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Study of the wear behavior of bronze coatings deposited by the EAS method

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Abstract. Research in the present paper has highlighted the availability of using bronze coatings, obtained by electric arc spray (EAS) method, for the purpose of increasing the life time of materials tested for abrasive sliding wear. The experimental plan of the work includes the analysis of three types of samples: S1 (samples deposited with a CuAl 90-10 layer on a steel-type base material), S2 (casted sample from CuAl9 material) and S3 (bearing material sample). The sliding wear analysis were obtained on a specific testing machine in a lubricated environment (clean oil) at a preset loading, obtaining both the friction coefficient for each material type and the material loss for each sample. The results showed an average strength of the bronze coated sample (S1), its mechanical characteristics being higher to the other two analyzed samples.

Keyword: electric arc spray, friction, wear, bronze coatings, microstructure.

1. Introduction

Damage of the surfaces of parts that operate in demanding work environments is one of the main causes of shortening their lifespan and, at the same time, causes higher operating costs [1,2]. Consequently, once with the technological development, the engineers have sought more efficient ways of improving the surface resistance for various types of wear. One of the methods that have grown exponentially in recent decades is the wear resistant coating from different materials by thermal spraying [3].

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Starting from a simple idea, patented by Ulrich Schoop in 1909, in which a material is brought to the melting temperature, and the droplets are accelerated by a gas flow to a substrate on which the coating is formed [4], have been developed until currently a multitude of thermal deposition technologies, to respond to the most unique applications [5 - 8].

Thermal spray deposition technologies are based on five basic processes: flame spray (FS), arc spraying (EAS), atmospheric plasma spraying (APS), high-velocity oxy / fuel (HVOF) and detonation gun spraying (DGS), based on which new applications have been developed: high velocity air fuel (HVAF), cold gas spraying (CGS), high-velocity suspension flame spraying (HVSFS), vacuum plasma spraying (VPS), liquid stabilized plasma spraying (LSPS), laser spraying (LS) a.s.o. [9 - 14].

One of the applications whose viability has been investigated is to cover some of the surfaces of the pumps, which are subject to wear during operation of cavitation and abrasion, as fluids flow in them are most often contaminated with solid particles in various proportions. These particles have sizes ranging from a few microns to hundreds of microns [15, 16].

An extreme case is that of slurry erosion, which is a complex wear process, because the effect of the turbulent flow of the fluid is combined with the strong abrasive effect of the particles entrained in it [17]. The presence of contaminated particles determines the production of several erosion mechanisms that produce the final wear of the surfaces: cutting mechanism, plowing mechanism, surface deformation and cracking [18, 19].

Other research [9] of slurry erosion redefines the erosion mechanism produced as follows:

- cutting mechanism is associated with the phenomenon of interaction of erosive particles with the surface at an oblique angle, with enough energy to detach a fragment from it, and
- the deformation mechanism is associated with the impact of solid particles from the erosive fluid, which falls perpendicular to the affected surface, with a kinetic energy high enough to produce plastic deformation and cracks in the immediate vicinity of the surface that cause its destruction.

This article presents a study of the wear resistance of a coating made by thermal spraying of bronze (Cu-Al 90-10), assuming its use to cover the inner surface of the cam ring of vane steering pumps. In the present study we started from the premise that, under the conditions of operation with impure fluid, its erosive action is accentuated by the action of the metal pallets and could be assimilated to the abrasive slip wear. It was considered appropriate to test the wear resistance of the studied coating on an Amsler type tribometer, with a working configuration in which the coated sample acts as brake shoe and the moving body is a bearing steel disc, the testing being performed in an oil-lubricated environment. For the comparative evaluation of the results, a cast CuAl9 alloy sample (close to the chemical composition of the coating) and a bearing steel sample were tested under the same conditions.

2. Experiment

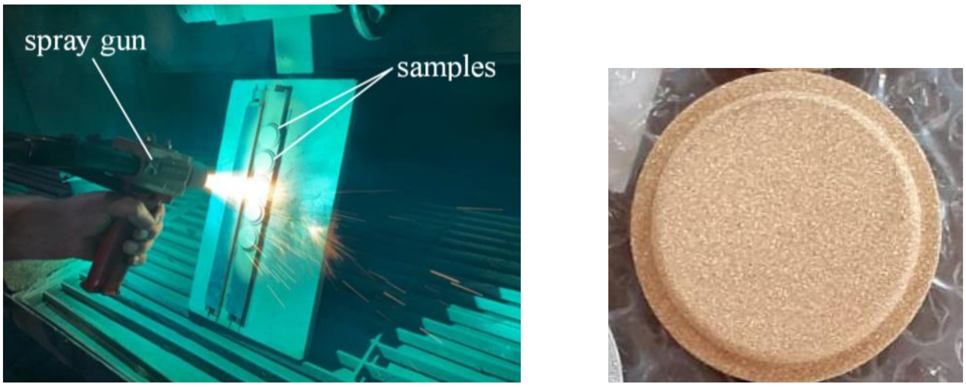
In order to study the possibility of using thermal sprayed CuAl coatings in assemblies subjected to abrasive wear, a set composed of three types of samples was prepared:

- S1 (sample coated with Cu-Al 90-10 powder);
- S2 (cast sample from CuAl9 Y80 alloy, according to ISO 1338);
- S3 (100Cr6 bearing steel sample, according to ISO 683-17).

The first sample (S1) is a thermal coated sample, produced by electric arc deposition method (see Fig. 1a) with a Cu-Al 90-10 commercial wire manufactured by FST Netherland, with a nominal composition of 10 wt% Al and 90 wt% Cu. The thermal spraying parameters were: output voltage - 30-32 V, output amperage - 200 A, spray distance - 150 mm. The substrate used for the coating is realized from low alloyed steel, which chemical composition is presented in Table 1.

Table 1. Chemical composition of the S1 substrate

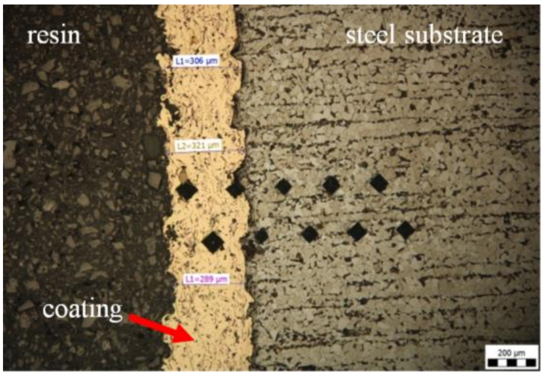
Chemical element	Fe	C	Si	Mn	Cr	Ni	Cu
%wt	bal.	0.22	0.25	0.58	0.22	0.14	0.36



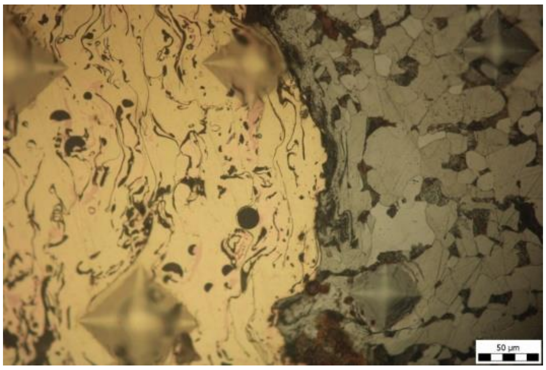
a) b)

Fig. 1. Aspects of: a) electric arc deposition process; b) as-coated sample S1.

As presented in Fig. 1b, the as-sprayed sample S1 has a rough aspect, specific to the one obtained by thermal coating. For the microstructure analysis of the coating, one of the samples was cross-sectioned and prepared by resin embedding, polishing, etching and observed using an optical microscope (OM). The microstructure of the coating is presented in Fig. 2. It has a thickness between 280 - 328 μm and a lamellar structure resulted after the stacking and rapid solidification of the molten or semi-molten droplets of bronze, accelerated toward the substrate during the thermal spray process.



a)



b)

Fig. 2. Microstructural (OM) aspects of the S1 cross-section at various magnifications: a)50x, b)400x.

The two last samples (S2 and S3) were considered necessary for the comparative evaluation of the wear behavior of the coating deposited by thermal spraying from CuAl, because the aimed application of this study involves the wear resistance of the cam ring inner surface in the case of a hydraulic power steering pump. The as cast bronze sample (S2) was used for comparative observation of similar materials (CuAl 90-10) produced by two different techniques, and the 100Cr6 bearing steel was used because most of the commercially available cam rings of the power steering pumps are produced from this type of material.

Before the wear tests, all the samples were finished using sandpapers of various grit and lapping (as presented in Fig. 3), to obtain a comparative roughness of the inner side of the cam rings, as close as possible to the one used in mass production, Rz = 0,3 μm accordingly to [20]. The roughness of the samples and disc was obtained as the arithmetic mean values of three identical measurements with the Form Talysurf 50 stylus Profilometer (Taylor Hobson, UK), and the results are presented in Table 2.

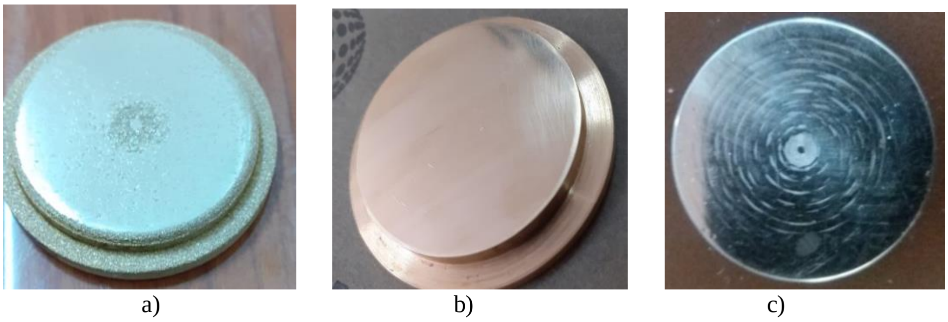


Fig. 3. Aspects of polished samples: a) S1 ; b) S2; c) S3.

The sliding wear tests were conducted on an Amsler type testing machine („two-disc machine"), which is successfully used for testing the rolling and sliding wear of various materials under a wide variety of testing conditions. The Amsler tribometer is a type A 135 commercially apparatus produced by Wolpert Werkstoffprüfmaschinen GmbH. in Switzerland and is located in the Faculty of Mechanics (Technical University of Iasi, Romania). The testing conditions used for this study were as follows: samples S1, S2 and S3 were mounted in the upper side (with a brake shoe role), in a fixed position obtained by interrupting the gears transmission chain [21]. The rotating disc is mounted in the lower part of the system (see Fig. 4) and is made of bearing steel AISI 52100 characterized by a hardness of 60-64 HRC. The disc has a thickness of 10 mm, a radius of 29.5 mm, both on radial and axial directions and a finished surface which roughness is presented in TABLE 2. After each test, the rolling disc was polished in order to maintain the initial Rz roughness around 0.9 μm. The tests were performed in a greased environment, in the conditions of a clean fluid, the rolling disc being immersed in the lower half part, in a container filled with oil (Castrol ATF Multivehicle), with the following characteristics: relative density (at 15°C) of 0.85 g/ml and kinematic viscosity (40°C) of 35 mm^2/s.

Fig. 4. Detailed aspect of the wear testing system (on Amsler type machine).

Table 2. Roughness of the tested samples, R_z

Sample	S1	S2	S3	Rolling disc (AISI 52100)
R_z roughness [μm]	1.43 ± 0.05	0.06 ± 0.003	0.34 ± 0.02	0.9 ± 0.1

The tests were performed at constant load value of 60 N (obtained by using dead weights), at a constant speed of 200 rpm during one hour for each test. Each test was repeated three times. The data regarding the friction torque variation were recorded using a data acquisition chain based on tensometric measurements and a Vishay P3 strain gage bridge. After that, the processing of the data was realized using a LabVIEW virtual instrument. For the evaluation of the material loss on each sample, the wear traces were measured also with the Talysurf 50 stylus Profilometer on longitudinal and transversal directions.

3. Results and Discussion

3.1. Topography of Worn Surfaces

After the tribological tests were performed, the aspect of the wear paths were observed, directly, for each sample. It was noticed that in each case a „spot" with different dimensions appeared, which means that all the surfaces were affected by the sliding wear. Fig. 5 a,b,c presents the resulted wear spots, marked with dotted line for each sample.

a) b) c)

Fig. 5. Wear mark aspect of:
a) bronze coated sample S1, b) bronze as-cast sample S2, c) bearing steel sample S3.

3.2. Friction Tests

The friction tests were conducted on the AMSLER type machine, in wet conditions, at constant load and speed. The evolution of the friction torque in time was recorded with a data acquisition system and the values were post-processed with LabVIEW software, in order to obtain the mean values of the friction coefficients. As presented in Fig. 6, the friction torque of samples S1 and S2 had a higher value at the beginning, which decreased after the first 200 seconds, but with a lower value than the overall friction torque of the sample S3. The lowest friction coefficient was recorded for sample S1, but very similar with the one of the S2 sample and smaller than the one of the steel samples, as presented in Fig. 7.

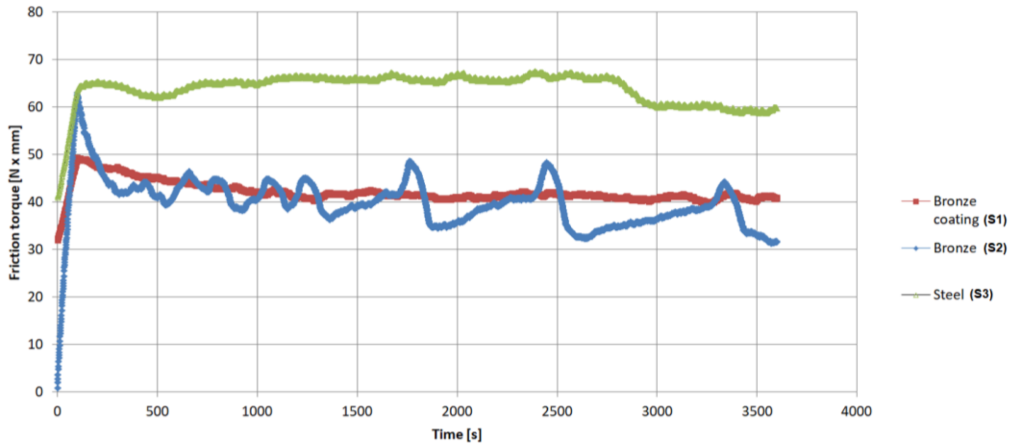


Fig. 6. Friction torque versus time.

These results must be interpreted taking into account the surface roughness of the samples, correlated with their morphology and the test environment. Thus, even if the roughness of S1 sample is much higher than that of S2 samples, respectively S3, the first one has a lamellar structure, slightly porous, specific to the layers made by thermal spraying. Given that the environment in which friction occurs is wet (power steering oil *Castrol ATF Multivehicle*) the low value of CoF can be explained by the fact that micro-porosities act as lubricant reservoirs.

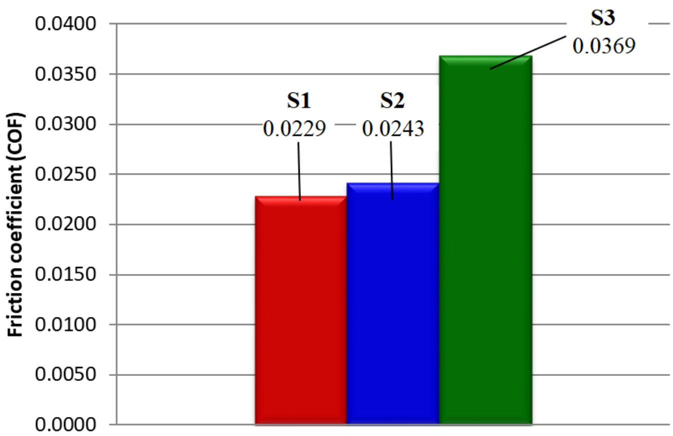


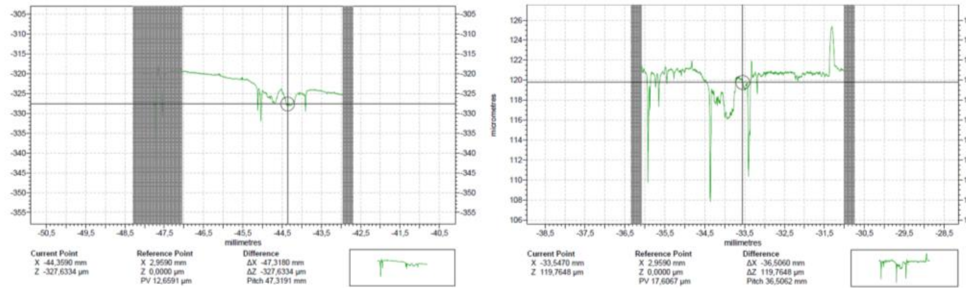
Fig. 7. Mean values of friction coefficient.

Another aspect that must be taken into account when interpreting the friction tests is the appearance of the curves of variation of the friction moment. As seen in Fig. 6, the smallest variations are registered in the case of sample S1, followed by sample S3 and finally by sample S2, which generated a stick-slip variation curve.

Taking into account these aspects that are specific to a sliding motion regime with periodic interruptions, we could conclude that we are dealing with a mixed lubrication regime, specific to more rough friction couplings, loaded and operating at relatively low speeds. In this case a thicker layer of lubricant is formed, which is pierced by the roughness of the surfaces in contact, so that it is formed simultaneously with thick film lubrication and areas with thin lubricant film, pierced by the highest roughnesses. This can also explain the behavior of the S2 sample, which, although has a very low initial roughness, registers a friction peak in the first 200 seconds (64 N·mm) when the wear spot is formed, following the break-in condition of the surface of the bronze piece worsening. This was followed by an abrupt decrease in the friction moment value and a stick-slip behavior due to the adhesion processes between the micro-irregularities of the surfaces in contact, with a slightly descending slope with values between 30 - 40 N·mm. In the case of the S3 sample it is observed that the variation is much less intense, but the values are much higher than in the previous cases. The moment of friction had a steep increase in the first 100 seconds to about 65 N·mm, followed by a moderate increase in the value between 65 - 70 N·mm (2800 seconds) and a decrease to the value of 60 N·mm until the end of the test.

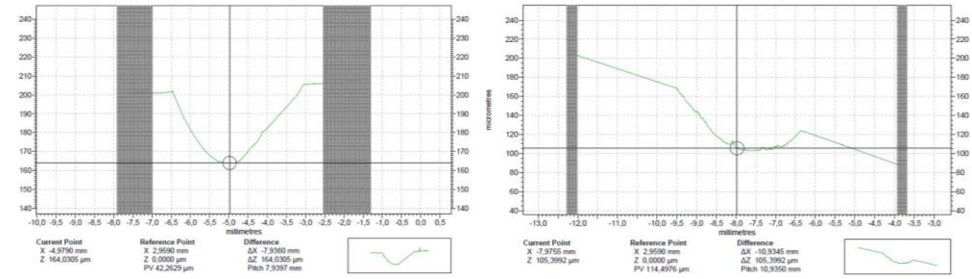
Wear Analysis

The wear assessment was performed by measuring the dimensions of the longitudinal and transverse wear spots, at the point of maximum depth. The wear profiles obtained are presented in Fig. 8 - 10, for each of the 3 samples.



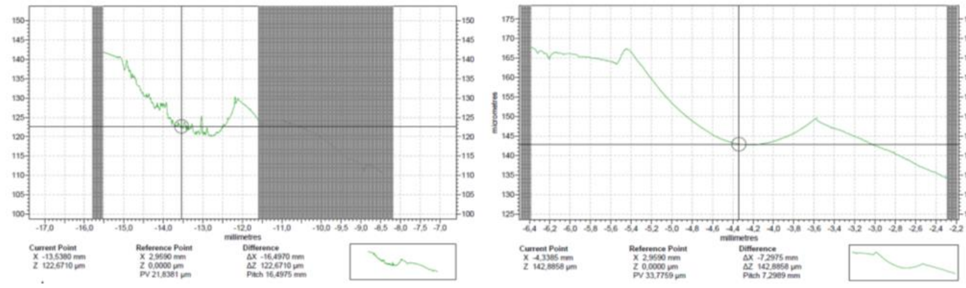
a) b)

Fig. 8. Wear profiles of sample S1 in longitudinal direction (a) and transversal direction (b)



a) b)

Fig. 9. Wear profiles of sample S2 in longitudinal direction (a) and transversal direction (b)



a) b)

Fig. 10. Wear profiles of sample S3 in longitudinal direction (a) and transversal direction (b).

The wear volume [21], [22] was calculated based on Eq (1) by approximating the wear mark with the geometry of a demi-ellipsoid whose half-axes a (longitudinal direction), b (transverse direction) and c (vertical direction) were measured on the raw profiles presented in Fig. 8 - 10.

$$V = 2/3 \cdot \pi \cdot a \cdot b \cdot c \quad (1)$$

Starting from the values of the wear volume, the evaluation of this phenomenon can be completed by the calculation W (computed wear rate) in $mm^3/N{\cdot}m$, expressed by the Eq (2),

$$W = V / (Q \cdot L), \quad (2)$$

where V is the volume of the demi-ellipsoid calculated with Eq (1), Q is the normal load applied during the tests (60 N) and L is the total sliding length obtained with Eq (3).

$$L = \pi \cdot D \cdot N \cdot T / 1000, \quad (3)$$

where D is the diameter of the disc (59 mm), N is the rotation speed (200 rpm) and T represents the duration of the test (3600 sec.). In the case of this experiment, the calculated value of L is 2223 m, being presented in Table 3 together with the other values used and calculated to evaluate the wear of the three samples.

Table 3. The measured and calculated values of the parameters used to evaluate the wear of the tested samples.

Sample	**Demi-ellipsoid dimensions [mm]**			**V [mm^3]**	**L [m]**	**Q [N]**	**T [sec]**	**W [mm^3/N·m]**
	a	**b**	**c**					
S1	0.8000	0.725	0.0050	0.00607	2223	60	3600	$1.365 \cdot 10^{-7}$
S2	1.7150	1.575	0.041	0.23182				$52.14 \cdot 10^{-7}$
S3	1.5050	0.9400	0.0126	0.03731				$8.392 \cdot 10^{-7}$

For a clearer evaluation of the volume of material lost due to wear, the resulting values were represented graphically in Fig. 11. It is observed that the biggest volume loss is the one recorded in the case of sample S2, followed in ascending order by sample S3 and in end of test S1, the difference between each other being about an order of magnitude. These observations are consistent with the data presented above, regarding the variation of the friction moment, which indicates a high wear of the S2 sample, medium in the case of the S3 sample and very small in the case of the S1 sample. The reduced hardness of sample S2 led to significant material losses, the variation curve of the friction moment indicating this phenomenon.

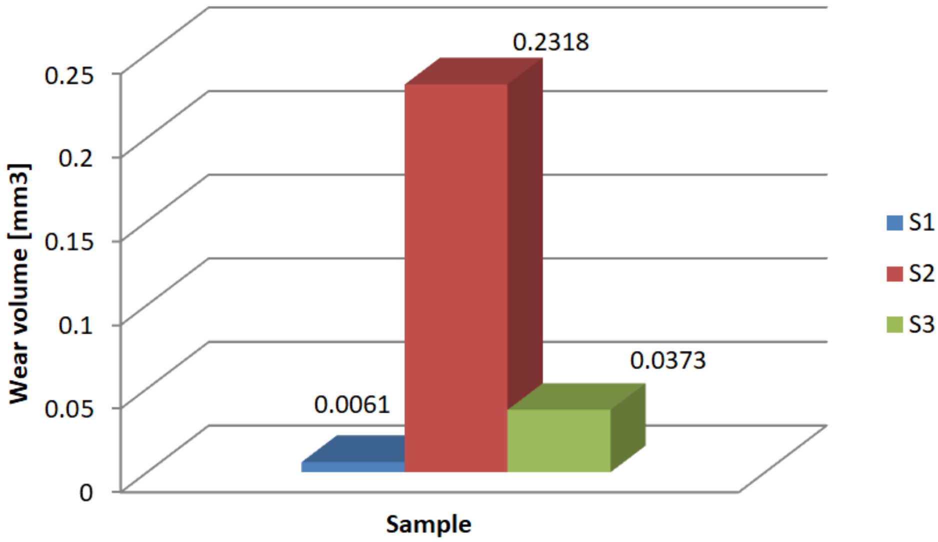


Fig. 11. Wear volume of tested samples.

4. Conclusions

In order to evaluate the friction and wear behavior of samples coated by electric arc deposition of Cu-Al 90-10 coating (sample denoted as S1), tests were carried out on Amsler machine at constant load, constant speed, and oil lubrication conditions. Comparative results were obtained for other two samples: S2 (cast CuAl9 sample) and S3 (bearing steel sample).

A satisfactory behavior of the bronze coating was registered, proved by the values of mean friction torque and mean friction coefficient, which were lower than the values registered for the bearing steel samples and very close to the values registered for the as-cast bronze sample. The low hardness sample of cast CuAl9 (S2) suffered an intensive running-in process at the beginning of the friction tests, the entire friction process being accompanied by stick-slip phenomena, indicating a mixed lubrication regime due to the applied high load.

Another performance parameter that recommends the use of the bronze coatings in sliding wear resistant applications is the wear rate, W, which is the smallest between the tested materials.

In conclusion, bronze thermal spray coatings for applications involving slurry erosion can be considered viable because they have demonstrated good strength during wear tests, compared to other materials commonly used for such applications (e.g. steel bearing). Another advantage in this case is the possibility to remedy the losses by wear more efficiently, by depositing new layers and not by completely replacing the worn part, as it usually happens.

References

[1] Paulin C., Chicet D.L., B. Istrate B., Panturu M., Munteanu C., IOP Conference Series: Materials Science and Engineering, **147,** 012034, 2016.
[2] Avram P., Imbrea M.S., Istrate B., Strugaru S.I., Benchea M., Munteanu C., Indian Journal of Engineering and Materials Sciences, **21,** 3, 315, 2014.
[3] Panturu M., Chicet D., Lupescu S., Istrate B., Munteanu C., Acta Technica Napocensis Series-Applied Mathematics Mechanics And Engineering, **61,** 137, 2018.
[4] Pawlowski L. (Ed.), *The Science and Engineering of Thermal Spray Coatings*, John Wiley & Sons Ltd, New York, 1995.
[5] Tan K.S., Wood R.J.K., Stokes K.R., *The slurry erosion behaviour of high velocity oxy-fuel (HVOF) sprayed aluminium bronze coatings*, **255**, 1, 6, 2003, p. 195-205.
[6] Istrate B., Munteanu C., Matei M.N., Oprisan B., Chicet D. Earar K., IOP Conference Series: Materials Science and Engineering, **133,** 1, 012010, 2016.
[7] Barik R.C., Wharton J.A., Wood R.J.K., Tan K.S., Stokes K.R., *Erosion and erosion–corrosion performance of cast and thermally sprayed nickel–aluminium bronze*, **259,** 2005, p. 230–242.
[8] Toma S.L., Badescu M., Ionita I., Ciocoiu M., Eva L., I*nfluence of the spraying distance and jet temperature on the porosity and adhesion of the Ti depositions, obtained by thermal spraying in electric arc - Thermal activated,* Applied Mechanics and Materials, **657**, 2014, p. 296-300.
[9] Istrate B., Munteanu C., Lupescu S., Benchea M., Vizureanu P., IOP Conference Series: Materials Science and Engineering, 2017, **209.** 012024.
[10] Vuoristo P., *Thermal Spray Coating Processes*, Comprehensive Materials Processing, 2014, **4**, p. 229-276.
[11] Haraga R.A., Bejinariu C., Cazac A., Toma B.F., Baciu C., Toma S.L., *Influence of surface roughness and current intensity on the adhesion of high alloyed steel deposits-obtained by thermal spraying in electric arc*, IOP Conference Series: Materials Science and Engineering, **572**, Issue 1, 2019, 012056.
[12] Toma S.L., *The influence of jet gas temperature on the characteristics of steel coating obtained by wire arc spraying*, Surface and Coatings Technology, **220**, 2013, p. 261-265.
[13] Ludwiga G.A., Malfattia C.F., Schroedera R.M., Zortéa Ferraria V., Mullera I.L., *WC10Co4Cr coatings deposited by HVOF on martensitic stainless steel for use in hydraulic turbines: Resistance to corrosion and slurry erosion*, Surface & Coatings Technology **377**, 2019, 124918.
[14] Talib R.J., Saad S., Toff M.R.M., Hashim H., *Thermal Spray Coating Technology – A Review,* Solid State Science and Technology, **11**, 1, 2003, p. 109-117.
[15] Javaheria V., Portera D., Kuokkalab V.T., *Slurry erosion of steel – Review of tests, mechanisms and materials,* **408–409**, 2018, p. 248–273.
[16] Vikash Gautama, Ashiwani Kumara, Lalta Prasad, Vinay Kumar Patel, *An Experimental Investigation on Slurry Erosion Wear Characteristics of Brass Alloy,* Materials Today: Proceedings, **4**, 2017, p. 9879–9882.
[17] Anurag, Nitish Kumar, Shivam Mishra, *Slurry erosion: An overview*, Materials Today: Proceedings, **25**, 2020 p. 659–663.
[18] Gurmeet Singh, *A review on erosion wear of different types of slurry pump impeller materials*, Materials Today: Proceedings xxx (xxxx) xxx - article in press 2021, https://doi.org/10.1016/j.matpr.2020.07.727.
[19] Gaurav Prashara, Hitesh Vasudeva, Lalit Thakurb, *Performance of different coating materials against slurry erosion failure in hydrodynamic turbines: A review*, Engineering Failure Analysis 115, 2020, 104622.
[20] Inaguma Y., Hibi A., *Reduction of friction torque in vane pump by smoothing cam ring surface*, Proc. IMechE Vol. **221** Part C: J. Mechanical Engineering Science, 2007, p. 527 - 534.
[21] Paulin C., Chicet D., Paleu V., Benchea M., Lupescu S., Munteanu C., *Dry friction aspects of Ni-based self-fluxing flame sprayed coatings*, IOP Conf. Ser. Mater. Sci. Eng. **227**, 2017, 012091.

[22] Paleu C.C., Munteanu C., Istrate B., Bhaumik S., Vizureanu P., Bălţatu M.S., Paleu V., *Microstructural Analysis and Tribological Behavior of AMDRY 1371 (Mo–NiCrFeBSiC) Atmospheric Plasma Spray Deposited Thin Coatings*, 2020 Coatings, **10,** 12, 2020, p. 1186.