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Dry friction aspects of Ni-based self-fluxing flame sprayed coatings

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Abstract. In this paper we present the results tribological obtained in the course of dry wear tests on samples coated with three types of coatings produced from self-fluxing Ni-based powders. In this purpose were used three commercial NiCrBSi powders produced by various manufacturers, which have been sprayed against a low alloyed steel substrate using the flame spray thermal deposition method followed by flame remelting, resulting three different samples, denoted as: A, M and P. The first test was conducted on an Amsler type machine, with rolling motion between tribological contacts of third class. The analysed coating was deposited on the generator of the low alloy steel disc and the shoe was realized from a grindstone. The test was conducted for two situations: (a) constant load of 10 kg and 6 kg applied for 5 hours; (b) progressive load starting from 2 to 10 kg for two different speeds of rotation of the disc. The second test was the one of sliding wear and it was conducted on the UMTR 2M-CTR tribometer. The analysed layers were deposited on the flat surface of a low alloy steel lamella, and the friction was achieved with a conical grinding stone. The working parameters were as follows: 20N constant load, constant speed of 10 mm / s, sliding linear length of 30mm, the test duration being 45 minutes. After conducting the tests and after analysing the results, the following conclusions are drawn: a) during the first test has been obtained a global friction coefficient between 0.3 and 0.4 - typical for dry friction, highlighting some lower values in the case of sample A, in which case there were recorded smaller mass losses; b) at the second test was recorded an approximately linear behaviour of the three samples, with a gradual increase of the friction coefficient and a superficial wear mark revealed both by SEM microscopy and by profilometry.

1. Introduction

The coatings manufactured by thermal spraying technique are used for decades and begin to earn their rightful place in various fields of industry, being used in order to improve wear resistance, corrosion, thermal stresses etc. One of the most important types of wear encountered in many applications of thermal spray coatings is abrasive wear. It is even considered that more than 50% of malfunctions cases are caused by abrasive wear [1].

The major problem brought by the appearance of such a phenomenon is related to the costs involved in remediation and replacement of worn parts, the machine operation time and high cost of maintenance, if the phenomenon occurs with a high frequency. The phenomenon of abrasive wear can be classified according to several aspects: position of abrasive particles, surface tension, and appearance of wear particles. In the first case, abrasive wear processes are classified as: abrasion between two bodies (if abrasive particles are fixed), or abrasion between three bodies (if abrasive particles have a sliding or rolling free movement in the production of wear).

Some studies have shown that the failure modes can be characterized easier depending on the hardness of the deposited layer and the substrate [1, 2] and the type of material deformation, which can be ductile or brittle.

Thus, there can be described four cases:

1. *through – thickness cracking*: the cracks are stopped at the interface with the substrate but may extend into substrate when it is brittle. It includes tensile cracking behind the indenter, Hertzian cracking and conformal cracking when coating is bent into the scratch scar. [3, 4]
2. *coating detachment*: compressive spallation or buckling spallation in front of the indenter tip, or elastic recovery – induced spallation behind indenter tip [3, 4]
3. *chipping within the coating*: observed in the case of thick coatings on a softer substrate [5].
4. *chipping within the substrate*: in case of hard/brittle coatings, with very good adherence on hard substrates, the system tends to behave as bulk; if the coating is very thin, the chipping can occur.

In the present paper, the abrasive wear resistance of three Ni-base self-fluxing coatings deposited on a low-alloyed steel substrate via flame-spray method was tested using two methods.

2. Materials and methods

2.1. Materials

The samples used for the wear tests presented in this article were made by thermal spraying of commercial Ni-based powders (from two different manufacturers) on a non-alloyed steel substrate, the chemical compositions of the powders and the substrate being shown in table 1.

Table 1. The chemical composition of the powders and substrate used for coatings.

Chemical composition	%C	%Si	%Mn	%P	%S	%Cr	%Mo	%Cu	%B	%Ni	%Fe
Powder 1060-00	0.78	4.31	-	-	-	14.92	-	-	3.17	balance	3.82
Powder 1355-20	0.54	4.07	-	-	-	15.8	2.96	2.95	3.49	balance	2.72
Powder JK 586	0.7	4.3	-	-	-	15.0	-	-	3.1	balance	4
Steel sample	0.34	0.22	0.56	0.01	0.02	0.07	0.035	0.11	-	0.081	balance

Thermal spraying was accomplished by the Flame Spray method, followed by a remelting of the deposited layers, made in order to decrease their porosity and to fuse with the substrate grace to the boron content, the process parameters being presented in table 2.

Table 2. Flame Spray working parameters.

No.	**Parameters / operations**	**Values**
1	Acetone cleaning of the substrate	yes
2	Aggressive sandblasting with electrocorundum F20 to activate substrate surface	yes
3	Oxygen pressure	3 - 4 bar
4	Acetylene pressure	0.7 - 1.5 bar
5	The temperature reached during the deposition process	1000°C
6	The distance between the tip of the torch (flames) and the substrate	20 cm
7	Pre-heating temperature of the substrate	50 - 80°C
8	The remelting temperature reached after coating	800°C

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Two kinds of samples of different geometries were made for the wear tests: a cylindrical sample (disc with Φ50mm x 10mm) on which the coating was deposited on the outside of the generator and a parallelepiped sample (10x5x100mm) coated on all the faces. Corresponding to the three types of powders, three types of coatings were produced, encoded as follows: powder 1066 - coating P; powder 1355 - coating A; powder JK 586 - M. coating.

For the wear tests, were also used synthetic commercial abrasive materials from electrocorundum powders: parallelepiped abrasive stone for test 1 and conical stone for test 2.

2.2. Methods

Wear tests were carried out by two different methods, on two different test facilities: Test 1 was the sliding-motion wear for Class III couplings made on an AMSLER machine, and Test 2 was the linear friction wear with the 2M-CTR UMTR Microtribometer.

2.2.1. Wear test with the sliding-motion for Class III couplings

The study of friction in different tribological couplings was performed by experimental testing using the AMSLER type machine with the appropriate test specimens described above. Figure 1 shows the schematic diagram of the AMSLER machine. From the electromotor, the rotation motion is transmitted to the two specimens 1 and 2 via the kinematic chains z1-z2, z3-z4, z5-z6 and z1-z2, z2-z7, z8-z9 respectively. For the study of friction in Class III couplings, the specimen 2 is in the form of a shoe and the wheel z9 disengages from wheel z8 such that the speed n2 becomes nil. Figure 2 shows the configuration of the roller-shoe contact.

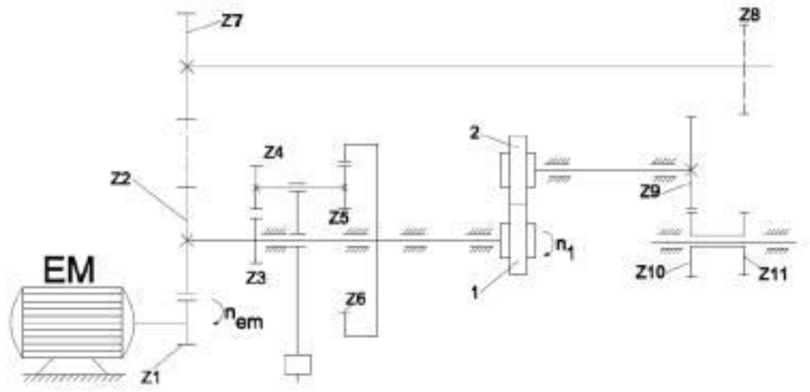

Figure 1. Schematic diagram of AMSLER machine.

Figure 2. Configuration of roller-shoe contact.

The measurement of friction momentum on the AMSLER type machine was carried out using the VISHAY P3 strain gauge bridge. Two strain gauges are mounted in shear half bridge configuration on the elastic lamella attached to the balancing system of the AMSLER machine. Once elastically deformed by a fixed pin, the strain gauges transmit a signal that is acquisitioned at each 1 second interval by the digital bridge Vishay P3, and then it is transmitted to a PC and stored for subsequent digital processing.

Under these conditions, tests were performed for two cases:

1. Constant loading of 10 kg and 6 kg respectively for a 5 hour test duration;
2. Progressive loading from 2 to 10 kg (each weight was added after 5 minutes, the minimum period required to stabilize the system) for two different rotation speeds of the rollers: 96 rpm, 192 rpm.

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2.2.2. Linear friction wear test

The linear sliding wear tests of the three types of coatings studied in this paper were performed on the UMTR 2M-CTR micro-tribometer, using as abrasive element a conical abrasive stone with spherical peak geometry, as presented in figure 3.

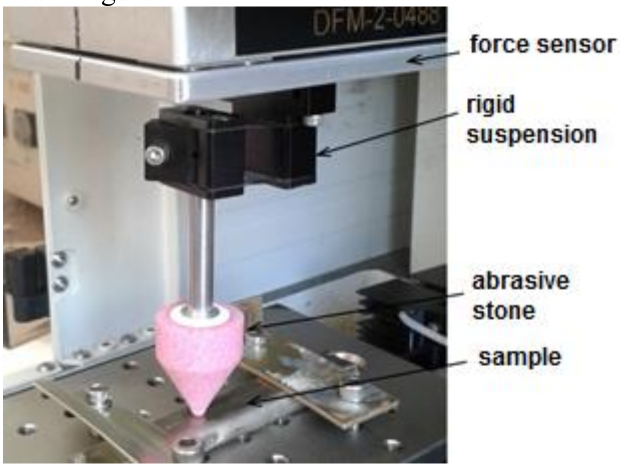


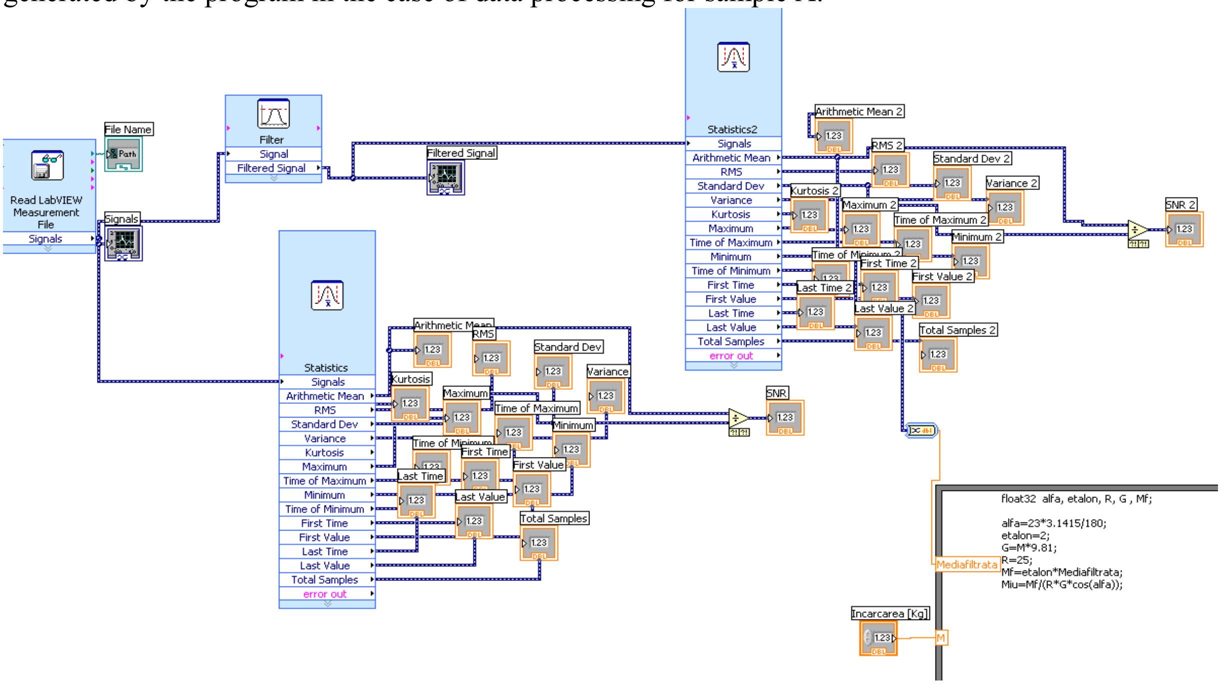
Figure 3. Working configuration for linear wear tests.

For each of the three samples, the tests were carried out at a constant load of 20N, with a constant speed of 10mm/second on a linear direction of 30mm in both ways for 45 minutes.

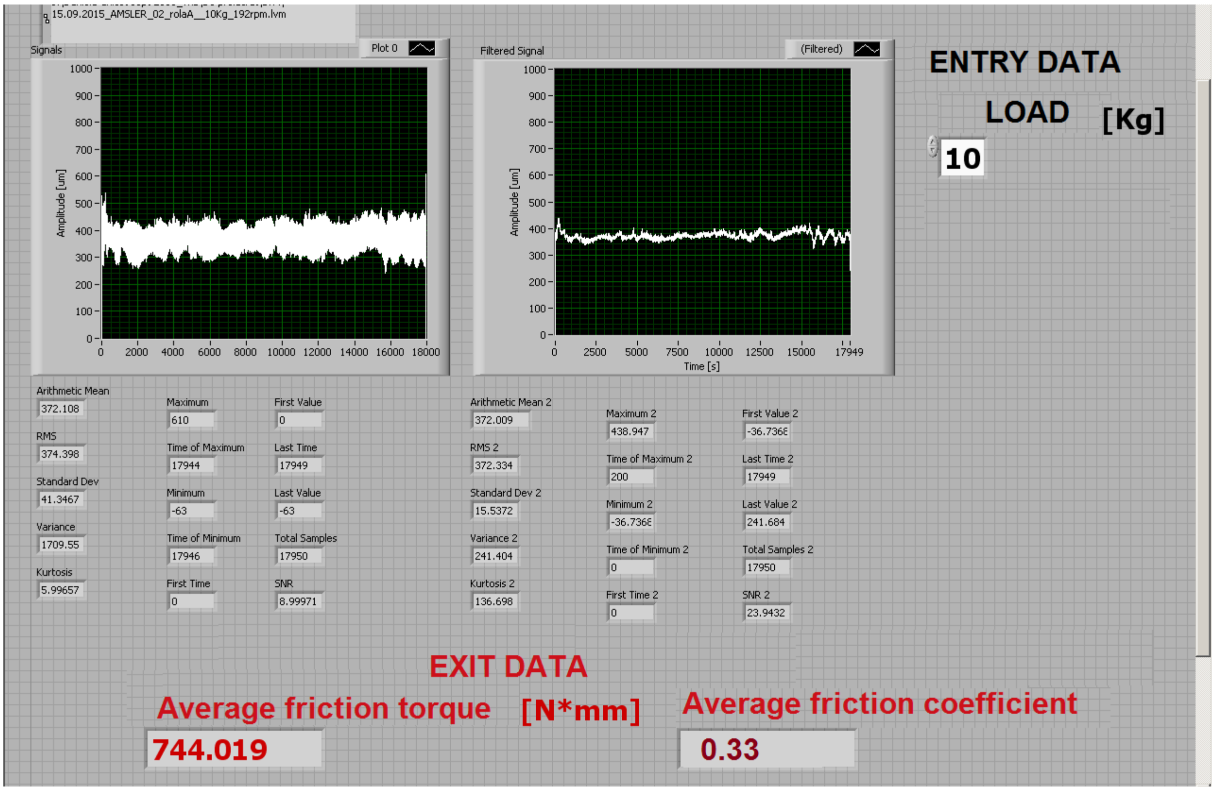
3. Results and discussions

3.1.1. Wear test with the sliding-motion for Class III couplings

The data recorded after the test 1 on AMSLER machine, regarding the variation of the friction momentum in the determination of the mass wear intensity were processed for mediation and filtering using the LabView program, figure 4a showing the program image, and figure 4b the graphic image generated by the program in the case of data processing for sample A.



a).



b).

Figure 4. Block diagram of the LabView program (a) and front panel image - data processing for sample A (b).

Based on the analysis of the results it was observed that, according to the dry friction law, the friction coefficient does not depend on speed, but only on load and on the nature of the materials in contact. Also, comparing the results, it was found that the dry friction torque increases with the load, according to the theory. It is observed that a global friction coefficient between 0.3 and 0.4, typical for dry friction is obtained, with a lower coefficient value for sample A. The phenomenon of pulling out of the abrasive particles is a dynamic one, as shown by the variation of the friction moment in time and by the friction coefficient values.

For the purpose of analysing the volume of material lost by wear friction, expressed gravimetrically (Δm), the weighing of the discs was performed before and after each test with an AGN 200 analytical balance. The results are summarized in table 3 and in figure 5a and 5b are presented graphically the corresponding mass variations.

Table 3. Mass variation of test specimens subjected to wear tests for a load of 10kg / 6kg.

Sample	Δm [g]	% mass loss [g] (from the initial weight – Δm*100/G_i)
disc P	0,1638 / 0.0816	0.1210 / 0.0603
disc A	0.1551 / 0.1119	0.1077 / 0.0778
disc M	0.1237 / 0.1080	0.0918 / 0.0802
shoe (P)	0.0135 / 0.0172	0.0635 / 0.0734
shoe (A)	0.0045 / 0.0205	0.0212 / 0.0303
shoe (M)	0.0067 / 0.0071	0.0315 / 0.0876

It is observed that the biggest percentage mass loss is produced in the case of sample P (coated with 1060-00 powder) in the 10 kg load test - 0.121%, respectively in the sample M (coated with JK 586

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powder) in the case of the 6 kg load test - 0.0802%. A mean loss value was recorded for sample A (coated with 1355-20 powder), which lost 0.1077% in the 10 kg load test and 0.0778% at the 6 kg load test.

An additional observation should be made with respect to the mass losses recorded for abrasive stones, which were higher in the 6 kg load test than the 10 kg load test, probably due to the formation of a lubricating film that was maintained within the contact and allowed a better slip for higher load test.

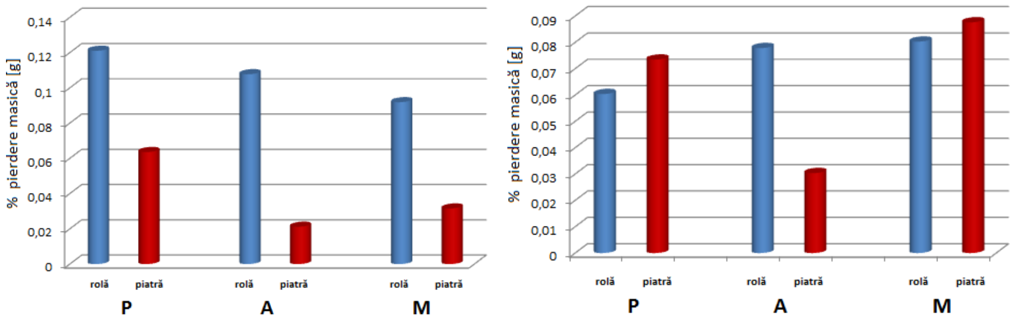


Figure 5.Graphical representation of the mass variations for the 10kg load (a) and 6kg load (b).

The values recorded after the test 2 - progressive load wear, variation of friction torque / coefficients are graphically represented in figures 6 and 7.

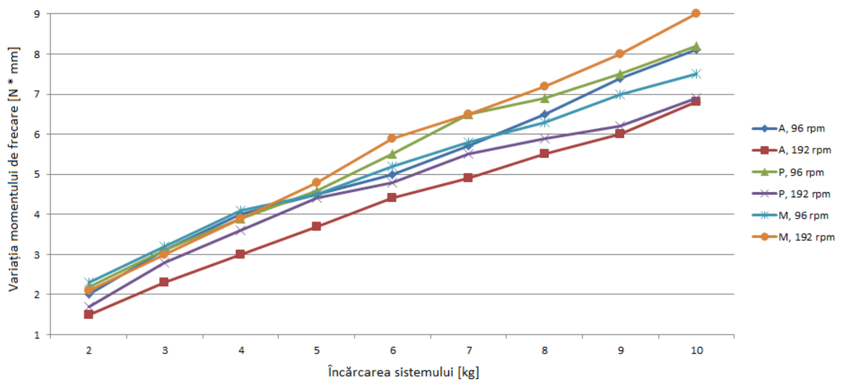


Figure 6. Friction torque variation during the wear tests with progressive load.

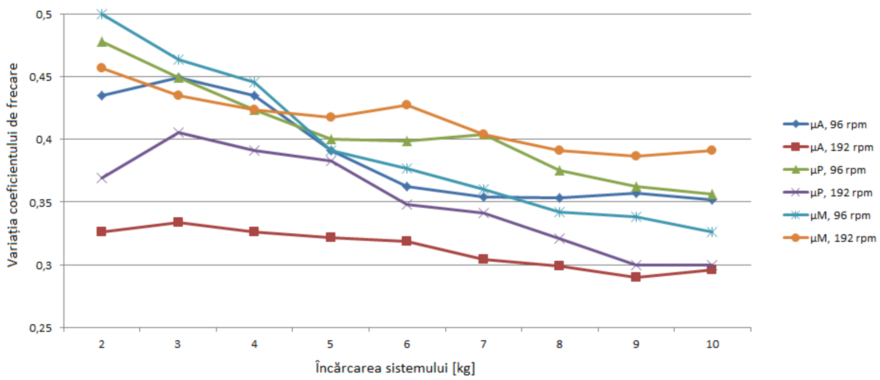


Figure 7. Friction coefficient variation during the wear tests with progressive load.

The behaviour registered during the tests can be explained by the fact that, at low speeds and small loads - at the beginning of the test - when there is no wear particles accumulation, the micro-cutting occurs and the friction coefficient is approaching the value 0.5.

As the load increases and time passes, there is an increase in the amount of wear particles (solid lubricant) which results in a slight decrease of the friction coefficient. It is also noticed that at higher speeds the formation of the solid lubricant film is favoured, the effect with the passage of time being the same, i.e. the slight decrease of the friction coefficient.

3.2. Linear friction wear test

The test parameters were recorded and processed, and charts of the friction coefficient variation over time were generated, as can be seen in figure 8 in the representative case of sample A.

There was observed an approximately linear behaviour, with a gradual increase in friction coefficient. In the details of each figure the "saw teeth" variation of the friction coefficient for small time intervals can be observed, which correspond to the 30 mm distance set for the tests.

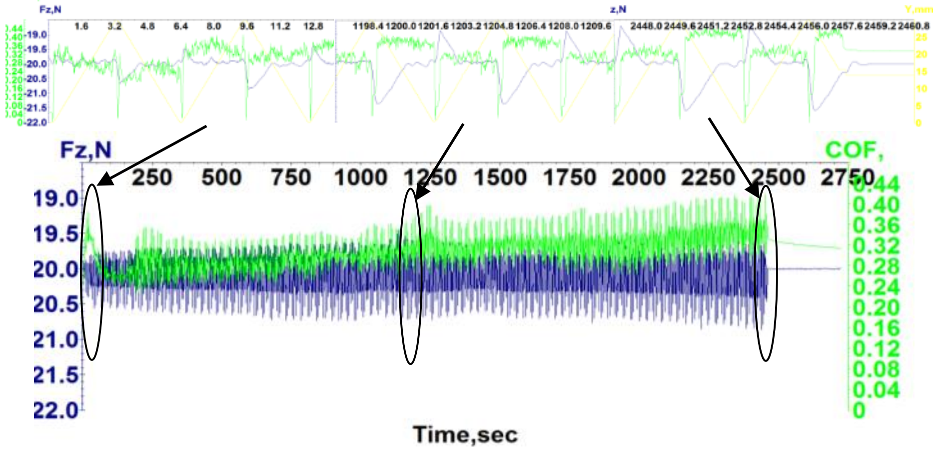


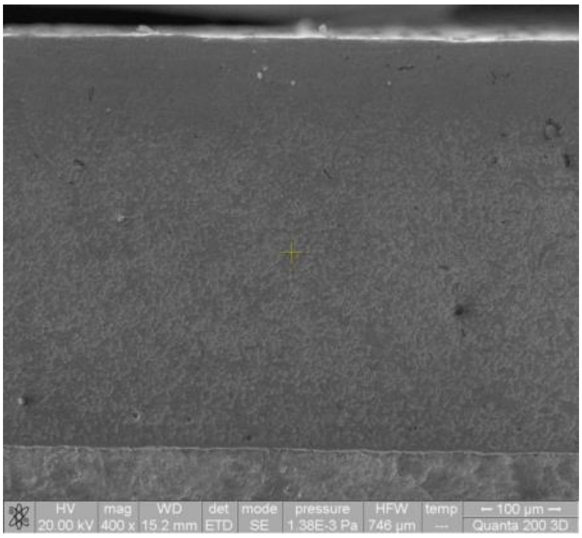
Figure 8. Variation chart with the time of COF/Fz for the sample A.

After each linear wear test, the wear of the coatings was evaluated by measuring the profile of the wear track on each of them, using the Form Talysurf Intra system. In all three cases, no major changes or visible wear signs were observed, but only a slight surface modification of the roughness, all of which confirming a good wear resistance of the studied coatings.

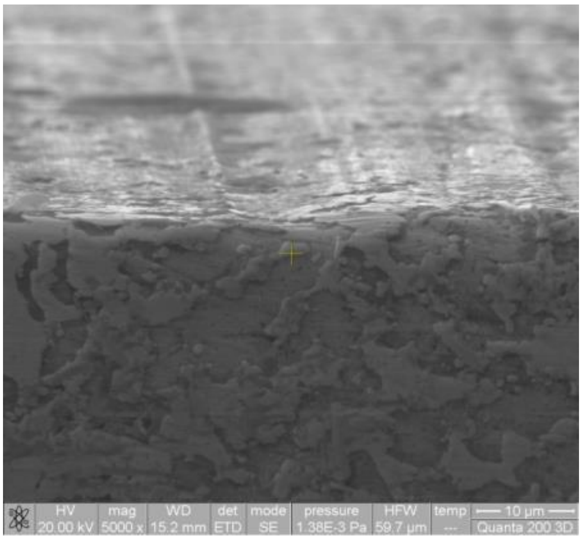
For further evaluation of the abrasion resistance of the three coatings, samples were taken from each linear friction wear specimen exactly from the area where the friction occurred. The cross section of these samples was metallographically prepared by grinding, polishing and chemical reagent attack (Vilella) to highlight the microstructure. The surfaces thus obtained were analysed by electronic microscopy, especially the way in which the wear was developed and how the coating was affected superficially and in depth.

The electron images acquired by electron microscope for each of the three samples are shown in figure 9 a-d. The slip surfaces resulting from linear wear tests were observed and highlighted; presenting no major differences depending on chemical composition of the studied coatings.

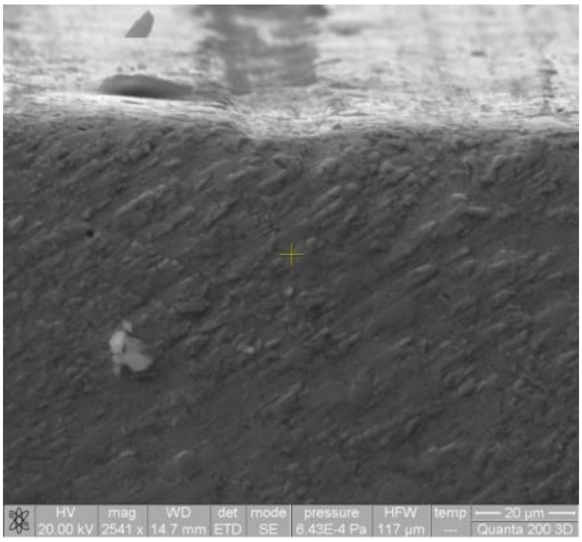
In figure 9a, both the microstructure of the deposited layer, the one of the steel substrate and the contact area between them are observed. No structural changes of the two materials are visible. It can be concluded that the wear phenomenon affected superficially the coating, without inducing cracks or weak points which subsequently generate peeling.



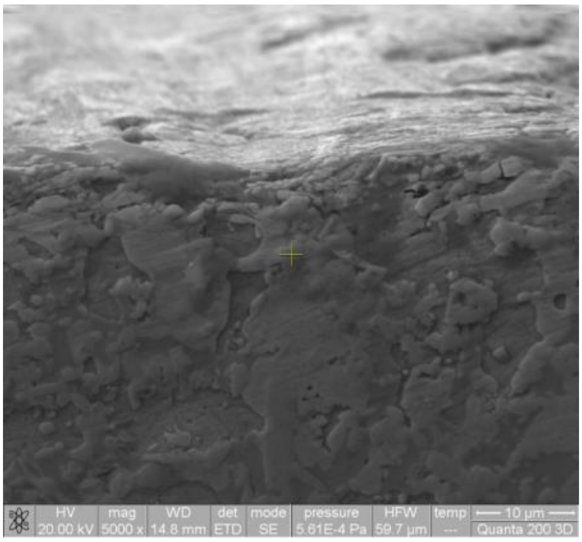
a)



b)



c)



d)

Figure 9. Secondary electron images in the cross section of the sample P- aspect at the coating – substrate interface at 160x (a); P – detail of the wear mark at 5000x (b); A - detail of the wear mark at 5000x (c) and M - detail of the wear mark at 5000x (d).

The figures 9b, c, d shows details of the resulting wear traces at magnification of 5000x. It is visible the preservation of the microstructure specific to these layers: columnar crystals (consisting of M7C3 carbides and M3B borides) and coarse crystals, all distributed in a metal matrix formed of Ni solid solution that supports these carbides and reacts to aggressive factors by a slight plastic deformation accompanied by a small loss of material. It is also clear the role of M7C3 type carbides to stop the cutting-breaking actions exerted by the abrasive particles.

4. Conclusions

Following the analysis of the obtained results, the following conclusions were synthesized:

- ✓ according to the dry friction law, the friction coefficient does not depend on the speed, but only on the load and the nature of the materials in contact;
- ✓ the dry friction moment increases with the load, according to the theory;

✓ a global friction coefficient with values between 0.3 and 0.4 was observed; typical for dry friction, with a lower coefficient for sample A;
✓ the phenomenon of the abrasive particles plucking is dynamic, as shown by the variation of the friction moment and of the friction coefficients in time;
✓ at low speeds and light loads, when there is no accumulation of wear particles, micro-spalling occurs and the values of the friction coefficient are approaching 0.5, but the increase of the load and the time passing conduct to an increase in the quantity of wear particles (solid lubricant), resulting a slight decrease of the friction coefficient;
✓ no major changes or visible signs of wear were observed, but only a slight superficial modification of the roughness, confirming a good wear resistance of the three studied coatings;
✓ abrasive wear behaviour is given by the microstructure specific to these coatings: column crystals (consisting of M7C3 type carbides which stop the cutting and breaking action of abrasive particles and M3B borides) and coarse crystals, distributed in a metal matrix formed by Ni solid solution that supports these carbides and reacts to aggressive factors by a paltry plastic deformation accompanied by a reduced wear.

5. References

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