Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2023, 17(1), 160–172
https://doi.org/10.12913/22998624/157422
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Received: 2022.12.04
Accepted: 2023.01.17
Published: 2023.02.01

Surface Texturing on a CNC Machine Tool Using a Laser

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ABSTRACT

In the paper stages of the process of constituting a surface with the texture of the injection mold of a wheeled vehicle steering wheel using laser technology was discusses. During micromachining process with texturing there is a 5-axis CNC-controlled CNC machine TOOL LASERTEC 65 Shape used with a rigid monoBLOCK structure with Siemens 840D sl control, equipped with a fiber laser with a power of 100 W, a wavelength of 1064 nm and a focal length of 181 mm. Processing technology was prepared using Autodesk Maya, Adobe Photoshop, Adobe Illustrator, NX9, Lastex v. 2.27.26 computer programs and machine tool control systems. Results of machining the steering wheel of a wheeled vehicle with a concentrated laser beam are discussed. Geometric structure of the surface after texturing was evaluated. Presented technology can be used to obtain the desired texture properties on the surface of the parts.

Keywords: laser micromachining, laser surface texturing, CNC machine tool, surface topography.

INTRODUCTION

Intensification of the working functions performed by the use of machines, such as lubrication, heat replacement, activationof the chemical surface or stimulation of micro-transmissions is possible due to structuralization of the surface geometry of the product [1-3]. Ability to process complex textures on the surfaces of products, often with complex shapes, requires the use of technology characterized by very high accuracy. One of the solutions that allows you to give specific geometric features to surfaces with high accuracy is laser texturing. Laser texturing gives the machined surface the final texture [4].

Laser texturing is the removal of material due to the directed, controlled and controlled action of a concentrated laser beam, during which thermal melting and evaporation occurs [5].

In a situation of insufficient surface density of energy, there is a relatively slower increase in the temperature value of the material and weakening of the bonds under the influence of thermal vibrations, which may lead to thermal melting and evaporation of the material [6]. Size of the heat zone is determined by the duration of laser pulses, which affects the quality of micromachining. Treatment with long pulses leaves clear traces of melting and structural and visual changes of the surface as a result of heat. In contrast, ablation induced by picosecond and femtosecond pulses is called the cold ablation, which does not induce a significant heat zone in the material [7].

Surface texturing has been recognized as an effective way to engineer surfaces to improve the tribological properties of sliding surfaces, which is one of the basic characteristics for materials [9-12]. Laser texturing makes it possible to increase the durability of kinematic pairs, improve the performance and efficiency and quality of motion joints. Hu et al. used a laser to produce patterns of microcavities of varying density on the surface of Ti-6Al-4V titanium alloy [13]. Overarching goal of the study was to determine the effect of indentation density on the course of dry friction of titanium alloy and under conditions of MoS_2 lubricant. With dry friction, it was shown that a textured surface with a higher density of pits had lower coefficients of friction only at low load and speed. After applying a solid lubricant, some textured samples showed good tribological properties for all applied loads. Brawn et al. conducted tribological tests on a pin-on-disk tribotester on textured steel samples. The experiments were conducted under sliding friction conditions at 50°C and 100°C. Authors proved that the friction reduction depends on the size of the texture indentations used (40–200 μm), the sliding speed and the temperature of the lubricant [14]. The overriding goal of surface texture formation in both cases discussed is to reduce friction resistance and wear of mating parts.

Surface texturing machining processes are also used to impart specific functional and aesthetic qualities to surfaces, which is now a mainstay of industrial design [15]. An example of this is achieving high surface hydrophobicity. Yilbas et al. dealt in their work with laser texturing of aluminum oxide surfaces to increase surface hydrophobicity. The shielding gas used in this process, according to the authors, causes the presence of AlN on the surface, which helped to enhance its hydrophobicity [16]. Control of surface wettability is very important and useful in many industrial and utility applications, which can be realized by simultaneously controlling the surface chemistry and microstructure. Wang et al. in their work demonstrated the possibility of controlling the wettability of a titanium alloy surface through laser texturing. They indicated the possibility of obtaining a surface ranging from hydrophilic to hydrophobic [17].

Texturing has applications including automotive, polymer processing, medicine (e.g., car cockpit dies and molds, sports equipment handles, specialized medical components, etc.) [18-20]. Madeira et al. dealt with laser texturing in their work by performing microgrooving on the surface of zirconium oxide used for dental implants. In their work, they proposed texturing with microgrooves in order to achieve an effective and tight seal between the artificial soft tissue and the surface of the implant, thus achieving protection against bacteria. The authors found that the strength of adhesion between the soft tissue and the surface with microgrooves is strongly dependent on their depth and width. It was shown that making microgrooves on the zirconia surface increased the adhesion of soft tissue to its surface significantly [21]. Zhan et al. in their work dealt with laser texturing of the cylinder walls of internal combustion engines. They found that the coefficient of friction and cylinder wear after laser texturing decreased by 50% and 85.7%, respectively, and piston ring wear decreased by 50%. The experiment was conducted under fully lubricated conditions [22]. The working surfaces of plastic injection molds are textured using techniques such as chemical etching or EDM (Electrical Discharge Machining). Soveja et al. in their work dealt with surface laser texturing of TA6V alloy molds. According to them, the energy and frequency of the laser pulse are the most important operational factors of the texturing process. According to the authors, the replacement of traditional technologies with laser texturing introduces, among other things: high flexibility of the process, there is no mechanical contact with the tool, there is a smaller leach volume, high precision of processing even for injection molds of even complex shape [23].

Owing to the development of technologies using a concentrated stream of energy – a laser beam (an electromagnetic wave that exhibits both temporal and spatial coherence – allowing to obtain a high concentration of energy (both in terms of area and time of impact on the workpiece material), which, in conjunction with the kinematic capabilities of multi-axis CNC machine tools and computer aided design programs for machining technology, creates great opportunities for the constitution of the surface topography of manufactured parts [24, 25]. Cho et al. in their work dealt with the texturing of polyoxymethylene surfaces using a CNC machine tool. Authors obtained the lowest coefficient of friction at a texturing density of 10%, where the friction reduction was about 50% compared to the non-textured material [26]. At present, one can venture to say that laser texturing of surfaces on CNC machine tools will make it possible to replace the scraping process used so far, which is used, among other things, by many machine tool companies (and others) to constitution the surface geometry of guideways [27]. Laser machining, often referred to as laser micromachining in the literature, is becoming increasingly popular and, more importantly, more accessible to users. This is partly because machine tool companies are increasingly offering machines with implemented laser micromachining technology in their commercial offerings. By controlling the surface topography achieved by laser interaction, it is possible to work at higher sliding speeds and pressures than is possible with non-textured parts [28]. It has also been shown that the surface texturing process allows for increased resistance to galling, including wear through fretting [29]. Laser texturing processes are also important wherever the adhesive properties of surface layers are important (joining of materials by various techniques, application of various coatings, printing technologies, chemical as well as biological activity of surfaces, etc.) [30]. In their work, Caro-Lara et al. dealt with the initial suppression of adhesion of Variovorax sp. biofilm-forming and copper-tolerant bacteria on copper surfaces subjected to laser microtexturing. They indicated that surface microtexturing represents a new approach to inhibit biofilm growth by preventing the initial stages of bacterial adhesion to surfaces. Their work examines the effect of linear copper texturization on the initial stages of adhesion. Linear patterns with periodicities of 4.7, 6.8, 14 and 18 µm were used. The periodicity of 4.7 µm was found to be the most effective pattern for suppressing the adhesion of Variovorax sp. Initial adhesion of the biofilm was 31.1 percent lower compared to the non-textured surface [31].

Laser micromachining is a technology used wherever high dimensional accuracy is required as well as for materials that are difficult to machine or impossible to machine with other mechanical technologies [32,33]. Micro-texturing of surfaces was dealt with in their work by Deshmukh et al. Ultra-short laser pulses, according to the authors, can produce controlled ablation and macro-texturing of surfaces. According to the paper, laser-induced surface texturing is a more accurate and cost-effective solution for improving tribological properties and cutting tool performance compared to traditional machining techniques [34]. Surface texture strongly influences the performance of workpieces, including tribological properties [35]. Assessing the geometric structure of a surface requires 3D parametric analysis. Three issues usually arise in surface topography analysis: parametric surface evaluation, surface representation and technical implementation of measurement. Parameters related to the area of the analyzed surface are most often used for evaluation [36].

The goal of investigations was to analyse the geometric structure of the different textured surface obtained by laser technology.

MATERIALS AND METHODS

Subject of the developed technology for a machine tool with CNC LASERTEC 65 Shape laser technology, is the geometric texture of the surface of the steering wheel of a wheeled vehicle. In the indicated object, the performance of the texture has an important ergonomic and functional justification. Steering wheel surfaces of a circular vehicle have quite a variety of micro-geometries, mainly due to considerations related to a stable and secure grip, preventing the hand from slipping around the circumference of the steering wheel and at the same time a comfortable and ergonomic grip. They are produced mainly by injection molding. Until now, the most common technology for texturing usable parts, such as handles and steering wheels, for example, has been EDM (Electrical Discharge Machining). Laser machining is the latest technology and a new quality in the texturing process. Using laser micromachining technology to texture the surface of the steering wheel matrix of a wheeled vehicle, it is possible to incorporate all the features that a proper design project should contain. A semi-finished steering wheel matrix of a wheeled motor vehicle was the subject of laser processing, as shown in Figure 1.

Material used was aluminum 7075. It is characterized by high strength properties, very good thermal conductivity and medium corrosion resistance, as well as very good machinability and polishability. Among other applications, it is used for blow molds and injection molds. For the chemical composition of aluminum 7075, see Table 1.

For laser micromachining, a 5-axis CNC LASERTEC 65 Shape rigid monoBLOCK machine tool with Siemens 840D sl control was used, equipped with a 100 W fiber laser, 1064 nm wavelength and 181 mm focal length (Figure 2). This machine tool allows for hybrid processing of molds and dies, among other things. Flexible integration of the laser head via an HSK interface allows laser texturing and milling processing on a single machine. Machining technologies were prepared using computer software, using programs such as Autodesk Maya, Adobe Photoshop, Adobe Illustrator, NX9, Lastex v. 2.27.26 and machine tool control system programs.

Fig. 1. Object of machining – semi-finished die of the steering wheel of a wheeled motor vehicle

Alicona's InfiniteFocus G5 optical 3D measurement device was used to measure and evaluate the geometric structure of the textured surface. Assessment was made for four different texturing patterns. Basic surface roughness parameters Sa, Sq, Sz, Sp, Sv, Ssk and Sku were considered for analysis.

RESULT AND DISCUSSION

Texturing matrix surface of wheeled motor vehicle's steering wheel

In the first stage of the design process, a reverse engineering technique was used to create the ideal geometry of the steering wheel matrix of a wheeled motor vehicle. A very important and required feature of the analyzed steering wheel is the surface texture. Particularly important are the anti-slip areas for safety and comfort while driving. In addition, in addition to functional characteristics, attention was paid to modern appearance (design). Texture of the surface of the steering wheel matrix of a wheeled motor vehicle was determined, as well as the distribution of its elementary geometric features. Since a laser machining method was used to create the texture, some subtle geometric features, impossible to be produced by other techniques, were incorporated into the geometry. In order to minimize the fabrication of the test specimens, four different textures were used, distributing them around the perimeter in the central part in four sections on both the lower and upper matrix as mirror images. A rhombic texture, a spherical bowl texture, a fuzzy texture and a square texture were used. One of the sections was left untreated in order to better visualize and expose the made textures, as well as to evaluate and compare the geometric structure. A view of the surface of the steering wheel matrix of a wheeled motor vehicle with the fabricated textures is shown in Figure 3.

Preparation of the processing technology required the use of graphic computer programs for both vector and raster graphics. Autodesk Maya program made it possible to develop the surface to be textured (Fig. 4). Thereafter, the resulting image was further processed in Adobe Photoshop and Adobe Illustrator obtaining the desired appearance, as shown in Figure 5. The texture is projected in grayscale tones, and the processing information is encoded in the tonal transitions of the image, as shown in Figure 6. Visualization

Table 1. Chemical composition of 7075 aluminum alloy (according to PN EN 573-3 standard)

Element (wt.%)								
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr
Max 0.40	Max 0.50	1.20-2.00	Max 0.30	2.10-2.90	0.18-0.28	5.10-6.10	Max 0.20	-

Fig. 2. Machining station – LASERTEC 65 Shape SAUER machine tool

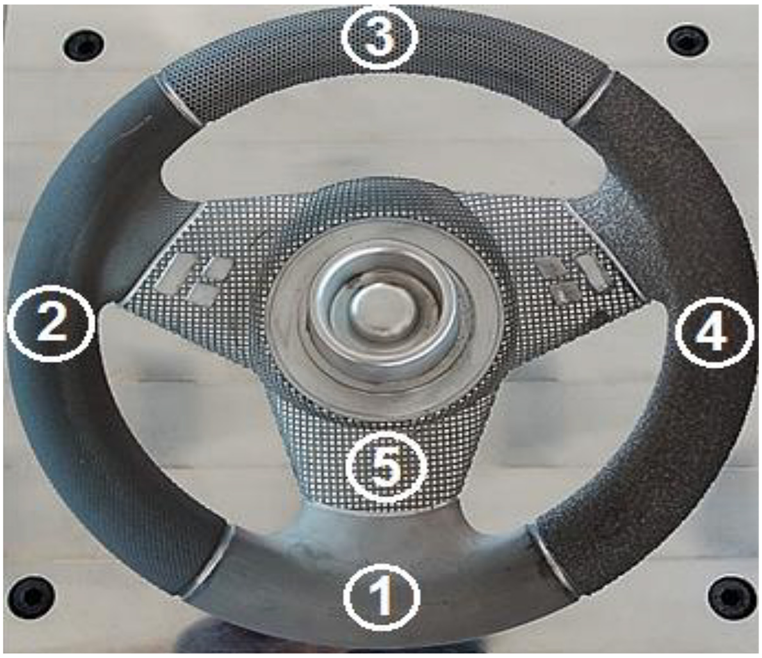

Fig. 3. View of the matrix surface of the steering wheel of a wheeled motor vehicle with textures made during laser micromachining in individual sections: 1 – surface before texturing, 2 – texture in the form of a rhombus, 3 – texture in the form of a spherical bowl, 4 – in the form of a blur, 5 – in the form of a square

of the applied and executed texture is illustrated in Figure 7.

Subsequent work used the Lastex v. 2.27.26 texturing CAM software package and LaserSoft 3D 5.5.9T program of the machine tool's laser control system. Lastec v. 2.27.26 performs calculations of subsequent machine movements (it serves as a postprocessor and generates the program for the machine). For the Lastex v. 2.27.26 program environment, 2 files were imported. For the first file, obtained from Autodesk Maya with the development of the cylindrical surface of the mold on the plane of the part along with the clamping on the machine tool. This allowed us to simulate and determine in what working area we can move freely to avoid collisions with the workpiece and its fixture. After importing, a die model with a chuck was run and set up with relatively high precision as it is mounted on the machine in reality. A 3D analysis of the workpiece surface was then performed after which it was segmented. After segmenting, a texture prepared earlier in the

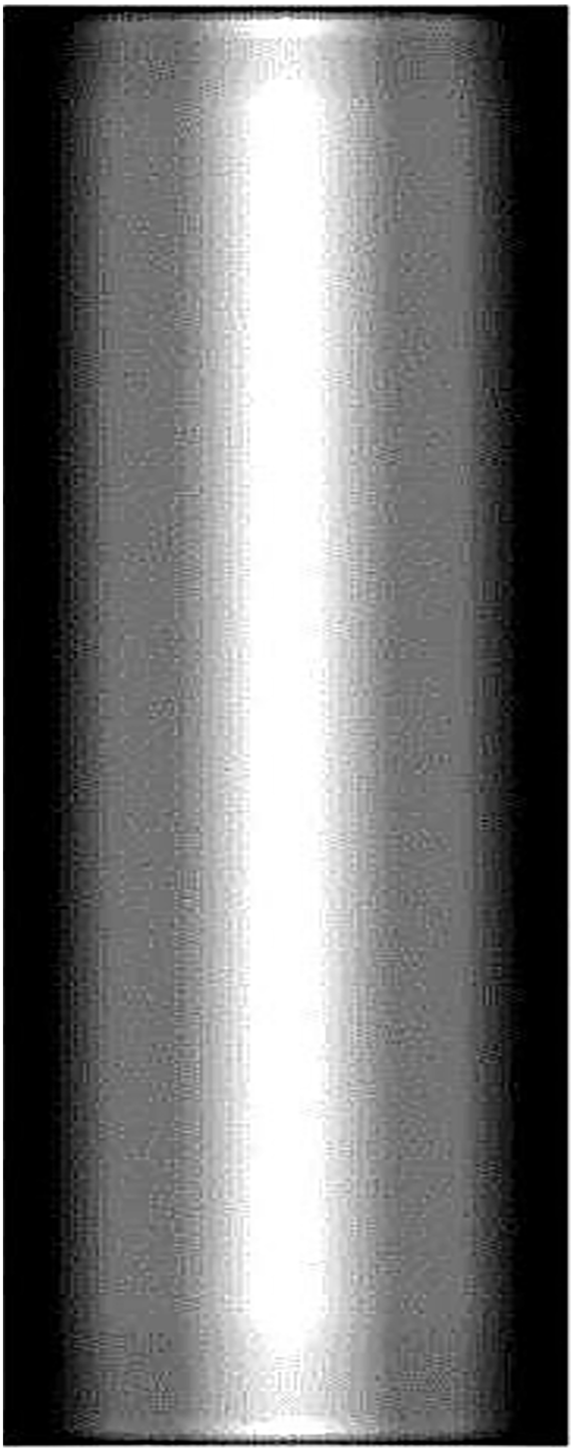

Fig. 4. Unfolded texturing surface

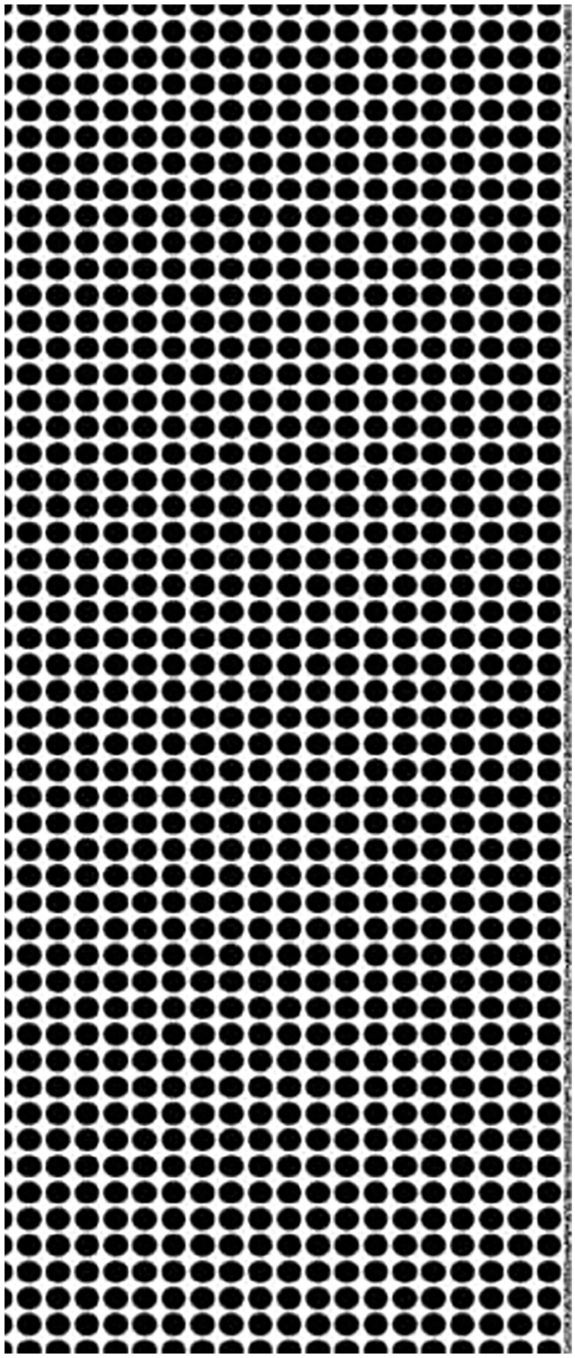

Fig. 5. Photoshop texture – negative

Adobe Photoshop environment was added. Then the total depth of the texture was set, which in the analyzed case was max. 0.2 mm. Recommendations for the depth of a single layer processed in a single pass range from 2 µm to 4 µm. Depth of a single layer during a pass was set at 2.8 µm. Program recalculates and creates the appropriate number of layers, depending on the total depth of the texture. In the case under review, the number of layers was 71 (from layer 0 to layer 70). After all settings were made, the technological and geometric data were transferred and the processing program was generated. Prepared program file, imported into LaserSoft 3D 5.5.9T program of the machine tool control system.

During processing of one part of the matrix, the machine made about 5100 "Jobs" (i.e., the head and table are in 5100 different positions). It took 10.5 hours to machine one part of the structure of the analyzed die with the parameters adopted as above (at 27.2% of the total

Fig. 6. Tonal transitions – texture elements

laser power, which is due to the chosen technology and depth of texturing during one pass (one layer)). Zero point on the machine and the model was established at the same place, in the center of the die, on its surface. Measurements of the zero point were made using a probe before the laser head was placed on the machine. Final views of the fabricated textures are shown in Figure 8.

Texture is a feature that modifies the appearance of a surface. Texture – in a general sense, it means a feature of the surface of an object, a sensation that is felt by touch. Texture is also called repetitive patterns on the surface of objects characteristic for a given material. Textures with various geometric surface shapes have many functional and exploitation features. They increase friction and improve the grip of the driver's hand on the steering wheel, improve the aesthetics and appearance of the finished product and extend its durability.

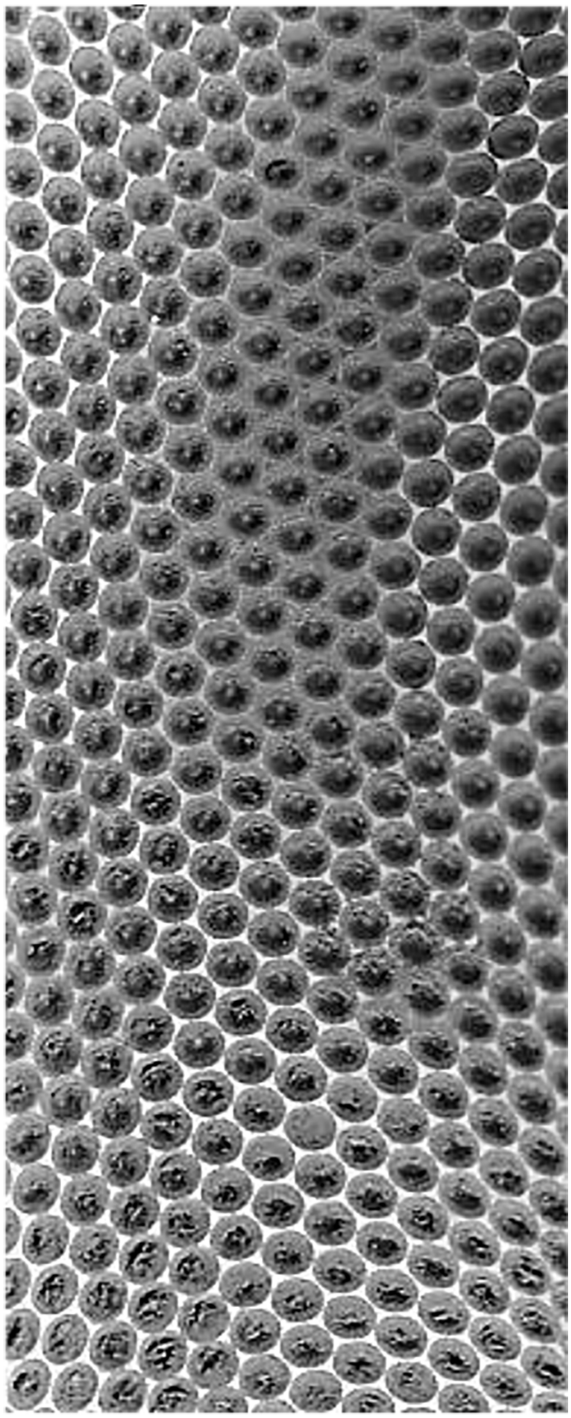

Fig. 7. Visualization of exemplary texture in the form of spherical times

Evaluation of the geometric structure of the textured surface

In a subsequent step, the obtained textured surface structure was examined and evaluated for the rhombus structure, fuzzy form, spherical times structure and square structure. Texture view of the surface of the motor vehicle steering wheel matrix in rhombus form is shown in Figure 9. The variety of forms and geometric shapes of the surface allows for increasing the ergonomics of the contact of the driver's hand with the polymer coating of the steering wheel manufactured in the injection mold. Texture is an important part of the overall aesthetic experience, even if most surfaces are not designed to be touched at all. Then the texture intuitively makes the surface appear smooth or rough – but let's add more complicated feelings to this. Texture affects the feeling of pleasure and comfort, and poorly done can lead to discomfort.

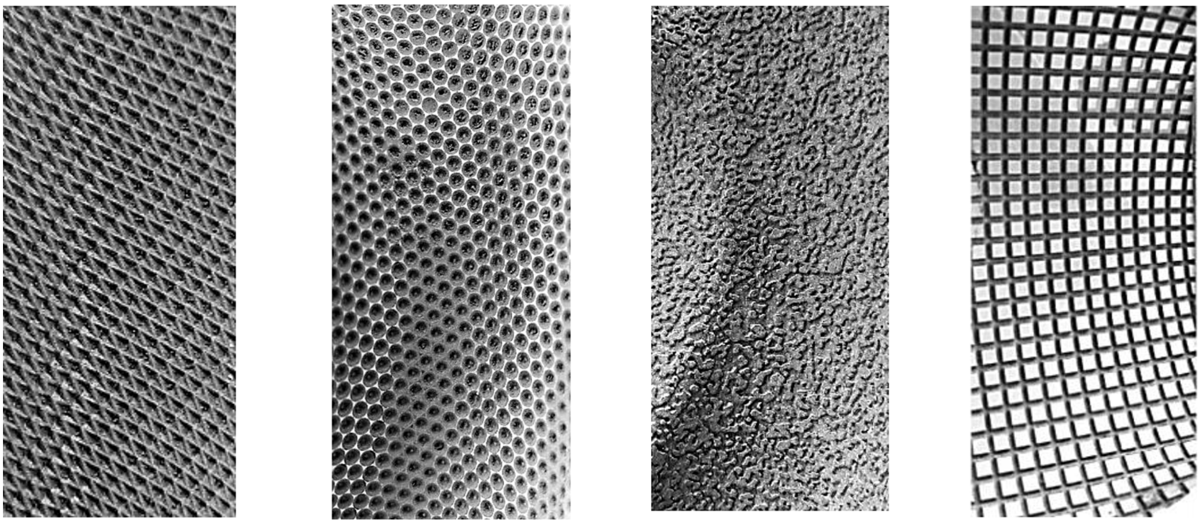

Fig. 8. Fabricated texture of the surface of a steering wheel matrix of a wheeled vehicle: a) in the form of a rhombus, b) in the form of a spherical bowl, c) in the form of a blur, d) in the form of a square

From the operational and manufacturing point of view, texture can facilitate or hinder the further manufacturing process (e.g. making it difficult or impossible to remove the molded part from the injection mold). Texture view of the motor vehicle steering wheel matrix surface in the form of a spherical bowl is shown in Figure 10. Such a geometric form allows you to give a real object abstract features, suggest dynamics and depth as well as high ergonomics.

A fuzzy view of the surface texture of a motor vehicle steering wheel matrix is shown in Figure 11. This form of texture is achieved through the natural feel of the natural materials used, such as leather (giving the feeling of sand grain, fabric roughness, peeling). It evokes the impression of space and the impression of multi-layeredness.

Square view of the texture of the surface of a motor vehicle steering wheel matrix is shown in Figure 12.

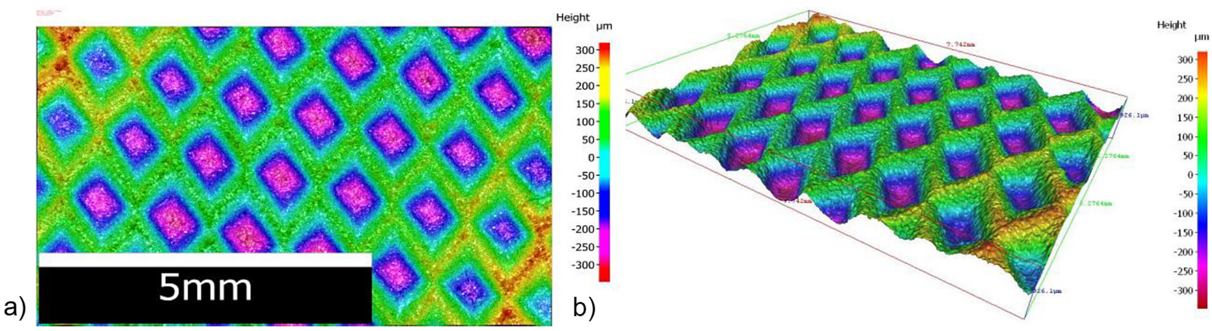

Fig. 9. Texture view of the motor vehicle steering wheel matrix surface in the form of a rhombus: (a) 2D view roughness of surface, (b) 3D view roughness of surface

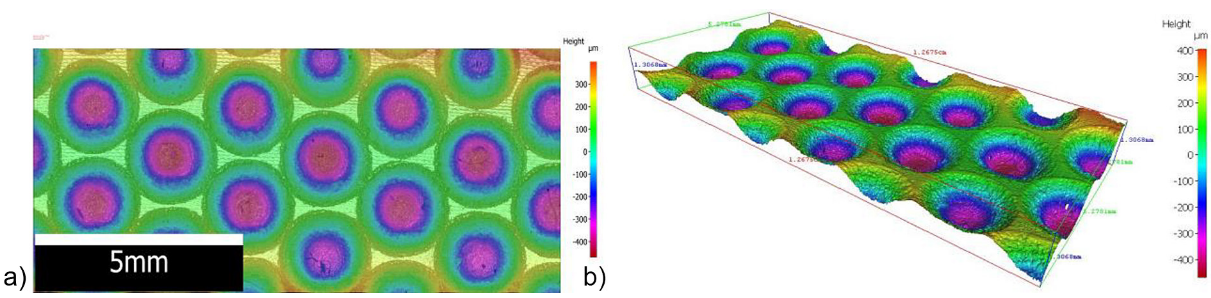

Fig. 10. Texture view of the surface of a motor vehicle steering wheel matrix in the form of a spherical bowl: (a) 2D view roughness of surface, (b) 3D view roughness of surface

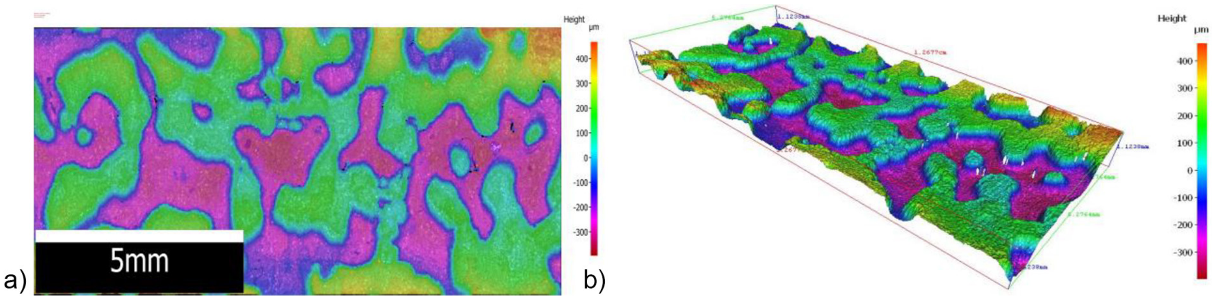

Fig. 11. Texture view of the surface of a motor vehicle steering wheel matrix as fuzzy form: a) 2D view roughness of surface, b) 3D view roughness of surface

Texture with geometric forms in the form of a square gives the impression as a visual element of order and elegance. Such a texture can affect the reception of a product through psychological associations, affect the mood, attract or distract attention from the product. The visual and tactile effect of the obtained product, regardless of whether we are to look at it, touch it or feel it with our senses – should have certain quality features of the manufactured surfaces. In a subsequent step, a parametric analysis of the 3D textured surface was fabricated. Obtained values of Sa, Sq and Sz parameters for the obtained texture types are shown in Figure 13. All measured 3D surface roughness parameters show an increasing trend. The highest values of the roughness parameter can be assigned to the Sz parameter for all types of textures.

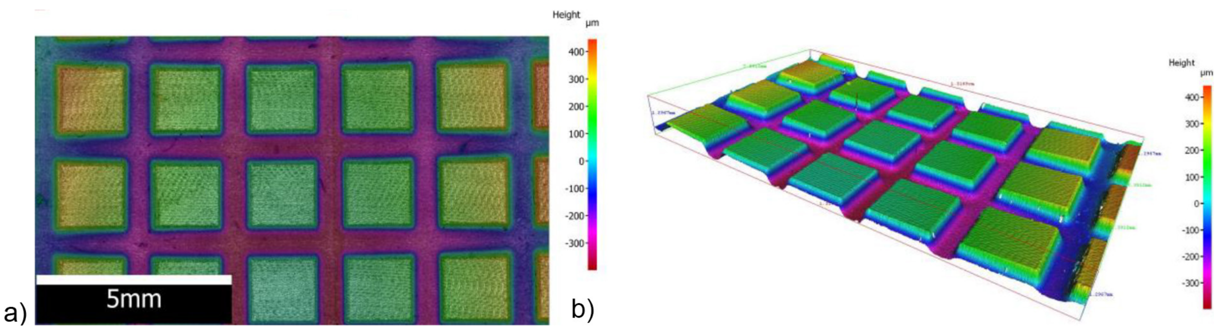

Fig. 12. Texture view of the surface of a motor vehicle steering wheel matrix in the form of a square: (a) 2D view roughness of surface, (b) 3D view roughness of surface

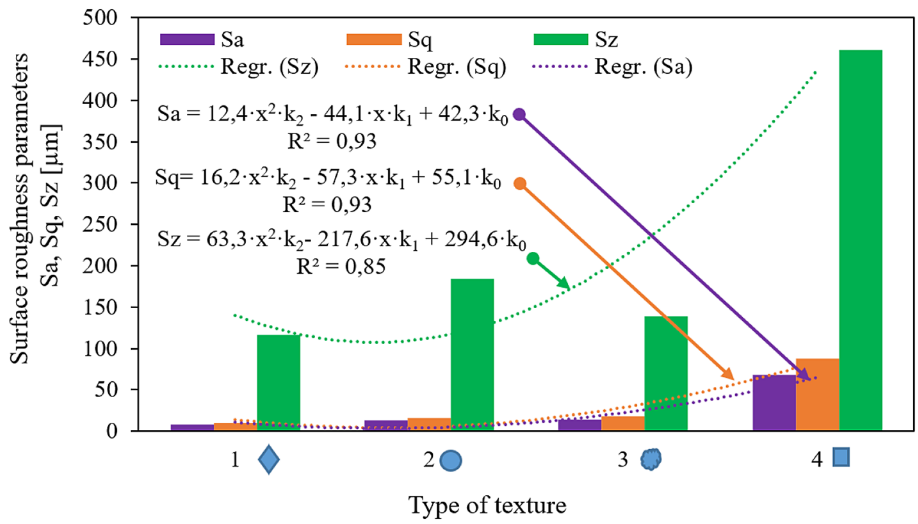

Fig. 13. Sa, Sq and Sz surface roughness parameters for: 1 – rhombic texture, 2 – spherical bowl texture, 3 – fuzzy texture, 4 – square texture

The surface described by roughness parameters Sa, Sq and Sz allows for a qualitative and, above all, quantitative assessment of the quality of the texture. The individual components of roughness tell about the surface features necessary to express the acceptability or rejection of the product. Above all, they determine the feasibility of the next stage of production of the car steering wheel coating, the ability to remove it from the injection mold, as well as the occurrence of incompatibilities and defects. The results presented in Figure 13 indicate the increasing roughness described by Sa (116÷460 μm), Sq (10÷88 μm) and Sz (8÷68 μm). This indicates that the increase in the complexity of the texture entails an increase in the geometric parameters of the surface roughness. The experimental results presented in Figure 13 are described by regression functions. The best results were obtained for second degree polynomial functions. This is evidenced by the highest degree of correlation R (0.92–0.96) and the value of the coefficient of determination R^2 (0.85–0.93).

Obtained values of Sp and Sv parameters for the obtained texture types are shown in Figure 14. The parameters presented in the chart describe the amplitudes values of the surface roughness. Values of the amplitude parameters: Sp describes the height of the highest peak of the surface, and Sv describes the depth of the lowest depression of the surface irregularities. These parameters are extremely important in assessing the quality of the textured surface, because in operational conditions of final products (parts), mapped on the contact surface, they can cause discomfort.

The values of the analyzed parameters are in the following ranges for texturing surfaces: Sp (83÷355 μm) and Sv (33÷125 μm). Although these values are at least 10 times higher than the after turning surface roughness, they are acceptable from the point of view of the accuracy of constituting the operating surface. Other analyzed surface roughness parameters describing operational and utility features are skewness Ssk and kurtosis Sku. Figure 15 shows the nature of the distribution of the parameters Ssk – skewness coefficient (asymmetry) and Sku – concentration coefficient (kurtosis). Obtained values of Ssk (-0.7–1.4) and Sku (3.5–4.8) parameters for the obtained texture types are shown in Figure 15 and gives information whether the vertices of the inequality are concave or convex.

Absolute kurtosis is always a non-negative number, while relative kurtosis can have both negative and positive values. Positive values characterize more peaked distributions compared to the normal distribution. leptokurtic. Negative values characterize distributions that are more flattened than normal distributions and are called platokurtic. The higher the kurtosis, the greater the concentration of the population around the mean value, which is reflected in the greater slenderness of the distribution curve. Its low value gives the opposite effect, i.e. a greater dispersion of values, poor concentration and, consequently, flattening of the number curve. For normal distribution, the kurtosis value equals 3, for values greater than 3 the distribution is more slender and for smaller values it is

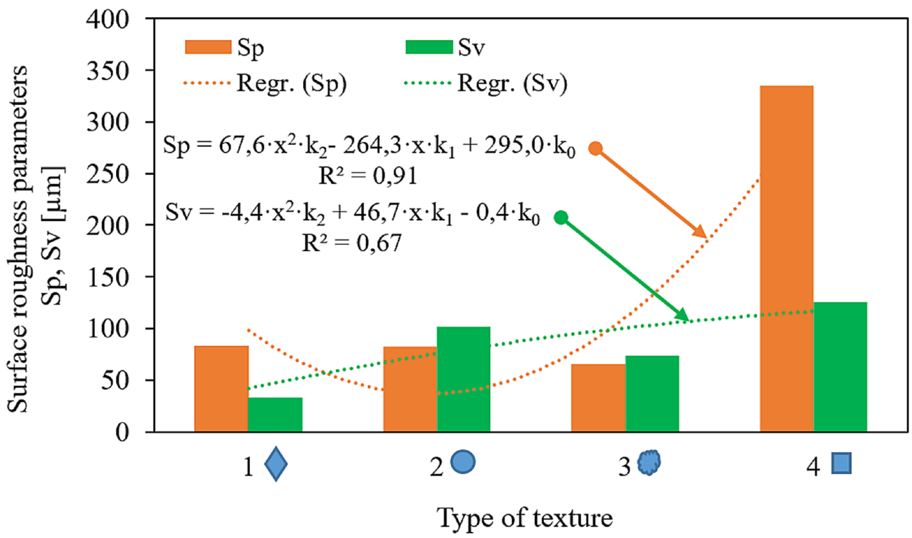

Fig. 14. Sp and Sv parameters of surface roughness for: 1 – rhombic texture, 2 – spherical bowl texture, 3 – fuzzy texture, 4 – square texture

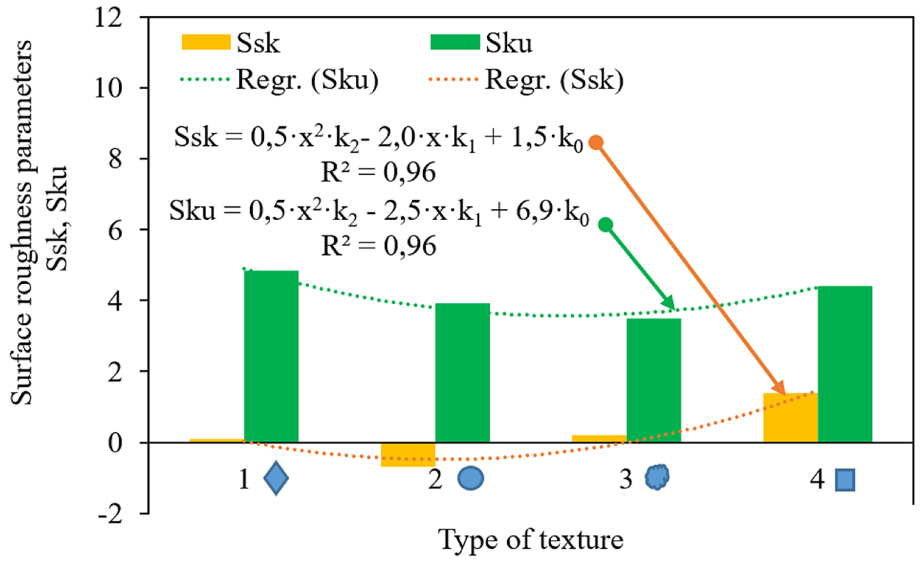

Fig. 15. Ssk and Sku surface roughness parameters for: 1 – rhombic texture, 2 – spherical bowl texture, 3 – fuzzy texture, 4 – square texture

more flattened. The kurtosis of the analyzed surfaces after texturing in the experiment in each of the appendages was higher than 3 and amounted to Sku (3.5–4.8). A different formula for calculating kurtosis is often used due to the above dependencies on the value of 3. Skewness is a measure of the symmetry/asymmetry of the distribution. If the distribution is perfectly symmetric, the value of skewness is zero. On the other hand, its negative values indicate a left-skewed distribution (the left arm of the distribution is extended), and its positive values indicate a right-skewed one (the right arm of the distribution is extended). The skewness coefficient is zero for symmetric distributions, negative values for distributions with a left asymmetry (left arm of the distribution) and positive values for distributions with a right asymmetry (right arm of the distribution). In the analyzed case of textures, skewness takes values from the range Ssk (-0.7÷1.4). This means both left asymmetry (for spherical bowl texture, Ssk= – 0.7)) and right asymmetry for rhombic texture (Ssk=0.1) and fuzzy texture (Ssk=0.2) and square texture (Ssk=1.4). The obtained results of experimental tests indicate very good geometrical properties of the obtained surface from the exploitation point of view.

CONCLUSIONS

Stages of the process of constituting a textured surface with the use of laser technology, presented in the paper, provides an ideal solution for shaping the ergonomic geometry of contact surfaces of the handle of sports equipment of a motor vehicle. At present, laser processing is a new direction of shaping products, which, combined with the possibility of numerical control of the path of the laser beam and processing parameters, is becoming invaluable. However, the impact of laser radiation on the workpiece depends on a number of important factors, which can be a source of problems during processing. Nevertheless, the use of laser technology makes it possible to achieve effects that are impossible or very difficult to achieve by other processing methods. Laser surface texturing is currently the most developing laser technique (next to laser cutting). It allows the production of complex geometric structures in a reproducible, relatively fast and economical way. In addition to texturing, laser technology is used for cleaning, strengthening and overmelting (remelting, alloying), imparting specific functional characteristics to mating surfaces. The type of application depends on the type of laser (the wavelength of the emitted radiation, the average power density or energy in the pulse delivered to the charge, the distribution of power density in the laser spot and the exposure time). Technology and an example of laser micromachining, presented in the paper, offers great technological opportunities for shaping. It allows its practical application in the processes of constituting ergonomic and responsible components of sports equipment, as well as in industrial design in the broadest sense (especially in the automotive and aerospace industries).

Acknowledgments

The publication was financed from the funds of the Polish Ministry of Education and Science as part of the program„Social Responsibility of Science / Excellent Science," support for Scientific Conferences„Synergy of Science and Industry," Challenges of the 21st Century, Science – Industry – Business.

REFERENCES

1. Wan Y., Xiong D-S. The effect of laser surface texturing on frictional performance of face seal. Journal of Materials Processing Technology 2008; 197(1): 96–100.
2. Józwik J., Dziedzic K., Barszcz M., Pashechko M. Analysis and Comparative Assessment of Basic Tribological Properties of Selected Polymer Composites. Materials 2020; 13: 1–24.
3. Józwik J., Ostrowski D., Milczarczyk R., Krolczyk G.M. Analysis of relation between the 3D printer laser beam power and the surface morphology properties in Ti-6Al–4V titanium alloy parts. Journal Of The Brazilian Society Of Mechanical Sciences And Engineering 2018; 40: 1–10.
4. Daskalova A., Angelova L., Carvalho A., Trifonov A., Nathala C., Monteiro F. Effect of surface modification by femtosecond laser on zirconia based ceramics for screening of cell-surface interaction. Applied Surface Science 2020; 513: 145914.
5. Kashyap V., Ramkumar P. Improved oxygen diffusion and overall surface characteristics using combined laser surface texturing and heat treatment process of Ti6Al4V. Surface and Coatings Technology 2021: 127976.
6. Stanciuc A-M., Flamant Q., Sprecher CM., Alini M., Anglada M., Peroglio M. Femtosecond laser multi-patterning of zirconia for screening of cell-surface interactions. Journal of the European Ceramic Society 2018; 38(3): 939–948.
7. Oyane A., Kakehata M., Sakamaki I., Pyatenko A., Yashiro H., Ito A. Biomimetic apatite coating on yttria-stabilized tetragonal zirconia utilizing femtosecond laser surface processing. Surface and Coatings Technology 2016; 296: 88–95.
8. Bonse J., Kirner SV., Griepentrog M., Spaltmann D., Krüger J. Femtosecond Laser Texturing of Surfaces for Tribological Applications. Materials 2018; 11(5): 801.
9. Wang X., Kato K., Adachi K., Aizawa K. The effect of laser texturing of SiC surface on the critical load for the transition of water lubrication mode from hydrodynamic to mixed. Tribology International 2001; 34(10): 703–711.
10. Pashechko M., Dziedzic K., Jozwik J. Analysis of Wear Resistance of Borided Steel C45. Materials 2020; 13(23): 5529.
11. Shum PW., Zhou ZF., Li KY. Investigation of the tribological properties of the different textured DLC coatings under reciprocating lubricated conditions. Tribology International 2013; 65: 259–264.
12. Antoszewski B., Tarelnyk V. Laser Texturing of Sliding Surfaces of Bearings and Pump Seals. Applied Mechanics and Materials 2014; 630: 301–307.
13. Hu T., Hu L., Ding Q. Effective solution for the tribological problems of Ti-6Al-4V: Combination of laser surface texturing and solid lubricant film. Surface and Coatings Technology 2012; 206(24): 5060–5066.
14. Braun D., Greiner C., Schneider J., Gumbsch P. Efficiency of laser surface texturing in the reduction of friction under mixed lubrication. Tribology International 2014; 77: 142–147.
15. Sierra D.R., Edwardson S.P., Dearden G. Laser surface texturing of titanium with thermal post-processing for improved wettability properties. Procedia CIRP 2018; 74: 362–366.
16. Yilbas B.S., Khaled M., Abu-Dheir N., Aqeeli N., Furquan S.Z. Laser texturing of alumina surface for improved hydrophobicity. Applied Surface Science. 2013; 286: 161–170.
17. Wang Q., Wang H., Zhu Z., Xiang N., Wang Z., Sun G. Switchable wettability control of titanium via facile nanosecond laser-based surface texturing. Surfaces and Interfaces 2021; 24: 101122.
18. Du D., He YF., Sui B., Xiong LJ., Zhang H. Laser texturing of rollers by pulsed Nd:YAG laser. Journal of Materials Processing Technology. 2005; 161(3): 456–461.
19. He X., Li G., Zhang Y., Lai X., Zhou M., Xiao L., i in. Bioinspired functional glass integrated with multiplex repellency ability from laser-patterned hexagonal texturing. Chemical Engineering Journal 2021; 416: 129113.
20. Guarnaccio A., Belviso C., Montano P., Toschi F., Orlando S., Ciaccio G., i in. Femtosecond laser surface texturing of polypropylene copolymer for automotive paint applications. Surface and Coatings Technology 2021; 406: 126727.
21. Madeira S., Barbosa A., Silva FS., Carvalho O. Micro-grooved surface laser texturing of zirconia: Surface characterization and artificial soft tissue adhesion evaluation. Ceramics International 2020; 46(16, Part A): 26136–26146.
22. Zhan J., Yang M. Investigation on the application of YAG laser texturing technology to the cylinder wall of auto engine. Industrial Lubrication and Tribology 2014; 66(3): 387–392.
23. Soveja A., Cicala E., Grevey D., Jouvard JM. Opti-

misation of TA6V alloy surface laser texturing using an experimental design approach. Optics and Lasers in Engineering 2008; 46(9): 671–678.

24. Dong B., Guo X., Zhang K., Zhang Y., Li Z., Wang W., i in. Combined effect of laser texturing and carburizing on the bonding strength of DLC coatings deposited on medical titanium alloy. Surface and Coatings Technology 2022; 429: 127951.
25. Orazi L., Montanari F., Campana G., Tomesani L., Cuccolini G. CNC Paths Optimization in Laser Texturing of Free Form Surfaces. Procedia CIRP 2015; 33: 440–445.
26. Cho MH., Park S. Micro CNC surface texturing on polyoxymethylene (POM) and its tribological performance in lubricated sliding. Tribology International 2011; 44(7): 859–867.
27. Antosze Ranjan P., Hiremath SS. Role of textured tool in improving machining performance: A review. Journal of Manufacturing Processes 2019; 43: 47–73.
28. Alvarez-Vera M., Ortega JA., Ortega-Ramos IA., Hdz-García HM., Muñoz-Arroyo R, Díaz-Guillén JC., i in. Tribological and microstructural characterization of laser microtextured CoCr alloy tested against UHMWPE for biomedical applications. Wear 2021; 477: 203819.
29. Kumar D., Nadeem Akhtar S., Kumar Patel A., Ramkumar J., Balani K.. Tribological performance of laser peened Ti–6Al–4V. Wear 2015; 322–323: 203–217.
30. Uhlmann E., Schweitzer L., Kieburg H., Spielvogel A., Huth-Herms K. The Effects of Laser Microtexturing of Biomedical Grade 5 Ti-6Al-4V Dental Implants (Abutment) on Biofilm Formation. Procedia CIRP 2018; 68: 184–189.
31. Caro-Lara L., Ramos-Moore E., Vargas IT., Walczak M., Fuentes C., Gómez AV., at all. Initial adhesion suppression of biofilm-forming and copper-tolerant bacterium Variovorax sp. on laser microtextured copper surfaces. Colloids and Surfaces B: Biointerfaces 2021; 202: 111656.
32. Vishnoi M., Kumar P., Murtaza Q. Surface texturing techniques to enhance tribological performance: A review. Surfaces and Interfaces 2021; 27: 101463.
33. Wang G., Wan Y., Ren B., Liu Z. Fabrication of an orderly micro/nanostructure on titanium surface and its effect on cell proliferation. Materials Letters 2018; 212: 247–250.
34. Deshmukh N., Rajurkar A., Kolekar O., Mule R., Chinchanikar S. Thermal modeling of laser surface micro-texturing: Investigation on effects of laser parameters on dimple-texture dimensions and aspect ratio. Materials Today: Proceedings 2021; 46: 8374–8380.
35. Sanguedolce M., Zekonyte J., Alfano M. Wear of 17-4 PH Stainless Steel Patterned Surfaces Fabricated Using Selective Laser Melting. Applied Science 2021; 11(19): 9317.
36. Jozwik J., Ostrowski D., Milczarczyk, R. Analysis of relation between the 3D printer laser beam power and the surface morphology properties in Ti-6Al-4V titanium alloy parts. Journal of the Brazilian Society of Mechanical Sciences and Engineering 2018; 40: 215.