The Wear Resistance During Oscillating Friction of Steel Specimens with Strengthened Nanocrystalline Layers

Ihor Hurey[1,2], Volodymyr Gurey[1](✉), Tetyana Hurey[1], Marian Bartoszuk[3], and Weronika Wojtowicz[2]

[1] Lviv Polytechnic National University, 12, Bandera Str., Lviv 79013, Ukraine
`Volodymyr.I.Hurei@lpnu.ua`
[2] Rzeszow University of Technology, 12, Powstancow Warszawy Ave., 35-959 Rzeszow, Poland
[3] Opole University of Technology, 5, Mikolajczyka St., 45-271 Opole, Poland

Abstract. Thermo-deformation treatment refers to methods of surface strengthening using highly concentrated energy sources. In the process of processing, the surface layers of the metal are modified, and strengthened white layers with a nanocrystalline structure are formed. The conducted studies showed that during the thermo-deformation treatment of the working surfaces of specimens made of steel 41Cr4 (quench-hardening and low-temperature tempering) using different technological media (mineral oil (MO), mineral oil with active additives containing polymers (APP) and saturated aqueous solution of mineral salts based on magnesium and calcium chlorides (ASMC)), a strengthened white layer with a thickness of 160 µm to 260 µm and a hardness of 7.6–8.2 GPa was formed. It is shown that the technological medium used during thermo-deformation treatment affects the wear resistance with reversible friction without lubrication. Thus, when using APP and ASMC, the wear resistance of steel-bronze friction pairs increased by 3.1–3.3 times, and when using MO, by 2.1–2.5 times, compared to the non-strengthened pair. During studies of friction pairs of "Steel 41Cr4 – Bronze CuAl10Ni5Fe4", "Steel 41Cr4 – Steel 30HGSA" in oscillating (reversible) friction without lubrication, as well as single-direction sliding friction, strengthened white layers with a nanocrystalline structure significantly increase their wear resistance.

Keywords: Industrial Growth · White Layer · Nanocrystalline Structure · Wear · Process Innovation

1 Introduction

Modern engineering products operate at high speeds and cyclic loads. Their reliability is determined by the quality of manufacturing machine parts, assembly processes, and operating conditions [1]. The operational characteristics of machine parts depend on the parameters of the quality of the working surfaces [2] and the surface layer [3]. The processes of destruction of machine parts begin from their contacting surfaces [4]. In the surface layers of the metal of machine parts [5], the crystal lattice accumulates various

V. Tonkonogyi et al. (Eds.): InterPartner 2023, LNME, pp. 265–275, 2024.
https://doi.org/10.1007/978-3-031-42778-7_24

defects [6], which lead to accumulation of various defects, which lead to the initiation and propagation of cracks [7] and the destruction of the surface layer and the part as a whole [8]. The geometric parameters of the contacting surfaces and the physical, mechanical, and electrochemical properties of the surface layers influence the durability of machine parts during operation [9]. The geometric parameters of the working surfaces of the parts depend on the conditions of their processing in the finishing operations and are characterized by roughness, waviness, and the bearing capacity of the contacting surface [10]. The physical and mechanical properties of the surface layers are determined by the chemical and phase composition, structure [11], grain size of the metal structure components, and stress state [1, 2, 12].

2 Literature Review

During operation, the contact surfaces of the machines are mostly destroyed due to friction processes [13]. One of the effective methods of increasing the durability of machines is the formation of a given surface so that it performs functions that differ from the functions required for the main material. Therefore, it is necessary to provide appropriate parameters for the working surfaces of the friction pair, as well as the quality of the surface layer [1, 11].

A new direction, "Surface Engineering", is used during manufacture to increase the durability of the contacting surfaces of machine parts during operation. During modification, it forms the specified parameters of the treated surfaces' quality and the metal's surface layer [11]. During the modification of the surface layer of metal [14], the process of strengthening [15]. The chemical and phase composition, structure, grain size, hardness, stress state of the metal [16], and crystal lattice dimensions are changing [17]. In this case, the section has no boundary between the strengthened surface layer and the base metal of the part [14]. The methods of modifying the surface layer of metal are processing methods using highly concentrated energy sources (laser [18], plasma [19], electron beam machining [20], and friction strengthening treatment [21, 22]), as well as intensive plastic deformation [23, 24]. In the process of these treatments, strengthened surface layers with a nanocrystalline structure are formed [25] (the grain size of the metal structure is less than 100 nm in at least one direction) [26], which have specific physical, mechanical, and other properties that are significantly different from the properties of the base metal [26, 27].

When applying surface treatment technologies using highly concentrated energy flows in the surface layers of metal under the action of high-temperature gradients [28], structural and phase transformations pass [18, 29]. The surface layers are heated at high speeds to temperatures above the point of phase transformations [30]. After escaping the source of thermal energy, the following rapid cooling of the surface layers due to heat dissipation into the depth of the metal passes [27]. As a result, the structure [31], phase and chemical compositions [29, 32], and physical, mechanical, and chemical characteristics of the metal change in the surface layers [25, 26].

Thermo-deformation treatment (TDT) refers to surface treatment methods using highly concentrated energy flows. Such a flow of energy is created by high-speed friction (60–80 m/s) of a strengthening tool on the work surface of the workpiece. Simultaneous shear deformation occurs during the processing in the contact area “tool-part” [33]. The surface layers of the metal are heated to temperatures above the point of phase transformations (Ac_3) [34]. After moving, the contact zone “tool-part” takes place in high-speed cooling of the metal surface layer. In the surface layer of machine parts, a specific structural-stressed state of metal [35] – a white layer with a nanocrystalline structure is formed [36].

Most studies of the durability of friction pairs, including white layers, were performed during single-directional sliding [13, 35]. Studies [33, 35] have shown that the strengthened white layers with nanocrystalline structure significantly increase the wear resistance of friction pairs during various types of wear.

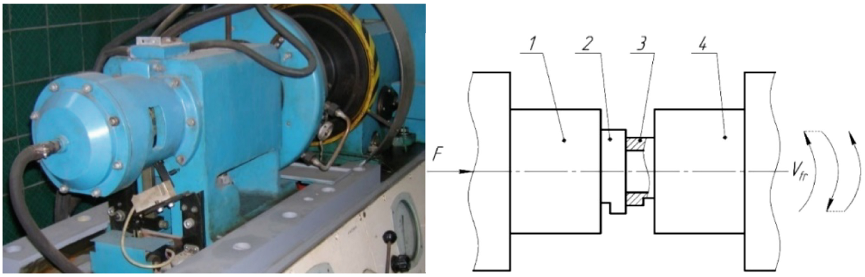
In practice, there are mechanisms in which friction pairs work in oscillating movements, and the oscillating (reversible) wear-and-tear is realized [37]. An example is the linkage and crank mechanisms, mated parts of the chain conveyors, and other surfaces of mated parts. The course of the wear process with oscillating (reversible) friction of a strengthened white layer with the nanocrystalline structure is unknown since the surface layers constantly change the direction of sliding to the opposite. Therefore, this work aims to influence the obtained strengthened nanocrystalline layers’ wear resistance during oscillating (reversible) friction.

3 Research Methodology

Studies of wear in the oscillating (reversible) friction were carried out on the friction and wear testing machine (UMT-1) (Fig. 1) installation according to the scheme “Plane-Plane” (Fig. 2a). Moveable and stationary (fixed) specimens were fixed in the clamps (Fig. 2b). The required load was applied to a fixed specimen by using a load device and the oscillating movements were formed by the crank mechanism and the eccentric for the moveable specimen. The study of wear resistance was carried out on specimens made of steel 41Cr4 (quench-hardening and low-temperature tempering, HRC 52–54). Moveable and stationary (fixed) specimens are in contact with the end (face) surfaces. The chemical composition of the steel 41Cr4 is as follows: mass %: 0.40 C; 0.78 Mn; 0.26 Si; 1.12 Cr; 0.01 S; 0.01 P; Fe: balance. The end surface of the fixed specimen has the shape of a circle with a diameter of 19 mm, and the moveable specimen – has the shape of a ring, an outer diameter is 15.8 mm and an inner – of 11 mm. The area of contact of the specimens is 100 mm^2.

TDT strengthened the end contact surface of the fixed specimens. Counter-specimens (moveable specimens) were made of bronze CuAl10Ni5Fe4 and steel 30HGSA (PL) (quench-hardening and low-temperature tempering, HRC 38–40). The chemical composition of the bronze CuAl10Ni5Fe4 is as follows: mass %: 3.5–5.5 Fe; 0.3 Mn; 0.1 Si; 3.5–5.5 Ni; 0.01 P; 9.5–11 Al; 77.4–83.5Cu; 0.02 Pb; 0.3 Zn; 0.1 Sn and the chemical composition of the steel 30HGSA (PL) is as follows: mass %: 0.28–0.34 C; 0.8–1.1 Mn; 0.9–1.2 Si; 0.8–1.1 Cr; 0.025 S; 0.025 P; 0.3 Cu; 0.3 Ni; Fe: balance. Studies of the wear resistance of friction pairs were carried out without lubrication. For comparison, similar non-strengthened friction pairs were investigated.

Before the test, all specimens of a friction pair were run in before stabilization of the moment of friction and alignment of mating surfaces, which was evaluated in the presence of traces of friction on the area of at least 90% of the friction working surface of each specimen.

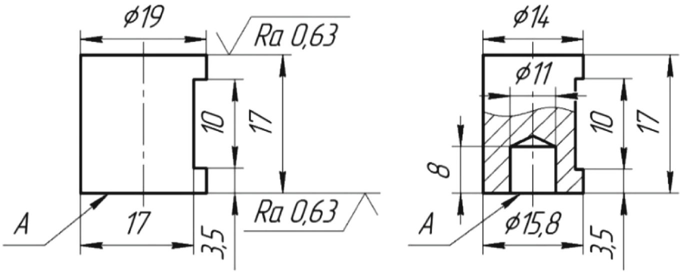


a

b

Fig. 1. The friction and wear testing machine (UMT-1) (a) and scheme of study the wear in the oscillating (reversible) friction according to the scheme “Plane-Plane” (b): 1 – fixed specimen; 2 – moveable specimen; 3, 4 – clamps; *F* – the force of pressing; V_{fr} – velocity of friction.

The criterion for the amount of wear was taken from the weight loss of specimens after a certain length of friction, which was determined by weighing on the analytical balance with an accuracy of ±0.2 mg. Also, during the experiments, the amount of linear wear on the working surfaces of the specimens was constantly recorded using the strain gauges, which also recorded the established friction coefficient (factor).



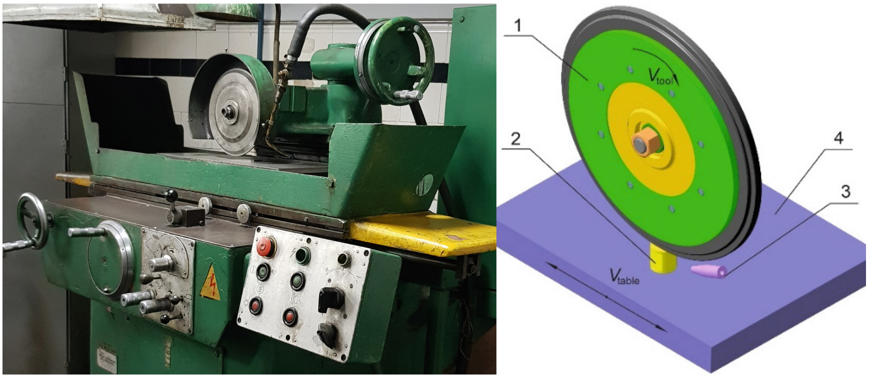
a

b

Fig. 2. Specimen (a) and counter-specimen (b) for studying the wear in the oscillating (reversible) friction according to the scheme “Plane-Plane”.

After the alignment of mating (contact) surfaces of the friction pair, the drive of friction and wear testing machine was switched on and set the required load. The load was given in the range F = 10…100 MPa and in steps of 10 MPa. The duration of experiments at each load was 100 cycles, and the total duration of the experiment was 1000 cycles. The load on each following range (step) was applied without interrupting the experiment. The angular displacement of the specimen was 90° and the displacement frequency – 5 double strokes per minute.

The TDT of the end (face) contact surfaces of fixed specimens made of steel 41Cr4 were carried out by a modernized surface-grinding machine of the SPC-20a (Jotes, Poland) (Fig. 3). Instead of a grinding wheel, the tool (disk) for TDT made of a stainless steel 1H18N10T (PL) was installed, as well as the modernization of the drive of the machine's main motion. The tool's dimensions correspond to the grinding wheel size used on the surface-grinding machine. The linear velocity on the periphery of the tool was 60–70 m/s. The technological medium was fed to ensure the appropriate quality parameters of the treated surfaces in the tool's contact area with the part during TDT. The media tested were: mineral oil (MO), mineral oil with active additives containing polymers (AAP), and a saturated aqueous solution of mineral salts based on magnesium and calcium chlorides (ASMC).



a b

Fig. 3. Surface-grinding machine of the SPC-20a (Jotes, Poland) (a), scheme of the process of strengthening by TDT (b): 1 – tool; 2 – specimen; 3 – nozzle to feed the technological medium; 4 – table of surface-grinding machine; V_{table} – velocity of the displacement of the table; V_{tool} – linear velocity of rotation of the tool.

The phase composition and average grain size L of the steel's surface layer after MPT was determined by X-Ray analysis using the diffractometer DRON-3 with a CuKα X-Ray source (voltage of 30 kV and intensity of 20 mA), spacing of 0.05° and the exposition of 4 s. The diffractograms were post-processed using the software CSD [38]. The X-Ray diffraction patterns were analyzed after the Joint Committee on Powder Diffraction Standards/American Society for Testing and Materials (JCPDS-ASTM) index [39].

The microhardness Hμ was measured using the microhardness testing machine PMT-3 at the load of 50 g on metallographic sections made from flat specimens of steel 41Cr4. Tests were carried out by indentation of a standard 136-degree Vickers diamond pyramid with a square base.

4 Results and Discussion

Metallographic studies have shown that qualitative and solid strengthened surface layers with the nanocrystalline structure are formed after TDT using various technological media on specimens made of steel 41Cr4 (quench-hardening and low-temperature tempering). The thickness of the strengthened white layer was 150–160 μm, and the hardness of the layer was 7.6 GPa, with the hardness of the main metal structure of 4.8 GPa after TDT using the MO as a technological medium. When used AAP as a technological medium, the thickness of the strengthened layer was more significant – 200–210 μm. After TDT with the use of ASMC, the thickness of the strengthened layer was even larger and was 250–260 μm. The hardness of the strengthening layer after processing using AAP and ASMC was almost the same and was 8.2 GPa.

X-ray studies of the obtained strengthened surface layers showed that the grain size of their structure near the surface is 20–50 nm. The structure's size with the layer's depth decreases and changes smoothly to the main structure. Accordingly, the obtained strengthened layers can be attributed to nanocrystalline.

As noted earlier, studies on determining the wear resistance of friction pairs were performed with single-direction sliding friction. During the reversible sliding motion in the friction pair's contact area, the cyclic changes in the load in the local zones of contact of the peaks of contacting surfaces are presented. Friction without lubrication is the severe type of interaction of contact surfaces in which their geometric parameters and surface layer properties are shown.

Experiments have shown that strengthened white layers with nanocrystalline structure significantly increase the wear resistance of oscillating friction (reversing) without lubrication of pair "Steel 41Cr4 (quench-hardening and low-temperature tempering) – Bronze CuAl10Ni5Fe4" (Fig. 4). The technological media used in the process of TDT significantly influenced the wear process. Thus, the increase in the wear resistance of the white nanocrystalline layer obtained by TDT using the technological medium of mineral oil reaches 2.5 times compared to non-strengthened specimens, AAP – 3.3 times, and ASMC – 3.5 times. This also increases the wear resistance of specimens made of bronze, which is paired with strengthened specimens made of steel. The increase in the wear resistance of bronze specimens exceeds 1.2–1.3 times. The magnitude of the established friction coefficient is also reduced.

During the study of the friction pair's non-strengthened specimens, the friction coefficient increases monotonously (Fig. 5). Study specimens have shown that with increasing load to 50 MPa, the friction coefficient at this time also increases monotonously. Its value is smaller than during the friction of non-strengthened pair. The friction coefficient stabilizes and even slightly decreases with the subsequent load increase of more than 50 MPa. It should be noted that the study of friction pairs with strengthened specimens by TDT with AAP and ASMC showed that the friction coefficient is less than in the study of pair, where TDT strengthened the specimen with MO. In the studies of the non-strengthened pair, the coefficient of friction is much higher than in friction pairs with strengthened specimens. Thus, during studies with a unit load of 90 MPa, the friction coefficient decreased by 1.2–1.4 times compared to the non-strengthened pair. The wear resistance during oscillating friction (reversing) without lubricating the pair with strengthened specimens using TDT with technological media AAP and ASMC is much higher than in pairs with non-strengthened specimens, as shown by studies.

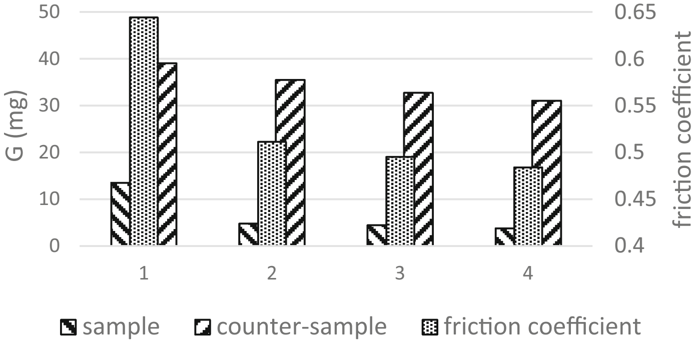


Fig. 4. The magnitude of wear and established friction coefficient of oscillating friction (reversing) without lubrication of the pair "Steel 41Cr4 (quench-hardening and low-temperature tempering) – Bronze CuAl10Ni5Fe4" ($F = 10\ldots100$ MPa; $V_{fr} = 0.005$ m/s; $N = 1000$ cycles): 1 – source (base) metal; 2 – TDT with MO; 3 – TDT with AAP; 4 – TDT with ASMC.

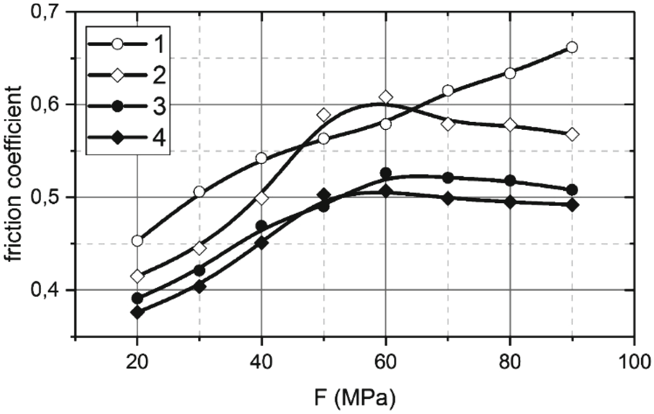


Fig. 5. The dependence of the established friction coefficient on the unit load of oscillating friction (reversing) without lubrication of the pair "Steel 41Cr4 (quench-hardening and low-temperature tempering) – Bronze CuAl10Ni5Fe4" ($V_{fr} = 0.005$ m/s; $N = 1000$ cycles): 1 – source (base) metal; 2 – TDT with MO; 3 – TDT with AAP; 4 – TDT with ASMC.

A similar situation is also observed in the case of oscillating friction (reversing) without lubrication when testing specimens made of steel 30HGSA (PL) (quench-hardening and medium-temperature tempering). In this case, strengthening of steel 41Cr4 (specimens made of steel 30HGSA (PL) were not strengthened, the working surface was only polished) also significantly increases the wear resistance of the friction pair (Fig. 6). So, for example, TDT with MO as a technological medium increases wear resistance by 2.1 times compared to non-strengthened pair, AAP – by 3.1 times, and using ASMC – by 3.3 times.

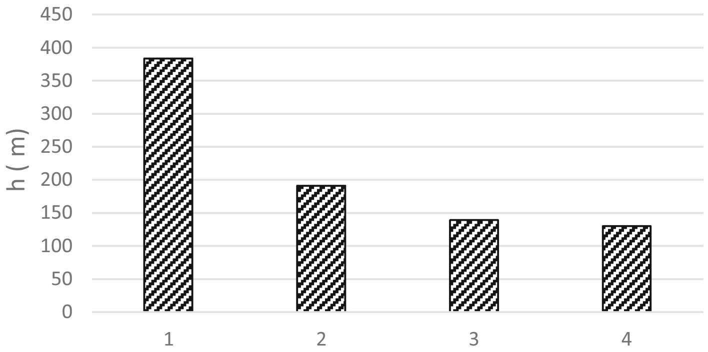


Fig. 6. The magnitude of wear of oscillating friction (reversing) without lubrication of the pair "Steel 41Cr4 (quench-hardening and low-temperature tempering) – Steel 30HGSA (PL)" (Vfr = 0.005 m/s; N = 1000 cycles): 1 – source (base) metal; 2 – TDT with MO; 3 – TDT with AAP; 4 – TDT with ASMC.

The friction coefficient increases monotonically with an increase in the unit load during the wear process of the non-strengthened pair. At the same time, the friction coefficient decreases during the wear process of the friction pair with the specimens after the TDT (Fig. 7). The friction coefficient is much lower after the TDT of specimens using APP and ASMC as a technological medium than the same treatment using MO. Thus, the friction coefficient decreased by almost 1.3 times compared to the non-strengthened pair at a unit load of 100 MPa.

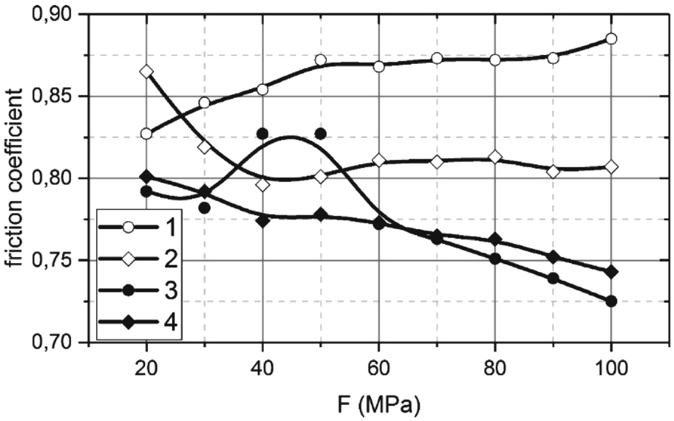


Fig. 7. The dependence of the established friction coefficient on the unit load of oscillating friction (reversing) without lubrication of the pair "Steel 41Cr4 (quench-hardening and low-temperature tempering) – Steel 30HGSA (PL)" ($V_{fr} = 0.005$ m/s; $N = 1000$ cycles): 1 – source (base) metal; 2 – TDT with MO; 3 – TDT with AAP; 4 – TDT with ASMC.

Strengthened surface layers significantly increase the wear resistance of contacting surfaces in oscillating friction. For example, paper [40] shows that applying chrome coatings to the working surfaces of plunger pairs of jet pumps operating in oil wells significantly increased their wear resistance. These parts of the pairs operate under oscillating friction. The thickness of the coatings was 250 μm and 350 μm and the hardness was 8.1 GPa and 11.8 GPa, respectively. The thickness and hardness of the strengthened chromium layers are similar to the parameters of the strengthened layers described in this paper.

5 Conclusions

During TDT with MO, AAP, and ASMC in the surface layers of specimens made of steel 41Cr4 (quench-hardening and low-temperature tempering), the high-quality, uniform, strengthened white layers with nanocrystalline structure are formed. Thus, when using AAP and ASMC, the wear resistance of the friction pair "Steel 41Cr4 – Bronze CuAl10Ni5Fe4" increased by 3.1–3.3 times, and with the use of MO – 2.1…2.5 times, compared to non-strengthened pair. During studies of friction pairs "Steel – Bronze" and "Steel – Steel" with reversible friction without lubrication and single-directional sliding, strengthened white layers with nanocrystalline structure significantly increased their wear resistance. It is advisable to strengthen by using the TDT only one part more technological of friction pair.

References

1. Dwivedi, D.K.: Surface Engineering. Enhancing Life of Tribological Components. Springer, New Delhi (2018). https://doi.org/10.1007/978-81-322-3779-2
2. Davis, J.R.: Surface Engineering for Corrosion and Wear Resistance. ASM International, Detroit (2001)
3. Troshchenko, V.T.: Deformation and destruction of metals under multicycle loading. Naukova Dumka, Kyiv (1981)
4. Troshchenko, V.T., Khamaza, L.A.: Stages of fatigue failure of metals and alloys. Rep. Natl. Acad. Sci. Ukr. **2**, 56–63 (2018). https://doi.org/10.15407/dopovidi2018.10.056
5. Pineau, A., McDowell, D.L., Busso, E.P., Antolovich, S.D.: Failure of metals II: fatigue. Acta Mater. **107**, 484–507 (2016). https://doi.org/10.1016/j.actamat.2015.05.050
6. Santecchia, E., et al.: A review on fatigue life prediction methods for metals. Adv. Mater. Sci. Eng. **2016**, 9573524 (2016). https://doi.org/10.1155/2016/9573524
7. Pedersen, M.M.: Introduction to metal fatigue. Technical report ME-TR-11. Aarhus University (2018). https://doi.org/10.13140/RG.2.2.25216.28163
8. Troshchenko, V.G.: Fatigue of metals at inhomogeneous stress state. Message 1. Methods of stress assessment and research results. Probl. Strengths **2**, 5–24 (2010)
9. Ropyak, L.Ya., Vytvytskyi, V.S., Velychkovych, A.S., Pryhorovska, T.O., Shovkoplias, M.V.: Study on grinding mode effect on external conical thread quality. IOP Conf. Ser. Mater. Sci. Eng. **1018**, 012014 (2021). https://doi.org/10.1088/1757-899X/1018/1/012014
10. Dzyura, V., Maruschak, P.: Optimizing the formation of hydraulic cylinder surfaces, taking into account their microrelief topography analyzed during different operations. Machines **9**(6), 116 (2021). https://doi.org/10.3390/machines9060116
11. Yushchenko, K.A., Borysov, Yu.S., Kuznetsov, V.D., Korzh V.M.: Surface engineering. Naukova dumka, Kyiv (2007)

12. Olugbade, T.O., Lu, J.: Literature review on the mechanical properties of materials after surface mechanical attrition treatment (SMAT). Nano Mater. Sci. **2**, 3–31 (2020). https://doi.org/10.1016/j.nanoms.2020.04.002
13. Hutchings, I., Shipway, P.: Tribology Friction and Wear of Engineering Materials. Butterworth-Heinemann, Oxford (2017)
14. Shaw, L.L.: The surface deformation and mechanical behavior in nanostructured alloys. In: Whang, S.H. (ed.) Woodhead Publishing Series in Metals and Surface Engineering, Nanostructured Metals and Alloys, pp. 481–506. Woodhead Publishing (2011). https://doi.org/10.1533/9780857091123.3.481
15. Quintino, L.: Overview of coating technologies Surface modification by solid state processing. In: Miranda, R. (ed.) Surface Modification by Solid State Processing, pp. 1–24. Woodhead Publishing (2014). https://doi.org/10.1533/9780857094698.1
16. Zhang, F., Duan, C., Sun, W., Ju, K.: Effects of cutting conditions on the microstructure and residual stress of white and dark layers in cutting hardened steel. J. Mater. Process. Technol. **266**, 599–611 (2019). https://doi.org/10.1016/j.jmatprotec.2018.11.038
17. Quintino, L.: Overview of coating technologies. In: Surface Modification by Solid State Processing, vol. 2014, pp. 1–24 (2014). https://doi.org/10.1533/9780857094698.1
18. Bartkowska, A.: Production and properties of FeB-Fe2B-Fe3(B, C). Surface layers formed on tool steel using combination of diffusion and laser processing. Coatings **10**(11), 1130 (2021). https://doi.org/10.3390/coatings10111130
19. Korzhyk, V., Tyurin, Yu., Kolisnichenko, O.: Theory and practice of plasma-detonation technology of surface hardening metal products. PC Technology Center, Kharkiv (2021). https://doi.org/10.15587/978-617-7319-46-6
20. Lukaszkowicz, K.: Review of nanocomposite thin films and coatings deposited by PVD and CVD technology. In: Rahman, M.M. (ed.) Nanomaterials, pp. 145–163. IntechOpen (2011). https://doi.org/10.5772/25799
21. Vilaça, P.: Friction surfacing. In: Miranda, R. (ed.) Surface Modification by Solid State Processing, pp. 25–72. Woodhead Publishing (2014). https://doi.org/10.1533/9780857094698.25
22. Lowe, T.C., Zhu, Y.T., Semiatin, S.L., Berg D.R.: Overview and outlook for materials processed by severe plastic deformation. In: Lowe, T.C., Valiev, R.Z. (eds.) Investigations and Applications of Severe Plastic Deformation. NATO Science Partnership Subseries: 3, pp. 347–356. Springer, Dordrecht (2000). https://doi.org/10.1007/978-94-011-4062-1
23. Segal, V.: Deformation mode and plastic flow in ultra fine grained material. Mater. Sci. Eng. A **406**(1), 205–216 (2005). https://doi.org/10.1016/j.msea.2005.06.035
24. Valiev, R.Z., Islamgaliev, R.K., Alexandrov, I.V.: Bulk nanostructured materials from severe plastic deformation. Progress Mater. Sci. **45**, 103–189 (2000). https://doi.org/10.1016/S0079-6425(99)00007-9
25. Hahn, H.: Unique features and properties of nanostructured materials. In: Zehetbauer, M., Valiev, R.Z. (eds.) Nanomaterials by Severe Plastic Deformation. WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim (2004). https://doi.org/10.1002/3527602461.ch1a
26. Inoue, A., Hashimoto, K.: Amorphous and Nanocrystalline Materials. Preparation, Properties, and Applications. Springer, Heidelberg (2001). https://doi.org/10.1007/978-3-662-04426-1
27. Javaheri, V., et al.: Formation of nanostructured surface layer, the white layer, through solid particles impingement during slurry erosion in a martensitic medium-carbon steel. Wear **204301**, 496–497 (2022). https://doi.org/10.1016/j.wear.2022.204301
28. Zhang, F.-Y., Duan, C., Wang, M., Sun, W.: White and dark layer formation mechanism in hard cutting of AISI52100 steel. J. Manuf. Process. **32**, 878–887 (2018). https://doi.org/10.1016/j.jmapro.2018.04.011

29. Wu, S., Liu, G., Zhang, W., Chen, W., Wang, C.: Formation mechanism of white layer in the high-speed cutting of hardened steel under cryogenic liquid nitrogen cooling. J. Mater. Process. Tech. **302**, 117469 (2022). https://doi.org/10.1016/j.jmatprotec.2021.117469
30. Hosseini, S.B., Klement, U.: A descriptive phenomenological model for white layer formation in hard turning of AISI 52100 bearing steel. CIRP J. Manuf. Sci. Technol. **32**, 299–310 (2021). https://doi.org/10.1016/j.cirpj.2021.01.014
31. Merino, P., et al.: An attempt to generate mechanical white etching layer on rail surface on a new rolling contact test bench. Wear **482–483**, 203945 (2021). https://doi.org/10.1016/j.wear.2021.203945
32. Xu, Y., Fang, L., Cen, Q., Zhu, J.: Nanostructure and transformation mechanism of white layer for AISI1045 steel during impact wear. Wear **258**, 537–544 (2005). https://doi.org/10.1016/j.wear.2004.06.002
33. Kyryliv, V., Maksymiv, O., Gurey, V., Hurey, I., Kyryliv, Y., Zvirko, O.: The mode deformation effect on surface nanocrystalline structure formation and wear resistance of steel 41Cr4. Coatings **13**, 249 (2023). https://doi.org/10.3390/coatings13020249
34. Gurey, V., Shynkarenko, H., Kuzio, I.: Mathematical model of the thermoelasticity of the surface layer of parts during discontinuous friction treatment. In: Ivanov, V., Pavlenko, I., Liaposhchenko, O., Machado, J., Edl, M. (eds.) DSMIE 2021. LNME, pp. 12–22. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-77823-1_2
35. Hurey, I., Hurey, T., Gurey, V.: Wear resistance of hardened nanocrystal-line structures in the course of friction of steel-grey cast iron pair in oil-abrasive medium. In: Ivanov, V., et al. (eds.) DSMIE 2019. LNME, pp. 572–580. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-22365-6_57
36. Gurey, V., Hurey, I.: Influence of surface hardened nanocrystalline layers on the resistance of contact fatigue destruction. In: Ivanov, V., Trojanowska, J., Pavlenko, I., Zajac, J., Peraković, D. (eds.) DSMIE 2020. LNME, pp. 483–491. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-50794-7_47
37. Bai, Z., Ning, Z., Zhou, J.: Study on wear characteristics of revolute clearance joints in mechanical systems. Micromachines **13**, 1018 (2022). https://doi.org/10.3390/mi13071018
38. Krous, W., Nolze, G.: Powder Cell – a program for the representation and manipulation of crystal structures and calculation of the resulting X-ray powder patterns. J. Appl. Cryst. **29**, 301–303 (1996). https://doi.org/10.1107/S0021889895014920
39. Powder Diffraction File Search Manual [inorganic]: Alphabetical Listing and Search Section of Frequently Encountered Phases. Joint Committee on Powder Diffraction Standards, Philadelphia, USA (1976)
40. Bazaluk, O., Dubei, O., Ropyak, L., Shovkoplias, M., Pryhorovska, T., Lozynskyi, V.: Strategy of compatible use of jet and plunger pump with chrome parts in oil well. Energies **15**, 83 (2021). https://doi.org/10.3390/en15010083