EFFECT OF HIGH-ENERGY XE ION IMPLANTATION ON TRIBOLOGICAL PROPERTIES OF CHROMIUM UNDER WET CONDITIONS

[1]Mariusz KAMIŃSKI, [1]Piotr BUDZYŃSKI, [2]Mirosław SZALA, [3]Zbigniew SUROWIEC, [4]Maxim ZDOROVETS, [5]Artem KOZLOVSKIY

[1]Lublin University of Technology, Faculty of Mechanical Engineering, Department of Automotive Vehicles, Lublin, Poland, EU, mariusz.kaminski@pollub.pl, p.budzynski@pollub.pl

[2]Lublin University of Technology, Faculty of Mechanical Engineering, Department of Materials Engineering, Lublin, Poland, EU, m.szala@pollub.pl

[3]M. Curie-Sklodowska University, Institute of Physics, Lublin, Poland, EU, zbigniew.surowiec@mail.umcs.pl

[4]Institute of Nuclear Physics, Almaty, Kazachstan, mzdorovets@inp.kz

[5]Satbayev University, Almaty, Kazakhstan, kozlovskiy.a@inp.kz

https://doi.org/10.37904/metal.2023.4710

Abstract

This paper presents the results of tribological wear resistance tests on pure chromium subjected to xenon ion implantation with an energy of 160 MeV. Chromium is a very popular engineering material used in many industries, including aerospace, automotive, power generation and electronics. It owes its popularity to its resistance to high temperatures, corrosion, and high mechanical strength. High-energy implantation of heavy ions causes a significant amount of radiation damage, which affects the crystalline structure of the material's surface layer and thus changes its mechanical properties. This is especially important in space and nuclear power applications. The research was aimed at demonstrating changes in frictional wear resistance as a result of exposure to Xe ions at different doses per unit area. The research was conducted using the pin-on-disc method in an aqueous environment. A statistically significant decrease in tribological wear of pure chromium subjected to Xe ion implantation with an energy of 160 MeV was observed.

Keywords: Ion implantation, tribological wear, chromium, Xe ions

1. INTRODUCTION

In the field of materials engineering, significant attention is paid to the investigation of tribological properties of surface layers of various materials, which are crucial for the functioning of many devices and systems in the industry [1]. Tribological properties, such as friction, wear, and lubrication, play a key role in the context of industrial applications, particularly for materials used as moving parts in machines and devices. Understanding these properties allows for designing more efficient systems and extending their service life. In the case of chromium (Cr), optimizing tribological properties can contribute to increased reliability and performance of devices in which it is used, as well as reducing costs associated with the need to replace worn parts [2,3].

Pure chromium is characterized by high corrosion resistance, hardness, and the ability to form durable protective coatings on the surfaces of other metals [4,5]. Due to these properties, chromium is widely used in the automotive, aerospace, energy, sports equipment, and medical industries [6]. Any studies focus on refining and modifying the structure of pure chromium to improve its properties and applications. It is also worth noting that pure chromium has significant applications in the nuclear and space industries, where it is exposed to intense radiation [7]. In these particularly demanding conditions, understanding the impact of Xe ion implantation on the tribological properties of chromium can contribute to the development of materials with better operational parameters, which demonstrate resistance to damage and long-term stability in challenging environmental conditions.

There is a wealth of information in scientific literature regarding the use of ion implantation to modify the surface layer properties of engineering materials. In many cases, through the use of appropriate elements such as nitrogen or carbon, improvements in tribological wear resistance, microhardness, and increased corrosion resistance are achieved [8-10]. The parameters of the ion implantation process, such as the dose of implanted ions and implantation energy, play a significant role in the effects obtained. When irradiating material with heavy element ions at high energies, there is an increased contribution of radiation damage associated with the applied process. High doses and energies of implanted ions can cause amorphous changes in the surface layer structure and even ion etching of the implanted surface [11-13].

The current state of knowledge contains little information about the impact of high-energy Xe ion implantation on the tribological properties of pure chromium. Wang et al. [14] indicated the influence of Xe ion implantation with an energy of 5 MeV on the nano-hardness and structural changes of chromium coatings. Hoffman and Gaerttner [15] studied the influence of Xe ion interaction on stress in the surface layer of chromium, albeit at relatively low implantation energies reaching 11.5 keV. The researchers did not address changes in tribological wear resistance. Therefore, there is a need for studies aimed at understanding the impact of high-energy Xe ion implantation on pure chromium to better comprehend the effects of such surface modification on the tribological properties of this material. Considering that chromium is often used in environments with elevated humidity due to its high corrosion resistance, tribological tests were conducted in a wet environment in the presence of water.

2. MATERIALS AND METHODS

Pure chromium (Cr) (99.9%) was used in the study, from which 10 x 10 mm samples were made. The samples were polished to an average value of roughness coefficients R_a=0.014 (stand. dev. 0.006), R_z=0.099 (stand. dev. 0.069), R_t=0.185 (stand. dev. 0.215). The samples were irradiated with the use of two ion accelerators. The irradiation process was performed in a swift heavy ion accelerator D-60 (L.N. Gumilyov Eurasian National University, Astana, Kazakhstan). The $^{132}Xe^{20+}$ ion beam had an energy of 160 MeV. The samples were irradiated with a fluence of $1 \cdot 10^{14}$, $2.5 \cdot 10^{14}$ and $5 \cdot 10^{14}$ (Xe/cm^2), respectively.

The aluminium grip of the sample protruded outside from the vacuum chamber and was air-cooled. The ion beam fluence did not exceed (2–8) $\cdot 10^{12}$ ions/cm$^2 \cdot$s, which limited the power introduced to the sample by the ion beam to a value of (100-400) W/m^2. As a result, the temperature of the sample during irradiation did not exceed 60 °C. The pressure in the chamber during irradiation was $1.1 \cdot 10^{-9}$ Pa.

Tribological testing was carried out via the pin/ball-on-disk method under wet friction conditions using the Anton Paar nanotribometer (NTR2) in an aqueous environment. During the test, the countersample was a tungsten carbide ball with a diameter of 1.0 mm pressed with a force of 300 mN. The relative speed of the countersample to the sample was 1.4 cm/s. Wear of the tested samples was measured as the cross-sectional area of the wear track on the surface of the sample and the material loss was stated. The track was measured using the Taylor Hobson Form Talysurf Intra profilometer in 12 locations.

3. RESULTS

A theoretical distribution of implanted ions over the sample depth was calculated using the SRIM software [16]. The results are shown in **Figure 1**. Based on the distribution of implanted ions, it can be determined that the maximum implantation depth was approximately 8.55 μm, while the highest concentration of implanted xenon ions was reached at depths in the range of 7.95–8.1 μm.

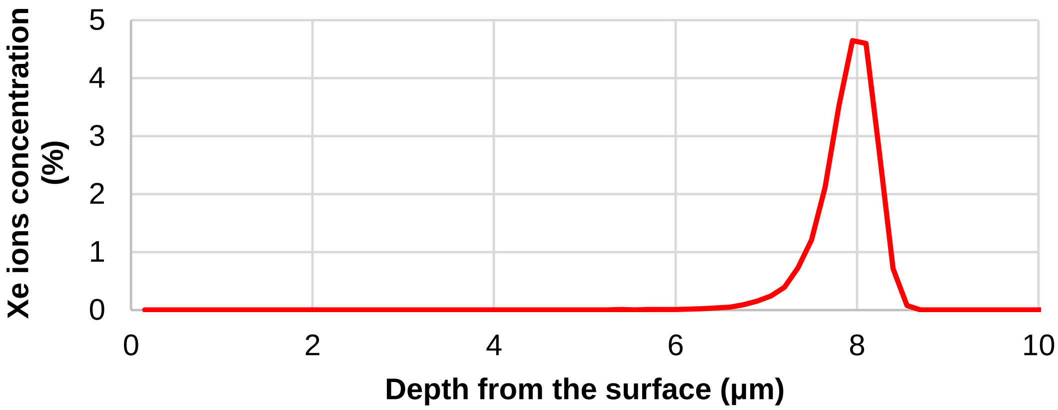

Figure 1 Range of 160 MeV Xe ions concentration in chromium after irradiation with a fluence of $5 \cdot 10^{14}$ Xe/cm²

Results of the coefficient of friction are shown in **Figure 2**. After irradiation, the friction coefficient of the chromium samples was similar to the unimplanted sample. Except of that sample which was implanted with the biggest dose. The sample irradiated with a fluence of $5 \cdot 10^{14}$ ion/cm² has a significantly lower coefficient of friction compared to the other samples. The decrease in the coefficient of friction of the sample subjected to implantation with the highest dose, may be due to increased degradation of the surface of the test sample caused by the interaction of a large number of high-energy ions. This is a common phenomenon when using high-energy implantation [17]. The surface deformation may have influenced an increase in the amount of lubricant (in this case, water), which caused a decrease in the coefficient of friction [18]. The counter-sample during the test induced deformation of the surface of the test sample and approximation of its morphology to that of the other samples, hence the approximation of the friction coefficient values during the test to those characteristics of the other samples.

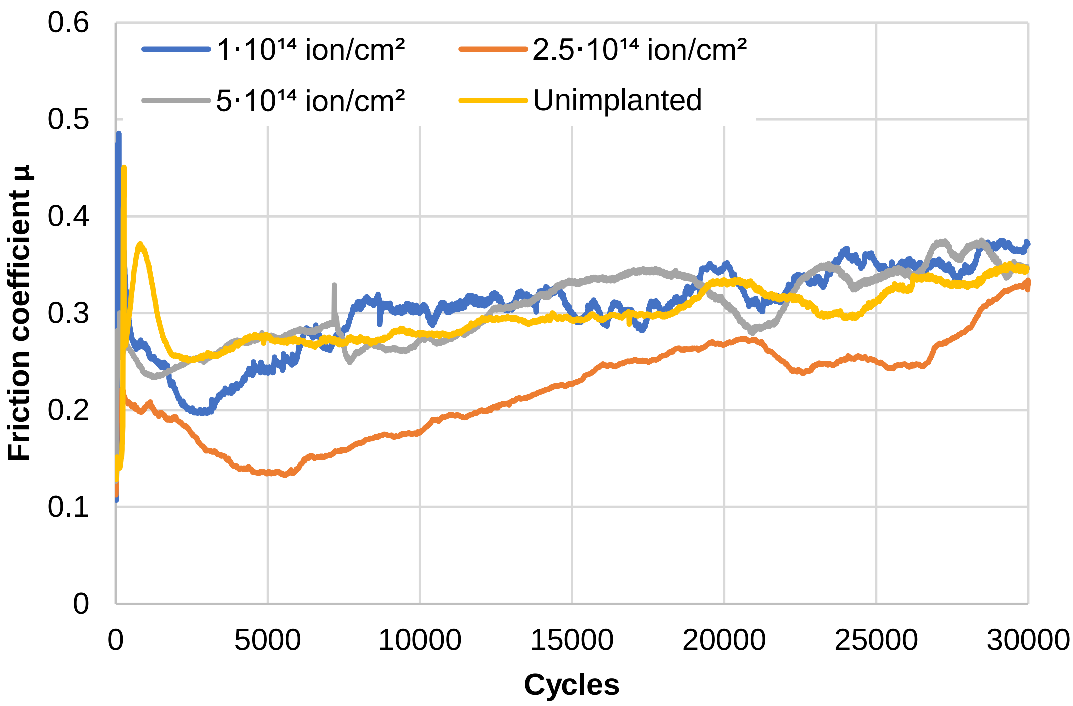

Figure 2 Friction coefficients of the irradiated samples

The wear results of individual samples are presented in **Figure 3**. The reported results include ten profilometric measurements of the wear track for each sample. In the chart, the median (line within the box) can be observed, indicating the central value, as well as the quartiles (lower - Q1 and upper - Q3), which define the boundaries of the box. The whiskers of the plot represent the minimum and maximum data values, taking into account extreme values. A significant decrease in the tribological wear of samples subjected to xenon ion irradiation can be seen, compared to the non-implanted sample.

The wear results were subjected to statistical analysis using Statistica software ver. 13.1. Based on the Kolmogorov-Smirnov test, the normality of the results distribution in each sample was confirmed. The variance among samples was compared using Levene's test, revealing consistency in variance across the samples. Statistically significant differences among the tested samples were demonstrated through ANOVA analysis. A Scheffe (post-hoc) test was performed, revealing statistically significant differences between the samples implanted with Xe ions and the non-implanted sample. A statistically significant decrease in wear was also demonstrated for samples implanted with doses of $2.5{\cdot}10^{14}$ and $5{\cdot}10^{14}$ Xe^{20+}/cm^2 compared to the sample implanted with a dose of $1{\cdot}10^{14}$ Xe^{20+}/cm^2. Increasing the dose of implanted ions from $2.5{\cdot}10^{14}$ to $5{\cdot}10^{14}$ Xe^{20+}/cm^2 did not result in statistically significant changes in the tribological wear of pure chromium.

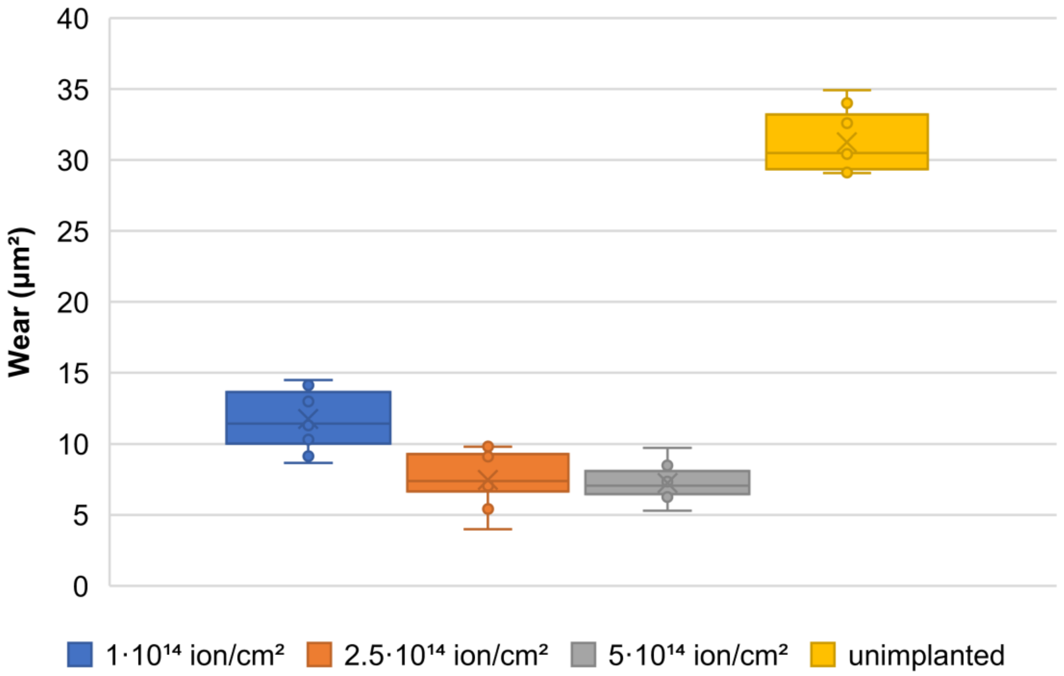

Figure 3 Distribution of tribological wear measurement results for pure chromium samples subjected to Xe ion irradiation and the non-irradiated sample

Figure 4 presents the results of profilometric measurements of chromium wear tracks following the conducted tribological test. The deepest and simultaneously widest wear track can be observed in the sample that was not subjected to ion implantation. As a result of the interaction of xenon ions within the chromium structure, changes occurred that significantly contributed to the increase in its resistance to tribological wear under water-lubricated conditions. It is worth noting that the study refers only to the implanted layer, as the maximum depth of the wear track for implanted samples does not exceed 0.6 µm, while considering the simulation results presented in **Figure 1**, the range of interaction for implanted ions exceeds 8.0 µm. It is also worth emphasizing that for pure chromium, high-energy ion implantation improved the resistance to tribological wear, while in the case of studies on the titanium alloy Ti6Al4V, an increase in tribological wear was observed after applying Xe ion implantation [19].

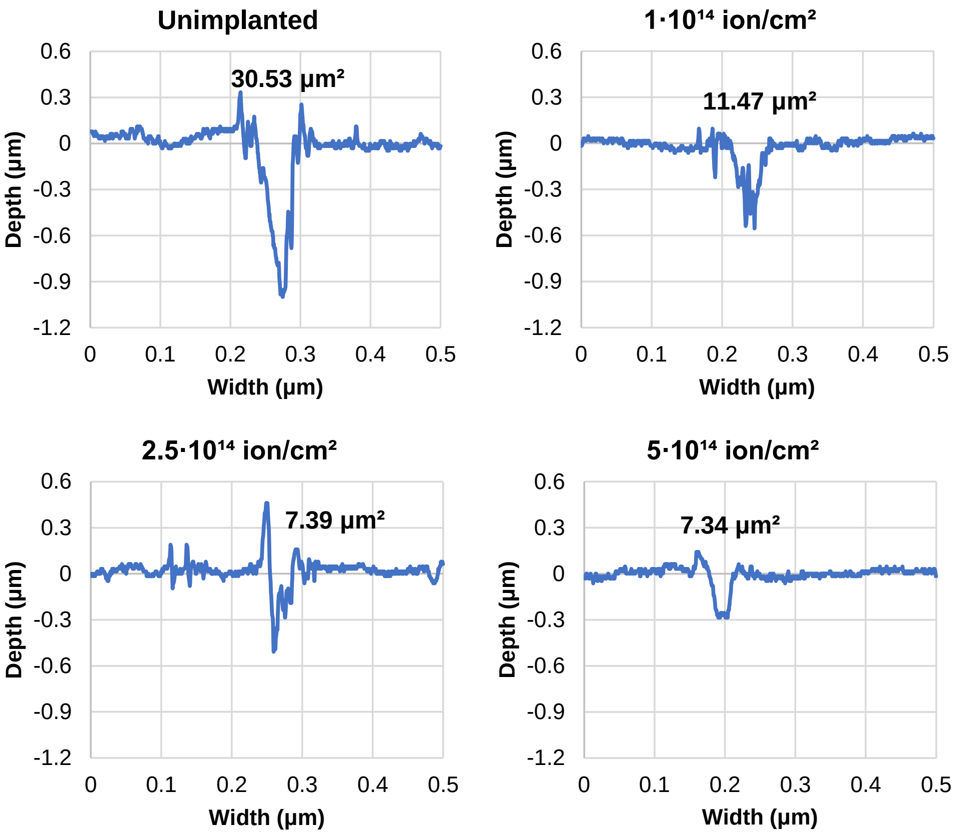

Figure 4 Results of profilometric measurements of wear tracks on pure chromium samples after tribological testing

4. SUMMARY

High-energy ion implantation of Xe ions has been shown to improve the tribological properties of pure chromium, including its resistance to wear. This is important in various industries such as automotive, aerospace, and energy. Based on the obtained research results, the following conclusions were drawn:

- High-energy Xe ion implantation allows for a reduction in tribological wear of pure chromium under wet friction conditions.
- When wear track depth does not exceed the depth of implanted ions, conclusions can be drawn regarding the resistance of the implanted layer without the influence of the non-implanted layer's resistance.
- The reduction of tribological wear in chromium in a water environment, after high-energy xenon ion implantation, is very promising. Many previous studies indicate a decrease in resistance to tribological wear after the application of high-energy implantation. The results of this study contribute to a better understanding of the effects of high-energy Xe ion implantation on pure chromium, potentially leading to the development of materials with improved performance parameters and resistance to damage in harsh environmental conditions.

REFERENCES

[1] BURAKOWSKI, T., WIERZCHOŃ, T. Znaczenie transformacji warstwy wierzchniej technologicznej w eksploatacyjną. *Tribologia*. 1997, vol. 5–6, pp. 477–485.

[2] ÖZKAN, D., YILMAZ, M.A., KARAKURT, D., Effect of AISI H13 Steel Substrate Nitriding on AlCrN, ZrN, TiSiN, and TiCrN Multilayer PVD Coatings Wear and Friction Behaviors at a Different Temperature Level. *Materials*. 2023. vol. 16, no. 4, pp. 1594. Available from: https://doi.org/10.3390/ma16041594.

[3] TAGHIZADEH TABRIZI, A., AGHAJANI, H., FARHANG LALEH, F., Tribological characterization of hybrid chromium nitride thin layer synthesized on titanium. *Surface and Coatings Technology.* 2021, vol. 419, pp. 127317. Available from: https://doi.org/10.1016/j.surfcoat.2021.127317.

[4] BALITSKII, A., KOLESNIKOW, W., KUBICKI, J. Role of chromium, vanadium and titanium alloying on the ferrous-manganese alloys tribological properties increasing. *Problems of Tribology.* 2003, vol. 1, pp. 94–100.

[5] HOLZWARTH, U., STAMM, H. Mechanical and thermomechanical properties of commercially pure chromium and chromium alloys. *Journal of Nuclear Materials.* 2002, vol. 300, no.2, pp. 161–177. Available from: https://doi.org/10.1016/S0022-3115(01)00745-0.

[6] ECK, R., MARTINZ, H.P., SAKAKI, T., KATO M. Powder metallurgical chromium. *Materials Science and Engineering: A.* 1989, vol. 120–121, pp. 307–312. Available from: https://doi.org/10.1016/0921-5093(89)90755-7.

[7] TERENTYEV, D., ZINOVEV, A., KHVAN, T. Irradiation embrittlement in pure chromium and chromium-tungsten alloy in a view of their potential application for fusion plasma facing components. *Journal of Nuclear Materials.* 2021, vol. 554, pp. 153086. Available from: https://doi.org/10.1016/j.jnucmat.2021.153086.

[8] CHEN, J., LI, X.Y., BELL, T., DONG, H. Improving the wear properties of Stellite 21 alloy by plasma surface alloying with carbon and nitrogen. *Wear*. 2008, vol. 264, no. 3, pp. 157–165. Available from: https://doi.org/10.1016/j.wear.2006.12.012.

[9] LI, B., JIN, Y., YAO, J. Influence of laser irradiation on deposition characteristics of cold sprayed Stellite-6 coatings. *Optics & Laser Technology.* 2018., vol. 100, pp. 27–39. Available from: https://doi.org/10.1016/J.OPTLASTEC.2017.09.034.

[10] SARITAS, S., PROCTER, R.P.M., GRANT, W.A. The use of ion implantation to modify the tribological properties of Ti6Al4V alloy. *Materials Science and Engineering.* 1987, vol. 90, pp. 297–306. Available from: https://doi.org/10.1016/0025-5416(87)90225-4.

[11] KAMIŃSKI, M., BUDZYŃSKI, P., SUROWIEC, Z. Surface morphology and phase stability of titanium irradiated with 168 MeV 136Xe ions. *International Journal of Materials Research.* 2018, vol. 109, no. 8, pp. 779–784. Available from: https://doi.org/10.3139/146.111653.

[12] LIU, B., DENG, B., TAO, Y. Influence of niobium ion implantation on the microstructure, mechanical and tribological properties of TiAlN/CrN nano-multilayer coatings. *Surface and Coatings Technology*. 2014, vol. 240, pp. 405–412. Available from: https://doi.org/10.1016/j.surfcoat.2013.12.065.

[13] YNSA, M.D., AGULLÓ-RUEDA, F., GORDILLO, N. Study of the effects of focused high-energy boron ion implantation in diamond. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms.* 2017, vol. 404, pp. 207–210. Available from: https://doi.org/10.1016/J.NIMB.2017.01.052.

[14] WANG, R., LI, B., LI, P. Effect of low-dose Xe20+ ion irradiation on the deformation behavior of the magnetron sputtered Cr coatings under nanoindentation. *Surface and Coatings Technology.* 2021, vol. 428, pp. 127907. Available from: https://doi.org/10.1016/j.surfcoat.2021.127907.

[15] HOFFMAN, D.W., GAERTTNER, M.R. Modification of evaporated chromium by concurrent ion bombardment. *Journal of Vacuum Science and Technology*, 1980, vol. 17, no. 1, pp. 425–428. Available from: https://doi.org/10.1116/1.570473.

[16] ZIEGLER, J.F., ZIEGLER, M.D., BIERSACK, J.P. SRIM – The stopping and range of ions in matter (2010). *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*. 2010, vol. 268, no. 11–12, pp. 1818–1823. Available from: https://doi.org/10.1016/J.NIMB.2010.02.091.

[17] SUDHAKAR S., GANESH, V., NAGARAJAN, M. Structural and surface characteristics of room temperature and low temperature swift heavy ion implanted InAs and InSb wafers. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms.* 2008, vol. 266, no. 8, pp. 1723–1728. Available from: https://doi.org/10.1016/j.nimb.2008.01.065.

[18] LIANG, X., QI, S., YANG, Z. Friction and wear behavior of cemented carbide self-matching pairs under different water lubrication conditions. *Wear*. 2023, vol. 523, pp. 204832. Available from: https://doi.org/10.1016/j.wear.2023.204832.

[19] BUDZYŃSKI, P., KAMIŃSKI, M., SUROWIEC Z., Effects of xenon-ion irradiation on the tribological properties and crystal structure of titanium and its alloy Ti6Al4V. *Tribology International.* 2021, vol. 156, pp. 106854. Available from: https://doi.org/10.1016/j.triboint.2021.106854.