DOI: 10.21062/mft.2025.033  http://www.journalmt.com

# Comparison of Bearing Surface Quality Parameters for Wind Turbines

Mariana Janeková (0000-0002-9380-2760), Daniela Koštialiková (0000-0003-4981-7698), Dana Bakošová (0000-0003-2936-8637), Andrej Dubec (0009-0001-6145-6357), Alžbeta Bakošová (0000-0003-3440-0689), Jana Králiková

Faculty of Industrial Technologies in Púchov, Alexander Dubček University of Trenčín. I. Krasku 491/30, 020 01 Púchov. Slovakia. E-mail: mariana.janekova@tnuni.sk, daniela.kostialikova@tnuni.sk, dana.bakosova@tnuni.sk, andrej.dubec@tnuni.sk, alzbeta.bakosova@student.tnuni.sk,jana.kralikova@student.tnuni.sk

**The thesis deals with the surface treatments of bearing steel processed for wind turbines, on which the quality parameters of the surface treatments performed were compared. This is blackening, which is a method of surface treatment that allows the protection of the base material from the negative effects of external influences, in particular from moisture and associated corrosion. The application of surface treatment by blackening contributes to a better and more efficient start-up of the bearing in service. In the experimental part, the individual results of the structural analysis carried out for all types of materials investigated are evaluated, with the analysis focusing on the structural properties, the quality of the adhesion properties and the influence on the service life of the machine components. Electron microscopy was used to investigate the structural properties of the layer as well as the base material, which allowed to obtain the necessary data to meet the objectives of this work.**

**Keywords:** Metal materials, Surface treatments, Blackening, Corrosion resistance, Adhesion

## 1 Introduction

The use of surface treatments is essential in many industries to ensure the required performance and durability of products. The surface as a boundary between two different environments is fundamentally influenced by its mechanical, physical and chemical properties. The essence of surface preparation is to create an environment that ensures the smooth progression of the reactions that take place downstream with the layers and surfaces being formed [1]. In spite of advanced metallurgy, the development of new grades of steels alloyed in different proportions, no universal material can be applied. The essence of surface preparation is the creation of an environment that ensures the smooth progression of reactions that take place downstream of the layers and surfaces being formed. Mechanical and chemical pretreatment of the surface is necessary to ensure good adhesion, durability of the future coating and homogeneous properties of the formed layers [1]. When a clean metal surface is exposed to external environmental influences, almost most metals develop a thin layer formed by their own reaction products on the surface, which protects the metal surface. If the surface of the metal becomes oxidised, it is up to the physical and electrical properties of the metal as to how quickly the oxidation continues or stops. In almost all types of metals, the growth of the oxidized layer is associated with a change in surface color and loss of the characteristic luster [2]. The oxide layer reaches a minimum thickness, so there is no change in the dimensions of the components after blackening. Due to the high adhesion capacity of this layer, it also prevents unnecessary slippage of the bodies when interacting with the outer and inner ring of the bearing.

Blackening is classified among diffusion methods of surface treatment, used for surface treatment of highly stressed components, such as gears in gearboxes, or for the protection of bearing surfaces [3]. Because of its advantages, especially the protection of surfaces against corrosion, blackening has found its application mainly in the armament industry and in engineering in the manufacture of machine components. Its use has found application mainly in metalworking, for example on drills, milling cutters, jaws, screws, and washers, on various decorative elements of door controls, handles, hinges for its visually rustic effect.

## 2 Materials used for the manufacture of bearings

Materials occupy an important role in a developing society since the various stages of human development are named after the material that was most abundantly used in each period. When assessing the suitability of material selection and the choice of a compatible surface treatment, it is necessary to take into account all the external and internal influences to which the treated material will be exposed in Fig. 1. In particular, the structure and topography, the chemical composition and the properties of the body material determine the surface properties and its behaviour. Metallic materials are characterised by high elastic moduli and toughness, while at the same time being well formable [3]. They have good thermal and electrical conductivity but are less resistant to corrosion. Their properties can be further improved by hardening or possible modifications of the material composition. In general, due to their mechanical and technological properties, metals, and in particular steels, dominate in a wide range of applications [4-6].

In addition to technical and quality parameters, bearing steels must meet high technological and design requirements for good machinability and uniform metal remelting while maintaining the required dimensions [4-8]. In addition to carbon, the chemical composition of steels contains a number of accompanying and alloying elements. Alloying elements are added to steels to meet the increasingly stringent requirements for use in demanding applications and operating conditions. By simply adjusting the ratio and increasing the content of certain elements, they improve in particular the mechanical properties of the resulting steel, but also the degree of remelting, remelting, carbide formability or technological processing [8]. The wear and thus the functionality and service life of individual steel components is also influenced by the running-in and especially by repeated start-ups of the bearing after the interruption of normal operation [9,13].

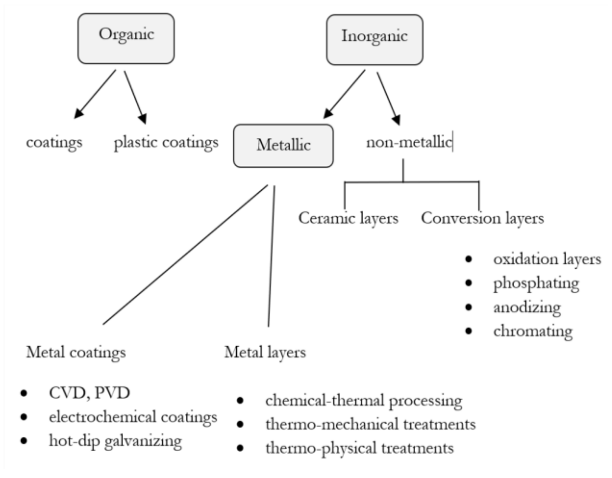


***Fig. 1*** *Categories of surface treatments*

## 3 Surface treatment of metal materials

For a smooth start-up without unwanted bearing slippage, it has been proven to increase adhesion by treating the contact surfaces with a surface treatment. The surface is the basic functional unit of a surface that forms the interface between the material and the surrounding environment. The surface of the material remains in equilibrium with the environment due to its own free energy. Wear and subsequent degradation occurs when the free energy is disturbed and the two phases interact. The surface properties and its behaviour are mainly determined by the structure and topography, chemical composition and material properties of the body [9]. Blackening of iron, cast iron and steel components is one of the oldest methods of metal protection and has been used since the past also for its decorative character. However, over time it has been extended to other technological applications due to its positive properties. Bearings taught for the operation of wind turbines must withstand various external influences [10]. The installation of such devices requires their stability in operation under different temperatures, speeds and load rates. In practice, this surface treatment is less suitable for use on cast irons or on high alloy steels; for the manufacture of bearings, it is usually most widely used to protect the surface of the contact surfaces of the bodies and rings of tapered roller, cylindrical roller, as well as ball rolling bearings [7-13]. The armouring of steels is carried out in baths of hot concentrated aqueous solution of salt hydroxides with inhibitors and other additives [7]. It improves appearance, abrasion resistance and corrosion resistance. It is usually combined with the use of a suitable lubricant or oil, which as a result positively influences the adhesion capability according to the type of application of the components treated in this way. The blackened layer is of particular importance as an effective protection against corrosion and external environmental influences, due to the porosity of the layer and thus a more uniform distribution of the lubricant, it contributes to better bearing run-in and also to repeated run-ins during bearing downtime. In this process, a chemical reaction takes place which forms an oxide layer on the surface of the blackened material. The selection of steel is the most important at all for these chemical processes and is connected to machining [10]. Materials science, and mechanical engineering are subjects that are always developing and upgrading. Still, scientists cannot achieve high quality at the lowest possible cost, and numerous products fail [11,12]. Due to the compactness and integrity of the layer, it helps to prevent cracks in the material and subsequent damage. It reduces the risk of fretting due to corrosion damage to the bearing, enables smoother bearing run-in, increases corrosion resistance, prevents body slippage during bearing run-in, improves bearing performance even at low lubrication levels, reduces hydrogen permeation into the bearing base material, the resulting layer is very thin, therefore it does not affect the geometry and dimensional accuracy of machine parts, the layer is resistant to abrasion and abrasion, resistant to temperatures up to 300 °C by the characteristic "blackening" of the component gives the workpiece an antique appearance (optical enhancement) [13,14].

## 4 Experimental part

In the experimental part, we compared the quality parameters of the surface treatment on three types of base material Fig. 2. The surface treatment consisted in blackening, which is a method of surface treatment that allows protection of the base material against negative effects of external influences, especially against moisture and the associated corrosive wear of the bearings. Blackening is classified as a diffusion method of surface treatment [15,16]. A layer is formed on the surface of the base material by controlled oxidation. The result is a porous layer with a thickness of about 0.5-2 μm.

The treatment involves the preparation of the solution and the blackening itself. The blackening salt is poured into cold water with stirring for optimum concentration at a ratio of 1 kilogram of mixture per 1 litre of water. The temperature rises sharply due to the exothermic process, with the temperature of the solution rising by up to 80°C as the salt dissolves. It is known that the boiling point of a mixture depends on the amount of salt dissolved. By adding salt or evaporating water, increasing the salt concentration, the boiling point temperature increases. If we want to lower the boiling point temperature, it is necessary to add water to the mixture solution [9].

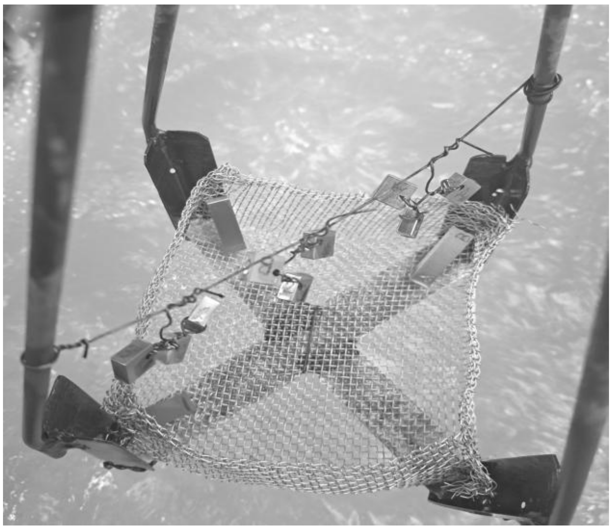

***Fig. 2*** *Immersion of components in a boiling alkaline salt solution*

The blackening process is initiated by immersing the components in a bath in racks, sieves or drums Fig. 2. To ensure the required quality of blackening of bearing components, a two-step process is used [14-17]. The reaction in the material layer takes place only in the boiling point region, so care must be taken to ensure that the solution bath is heated. The components are removed from the bath as soon as they turn dark black. After blackening, the heating can be switched off and the bath is turned off [15]. When restarting, heating power is first added to bring the solution to the boiling point. As the blackening salt is replenished during operation, the solution bath has a long service life under normal operating conditions [15-17]. After the blackening process is complete, a thorough rinse is required to remove any residual salts that may later crystallize on the surface of the blackening layer [13,15]. After rinsing, the surface is dried. Since the resulting layer is porous and not completely anticorrosive, the application of oil or lubricant becomes an essential part of the process [16,18]. The oil preservative is retained in the micropores and acts as additional protection against corrosive wear of the surface. Bodies made from bearing after heat treatment and chemical-thermal treatment were the subject of investigation and comparison of surface quality properties [15-19]. The experimental material is used in the engineering industry to produce bearings for wind turbines. In Fig. 3 below, the bodies made from three different all-coatable materials that were designed for the experiment are documented.

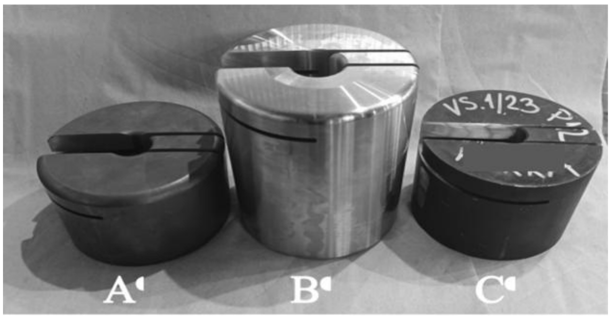


***Fig. 3*** *Bodies sampled for surface treatment blackening - from the left sample A, B and C*

The 18NiCrMo14-6 - (sample A) cementitious steel material was cut from a body that had undergone a chemical-heat treatment cementation process. The hardness after processing is guaranteed at 60-64 HRC. The chemical composition of the base material is given in Table 1.

***Tab. 1*** *Chemical composition of sample A*

| Element | Ni | Mo | Cr | Si | Mn | C | P | S | O | Ca |
|---|---|---|---|---|---|---|---|---|---|---|
| Content [wt. %] | 3.29 | 0.16 | 1.34 | 0.33 | 0.47 | 0.17 | 0.008 | 0.003 | 0.0003 | 0.0002 |

Sample B of 100CrMnSi6-4 - (sample B) steel was cut from the body after heat treatment by quenching, the hardness after quenching is guaranteed at 59-63 HRC. The chemical composition of the base material is shown in Table 2.

***Tab. 2*** *Chemical composition of sample B*

| Element | Ni | Mo | Cr | Si | Mn | C | P | S | O | Ca |
|---|---|---|---|---|---|---|---|---|---|---|
| **Content [wt. %]** | 0.05 | 0.013 | 1.44 | 0.49 | 1.04 | 0.95 | 0.015 | 0.001 | 0.0006 | 0.0001 |

The material of 100CrMo7-3 - (sample C) steel was cut from the body after heat treatment hardening, the hardness after hardening is guaranteed at 59-63 HRC. The chemical composition of the base material is given in Table 3.

***Tab. 3*** *Chemical composition of steel sample C*

| Element | Ni | Mo | Cr | Si | Mn | C | P | S | O | Ca |
|---|---|---|---|---|---|---|---|---|---|---|
| **Content [wt. %]** | 0.18 | 0.23 | 1.65 | 0.24 | 0.64 | 0.94 | 0.012 | 0.010 | 0.0003 | 0.0002 |

To verify the influence of the surface integrity quality and the related adhesion of the deposited layers, it was necessary to verify the roughness on the selected materials on the Mitutoyo Superftest SJ-410 v. According to the calculation in Table 4, after polishing, the average roughness of all samples was Ra ≤ 0.40 μm. To avoid confusion, each of the samples was marked with a letter according to the corresponding base material and a sample sequence number.

***Tab. 4*** *Measurement of roughness of prepared samples*

| | **Measure 1** | | **Measure 2** | | **Measure 3** | | **Diameter** | |
|---|---|---|---|---|---|---|---|---|
| Sample A | 0.350 | μm | 0.417 | μm | 0.351 | μm | 0.373 | μm |
| Sample B | 0.381 | μm | 0.403 | μm | 0.333 | μm | 0.372 | μm |
| Sample C | 0.349 | μm | 0.343 | μm | 0.377 | μm | 0.356 | μm |

## 5 Structural analysis of the black layer

The introduced work deals with the microscopic analysis of metallographically prepared selected metal materials structures, using a scanning electron microscope (SEM) [20]. Using the SEM method, we assessed the morphology and topography of the analysed sample regions. In sample A, which was cemented prior to the experimental application of the surface treatment, we observed an unevenly distributed occurrence of pores in Fig. 4 of smaller size in the surface and subsurface region of the blackened layer. The average pore size occurring in the blackened layer of this material was 0.44 μm.

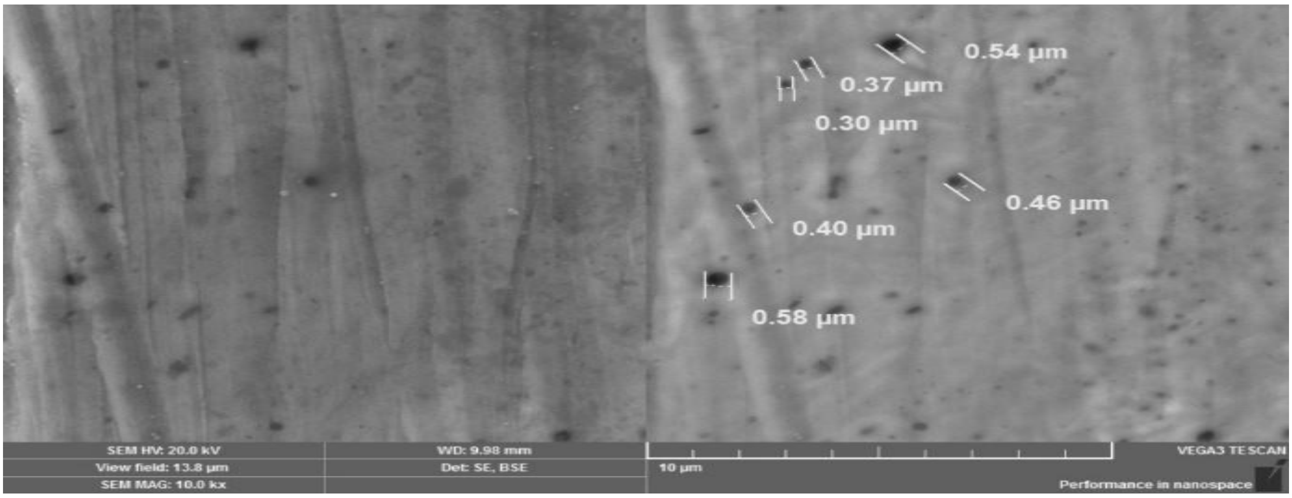


***Fig. 4*** *Pore size measurements of the blackened layer of sample A*

The EDS energy-dispersive spectroscopy method provides a means of obtaining the exact chemical composition of the material from the analyzed areas by several types of chemical composition analyses. For the determination of chemical composition, the X-act Oxford Instruments EDX detector was chosen.

The chemical analysis carried out from the black layer area as well as the area of the starting material of sample A, we confirmed the presence of the predicted chemical elements see in Fig. 4. In the blackened layer area, the presence of iron oxides, which were the dominant component of the deposited layer, was confirmed in Fig. 5.

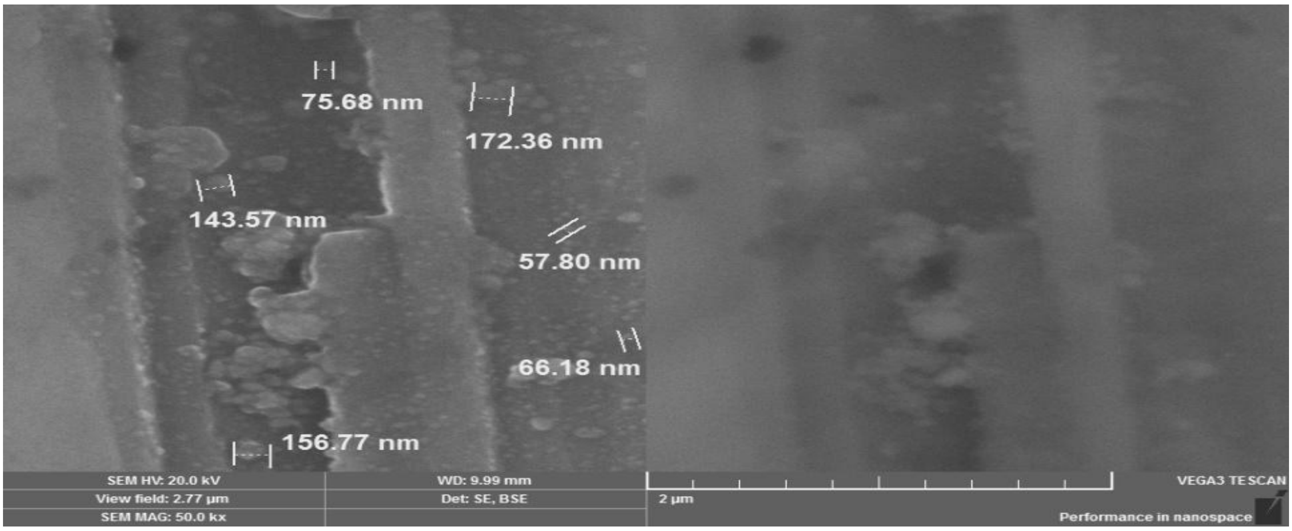


***Fig. 5*** *Pore size measurements of the blackened layer of sample A*

Fig. 4 and Fig. 5 above show the oxides present in the layer whose average size was 112.06 nm. Their presence is due to the blackening technology as a natural part of the diffusion process and the ongoing reaction in the surface region of the material. From the result of the chemical spectrum analysis of the 1 area of the layer in Fig. 6, we found the presence of Fe in the representation of 91 wt.%, oxygen had a value of 4.7 wt.%.

In sample B, a higher frequency of microscopic pores of similar size was observed, which were evenly distributed throughout the observed area. Their average size was 0.77 µm in Fig. 7. Like the material of sample A, oxides were also observed in the surface area of sample B see in Fig. 8, their average size was 181.58 nm.

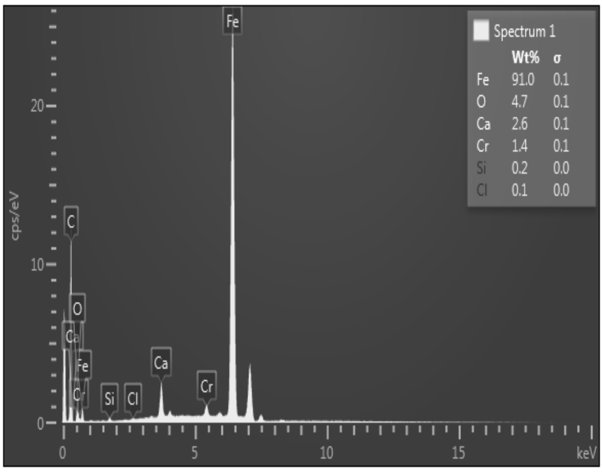


***Fig. 6*** *Measurement of the relative size of oxides in the surface structureof the blackened layer of sample A*

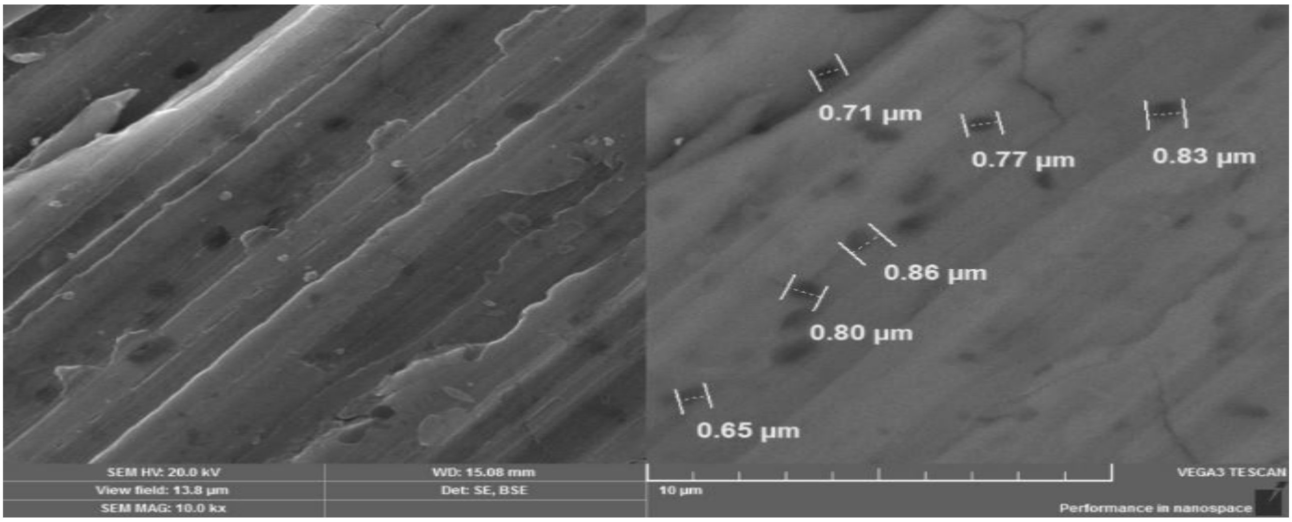


***Fig. 7*** *Pore size measurements of the blackened layer of sample B*

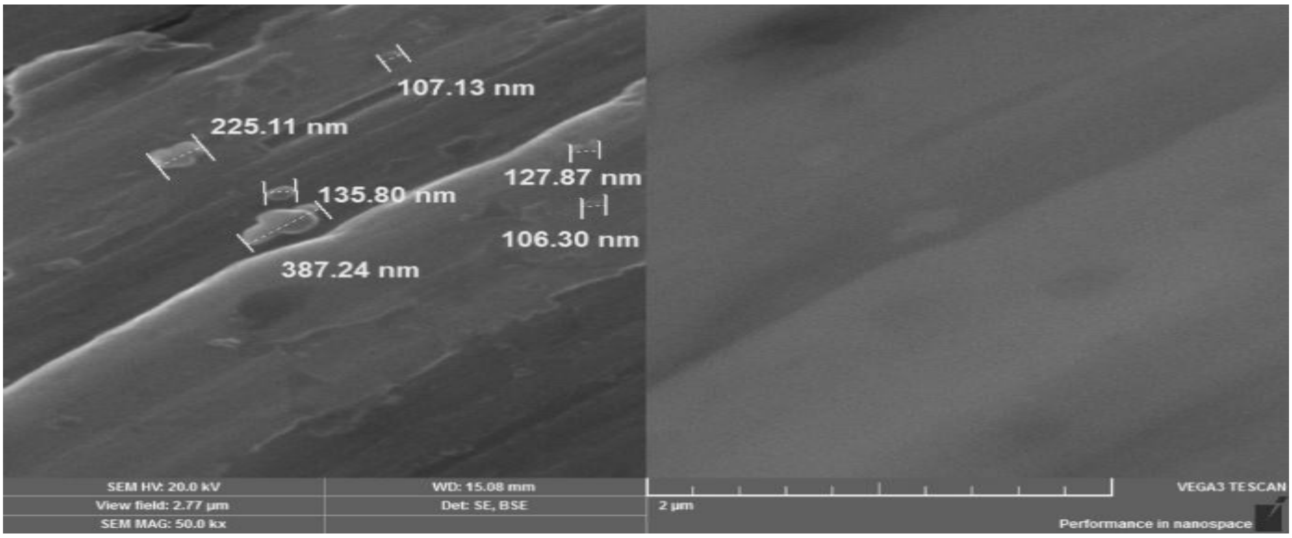


***Fig. 8*** *Measurement of the relative size of oxides in the surface structure of the blackened layer of sample B*

In the chemical analysis of sample B, the oxygen values reached a higher mass amount than that of sample A. We assume that this is due to the carbon content diffused into the base material layer during the chemical-thermal treatment by cementation. At the end of the 19th century, it was found that an increase in hardness and resistance to wear of steel components was possible due to the carbon diffusion deep into their surface layer [19,20]. There have also been a significant improvement in corrosion resistance and thermal resistance of many steels exposed to the diffuse process [21,22]. Bearing is an important mechanical functional component [23].The presence of the remaining chemical elements for sample B in Spectrum 5 (layer) confirmed to us the Fe content was 78.7 wt.%, oxygen 16.7 wt.%. which is documented in Fig. 9.

In the sample C-labelled material, a different structure of the surface region was observed. As can be seen in the above images, the occurring pores tended to cluster together. Their average size was 0,48 µm. In Fig. 10 we can see the transverse grinding marks from the sample preparation process. The average oxide size in the sample layer C from the measurement shown in Fig. 11 was 135.36 nm.

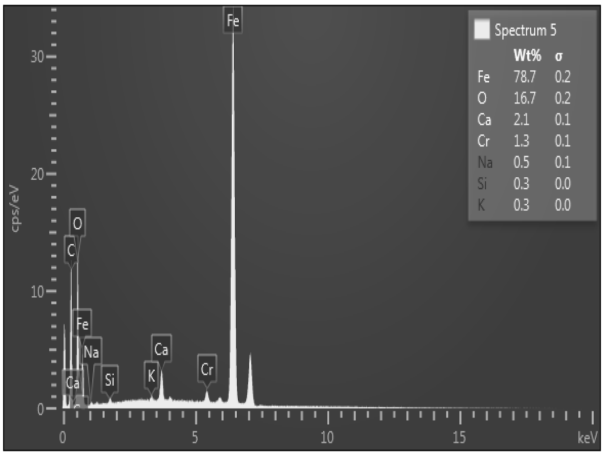


***Fig. 9*** *Chemical spectrum of selected area of sample B: black layer*

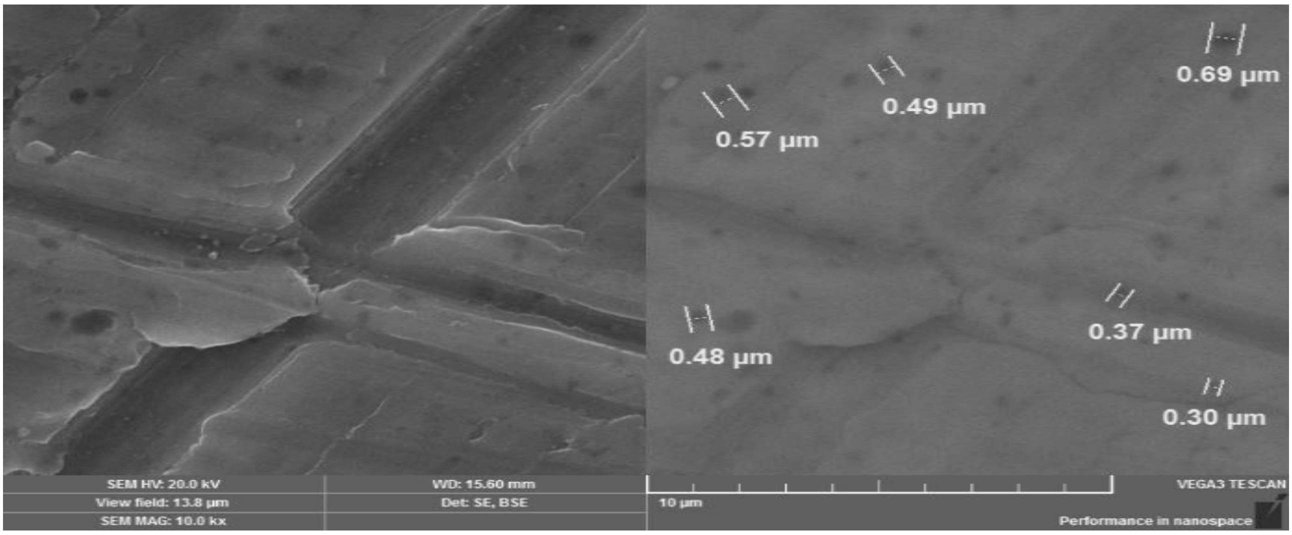


***Fig. 10*** *Pore size measurement views of the blackened layer of sample C*

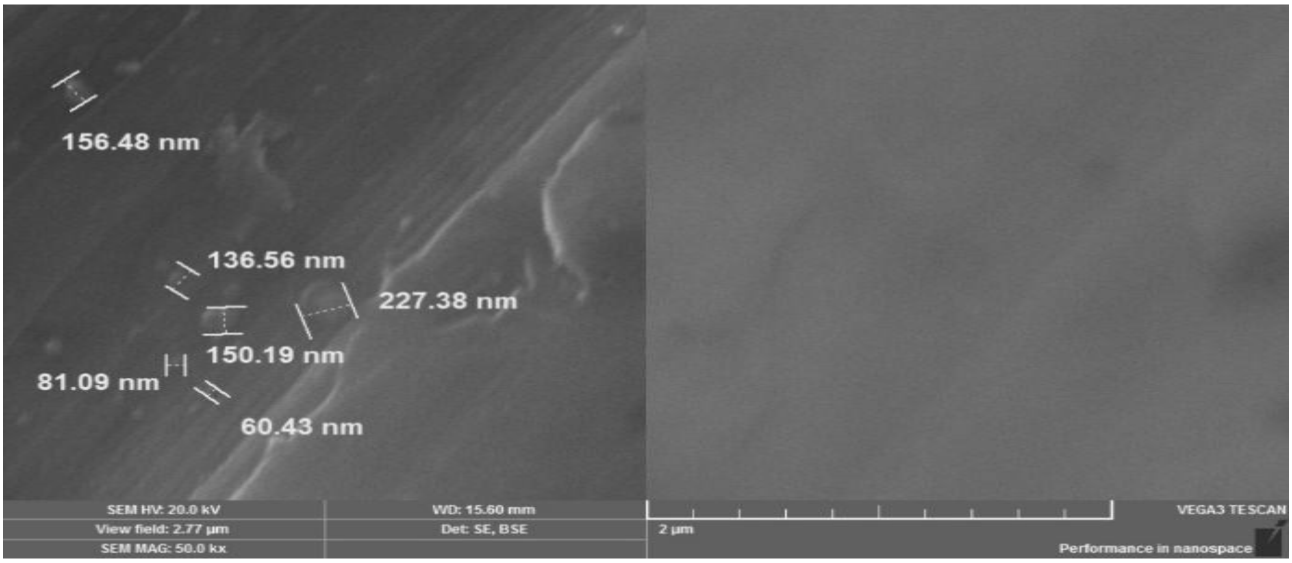


***Fig. 11*** *Measurement of the relative size of oxides in the surface structure of the C*

When considering sample C, the oxygen values reached a lower mass amount than sample B. We assume that this is due to the presence of additional passivating alloying elements which would affect the oxide layer formation process. In sample C of Spectra 3 from the layer region, the Fe content was 83.1 wt%, O was 13.1 wt%. The presence of the remaining chemical is recorded in Fig. 12.

The evaluation of the black layer adhesion for all the materials investigated was performed using the SEM method in BE, BSE [20-22]. The SEM method determines us the nature of the topography and micromorphology of each surface in Fig. 13.

Bearing is an important mechanical functional component [23]. We investigated the adhesion of the layer on the experimental materials in cross-sections for all samples of the selected materials see in Fig. 14, Fig. 15 where we identified uniformity and continuity of the deposited blackened layer for all layer materials.

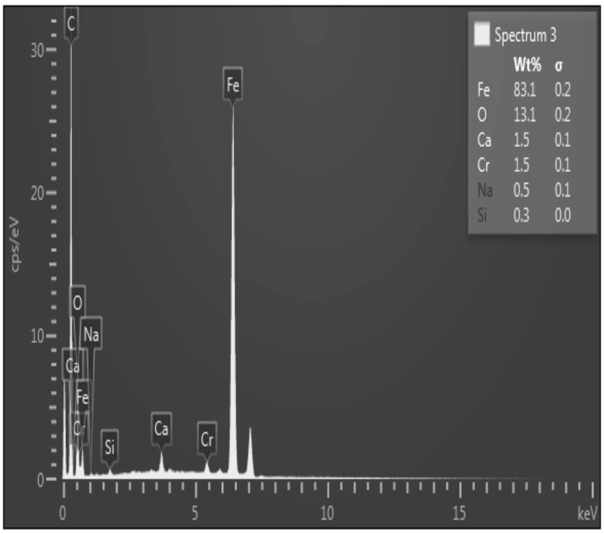


***Fig. 12*** *Chemical spectrum of a selected region of sample C*

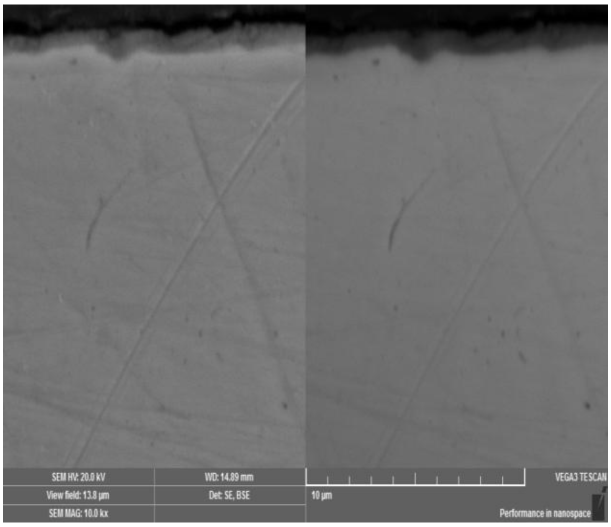

***Fig. 13*** *Representation of the local non-uniformity of the adhesion of the blackened layer of sample A in the cross-section*

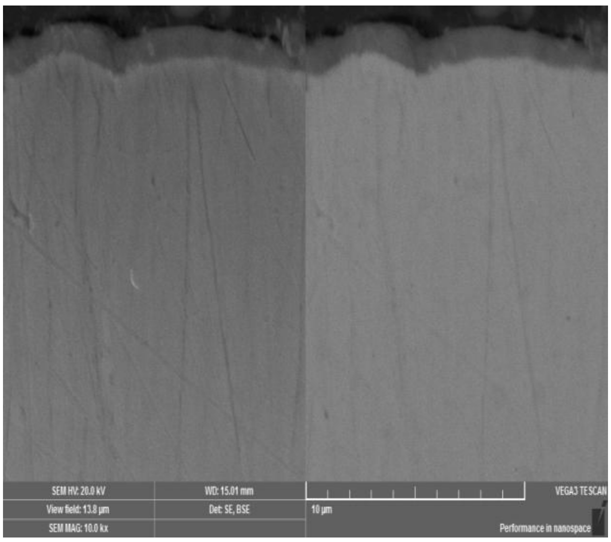

***Fig. 14*** *Cross-sectional representation of the small local non-uniformity of the adhesion of the blackened layer of specimen B*

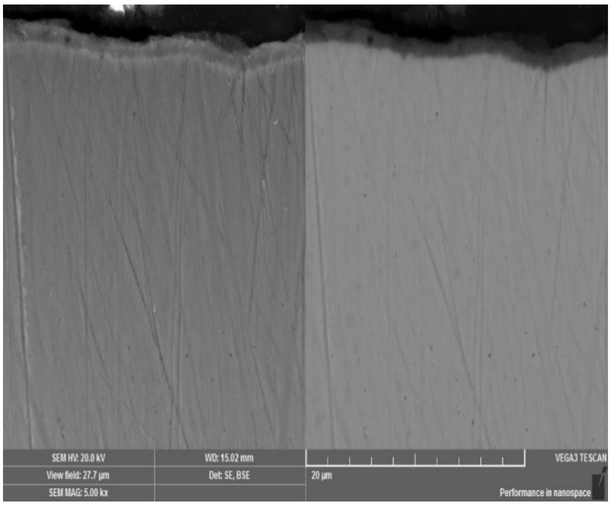


***Fig. 15*** *Sample C Showing minor local non-uniformity of adhesion of the blackened layer of Sample C in cross-section*

## 6 Evaluation of the layer resistance test and confirmation of the degree of blackening

The test of the resistance of the black layer shall be carried out in accordance with the control standard DIN 50938, point 7.5. After preparation (degreasing) of the surface, a drop of 5 % oxalic acid solution was applied to the samples with a laboratory pipette. The standard solution was applied to the samples for 8 minutes and after wiping, a colour difference was observed on the surface of the sample. All the three experimental samples showed adequate colour change, the visible black to brown-black target or pale grey rim visible on sample B is also permissible within the abovementioned prescription see in Fig. 16.


***Fig. 16*** *Test for confirmation of the degree of blackening on individual samples*

The test for confirmation of the degree of blackening of the layer was carried out in accordance with DIN 50938, paragraph 7.4. The surface of the samples was degreased, and a drop of a 20 % acetic acid solution was applied to the samples using a laboratory pipette. The exposure time was according to the standard 20 minutes. As in the previous case of the experiment, tolerable colour changes were observed on the surface of the samples, so that the degree of blackening (two-stage process) was confirmed by this test.

## 7 Results

In our experiment, the suitability of depositing thin films on all-calcible materials that are low or encounter alloyed was confirmed. For cemented components, on the other hand, our research has shown deteriorated properties of the blackened layer, which were particularly evident in the thickness of the resulting layer. This fact confirms the fact that the carbon already diffused in the layer by the previous cementation influences the course of further reactions on the surface of the material. For this reason, in practice it does not make sense to use a combination of different surface treatments, or a combination of diffusion coatings and subsequent blackening. From the obtained results of the chemical and structural analysis of the experimental part, we can conclude that under optimal conditions of the blackening technology and proper selection of the base material, this method of surface treatment is effective with respect to the requirements of bearing functionality.

Structural analysis of the black layer was performed using the SEM method of SE mode, and we evaluated the micromorphology and topography of the analyzed areas, focusing on the detailed microstructural characteristics of the material. In sample A, which was cemented, we observed an unevenly distributed occurrence of pores in he surface and subsurface region of the blackened layer. In sample B, a more frequent occurrence of microscopic pores of similar size was observed, which were uniformly distributed throughout the observed area. In the material labelled C, significant heterogeneity in the structure of the surface area was observed. The occurring pores tended to cluster; their distribution was non-uniform with an average size of 0.48 µm. After the analysis of the blackened layer, we evaluated the adhesion properties. We identified uniformity and continuity of the layer for all the coated materials investigated; the adhesion properties for all materials were in accordance with the prescribed specification for this method of treating functional surfaces.

Chemical analysis was performed on all three experimental materials in the layer region. The evaluation of the chemical composition confirmed the fact that in the case of the already cemented surface of the material, it is not possible to apply another, additional surface treatment method, since the presence of diffused carbon prevents further absorption of other chemical elements. In the chemical analysis of the blackened layer on the all-calcible materials, a higher occurrence of oxides was confirmed, thus confirming the higher blackening effect and efficiency of these materials.

A porosity and copper sulphate layer follow-up test were carried out and evaluated according to ISO 11408. No visible red dots were observed on the compared samples by this test, thus confirming satisfactory porosity of the layer. For the blackening process, it was necessary to perform a test of the layer resistance in accordance with DIN 50938, paragraph 7.5. According to the colour contrast, we visually evaluated that all three experimental samples showed an adequate colour change.

## 8 Conclusion

In general, surface treatment refers to any process that alters the physical or chemical properties of the surface of a material in order to increase the quality parameters. In addition to improving the appearance, mechanical and technological properties of the surface, the main role of coatings is to improve the resistance of the material to moisture and associated corrosion. As wind turbines are exposed to environmental influences, various surface treatments find their justification here. Unlike other surface treatments where a coating is applied to the steel surface, black oxide coating (blackening/bronzing) is the result of a chemical reaction between the ferrous metal and oxidizing salts. This means that where additional surface treatments are added to the metal surface and dimensions are increased, causing a reduction in g-tolerance during production, the black oxide coating has a negligible effect on the dimensional tolerances of the parts. This is of great benefit where tolerances are very important, such as threaded bolts, bearing housings, threaded holes or simply just internal machine components. They contribute to the improvement of the functional properties of the bodies and rings in mutual movement, act as a barrier against chemical damage and wear, which ultimately increases the service life of the bearings used in the main shaft of wind turbines. The surface layers must meet the prescribed parameters to achieve the highest possible quality, maintenance-free, safe, energy-efficient and, above all, environmentally friendly. The choice of metal material for this type of treatment is very important, since the properties of the layer depend on the base material on which the black was applied.

The experiment confirmed the suitability of applying thin layers to solid materials that are low or medium alloyed. In the case of cemented components, the research showed us the deteriorated properties of the black layer, which were mainly reflected in the thickness of the resulting layer. This fact confirms that carbon, which is already diffused in the layer by previous cementation, dampens the course of further reactions on the surface of the material. For this reason, it makes no sense to use combinations of different surface treatments, or combinations of diffusion surface treatments. From the achieved results of chemical and structural analysis, we can conclude that under optimal conditions of blackening technology and with the correct selection of the base material, this method of surface treatment is effective with respect to the requirements of bearing functionality. From the given results of the experimental part of the thesis, we can confirm that surface treatments have their importance in protection against wear in operating conditions. From an economic point of view, the aforementioned surface treatment method is advantageous, as it is time-, material- and technologically undemanding for a company engaged in the production and processing of bearing steels.

## References

[1] DOMINGUEZ, S., PEREZ BUENO, J.J., ZAMUDIO TORRES, I., MENDOZA LOPEZ, M.L. (2017). Characterization and corrosion resistance of electroless black Ni-P coatings of double black layer on carbon steel. In: *Surface and Coatings Technology,* Vol. 326, pp.192-199. DOI:10.1016/j.surfcoat.2017.07.044.

[2] FARMER, J., CHOI, J.S., SAW, CH., HASLAM, J., DAY, D., HAILEY, P., LIAN, T., REBAK, R., PEREPEZKO, J., PAYER, J., BRANAGAN, D., BEARDSLEY, B., D'AMATO, A., APRIGLIANO, L. (2009). Iron-Based Amorphous Metals: High-Performance Corrosion-Resistant Material Development. In: *Metallurgical and Materials Transactions*, Vol. 40, pp.1289-1305. DOI: 10.1007/s11661-008-9779-8.

[3] WANG., *L* . (2014). Use of structured surfaces for friction and wear control on bearing surfaces, In: *Surface Topography: Metrology and Properties*, Vol. 2, Number 4. DOI: 10.1088/2051-672X/2/4/043001.

[4] DU PLESIS, A., RAZAVI, N., BENEDETTI, M., MURCHIO, S., LEARY, M., WATSON, M., BHATE, D., BERTO, F.(2022). Properties and applications of additively manufactured metallic cellular materials: A review. In: *Progress in Materials Science*, Elsevier ,Vol. 125. DOI: 10.1016/j.pmatsci.2021.100918.

[5] LI, C., LI, J.C., ZHAO, M., JIANG, Q. 1(2009). Effect of alloying elements on microstructure and properties of multiprincipal elements high-entropy alloys, In: *Journal of Alloys and Compounds*, *Elsevier,* Vol. 475, pp. 752-757. DOI: 10.1016/j.jallcom. 2008.07.124.

[6] REGHURAJ, A.R., SAJU, K.K. (2017). Black oxide conversion coating on metals: A review of coating techniques and adaptation for SAE 420A surgical grade stainless steel, In: *Materials Today Proceedings,* Vol. 4, pp. 9534- 9541. DOI:10.1016/j.matpr.2017.06.219.

[7] HART, E., CLARKE, B., NICHOLAS, G., AMIRI, A.K., STIRLING, J., CARROLL, J., DWYER-JOYCE, R., MCDONALD, A.,

LONG, H.(2020). A review of wind turbine main bearings: design, operation, modelling, damage mechanisms and fault detection, In: *Wind Energy Science*, Vol. 5, pp. 105–124, ISSN: WES 2366-7451, WESD 2366-7621. DOI: 10.5194/wes-5-105-2020.

[8] BAKER, C. RAHNEJAT, H. (2010). 18 - Fundamentals of hydrodynamic journal bearings: an analytical approach. In: T*ribology and Dynamics of Engine and Powertrain*, pp. 591-614, Elsevier. ISBN 978-1-84569-361-9.

[9] ARTZ, E., QUAN, H., MCMEEKING, R.M., HENSEL, R. (2010). Functional surface microstructures inspired by nature – From adhesion and wetting principles to sustainable new devices. In: *Progress in Materials Science,* Vol. 120*,* Elsevier*,* 100823. DOI: 10.1016/j.pmatsci.2021.100823.

[10] POKORNY, Z., DOBROCKY, D., JOSKA, Z: (2020). The modification of surface of barrels by gas nitriding. In: *Manufacturing Technology,* Vol. 20, pp. 802-808. DOI: /10.21062/mft.2020.118.

[11] MUSTAFA AL-SARAIREH, M.:(2024). Experimental Investigation of Thermofriction's Impact on Surface Hardness of Steel Products'. In: *Manufacturig Technology*, Vol. 24, pp. 645-651. DOI: 10.21062/mft.2024.065.

[12] QIN, Z., WU, Y. T., EIZAD, A., LYU, S. K., & LEE, C. M. (2021). Advancement of mechanical engineering in extreme environments. In: *International Journal of Precision Engineering and Manufacturing-Green Technology,* No. 6, p. 1767-1782. DOI:10.1007/s40684-020-00295-3.

[13] DE LA PRESILA, R., WANDEL, S., STAMMLER, M., GREBE, M., POLL, G., GLAVATSKIH, S. (2023). Oscillating rolling element bearings: A review of tribotesting and analysis approaches. In: *Tribology International,* Vol. 188. DOI:10.1016/j.triboint.2023.108805.

[14] HANOZ, D., SETTIMI, G. A., DABALÁ, M. (2021). Characterization of black coating on Fe360 steel obtained with immersion in aqueous solutions. In: *Surfaces and Interfaces,* Vol. 26, Elsevier 101317. DOI: 10.1016/j.surfin.2021.101317.

[15] FARELL, R.W. Jr. (2007). Blackening of ferrous metals In: *Metal Finishing,* Vol. 105, pp. 390-396, DOI: 10.1016/S0026-0576(07)80358-8.

[16] REGHURAJ, A.RA., SAJU, K. K. B. (2017). Black oxide conversion coating on metals: A review of coating techniques and adaptation for SAE 420A surgical grade stainless steel. In: *ScienceDirect,* Vol. 4, pp. 9534–9541, Elsevier 10.1016/j.matpr.2017.06.219.

[17] FATTAH-ALHOSSEINI, A., YAZDANI KHAN, H., HEIDARPOUR, A. (2016). Comparison of anti-corrosive properties between hot alkaline nitrate blackening and hydrothermal blackening routes. In: *Journal of Alloys and Compounds,* Vol. 676*,* pp. 474-480, Elsevier. DOI: 10.1016/j.jallcom.2016.03.114.

[18] ZHONG CHENG, Z. (2003) Compound-layer blackening of steel at room temperatures. In: *Plating and Surface Finishing* , Vol. 90, pp. 49-50, ISSN03603164.

[19] ZHU, H., CAO, F., ZUO, D., ZHU, L., JIN, D., YAO, K. (2008). A new hydrothermal blackening technology for Fe3O4 coatings of carbon steel. In: *Applied Surface Science,* Vol. 254, pp. 5905-5909. DOI: 0.1016/j.apsusc.2008.03.184.

[20] MARCEK, L., VAVRO, jr., J., VAVRO, J. (2023). Microscopic analysis of selected materials used for hot water heating using SEM. In: *Manufacturing Technology,* Vol. 20, pp. 802-808. https://dou.org./ 10.21062/mft.2025.003.

[21] DRAJEWICZ, M., PRZYBYLO, A., JOPEK, J., GORAL, M., KOSCIELNIAK, B., OCHAL, K., KUBASZEK, T., GURAK, A., DYCHTON, K., WOZNIAK, M., KWASNIEWSKI, P., KAWECKI, A., GLUCHOWSKI, W., LAGODA., M. (2022). The Diffusion Coatings for Industrial Tool Application. In: *Manufacturing Technology*, Vol. 22, pp. 530-541. DOI: 0.21062/mft.2022.066.

[22] KAOUKA, A., ALLAF, H., KEDDAM, M., ALAOUI, O. (2022). Evaluating the Corrosion Be haviour of Borided Carbon Steel C35. *Materials Research* 25, 1-8.

[23] CHANG, Z., HU, L. (2021). Study on scatter of surface integrity of bearing raceway grinding. In: *Manufacturing Technology.* Vol. 21, pp. 781-787. DOI: 10.21062/mft.2021.090.