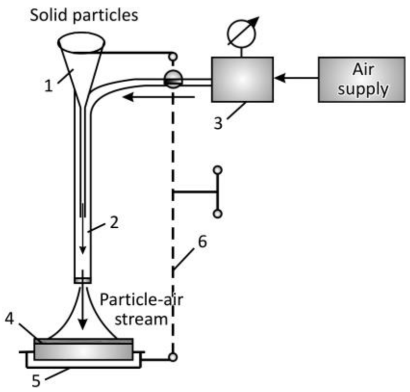

Figure 5. Schematic diagram of erosive wear testing.

The mass flow rate $\dot{m}_a$ of a given abrasive material with mass m_a in the device is determined by measuring the time t_a for the gravitational flowing out of the abrasive material - $\dot{m}_a = m_a/t_a$. The methodology for studying the erosion wear and wear resistance by means of the described device consists of measuring the mass of the sample before stream treatment and its mass after exposure to treatment with two-phase stream under the same fixed parameters: distance l angle of interaction α working pressure P, type and average size of the abrasive particles, mass flow rate of the abrasive material $\dot{m}_a$. The difference in the mass of the sample before and after the treatment represents the mass erosion wear – $\mathrm{m_e}$. The rate of erosion wear is determined by the formula $\dot{\mathrm{m}}_\mathrm{e} = m_e/t_e$, where $\mathrm{t_e}$ is the time duration of the treatment of the coating. The intensity of the erosion is determined by the formula $\mathrm{i_e} = \dot{m}_e/\dot{\mathrm{m}}_\mathrm{a}$. The erosion wear resistance $\mathrm{I_e}$ is defined as the reciprocal value of the intensity of erosion, i.e. $\mathrm{I_e} = 1/\mathrm{i_e} = \dot{\mathrm{m}}_\mathrm{a}/\dot{\mathrm{m}}_\mathrm{e}$. The relative erosion wear resistance $\mathrm{R_{i,j}}$ is determined by the formula: $\mathrm{R_{i,j}} = \mathrm{I_e^i}/\mathrm{I_e^j}$, where $\mathrm{I_e^i}$ is the erosion wear resistance of the tested sample, while $\mathrm{I_e^j}$ is the wear resistance of a sample, accepted as a standard for comparison, evaluated under the same conditions of wearing. The samples of the tested coatings and the substrate have the form of a parallelepiped of dimensions 25x30x5 mm. The parameters of the erosion are: solid particles material - black corundum (Al_2O_3); size of the particles – 600 µm; air stream pressure - 0.1 MPa; particles flow - 166.67 g $\mathrm{min^{-1}}$; distance between the sample and the nozzle - 10 mm; duration of the test - 5 min; ambient temperature - 24˚C.

4.2. Experimental results

Results have been obtained by the described methodology and testing device for erosive mass wear, for the rate, the intensity and the wear resistance during erosion at two values of the angle of interaction of the jet with the surface – 90º and 60º (figures 6, 7, 8, 9).

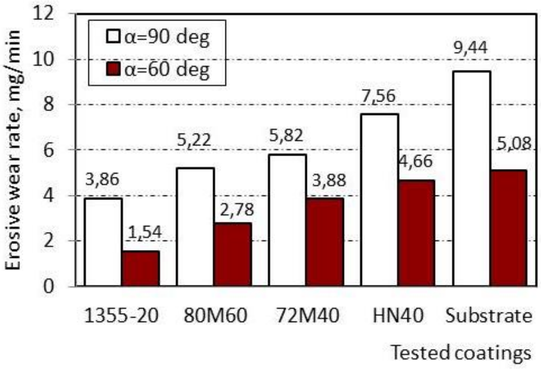

Figure 6. Influence of the angle of interaction of the jet with the surface of the coatings on the erosive wear rate.

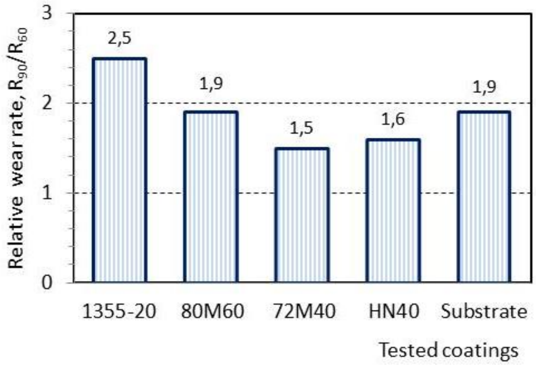

Figure 7. Relative erosive wear rate at two jet interactions with the surface area of the coatings - 90° and 60°.

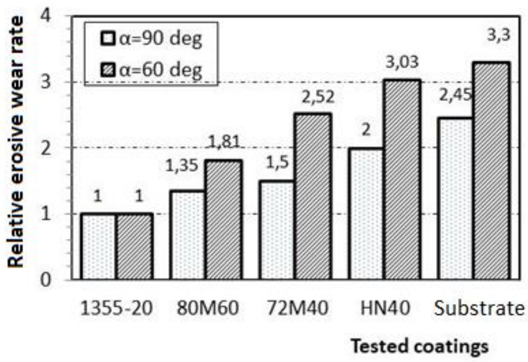

Figure 8. Relative erosive wear rate when compared to a coating with the lowest wear rate.

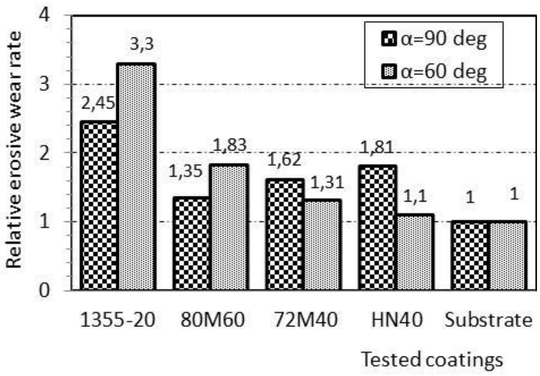

Figure 9. Relative erosive wear rate when compared to substrate coatings.

The analysis of the obtained results, shown in Figure 6 leads to the conclusion that the angle of interaction of the jet α with the surface exerts substantial influence on the rate of erosion. At $\alpha = 90^\mathrm{o}$ the rate of erosion of all the coatings is larger than that at $\alpha = 60^\mathrm{o}$. This is the result of the interaction of the surface with the field of distribution of rates of particles at the two angles. The lowest rate of wearing off at the two angle values is manifested by the coating 1355-20 having the highest content of Cr, B, Si. At angle $\alpha = 90^\mathrm{o}$ its rate of erosion is 2.5 times higher than that at angle $\alpha = 60^\mathrm{o}$. The highest wear rate is displayed by the coating HN40, which is 1.5 times higher at angle $\alpha = 90^o$ in comparison with that at $\alpha = 60^o$. The relative rates of wearing off with respect to the angle α for the coatings 72M40 and HN40 are almost identical – respectively 1.5 and 1.6. The coating 80M60 has the same relative rate of wear as that of the substrate – 1.9 (figure 7). The latter fact means that the coating 80M60 is not suitable for operation under conditions of erosion at angle $\alpha = 90^o$, that is - it does not fulfill its designed function.

4. Conclusions

Results have been obtained about the characteristics of the wearing off process for 4 kinds of coatings with nickel matrix having different contents of Cr, B and Si under two different regimes of contact interaction: dry friction along the surface with solid fixed attached abrasive particles (abrasion) and also in the case of interaction with air jet, carrying abrasive particles (erosion).

It has been ascertained that the lowest rate of abrasive and erosive wear is shown by the coating 1355-20, containing the highest concentration of the elements Cr-16%, B – 3.4%; Si – 4%. Its abrasive wear resistance is more than twice higher than its erosive wear resistance. It has been shown that the angle of interaction of air jet-abrasive stream exerts substantial influence on the rate of erosion wear, whereupon the wear rate is higher at an angle of 90 degrees.

The basic conclusion from this investigation is that the coating 1355-20 is appropriate for operation under conditions of dry abrasive friction and also under conditions of erosion at prevailing angles of interaction of 60^o.

Acknowledgments

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5. References

[1] Kandeva M 2012 *The Contact Approach in Engineering Tribology* (Sofia: Publishing House TU-Sofia) p 504
[2] Bhushan B 2013 *Principles and Applications of Tribology* (New York: John Wiley & Sons) p 980
[3] Frolov KV 2014 *Modern Tribology Results and Prospects* (Moscow: LC p 580
[4] Kandeva M, Kamburov V, Zadorozhnaya E and Kalitchin Zh 2018 Abrasion Wear of Electroless Nickel Composite Coatings Modified with Boron Nitride Nanoparticles *JEPE of B.EN.A.* **19** (4) pp 1690-703
[5] Martin P M 2011 *Introduction to Surface Engineering and Functionally Engineered Materials*. (Hoboken: John Wiley & Sons) p 584
[6] Kandeva M, Karastoyanov D and Vencl A 2016 *Advanced Tribological Coatings for Heavy-Duty Applications: Case Studies* (Sofia: Marin Drinov Academic Publishing House) p 147
[7] Tashev P and Lazarova R 2013 Examination of layer overlaid with addition of TIN nanoparticles *MTC AJ* **11** (2) pp 7-12
[8] Wood R J K and Roy M 2013 *Tribology of thermal-sprayed coatings in Surface Engineering for Enhanced Performance against Wear* ed M Roy (Wien: Springer) pp 1-43
[9] Kamburov V, Dimitrova R and Nikolov K 2019 Electroless nickel coating of carbon microfibres and nanotubes intended for a reinforcing phase in metal / polymer matrix composites *J. Oxid. Commun.* **42** (1) pp 63–73
[10] Datcheva M, Dimitrova R, Iankov R, Sofronov Y and Kamburov V 2015 *Hardness characterization of laser cladding microsurfaced SiCp layers using instrumented indentation technique* Proc. Int. Conf. „70 years FIT" (Sozopol Bulgaria) pp 205-11