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D. CRISTISOR[1], D.L. CHICET[2*], C. CIRLAN PALEU[1], C. STESCU[1], C. MUNTEANU[1,3*]

SUBSTRATE TEXTURE INFLUENCE ON THE DRY SLIDING WEAR BEHAVIOUR OF CO-BASED PLASMA SPRAY COATING

The mechanism in which the coatings made by thermal spraying adhere to the substrate is in most cases of a mechanical nature, thus being dependent on the morphology of the substrate surface. This paper study how the texture of the substrate influences the behavior of dry sliding wear, a behavior based on the adhesion to the substrate of the analyzed coatings. For this purpose, a Co – base powder, was chosen for atmospheric plasma spraying. For the substrate, a rectangular profile made of low-alloy steel was chosen, the surface of which was textured by mechanical abrasion, in order to obtain different degrees of roughness: sample S1 – Ra1 = 1.59 µm, sample S2 – Ra2 = 2.32 µm, sample 3 – Ra3.1 = 1.25 µm, Ra3.2 = 3.88 µm. In the case of sample 3, the texturing was done on one direction, with an elongated profile, so that the effect of the main direction of dry sliding wear on the quality of the coating could be studied. The tests were performed on an Amsler test machine, at constant load, for 1 hour. The samples were mounted in a fixed position, and the wear occurred on the basis of the rotation of the metal disc, without lubrication. It was found that the coating of sample 1 was the most affected, resulting even a partial delamination, and the best behavior was recorded in the case of sample 3.1.

Keyword: Co-base coating; substrate texture; plasma spray coating; dry sliding wear

1. Introduction

Thermal spraying, commonly known as metallization, is the process of applying a metallic, ceramic or ceramic-metallic coating to the surfaces of parts made of different materials. Depending on the type of coating chosen and the technology used (flame spray, high velocity oxi-fuel, plasma spray, electric arc, cold spray, kinetic spray, D-gun and other variants [1-7]) this process can be used to modify the functionality of the coated surfaces by improving their physio-chemical or mechanical properties: resistance to different types of wear, corrosion, high temperatures (thermal barrier coatings – TBC), increase or decrease of the friction coefficient, resistance to mechanical shock [8,9].

In order to obtain a reliable coating, which successfully fulfils its role but also has durability, the substrate surface preparation stage must be strictly fulfilled [10]. This stage is very important because it has a decisive influence on the quality of the bond of the coating to the substrate surface on which it is applied [11].

Thermal spray deposition techniques are generally based on bringing the coating material into a molten or semi-molten state and accelerating the droplets thus formed towards the substrate, with which they interact very strongly resulting in specific splats, which build up the coating layer by successive deposition [12].

If the surface of the substrate were also in a liquid (molten) state, then metallurgical bonds would be formed between the coating and the substrate, which would ensure a very good adhesion to the substrate [13]. However, in most thermal deposition technologies, the substrate surface is in a solid (non-molten) state, which is why such bonds cannot be created (except in the case of post-coating treatment by re-melting [14], and they are replaced by mechanical bonds – interlocking bonds.

Hence the importance of the preparation of the surface on which the coatings are applied by thermal spraying, which can ensure the formation of these bonds and thus a superior quality of the coating applied.

The substrate preparation stage can be customised according to several factors: the texturing method, which can be mechanical, chemical or thermal, the type of substrate, which

1 GHEORGHE ASACHI TECHNICAL UNIVERSITY OF IASI, DEPARTMENT OF MECHANICAL ENGINEERING, BLVD. MANGERON, NO. 61, 700050, IASI, ROMANIA
2 GHEORGHE ASACHI TECHNICAL UNIVERSITY OF IASI, DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING, BLVD. MANGERON, NO. 41, 700050, IASI, ROMANIA
3 TECHNICAL SCIENCES ACADEMY OF ROMANIA, 26 DACIA BLVD, BUCHAREST, 030167, ROMANIA

* Corresponding authors: daniela-lucia.chicet@academic.tuiasi.ro; corneliu.munteanu@academic.tuiasi.ro

can be compact or obtained by additive manufacturing [15], the geometrical complexity of the surface. However, there are two common actions that must be applied in any of these cases, as shown in Garcia-Alonso's work [13]:

1. rigorous cleaning of the surface: removal of any traces of contaminants (oil, oxides, dust, previous coatings, etc.) that may become barriers between the substrate and the coating,
2. modification of surface roughness (texturing).

The most commonly used texturing method applied at industrial level is grit-blasting, which ensures simultaneous cleaning of impurities and modification by plastic deformation of the surface [16], that will acquire a roughness equivalent to that obtained after the use of 80 or 100 grit abrasive paper.

In this process, hard particles (usually corundum of various grain sizes) are accelerated by a jet of compressed gas and hit the surface of the substrate with very high energy, creating pits and crevices. These provide a larger contact surface (grip surface or foot-hold) for the thermally sprayed layer to form the interlocking bonds with the substrate [17].

With the diversification of the materials on which thermal spray deposition can be carried out, the need to develop other methods of surface texturing has arisen, one example being that of soft materials which can be damaged by blasting through the formation of cracks or grit inclusions [18,19]. Thus, substrate preheating [20], water-jet or carbonic-jet gas and laser pre-treatments started to be used, an example of this category being the PROTAL process [21] based on laser ablation, which provides a reduction in processing time and a minimization of the risk of surface contamination. Another laser-based approach is texturing by drilling holes on the surface of the substrate of different depths, diameters and distribution [22]. A further study [23] shows that laser surface texturing brings with it an improvement in wear resistance by increasing adhesion to the substrate, and of the texturing directions considered (parallel, perpendicular and square), the latter is the most effective for WS2-coated machining tools.

In the case of the TBC coatings studied by Tang et al. [24], a layer of 8YSZ/CoNiCrAlY was deposited by APS on linear and diamond textured substrate with femto-laser. The thermal shock resistance tests showed that linear texture improves more than diamond texture the concentration mode of thermal stresses in the deposited layer and is preferred. Also, in the case of TBC made of 8YSZ top coat by supersonic plasma spray, L. Wang et al. [25] studied the effect of parallel direction texturing of the bonding layer (made of NiCoCrAlY) with nanosecond fibre pulse laser. It was observed that in this case, bond coat texturing provides crack propagation control and separation mode of the exfoliated portions, thus prolonging the overall durability of the coating.

In the literature there are other studies [26] indicating that different texturing patterns influence the substrate adhesion strength of the TBC coatings, those with groove pattern being most effective. Another approach to the influence of texture on adhesion is related to the existing contact stresses as they determine delamination propagation [27]. When the value of the existing stress (normal stress) is higher than the crack resistance between layers, spalling propagates at high speed and delamination becomes the main mechanism of coating destruction. Surface texturing plays a very important role in this case as it ensures the redistribution of stresses formed at the coating-substrate interface and can reduce the speed of crack propagation.

Another pre-treatment method applied to surfaces prior to thermal spray coating is the ultrasonic surface rolling process (USRP), which can be applied to metallic materials because it can induce severe plastic deformation and refine surface grain, simultaneously leading to a change in surface morphology [28]. The applied tribological tests showed a decrease in the wear rate by 44.2% (dry friction) and 73.4% (wet friction) compared to the results obtained for the same coatings applied to surfaces prepared by grinding.

Based on the observation that particle blasting involves high particle consumption and the energy required to pulverise the particles, a method of surface activation by mechanical abrasion was developed based on the use of a specially designed rotating brush-like wheel, called bristle blasting [29]. This method has been tested by comparison with grit blasting and mechanical grinding on two different substrates (aluminium alloy 7075 and low-alloy steel A283), and it has been observed that the texture obtained in this way has an intermediate geometry between the two, being characterised by surfaces with peaks and troughs on parallel surfaces and can be a solution for substrate preparation when neither of the other two can be applied.

Starting from the data collected from the literature on surface texturing methods used during the surface preparation stage for thermal coating, we considered it appropriate to study the mechanical processing texturing method, which can be easily adapted to most types of materials, to different geometries of the surfaces on which deposition is made, does not affect the environment and is portable. Thus, in this paper, the influence of roughness and texturing direction realised by mechanical grinding of the substrate surface on the abrasive sliding wear resistance of a thermal spray coating produced by the atmospheric plasma spray (APS) method is studied.

2. Materials and methods

In order to study the influence of the surface texture onto the wear resistance of the thermal spray coating, a commercial Co-base superalloy (Co-Ni-Cr-Fe) powder with a hardness of about 55 HRC was chosen for coating by atmospheric plasma spraying. This special composition, as presented in TABLE 1, ensures good mechanical properties and oxidation resistance, providing at the same time excellent corrosion resistance for high temperature applications [30].

The SprayWizard 9MCE Facility (Metco-Oerlikon, 2006) was used for the thermal spraying, with the following parameters: voltage – 62.2 V, intensity – 492 A, primary gas flow (argon) – 62 NLPM, secondary gas flow (hydrogen) – 49 NLPM, powder feed rate – 91 gr/minute, stand-off distance – 85 mm.

For the substrate, a rectangular profile (100×40×5 mm) made of low-alloy steel (see TABLE 1) was chosen, from which the samples were cut. The surface of each sample was textured by mechanical grinding, in order to obtain different degrees of roughness. The substrates of Samples 1 and 2 were grinded with abrasive paper: 1000-grit for Sample 1 and 100-grit for Sample 2.

TABLE 1

Chemical composition of the base powder

Chemical element %wt	Co	Ni	Cr	Fe	Si	C	Mn
Powder	34-37	28-32	24-27	1.2-3	1.4-1.6	max 0.2	0,1-0,3
Steel substrate	—	—	—	bal	1,2-2,1	max 0.1	0,8-1,2

In the case of Sample 3, the surfaces were machined by abrasion with an abrasive stone mounted on a commercial bench grinder, with an 80 grit grinding stone and an idle speed of 2950 rpm. The texture was obtained on one direction, with an elongated profile, so that the effect of the main direction of dry sliding wear on the adhesion of the coating to the substrate could be studied. The resulted samples were studied on parallel direction with the principal texture axis (RS3.1) and on perpendicular direction with the principal texture axis (RS3.2).

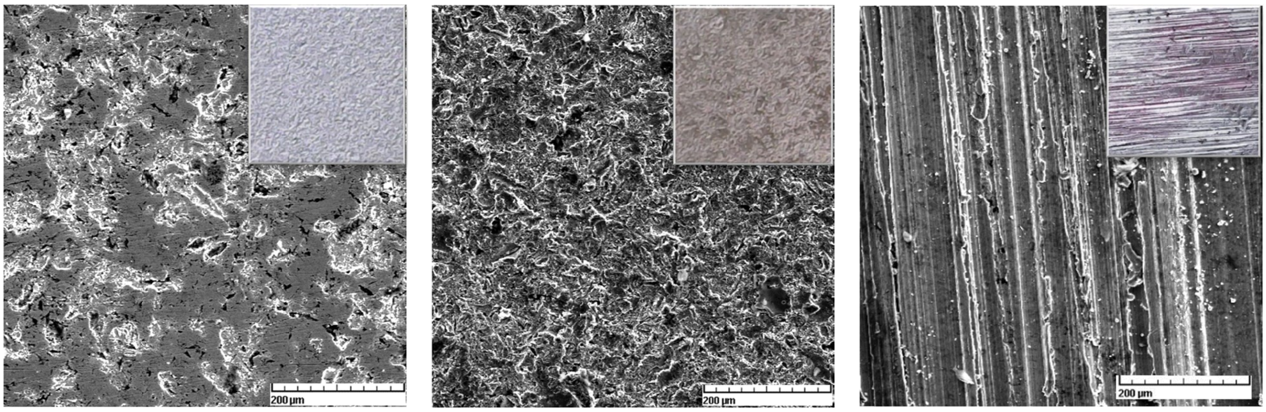
Mitutoyo SJ-301 portable surface roughness Tester was used for the roughness measurements of the sample's substrate and of the coated layers, with a measurement medium speed of 0.5mm/s, the resulted values being presented in TABLE 2.

TABLE 2

Surface roughness values of the samples

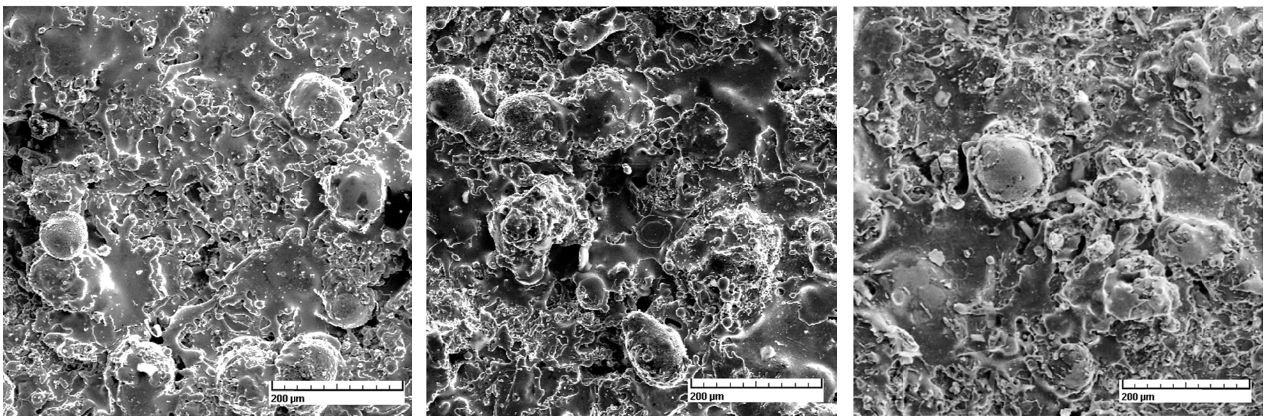
Sample type	S1 (μm)	S2 (μm)	S3.1 (μm)	S3.2 (μm)
substrate surface – Ra	1.59	2.32	1.25	3.88
substrate surface – Rz	13.25	17.79	7.66	28.90
substrate surface – Rq	2.20	3.02	1.58	5.29
coating surface – Ra	16.34	13.00	15.55	15.55
coating surface – Rz	79.52	68.04	74.14	74.14
coating surface – Rq	19.57	16.02	19.30	19.30

The aspect of the substrate surfaces is presented in Fig. 1a-c for the four samples. The secondary electron (SE) images show the morphology of the substrate and its texture correlated with the texturing mode described above and the measured roughness. To complete the characterization of the samples in their initial state, images of the coatings resulting from thermal spraying



a) b) c)

Fig. 1. The substrate SE and optical (detail) image of representative samples from each batch: a) Sample 1 (S1), b) Sample 2 (S2), c) Sample 3 with parallel direction of texture (S3.1), respectively with perpendicular direction of texture (S3.2 – detail image)



a) b) c)

Fig. 2. The SE image of representative coatings from each batch: a) Sample 1 (S1), b) Sample 2 (S2), c) Sample 3 (S3.1)

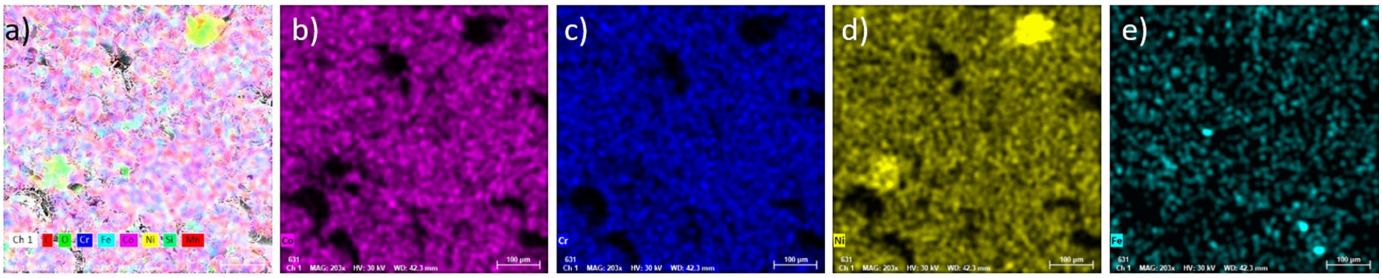


Fig. 3. The chemical composition map of a representative S1 coating: a) general distribution of all chemical elements from the coating, b) Co distribution, c) Cr distribution, d) Ni distribution, e) Fe distribution

on the substrates with different textures, shown in Fig. 2, were taken for each of the three types. No major influence of substrate morphology on the coatings is observed, as they are characterized by a uniform distribution of the component chemical elements, shown in Fig. 3, on the distribution maps obtained for sample S1 by EDS (energy dispersive X-Ray) analysis.

The dry sliding wear tests were performed by experimental testing using the AMSLER wear test machine, with the test specimens previous presented. Fig. 4 [14] presents the specific diagram of a universal AMSLER machine, characterized by the transmission of the rotation from the electromotor to the samples through the kinematic chains z1-z2, z3-z4, z5-z6 and z1-z2, z2-z7, z8-z9 respectively. For the study of dry sliding wear, the machine was used with the class III couplings: the sample with fixed position replaced the z9 wheel (z8 wheel was also removed from the chain) so that the speed n2 becomes n1, as presented in Fig. 5. The tests were carried out at constant load of 80N, for 40 minutes, at 100 rpm. As presented, the samples were mounted in a fixed position, and the wear occurred on the basis of the rotation of the metal disc, without lubrication.

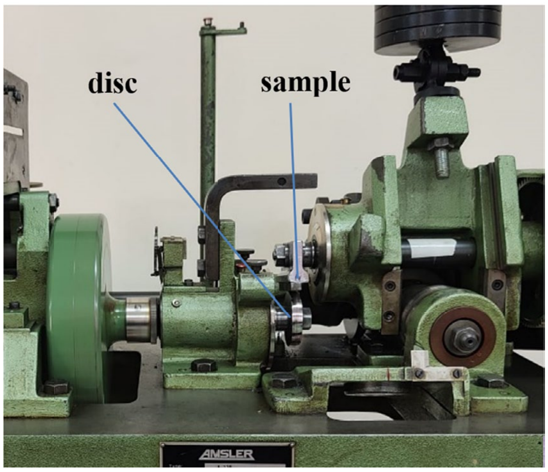


Fig. 5. Configuration of disc – sample contact

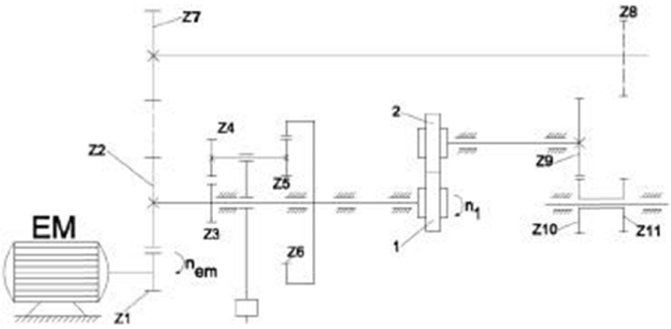


Fig. 4. Schematic diagram of AMSLER machine

3. Results and Discussion

After the mechanical tests were performed, the aspect of the samples was analysed by direct observation and by SE images, a representative aspect of each being presented in Fig. 6a-d. It was noticed that in each case the coatings were affected by the contact with the rotating metallic disc, the major failure being the one observed in the case of Sample 1, which exfoliated in the first 5 minutes of the test. This is the reason for which Sample 1 was not included in any further investigation.

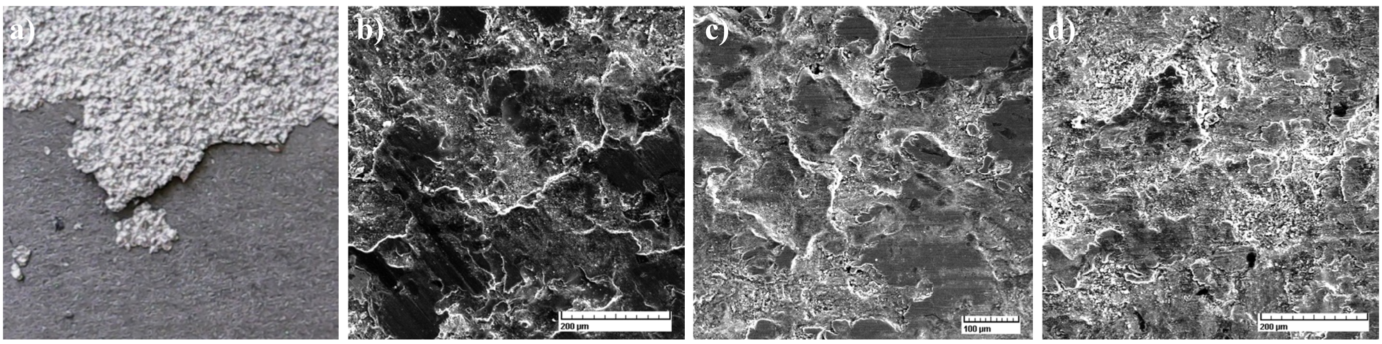


Fig. 6. The coating wear mark aspects of representative samples from each batch: a) S1 (exfoliation), b) S2, c) S3.1 and d) S3.2, after the dry sliding wear test

On the other three types of samples, traces of wear were observed in the form of darker stains, caused by the accumulation of oxide residue resulted from dry friction against the metallic disc. An explanation of this behaviour can be sought in correlation with the texture of the surfaces, as it can be observed that, although sample 1 had a roughness several units higher than sample 3.1, the layer deposited on the former was immediately exfoliated. This can be explained in terms of the linear texture parallel to the direction of application of the dry wear of sample 3.1, which formed more effective locking areas of the coating than those on the surface of sample 1, which was not textured in any direction.

In order to fully characterize the wear marks, distribution maps of the chemical elements on their surfaces were made and the results are shown in Figs. 7, 8 and 9 for samples 2, 3.1 and 3.2 respectively. Compared to the uniform appearance of the coatings in their initial state, the zonally differentiated distribution of the elements Co, Cr and Ni is evident compared to that of Fe, resulted from the dry wear of the metallic disc. This aspect is confirmed by the increase of the Fe percentage from the initial value of 1,2-3 wt% to a percentage of 26-28 wt% after the dry wear test, as measured by the EDS analysis.

Regarding the dry sliding wear, the mean values of the recorded friction coefficient (μ), respectively friction torques (Tf) for each type of sample are presented in TABLE 3. Also, the measurements of the friction torque recorded and processed using LabView software are summarized in Fig. 10.

TABLE 3

Mean values of friction coefficient and friction torque

Sample / Measured parameters	S2	S 3.1	S 3.2
Friction coefficient (μ)	0.234	0.229	0.223
Friction torque (Tf)	542.79	530.47	515.40

It is observed that the increase in the roughness of the substrate produces a change in the roughness of the coating deposited by thermal spraying. This is observed both from the roughness measurements and from the friction behaviour, where

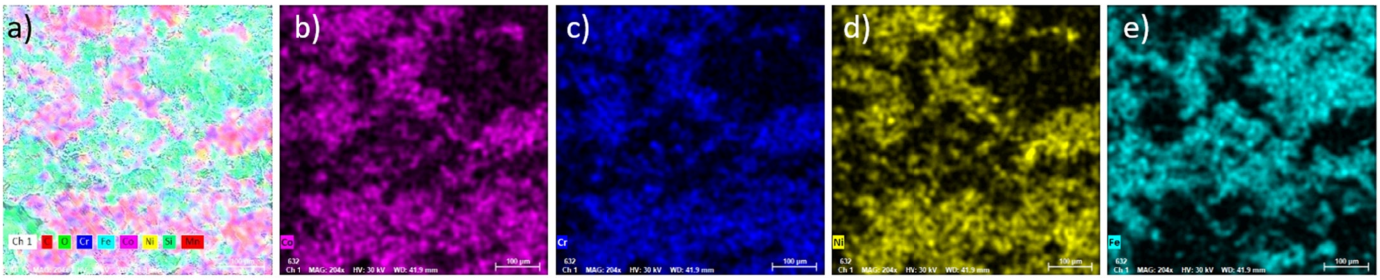


Fig. 7. The chemical composition map of a representative S2 wear mark area: a) general distribution of all chemical elements from the coating, b) Co distribution, c) Cr distribution, d) Ni distribution, e) Fe distribution

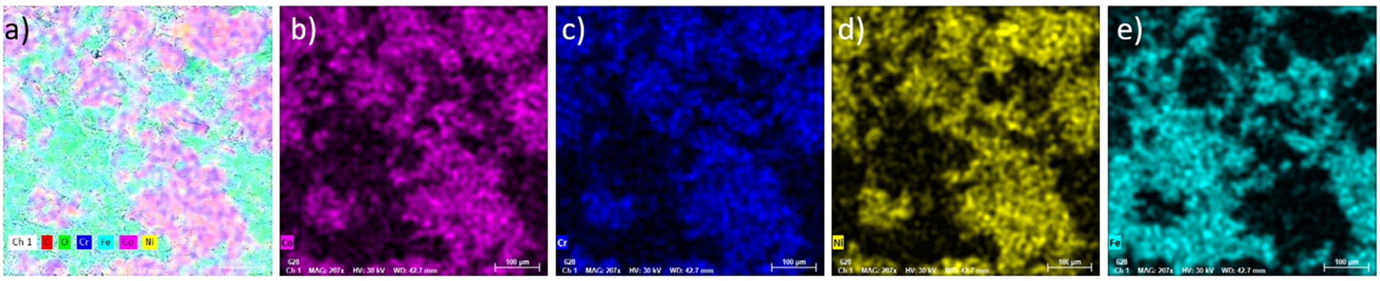


Fig. 8. The chemical composition map of a representative S3.1 wear mark area: a) general distribution of all chemical elements from the coating, b) Co distribution, c) Cr distribution, d) Ni distribution, e) Fe distribution

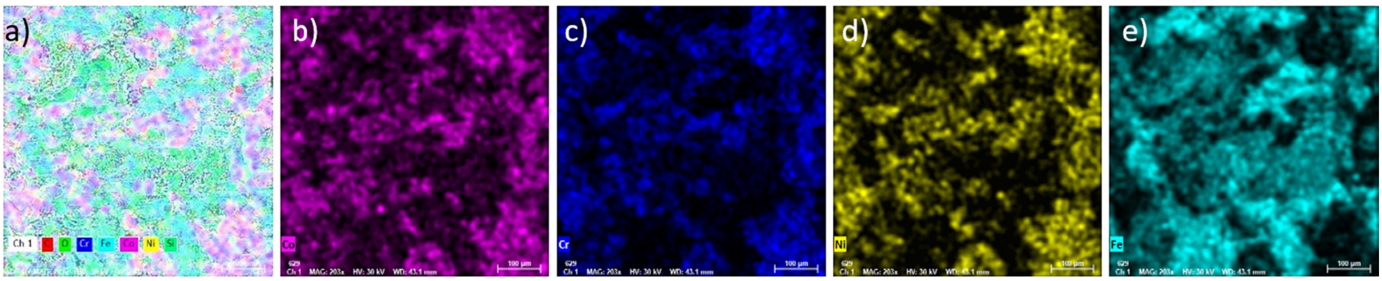


Fig. 9. The chemical composition map of a representative S3.2 wear mark area: a) general distribution of all chemical elements from the coating, b) Co distribution, c) Cr distribution, d) Ni distribution, e) Fe distribution

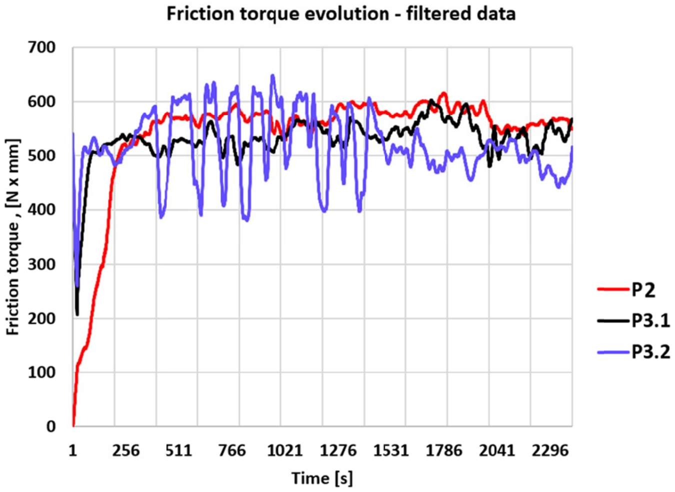


Fig. 10. Friction torque evolution, filtering smoothing moving average, half-width of moving average 10

the friction torque of the S 3.2 sample fluctuates very strongly during the first 30 minutes, after which it decreases to a value of 515.4 N*mm, once with the friction coefficient that has a final value of 0.223.

4. Conclusions

The samples tested were named S1, S2, S3.1, and S3.2. The S1 and S2 substrate were prepared by 1000-grit and 100-grit sandpaper grinding with roughness's of Ra1 = 1.59 μm, respectively Ra2 = 2.8 μm. The texture of the samples S3 was obtained by unidirectional abrasion with an abrasive 80-grit grinding stone mounted on a commercial bench grinder. Sample S3.1 showed a longitudinal roughness Ra3.1 = 1.29 μm of the substrate, while the substrate of sample S3.2 was obtained with a roughness transverse to the direction of friction Ra3.2 = 3.8 μm.

Following the friction results, it appears that the higher substrate roughness influenced the homogeneity of the coating and sample S1 failed by exfoliation after 5 minutes of dry sliding wear test. Accordingly, sample S3.2 showed a strong fluctuation of friction torque in the first 30 minutes, after which the friction torque became stable and the average friction coefficient at the end of the test was the lowest for sample S3.2. Sample S3.1 with longitudinal roughness Ra = 1.29 μm showed the lowest frictional torque at the beginning of the tests. For samples S2, S3.1, and S3.2, the average friction coefficients during the tests were very similar: 0.234, 0.229, and 0.223 respectively.

Further tests will be conducted in order to elucidate the optimum roughness required and the best method of substrate preparation in terms of the lowest friction coefficient and wear intensity as well as the highest scratch resistance.

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