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Experimental Investigation of Thermofriction's Impact on Surface Hardness of Steel Products

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The impact of thermofriction on surface hardness has been investigated in this study, the surface of treated products is one indication of quality indicators. It has been noted that the thermal conductivity of the workpiece and tool material affects the irregular dispersion of heat in the processing zone. For evaluating the average integral rates of heating and cooling of the layer, the metal dependences have a significant impact on the form and properties of the friction-strengthened layer. It was found that when the feed rate increases, the hardened layer's depth decreases. The harder layer's depth increases as disk rotation speed (rpm) increases. when the disk rotation speed is increased to 265 rpm and the hardening depth (h) is 0.2 mm or less, it is said to be at N = (190-250) rpm. After heating the treated surface areas to a temperature between 130°C and 160°C above the critical temperature, the treated surface areas were then cooled applying compressed air to achieve the ideal surface hardness. After the hardening process, the surface hardness of blanks made of steel 1045 reached HRC 65, which is higher than conventional hardening.

Keywords: Surface hardening, Friction hardening, Mechanical properties, Surface quality, Wear resistance

1 Introduction

Machine parts, 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 [1].

The quality of the surface layer, which is influenced by several variables such as residual stresses, microhardness, waviness, physical and mechanical properties, and the microstructure of the metal, significantly impacts the dependability and durability of products [2]. One technique to raise the quality is to harden the outer layer.

Surface integrity describes the properties of a material after a manufacturing process or modification [3]. Product designers and engineers often focus their project development decisions on the well-known characteristics of a given metal [4]. These designers know, for example, that a specific steel alloy offers a specific strength or hardness. Since many production processes result in long-lasting modifications to the material, these original features might no longer hold once the material has been improved. When a material is predicted to change under particular conditions, engineers can compare the increased strength or moisture resistance, which are also seen as beneficial improvements to surface integrity [5]. Owing to surface integrity, attributes to the older ones [6]. The surface integrity of any material consists of two fundamental components. These are the features of the internal surface and the topography

Though this isn't always the case, most production procedures will eventually have an impact on surface integrity [7]. Routine milling, grinding, and lathe work do not compromise surface integrity when done properly. However, if these processes are done poorly or with antiquated machinery, they can drastically change the properties of the materials. Excessive heat, cold, speed, or work can also cause significant changes [8]. During more intrusive operations, the integrity of the surface is almost always affected [9]. The electro-treatments that give the metal a hard surface, such as plating, could be among them [9]. Chemical treatments are also possible. Almost any chemical treatment combined with high heat can modify the material at the molecular level, meaning that its structure will always be altered. The use of deformation procedures such as burnishing results in changes [10]. Changes in surface integrity may be advantageous or disadvantageous. The material may no longer be useful for the original function if there are detrimental alterations [11]. For example, a quenched steel column may eventually become too brittle to hold up a building. Adding a desirable finish or appearance to a material by techniques like burnishing can be considered a positive change. Increases in hardness [12], the proper operation of all the different current technologies depends on their processes operating efficiently on the special characteristics of certain solids. These features apply not only to a major subset of surface-related events but also to the bulk of a phenomenon.

This is especially true for wear-resistant components, which need surfaces capable of handling a variety of difficult situations and carrying out a broad range of technical functions. [13] Therefore, a material's behaviour is greatly influenced by its surface, surface contact area, and operational environment. The goal of surface science is to get a deeper understanding of surface properties and how they impact the operation of different components, systems, and machinery. A surface's basic definition is being the topmost layer [14]. To make materials softer and more resilient, surface hardening is a multi-step technique that prevents internal damage and increases wear resistance [15]. In components that require an exceptionally hard surface to withstand wear, such as a cam or ring gear, advantageously, this combination of a hard surface and resistance to fracture upon contact offers a robust interior that can sustain knocks that may arise during operation. Surface hardening also offers an advantage over hardening in that thick sections cannot be hardened, which results in distortion and cracking, and it can be done with less expensive low- and medium-carbon steels [16]. Three categories can be used to group the various surface-hardening methods:

Using thermochemical diffusion techniques, elements such as carbon, nitrogen, and boron are added to the surface to modify their chemical composition and make it tougher [17]. Diffusion methods are usually employed when a large number of elements need to be surface hardened since they harden the whole surface of the item.

Applying energy or heat alone, without the addition of new alloying species, produces hard quenched surfaces; the surface metallurgy is modified to enhance properties without changing the surface's chemical composition [18].

To change the chemical composition of the subsurface, surface modification techniques like ion implantation or surface coating purposefully apply a new layer to the steel substrate [19].

One method that can significantly improve the reliability, durability, and quality indicators of a part's surface layers is friction hardening at high sliding speeds [20]. It is well known that complex processes leading to the development of a distinct structurally stressed condition are caused by friction in the surface layer [21]. Friction-hardened layers are characterized by high hardness and flexibility. Their wear, fatigue, and corrosion resistance are much higher than those Workpieces by high-frequency currents [22]. The part's wear resistance on the machined surface is mostly determined by the depth of hardening distribution and the amount of residual stresses in the surface layer. Many methods of hardening have been developed. Surface plastic deformation, chemical-thermal treatment, and surface hardening are the categories into which these can be divided [23]. Thermofriction hardening falls under the last category; it allows surface layer quality enhancement without requiring expensive methods or tools.

The metal being treated is subjected to mechanical and thermal impacts when it comes to direct contact between the workpiece and a friction disk rotating at a high peripheral speed [24]. Heat treatment is applied to the material in the contact zone, and temperature and applied pressure cause the friction surfaces to deform. Friction-hardened layers exhibit higher hardness, microhardness, and elasticity values. They exhibit considerably higher resistance to wear, fatigue, and corrosion as compared to layers toughened by high-frequency currents [25]. Temperature is the most important factor in thermofriction hardening. It has a major impact on wear, friction disk resistance, product quality, and precision. Depending on the processing conditions, the temperature in the contact zone can range from 900°C to 1200°C; this is higher than the temperature at which the majority of processed materials recrystallize. It encourages the cutting zone to become more malleable and less resistant to deformation. Hot deformation typically looks like this. The zone's temperature is known to be The rotating object's peripheral speed is impacted by friction. disk, components, feed, lubrication, and contact area [26].

Phase transition during frictional hardening complicates the mechanism of carbon steel, especially hypoeutectoid steel. Rapid heat buildup at the friction interface may occur when the revolving disc runs across the surface of primary cementite (Fe_3C). Following frictional hardening, the cementite dissolves into the ferrite phase (α), and the sample's hardness is influenced by its ratio. This phase change behavior is highly complex and unstable, and it is dependent on a number of factors, including cooling medium, friction pressure, and rotation speed. Several studies successfully reduced the residual austenite and stabilized the microstructures of 1045 steel by utilizing various cooling techniques.

The lack of appropriate research has restricted the application of thermomechanical hardening in industry.

The most crucial element of thermofrictional hardening is cutting temperature. It significantly affects the precision and quality of the products as well as the wear and resistance of the friction disk.

2 Methodology

A horizontal X6140 milling machine was utilized for the research. To regulate the speed of the disc and the feeding of the piece, a 30-cm diameter steel disc was installed in place of the cutting tool, and the piece to be processed was fixed in the milling table.

Additionally, thermocouples have been embedded into the sample to monitor its temperature throughout the process.

Fig. 1 illustrates a method of treating surfaces with a hardening disk. It is based on the synthesis of two ideas regarding the relationship between the tool and the processed object, throughout the cutting operation, sliding warms the contact zone while the blade is moving tangentially. The rotational axis O of the structural steel hardening disk 1 runs parallel to the processing plane [21]. With a rotational speed of N rpm, the disc experiences primary motion (rotating motion), while Workpiece 2, mounted in a fixture or on the machine table, gets translational motion at an f_{WP} feed rate (mm.sec^{-1}). If the width of the hardening disc is smaller than the width B of the machined surface, the operation is performed in separate strips over many passes. Here, a periodic feed is also applied to the disc (or workpiece) in the direction of the workpiece's breadth.

The chemical composition of high-speed cutting tools and workpieces should be characterized because commercial tools differ from standard ones. An SEM-EDX device (Scanning Electron Microscopy - Energy Dispersive X-Ray Analysis, company: FEI, Model: Quanta 600) was utilized. In tables (1 to 4) given the chemical composition and mechanical properties of steels 1045 and 1050.

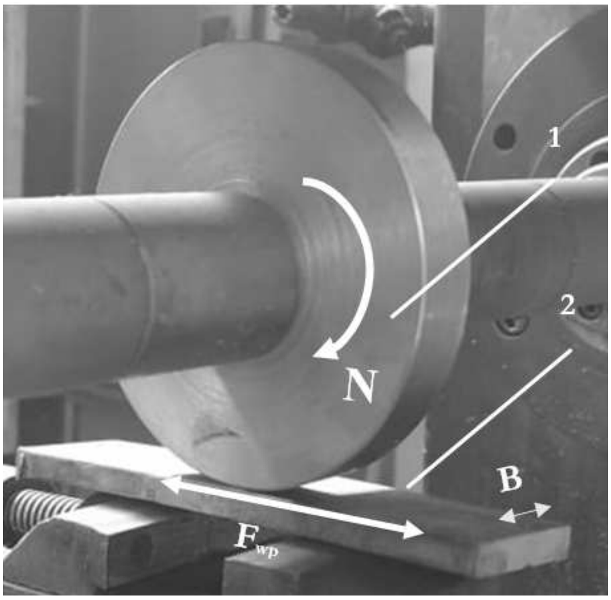

Fig. 1 *The hardening disc with the workpiece; 1. hardening disc, 2. workpiece*

Tab. 1 *Steel 1050 (disc) chemical composition*

C	Si	Mn	S	P	Cr
0.48	0.33	0.7	0.03	0.034	0.24

Tab. 2 *Steel 1050 (disc) mechanical characteristics*

Limit of creep, (MPa)	Tensile strength in the short term (MPa)	Min elongation ratio σ, %	The ratio of contraction, %
354	601	17	41

Tab. 3 *The workpiece's (1045 steel) chemical composition*

C	Si	Mn	P	Ni	Cr	S	Cu	As	Fe
0.55	0.27	0.6	0.031	0.19	0.21	0.03	0.16	0.05	0.95

Tab. 4 *Mechanical characteristics of 1045 steel (workpiece) after normalizing*

Min yield strength, MPa	Min temporary resistance, MPa	Min elongation, %	Min relative contraction, %
374	631	15	41

Through analysis, it was found that the depth, and microhardness of the hardened layer-all indicators of its quality-were affected by the processing technique as well as individual features. Structural stress conditions, roughness, and physical and mechanical properties.

3 Results and discussion

Fig. 1 depicts the hardened disk operating scheme. The high circumferential speed of the revolving disk, ranging from 80 to 140 m.sec^{-1}, produces thermal energy in the friction zone to reach a particular toughened layer depth. Increased disk rotation speed results in a deeper hardened layer. At N = 120–170 rpm, at a disk rotation speed of 260 rpm, up to 2.5 mm of hardened surface can be formed. At N = (190–250) rpm, the hardening depth (h) is 0.7 mm or less.

Figures 2 and 4 illustrate the correlations between the metal temperature in the contact zone, feed rate, allowance, and the depth of the hardened layer. The analysis of the relationship between the feed rate and layer depth graphically shows that as the crush rate increases, the value of the hardened layer decreases (Fig. 2). Heat accumulation causes the surface layer of the workpiece to temper because hard materials take longer to be processed at feed rates less than 2 $mm.sec^{-1}$ than at feed rates more than 30 $mm.sec^{-1}$.

Here, the depth of the hardening layer is extremely shallow. As a result, the study has shown that the hardening depth is between 0.6 and 2.4 mm, and the workpiece's feed rate throughout the process should be within 3 to 30 $mm.sec^{-1}$ when a disk is rotating at 150–230 rpm. As the feed rate rises, the hardened layer's depth decreases.

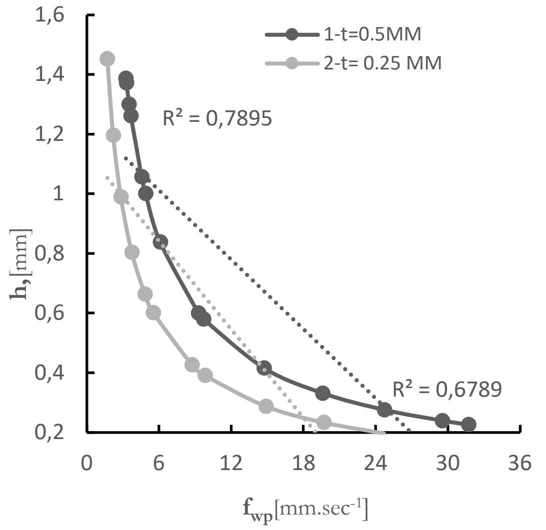

Fig. 2 *The hardened layer h and the workpiece's feed rate f_{wp} relationship*

In this case, the depth of the hardened layer increases as the depth to be removed (t) increases due to an increase in heat release power that raises the temperature throughout the contact zone (Fig. 3). The more the depth to be lowered, the larger the area of contact between the disk and the workpiece, and a decrease in the heat flow density causes the depth of the hardened layer to rise somewhat. Investigation of the variations in the hardened layer's thickness.

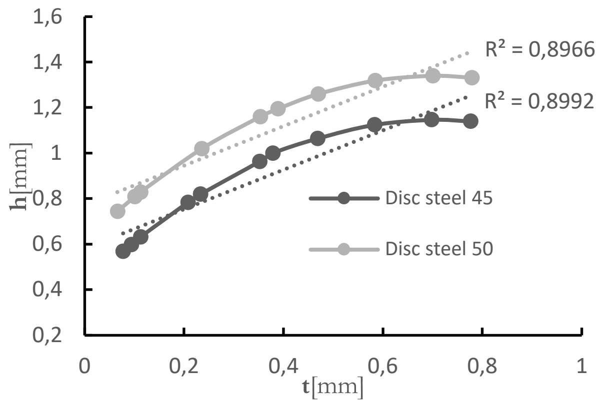

Fig. 3 *Relationship between allowance t and the hardened layer's depth.at feed rate f_{wp} of 8 $mm.sec^{-1}$*

Fig. 4 illustrates the relationship between the contact zone temperature and the hardened layer's depth when steel 1045 workpieces are treated at different feed rates. We could conclude from our analysis of the data that temperature plays a critical role in identifying the best disk hardening options.

Because heat is distributed throughout the workpiece, not just in its depth but also along its sides, it has been found that the width of the hardened layer differs depending on the feed rate and thermophysical properties of the disk. When the coefficient of thermal conductivity of the disk material decreases, the hardened layer's width increases. As the feed rate of the workpiece increases, the hardened layer becomes narrower.

The percentage of carbon in the workpiece, the disc's and its material's thermal conductivity, and plastic deformation all contribute to the hardened surface's increased hardness. The heated surface reaches a temperature where austenite is formed, and rapid cooling transforms it into martensite.

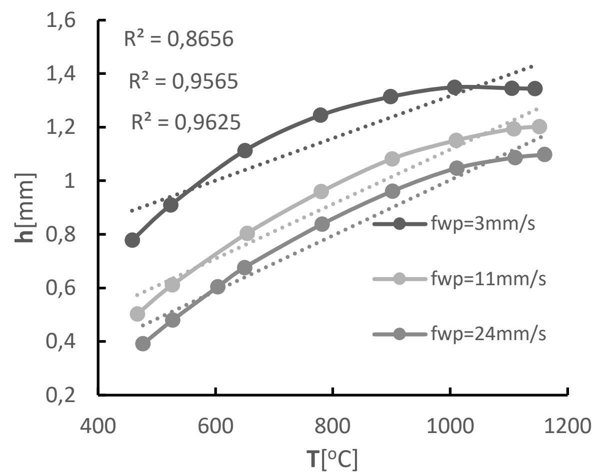

Fig. 4 *The relationship between the hardened layer's depth and the contact zone's temperature (The workpiece is steel 1045; the disk is steel 1050) 1- f_{wp} =3$mm.sec^{-1}$. 2- f_{wp} =11$mm.sec^{-1}$. 3- f_{wp} = 24$mm.sec^{-1}$)*

As previously indicated, the disk's thermal conductivity affects the metal's temperature in the contact zone, which in turn affects the hardened layer's hardness. Much of the hardness and deformation of the martensite temperature lattice is determined by the carbon content of the treated metal, which also has a greater effect on the hardness of the hardened surface. The study's findings indicate that blanks formed of steel 1045 have a higher surface hardness after the hardening process reaches HRC 65 than applying traditional hardening, at high heating, deformation, and cooling rates, the crystal structure, stress state, and phase composition deform when exposed to high temperatures in the contact zone. There is an increase in the surface layer's carbon content due to its diffusion from deeper layers. Furthermore, according to the researchers' experimental testing, the average hardness values are constant within the f_{wp} = 3.1...27.5 mm.s^{-1} range of the feed rates examined.

Once thermal friction hardening is complete, the workpiece's surface layer exhibits two zones. With a high hardness HV of 836 for steel 1045, the first one is located at a depth of up to 1.3–1.8 mm, closer to the surface. With an increase in the amount of time needed for carbon burnout and hardness heating, the pro surface decreases because of the second zone's deeper microhardness.

Thus, we may conclude that the thermofriction hardening of steel causes the production of a new kind of structure after carefully examining the results that were obtained. The surface layer steel samples undergoing thermofriction hardening strengthening showed this structure. This layer's structure is irregular, with small, spherical grains that are somewhat extended along the same axis. The term "deformed granular martensite," which captures the essence of this microstructure, can be used to categorize it as a novel kind of structure. Such a structure's creation is described by the severe effect on the material during thermofriction hardening when strain and heat hardening take place at the same time. The kinetics of this process involve the influence of deformation on the surface layer's structure during the short-term heating phase of thermofriction hardening. It is my opinion that the most efficiency is attained when the structure is initially martensitic (that is, after hardening). Additionally, even if the martensitic structure is incapable of accepting hardening, this option is made possible by its brief heating during thermofriction hardening. This can be explained by the fact that, like any diffusion process, the open-hearth sieve's structure is nonequilibrium and will tend to disintegrate under heating circumstances. This could happen after a certain amount of time. Heating and cooling at thermofriction hardening happen so quickly that surface diffusion processes aren't given enough time to begin. Consequently, the tempered martensite structure that was produced by the earlier thermal processing (hardening and low-temperature tempering), because of the rapid thermofriction hardening process, does not dissolve with the creation of the tempered sorbitol structure and does not enter the austenitic state when heated above Ac_1. Simultaneously, during thermofriction hardening, the deformation energy supplied to the surface layer under the deformation effects of a spinning tool pulses the martensite structure, causing distortion and fragmentation. Furthermore, it only goes as deep as the material was heated to a temperature exceeding 350 °C at the time of deformation—that is, temperatures at which the martensite structure's breakdown process starts whether there is enough time for this. This also explains why the reinforced layer's characteristics and structure remain stable throughout the depth.

The wear resistance was tested on steel 1045 samples, whose flat surfaces experienced severe friction hardening. The test findings were contrasted with experimental tests of comparable components that had undergone successful normalization and had the same surface characteristics. Thermofriction-hardened components feature surfaces that are 4-5 times more wear-resistant than non-hardened components, according to the experiments. During the test, the part's surface was toughened by highly compressed air blowing because of the usage of a blower and the airflow created by a rapidly revolving disk. Heating was done at temperatures of 100 and 150 degrees Celsius over the minimum. The temperature of the workpiece was measured in several places using thermocouples According to experimental data, treated surface areas heated to between 130 °C and 160 °C over the critical temperature are best attained when cooled with compressed air. This gives the best surface quality indicators. For a low cost, the proposed method promises to raise the treated materials' quality surface indicators. By analyzing data on the impacts of peripheral speed rotation, feed, materials, lubrication, and contact area on the value of the cutting temperature in the friction zone in the workpiece and tool, one can ascertain the quantitative relationship between the metal's thermal conductivity, the temperature gradient, and the heat flow. It has been determined that the thermal conductivity of the workpiece and tool materials affects the unequal distribution of heat in the treatment zone. The average integral rates of heating and cooling of the metal layer can be used to calculate their influence on the structure and properties of the friction-strengthened layer. It is shown that processing methods determine the heat flux density and power functions of the set during the hardening process.

Fig. 5 shows the Vickers hardness according to distance from the hardened surface.

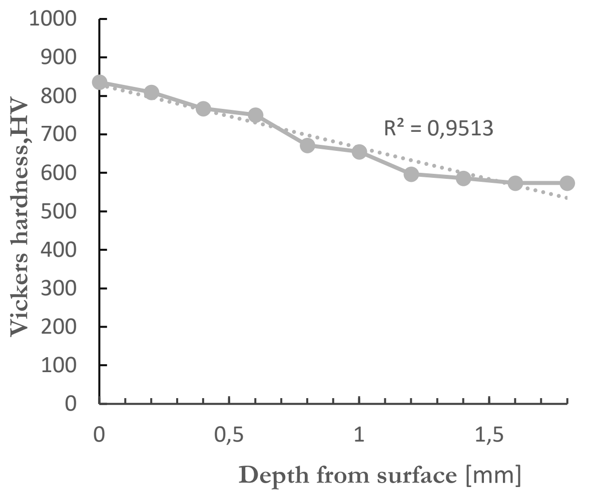

Fig. 5 *Vickers hardness according to distance from the hardened surface*

The workpiece is first heated to an appropriate temperature to regulate the final microstructure. This is the first step in the normalization process. The troublesome active area of 1045 steel can typically be grain-coarsened and internal tension reduced at temperatures between 900 and 950 °C. Subsequently, this temperature was maintained for the workpiece until it was heated evenly. By lowering the workpiece's heating rate, surface decarburization can be prevented, which is otherwise known as overheating the workpiece. In addition, a suitable temperature and a slow, sufficient holding period will facilitate the carbon's diffusion from the carbide to the ferrite and pearlite, giving the internal stress resulting from the phase transition enough time to dissipate. After the workpiece is ferritic, it is transferred to the air and gradually cooled to below the ferrite transition temperature. "Soaking" refers to this gradual cooling procedure. Grain coarsening and more carbon atom diffusion from martensite to austenite cause the hardenability system 1045 steel's internal stress to drop. The workpiece cools rapidly to room temperature through air cooling after the temperature falls to the pearlite transition temperature. Air cooling is the process that this uses. It causes the austenite to transform rapidly at room temperature, and the hard martensite structure is formed. The main goal of the induction hardening treatment is to gain a workpiece with an even hard layer on its surface and a tough core inside. The mechanical characteristics and microstructure development of 1045 steel after austenitization under air cooling were the main subjects of the current study. It is expected that a thorough treatment guide for 1045 steel will be available upon comparison of all these approaches.

4 Conclusions

- The study conducted made it possible to establish the high efficacy of thermofriction hardening as a technological guarantee for the surface layer's quality and the machine parts' operational attributes.
- It has been shown that temperature affects the relation between the contact's mechanical and functional characteristics, which, when disks and workpiece surfaces interact, are mainly responsible for the results. Temperature must be carefully taken into account when selecting the best disk hardening solutions.
- The metal disk method forms a hardened layer at a certain depth that has the required physical mechanical properties when used to harden the surfaces of products.

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References

[1] QIN, Z., WU, Y. T., EIZAD, A., LYU, S. K., & LEE, C. M. (2021). Advancement of mechanical engineering in extreme environments. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 1-16.

[2] ULUTAN, D., & OZEL, T. (2011). Machining induced surface integrity in titanium and nickel alloys: A review. *International Journal of Machine Tools and Manufacture*, 51(3), 250-280.

[3] THAKUR, A., & GANGOPADHYAY, S. (2016). State-of-the-art in surface integrity in the machining of nickel-based superalloys. *International Journal of Machine Tools and Manufacture*, 100, 25-54.

[4] LIKER, J. K., SOBEK, D. K., WARD, A. C., & CRISTIANO, J. J. (1996). Involving suppliers in product development in the United States and Japan: Evidence for set-based concurrent engineering. *IEEE Transactions on Engineering Management*, 43(2), 165-178.

[5] AL-SARAIREH, F. M. (2023). Experimental Study on the Effect of Oxidation on the Compressibility of Iron Powder. *Manufacturing Technology*, 23(3), 319-325.

[6] SUTKA, J., & KONAR, R. (2023). The Effect of Mixing the Additive Material with the Substrate during the Renovation of the Foundry Mold by TIG Welding Hardfacing. *Manufacturing Technology*, 23(3), 341-347.

[7] LIPIŃSKI, T. (2023). Influence of Impurity Morphology on the Fatigue Strength of High-Purity Structural Steel Melted in an Electric Furnace. *Manufacturing Technology*, 23(1), 53-59.

[8] BURAWOY, M. (1982). Manufacturing consent: Changes in the labor process under monopoly capitalism. University of Chicago Press.

[9] YANG, S., ET AL. (2013). Effect of cryogenic burnishing on surface integrity modifications of Co-Cr-Mo biomedical alloy. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, 101(1), 139-152.

[10] MANDAL S, THANGARASU S, THONG PT, KIM SC, SHIM JY, JUNG HY. Positive electrode active material development opportunities through carbon addition in the lead-acid batteries: A recent progress. *Journal of Power Sources*. 2021 Feb 15; 485:229336.

[11] UDDIN, M., HALL, C., SANTOS, V., VISALAKSHAN, R., QIAN, G. AND VASILEV, K., 2021. Synergistic effect of deep ball burnishing and HA coating on surface integrity, corrosion, and immune response of biodegradable AZ31B Mg alloys. *Materials Science and Engineering: C*, 118, p.111459.

[12] ZEIN EL-DIN AM, YOUSSEF TAHA RM, ABDEL HAMIED RG. Nanotechnology Sector Applications in Power and Farm Machinery: A Review. *Journal of the Advances in Agricultural Researches*. 2021 Jun 1;26(2):38-47.

[13] LIAO Z, LA MONACA A, MURRAY J, SPEIDEL A, USHMAEV D, CLARE A, AXINTE D, M'SAOUBI R. Surface integrity in metal Machining-Part I: Fundamentals of surface characteristics and formation mechanisms. *International Journal of Machine Tools and Manufacture*. 2021 Mar 1; 162:103687.

[14] ZHAI W, BAI L, ZHOU R, FAN X, KANG G, LIU Y, ZHOU K. Recent progress on wear-resistant materials: designs, properties, and applications. *Advanced Science*. 2021 Jun;8(11):2003739.

[15] VAISHNAVI B, ADHIYAMAAN A, GABRIEL DJ, CHANDRASEKAR VK. Wear and Hardness Behavior of Duplex-Treated AISI 1045 and AISI 4142 sheets of steel. *Advances in Micro and Nano Manufacturing and Surface Engineering* 2023 (pp. 235-244). Springer, Singapore.

[16] UNUNE DR, BROWN GR, REILLY GC. Thermal based surface modification techniques for enhancing the corrosion and wear resistance of metallic implants: A review. *Vacuum*. 2022 Jun 29:111298.

[17] SARIKAYA M, GUPTA MK, TOMAZ I, PIMENOV DY, KUNTOĞLU M, KHANNA N, YILDIRIM ÇV, KROLCZYK GM. A state-of-the-art review on tool wear and surface integrity characteristics in the machining of superalloys. *CIRP Journal of Manufacturing Science and Technology*. 2021 Nov 1;35:624-58.

[18] QI J, GUAN D, NUTTER J, WANG B, RAINFORTH WM. Insights into tribofilm formation on Ti-6V-4Al in a bioactive environment: Correlation between surface modification and micro-mechanical properties. *Acta Biomaterialia*. 2022 Mar 15;141:466-80.

[19] JIANG T, KIM HS. Simultaneous improvement in the hardness and friction characteristics of Ti-6Al-4V through laser cladding with nanoscale SiC particles in an air environment. *The International Journal of Advanced Manufacturing Technology*. 2021 Sep;116(3):1041-51.

[20] GREINER C, GAGEL J, GUMBSCH P. Solids Under Extreme Shear: Friction-Mediated Subsurface Structural Transformations. *Advanced Materials*. 2019 Jun;31(26):1806705.

[21] PALIERSE E. Development of a hybrid coating associating biomimetic hydroxyapatite and natural antibiotics with antibacterial properties (Doctoral dissertation, Sorbonne université).

[22] CHENG Y, DING Y, GUAN R, GAI X, JIN Y, LU M. Simulation and Experimental Study of Tool Wear and Damage in Milling SA 508III steel. *Surface Topography: Metrology and Properties*. 2022 Sep 8.

[23] KUSMIČ, D., ČECH, O., & KLAKURKOVÁ, L. (2021). Corrosion Resistance of Ferritic Stainless Steel X12Cr13 After Application of Low-Temperature and High-Temperature Plasma Nitriding. *Manufacturing Technology*, 21(1), 98-104.

[24] GUO, S., ZHENG, H., LIU, X., & GU, L. (2021). Comparison of Milling Force Model Prediction of New Cold Saw Blade Milling Cutter Based on Deep Neural Network and Regression Analysis. *Manufacturing Technology*, 21(4), 456-463.

[25] SEDLÁK, J., HRUŠECKÁ, D., CHROMJAKOVÁ, F., MAJERÍK, J., & BARÉNYI, I. (2021). Analysis of the wear on machined groove profiles using reverse engineering technology. *Manufacturing Technology*, Vol. 21(4), 529-538.

[26] DU, F., HE, L., ZHOU, T., TIAN, P., ZOU, Z., & ZHOU, X. (2022). Analysis of droplet characteristics and cooling lubrication effects in MQL milling of 316L stainless steel. *Journal of Materials Research and Technology*, 19, 4832-4856.