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Thin Solid Films xx (2003) xxx–xxx
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Laser cladding of wear resistant metal matrix composite coatings

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Abstract

A number of coatings with wear-resistant properties as well as a low friction coefficient is produced by laser cladding. The structure of these coatings is determined by required performance and realized as metal matrix composite (MMC), where solid lubricant serves as a ductile matrix (e.g. CuSn), reinforced by appropriate ceramic phase (e.g. WC/Co). One of the engineered coating with functionally graded material (FGM) structure has a dry friction coefficient 0.12. Coatings were produced by coaxial injection of powder blend into the zone of laser beam action. Metallographic and tribological examinations were carried out confirming the advanced performance of engineered coatings.

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PACS: 42.62.C; 81.15

Keywords: Laser cladding; Metal matrix composite; Coaxial nozzle; Dry friction; Solid lubricant

1. Introduction

The improved machinery performance and safety (aerospace, automotive, etc.) can be realized by development of protective wear-resistant coatings with advanced tribological properties. To solve any specific tribological problem, one should perform a certain consequence of steps: (1) Analysis of given working condition to define the requirements for coating performance. (2) The choice of appropriate materials and coating structure to satisfy the above requirements. For example, functionally graded materials (FGM) coating allows to expand the range of coating's operational temperatures as well as to deposit materials with different properties without residual stresses [1]. If coating has to work under shock loads, the multilayered structure can be applied. (3) The choice of appropriate method for coating deposition, flexible enough to provide desired microstructure.

One can find a variety of challenging tribological situations in heavy industry and aerospace applications: dry (emergency) friction, high contact loads (e.g. 50 DaN, resulting pressure 10 MPa), relatively low sliding velocity (1 mm/s). To meet these requirements, three types of coating structure are proposed: (i) A metal matrix composite (MMC) coating consisting from solid lubricant (SL), e.g. CuSn, reinforced by ceramic phase, e.g. nanostructured WC/Co (Fig. 1). Deposition of MMC coating by simultaneous injection of WC with Co- or Ni-based alloys during laser cladding is described in Ref. [2]. (ii) A coating consisting from traditional metal matrix composite possessing good wear resistance, with addition of up to 30% vol. of solid lubricants (MoS_2, graphite, hexagonal BN, CuSn). The inclusions of SL serve as reservoirs of lubricating phase during wear, providing low friction coefficient (Fig. 2). (iii) A coating consisting of hard separated bars (e.g. stellite) with equal gaps between them, filled up with solid lubricant (e.g. CuSn), reinforced by dispersed ceramic phase. Thus, the wear resistant coating with low friction coefficient can be produced. The schematic view of such structure is shown in Fig. 3. The tough internal core has the following functional load: (a) coating reinforcement for shear action of the counterbody; (b) reservoir for the soft solid lubricant preventing its fast removal; (c) barrier for crack propogation, which allows to increase operational contact load. Such a coating can be made in one-stage process applying coaxial nozzle and mixture of insoluble components of the core and SL matrix. Each internal 'bar' is produced by appropriate

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0040-6090/03/$ - see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/S0040-6090(03)01669-9

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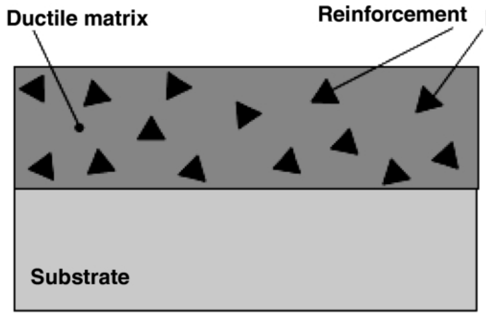

Fig. 1. Coating from metal matrix composite with solid lubricant applied as ductile matrix.

pass of coaxial nozzle, in Fig. 3 one can see three lines made by three passes of the nozzle.

The methods for coating deposition have to be flexible enough to satisfy the following requirements: (1) possibility to mix different components, producing coating with desired composition 'in situ'; (2) possibility to create desired material distribution, internal structure of a coating (e.g. FGM [3], multilayered, engineered coatings). Laser cladding with coaxial powder injection [4,5] was applied as a method satisfying the abovementioned requirements. The particular advantages of the method are the following: process flexibility (wide range of controllable parameters), excellent adhesion to a substrate, low coating porosity, local action of the laser beam, free-directional cladding, protection from the ambient atmosphere, relatively small HAZ. The coating thickness can be varied in the wide range 10–1000 μm. This method allows to obtain local coating deposition, line width is in the range 1–7 mm. It is possible to deposite protective coating exactly on desired area exposed to severe wear conditions. The technique of 'in situ' creation of functionally graded coating by laser cladding is described in Ref. [6].

2. Materials and experimental facilities

The process of coating deposition consists from the following stages: powder preparation, delivery to the zone of laser beam and coating deposition. Powder preparations include drying in thermal chamber and sorting powder with desired granularity on the 'RETSCH' device. The powder mixer 'Bioengineering Inversina 2I' is applied to mix powder blends. Powder feeder MEDICOAT provides delivery of powder (carrying gas is argon) from two independent channels through antistatic tubes to the coaxial nozzle. The coaxial nozzle provides forming and orientation of powder flow relatively to the laser beam. Applied laser source is continuous wave (CW) Nd:YAG HAAS 2006D (maximal output power is 2 kW), laser radiation is delivered by optical fibre. The CNC 3D table LASMA 1054 provides precise movement (position accuracy is up to 1 μ) of the substrate relatively to the laser beam.

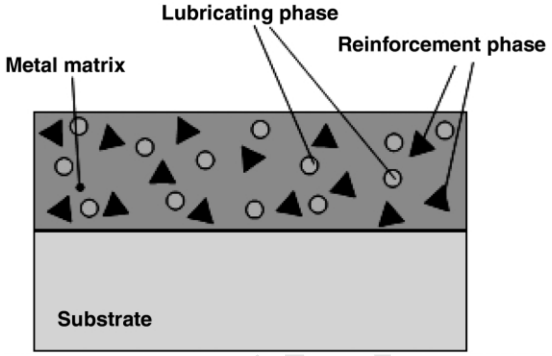

Fig. 2. Coating from traditional metal matrix composite with inclusions of solid lubricant.

The quality of coatings is examined with metallographic analysis and tribological tests. Metallographic facilities are fabricated by 'Wirtz-Buehler GmbH' and include linear precision saw, automated mounting press, polishing machine 'Phoenix 4000V', device for electrolytic polishing and etching 'Polimat', optical microscope 'Olympus' (up to ×1000), digital microhardness (HV) tester. HEF (F) and Teer Coatings Ltd. (UK) provide the tribological examination of samples. The distribution of key components through coating's thickness for sample with engineered structure shown in Fig. 3 was examined on Spectrometer 'SA-2000' in INOP, Poland.

The powders applied in laser cladding are presented in Table 1.

3. Results and discussion

Process parameters are the following: power density $\sim 5\times 10^3$ W/cm^2, scanning velocity 300–1000 mm/min, powder feed rate 20–30 g/min. The coating with the structure shown in Fig. 1 is produced from CuSn, as a solid lubricant matrix, reinforced by ceramic phase WC/Co, see Table 1. The microstructure of coating is

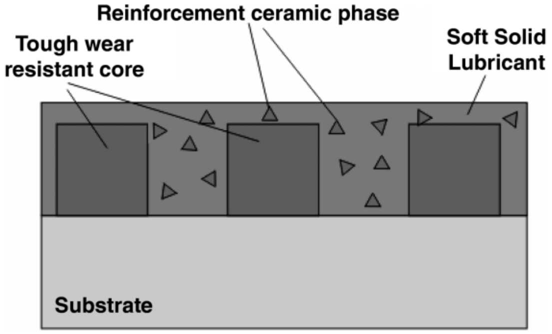

Fig. 3. Engineered coating structure: tough core stellite bars covered with solid lubricants, reinforced by ceramic.

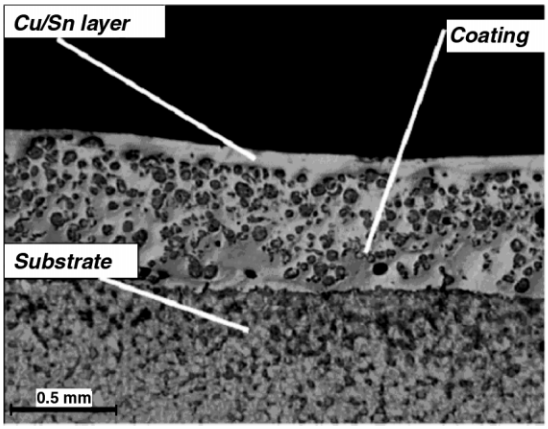

Fig. 4. The microstructure of coating from solid lubricant (CuSn), reinforced by ceramic phase (WC/Co).

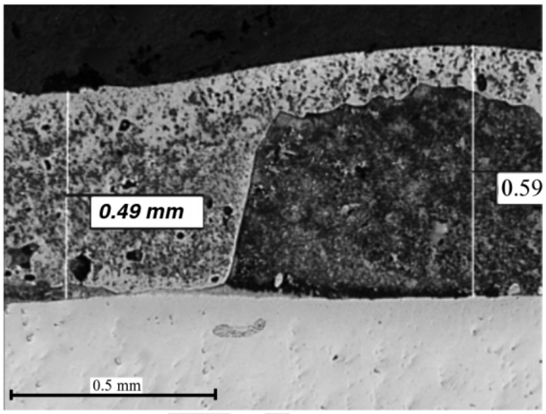

Fig. 6. The microstructure of coating with tough stellite core, covered with solid lubricant (CuSn) reinforced by nanostructured WC/Co.

shown in Fig. 4. The coating with structure shown in Fig. 2 is produced from FeCr-base matrix (stainless steel 430L) with inclusions of solid lubricant CuSn, reinforced by ceramic phase. The coating microstructure is shown in Fig. 5.

The coating with structure shown in Fig. 3 is produced from stellite applied as a tough internal structure, covered by a solid lubricant matrix, reinforced by ceramic phase (Stellite/CuSn/nanostructured WC/Co). The coating microstructure is shown in Ref. Fig. 6.

The latter two coatings (shown in Figs. 5 and 6) were examined by tribological reciprocating tests (HEF). The conditions are the following: load 50 DaN (resulting pressure 10 MPa), sliding velocity 1 mm/s, displacement 5 mm, duration 360 cycles (1 h), temperature 25 °C. Results are presented in Fig. 7. The sample Stellite/CuSn/nanoWC/Co has a stable coefficient of dry friction 0.12 which is the lowest one among the examined coatings.

The analysis of basic elements distribution depending on coating depth is performed on Spectrometer SA-2000. Optical emission spectrometer (OES) is applied as a basic measurement instrument for analysis of coating composition. Glow discharge is used for spectrum excitation. Glow discharge-optical emission spectrometer is an appropriate tool for accurate bulk analysis, as well as quantitative depth profiling on a wide variety of materials. For the considered coating, the distribution of elements is analyzed in two zones: at depth 0–40 and 40–100 μm from the surface correspondingly. The distribution of basic elements in the two zones is shown in Figs. 8 and 9.

The first zone is characterized by practically uniform distribution of Ni (1.8%), Fe (2%). Relatively uniform distribution with slight variation of concentration is also observed for Cr (12–12.5%), Co (13–14%), Sn (16–17%). Increase of W (16–20%) concentration and decrease of Cu (28-23%) concentration is observed as well.

The second zone is characterized by practically uniform distribution of the following elements: Ni (1.4%), Fe (2.5%), Sn (12%), Co (15.5%), Cr (17.5%). The decrease of Cu (17.5-13%) and increase of W (20–23.5%) with the depth is also observed for this zone.

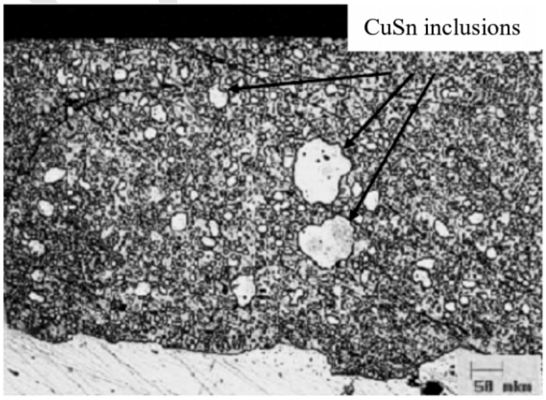

Fig. 5. The microstructure of metal matrix composite coating (SS430L/WC) with inclusions of solid lubricant (CuSn).

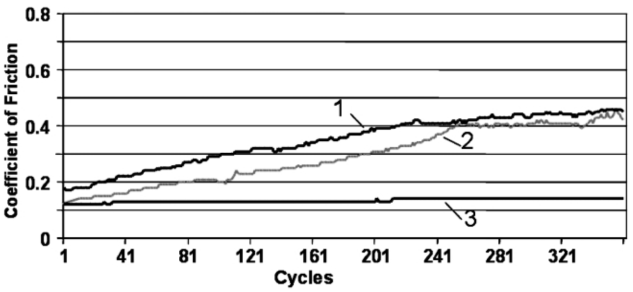

Fig. 7. Results of coatings tribological examination: 1 – Steel 430L/CuSn/WCCoCr 70/25/5 vol.%; 2 – Steel 430L/CuSn/nano WCCo 73/20/7 vol.%, 3 – Stellite/CuSn/nanoWC 56/24/20 vol.%.

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Table 1
Powders applied in laser cladding

Powder type	Powder composition (wt.%)	Paricle size (μm)
Stellite grade 12 HMSP 2541	C 1.35, Cr 30.5, Fe 3, Ni 3, Si 1, Mn 1, W 8.5, Co bal.	−150+53
CuSn 60/40 Osprey powders	Sn 38.9, P 0.16, O 0.012, Cu bal.	−106+10
Bronze BROV 10-1	Sn 10, P 1.0, Cu bal.	−85+10
WC/Co/Cr Dimalloy 5849 Sulzer Metko	WC 86, Co 10, Cr 4	−45+11
Nanostructured WC/Co MBN	WC 70, Co 30.	−75+38
BN Grade HCP advanced ceramics	Oxygen 0.229, BN bal.	−53+10
Stainless steel 430L	Fe 81.790, Cr 17.000, Si 0.700, Mn 0.500,C 0.01–0.03	−75+22

The concentration of Cu is gradually decreased by 10% from the surface to the 100-μm depth; concentration of Sn is also decreased by 7%. At the same time, the concentration of W is gradually increased by 8% from the surface up to the depth 100 μm. Thus, the coating has Functionally Graded structure not only in *X*–*Y* plane (see Fig. 6), but also along *Z*-axis (direction, normal to the surface). This distribution can be explained by segregation of components due to the difference in chemical–physical properties (e.g. density) during process of coating elaboration. The described distribution of components (with increase of CuSn concentration to the top of coating) is well adapted for the coating exploitation conditions, providing excess of solid lubricant during initial stage of wear when tribological interface is created.

When materials with different physical–chemical properties are mixed in a melt, segregation of components takes place during solidification. If the segregation is not desirable, the pulsed-periodic (PP) radiation can be applied instead of the continuous wave one to improve components remixing. The microstructure of samples with the identical composition (bronze+WCCoCr 50/50 vol.%) but produced with different radiation modes is shown in Fig. 10 (CW) and Fig. 11 (PP). The nanostructured WC/Co was applied as reinforcement phase with the same matrix as in the samples from Bronze+WCCoCr 50/50 vol.%. The photo of coating's microstructure is presented in Fig. 12.

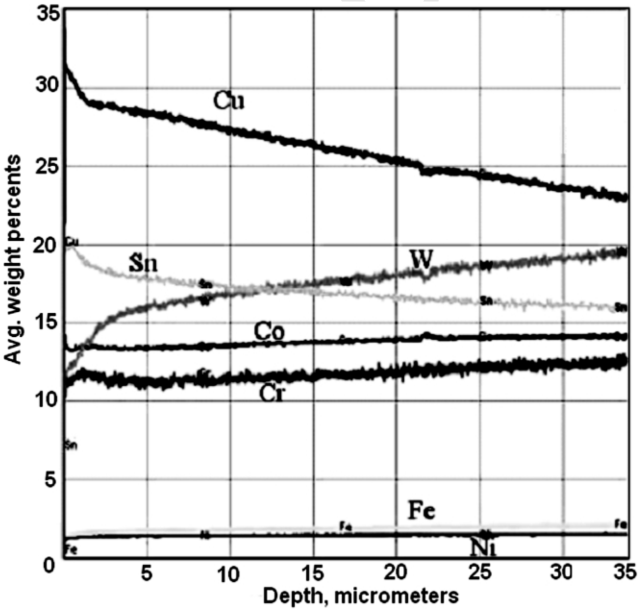

Fig. 8. Distribution of key elements at distance 0–40 μm from the surface.

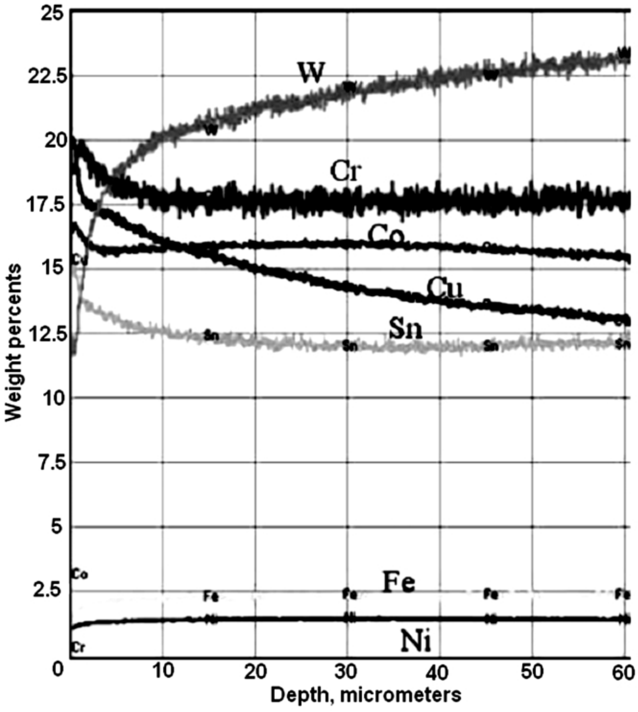

Fig. 9. Distribution of key elements at distance 40–100 μm from the surface.

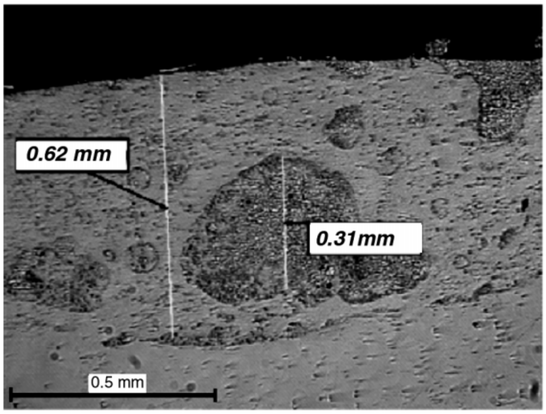

Fig. 10. The microstructure of coating deposited with continuous wave radiation.

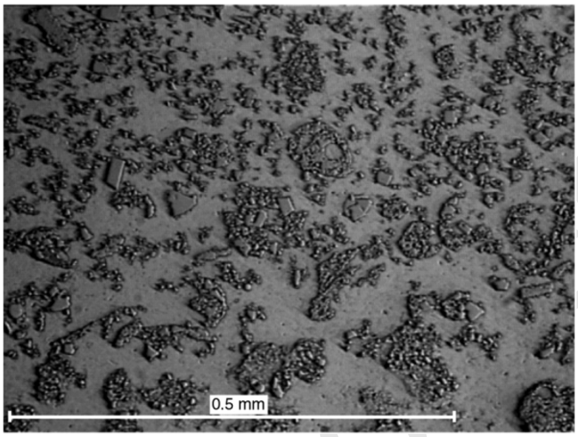

Fig. 11. The microstructure of coating deposited with pulse-periodic radiation.

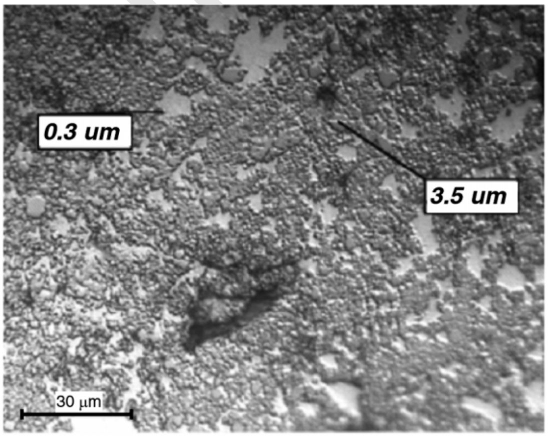

Fig. 12. The microstructure of coating reinforced by nanostructured WCCo, 1000X.

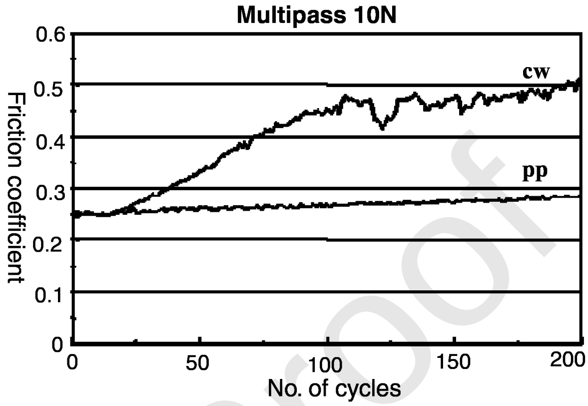

Fig. 13. The evolution of friction coefficient for samples Bronze+WC/Co made with continious wave (CW) and pulsed-periodic (PP) radiation. Table speed is 150 mm min^{-1}, 2-mm displacement, 200 cycles.

Although particle size is smaller for commercial hardalloy WC/Co/Cr ($-45+11$ μm) then the size of nanostructured WC/Co ($-75+38$ μm) powder it is clear, that nanostructured reinforcement phase is more fine dispersed in a bulk of MMC.

The microhardness is measured with load 300 g and then is averaged (Table 2). The microhardness of the coating Stellite/CuSn/nanostructured WC/Co (Fig. 6) is characterized by the two values—first number is for 'core' material and second number is for solid lubricant.

When CW radiation is applied, the significant segregation of components is observed. For pulsed-periodic radiation, the microstructure is much more uniform, reinforcement phase is dispersed more homogeneously. The difference in microstructure leads to the difference in tribological properties as well. Results of coatings examination are presented in Table 2.

Friction coefficient is found from reciprocating tests provided by HEF (F); the last two samples presented in Table 2 have a coating's structure shown in Figs. 10 and 11 and were tested by Teer Coatings Ltd. (UK) on their tribotester machine ST3001. The friction conditions

Table 2
Average microhardness measured with load

Composition of coating	Average microhardness, $HV_{0.3}$	Average friction coefficient
CuSn/WC/Co	500	0.32
Stellite/CuSn/ nanostructured WC/Co	730/480	0.12
SS 430L/CuSn	500	0.41
NanoWCCo/BN	400	0.6
Bronze Brov10-1/WCCoCr, CW radiation	280	0.45
Bronze Brov10-1/WCCoCr, PP radiation	300	0.25

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are different from those applied by HEF: bi-directional wear test was performed under applied load of 10 N, table velocity is 150 mm min^{-1}, 2-mm displacement, 200 cycles. A ∅5 mm WC-6%Co ball was used as the counterface material for the tests.

The evolution of friction coefficient is presented in Fig. 13.

The sample made with PP radiation (coating with well dispersed reinforcement phase, Fig. 11) shows no damage of the counterbody in contrast with the one made with CW radiation (Fig. 10). The friction coefficients are 0.25 and 0.45, correspondingly.

4. Conclusions

Coatings with tailored properties were deposited by laser cladding through coaxial nozzle. The coating Stellite/CuSn/nanoWC/Co with solid lubricant matrix reinforced both by internal structure (Stellite lines) and dispersed ceramic phase have shown the best performance with stable dry friction coefficient 0.12. The distribution of the main components shows gradual change of their concentrations: the decrease of Cu and Sn and the increase of WC concentrations from the surface to the 100-μm depth. It is shown that radiation mode is one of the critical parameters defining the coating's microstructure (and therefore, wear properties). Application of pulsed-periodic mode provides much better component remixing (e.g. in a case of producing coatings from MMC) in comparison with continuous wave mode. In the present study, the difference only in the coating microstructure (for the same composition) shows different friction coefficients—0.45 and 0.25 for continuous wave and pulsed-periodic modes, correspondingly.

Acknowledgments

European Commission Directorate General for Science Research and development supported the work under GROWTH Project '*TRIBO*' GRD1-2000-26824. To HEF (F) and Teer Coatings (UK) for provided tribological tests to INOP (Pol) for analysis of the sample Stellite/CuSn/nanoWC/Co on SA2003 spectrometer.

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