A study on PVD coatings for reduction of friction and wear of swashplate axial piston pumps and motors

R. Sola, P. Veronesi, B. Zardin, M. Borghi

Swashplate axial piston pumps and motors are widely used under severe conditions because of their capability to operate at high pressure values and various ranges of speeds, maintaining a good efficiency. In some operating conditions however, the machine efficiency may be relatively low because of insufficient lubrication and this causes rapid wear and high friction losses. PVD coatings may help in reducing the friction thus having a positive impact on the machine efficiency. For this reason, pin on disk testing were conducted to investigate the friction and wear behavior of different PVD coatings on various metallic substrates. A copper and tin alloy coated with PA-CVD DLC, a carburized 17NiCrMo7 with a PVD DLC coating and a nitrided 41CrAlMo7 PVD coated with TiCN were studied. Results of tribological testing, carried out at 0.2 and 0.5 m/s as sliding speed and 5000, 10000 and 20000 rounds as ending conditions, showed that wear and friction had been reduced; moreover, microstructure features were analyzed for understanding underlying mechanism and to allow selecting the most suitable coating for the application on the swashplate axial piston machine.

PAROLE CHIAVE: PVD COATINGS, WEAR, FRICTION, STEEL, BRONZE, SWASHPLATE AXIAL PITON PUMP, LUBRICATION

INTRODUCTION

Axial piston pumps are positive displacement pumps, which typically transfer a definite volume of fluid from a low pressure port to a high pressure port at each shaft rotation by means of variable volume chambers (1). They convert the mechanical power coming from a prime mover into hydraulic power. The shaft rotation is transmitted to the cylinder block of the pump which drives into rotation the piston-shoes assemblies. As the shoes slides on the swashplate, the pistons are forced to translate within the cylinder block and to de-liver fluid. The valve plate then allows distribution of the fluid in the circuitry. Hydraulic fluid act also as a lubricant. However, these interfaces can be critical and influence the efficiency of the pump. Moreover, the complex lubrication mechanism involved in this kind of pumps play a relevant role also in determining the wear of their components and the leakage flows. Deterioration

R. Sola
Industrial Research Centre for Advanced Mechanics and Materials (CIRI-MAM), University of Bologna, Bologna (Italy)
e-mail address: ramona.sola@unibo.it

P. Veronesi, B. Zardin, M. Borghi
Engineering Department "E. Ferrari", University of Modena and Reggio Emilia (Italy)

of the lubrification mechanism leads to poor performance and reduced life of the component (2). Also, the presence of wear debris in the hydraulic fluid worsen the wear on the piston oil pumps components

This study consists in an experimental comparison of thermochemical treatments and coatings to improve wear resistance and to reduce friction of axial pistons pumps. Solutions are chosen based on the most common metallic alloy used in fabrication of axial pistons pumps. Ankint Tyagi et al. in (3) reveal that even 15-20% reduction in wear friction can significantly reduce economic costs in relation to environmental benefits and the application of coatings is one of the most widely used route. Among the employed tribology techniques for coating deposition the most known are physical vapor deposition/chemical vapor deposition (PVD/CVD), ion beam deposition, radio frequency magnetron sputtering and electro deposition. Nesbit in (4) proposes a list of suitable materials for pump design, Kalin et al in (5) studied the influence of wear resistance of DLC-coated shoes by following wear evolution with optical microscopy and leakage monitoring while Sun in (6) focuses on the effect of a N based coatings on the barrel surface in the contact barrel/valve plate, Sola et al. in (7,8) studied the effect of "duplex treatment" of wear and corrosion resistance of steels and Tonelli et al. in (9) tested new solutions coating/substrate for Improvement of wear resistance of components for hydraulic actuators. DLC coatings are famous for their excellent wear resistance, low friction, corrosion resistance and damping capacity, because the combination of the properties of carbons allotropes of sp2 and sp3 hybridizations (3). Titanium ni-tride coating (TiN) are still regarded as coatings suitable con anti-wear protection (10) in order to extend the service life of cutting tools, stamping tools, bearings. However, com-parative tests of multiple different solutions that solve a problematic or improve a specific property, such as durability of the coatings, lack in literature.

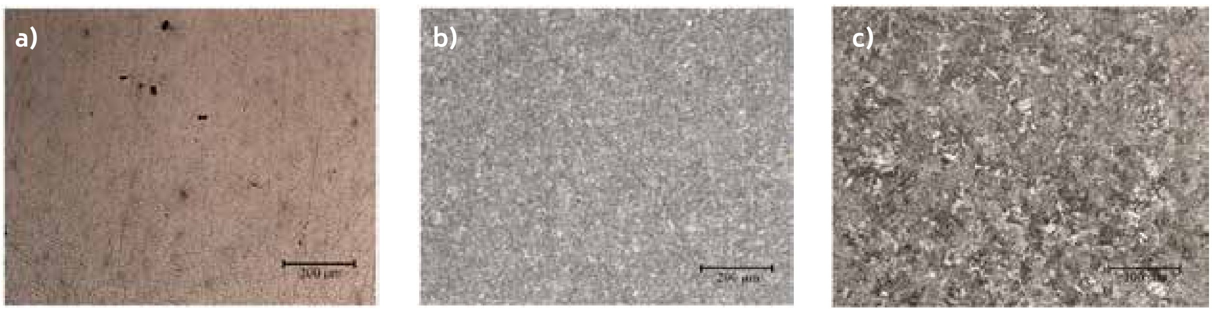
Finally, this literature review displays a lack of combination between laboratory comparative studies of surface treatments and test for industrial applications. This study combines two approach by proposing wear tests on solutions (DLC and TiCN coatings) to improve wear resistance on an industrial axial piston pump.

EXPERIMENTAL TECHNIQUES

In the current study several types of metallic materials with different heat treatment and coatings are investigated: a bronze CuSn12 (nominal composition wt%: C 0.25%, Pb 0.35%, P 0.30%, Cu balanced), a carburized 16NiCrMo7 (nominal composition wt%: C 0.20%, Si 0.75%, Cr 1.10%, Ni 1%, Fe balanced) and a 41CrAlMo7 quenched and tempered (nominal composition wt%: C 0.40%, Mn 0.75%, Cr 1.70%, Mo 0.40%, Al 1%, Fe balanced). In Fig. 1 the microstructures of as received materials, by optical microscope, are reported: bronze CuSn12 presents a rough as casted microstructure, while two steel exhibit tempered martensite with different morphology due to carbon content.

CuSn12 **16NiCrMo7** **41CrAlMo7**

Fig.1 - Optical micrographs of as received materials.



For all the metal alloys disc-shaped samples were cut from a 40 mm in diameter bar and then hardened with different treatment and coatings. Before the thin coating deposition, the substrate was carefully polished (Ra maximum 0.2) and cleaned with ultrasonic alkaline bath and de-ionized water. Commercial anti-wear coatings are selected for the analysis purpose. This has been done to obtain credible analysis on the impact on the performance of the analysed film. Bronze CuSn12 was coated with functional coating deposited by plasma-assisted chemical vapor deposition (PACVD) using acetylene of 99.6% purity with substrate pulsed bias in the frequency range (20-100) kHz. The deposition temperature was 350°C and the acetylene flow rate was $8.3x10^{-6}$ m^3/s. PLC PA-CVD coating on 16NiCRMo7 steel was deposited in same condition as bronze but the deposition temperature was lower than 200°C to not soften carburized substrate. 41CrAlMo7 was treated with a duplex treatment combining plasma nitriding and TiCN deposition. Nitriding was carried out in an industrial reactor using DC pulse discharge at 390°C for 10h in a 25% N_2 + 75% H_2 gas mixture. Then thin coating was deposited by cathodic arc evaporation (PVD) from Ti target in Ar + N_2 mixture. The process was conducted at temperature of 350°C, under working pressure range from 0.1 - 0.2 Pa. The substrate bias was -70 V.

Tribological test was performed on a ball-on-disk tribometer (CSM Instruments, Switzerland) in the rotating mode. An alumina ball with 6 mm diameter were used as friction pairs. All of the disks were cleaned with acetone and dried. The tests were conducted at room temperature and ambient humidity under dry sliding conditions of 10N load, with two sliding velocity 0.2 m/s e 0.5 m/s. After the total distances of 5000, 10 000, 20 000 laps (for durability analysis) friction, morphology of wear tracks using SEM (Oxford instrument) and cross-section profile of wear tracks by confocal microscope (Leika) are evaluated to understand the tribological behavior and the durability of the solutions proposed. Tribological parameter are chosen to simulate the real common operating conditions of industrial oil pumps. The wear rate was calculated from formula (1):

$$W = \frac{V}{PL} \quad \left[\frac{mm^3}{Nm}\right]$$

where V is the wear volume [mm^3], P is normal force [N] and L is total sliding distance [m]. Much more information on the application of pin on disk test as method for tribological characterizations of heat treated and hardened metallic materials are visible in (11-12).

The adhesion of the coatings was determinded by scratch test. In the scratch testing, as described in (13-16), a diamond Rockwell C stylus (120° cone, 100 μm radius spherical tip) was pulled over the coated surface with continuously increasing normal load from 1 to 30 N. Scratch test were performed on a Micro-combi Tester (Anton Paar Gmbh, Germany) according to the ASTM C1624 – 05 (2015) standard for ceramic coatings scratch testing. The loading rate was 11,6 N/min and stylus progressive speed was 2 mm/min. The scratch length was 5 mm. Optical (OM, MCT, Anton Paar GMBH, Germany) microscopy examination was carried out for the coatings after each scratch testing in order to determine the crack behavior and the critical loads Lc1, corresponding to the cohesive failure (occurrence of the first cracks on the surface), Lc2 – the first symptoms of adhesive failure (spalling or chipping), Lc3 – severe exposition of the removal.

RESULT AND DISCUSSION

Figs. 2 – 6 show optical and scanning electron micrographs of analyzed samples. 41CrAlMo7 "duplex" treated steel present a homogeneous diffusion layer, 100 μm thick, under a little porous white layer, 4 μm thick (Figs. 2 - 3). Thin and homogeneous TiCN layer is visible above white layer, well adherent to the substrate with 1-2 μm thickness. Carburized 16NiCrMo7 steel, Figs. 4 - 5, presents a hardened layer 400 μm thicks underlying PLC coating, homogeneous, well adherent to substrate and 2-3 μm thick. DLC coating on CuSn12 bronze, visible in Fig. 6, is homogeneous, not porous, well adherent to substrate with 2-3 μm as thickness. In Fig. 7 and 8 microhardness profile of 41CrAlMo7 "duplex" treated steel and 16NiCrMo7 carburized steel respectively are reported. Total hardening depth of 41CrAlMo7 is about 250 μm and effective hardening depth is 120 μm. In carburized 16NiCrMo7 total hardening depth is near 1 mm.

Figs. 9 – 11 exhibit friction trends during 20 000 laps as sliding for all the samples examined in untreated and coated conditions, and in Tab. I mean friction values are reported. From Table I and friction behavior of Fig. 9 it can be seen that "duplex" treatment does not improve friction compare to untreated 41CrAlMo7 steel, but in some case friction value of TiCN sample increase in 10-20%. TiCN coatings are well-known to increase wear resistance and not for reduction of friction but improving surface finishing could be possible decrease friction.

Fig.2 - Optical Micrograph of 41CrAlMo7 with "duplex" treatment

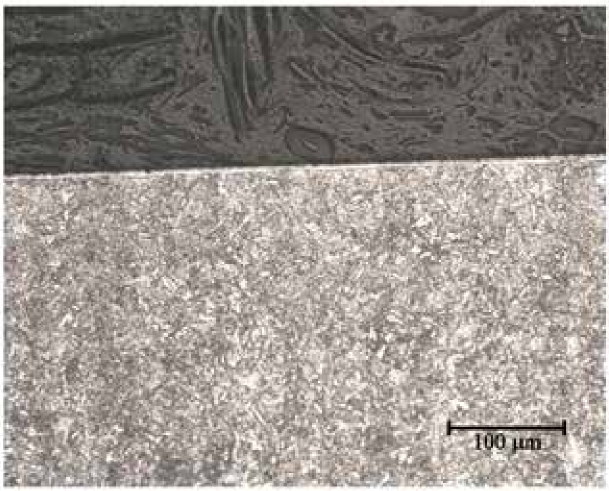


Fig.3 - SEM-BSE Micrograph of 41CrAlMo7 with "duplex" treatment

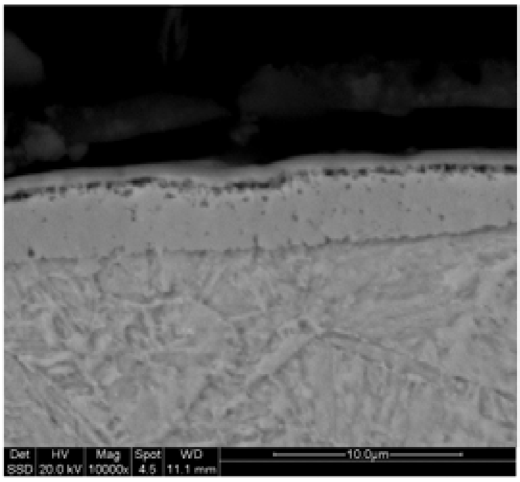


Fig.4- Optical Micrograph of carburized 16NiCrMo7 with PLC coating

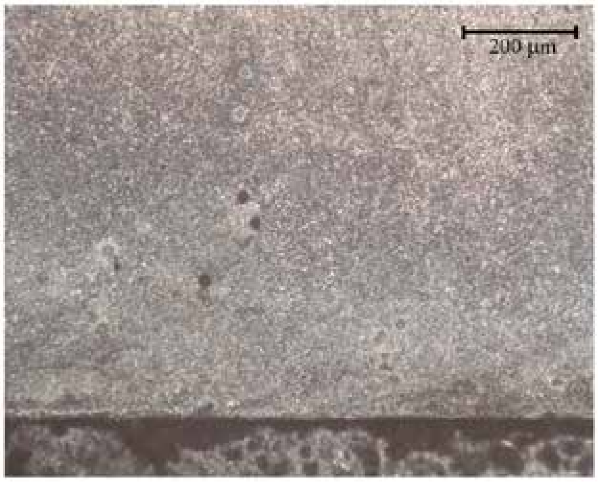


Fig.5 - SEM-BSE Micrograph of carburized 16NiCrMo7 with PLC coating

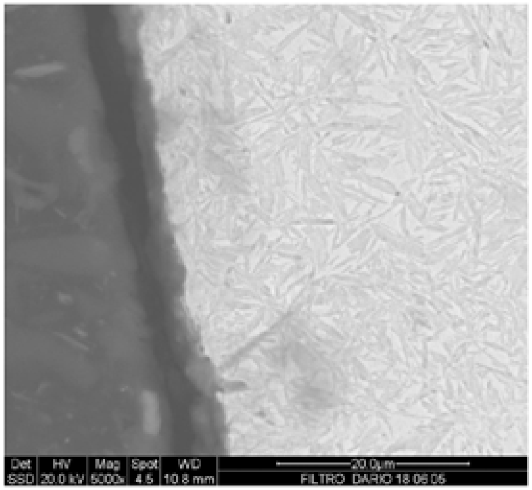


Fig.5 - SEM-BSE Micrograph of carburized 16NiCrMo7 with PLC coating

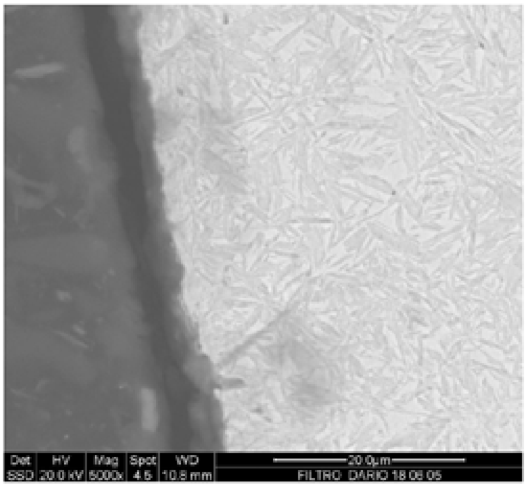


Fig.6 - SEM-BSE Micrograph of bronze with DLC coating

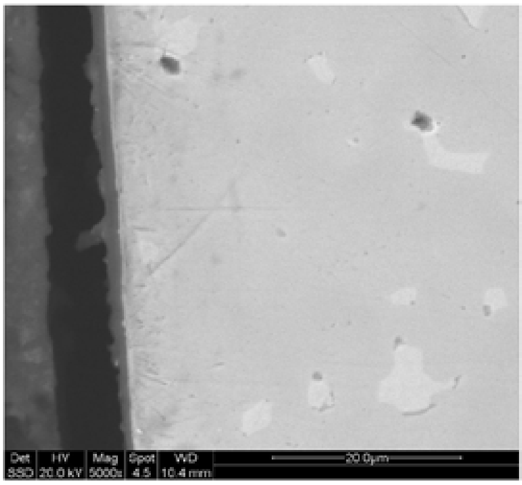


Fig.7 - Microhardness profile of 41CrAlMo7 duplex treated steel

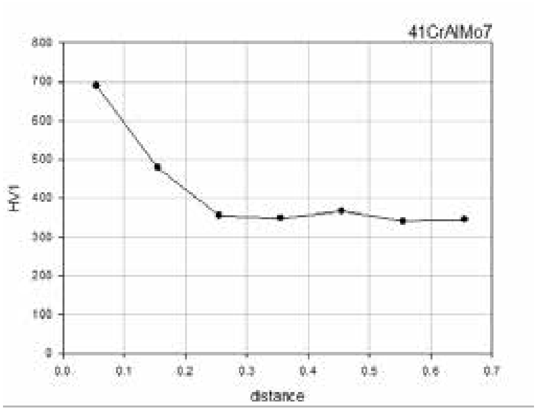
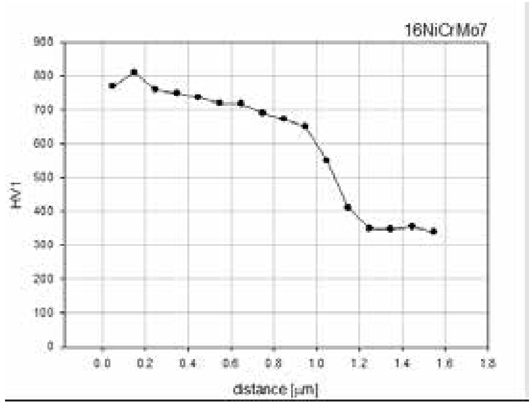


Fig.8 - Microhardness profile of carburized 16NiCrMo7



Carbon based coatings (PLC and DLC) exhibited a different behavior from TiCN because they greatly decrease friction values in more than 50%. This implies that the frictional forces during the dry sliding test against the Al2O3 ball are dramatically reduced after deposition on the PLC and DLC coatings. The best anti-frictional properties are exhibited by the DLC coating – the coefficient of friction (COF) is reduced by more than 5 times. Regarding PLC on carburized 16NiCrMo7, it can be seen that friction during sliding is always lower that uncoated sample, also after 10 000 laps when friction value little increase due to wear of coatings. Similar friction trend of CuSn12 bronze in which DLC coating contributes to decrease friction and after 10 000 laps friction value increase because of wear of coating, especially at lower sliding speed because adhesion mechanism is help. At 0.5 m/s at sliding speed DLC coating is almost untouched from tribological test.

At the end of tribologial test, wear track of the sample are analyzed with a confocal microscope to estimate the wear volume and then calculate the Wear rate value (W). High W value means high volume removed during sliding and so low wear resistance. In Figs. 12 – 14 W values during sliding for all the sample analyzed in the treatment condition considered are reported. W value of CuSn12 bronze with DLC coating is greatly lower than untreated sample (Fig. 14), especially at 0.5 m/s as sliding speed where the reduction of W value (and so wear resistance increase) is about 91%, 89% and 99% after 5000 laps, 10 000 laps and 20 000 laps respectively, compared to untreated bronze. At 0.2 sliding speed adhesion mechanism are favored and the improvement in W value is near to 90% at 10 000 and goes to 40% at the end of the test. PLC coating (Fig. 14) improves wear resistance strongly decreasing W value about 90% to 10 000 laps and then, due to little wear of coating, near 60%, compare to carburized steel. "Duplex" treatment on 41CrAlMo7 (Fig. 14) does not alter friction coefficient but it greatly improves wear resistance because it promotes a reduction of W value greater than 90%, compare to untreated sample, in any sliding condition tested. "Duplex" treatment, combining plasma nitriding and TiCN coating, improves wear resistance of 41CrAlMo7 quenched and tempered steel and this solution guarantees a high duration.

Fig.9 - Friction behavior during sliding for 41CrAlMo7 untreated (NT) and "duplex" treated (TiCN)

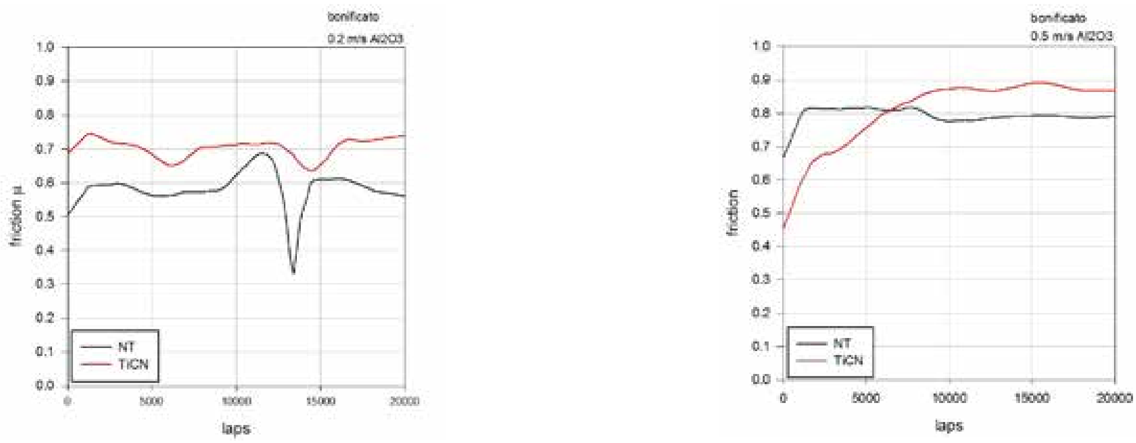


Fig.10 - Friction behavior during sliding for 16NiCrMo7 carburized (NT) and with PLC coating (PLC)

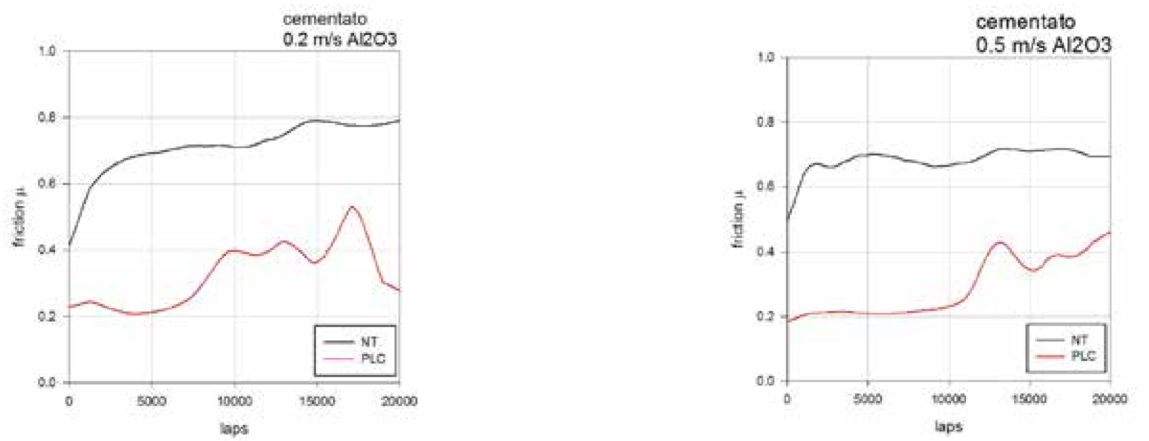
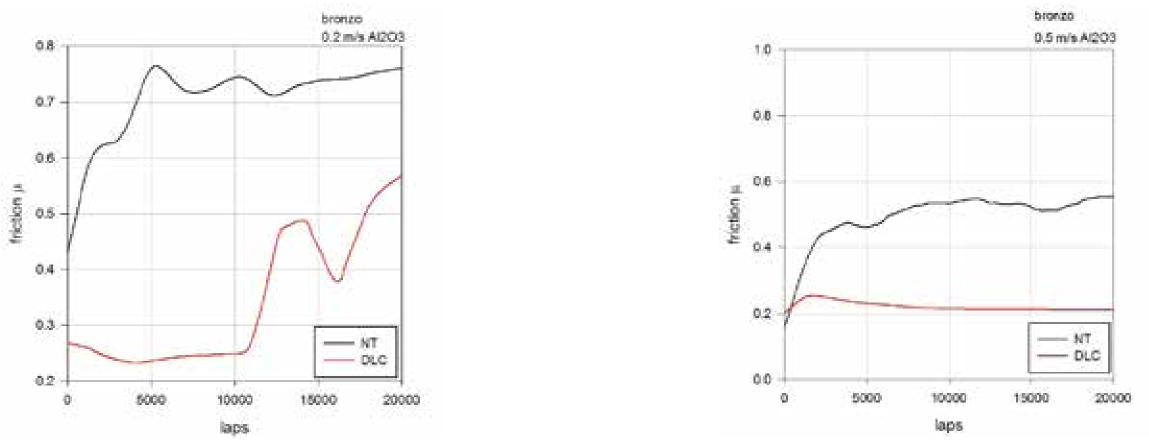


Fig.11 - Friction behavior during sliding for CuSn12 bronze as received (NT) and with DLC coating (DLC)



Tab.1 - coefficient of friction means (COF) values

alloy	treatment	sliding speed [m/s]	5000 laps	10 000 laps	20 000 laps
16NiCrMo7 carburized	NT	0.2	0.62	0.59	0.71
		0.5	0.69	0.74	0.69
	PLC	0.2	0.22	0.21	0.33
		0.5	0.21	0.23	0.29
41CrAlMo7	NT	0.2	0.56	0.67	0.57
		0.5	0.69	0.69	0.79
	TICN ("DUPLEX")	0.2	0.71	0.67	0.70
		0.5	0.60	0.69	0.80
CuSn12 bronze	NT	0.2	0.58	0.64	0.71
		0.5	0.56	0.50	0.49
	DLC	0.2	0.27	0.25	0.34
		0.5	0.29	0.25	0.22

Fig.12 - Wear rate graph of CuSn12 bronze

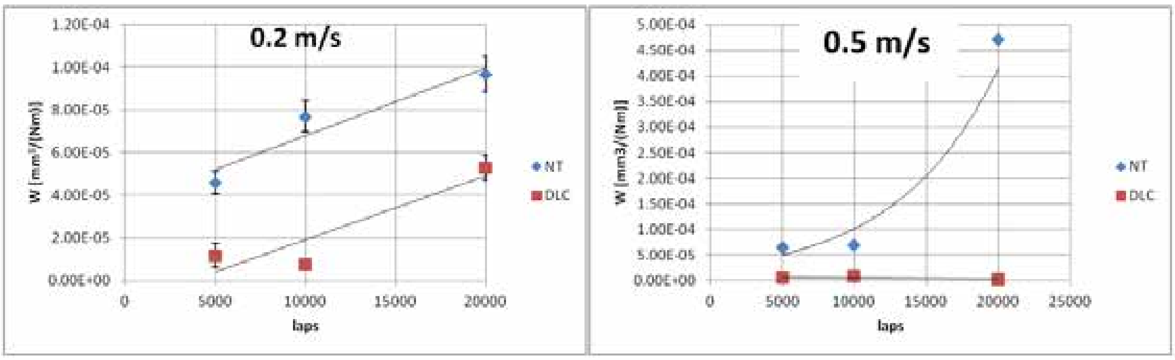


Fig.13 - Wear rate graph of 16NiCrMo7 steel

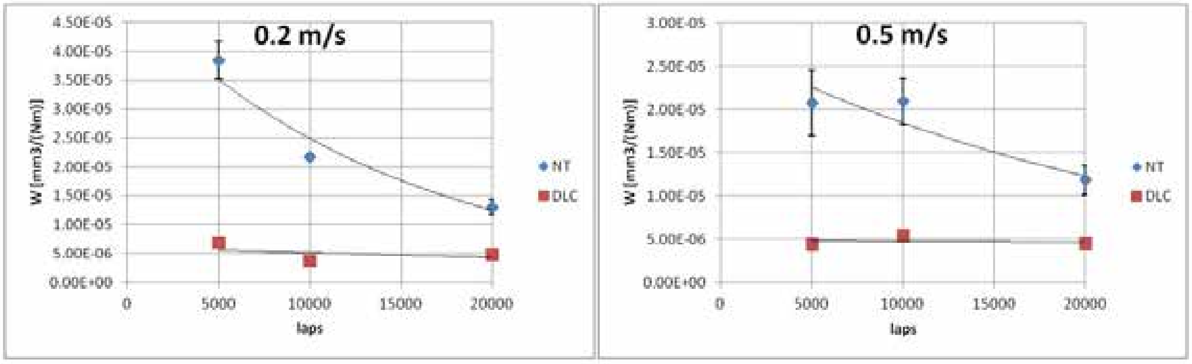
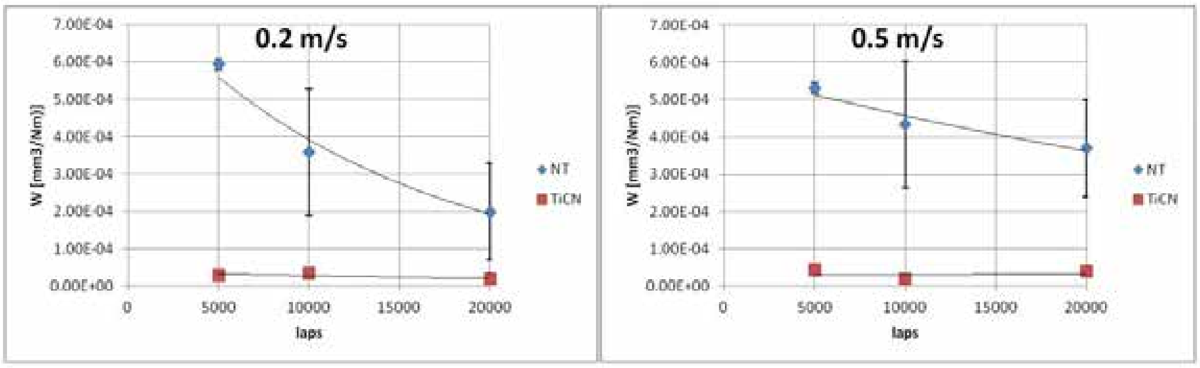


Fig.14 - Wear rate graph of 41CrAlMo7 steel



Reduction of the frictional forces resulted in a significant reduction of the wear rate in tribological tests as confirmed observing the surface topography of wear track reported in the Figs.15 – 19, in which it is clearly visible that the wear tracks differ significantly for all the samples. Severe wear on the uncoated CuSn12 can be observed in Fig. 15. Some of the wear products are plastically deformed and form chip-like areas. Figs. 18-19 show wear tracks of coated with DLC. A great abrasive wear is visible in untreated sample while DLC coating is little worn and its main wearing mechanism is delamination (Fig. 16) because of cracking of the coating. A high hardness coating, indeed, is layered on a soft bronze; during sliding substrate and coating are deformed in different way, and this causes high stresses in DLC coating and so its cracking. The morphology of the wear track of the DLC coating shows that the film was practically deformed along with the substrate. The black areas are attributed to the presence of DLC coating and small patches of the coating were detached from the substrate and acted as an abradant in the bell-disk contact site. Tensile cracks emerged as a result of ploughing.

Wear tracks of carburized 16NiCrMo7 and PLC coated steel are reported in Figs. 17 and 18. Abrasive and triboxidative wear is visible in uncoated steel with deep grooves inside track and accumulation of oxidized wear debris at boarder track. Steel with PLC coating is little worn and its wear track presents only a little triboxidation without abrasion grooves.

Wear tracks of 41CrAlMo7 untreated and "duplex" treated are shown in Fig. 19. Tracks analysis confirms the great improvement in wear resistance promoted by nitriding combined with TiCN coating. Untreated steel is abraded while coated is very wore after 20 000 laps. This solution guarantees a high durability of the coating.

A comparison of the wear rate of the all solutions considered for application in industrial pistons pumps in reported in Fig. 20, in which it is clearly visible that CuSn12 exhibits high wear resistance at the beginning of the sliding but, due to the cracking and detachment of the coating, it suffer a low durability. Duplex treated 41CrAlMo7 is a good solution for high number of laps. The best wear performance, among the solutions considered, is presented by 16NiCrMo7 carburized and coated with PLC.

Fig.15 - SEM-SE micrographs of untreated CuSn12 bronze wear track (A). (B) wear track at high magnification

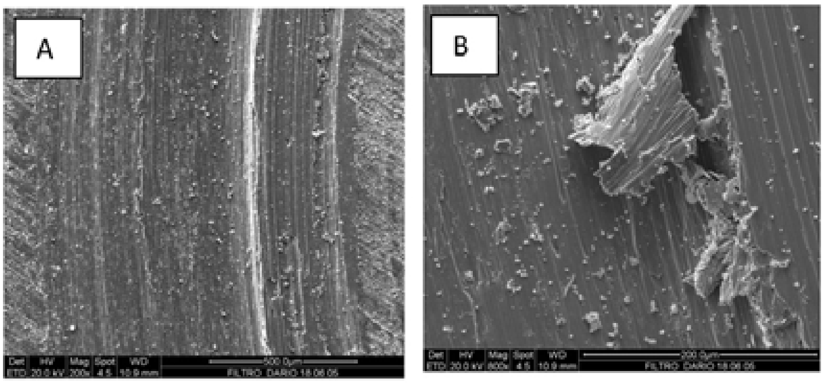


Fig.16 - SEM-SE and SEM-BSE micrographs of CuSn12 bronze with DLC coating. A. SEM-SE micrograph. B. SEM-BSE micrograph. C. SEM-BSE micrograph at high magnification

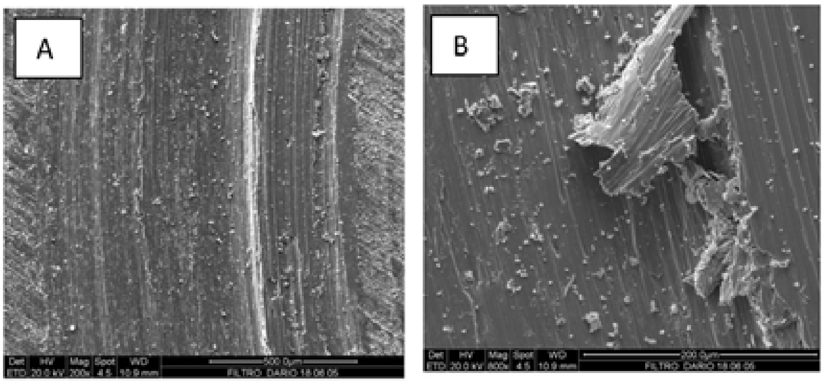


Fig.17 - SEM-BSE (A) and SEM-SE (B) micrographs of carburized 16NiCrMo7 steel

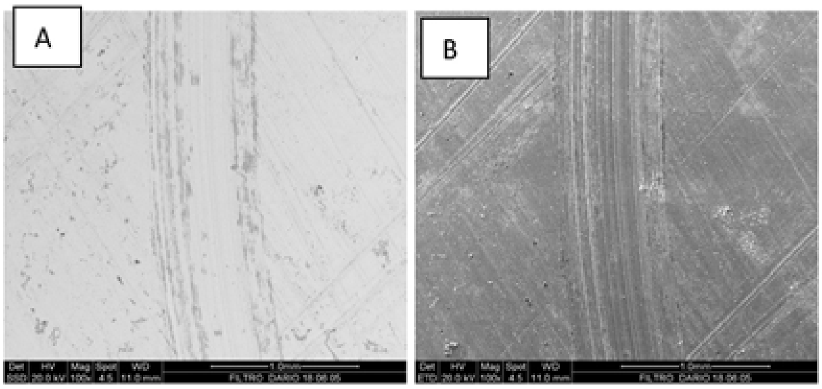


Fig.18 - SEM-SE (A) and SEM-BSE (B) micrographs of 16NiCrMo7 steel with PLC coating

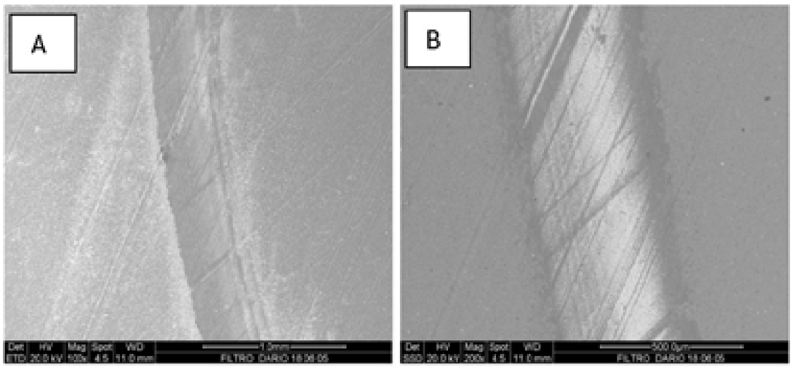


Fig.19 - SEM-SE micrograph of wear track of 41CrAlMo7 untreated steel (A) and "duplex" treated (B)

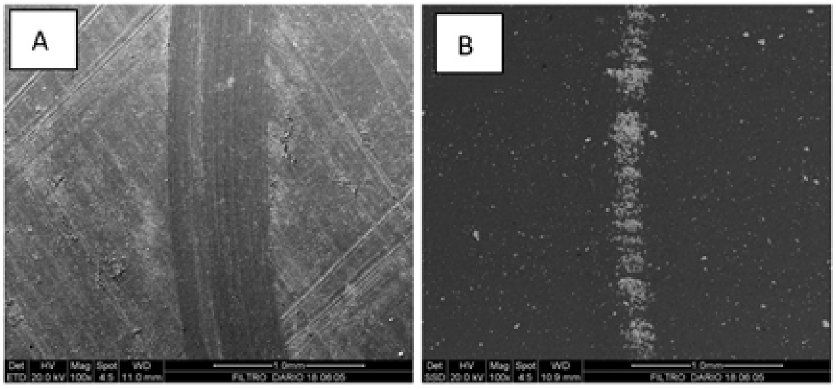
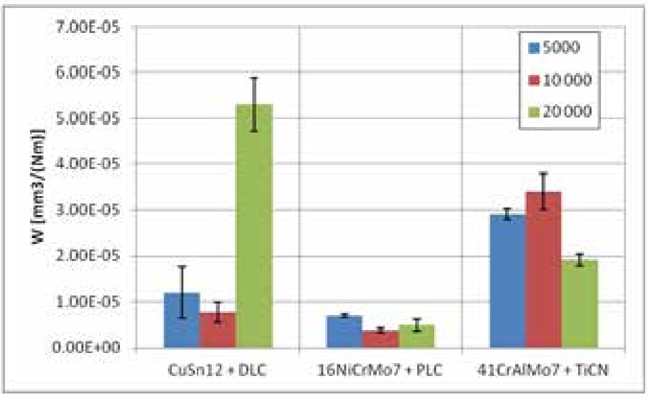


Fig.20 - wear rate comparison of the solutions analyzed



CONCLUSIONS

Present research work studied different combination of metal substrates and coatings for reduction of friction and wear and efficiency optimization of axial motors and oil pumps. The proposed solutions are CuSn12 bronze with DLC coating, carburized 16NiCrMo7 with PLC coating and quenched and tempered 41CrAlMo7 with "duplex" treatment combined plasma nitriding and TiCN coating. Microstructural analyses show that in all the samples a thin, homogeneous and well adherent to substrate coating is present. DLC and PLC coatings promote a great reduction of friction coefficient. All the solutions investigated guarantee a high and long-lasting improvement of wear resistance. A reduction of friction and wear rate could increase global efficiency of oil pups and motors. The solution combining 16NiCrMo7 carburized and coated with PLC presents the best tribological performance in friction and wear.

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