PROTECTIVE COATINGS FOR TUBULAR BOOMS APPLICATIONS

Maciej Ossowski(1, 2), Kamil Bochra(1, 2), Andrzej Czyżniewski(3), Marta Tokarz(1)

(1)Astronika Sp z o.o., Bartycka 18, Office no. 33, 00-716 Warsaw, Poland, mossowski@astronika.pl
(2) Warsaw University of Technology, Faculty of Materials Science and Engineering, Woloska 141, 02-507 Warsaw, Poland,
(3)Koszalin University of Technology, Faculty of Technology and Education, Sniadeckich 2, 75-453 Koszalin, Poland

ABSTRACT

The tubular boom is a generic technology of deployable structures for space applications, which may be adapted to fit many missions and instruments. An advantage of such technology is small volume and mass of such mechanisms due to using tensioned tapes, not standard tubes. In stowed configuration of the boom, the tape is stored on a reel, during deployment it is unwounded from the storage reel and changes its shape into a tubular boom. Depending on the material type and dimensions of the tape, such boom can reach the length of up to 5 m.
The application of such technology often depends on the boom material: stainless steel is usually used for manipulators, CFRP composites for large structural booms, while copper alloys seem perfect for miniature booms and antennas. All of these tubular boom applications need to fulfil almost identical conditions in order to ensure their correct and reliable operation.
Astronika company has a great experience in a tubular boom technology and is a manufacturer of both, mechanisms and booms which were already used in several flight missions. The presented results are part of the development of a new material solution for these products.
The main objective of this research was to propose, develop and test the surface modifications: coating and mechanical surface finish of thin – 0.08 mm thick – metallic copper beryllium tapes used for tubular boom applications in space instruments and mechanisms. The need to develop these surface modifications is associated with preventing the cold-welding effect, improving wear resistance, decreasing the friction coefficient, and achieving the proper thermo-optical parameters and electrical conductivity of ready-made tubular booms.
To achieve these, three thin (below 1 μm) DLC composite coatings – Cr/W-C:H, Cr/CrN+CrCN/Cr-C:H, Cr/CrN+Ag/Cr-C:H – were produced by the PVD method on the CuBe2 tapes. Such materials were characterised using the SEM observation and EDS chemical composition measurements and tested using the scratch test, nanoindentation and cold welding test. Furthermore, the additional mechanical surface treatments of the CuBe2 tapes were performed: polishing and grinding, and the thermo-optical properties of the modified CuBe2 tapes were measured and compared to both bare material and the CuBe2 tapes coated with DLC.

INTRODUCTION

Carbon-based a-C, a-C:H coatings, commonly called DLC (Diamond-Like Carbon) coatings, due to their low friction coefficient and high wear resistance are more and more often used for tribological applications, especially under conditions of dry friction.
A separate group of carbon-based coatings are the X–C:H, XC/a-C:H or XC/a-C types, where X= Ti, Cr, Nb W, Zr, Si, B, F, etc., often classified as doped DLC. The coatings of this type, depending on a mutual share of a carbide phase XC and an amorphous carbon phase a-C or a-C:H, show the mechanical properties diversified to a considerable extent [1–3]. If a carbide phase is nanocrystalline (grain size 3–10 nm), its share is about 80% and a share of an amorphous matrix is about 20%, these coatings may show high hardness and strength [2, 4], while when a share of an amorphous phase is of the order of 80–95%, these coatings have lower hardness but at the same time a significantly lower friction coefficient and higher wear resistance [1, 2].
Over recent years many investigations were focused on a friction mechanism affected by DLC coatings, hydrogenated [5–8] as well as the hydrogen-free ones [7, 8] and the doped ones [6], but only few of them considered DLC coatings as coating for space applications.
Using DLC coatings was considered mostly by their tribological performance as a substitute for widely used MoS2 solid lubricants, especially for on-ground tests where degradation of MoS2 is a well-known problem.
Since many space mechanisms must be ground tested before launch, sometimes in the atmospheric air, there has been much research performed to improve the performance of MoS2 under atmospheric conditions. One method is the co-deposition of MoS2 with DLC [9]. A good performance was obtained with WC/DLC/WS2 coatings in vacuum and air [10].
But DLC coating can be used without MoS2 as a standalone coating as well; vacuum tests performed in recent years show that highly hydrogenated DLC (~ 50 at % hydrogen) offers a good tribological performance both in vacuum and ambient environment [11]. A functional test shows that a working life of the grease lubricated harmonic drive gears with W-C:H coating tested in a vacuum simulator can reach more than 5,000 h, which is beyond twice times that of the uncoated ones [12].

The development of DLC surface coatings as a protective coating for tubular booms was first investigated by Astronika in 2015, during the B/B2 phase of the ESA JUICE project. Three dipole RF antennas for the Radio Wave Instrument required protection against overheating after deployment during the Sun close approach (SCA) and Venus flyby (hot case) and against cold welding in the stored position during launch and LEO. At this stage different coatings produced with different surface engineering methods like electrochemical treating, spraying or PVD were analysed and only one coating met all requirements and passed functional tests – this was the Ti-C:H type DLC coating produced by a reactive magnetron sputtering method.
This activity showed how difficult, from an engineering point of view, it is to produce the functional coating on such element as a tubular boom, and confirmed that DLC coatings are very interesting and promising materials for space applications not only because of their tribological performance, but also because of their thermo-optical conductive properties.

METHODOLOGY

As a substrate material Berylco 25 (CuBe2) metallic tape, 0.08 mm thick, was used. This is the same material which is used for manufacturing of tubular booms by Astronika company. Coatings were produced on 100 cm long tapes at an initial state, without any additional surface finish, and then cut into samples.
DLC coatings were deposited in the system shown in Figure 1. Two ARC-MAG sources operating in a magnetron or arc mode and equipped with chromium (99.8%), tungsten (99.99%) or silver (99.9%) targets of 100 mm in diameter were used. The ARC-MAG sources were powered by a DC-arc or pulsed magnetron supply. A planetary substrate holder was also pulse biased. Application of pulsed power at the frequency of 100 kHz, with 1 kHz modulation, to magnetron sources and substrates as well, enables stable, arc free deposition and limits plasma heating of the substrate. Working gases (argon 99.995%, nitrogen 99.995% and acetylene 96.8%) were introduced to the deposition chamber through flow meters driven by the Flow Controller MGC-147 coupled with the Baratron® 250 B pressure control system.
The microstructure of the produced coatings was observed with the use of the Scanning Electron Microscope (SEM) HITACHI 5500; due to the low thickness, samples for observation had to be prepared using the Focus Ion Beam (FIB) etching method.
The thermo-optical measurements and calculations were performed in the Ångström Laboratory at Uppsala University. The optical spectra were recorded in the solar wavelength range (uv-vis-nir) by using the Perkin Elmer Lambda 900 double beam spectrophotometer equipped with the Spectralon 15 cm in diameter integrating sphere. In the thermal infrared wavelength range (ir) the Bruker Tensor 27, FTIR single beam spectrophotometer equipped with a 7 cm gold coated integrating sphere, was used.

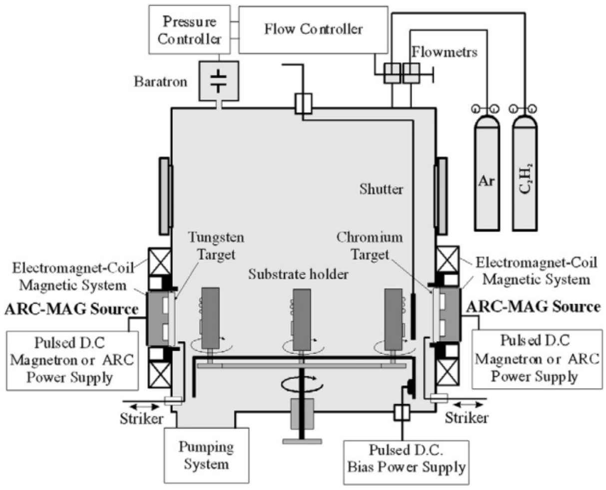


Fig. 1. Deposition chamber equipped with two planar ARC-MAG sources and substrate holder with planetary rotation.

The adhesion tests were performed using two methods: the "Peel and Pull-off" test and the "Scratch test". The "Peel and Pull-off" test was performed on the MTS QTest 10 device, in accordance with ECSS-Q-ST-70-13C, using the 3M8915 (6.7 N/cm) tape. The "Scratch test" method was used, in accordance with the ASTM Standard G171, and using the CSM Revetest equipment. Test parameters:

- Progressive loading: 1–100 N,
- Lading rate: 50 N/min,
- Scratch length: 20 mm,
- Indenter type: diamond Rockwell r=0.8 mm.

Cold welding tests were performed at the facilities of Aerospace & Advanced Composites GmbH (AAC). The value of Hertzian contact pressure for the cold welding test was given by Astronika and was calculated considering real-life conditions of usage of the antenna. For the representative cold welding tests parameters, a pin radius set on 25 mm and a load of 1 N which gives a maximum Hertzian pressure of 114 MPa were applied. Fretting was carried out with a frequency of 210 Hz and a 50 μm stroke, every 10 s a separation for adhesion testing was done to get an "evolution" of the adhesion with ongoing time. Tests were done in high vacuum with a duration of 5,000 cycles.
Microhardness measurements were performed on the Hysitron Triboindenter. Due to the low thickness of the produced coatings, it was necessary to use a very low load, F=10 μN, to obtain results representative for the coating, not for the substrate material underneath.

RESULTS

1.1. Microstructure and chemical composition

The first Cr/CrN+CrCN/Cr-C:H coating, then called DLC1, was about 1 µm thick; it had the greatest thickness of all the produced coatings (Figure 2). DLC1 comprises three different zones: the first one, closest to the substrate, is a pure Cr zone, next there is a laminate composite zone of CrN and CrCN – thin layers, each about 0.1 µm thick, with no clear border between them as they were produced only by gradual changing the chemical composition of the reactive gas atmosphere during the coating process. The last, surface Cr-C:H zone, is a layer of chromium doped hydrogenated carbon DLC, and again in the top layer there is no clear border, only a gradient of chemical composition.

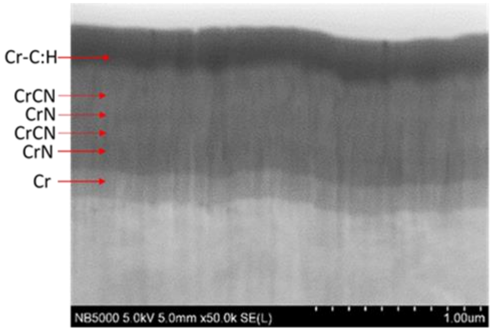


Fig. 2. Cross section of Cr/CrN+CrCN/Cr-C:H (DLC1) coating produced on CuBe2 tape.

The second Cr/W-C:H coating, then called DLC2, was about 0.6 µm thick and it is the thinnest of the produced coatings (Figure 3). It combines two zones: a technical chromium zone, and an upper W-C:H, tungsten doped hydrogenated carbon DLC layer. It was observed that there is a clear border between the Cr and W-C:H zones.

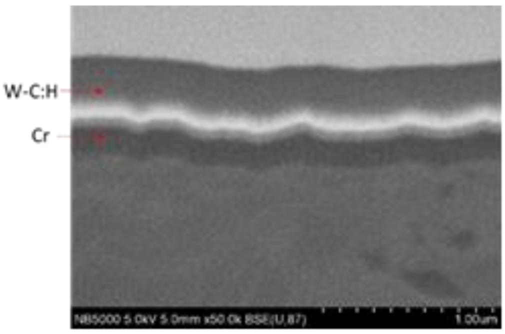


Fig. 3. Cross section of Cr / W-C:H (DLC2) coating produced on the CuBe2 tape.

Like all doped hydrogenated coatings produced, in the W-C:H zone there was observed a gradual change in the composition from a 100% of tungsten to the final carbon coating, where the only participation of carbides from the doped element can be found.

The final third Cr/CrN+Ag /Cr-C:H coating, then called DLC3, was about 0.9 µm thick and was composed of three zones (Figure 4). This coating was similar to the DLC1 coating, but its middle composite zone was a laminate mixture of CrN with Ag instead of CrCN.

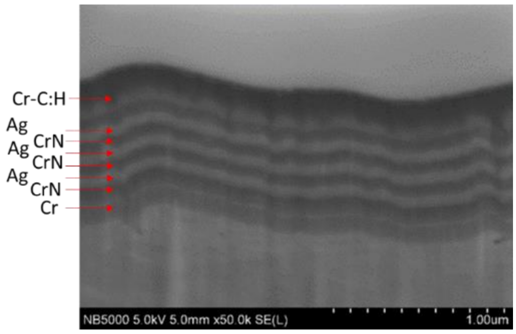


Fig. 4. Cross section of Cr/CrN+Ag/Cr-C:H (DLC3) coating produced on CuBe2 tape.

1.2. Thermo-optical properties

All three DLC coatings visually looked similar, they all had dark, black, graphite glossy colour and changed visually the initial copper beryllium tape (Figure 5).

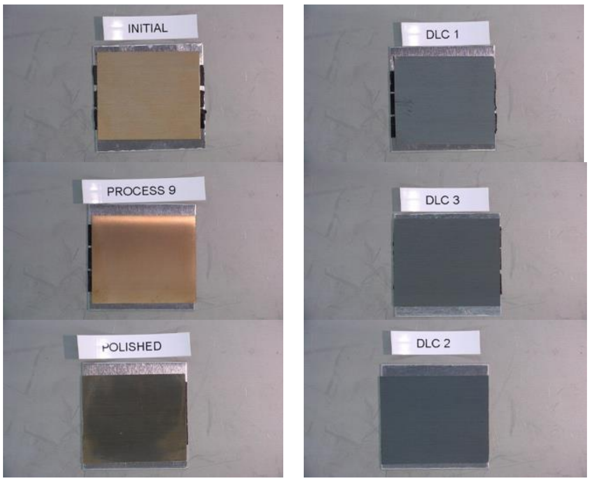


Fig. 5. DLC coated and mechanically modified CuBe2 samples used for thermo-optical measurements.

Producing such a thin coating does not have impact on the surface roughness which was almost the same as for the substrate material. To compare the effect of the produced coatings on the thermo-optical parameters, the coated samples were measured together with three CuBe2 tapes with a different surface finish: polished, grinded (Process 9) and at an initial state. The total reflectance spectra were measured on flat square 33x33 mm samples (Figure 5) cut from the coated CuBe2 tapes in the solar wavelength range of 300–2,500 nm and in the infrared wavelength range of 2.5–20 µm. The total reflectance spectra are presented in Figure 6.

a)

b)

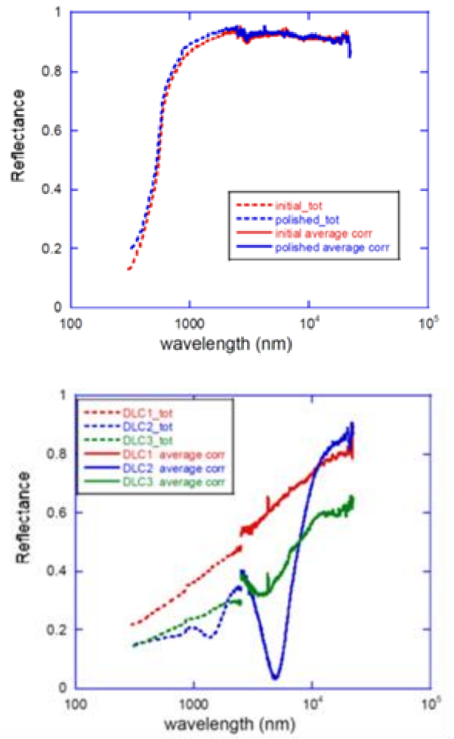


Fig. 6. Total reflectance spectra in solar wavelength range 300–2,500 nm and in infrared wavelength range 2.5–20 µm for DLC coatings and CuBe2 tape.

The solar absorptance value (alpha) was calculated using the solar spectrum for AM1.5 at the surface of the Earth, in accordance with ISO 9845. The emissivity (emittance) value was calculated for blackbody radiation at room temperature. The reflectance value for wavelengths over 20 µm was extrapolated using a constant value**.** The thermo-optical values calculated for the coated and uncoated CuBe2 tape with different surface finish are shown in Table 1.

Table 1. Thermo-optical parameters values for DLC coatings and CuBe2 tape after different mechanical treatments.

Sample	Alpha	Epsilon	α/ε
CuBe2	0.304	0.022	13.82
CuBe2 polished	0.276	0.021	13.14
CuBe2 grinded	0.39	0.043	9.07
DLC1	0.676	0.177	3.82
DLC2	0.813	0.21	3.87
DLC3	0.786	0.379	2.07

Considering the thermo-optical values, DLC coatings have greater impact on the CuBe2's properties than their surface finish. The lowest α/ε value obtained with the DLC3 coating gives 15% of the original value measured for the CuBe2 tape, while the DLC2 and DLC1 coatings decrease this value by 70% of the original one. Analysing the influence of the chemical composition on the properties of DLC coatings, the beneficial effects of the Ag sub-layers are visible, this slight change between DLC1 and DLC2 coatings affects the increase of the emissivity coefficient and consequently the reduction of the α/ε coefficient almost twice. When we look at the mechanically treated samples, different surface finish can scatter the α/ε value in the range of maximum 30% for the CuBe2 tape.

1.3. Cold welding test

For "Cold welding" tests under fretting conditions the similar types of samples as for thermo-optical measurements were used. All tapes were glued using glue-on-steel discs, while the pins were produced using a CuBe2 alloy (Berylco 25) and heat treated in the same process as the coated tapes, detailed characteristics obtained during the tests are presented in Figure 7.

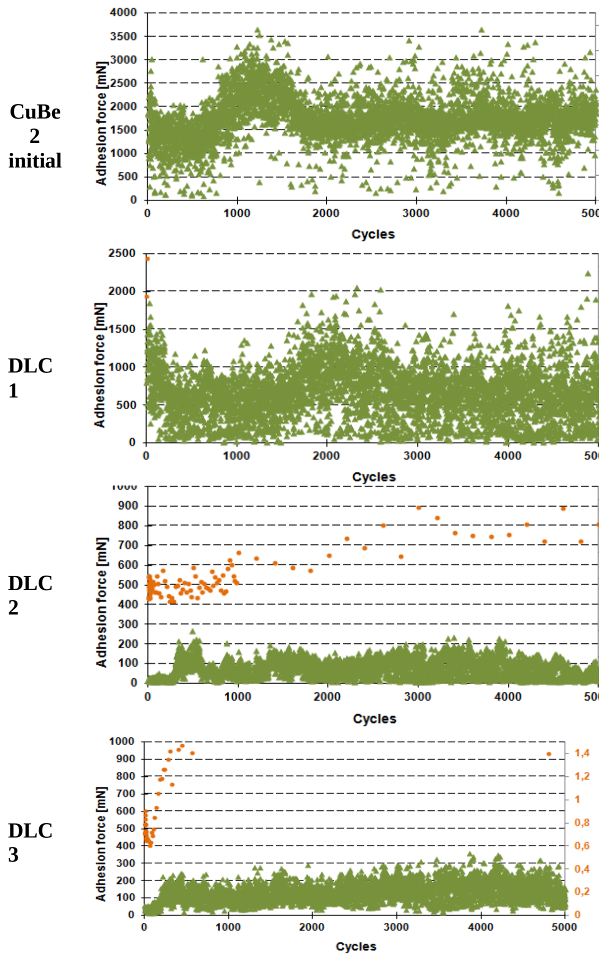
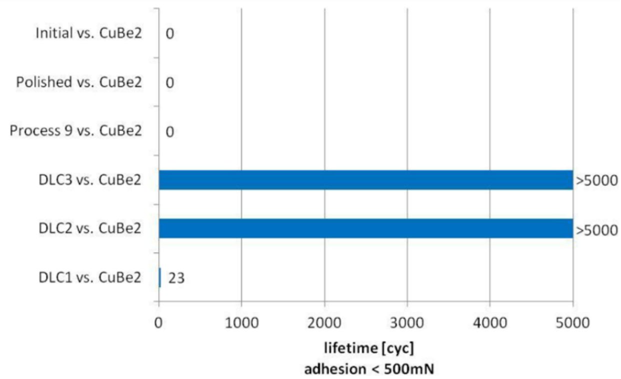


Fig.7. Adhesion force and friction coefficient evaluation through 5,000 cycles.

Out of all DLC coatings, the following two had the best performance: DLC2, DLC3. In comparison to the uncoated CuBe2 substrate, they deliver a 10 times lower adhesion force during all 5,000 fretting cycles. The third of the tested coatings, DLC1, showed slightly higher adhesion forces, however these were still 50% lower than for the initial material. It is clearly visible that the presence of hard CrCN sub-layers is not beneficial for DLC coating, both DLC2 and DLC3 without these hard zones coatings presented a much better performance in the fretting tests.

Figure 8 presents the number of cycles where the measured adhesion force was smaller than 500 mN (a) and 200 mN (b). Figure 9 shows the summary results of the maximum adhesion force measured during the test between the coated sample and the CuBe2 pin.

a)



b)

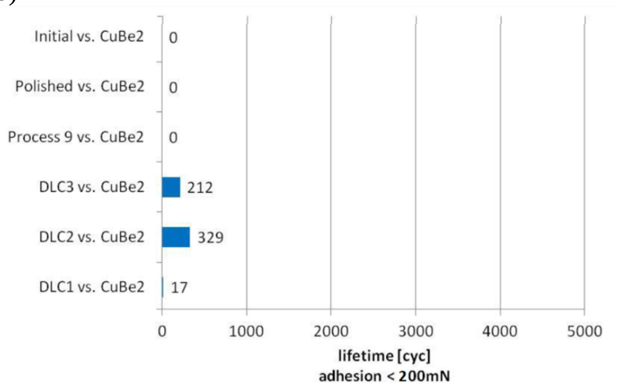


Fig. 8. Number of cycles where measured adhesion force.

Considering only the CuBe2 substrate subjected to different surface finishes, the most stable force during all the tests was observed for the polished surface, but this sample also had the highest maximum adhesion force from all the samples. The grinding process increased the cold welding maximum adhesion force of the CuBe2 substrate as well. In summary, the best cold welding performance was observed for the initial material without any additional surface finish.

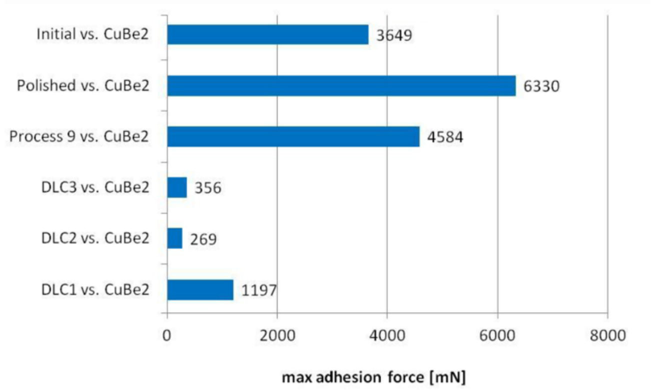
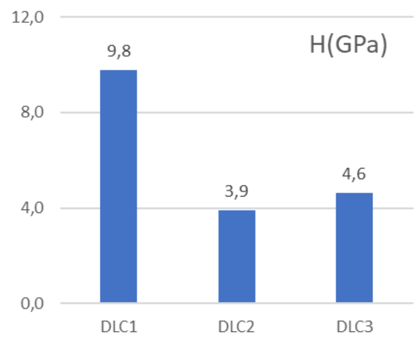


Fig. 9. Maximum adhesion force measured during 5,000 cycles.

1.4 Nano-indentation

Microhardness measurements were performed using the same samples which were used previously for the cold welding test. For all samples a matrix of over 50 measurements was used. The graphs below (Figure 10) present the equal values of microhardness (H) and Young's modulus (E) obtained for the measurement matrices for each type of the sample.

a)



b)

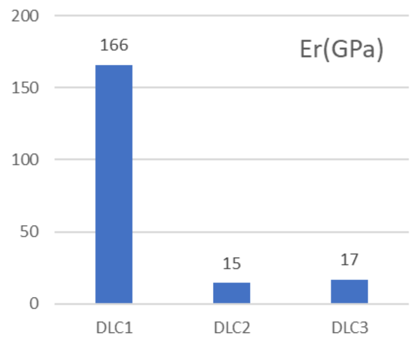


Fig. 10. Microhardness (a) and Young's modulus (b) equal values for DLC coatings produced on CuBe2 substrate.

These values show that the DLC1 coating has the highest hardness, while the other coatings present similar lower values. Both the DLC2 and DLC3 coatings also represent the lowest Young's modulus values, with a 10 times difference compared to DLC1. It is very important, if we consider these values with the cold welding results in mind, where both DLC2 and DLC3 showed the best results, while DLC1 had clearly worse results.

1.5. Adhesion tests

For adhesion tests, three types of the DLC samples were used, they represented various states of the life cycle of the protective coatings on tubular booms:

- initial state samples (IN) with coatings produced on the tapes delivered by the supplier,
- samples additionally heat treated (HT) in accordance with the standard procedures of the tubular boom production (heated up to 315 °C for 2h at technical vacuum), to simulate the real application conditions,
- samples heat treated and subjected to 10 thermal cycles (HT+TC) within the range of -180–150 °C using liquid nitrogen bath and standard furnace, to simulate the space environment conditions.

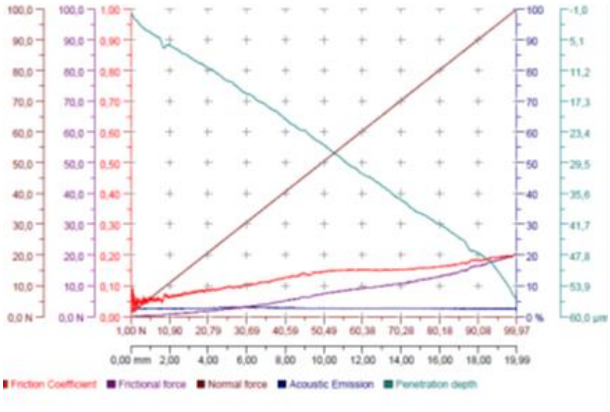
During the "Peel and Pull-off" tests none of the tested coatings before or after the heat treatment or thermal cycling showed any sign of delamination or peeling off when inspected at a 7 times magnification.
This showed that all DLC coatings represent much higher surface adhesion in comparison to other types of adhesive coatings, such as paints or sprayed coatings typically used in thermo-optical applications.
Moreover, the results obtained from force measurements showed that the 3M8915 tape used in the tests give higher adhesion values than those delivered in the datasheet. The maximum measured pull-off (unloading) force in all the tests was higher than 50 N, which means an almost 100% higher tape adhesion than the predicted 26.8 N measured for a surface contact of 4 cm^2.

It turned out that the "Scratch test" method is more appropriate and accurate in testing of the PVD produced DLC coatings. For each "Scratch test" step, two or three scratches were done per a single sample for statistics. The penetration depth, friction coefficient, and acoustic emission were recorded during the "Scratch test". The critical values of loads Lc1, Lc2 and Lc3 were measured in accordance with the recorded values and microscopic observations of scratches, where:

- Lc1 is the load where the first initial single chipping of coating was observed,
- Lc2 is the load where cracks inside the trace were observed,
- Lc3 is the load where abrasions of coating were observed.

The results of the tests show a great impact of the heat treatment on the adherence of all DLC coatings. The heat treatment of the substrate dramatically increases the adherence of all coatings. Thermal cycling tests which were then performed do not have a significant impact on these properties.
Heat treatment is an aging process of beryllium copper alloy which increases hardness and other mechanical properties of the tape, and as far as the produced PVD coatings are considered, they change the internal stresses of the coatings too.

a)



b)

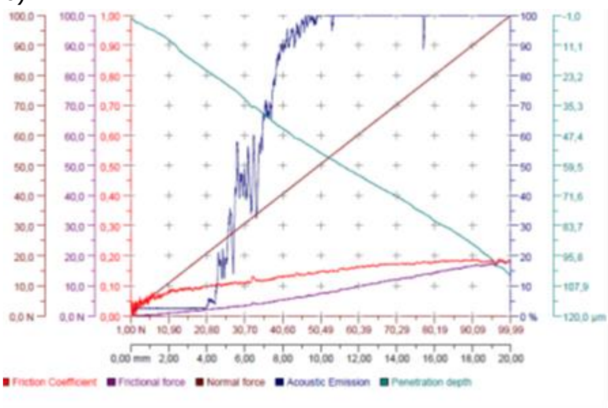


Fig. 11. Graphs obtained for scratch test of DLC3 coating before (a) and after (b) heat treatment (red – friction coefficient, blue – acoustic emission signal, green – penetration depth).

After the heat treatment on graphs for all DLC coatings there are visible strong signals from an acoustic emission sensor – it provides information about crack propagation which can appear inside the coatings or on the interface between the substrate and the coating (Figure 11). Such signals were not present for coatings produced on the substrate before the heat treatment.
All the produced DLC coatings showed the low friction coefficient in whole applied 1–100 N load range, and in all tests did not exceed maximum value of $\mu=0.2$.
A visual inspection of the scratches shows that before the

heat treatment the coatings revealed some signs of wear and cohesive cracks inside the trace (Figure 12), however after the heat treatment it is difficult to observe any cracks or final wear on the tested coatings, even at a 500 times magnification. It is also difficult to compare the scratches on the samples before and after thermal cycling, as they look the same, which means that the tested DLC coatings show great resistance to thermal cycling within the tested temperature range.

It is also a proof of the nature of the cracks that form, which must be the effect of relaxation and compressive stress on the inner layer and do not negatively affect the adhesion of the coatings.

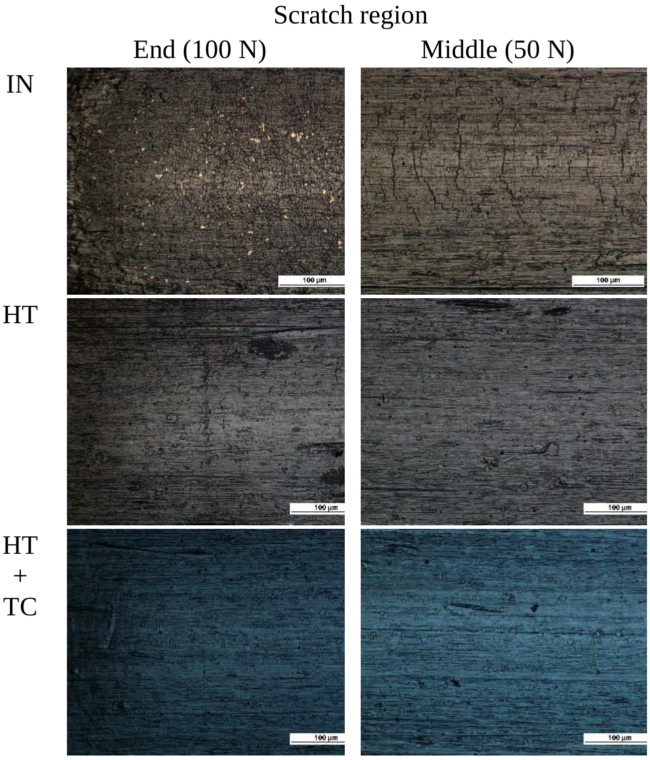


Fig. 12. The appearance of scratches performed on DLC3 coating produced on CuBe2 substrate after different treatments.

Some differences between all three DLC coatings can be observed in the values of critical loads which are presented in Table 2, but these values were determined using microscopic observation, which is still problematic when we consider surfaces where there are no visible cracks.

Table 2. Critical loads values for DLC coatings on CuBe2 substrate after different treatments.

Coating type	IN [N]			HT [N]			HT+TC [N]		
	Lc1	Lc2	Lc3	Lc1	Lc2	Lc3	Lc1	Lc2	Lc3
DLC1	-	37	-	-	-	-	-	70	-
DLC2	-	25	60	-	53	-	-	76	-
DLC3	-	43	90	-	95	-	-	85	-

RESULTS DISCUSSION

The idea of this research was to test different DLC coatings which can be applied as protective coatings on tubular booms made of the CuBe2 alloy metallic tapes.

All coatings had different zones and phase composition. Each DLC coating was produced on the metallic "technical" W or Cr coating, which increased the adherence of DLC to the substrate material. These elements as well as the doped elements were used for the upper DLC coating.

The comparison of the laminate zones in the DLC1 and DLC2 coatings located between the technical layer and the upper DLC coating shows that their phase composition can change the properties of the whole coating. It has an impact on both the thermo-optical parameters and the functional-mechanical properties.

Due to the presence of the DLC upper layer, such coatings have a very low friction coefficient (also in vacuum due to its high hydrogen amount) and great wear resistance due to its high hardness and great mechanical properties (an addition of W or Cr reduces internal stresses typical for DLC coatings).

SUMMARY

The results presented in this paper allow to define some main conclusions about the protective properties of DLC coatings produced on the CuBe2 metallic tapes used for tubular boom instruments:

- the results of thermo-optical measurements show that the produced DLC coatings have a great impact on the CuBe2 metallic tape properties.

- the tested DLC coatings decreased the alpha/epsilon value up to 85% of the value representative for the bare CuBe2 alloy.

- adhesion of DLC coating is improved after the heat treatment of the CuBe2 substrate, which can be connected with the increased internal compressive stresses, or even a change in the character of the stresses from tensile to compressive,

- the scratch test results show higher acoustic emission signals (which are typical for the cracking process) for the heat treated samples, however the visual inspection and the critical load values show less cracks and a higher resistance to scratching then in coatings before heat treatment. It means that producing coatings as the first stage of the tubular boom production process is an optimum solution, both for manufacturing convenience and the coatings properties,

- thermal cycling of the coated samples showed a limited impact on their properties, only a small decrease in the critical load values during the scratch tests. The tested coatings overall showed a very good performance after thermal cycling within the range of -180–150 °C.

- the cold welding tests showed a significant improvement in reducing the separation force values for two of the coatings: DLC2, DLC3. This observation can be connected with the results obtained from the nanoindentation tests which clearly show that these two coatings represent the lowest E value.

- there is no significant influence of the hardness of the coatings on their cold welding performance.

- comparing the two types of the mechanical treatment of the tape surface, both polishing and brushing increase the separation force, but this is more visible for the polished surface, as expected.

ACKNOWLEDGMENT

The present work has been accomplished within the framework research of ESA - POLISH INDUSTRY INCENTIVE SCHEME – “BoomCoat” project.

REFERENCES

1. Y.L. Su, W.H. Kao, “Tribology and application of Ti-C:H- and Cr-C:H-coated cemented tungsten carbide substrates”, Surface and Coatings Technology 137 (2001) 293.

2. T. Zehnder, J. Patscheider, “Nanocomposite TiC/a–C: H hard coatings deposited by reactive PVD”, Surface and Coatings Technology 133–134 (2000) 138.

3. M. Grischke, K. Bewilogua, H. Dimigen, “Preparation, properties and structure of metal containing amorphous hydrogenatedcarbon films”, Materials and Manufacturing Processes 8 (4–5) (1993) 407.

4. A. Leonhardt, H. Liepack, K. Bartsch, “CVD of TiCx/a-C-layers under d.c.-pulse discharge”, Surface and Coatings Technology 133–134 (2000) 186.

5. Y. Liu, A. Erdemir, E.I. Meletis, “A study of the wear mechanism of diamond-like carbon films”, Surface and Coatings Technology 82 (1996) 48.

6. A. Czyżniewski, “Characterisation of Transfer Layer and Wear Debris on Various Counterparts Sliding Against Undoped and Doped DLC Coatings”, Plasma Processes and Polymers 4 (2007) 231.

7. H. Ronkainen, J. Koskinen, J. Likonen, S. Varjus, J. Vihersalo, “Characterization of wear surfaces in dry sliding of steel and alumina on hydrogenated and hydrogen-free carbon films”, Diamond and Related Materials 3 (1994) 1329.

8. H. Ronkainen, J. Likonen, J. Koskinen, S. Varjus, “Effect of tribofilm formation on the tribological performance of hydrogenated carbon coatings”, Surface and Coatings Technology 79 (1996) 87.

9. J. Noshito, S. Watanabe, T. Sakurai, and S. Miyake, “Friction properties of co-sputtered sulphide/DLC solid lubricating films”, Surface and Coatings Technology 200 (2006) 5849–5854.

10. A. Voevodin, J.P. Oneill and J.S. Zabinski, “Nanocomposite tribological coatings for aerospace applications”, Surface and Coatings Technology 116–119 (1999) 36.

11. Z. Hui, Z. Jun, S. Rui-peng, H. Hong, Y. La-mao-cao, “tungsten containing hydrogenated dlc coatings on grease lubricated harmonic drive gear for space application”, Proceedings of ‘14th European Space Mechanisms & Tribology Symposium – ESMATS 2011’.

12. A. Vanhulsel, F. Velasco, R. Jacobs, E. W. Roberts, I. Sherrington, M. J. Anderson, L. Gaillard, “Development of highly hydrogenated DLC coatings for solid lubricant applications in space”, Proceedings of ‘11th European Space Mechanisms & Tribology Symposium – ESMATS 2011’.

13. A. Czyżniewski, W. Gulbiński, G. Radnóczi, M. Szerencsi, M. Pancielejko, “Microstructure and mechanical properties of W-C:H coatings deposited by pulsed reactive magnetron sputtering”, Surface and Coatings Technology 205 (2011) 4471–4479.