ABSTRACT AND REFERENCES

MATERIALS SCIENCE

DOI: 10.15587/1729-4061.2019.185674

DETERMINATION OF INFLUENCE OF ELECTROLYTE COMPOSITION AND IMPURITIES ON THE CONTENT OF α-Al_2O_3 PHASE IN MAO-COATINGS ON ALUMINUM (p. 6–13)

Valeria Subbotina
National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0002-3882-0368

Ubeidulla F. Al-Qawabeha
Al-Zaytoonah University, Amman, Jordan

Valery Belozerov
National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0002-7623-3658

Oleg Sobol
National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0002-4497-4419

Alexander Subbotin
National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0002-9422-4480

Taha A. Tabaza
Al-Zaytoonah University, Amman, Jordan

Safwan M. Al-Qawabah
Al-Zaytoonah University, Amman, Jordan

Coatings with a thickness of about 100 μm were obtained by microarc oxidation of technically pure aluminum and aluminum alloyed with copper and zinc in an alkaline silicate electrolyte at a current density of ~20 A/dm^2. The results of studying the surface morphology, phase composition, and hardness of MAO coatings are presented. The change parameters were the electrolyte composition and the concentration of alloying (Cu and Zn) elements. This study was carried out because the currently available data are not enough to understand the nature of the influence of the chemical composition of the aluminum alloy and electrolysis conditions (in particular, electrolyte composition) on the mechanism and kinetics of $\gamma \rightarrow \alpha$ transformation. Without understanding this, a directed change in the structural state and properties of MAO coatings becomes impossible. As a result of the studies, it was found that during microarc oxidation of aluminum alloys in an alkaline electrolyte with the addition of liquid glass (Na_2SiO_3) of various concentrations, the strengthened layer consists of oxides α-$A1_2O_3$, γ-$A1_2O_3$ and mullite $3Al_2O_3{\cdot}2SiO_2$. The data of x-ray diffraction analysis of the coatings indicate the crystal structure of the coatings. It was established that aluminum alloying with copper and zinc significantly affects the phase composition of the coating, changing the quantitative ratio of the phases in a nonlinear manner. The highest content of the α-$A1_2O_3$ phase (up to 60 vol. %) is achieved by Cu doping. The highest hardness of MAO coatings is achieved using an electrolyte with a composition of 1 g/l KOH and 6 g/l Na_2SiO_3 in aluminum alloys with a copper content of more than 3 %, and zinc – 2–3 %. It is established that the mechanism of formation of the phase composition should be associated with stabilization and destabilization of the γ-$A1_2O_3$ phase. Therefore, to achieve high hardness, it is necessary to choose those alloying elements that affect the destabilization of γ-$A1_2O_3$, which ensures the formation of the α-$A1_2O_3$ phase (corundum). In this regard, it was revealed that Cu^{2+} cations contribute to the destabilization of the γ-$A1_2O_3$ phase, and Zn^{2+} cations lead to stabilization of the γ-$A1_2O_3$ phase at a Zn content >3 %.

Keywords: microarc oxidation, anodic-cathodic mode, electrolyte composition, alloying, phase composition, corundum.

References

1. Radionenko, O., Kindrachuk, M., Tisov, O., Kryzhanovskyi, A. (2018). Features of transition modes of friction surfaces with partially regular microrelief. Aviation, 22 (3), 86–92. doi: https://doi.org/10.3846/aviation.2018.6204
2. Panarin, V. Y., Svavil'nyy, M. Y., Khominych, A. I., Kindrachuk, M. V., Kornienko, A. O. (2017). Creation of a Diffusion Barrier at the Interphase Surface of Composite Coatings Reinforced with Carbon Nanotubes. Journal of Nano- and Electronic Physics, 9 (6), 06023-1–06023-5. doi: https://doi.org/10.21272/jnep.9(6).06023
3. Sobol', O. V., Andreev, A. A., Gorban', V. F., Meylekhov, A. A., Postelnyk, H. O. (2016). Structural Engineering of the Vacuum Arc ZrN/CrN Multilayer Coatings. Journal of Nano- and Electronic Physics, 8 (1), 01042-1–01042-5. doi: https://doi.org/10.21272/jnep.8(1).01042
4. Sobol', O. V. (2016). Structural Engineering Vacuum-plasma Coatings Interstitial Phases. Journal of Nano- and Electronic Physics, 8 (2), 02024-1–02024-7. doi: https://doi.org/10.21272/jnep.8(2).02024
5. Mayrhofer, P. H., Mitterer, C., Hultman, L., Clemens, H. (2006). Microstructural design of hard coatings. Progress in Materials Science, 51 (8), 1032–1114. doi: https://doi.org/10.1016/j.pmatsci.2006.02.002
6. Sobol', O. V., Andreev, A. A., Gorban', V. F. (2016). Structural Engineering of Vacuum-ARC Multiperiod Coatings. Metal Science and Heat Treatment, 58 (1-2), 37–39. doi: https://doi.org/10.1007/s11041-016-9961-3
7. Morton, B. D., Wang, H., Fleming, R. A., Zou, M. (2011). Nanoscale Surface Engineering with Deformation-Resistant Core-Shell Nanostructures. Tribology Letters, 42 (1), 51–58. doi: https://doi.org/10.1007/s11249-011-9747-0
8. Barmin, A. E., Zubkov, A. I., Il'inskii, A. I. (2012). Structural features of the vacuum condensates of iron alloyed with tungsten. Functional Materials, 19 (2), 256–259.
9. Glushchenko, M. A., Belozyorov, V. V., Sobol, O. V., Subbotina, V. V., Zelenskaya, G. I. (2017). Effect of Tantalum on the Texture of Copper Vacuum Condensates. Journal of Nano- and Electronic Physics, 9 (2), 02015-1–02015-5. doi: https://doi.org/10.21272/jnep.9(2).02015
10. Glushchenko, M. A., Lutsenko, E. V., Sobol', O. V., Barmin, A. E., Zubkov, A. I. (2016). The Influence of Copper Condensates Alloying with Co, Mo, Ta Transition Metals on the Structure and the Hall-Petch Dependence. Journal of Nano- and Electronic Physics, 8(3), 03015-1–03015-4. doi: https://doi.org/10.21272/jnep.8(3).03015
11. Krause-Rehberg, R., Pogrebnyak, A. D., Borisyuk, V. N., Kaverin, M. V., Ponomarev, A. G., Bilokur, M. A. et. al. (2013). Analysis of local regions near interfaces in nanostructured multicomponent (Ti-Zr-Hf-V-Nb)N coatings produced by the cathodic-arc-vapor-deposition from an arc of an evaporating cathode. The Physics of Metals and Metallography, 114 (8), 672–680. doi: https://doi.org/10.1134/s0031918x13080061

12. Sobol', O. V., Andreev, A. A., Gorban', V. F., Krapivka, N. A., Stolbovoi, V. A., Serdyuk, I. V., Fil'chikov, V. E. (2012). Reproducibility of the single-phase structural state of the multielement high-entropy Ti-V-Zr-Nb-Hf system and related superhard nitrides formed by the vacuum-arc method. Technical Physics Letters, 38 (7), 616–619. doi: https://doi.org/10.1134/s1063785012070127
13. Sobol', O. V., Meilekhov, A. A. (2018). Conditions of Attaining a Superhard State at a Critical Thickness of Nanolayers in Multiperiodic Vacuum-Arc Plasma Deposited Nitride Coatings. Technical Physics Letters, 44 (1), 63–66. doi: https://doi.org/10.1134/s1063785018010224
14. Sobol, O. V., Postelnyk, A. A., Meylekhov, A. A., Andreev, A. A., Stolbovoy, V. A. (2017). Structural Engineering of the Multilayer Vacuum Arc Nitride Coatings Based on Ti, Cr, Mo and Zr. Journal of Nano- and Electronic Physics, 9 (3), 03003-1–03003-6. doi: https://doi.org/10.21272/jnep.9(3).03003
15. Nashrah, N., Kamil, M. P., Yoon, D. K., Kim, Y. G., Ko, Y. G. (2019). Formation mechanism of oxide layer on AZ31 Mg alloy subjected to micro-arc oxidation considering surface roughness. Applied Surface Science, 497, 143772. doi: https://doi.org/10.1016/j.apsusc.2019.143772
16. Muhaffel, F., Kaba, M., Cempura, G., Derin, B., Kruk, A., Atar, E., Cimenoglu, H. (2019). Influence of alumina and zirconia incorporations on the structure and wear resistance of titania-based MAO coatings. Surface and Coatings Technology, 377, 124900. doi: https://doi.org/10.1016/j.surfcoat.2019.124900
17. Yerokhin, A. L., Nie, X., Leyland, A., Matthews, A., Dowey, S. J. (1999). Plasma electrolysis for surface engineering. Surface and Coatings Technology, 122 (2-3), 73–93. doi: https://doi.org/10.1016/s0257-8972(99)00441-7
18. Wang, S., Xie, F., Wu, X. (2017). Mechanism of Al_2O_3 coating by cathodic plasma electrolytic deposition on TiAl alloy in $Al(NO_3)_3$ ethanol-water electrolytes. Materials Chemistry and Physics, 202, 114–119. doi: https://doi.org/10.1016/j.matchemphys.2017.09.006
19. Yang, Y., Gu, Y., Zhang, L., Jiao, X., Che, J. (2017). Influence of MAO Treatment on the Galvanic Corrosion Between Aluminum Alloy and 316L Steel. Journal of Materials Engineering and Performance, 26 (12), 6099–6106. doi: https://doi.org/10.1007/s11665-017-3037-4
20. Zhang, X., Li, C., Yu, Y., Lu, X., Lv, Y., Jiang, D. et. al. (2019). Characterization and property of bifunctional Zn-incorporated TiO_2 micro-arc oxidation coatings: The influence of different Zn sources. Ceramics International, 45 (16), 19747–19756. doi: https://doi.org/10.1016/j.ceramint.2019.06.228
21. Zong, Y., Cao, G. P., Hua, T. S., Cai, S. W., Song, R. G. (2019). Effects of electrolyte system on the microstructure and properties of MAO ceramics coatings on 7050 high strength aluminum alloy. Anti-Corrosion Methods and Materials, 66 (6), 812–818. doi: https://doi.org/10.1108/acmm-02-2019-2083
22. Sedelnikova, M. B., Komarova, E. G., Sharkeev, Y. P., Ugodchikova, A. V., Mushtovatova, L. S., Karpova, M. R. et. al. (2019). Zn-, Cu- or Ag-incorporated micro-arc coatings on titanium alloys: Properties and behavior in synthetic biological media. Surface and Coatings Technology, 369, 52–68. doi: https://doi.org/10.1016/j.surfcoat.2019.04.021
23. Dehghanghadikolaei, A., Ibrahim, H., Amerinatanzi, A., Hashemi, M., Moghaddam, N. S., Elahinia, M. (2019). Improving corrosion resistance of additively manufactured nickel – titanium biomedical devices by micro-arc oxidation process. Journal of Materials Science, 54 (9), 7333–7355. doi: https://doi.org/10.1007/s10853-019-03375-1
24. Zlotnikov, I. I., Shapovalov, V. M. (2019). Improving the Antifriction Properties of Ceramic Coatings Obtained by the Method of MAO on Aluminum Alloys. Journal of Friction and Wear, 40 (5), 360–363. doi: https://doi.org/10.3103/s1068366619050222
25. Shao, Q., Jiang, B., Huang, S. (2019). A comparative study on the microstructure and corrosion resistance of MAO coatings prepared in alkaline and acidic electrolytes. Materials Research Express, 6 (8), 0865b4. doi: https://doi.org/10.1088/2053-1591/ab2014
26. Li, G., Wang, Y., Qiao, L., Zhao, R., Zhang, S., Zhang, R. et. al. (2019). Preparation and formation mechanism of copper incorporated micro-arc oxidation coatings developed on Ti-6Al-4V alloys. Surface and Coatings Technology, 375, 74–85. doi: https://doi.org/10.1016/j.surfcoat.2019.06.096
27. Huang, H., Qiu, J., Sun, M., Liu, W., Wei, X. (2019). Morphological evolution and burning behavior of oxide coating fabricated on aluminum immersed in etidronic acid at high current density. Surface and Coatings Technology, 374, 83–94. doi: https://doi.org/10.1016/j.surfcoat.2019.05.081
28. Gecu, R., Yurekturk, Y., Tekoglu, E., Muhaffel, F., Karaaslan, A. (2019). Improving wear resistance of 304 stainless steel reinforced AA7075 aluminum matrix composite by micro-arc oxidation. Surface and Coatings Technology, 368, 15–24. doi: https://doi.org/10.1016/j.surfcoat.2019.04.029
29. Yang, X., Chen, L., Jin, X., Du, J., Xue, W. (2019). Influence of temperature on tribological properties of microarc oxidation coating on 7075 aluminium alloy at 25 °C–300 °C. Ceramics International, 45 (9), 12312–12318. doi: https://doi.org/10.1016/j.ceramint.2019.03.146
30. Belozerov, V., Mahatilova, A., Sobol', O., Subbotina, V., Subbotin, A. (2017). Improvement of energy efficiency in the operation of a thermal reactor with submerged combustion apparatus through the cyclic input of energy. Eastern-European Journal of Enterprise Technologies, 2 (5 (86)), 39–43. doi: https://doi.org/10.15587/1729-4061.2017.96721
31. Belozerov, V., Sobol, O., Mahatilova, A., Subbotina, V., Tabaza, T. A., Al-Qawabeha, U. F., Al-Qawabah, S. M. (2017). The influence of the conditions of microplasma processing (microarc oxidation in anode-cathode regime) of aluminum alloys on their phase composition. Eastern-European Journal of Enterprise Technologies, 5 (12 (89)), 52–57. doi: https://doi.org/10.15587/1729-4061.2017.112065
32. Tihonenko, V. V., Shkil'ko, A. M. (2012). Method of microarc oxidation. Eastern-European Journal of Enterprise Technologies, 2 (13 (56)), 13–18. Available at: http://journals.uran.ua/eejet/article/view/3940/3608
33. Curran, J. A., Clyne, T. W. (2005). Thermo-physical properties of plasma electrolytic oxide coatings on aluminium. Surface and Coatings Technology, 199 (2-3), 168–176. doi: https://doi.org/10.1016/j.surfcoat.2004.09.037
34. Martin, J., Nominé, A. V., Stef, J., Nominé, A., Zou, J. X., Henrion, G., Grosdidier, T. (2019). The influence of metallurgical state of substrate on the efficiency of plasma electrolytic oxidation (PEO) process on magnesium alloy. Materials & Design, 178, 107859. doi: https://doi.org/10.1016/j.matdes.2019.107859
35. Belozerov, V., Sobol, O., Mahatilova, A., Subbotina, V., Tabaza, T. A., Al-Qawabeha, U. F., Al-Qawabah, S. M. (2018). Effect of electrolysis regimes on the structure and properties of coatings on aluminum alloys formed by anodecathode micro arc oxidation. Eastern-European Journal of Enterprise Technologies, 1 (12 (91)), 43–47. doi: https://doi.org/10.15587/1729-4061.2018.121744
36. Subbotina, V. V., Sobol, O. V., Belozerov, V. V., Makhatilova, A. I., Shnayder, V. V. (2019). Use of the Method of Micro-arc Plasma Oxidation to Increase the Antifriction Properties of the Titanium Alloy Surface. Journal of Nano- and Electronic Physics, 11 (3), 03025-1–03025-5. doi: https://doi.org/10.21272/jnep.11(3).03025
37. Madhavi, Y., Rama Krishna, L., Narasaiah, N. (2019). Influence of micro arc oxidation coating thickness and prior shot peening on the fatigue behavior of 6061-T6 Al alloy. International Journal of Fatigue, 126, 297–305. doi: https://doi.org/10.1016/j.ijfatigue.2019.05.013

38. Li, C.-Y., Feng, X.-L., Fan, X.-L., Yu, X.-T., Yin, Z.-Z., Kannan, M. B. et. al. (2019). Corrosion and Wear Resistance of Micro-Arc Oxidation Composite Coatings on Magnesium Alloy AZ31–The Influence of Inclusions of Carbon Spheres. Advanced Engineering Materials, 21 (9), 1900446. doi: https://doi.org/10.1002/adem.201900446
39. Lai, P., Zhang, H., Zhang, L., Zeng, Q., Lu, J., Guo, X. (2019). Effect of micro-arc oxidation on fretting wear behavior of zirconium alloy exposed to high temperature water. Wear, 424-425, 53–61. doi: https://doi.org/10.1016/j.wear.2019.02.001
40. Zhang, Y., Chen, F., Zhang, Y., Liu, Z., Wang, X., Du, C. (2019). Influence of graphene oxide on the antiwear and antifriction performance of MAO coating fabricated on Mg Li alloy. Surface and Coatings Technology, 364, 144–156. doi: https://doi.org/10.1016/j.surfcoat.2019.01.103
41. Lesnevskiy, L. N., Lyakhovetskiy, M. A., Kozhevnikov, G. D., Ushakov, A. M. (2019). Research of the AK4-1 alloy microarc oxidation modes effect on the composite ceramic coatings erosion resistance. Journal of Physics: Conference Series, 1281, 012048. doi: https://doi.org/10.1088/1742-6596/1281/1/012048
42. Hua, T. S., Song, R. G., Zong, Y., Cai, S. W., Wang, C. (2019). Effect of solution pH on stress corrosion and electrochemical behaviour of aluminum alloy with micro-arc oxidation coating. Materials Research Express, 6 (9), 096441. doi: https://doi.org/10.1088/2053-1591/ab30fc
43. Wang, J., Huang, S., Huang, H., He, M., Wangyang, P., Gu, L. (2019). Effect of micro-groove on microstructure and performance of MAO ceramic coating fabricated on the surface of aluminum alloy. Journal of Alloys and Compounds, 777, 94–101. doi: https://doi.org/10.1016/j.jallcom.2018.10.374
44. Li, Z., Cai, Z., Cui, Y., Liu, J., Zhu, M. (2019). Effect of oxidation time on the impact wear of micro-arc oxidation coating on aluminum alloy. Wear, 426-427, 285–295. doi: https://doi.org/10.1016/j.wear.2019.01.084
45. Zhang, J., Kong, D. (2019). Effect of Micro-Arc Oxidation on Friction-Wear Behavior of Cold-Sprayed Al Coating in 3.5 wt.% NaCl Solution. Journal of Materials Engineering and Performance, 28 (5), 2716–2725. doi: https://doi.org/10.1007/s11665-019-04076-1

DOI: 10.15587/1729-4061.2019.188936

DETERMINATION OF THE PECULIARITIES OF OBTAINING COATINGS OF DIFFERENT HARDNESS ON STRUCTURAL STEEL AT DIFFUSION METALIZATION (p. 14–21)

Oleg Markov
Donbass State Engineering Academy, Kramatorsk, Ukraine
ORCID: http://orcid.org/0000-0001-9377-9866

Yurii Diachenko
Donbass State Engineering Academy, Kramatorsk, Ukraine
ORCID: http://orcid.org/0000-0003-0711-8354

Leila Aliieva
Donbass State Engineering Academy, Kramatorsk, Ukraine
ORCID: http://orcid.org/0000-0002-5283-925X

Serhii Zharikov
Donbass State Engineering Academy, Kramatorsk, Ukraine
ORCID: http://orcid.org/0000-0002-8754-9447

Natalia Hrudkina
Donbass State Engineering Academy, Kramatorsk, Ukraine
ORCID: http://orcid.org/0000-0002-0914-8875

Volodymyr Bondarenko
Donbass State Pedagogical University, Slavyansk, Ukraine
ORCID: http://orcid.org/0000-0003-0495-9756

Mykhailo Pohorielov
Donbass State Pedagogical University, Slavyansk, Ukraine
ORCID: http://orcid.org/0000-0003-4706-3263

The features of obtaining coatings on carbon steel, structural steel St 3 are studied during diffusion metallization – simultaneous saturation of steel with boron, chromium and aluminum (boron chromium aluminizing), without the use of special heat treatment. The basic compositions of powder mixtures are established using the simplex lattice method, which make it possible to obtain boride structures of increased hardness, phases of a solid solution of boron, chromium and aluminum in Feα and the predicted depth of the surface layer on the surface of carbon steel. The characteristic features of the microhardness formation of the surface layer of coatings are established depending on the composition of the saturating mixture. An important factor is established for the effect of aluminum on the microhardness of the surface layer in multicomponent systems. Its presence contributes to the formation of solid solutions. New data are obtained on the formation of surface layers during steel saturation with boron, chromium and aluminum, and the conditions for obtaining layers of high hardness and high ductility are determined. The optimal areas for the formation of coatings of various structures and depths by the simplex planning method are found. As optimization factors, let's use the relative planes occupied by borides and solid solution, as well as the depth of the surface layers. It is clearly shown how the structure of surface layers changes depending on the quantitative relations between the components of saturating mixtures. The graphical dependences of the boride phase, the phase of the solid solution and the depth of the layer, on the composition of the saturating mixture during diffusion metallization (boron chromium aluminizing) allow to improve the process in order to obtain coatings with increased wear resistance on the surface of carbon steel.

Keywords: chemical-thermal treatment, diffusion metallization, structure, microhardness, wear resistance, boride phase.

References

1. Karunanayake, G., Ng, Y.-L., Knowles, J. C., Delgado, A. H. S., Young, A. M., Gulabivala, K., Nazhat, S. N. (2019). The effect of NaOCl and heat treatment on static and dynamic mechanical properties and chemical changes of dentine. Journal of the Mechanical Behavior of Biomedical Materials, 97, 330–338. doi: https://doi.org/10.1016/j.jmbbm.2019.05.042
2. Chien, Y.-C., Yang, T.-C., Hung, K.-C., Li, C.-C., Xu, J.-W., Wu, J.-H. (2018). Effects of heat treatment on the chemical compositions and thermal decomposition kinetics of Japanese cedar and beech wood. Polymer Degradation and Stability, 158, 220–227. doi: https://doi.org/10.1016/j.polymdegradstab.2018.11.003
3. Bhowmik, R. N., Venkata Siva, K., Reddy, V. R., Sinha, A. K. (2019). Study of the lattice structure and magnetic spin order modification in chemical routed α-Fe1.4Cr0.6O3 oxide as an effect of heat treatment. Journal of Magnetism and Magnetic Materials, 484, 42–54. doi: https://doi.org/10.1016/j.jmmm.2019.03.126
4. Markov, O., Zlygoriev, V., Gerasimenko, O., Hrudkina, N., Shevtsov, S. (2018). Improving the quality of forgings based on upsetting the workpieces with concave facets. Eastern-European Journal of Enterprise Technologies, 5 (1 (95)), 16–24. doi: https://doi.org/10.15587/1729-4061.2018.142674
5. Karpov, L. P. (2003). Primenenie dvoynoy himiko-termicheskoy obrabotki pri izgotovlenii rezhushchego instrumenta iz konstruktsionnyh staley. Metallovedenie i termicheskaya obrabotka metallov, 1, 7–8.
6. Markov, O., Gerasimenko, O., Aliieva, L., Shapoval, A. (2019). Development of the metal rheology model of high-temperature deformation for modeling by finite element method. EUREKA: Physics

and Engineering, 2, 52–60. doi: https://doi.org/10.21303/2461-4262.2019.00877
7. Stepanov, M. S. (2007). The structure and phase composition of a diffusion layer of alloyed pm steel at lowtemperature diffusion saturation by nitrogen and carbon. Vestnik Donskogo gosudarstvennogo tehnicheskogo universiteta, 7 (1), 39–46.
8. Markov, O. E., Perig, A. V., Zlygoriev, V. N., Markova, M. A., Kosilov, M. S. (2017). Development of forging processes using intermediate workpiece profiling before drawing: research into strained state. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 39 (11), 4649–4665. doi: https://doi.org/10.1007/s40430-017-0812-y
9. D'yachenko, Yu. G. (2014). Issledovanie iznosostoykogo poverhnostnogo sloya uglerodistoy stali U7 poluchennogo pri himiko-termicheskoy obrabotke. Visnyk Donbaskoi derzhavnoi mashynobudivnoi akademiyi, 1, 71–74.
10. Kang, Y., Guo, F., Li, M. (2019). Effect of chemical composition and heat treatment on microstructure and mechanical properties of Nb-xTi-16Si-3Cr-3Al-2Hf-yZr alloy. Materials Science and Engineering: A, 760, 118–124. doi: https://doi.org/10.1016/j.msea.2019.05.117
11. Liu, X. Y., Yi, H., Che, J. W., Liang, G. Y. (2019). Phase, compositional, structural, and chemical stability of La2Ce2O7 after high temperature heat treatment. Ceramics International, 45 (4), 5030–5035. doi: https://doi.org/10.1016/j.ceramint.2018.11.204
12. Pettinari-Sturmel, F., Vultos, W., Hantcherli, M., Warot-Fonrose, B., Marcelot, C., Douin, J. et. al. (2019). Creep behavior in the new AD730TM nickel-based disk superalloy – Influence of aging heat treatment and local chemical fluctuations. Materials Science and Engineering: A, 754, 9–17. doi: https://doi.org/10.1016/j.msea.2019.02.088
13. Chung, J., Kwak, S.-Y. (2018). Solvent-assisted heat treatment for enhanced chemical stability and mechanical strength of meta-aramid nanofibers. European Polymer Journal, 107, 46–53. doi: https://doi.org/10.1016/j.eurpolymj.2018.07.051
14. Liu, X., Zhao, G., Lei, L., Jia, J. (2018). The effect of heat treatment temperature on superconductivity of Bi-2212/YBCO heteroepitaxial structure fabricated by chemical solution deposition approach. Ceramics International, 44 (9), 10820–10823. doi: https://doi.org/10.1016/j.ceramint.2018.03.126
15. Bruton, T. A., Sedlak, D. L. (2018). Treatment of perfluoroalkyl acids by heat-activated persulfate under conditions representative of in situ chemical oxidation. Chemosphere, 206, 457–464. doi: https://doi.org/10.1016/j.chemosphere.2018.04.128

DOI: 10.15587/1729-4061.2019.186989

DETECTING PATTERNS OF STRUCTURE FORMATION AT VARIOUS TYPES OF METAL MACHINING (p. 22–30)

Valerij Kassov
Donbass State Engineering Academy, Kramatrosk, Ukraine
ORCID: http://orcid.org/0000-0003-2387-8003

Eduard Gribkov
Donbass State Engineering Academy, Kramatrosk, Ukraine
ORCID: http://orcid.org/0000-0002-1565-6294

Olena Berezshnaya
Donbass State Engineering Academy, Kramatrosk, Ukraine
ORCID: http://orcid.org/0000-0001-6205-1987

Svetlana Malyhina
Donbass State Engineering Academy, Kramatrosk, Ukraine
ORCID: http://orcid.org/0000-0002-2622-5473

Andrej Sumets
PSC «Severodonetsk Association «AZOT», Severodonetsk, Ukraine
ORCID: http://orcid.org/0000-0002-2759-7375

This paper reports a research into influence of different types of thermal cutting, namely argon-plasma, air-plasma, and oxygen-flux cutting, on regularities in the formation of a thermal impact zone and structure formation in the cutting area. The formation of structural components of the heat-treated layers has been analyzed in detail in terms of depth of the thermal impact zone after different types of thermal cutting for steels of varying degree of doping. It was established that the result of thermal cutting is the formation of conditional sections, which are characterized by different structural components depending on the chemical composition of steels and the type of treatment. This paper describes patterns in the phase and structural transformations at thermal cutting of steels. The effect of a thermal cutting technique is shown on the formation of structural components both in the zone of melting and at sections near a main metal. The influence of the cutting technique on the depth of melted and transitional sections is given. The phenomena associated with the process of crystallization after cutting are described. The influence of cooling rate on the structure of metals in the cutting zone was considered in detail for a wide range of steel grades. The basic regularities of structure formation at the crystallization of a melted metal in the cutting zone depending on a chosen thermal cutting technique were established. The effect of a thermal cutting technique on change in the microhardness of cut surface and the depth of thermally treated layers is shown. It has been demonstrated that choosing an air-plasma-cutting method as a technological operation makes it possible to considerably reduce the depth of a thermal impact zone and microhardness in a cutting zone compared to argon-plasma and oxygen-flux cutting. The efficiency of the technological process of air-plasma cutting has been proven in comparison with other considered methods due to the reduction of depth in the thermal impact zone, which predetermines lower labor and economic expenses for the further machining of a cut surface. This reduces the production of parts and assemblies from structural steels of large thickness, for which high-performance thermal cutting is applied. Implementation of the established research results under industrial conditions would make it possible to significantly improve the efficiency and productivity of the technological process by obtaining high quality of the surface.

Keywords: thermal cutting, thermal impact zone, cutting speed, crystallization, metallographic analysis.

References

1. Anakhov, S. V., Pyckin, Y. A., Matushkin, A. V. (2016). Narrow Jet Plasma as the Energy Efficient and Safe Technology for Metal Cutting. Materials Science Forum, 870, 523–527. doi: https://doi.org/10.4028/www.scientific.net/msf.870.523
2. Novosel'tsev, Y. G., Vasil'ev-Polikin, K. S., Krylov, V. M., Tuf, S. M. (2013). Analysis of the conditions of efficient and stable operation of plasma in welding processes. Welding International, 27 (2), 136–138. doi: https://doi.org/10.1080/09507116.2012.695544
3. Salonitis, K., Vatousianos, S. (2012). Experimental Investigation of the Plasma Arc Cutting Process. Procedia CIRP, 3, 287–292. doi: https://doi.org/10.1016/j.procir.2012.07.050
4. Das, M. K., Kumar, K., Barman, T. K., Sahoo, P. (2014). Optimization of Process Parameters in Plasma arc Cutting of EN 31 Steel Based on MRR and Multiple Roughness Characteristics Using Grey Relational Analysis. Procedia Materials Science, 5, 1550–1559. doi: https://doi.org/10.1016/j.mspro.2014.07.342
5. Ramakrishnan, H., Balasundaram, R., Ganesh, N., Karthikeyan, N. (2018). Experimental investigation of cut quality characteristics on SS321 using plasma arc cutting. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40 (2). doi: https://doi.org/10.1007/s40430-018-0997-8
6. Loktionov, A., Gaar, N. (2015). Influence of Technological Parameters of High-Precision Plasma Cutting on the Position of the

Anode Spot on the Cut Edge. Applied Mechanics and Materials, 788, 46–51. doi: https://doi.org/10.4028/www.scientific.net/amm.788.46
7. Yuan, X. Q., Li, H., Zhao, T. Z., Wang, F., Guo, W. K., Xu, P. (2004). Comparative Study of Flow Characteristics Inside Plasma Torch with Different Nozzle Configurations. Plasma Chemistry and Plasma Processing, 24 (4), 585–601. doi: https://doi.org/10.1007/s11090-004-7934-6
8. Schitsin, Y. D., Kuchaev, P. S., Schitsin, V. Y. (2013). Plasma cutting of metals with reversed polarity and mixed supply of gases. Welding International, 27 (11), 890–892. doi: https://doi.org/10.1080/09507116.2013.796640
9. Krivonosova, E. A., Schitsin, Y. D., Trushnikov, D. N., Myshkina, A. V., Akulova, S. N., Neulibin, S. D., Dushina, A. Y. (2018). Structure formation of high-temperature alloy by plasma, laser and TIG surfacing. Journal of Physics: Conference Series, 1089, 012019. doi: https://doi.org/10.1088/1742-6596/1089/1/012019
10. Ramakrishnan, S., Shrinet, V., Polivka, F. B., Kearney, T. N., Koltun, P. (2000). Influence of gas composition on plasma arc cutting of mild steel. Journal of Physics D: Applied Physics, 33 (18), 2288–2299. doi: https://doi.org/10.1088/0022-3727/33/18/313
11. Harničárová, M., Valíček, J., Zajac, J., Hloch, S., Čep, R., Džubáková, I. et. al. (2012). Techno-economical comparison of cutting material by laser, plasma and oxygen. Tehnički vjesnik, 19, 813–817.
12. Kadirgama, K., Noor, M. M., Harun, W. S. W., Aboue-El-Hossein, K. A. (2010). Optimisation of heat affected zone by partial swarm optimisation in air plasma cutting operation. Journal of Scientific and Industrial Research, 69, 439–443.
13. Kechagias, J., Petousis, M., Vidakis, N., Mastorakis, N. (2017). Plasma Arc Cutting Dimensional Accuracy Optimization employing the Parameter Design approach. ITM Web of Conferences, 9, 03004. doi: https://doi.org/10.1051/itmconf/20170903004
14. Rakhimyanov, K., Rakhimyanov, A., Heifetz, M. (2015). High-Precision Plasma Cutting of the Steel – Aluminum «Bimetallic Composition». Applied Mechanics and Materials, 788, 41–45. doi: https://doi.org/10.4028/www.scientific.net/amm.788.41
15. Akkurt, A. (2015). The effect of cutting process on surface microstructure and hardness of pure and Al 6061 aluminium alloy. Engineering Science and Technology, an International Journal, 18 (3), 303–308. doi: https://doi.org/10.1016/j.jestch.2014.07.004
16. Rakhmyanov, K., Rakhmyanov, A., Zhuravlev, A. (2014). Advantages of High-Precision Plasma Cutting for Processing Bimetallic Compositions. Applied Mechanics and Materials, 698, 294–298. doi: https://doi.org/10.4028/www.scientific.net/amm.698.294

DOI: 10.15587/1729-4061.2019.154384

TENSILE STRENGTH AND FATIGUE CRACK GROWTH RATE OF CHAMFERED AND CLAMPED A6061 FRICTION WELD JOINTS (p. 31–39)

Yudy Surya Irawan
Brawijaya University, Malang, Indonesia
ORCID: http://orcid.org/0000-0001-7593-8931

Fakhri Razaq
Brawijaya University, Malang, Indonesia
ORCID: http://orcid.org/0000-0001-7192-6570

Wahyono Suprapto
Brawijaya University, Malang, Indonesia
ORCID: http://orcid.org/0000-0003-3510-2448

Bayu Satria Wardana
Brawijaya University, Malang, Indonesia
ORCID: http://orcid.org/0000-0001-7801-1568

Friction welding is a solid-state joining technique. It is suitable to be used to join a round bar of aluminum that has problems in joining. This paper reports measurements of the tensile strength and fatigue crack growth rate of a continuous drive friction welding (CDFW) joint of aluminum alloys A6061. The CDFW process was conducted by using the round bar A6061 machined to form a chamfer angle and applying a clamping process before the upset stage. Various chamfer angles of 0, 30, 45, and 60 degrees were machined on the stationary round bar. In order to increase the tensile strength and to reduce the fatigue crack growth rate of the CDFW joint, round clamps were applied on the CDFW joint. CDFW process was conducted with the revolution speed of 1,100 rpm, the initial compression force of 3.9 kN during friction stage for 4 seconds, and an upset force of 28 kN for 60 seconds. The specimens of friction weld joints were machined to shape the specimens of tensile strength testing and fatigue crack growth testing. Fatigue crack growth testing was performed using a cantilever rotary bending machine. The testing results show that using a small chamfer angle together with the round clamp produced a CDFW joint that exhibited higher tensile strength than the joint without chamfer or clamping. The specimen created with a chamfer angle of 30 degrees and the clamping method had the highest tensile strength and the the slowest fatigue crack growth rate among the samples studied. This result was caused by smaller heat input as a result of using a small one-sided chamfer together with two stages of plastic deformation from the clamping process and upset process during CDFW. The fatigue crack growth rate is also confirmed by macro and scanning electron microscope imaging of the fracture surfaces. The area of fatigue crack growth of the specimen with higher tensile strength is wider than the specimen with lower tensile strength. The striations are also observed more clearly in the fracture surface of the specimen with the highest tensile strength and the the slowest fatigue crack growth rate, namely the specimen, which has a chamfer angle of 30 degrees with clamping.

Keywords: Aluminum, Continuous Drive Friction Welding, Tensile Strength, Fatigue Crack Growth Rate, Fracture Surface.

References

1. Nicholas, E. D. (2003). Friction Processing Technologies. Welding in the World, 47 (11-12), 2–9. doi: https://doi.org/10.1007/bf03266402
2. Maalekian, M. (2007). Friction welding – critical assessment of literature. Science and Technology of Welding and Joining, 12 (8), 738–759. doi: https://doi.org/10.1179/174329307x249333
3. Yilbas, B. S., Sahin, A. Z. (2014). Friction welding. Thermal and metallurgical characteristics. Springer. doi: https://doi.org/10.1007/978-3-642-54607-5
4. Bauccio, M. (Ed.) (1993). ASM Metals Reference Book. ASM International, 614.
5. Barnes, T. A., Pashby, I. R. (2000). Joining techniques for aluminium spaceframes used in automobiles. Journal of Materials Processing Technology, 99 (1-3), 62–71. doi: https://doi.org/10.1016/s0924-0136(99)00367-2
6. Uday, M. B., Ahmad Fauzi, M. N., Zuhailawati, H., Ismail, A. B. (2010). Advances in friction welding process: a review. Science and Technology of Welding and Joining, 15 (7), 534–558. doi: https://doi.org/10.1179/136217110x12785889550064
7. Sahin, M., Akata, H. E., Gulmez, T. (2007). Characterization of mechanical properties in AISI 1040 parts welded by friction welding. Materials Characterization, 58 (10), 1033–1038. doi: https://doi.org/10.1016/j.matchar.2006.09.008
8. Lin, C. B., Mu, C. K., Wu, W. W., Hung, H. C. (1999). The effect of joint design and volume fraction on friction welding properties of A360/SiC (p) composites. Welding Journal, 78 (3), 100–108.

9. Irawan, Y. S., Wirohardjo, M., Ma'arif, M. S. (2012). Tensile Strength of Weld Joint Produced by Spinning Friction Welding of Round Aluminum A6061 with Various Chamfer Angles. Advanced Materials Research, 576, 761–765. doi: https://doi.org/10.4028/www.scientific.net/amr.576.761
10. Irawan, Y. S., Amirullah, M., Gumilang, G. B. D., Oerbandono, T., Suprapto, W. (2016). Torsion strength of continuous drive friction weld joint of round bar aluminum A6061 affected by single cone geometry of friction area. AIP Conference Proceedings, 1717, 040010. doi: https://doi.org/10.1063/1.4943453
11. Callister, W. D. (2001). Fundamentals of Materials Science and Engineering. John Wiley & Sons Inc.
12. Yamamoto, Y., Ochi, H., Sawai, T., Yamaguchi, H., Ogawa, K. (2007). Fatigue Strength of Friction-Welded 6061 Aluminum Alloy Joints. MATERIALS TRANSACTIONS, 48 (11), 2909–2913. doi: https://doi.org/10.2320/matertrans.l-mra2007880
13. Mercan, S., Aydin, S., Özdemir, N. (2015). Effect of welding parameters on the fatigue properties of dissimilar AISI 2205–AISI 1020 joined by friction welding. International Journal of Fatigue, 81, 78–90. doi: https://doi.org/10.1016/j.ijfatigue.2015.07.023
14. Zhang, Y., Sakai, T., Osuki, H., Yamamoto, T., Kokubu, A. (2011). Very High Cycle Fatigue Characteristics of Zr-Base Bulk Amorphous Alloy in Rotating Bending. Journal of Solid Mechanics and Materials Engineering, 5 (10), 519–533. doi: https://doi.org/10.1299/jmmp.5.519
15. Standard Methods for Mechanical Testing of Welds (2007). Miami: American Welding Society, 2007.
16. Kuhn, H., Medlin, D. (Eds.) (2000). ASM Handbook Volume 8: Mechanical Testing and Evaluation. Ohio: ASM International, 998.
17. Rafi, H. K., Ram, G. D. J., Phanikumar, G., Rao, K. P. (2010). Microstructure and tensile properties of friction welded aluminum alloy AA7075-T6. Materials & Design (1980-2015), 31 (5), 2375–2380. doi: https://doi.org/10.1016/j.matdes.2009.11.065

DOI: 10.15587/1729-4061.2019.188512

APPLICATION OF MULTIPLE CORRELATION ANALYSIS METHOD TO MODELING THE PHYSICAL PROPERTIES OF CRYSTALS (ON THE EXAMPLE OF GALLIUM ARSENIDE) (p. 39–45)

Maryna Litvinova
Kherson Branch of Admiral Makarov National University of Shipbuilding, Kherson, Ukraine
ORCID: http://orcid.org/0000-0002-4917-2132

Nataliia Andrieieva
Kherson Branch of Admiral Makarov National University of Shipbuilding, Kherson, Ukraine
ORCID: http://orcid.org/0000-0001-5838-6610

Viktor Zavodyannyi
Kherson State Agrarian University, Kherson, Ukraine
ORCID: http://orcid.org/0000-0002-8224-8215

Sergii Loi
Kherson Branch of Admiral Makarov National University of Shipbuilding, Kherson, Ukraine
ORCID: http://orcid.org/0000-0002-1936-6390

Olexandr Shtanko
Kherson Branch of Admiral Makarov National University of Shipbuilding, Kherson, Ukraine
ORCID: http://orcid.org/0000-0003-3572-7915

The use of modern applied computer programs expands the possibility of multicomponent statistical analysis in materials science. The procedure for applying the method of multiple correlation and regression analysis for the study and modeling of multifactorial relationships of physical characteristics in crystalline structures is considered. The consideration is carried out using single crystals of undoped gallium arsenide as an example. The statistical analysis involved a complex of seven physical characteristics obtained by non-destructive methods for each of 32 points along the diameter of the crystal plate. The data array is investigated using multiple correlation analysis methods. A computational model of regression analysis is built. Based on it, using the programs Excel, STADIA and SPSS Statistics 17.0, statistical data processing and analytical study of the relationships of all characteristics are carried out. Regression relationships are obtained and analyzed in determining the concentration of the background carbon impurity, residual mechanical stresses, and the concentration of the background silicon impurity. The ability to correctly conduct multiple statistical analysis to model the properties of a GaAs crystal is established.

New relationships between the parameters of the GaAs crystal are revealed. It is found that the concentration of the background silicon impurity is related to the vacancy composition of the crystal and the concentration of cents EL2. It is also found that there is no relationship between the silicon concentration and the value of residual mechanical stresses. These facts and the thermal conditions for the formation of point defects during the growth of a single crystal indicate the absence of a redistribution of background impurities during cooling of an undoped GaAs crystal.

The use of the multiple regression analysis method in materials science allows not only to model multifactor bonds in binary crystals, but also to carry out stochastic modeling of factor systems of variable composition.

Keywords: correlation and regression analysis, multiple regression, gallium arsenide, crystal structure.

References

1. Bombicz, P. (2019). A history and an industry perspective of crystallography. Crystallography Reviews, 25 (4), 263–263. doi: https://doi.org/10.1080/0889311x.2019.1641098
2. Luo, F., Cai, L.-C., Chen, X.-R., Jing, F.-Q., Alfè, D. (2012). Ab initiocalculation of lattice dynamics and thermodynamic properties of beryllium. Journal of Applied Physics, 111 (5), 053503. doi: https://doi.org/10.1063/1.3688344
3. Chen, V. B., Arendall, W. B., Headd, J. J., Keedy, D. A., Immormino, R. M., Kapral, G. J. et. al. (2009). MolProbity: all-atom structure validation for macromolecular crystallography. Acta Crystallographica Section D Biological Crystallography, 66 (1), 12–21. doi: https://doi.org/10.1107/s0907444909042073
4. Suharso, S. (2010). Growth rate distribution of borax single crystals on the (001) face under various flow rates. Indonesian Journal of Chemistry, 6 (1), 16–19. doi: https://doi.org/10.22146/ijc.21766
5. Zlomanov, V., Zavrazhnov, A. (2008). Nonstoichiometric compounds. Intermetallics Research Progress. New York: Nova Science Publishers, 290.
6. Kovalenko, V. F., Shutov, S. V., Baganov, Y. A., Smyikalo, M. M. (2009). Near band-edge luminescence of semi-insulating undoped gallium arsenide at high levels of excitation. Journal of Luminescence, 129 (9), 1029–1031. doi: https://doi.org/10.1016/j.jlumin.2009.04.017
7. Zhukov, N. D., Kabanov, V. F., Mihaylov, A. I., Mosiyash, D. S., Pereverzev, Y. E., Hazanov, A. A., Shishkin, M. I. (2018). Peculiarities of the Properties of III–V Semiconductors in a Multigrain Structure. Semiconductors, 52 (1), 78–83. doi: https://doi.org/10.1134/s1063782618010256
8. Gabibov, F. S., Zobov, E. M., Zobov, M. E., Kramynin, S. P., Pashuk, E. G., Khalilov, S. A. (2015). The effect of ultrasonic treatment on the energy spectrum of electron traps in *n*-GaAs single

crystals. Technical Physics Letters, 41 (4), 362–365. doi: https://doi.org/10.1134/s1063785015040239
9. Shtan'ko, A. D., Litvinova, M. B., Kurak, V. V. (2010). Decrease of exciton radiation intensity in compensated gallium arsenide single crystals under influence of low electric field. Functional Materials, 17 (1), 46–51.
10. Zhukov, N. D., Kryl'skiy, D. V., Shishkin, M. I., Khazanov, A. A. (2019). On the Synthesis and Photoluminescence and Cathodoluminescence Properties of CdSe, CdTe, PbS, InSb, and GaAs Colloidal Quantum Dots. Semiconductors, 53 (8), 1082–1087. doi: https://doi.org/10.1134/s1063782619080232
11. Badea, A., Dragan, F., Fara, L., Sterian, P. (2016). Quantum mechanical effects analysis of nanostructured solar cell models. Renewable Energy and Environmental Sustainability, 1, 3. doi: https://doi.org/10.1051/rees/2016003
12. Lehmkühler, F., Fischer, B., Müller, L., Ruta, B., Grübel, G. (2016). Structure beyond pair correlations: X-ray cross-correlation from colloidal crystals. Journal of Applied Crystallography, 49 (6), 2046–2052. doi: https://doi.org/10.1107/s1600576716017313
13. Lilvinova, M. B., Hertcova, N. Y., Seliverstova, S. R. (2003). The optical measurement technique of the definition of the GaAs structure deflection degree from stexiometry. Proceedings of CAOL'2003. 1st International Conference on Advanced Optoelectronics and Lasers. Jontly with 1st Workshop on Precision Oscillations in Electronics and Optics (IEEE Cat. No.03EX715). doi: https://doi.org/10.1109/caol.2003.1251297
14. Litvinova, M. B., Shtan'ko, A. D. (2005). Influence of Structural Defects on the Mechanical Stress in the Impurity Diffusion Zone of GaAs Single Crystals. Inorganic Materials, 41 (8), 789–792. doi: https://doi.org/10.1007/s10789-005-0211-0
15. Elliott, A., Woodward, W. (2007). Statistical Analysis Quick Reference Guidebook. SAGE Publication. doi: https://doi.org/10.4135/9781412985949
16. Cankaya, S., Kayaalp, G. T., Sangun, L., Tahtali, Y., Akar, M. (2006). A Comparative Study of Estimation Methods for Parameters in Multiple Linear Regression Model. Journal of Applied Animal Research, 29 (1), 43–47. doi: https://doi.org/10.1080/09712119.2006.9706568
17. Kleinbaum, D., Kupper, L. L., Muller, K. E. (1988). Applied Regression Analysis and Other Multivariable Methods. Boston, USA: PWS-Kent, 664.
18. Saunders, L. J., Russell, R. A., Crabb, D. P. (2012). The Coefficient of Determination: What Determines a UsefulR2Statistic? Investigative Opthalmology & Visual Science, 53 (11), 6830. doi: https://doi.org/10.1167/iovs.12-10598

DOI: 10.15587/1729-4061.2019.185628

DEGRADATION OF CDTE SC DURING OPERATION: MODELING AND EXPERIMENT (p. 46–51)

Olexander Bolbas
Research, Design and Technology Institute of Micrography, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0001-9483-2673

Natalya Deyneko
National University of Civil Defence of Ukraine, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0001-8438-0618

Sergey Yeremenko
Institute of Public Administration in the Field of Civil Protection, Kyiv, Ukraine
ORCID: http://orcid.org/0000-0003-3685-4713

Olena Kyryllova
Odessa National Maritime University, Odessa, Ukraine
ORCID: http://orcid.org/0000-0002-3414-7364

Oksana Myrgorod
National University of Civil Defence of Ukraine, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0002-5989-3435

Olexander Soshinsky
National University of Civil Defence of Ukraine, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0002-7921-1294

Nataliya Teliura
O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0003-0732-7789

Nataliia Tsapko
Ukrainian Scientific-Research Institute of Environmental Problems, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0003-2480-3636

Roman Shevchenko
National University of Civil Defence of Ukraine, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0001-9634-6943

Yuliia Yurchyk
Research, Design and Technology Institute of Micrography, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0002-0180-7397

The mechanisms of CdTe SC degradation during operation are experimentally studied. Two mechanisms of degradation of such solar cells are identified. The first is the generation of defects in the transition region, which is caused by excess charge carriers and defects. The second is the increase in the back barrier. The study of the current-voltage and voltage-capacitance characteristics of solar cells allowed proposing a model of degradation of solar cells based on CdTe. It is found that the presence of copper in the back contact is associated with better initial efficiency, but also the fastest degradation during operation. In accordance with the proposed model, the occurrence of additional elementary defects as a result of dissociation of three types of point defect complexes $(Cu_i^+–2Cu_{Cd–})^–$, $(V_{Cd2}^––Cu_{i+})^–$, $(2Cu_{Cd}^––V_{Te+})^–$ is explained. Shunting of the *n-p* heterojunction and phase transformations from the $p^+–Cu_{2–x}Te$ side due to electrodiffusion of $Cu_{Cd}^–$ with *p*-CdTe at the *n*-CdS/*p*-CdTe and *p*-CdTe/$p^+–Cu_{2-x}Te$ boundaries is considered. On the other hand, the diffusion of Cu_i+ (interstitial copper) into the absorber volume is possible. Electrodiffusion of defects from heterojunctions to the absorber volume is possible, which leads to the compensation of effective acceptor centers and a decrease in the lifetime of minority charge carriers and, accordingly, a decrease in J_{ph}. In addition, there is a growth of shunting metal chains along the longitudinal grain boundaries of *p*-CdTe between *n-p* and *p-p*+ heterojunctions and the possibility of appearance of high-resistance phases of the Cu–Te system. The proposed model explains the possibility of occurrence of the $p^+–Cu_{2–\delta}S$ phase on the CdS/CdTe boundary, which constrains the passage of the photoactive part of the solar spectrum in *p*-CdTe.

Keywords: cadmium telluride, solar cell degradation, output parameters, light-emitting diode characteristics.

References

1. Inganäs, O., Sundström, V. (2015). Solar energy for electricity and fuels. Ambio, 45 (S1), 15–23. doi: https://doi.org/10.1007/s13280-015-0729-6
2. Deyneko, N., Semkiv, O., Khmyrov, I., Khryapynskyy, A. (2018). Investigation of the combination of ITO/CdS/CdTe/Cu/Au solar cells in microassembly for electrical supply of field cables. Eastern-European Journal of Enterprise Technologies, 1 (12 (91)), 18–23. doi: https://doi.org/10.15587/1729-4061.2018.124575

3. Khrypunov, G., Meriuts, A., Klyui, N., Shelest, T., Deyneko, N., Kovtun, N. (2010). Development of back contact for CdS/CdTe thin-film solar cells. Functional Materials, 17 (1), 114–119.
4. Watthage, S. C., Phillips, A. B., Liyanage, G. K., Song, Z., Gibbs, J. M., Alfadhili, F. K. et. al. (2018). Selective Cd Removal From CdTe for High-Efficiency Te Back-Contact Formation. IEEE Journal of Photovoltaics, 8 (4), 1125–1131. doi: https://doi.org/10.1109/jphotov.2018.2830302
5. Cardinaletti, I., Vangerven, T., Nagels, S., Cornelissen, R., Schreurs, D., Hruby, J. et. al. (2018). Organic and perovskite solar cells for space applications. Solar Energy Materials and Solar Cells, 182, 121–127. doi: https://doi.org/10.1016/j.solmat.2018.03.024
6. Miyazawa, Y., Ikegami, M., Chen, H.-W., Ohshima, T., Imaizumi, M., Hirose, K., Miyasaka, T. (2018). Tolerance of Perovskite Solar Cell to High-Energy Particle Irradiations in Space Environment. iScience, 2, 148–155. doi: https://doi.org/10.1016/j.isci.2018.03.020
7. Aierken, A., Fang, L., Heini, M., Zhang, Q. M., Li, Z. H., Zhao, X. F. et. al. (2018). Effects of proton irradiation on upright metamorphic GaInP/GaInAs/Ge triple junction solar cells. Solar Energy Materials and Solar Cells, 185, 36–44. doi: https://doi.org/10.1016/j.solmat.2018.04.035
8. Krishnan, S., Sanjeev, G., Pattabi, M., Mathew, X. (2009). Effect of electron irradiation on the properties of CdTe/CdS solar cells. Solar Energy Materials and Solar Cells, 93 (1), 2–5. doi: https://doi.org/10.1016/j.solmat.2007.12.002
9. Hirose, Y., Warasawa, M., Tsunoda, I., Takakura, K., Sugiyama, M. (2012). Effects of Proton Irradiation on Optical and Electrical Properties of Cu(In,Ga)Se2 Solar Cells. Japanese Journal of Applied Physics, 51 (11R), 111802. doi: https://doi.org/10.7567/jjap.51.111802
10. Bätzner, D. L., Romeo, A., Terheggen, M., Döbeli, M., Zogg, H., Tiwari, A. N. (2004). Stability aspects in CdTe/CdS solar cells. Thin Solid Films, 451-452, 536–543. doi: https://doi.org/10.1016/j.tsf.2003.10.141
11. Abramov, Y., Basmanov, O., Salamov, J., Mikhayluk, A., Yashchenko, O. (2019). Developing a model of tank cooling by water jets from hydraulic monitors under conditions of fire. Eastern-European Journal of Enterprise Technologies, 1 (10 (97)), 14–20. doi: https://doi.org/10.15587/1729-4061.2019.154669
12. Chander, S., Purohit, A., Lal, C., Dhaka, M. S. (2017). Enhancement of optical and structural properties of vacuum evaporated CdTe thin films. Materials Chemistry and Physics, 185, 202–209. doi: https://doi.org/10.1016/j.matchemphys.2016.10.024
13. Demtsu, S. H., Albin, D. S., Pankow, J. W., Davies, A. (2006). Stability study of CdS/CdTe solar cells made with Ag and Ni back-contacts. Solar Energy Materials and Solar Cells, 90 (17), 2934–2943. doi: https://doi.org/10.1016/j.solmat.2006.05.007
14. Rotlevi, O., Dobson, K. D., Rose, D., Hodes, G. (2001). Electroless Ni and $NiTe_2$ ohmic contacts for CdTe/CdS PV cells. Thin Solid Films, 387 (1-2), 155–157. doi: https://doi.org/10.1016/s0040-6090(00)01738-7
15. Deyneko, N., Khrypunov, G., Semkiv, O. (2018). Photoelectric Processes in Thin-film Solar Cells Based on CdS/CdTe with Organic Back Contact. Journal of Nano- and Electronic Physics, 10 (2), 02029-1–02029-4. doi: https://doi.org/10.21272/jnep.10(2).02029
16. Bätzner, D. L., Romeo, A., Zogg, H., Tiwari, A. N., Wendt, R. (2000). Flexible CdTe solar cells on polymer films. 16th European Photovoltaic Solar Energy Conference, Glasgow, 353–356.
17. Romeo, N., Bosio, A., Tedeschi, R. (1998). High-efficiency and stable CdTe/CdS thin-film solar cells on soda lime glass. 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion. Vienna, 446–449.
18. Hiltner, J. F., Sites, J. R. (1998). Stability of CdTe solar cells at elevated temperatures: Bias, temperature, and Cu dependence. AIP Conference Proceedings, 462, 170–175. doi: https://doi.org/10.1063/1.57895
19. Khrypunov, G., Vambol, S., Deyneko, N., Sychikova, Y. (2016). Increasing the efficiency of film solar cells based on cadmium telluride. Eastern-European Journal of Enterprise Technologies, 6 (5 (84)), 12–18. doi: https://doi.org/10.15587/1729-4061.2016.85617
20. Deyneko, N., Kovalev, P., Semkiv, O., Khmyrov, I., Shevchenko, R. (2019). Development of a technique for restoring the efficiency of film ITO/CdS/CdTe/Cu/Au SCs after degradation. Eastern-European Journal of Enterprise Technologies, 1 (5 (97)), 6–12. doi: https://doi.org/10.15587/1729-4061.2019.156565
21. Deyneko, N., Semkiv, O., Soshinsky, O., Streletc, V., Shevchenko, R. (2018). Results of studying the Cu/ITO transparent back contacts for solar cells SnO2:F/CdS/CdTe/Cu/ITO. Eastern-European Journal of Enterprise Technologies, 4 (5 (94)), 29–34. doi: https://doi.org/10.15587/1729-4061.2018.139867
22. Pavlov, L. P. (1987). Metody izmereniya parametrov poluprovodnikovyh materialov. Moscow: Vysshaya shkola, 239.
23. Agostinell, G., Batzner, D. L., Burgelman, M. (2002). An alternative model for V, G and T dependence of CdTe solar cells IV characteristics. Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002. doi: https://doi.org/10.1109/pvsc.2002.1190672
24. Niemegeers, A., Burgelman, M. (1997). Effects of the Au/CdTe back contact on IV and CV characteristics of Au/CdTe/CdS/TCO solar cells. Journal of Applied Physics, 81 (6), 2881–2886. doi: https://doi.org/10.1063/1.363946

DOI: 10.15587/1729-4061.2019.184496

DETERMINING THE RATIONAL COMPOSITION OF TRIBOLOGICALLY ACTIVE ADDITIVE TO OIL TO IMPROVE CHARACTERISTICS OF TRIBOSYSTEMS (p. 52–64)

Viktor Aulin
Central Ukrainian National Technical University, Kropyvnytskyi, Ukraine
ORCID: http://orcid.org/0000-0003-2737-120X

Andrii Hrynkiv
Central Ukrainian National Technical University, Kropyvnytskyi, Ukraine
ORCID: http://orcid.org/0000-0002-4478-1940

Sergii Lysenko
Central Ukrainian National Technical University, Kropyvnytskyi, Ukraine
ORCID: http://orcid.org/0000-0003-0845-7817

Taras Zamota
Volodymyr Dahl East Ukrainian National University, Severodonetsk, Ukraine
ORCID: http://orcid.org/0000-0002-9904-4518

Andrii Pankov
Volodymyr Dahl East Ukrainian National University, Severodonetsk, Ukraine
ORCID: http://orcid.org/0000-0003-2813-8231

Andrii Tykhyi
Central Ukrainian National Technical University, Kropyvnytskyi, Ukraine
ORCID: http://orcid.org/0000-0001-5323-4415

The conducted studies of the formation of the rational composition of a tribologically active additive to basic oil showed the possibility to improve the characteristics of tribosystems. It was revealed that this tribologically active additive enables the formation

of tribological properties that ensure normal working conditions for the operation of the mated parts of a tribosystem. Based on the optimization of technical condition of a tribologically active additive, the rational values of each of its components were obtained. Optimization was carried out on condition that the magnitude of wear should be minimized, while critical load and welding load should be maximized. Based on the experimental database, on a four-ball friction machine, the equations for each of the response functions of the resulting features were obtained. The obtained regression equations and values of desirability function of the order of 0.698 allow determining the composition of a tribologically active additive: metakaolin, dispersive clay powder from Katerynivka deposit, sodium oleate, hydroxide of lithium and sulfur. It was established that when using the obtained tribologically active additive under laboratory conditions, the decrease in the wear of samples by 26.8 %, the increase in critical load by 17.2 %, the increase in welding load by 4.89 % were observed. Analysis of the experimental data shows that it is possible to use the proposed tribologically active additive in contact loading at the contact up to 1078 N and at peak overload up to 2,372 N.

Research results give grounds to argue that the proposed tribologically active additive makes it possible to improve the characteristics of tribosystems. It can be useful for service and motor transport companies during technical servicing and in production of composite oil.

Keywords: tribologically active additive, geomodifier, wear, sulfur, lithium soaps, sodium soaps, metakaolin, welding loading.

References

1. Aulin, V., Hrinkiv, A., Dykha, A., Chernovol, M., Lyashuk, O., Lysenko, S. (2018). Substantiation of diagnostic parameters for determining the technical condition of transmission assemblies in trucks. Eastern-European Journal of Enterprise Technologies, 2 (1 (92)), 4–13. doi: https://doi.org/10.15587/1729-4061.2018.125349
2. Aulin, V., Lysenko, S., Lyashuk, O., Hrinkiv, A., Velykodnyi, D., Vovk, Y. et. al. (2019). Wear Resistance Increase of Samples Tribomating in Oil Composite with Geo Modifier KGMF-1. Tribology in Industry, 41 (2), 156–165. doi: https://doi.org/10.24874/ti.2019.41.02.02
3. Ropyak, L. Y., Shatskyi, I. P., Makoviichuk, M. V. (2017). Influence of the Oxide-Layer Thickness on the Ceramic–Aluminium Coating Resistance to Indentation. METALLOFIZIKA I NOVEISHIE TEKHNOLOGII, 39 (4), 517–524. doi: https://doi.org/10.15407/mfint.39.04.0517
4. Aleksandr, D., Dmitry, M. (2018). Prediction the wear of sliding bearings. International Journal of Engineering & Technology, 7 (2.23), 4. doi: https://doi.org/10.14419/ijet.v7i2.23.11872
5. Kryshtopa, S. I., Petryna, D. Y., Bogatchuk, I. M., Prun'ko, I. B., Mel'nyk, V. M. (2017). Surface Hardening of 40KH Steel by Electric-Spark Alloying. Materials Science, 53 (3), 351–358. doi: https://doi.org/10.1007/s11003-017-0082-y
6. Aulin, V., Hrynkiv, A., Lysenko, S., Rohovskii, I., Chernovol, M., Lyashuk, O., Zamota, T. (2019). Studying truck transmission oils using the method of thermal-oxidative stability during vehicle operation. Eastern-European Journal of Enterprise Technologies, 1 (6 (97)), 6–12. doi: https://doi.org/10.15587/1729-4061.2019.156150
7. Kopčanová, S., Kučera, M., Kučera, M., Kučera, M., Kučerová, V. (2018). The Effect of Friction Behaviour and Wear Protection Ability of Selected Base Lubricants on Tribo-pairs Parameters of Machine Components. Tribology in Industry, 40 (4), 681–691. doi: https://doi.org/10.24874/ti.2018.40.04.14
8. Kryshtopa, S., Kozhevnykov, A., Panchuk, M., Kryshtopa, L. (2018). Influence of triboelectric processes on friction characteristics of brake units of technological transport. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 3, 87–93. doi: https://doi.org/10.29202/nvngu/2018-3/10
9. Aulin, V., Hrynkiv, A., Lysenko, S., Dykha, A., Zamota, T., Dzyura, V. (2019). Exploring a possibility to control the stressedstrained state of cylinder liners in diesel engines by the tribotechnology of alignment. Eastern-European Journal of Enterprise Technologies, 3 (12 (99)), 6–16. doi: https://doi.org/10.15587/1729-4061.2019.171619
10. Levanov, I., Zadorozhnaya, E., Vichnyakov, D. (2018). Influence of Friction Geo-modifiers on HTHS Viscosity of Motor Oils. Lecture Notes in Mechanical Engineering, 967–972. doi: https://doi.org/10.1007/978-3-319-95630-5_101
11. Abd Al-Samieh, M. F. (2019). Surface Roughness Effects for Newtonian and Non-Newtonian Lubricants. Tribology in Industry, 41 (1), 56–63. doi: https://doi.org/10.24874/ti.2019.41.01.07
12. Prysyazhnyuk, P., Lutsak, D., Shlapak, L., Aulin, V., Lutsak, L., Borushchak, L., Shihab, T. A. (2018). Development of the composite material and coatings based on niobium carbide. Eastern-European Journal of Enterprise Technologies, 6 (12 (96)), 43–49. doi: https://doi.org/10.15587/1729-4061.2018.150807
13. Ashmarin, G. M., Aulin, V. V., Golubev, M. Yu., Zvonkov, S. D. (1986). Grain boundary internal friction of unalloyed copper subjected to continuous laser radiation. Physics and chemistry of materials treatment, 20 (5), 476–478. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0022781198&partnerID=40&md5=12a45ba637bf291f2ffb4fe3a9da90e0
14. Shatskyi, I. P., Makoviichuk, M. V., Shcherbii, A. B. (2017). Equilibrium of cracked shell with flexible coating. Shell Structures: Theory and Applications Volume 4, 165–168. doi: https://doi.org/10.1201/9781315166605-34
15. Osadchiy, S. I., Zozulya, V. A. (2013). Combined Method for the Synthesis of Optimal Stabilization Systems of Multidimensional Moving Objects under Stationary Random Impacts. Journal of Automation and Information Sciences, 45 (6), 25–35. doi: https://doi.org/10.1615/jautomatinfscien.v45.i6.30
16. Aulin, V., Lyashuk, O., Pavlenko, O., Velykodnyi, D., Hrynkiv, A., Lysenko, S. et. al. (2019). Realization of the logistic approach in the international cargo delivery system. Communications – Scientific Letters of the University of Zilina, 21 (2), 3–12. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85066994460&partnerID=40&md5=105d35bd46f8ab7b6de0b6688948d0e3
17. Osadchiy, S. I., Kalich, V. M., Didyk, O. K. (2013). Structural identification of unmanned supercavitation vehicle based on incomplete experimental data. 2013 IEEE 2nd International Conference Actual Problems of Unmanned Air Vehicles Developments Proceedings (APUAVD). doi: https://doi.org/10.1109/apuavd.2013.6705294
18. Dykha, A., Aulin, V., Makovkin, O., Posonskiy, S. (2017). Determining the characteristics of viscous friction in the sliding supports using the method of pendulum. Eastern-European Journal of Enterprise Technologies, 3 (7 (87)), 4–10. doi: https://doi.org/10.15587/1729-4061.2017.99823
19. Kryshtopa, S., Kryshtopa, L., Bogatchuk, I., Prunko, I., Melnyk, V. (2017). Examining the effect of triboelectric phenomena on wear-friction properties of metal-polymeric frictional couples. Eastern-European Journal of Enterprise Technologies, 1 (5 (85)), 40–45. doi: https://doi.org/10.15587/1729-4061.2017.91615
20. Prokopenko, A. K., Golubev, A. P., Korneev, A. A. (2019). Research on Wear Resistance of Multifunctional Coatings Used in the Manufacture of Art and Industrial Products. Materials Science Forum, 945, 670–674. doi: https://doi.org/10.4028/www.scientific.net/msf.945.670
21. Michalec, M., Svoboda, P., Krupka, I., Hartl, M. (2018). Tribological Behaviour of Smart Fluids Influenced by Magnetic and Electric Field – A Review. Tribology in Industry, 40 (4), 515–528. doi: https://doi.org/10.24874/ti.2018.40.04.01
22. Kim, D. W., Eum, K., Kim, H., Kim, D., Mello, M. D. de, Park, K., Tsapatsis, M. (2019). Continuous ZIF-8/reduced graphene oxide

nanocoating for ultrafast oil/water separation. Chemical Engineering Journal, 372, 509–515. doi: https://doi.org/10.1016/j.cej.2019.04.179

23. Levanov, I., Doykin, A., Zadorozhnaya, E., Novikov, R. (2017). Investigation Antiwear Properties of Lubricants with the Geo-Modifiers of Friction. Tribology in Industry, 39 (3), 302–306. doi: https://doi.org/10.24874/ti.2017.39.03.04
24. Schott, M., Schlarb, A. K. (2018). Simulation of the thermal budget of plastic/metal tribological pairings by means of FEM. Tribologie und Schmierungstechnik, 65 (1), 20–26. Available at: https://www.scopus.com/record/display.uri?eid=2-s2.0-85042685942&origin=inward&txGid=bb4744e1ee5afd75d17e3d859692393a
25. Riva, G., Perricone, G., Wahlström, J. (2019). Simulation of Contact Area and Pressure Dependence of Initial Surface Roughness for Cermet-Coated Discs Used in Disc Brakes. Tribology in Industry, 41 (1), 1–13. doi: https://doi.org/10.24874/ti.2019.41.01.01
26. Prysyazhnyuk, P. M., Shihab, T. A., Panchuk, V. H. (2016). Formation of the Structure of Cr_3C_2-MNMts 60-20-20 Cermets. Materials Science, 52 (2), 188–193. doi: https://doi.org/10.1007/s11003-016-9942-0
27. Ashmarin, G. M., Aulin, V. V., Golobev, M. Yu., Zvonkov, S. D., Malyuchkov, O. T. (1986). Electrical conductivity of copper after laser treatment. Russian metallurgy. Metally, 5, 185–189. Available at: https://www.scopus.com/record/display.uri?eid=2-s2.0-0022959597&origin=inward&txGid=28bce36b14862581cc8542126d58d41a
28. Aulin, V., Lyashuk, O., Tykhyi, A., Karpushyn, S., Denysiuk, N. (2018). Influence of Rheological Properties of a Soil Layer Adjacent to the Working Body Cutting Element on the Mechanism of Soil Cultivation. Acta Technologica Agriculturae, 21 (4), 153–159. doi: https://doi.org/10.2478/ata-2018-0028
29. Fedorov, S. V. (2018). Nano-Structural Standard of Friction and Wear. Tribology in Industry, 40 (2), 225–238. doi: https://doi.org/10.24874/ti.2018.40.02.06
30. Chernets, M. (2019). A Method for Predicting Contact Strength and Life of Archimedes and Involute Worm Gears, Considering the Effect of Wear and Teeth Correction. Tribology in Industry, 41 (1), 134–141. doi: https://doi.org/10.24874/ti.2019.41.01.15
31. Ratnam, C., Jasmin, N. M., Rao, V. V., Rao, K. V. (2018). A Comparative Experimental Study on Fault Diagnosis of Rolling Element Bearing Using Acoustic Emission and Soft Computing Techniques. Tribology in Industry, 40 (3), 501–5013. doi: https://doi.org/10.24874/ti.2018.40.03.15
32. Gritsenko, A. V., Zadorozhnaya, E. A., Shepelev, V. D. (2018). Diagnostics of Friction Bearings by Oil Pressure Parameters During Cycle-By-Cycle Loading. Tribology in Industry, 40 (2), 300–310. doi: https://doi.org/10.24874/ti.2018.40.02.13
33. Dykha, A., Makovkin, O. (2019). Physical basis of contact mechanics of surfaces. Journal of Physics: Conference Series, 1172, 012003. doi: https://doi.org/10.1088/1742-6596/1172/1/012003
34. Kryshtopa, S., Panchuk, M., Kozak, F., Dolishnii, B., Mykytii, I., Skalatska, O. (2018). Fuel economy raising of alternative fuel converted diesel engines. Eastern-European Journal of Enterprise Technologies, 4 (8 (94)), 6–13. doi: https://doi.org/10.15587/1729-4061.2018.139358
35. Aulin, V. V., Chernovol, M. I., Pankov, A. O., Zamota, T. M., Panayotov, K. K. (2017). Sowing machines and systems based on the elements of fluidics. INMATEH - Agricultural Engineering, 53 (3), 21–28. Available at: https://www.scopus.com/record/display.uri?eid=2-s2.0-85039172369&origin=inward&txGid=805c325ab302d5ad2bec25c2388cc184
36. Hiilser, P. (2018). Electroplating meets lamella - Successful combination of two coating technologies (Part 1). Galvanotechnik, 109 (10), 1964–1972. Available at: https://www.scopus.com/record/display.uri?eid=2-s2.0-85056282820&origin=inward&txGid=dc182ae475b723d4d3bf7a2668378187
37. Aulin, V., Warouma, A., Lysenko, S., Kuzyk, A. (2016). Improving of the wear resistance of working parts agricultural machinery by the implementation of the effect of self-sharpening. International Journal of Engineering & Technology, 5 (4), 126. doi: https://doi.org/10.14419/ijet.v5i4.6386
38. Painuly, A., Arora, A. (2019). Rayleigh wave at composite porous half space saturated by two immiscible fluids. Applied Mathematical Modelling, 73, 124–135. doi: https://doi.org/10.1016/j.apm.2019.03.038
39. Matviienkiv, O., Prysyazhnyuk, P., Myndiuk, V. (2016). Development of the zinc coating pipe connection technology with arc soldering method using. Eastern-European Journal of Enterprise Technologies, 3 (5 (81)), 50–54. doi: https://doi.org/10.15587/1729-4061.2016.70346
40. Bautista-Ruiz, J., Caicedo, J. C., Aperador, W. (2019). Evaluation of the Wear-Corrosion Process in Beta-Tricalcium(β-TCP) Films Obtained by Physical Vapor Deposition (PVD). Tribology in Industry, 41 (1), 126–133. doi: https://doi.org/10.24874/ti.2019.41.01.14
41. Aulin, V., Derkach, O., Makarenko, D., Hrynkiv, A., Pankov, A., Tykhyi, A. (2019). Analysis of tribological efficiency of movable junctions «polymericcomposite materials – steel. Eastern-European Journal of Enterprise Technologies, 4 (12 (100)), 6–15. doi: https://doi.org/10.15587/1729-4061.2019.176845
42. Vojtov, V. A., Levchenko, A. V. (2001). The integral criterion of rating the tribological behavior of lubricating materials using a four-ball workbench. Trenie i Iznos, 22 (4), 441–447. Available at: https://www.scopus.com/record/display.uri?eid=2-s2.0-0035551335&origin=inward&txGid=b52837db51c0488cfa2ed8491e49fde3
43. Zheleznyi, L., Pop, G., Papeikin, O., Venger, I., Bodachivska, L. (2017). Development of compositions of urea greases on aminoamides of fatty acids. Eastern-European Journal of Enterprise Technologies, 3 (6 (87)), 9–14. doi: https://doi.org/10.15587/1729-4061.2017.99580
44. Vojtov, V., Biekirov, A., Voitov, A. (2018). The Quality of the Tribosystem as a Factor of Wear Resistance. International Journal of Engineering & Technology, 7 (4.3), 25–29. doi: https://doi.org/10.14419/ijet.v7i4.3.19547