applied sciences

MDPI

Article

Computer-Aided Analysis of the Formation of the Deformation Zone in the Burnishing Process

Andrzej Piotrowski [1], Andrzej Zaborski [1] and Artur Tyliszczak [2,*]

[1] Department of Technology and Automation, Czestochowa University of Technology, 42-201 Częstochowa, Poland; andrzej.piotrowski@pcz.pl (A.P.); andrzej.zaborski@pcz.pl (A.Z.)

[2] Department of Thermal Machinery, Czestochowa University of Technology, 42-201 Częstochowa, Poland

* Correspondence: artur.tyliszczak@pcz.pl; Tel.: +48-3250-509

Abstract: The study presents the use of spatial imaging of the shape of the deformation formation area occurring at the point of contact between the burnished tool and the processed material surface in the burnishing process. In the analysis of changes in the shape of surfaces processed by ball and disc pressure burnishing, an integrated measurement station was used to measure surface stereometry (New Form Talysurf 2D/3D 120 by Taylor Hobson) and to carry out a series of axially shifted roundness measurements (Talyrond 365 by Taylor Hobson). The geometric parameters of the deformation zone determined in the direction of the circumference of the cylindrical surface (direction of the main movement) and in the axial direction (in the feed plane) are presented. The data obtained as a result of metrological measurements were analysed using specialized computer software.

Keywords: surface stereometry measurements; burnishing; metrology

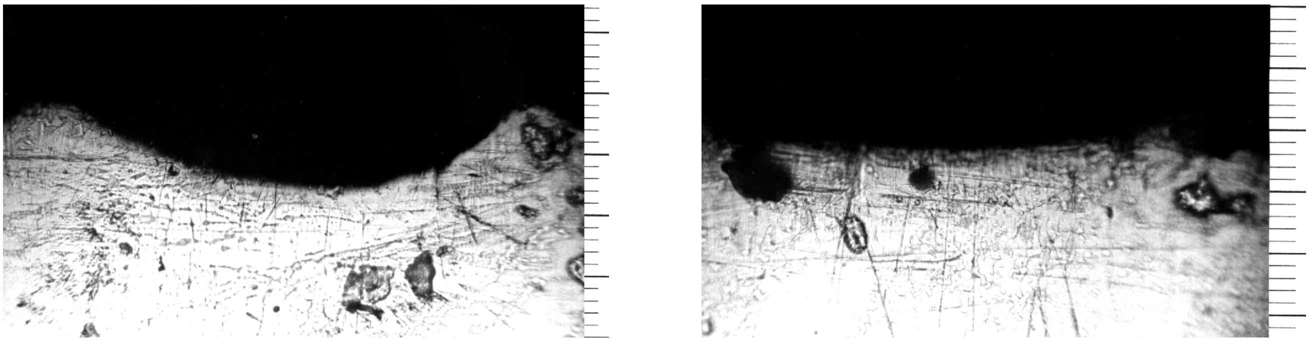
1. Introduction

Burnishing is one of the popular machinery industry finishing methods that allows relatively easy control of the surface layer condition parameters determining its service properties [1–3]. The process of forming the surface layer is carried out as a result of plastic deformation of the material, occurring in the contact area between the burnishing tool and the processed material [4,5]. Burnishing is carried out to achieve two basic technological objectives: strengthening the material at the depth of the surface layer and improving the stereometric condition of the machined surface [6–9] (Figure 1). Burnishing allows the creation of compressive residual stresses in the top surface layer of metal and also increases its strength as a result of work hardening, which increases the fatigue, friction and corrosion resistance of the processed part. Due to its low costs, it is competitive with laser impact strengthening. Its advantage is the lack of thermal stresses characteristic of thermal processing. It is evident that both of these technological objectives are realized by selecting the appropriate machining method and technological parameters for this process [10–14]. By using tools of different shapes as burnishing elements—for example, a ball or a disc—under the same technological conditions, or by changing the machining parameters, it is possible to achieve different degrees of deformation of irregularities [15–19]. Depending on expectations, it is possible to achieve partial deformation of the irregularities, which occurs when the burnishing element has too large a profile radius and is not able to generate the unitary pressures necessary for the full deformation of the irregularities (the bottoms of the irregularity notches remain on the surface after the pre-burnishing machining), neither their complete deformation when the burnishing element exerts such large surface pressures in the burnishing zone that the irregularities are completely deformed. The properties of the resulting surface layers depend to a large extent on the set of phenomena occurring during the formation of deformations in the contact zone of the burnishing tool with the material [20–25].

Citation: Piotrowski, A.; Zaborski, A.; Tyliszczak, A. Computer-Aided Analysis of the Formation of the Deformation Zone in the Burnishing Process. *Appl. Sci.* **2024**, *14*, 1062. https://doi.org/10.3390/app14031062

Academic Editors: Junfeng Liu, Xiaoqiang Peng and Tao Lai

Received: 17 December 2023
Revised: 20 January 2024
Accepted: 23 January 2024
Published: 26 January 2024



(**a**) (**b**)

Figure 1. Surface profile: (**a**) before burnishing–turned zone (r = 0.4 mm, f_{turn} = 0.410 mm/rev), (**b**) ball burnished zone (R = 5 mm, F = 5 kN, f_{burn} = 0.410 mm/rev) (magn. 100×).

During the burnishing process, after reaching a sufficiently high level of unit pressure in the deformation zone, a wave of material piled up by the burnishing tool is formed on the processed surface. This happens both in the axial and circumferential directions [26–29]. According to many publications, the deformation zone obtained in this way has a three-dimensional shape characteristic of the ongoing processes resulting from its geometric and kinematic parameters [27–31]. What is determined here is primarily the burnishing force, as well as the characteristics of the tool used for processing (ball or disc).

The analyses carried out allow us to conclude that the first type of deformation focus (I) occurs when the burnishing element is slightly recessed into the surface, less than the distance of the surface roughness vertices from the mean line. The surface irregularities are then only partially smoothed out due to the insufficient pressure force. Increasing the force leads to the second type of deformation focus (II), which is characterized by the appearance of a wave of material in front of the face of the pressing element, the apex of which, however, does not rise higher than the roughness vertices. A further increase in the force leads to an increase in the wave and the formation of a distortion focus of the third type (III). A characteristic feature of this type of focusing is that the material wave rises above the profile of the workpiece. The formation of a deformation centre of the third kind is a prerequisite for the optimum quality of the workpiece surface and the favourable operating characteristics of the surface layer obtained in the burnishing process [32,33]. A further increase in the force (IV) causes a further increase in the wave, to a significant level, which induces damage to the surface layer, manifested by rippling on the surface and tarnishing caused by peeling of the thin near-surface layer. The analysis results presented in this article concern the process of forming a spatial deformation zone during the burnishing process carried out using various tools (balls and discs) and various technological parameters of the process (forces and feeds). The presented article is an in-depth review of computer-aided analysis of the surface layer after the burnishing process, resulting from many years of experience and research and many scientific articles.

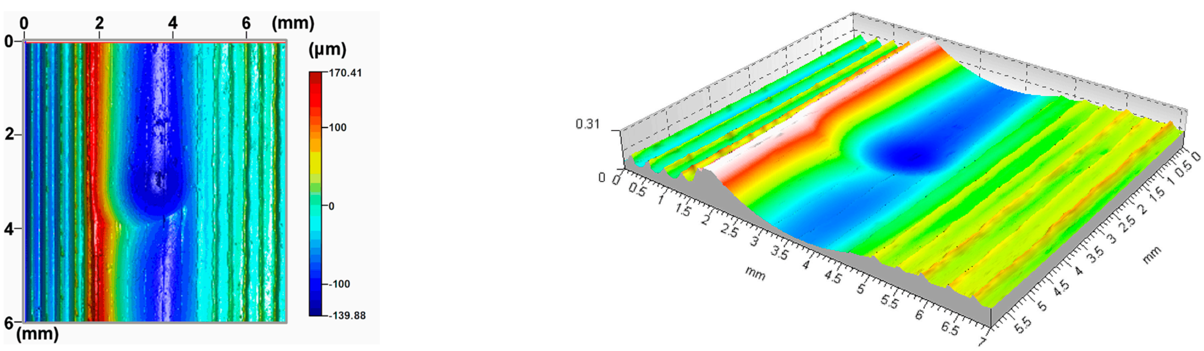
2. Analysis of the Stereometry of the Deformation Zone

To numerically analyse the stereometry of the contact area of the burnishing tool with the processed material, a New Form Talysurf 2D/3D 120 Taylor Hobson profilographometer was used with the software "Ultra Surface 5.16" and "TalyMap Platinium 5.1.1". This instrument enables measurements of surface roughness and stereometry. A measuring head with a resolution of 3.2 nm was used for the tests. Reproducing the shape of the deformation area caused by burnishing required equipping the station with a measuring table enabling the displacement of the measured samples in a direction perpendicular to the direction of travel of the measuring tip (an area with given geometric dimensions depending on the type of test performed). Measurements were performed on the burnished object. It was a cylinder (shaft) with a diameter of 50 mm made of C55 (1.0535), very popular in the machinery industry (Table 1). The burnishing tools were balls and discs made of 100Cr6 [34] bearing steel. It was a typical, real machining on a CU-500 conventional lathe. During the tests, the lowest possible spindle revolutions were used (18 rpm) due to the need to stop the process to obtain the geometry of the formed deformation centre. The analysis of the literature [3,4,32] allows us to conclude that due to the low rotational speeds used during static pressure burnishing carried out using balls or discs, the linear burnishing speed of several meters per minute is not a parameter that significantly affects the machining process. The most important parameters controlling the process are the tool geometry (radius of curvature) (R for ball and R_k for disc), burnishing force (F) and feed (f_{burn}). Therefore, during the described research, it was not a parameter analysed as a parameter controlling the machining process. Only the most characteristic results of the obtained tests are presented. As a rule, 10 repetitions of the surface examination were carried out with the given parameters.

Table 1. Chemical characteristics of C55/1.0535 steel.

C	Mn	Si	P	S	Cr	Ni	Mo
0.52–0.60	0.60–0.90	Max 0.40	Max 0.045	Max 0.045	Max 0.40	Max 0.40	Max 0.10

Burnishing is the last finishing treatment; therefore, any roughness remaining after the previous machining process, e.g., turning or milling, is permanently deformed. As a result, the geometric structure of the surface is completely changed. Its parameters are the result of the processes occurring during its formation. The spacing of the formed irregularities is close to the feed rate used during burnishing. The deformed material gradually fills the original grooves of the surface irregularities remaining after the previous machining. Optical observation (microscope) and computer-aided analysis show that a wave of irregularities is formed in front of the moving burnishing tool. The wave is shaped both in the axial direction—the direction of feed—and in the circumferential direction—the direction of the main movement (Figure 2). Figure 3 illustrates cross-sections of the deformation zone determined in the direction perpendicular and parallel to the main movement. The burnishing process parameters and the selected tool determine the machining results and the amount of surface strengthening. The software, which was used during the scientific research, enables a way to analyse differences in the height and distance of any indicated areas of the analysed zone. It becomes possible to determine the most important geometric parameters of the deformation zone. The presented analysis is therefore very important for the machinery industry because it enables the possibility of optimization of the burnishing process.



(**a**) (**b**)

Figure 2. Ball burnishing: (**a**) planar (top view), (**b**) stereometric image of the contact zone of the burnishing tool. R = 5 mm, F = 5 kN; feeds: f_{turn} = 0.410 mm/rev, f_{burn} = 0.102 mm/rev (area after turning: S_z = 92.4 µm, S_a = 17.5 µm; area after burnishing: S_z = 72.2 µm, S_a = 9.6 µm).

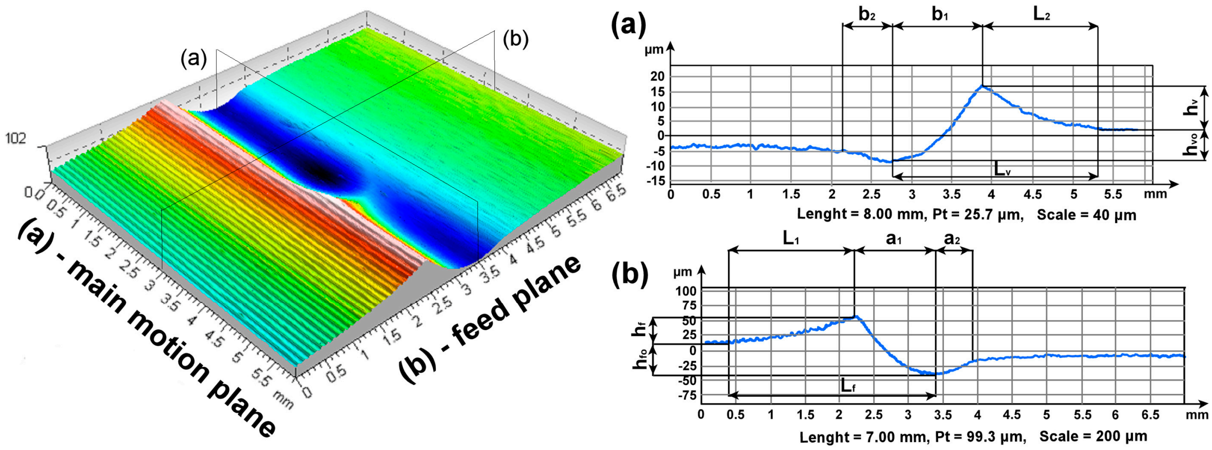


Figure 3. Description of the geometric parameters of the deformation centre. Ball burnishing. R = 5 mm, F = 2.75 kN, f_{turn} = 0.410 mm/rev, f_{burn} = 0.102 mm/rev (area after turning: S_z = 91.7 µm, S_a = 18.9 µm; area after burnishing S_z = 21.2 µm, S_a = 2.4 µm): (**a**) main motion plane, (**b**) feed plane.

To describe the three-dimensional shape (Figure 2) of the deformation zone obtained after the burnishing process, it was proposed to use parameters describing its shape both in the axial section (in the feed plane)—the letters with parameter f—and in the circumferential section (in the plane of the main movement)—the letters with parameter v:

- h_f/h_v: deformation wave height,
- h_{fo}/h_{vo}: tool cavity height relative to the surface of the raw material,
- L_1/L_2: initial deformation wavelength,
- $a = a_1 + a_2/b = b_1 + b_2$: length and width of the deformation centre,
- L_f/L_v: length and width of the deformation wave.

Additionally, the parameters describing forces, geometry and roughness were used:

- F—burnishing force [kN],
- R—radius of the ball-shaped tools [mm],
- R_k—radius of the disc-shaped tools [mm],
- f_{turn}—feed used in turning [mm/rev],
- f_{burn}—feed used in burnishing process [mm/rev],
- S_a—parameter, similar to Ra, characterizing the stereometric profile [µm]. The arithmetic averages of roughness from the average plane within the sampling area—the elementary square,
- S_z—parameter, similar to Rz, characterizing the stereometric profile [µm]. The ten-point height of the surface irregularities—the average value of the absolute heights of the five highest peaks and the five lowest depressions within the sampling area—the elementary square.

It can be concluded that, during the burnishing process using tools with larger radii (Figure 4c,d), the moment of transition from parameters leading to the formation of a deformation centre of type I, typical for small unit pressures, to parameters leading to the formation of a centre of deformation of type II and III can occur using greater burnishing forces [1,3,4,32]. However, the significance of the increase in the burnishing feed is not so clear. At small feed rates (0.05–0.2 mm/rev) (Figure 5), the course of deformation formation is to some extent similar to the phenomena characteristic of the process of forming a circumferential groove. For this reason, the mere increase in the feed rate without a simultaneous increase in the burnishing force does not result in an increase in the dimensions of the deformation area and the penetration of the burnishing ball into the material (Figure 5). The obtained results made it possible to present the dependence of selected parameters of the deformation zone on the feed and force used during ball pressure burnishing (Figure 6).

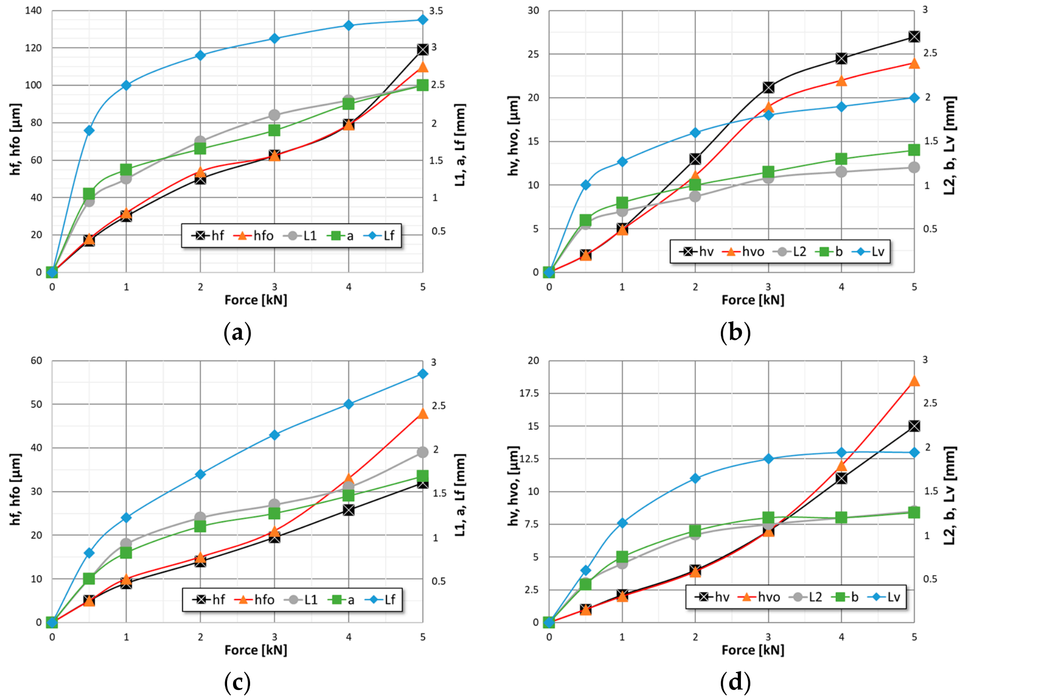


Figure 4. Ball burnishing—the impact of force on some parameters of the deformation centre (f_{burn} = 0.102 mm/rev) determined in (**a**,**c**) axial cross-section (h_f, h_{fo}, L_1, a, L_f,), (**b**,**d**) cross-section peripheral (h_v, h_{vo}, L_2, b, L_v), (**a**,**b**) ball radius R = 5 mm, (**c**,**d**) ball radius R = 13.5 mm.

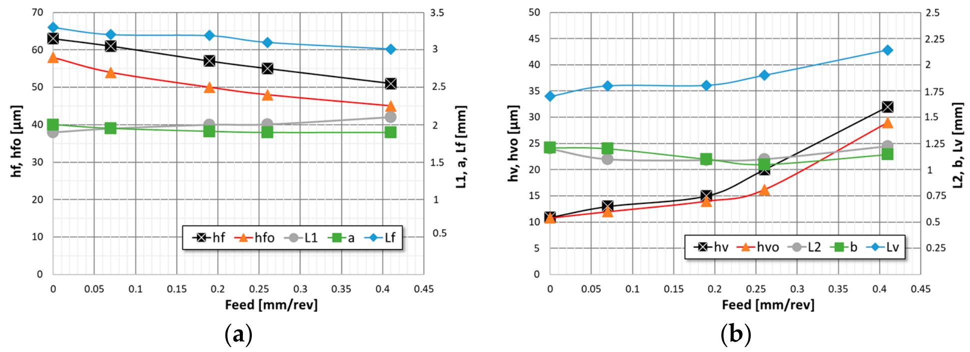


Figure 5. Ball burnishing (R = 5 mm, F = 2.75 kN)—the impact of feed on some parameters of the deformation centre determined in: (**a**) axial section (h_f, h_{fo}, L_1, a, L_f,), (**b**) circumferential section (h_v, h_{vo}, L_2, b, L_v).

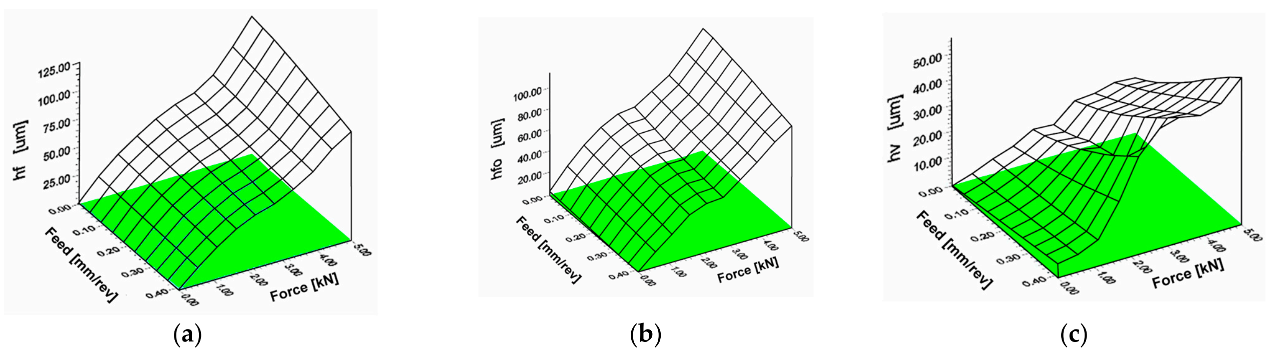
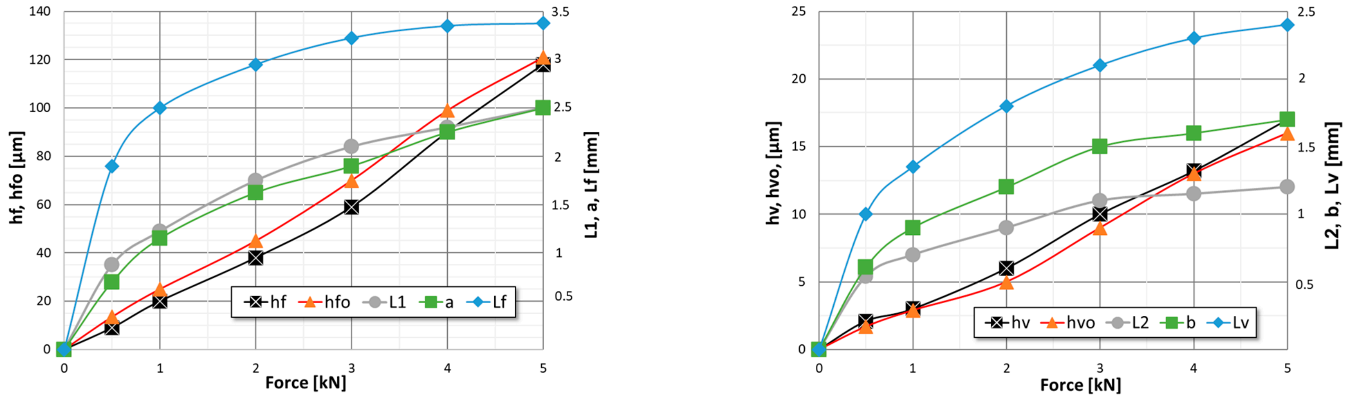


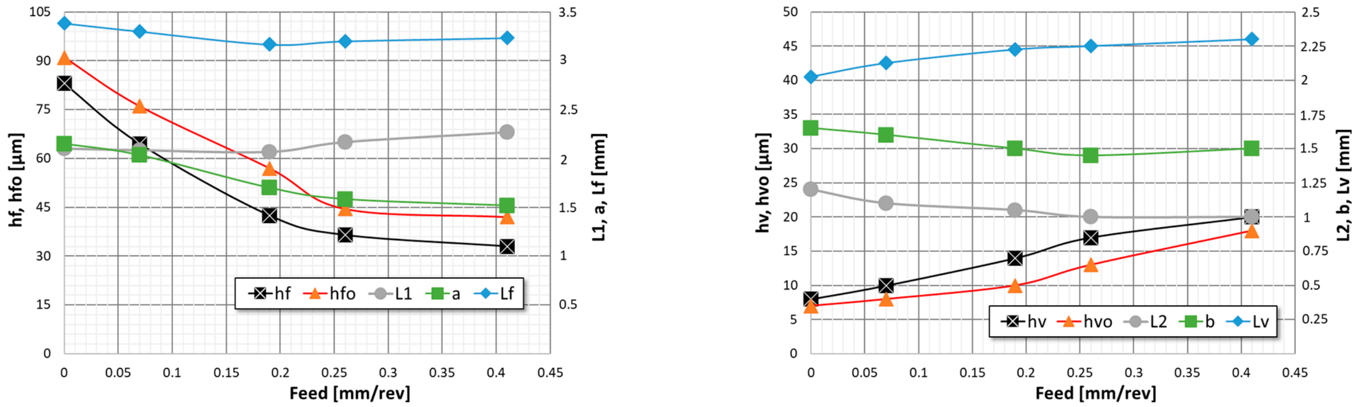
Figure 6. Ball burnishing (R = 5 mm)—computer-aided analysis of the dimensions of the axial and circumferential wave of the material depending on the burnishing process parameters: (**a**) h_f, (**b**) h_{fo}, (**c**) h_v.

During pressure burnishing with a disc, the material deformation process occurred in a very similar way. The amount of force applied during the burnishing process determined the shape and size of the resulting zone of deformed material (Figure 7). However, in accordance with Figure 8, the influence of feed rate on changes in the geometric parameters of the deformation wave—particularly for the circumferential section—was more pronounced than for ball burnishing. For this machining method, the influence of the variation in feed and burnishing force on selected geometry parameters of the deformation zone was also determined (Figure 9).



(**a**) (**b**)

Figure 7. Disc burnishing—the impact of the force on some parameters of the deformation centre (R_k = 5 mm, f_{burn} = 0.102 mm/rev) determined in (**a**) axial section (h_f, h_{fo}, L_1, a, L_f), (**b**) circumferential section (h_v, h_{vo}, L_2, b, L_v).



(**a**) (**b**)

Figure 8. Disc burnishing (F = 2.75 kN, R_k = 5 mm)—the impact of the feed on some parameters of the deformation centre determined in: (**a**) axial section (h_f, h_{fo}, L_1, a, L_f), (**b**) circumferential section (h_v, h_{vo}, L_2, b, L_v).

To fully describe the process occurring during burnishing, it is necessary to determine the contact area of the burnishing tool with the processed surface. The actual shape and size of this area depend on the adopted processing parameters, including, primarily, the value of the burnishing force and, secondly, the values of the feed used in machining. The selection of the optimal forces of the burnishing process necessary to completely deform the irregularities and induce the expected changes in the state of the physical parameters of the burnished surface layer is possible if the value of the unit pressures accompanying the machining process is known. The proper selection of burnishing conditions, which is the basis for the correct execution of the machining process in industrial conditions, is only possible using computational methods. However, they require knowledge, at least approximate, of the size of the contact area between the tool and the processed material. Meanwhile, according to the literature and research works using classic methods of metrology and surface analysis, determining the actual shape and dimensions of the deformation zone has not yet been fully feasible. The formulas known from the literature lead to approximate solutions, which makes them practically useless in practice. Research carried out in industrial conditions confirmed this thesis. Only the use of modern, computer-aided analysis techniques of the deformation zone, obtained as a result of image measurement with microscopes and ultrafast cameras, allows the precise determination of the contact area (Figure 10).

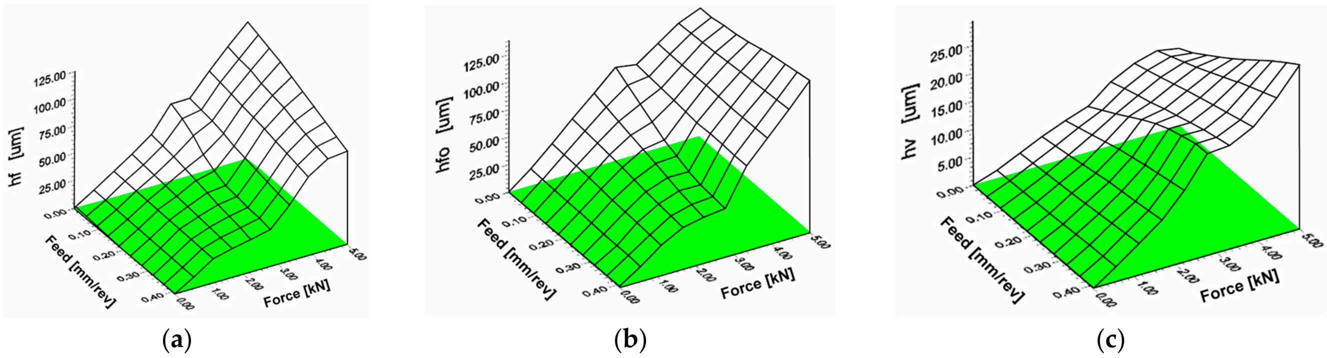


Figure 9. Computer-aided analysis of the disc-burnishing process (R_k = 5 mm)—dimensions of the axial and circumferential wave of the material depending on the parameters: (**a**) h_f, (**b**) h_{fo}, (**c**) h_v.

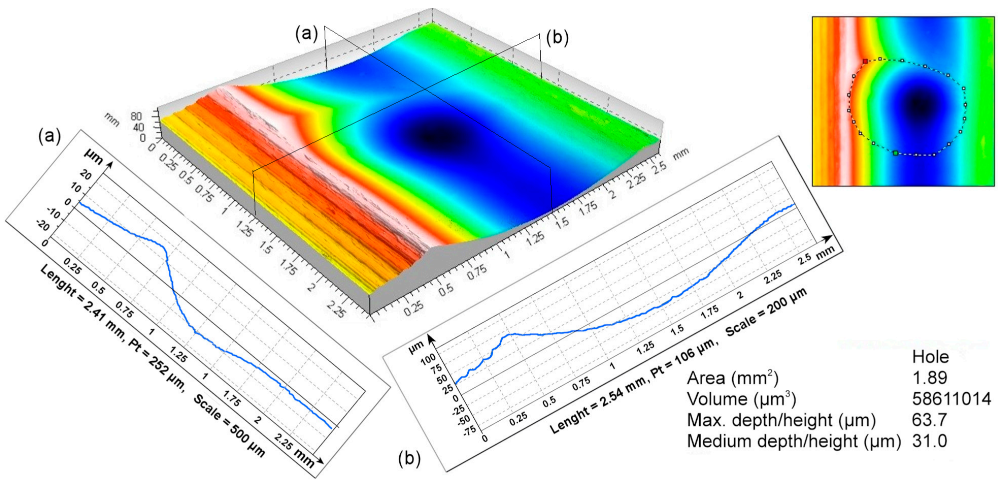
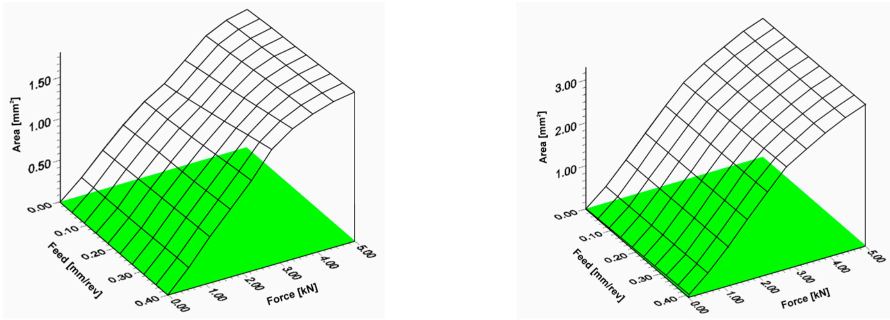


Figure 10. Ball burnishing (R = 5 mm, F = 2.75 kN, f_{burn} = 0.068 mm/rev)—analysis of the contact area of the tool with the burnished material: (**a**) main motion plane, (**b**) feed plane.

The computer-aided measurement methodology presented in the study made it possible to link the actual size of the tool contact area with the processed surface depending on the two basic parameters of the burnishing process—force and feed (Figure 11).

The software used in the research, the proposed measurement methodology and the method of describing the deformation zone also enable spatial visualization of a selected fragment of the analysed area of the actual contact zone of the tool with the burnished material. This allows for a more detailed analysis of phenomena occurring in a selected area, compared to classical metrology (Figures 11 and 12).



(a) (b)

Figure 11. Computer-aided analysis of the dependence of the contact surface area of the burnishing tool on the burnishing process parameters: (**a**) ball R = 5 mm, (**b**) disc R_k = 5 mm.

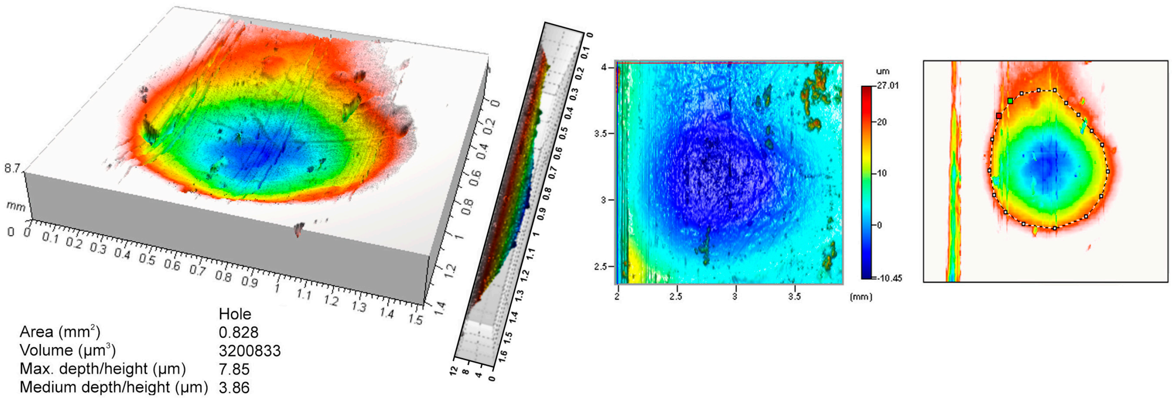


Figure 12. Disc burnishing (R_k = 10 mm, F = 2.5 kN)—numerical analysis of the digitally processed area of contact between the tool and the burnished material.

3. Three-Dimensional Deformation Zone Imaging

The measurement results presented in the study were obtained using the Talyrond 365 roundness measurement station (with Ultra Roundness 5.17 control program) [35]. It is equipped with a self-levelling, aerostatic measuring table, facilitating the measurement process. The equipment enables comprehensive, three-dimensional analysis of the shape of cylindrical surfaces with a resolution of 1.3 nm. During measurement, points located on the circumference of the cylindrical surface are collected in the form of a digital point cloud in the number of 3600 or 18,000 points (optionally) per 1 revolution of the table. The positioning resolution of the measuring table is 0.02 degrees. The methodology used in the research consisted of performing a series of axially shifted measurements, allowing the creation of a three-dimensional image of the deformation zone area for the entire circumference of the analysed cylindrical surfaces. This makes it possible to perform three-dimensional imaging of changes in the shape of the obtained burnished surfaces depending on the method and technological parameters of the burnishing treatment performed (Figure 13). As a result, thanks to the use of computer technology, i.e., digital processing of a cloud of measurement points, it became possible to analyse the shape of the unevenness formation zone in selected cross-sections perpendicular to the axis of the burnished cylindrical surface. It was possible to recreate the shape of the material wave forming in front of the burnishing tool in the direction of the main burnishing movement. The computer-aided measurement allowed for the analysis of changes occurring in the geometry of the pressed surface, as well as the initial turned surface after the preceding machining (Figures 13 and 14).

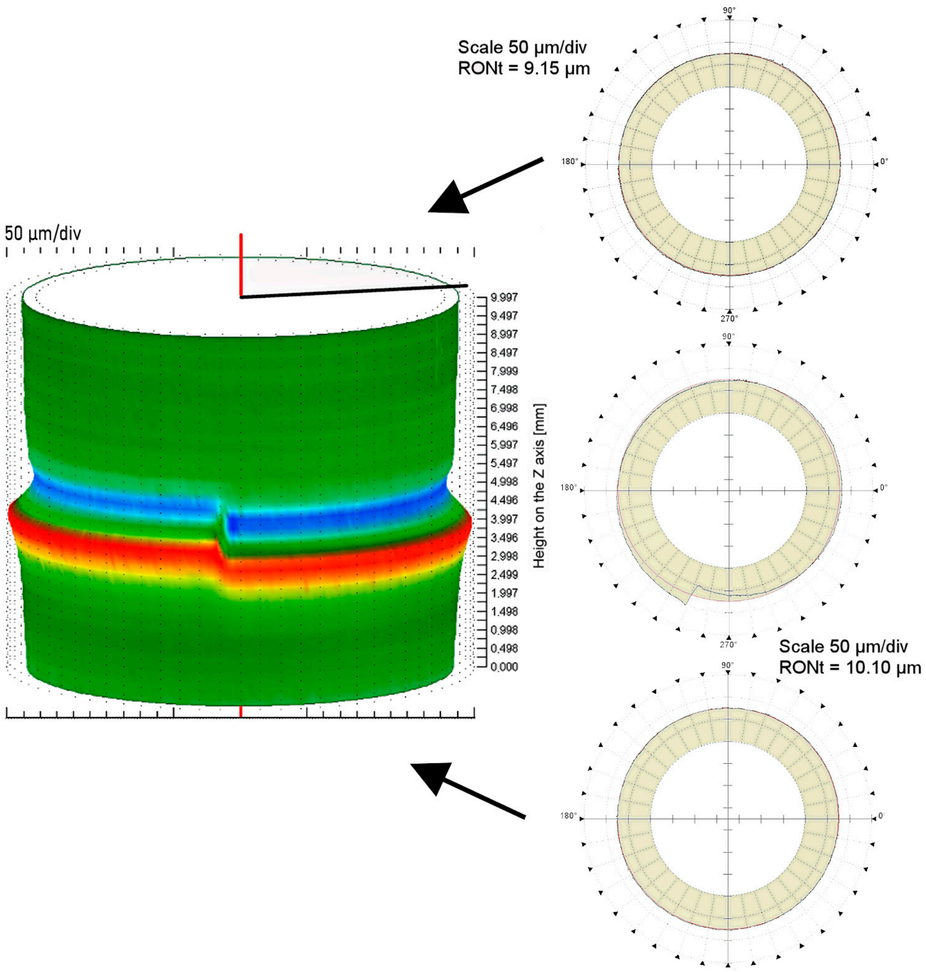
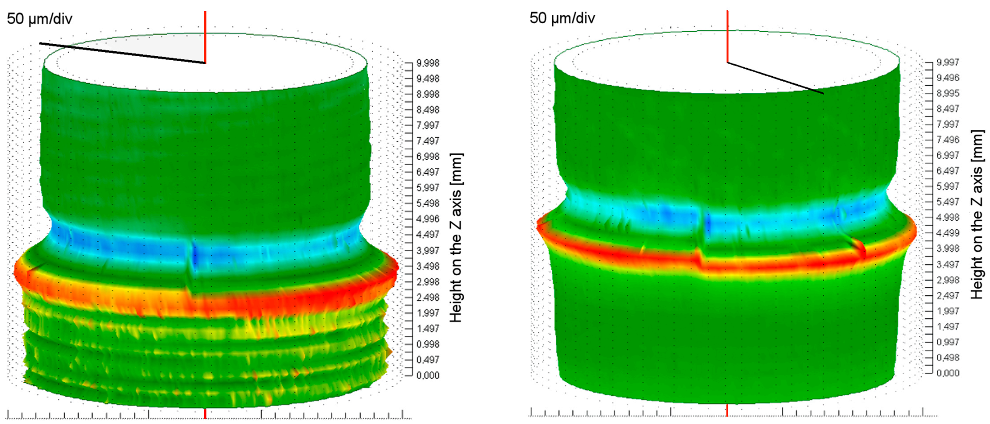


Figure 13. Ball-burnished surface (R = 5 mm, F = 2.5 kN, f_{burn} = 0.5 mm/rev)—the three-dimensional image of the burnishing zone.



(**a**) (**b**)

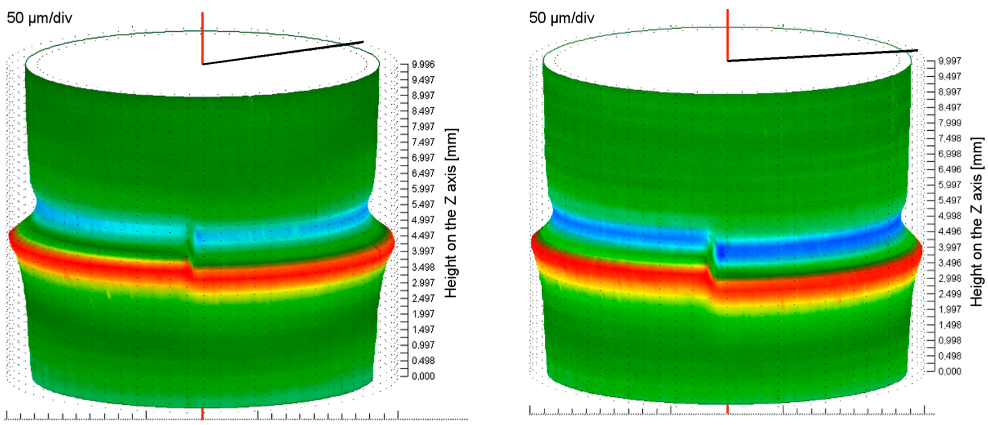
Figure 14. Ball burnished surfaces—the three-dimensional image of the burnishing zone: (**a**) (R = 5 mm, F = 2.75 kN, f_{turn} = 0.410 mm/rev, f_{burn} = 0.102 mm/rev), (**b**) (R = 5 mm, F = 2.75 kN, f_{turn} = 0.102 mm/rev, f_{burn} = 0.186 mm/rev).

The analysis of the data obtained as a result of the measurements made it possible to draw conclusions regarding the nature of changes taking place in the surface layer of the processed material. The burnishing process leads to plastic deformation of the material and, as a result, to the formation of a wave of piled-up material both in the circumferential (direction of the main movement of the tool) and axial (in the feed direction) directions. A helical groove is created around the machined surface, with a helical pitch corresponding to the feed value (Figures 13 and 14). In the area of the deformation zone, a displaced "fault" is observed—a wave of the material formed in front of the tool. Shape deviations of the pressed material are the result of processes occurring within the displaced deformation zone. The geometry of the created deformation (width and depth of the groove, pitch of the formed helix, geometry of the formed material wave) results from the material parameters (mechanical properties, shape of the primary surface, initial roughness) and the adopted technological parameters of the process (selected tool).

Figures 13 and 14 show images of the deformation zone for typical cases of burnishing (ball or disc with different radii). The comparison of deformation zones obtained for the minimum and close to the maximum burnishing forces that can be used in given conditions illustrates the variability of the formed deformation wave caused by the increasing processing force obtained for burnished surfaces characterized by different initial roughness values. In the case of significant roughness, large radius of the burnishing ball and low burnishing forces, the surface irregularities after the previous treatment were not fully deformed.

It should also be noted that the analysis of the charts (Figure 3) and drawings (Figures 12–14) leads to the conclusion that plastic deformations are not permanent, and, under the impact of elastic forces, the surface after burnishing partially returns to its original geometric dimensions. For example, the wave height of the piled-up material is approximately 1 mm, and the height difference after processing is approximately 0.01 mm to 0.02 mm, which is smaller than after the previous processing.

The analysis of the impact of changing (increasing) the burnishing feed rate (f_{burn}), from 0.186 mm/rev to 0.410 rev/mm, on changes in the geometry of the deformation zone during ball pressure burnishing allows us to conclude that the increase in feed, with other burnishing parameters remaining unchanged, leads to a clear change in the shape of the deformation zone. It is particularly visible in the case of pressure burnishing performed with a disc tool (Figure 15). There is a large increase in the height of the axial wave of material growing in front of the tool. Moreover, the shape and direction of material deformation occurring within the tool–material contact zone also changes.

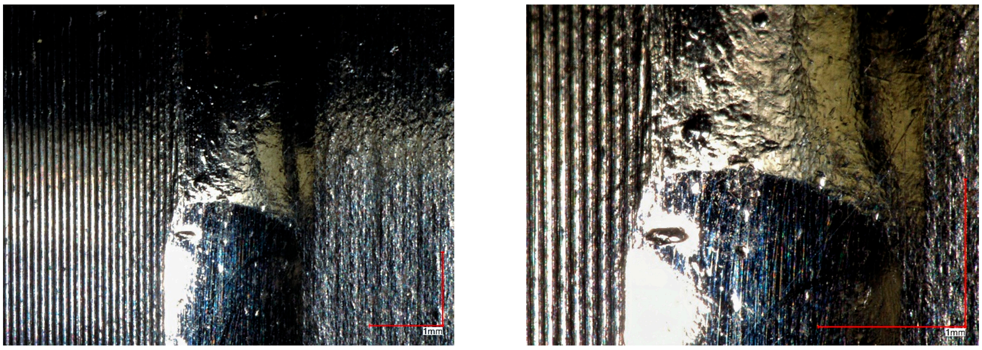


(**a**) (**b**)

Figure 15. Disc-burnished surfaces—the three-dimensional image of the burnishing zone: (**a**) (R_k = 5 mm, F = 2.75 kN, f_{turn} = 0.102 mm/rev, f_{burn} = 0.186 mm/rev), (**b**) (R_k = 5 mm, F = 2.75 kN, f_{turn} = 0.102 mm/rev, f_{burn} = 0.410 mm/rev).

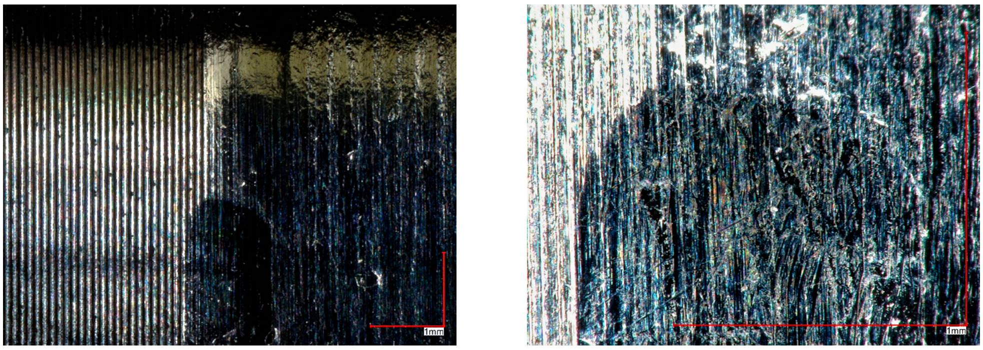
4. The Use of a Digital Microscope to Examine the Deformation Area

The three-dimensional analyses of the area of deformation occurring during burnishing presented in the article were supplemented with digital microscopic photographs illustrating the changes occurring as a result of the burnishing process on the surface of the processed material (Figures 16–20). The KEYENCE VHX-7000, Japan, digital microscope was used in the research.



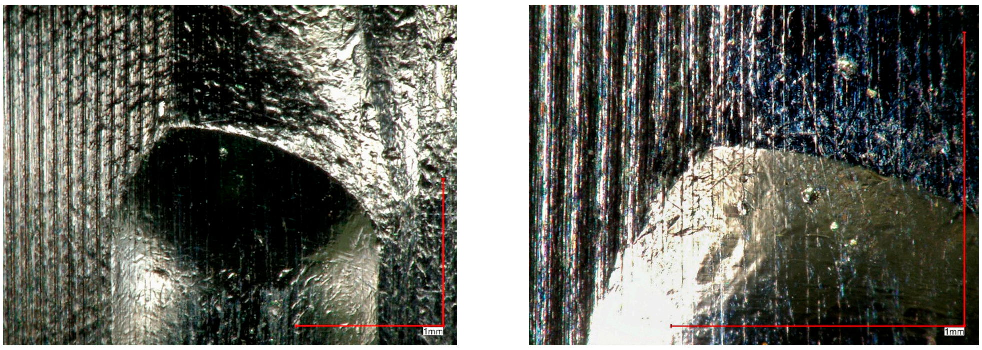
(**a**) (**b**)

Figure 16. Ball burnishing zone (R = 5 mm, F = 2.75 kN, f_{burn} = 0.186 mm/rev), mag.: (**a**) 50×; (**b**) 100×.



(**a**) (**b**)

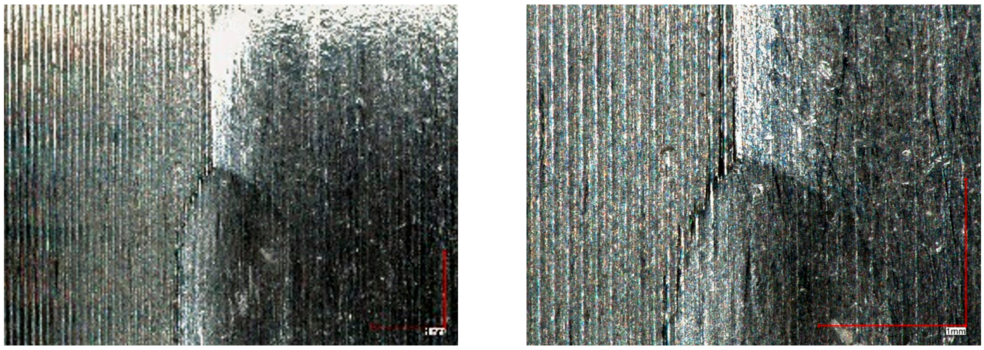
Figure 17. Ball burnishing zone (R = 5 mm, F = 2.75 kN, f_{burn} = 0.29 mm/rev), mag.: (**a**) 50×; (**b**) 200×.



(**a**) (**b**)

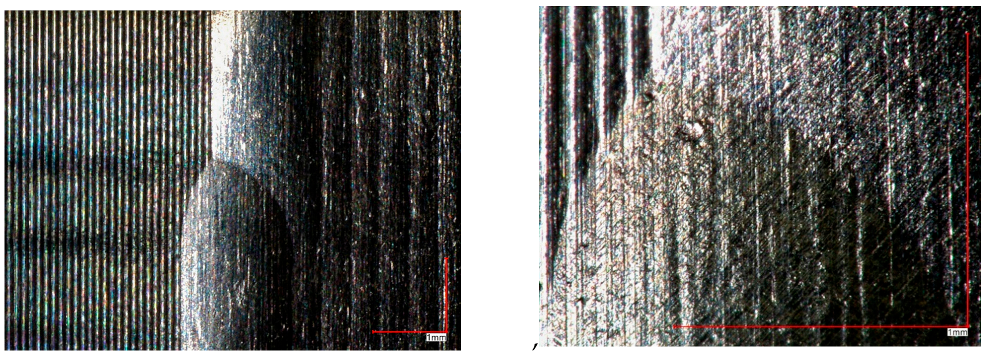
Figure 18. Ball burnishing zone (R = 5 mm, F = 2.75 kN, f_{burn} = 0.41 mm/rev), mag.: (**a**) 100×; (**b**) 200×.

The directional geometric structure of the surface resulting from the process preceding the burnishing process—machining (turning)—was replaced by a structure obtained as a result of the plastic deformation process carried out during burnishing. Microscopic photographs taken at different magnifications (from 50× to 200×) show the deformation zone caused by the burnishing process. A very characteristic feature is the occurrence of a clear, strongly plastically deformed boundary (Figures 16 and 18) between the deformed material and the area of the structure after the previous machining, which was already observed using other imaging methods. A completely new geometric structure of the surface is formed on the treated surface, resulting from the deformation taking place during ball pressure burnishing (Figures 16–18). The course of deformations occurring during the rolling pressure burnishing process with a disc tool (Figures 19 and 20) is very similar. Due to the high feed (0.41 mm/rev) used during burnishing, the surface irregularities formed as a result of the kinematic mapping of the burnishing disc passage also become visible. Microscopic photos taken with different magnifications also reveal changes in the structure of the material.



(**a**) (**b**)

Figure 19. Disc burnishing zone (R_k = 5 mm, F = 2.75 kN, f_{burn} = 0.29 mm/rev), mag.: (**a**) 50×; (**b**) 100×.



(**a**) (**b**)

Figure 20. Disc burnishing zone (R_k = 5 mm, F = 2.75 kN, f_{burn} = 0.41 mm/rev), mag.: (**a**) 50×; (**b**) 200×.

From the point of view of the analysed process, observation of the phenomena occurring at the deformation centre becomes the most important component. In the deformation zone, the roughness remaining after turning is overformed. The process begins with a boundary, shaped as a result of the kinematic reflection of the geometry of the burnishing tool. The microscopic photos taken confirm previous analyses that show that the tops of the irregularities are plastically deformed. As a result of the occurring deformation, the entire area of contact between the tool and the material changes its character. Instead of the longitudinally oriented traces of the transition of the cutting edges of the lathe tool, very characteristic of the preceding turning process (Figure 1a and the left side in Figures 16–20), a geometric structure of the material appeared on the surface, shaped as a result of the plastic deformation taking place. In the area of the deformation zone (middle part in Figures 16–20) located under the burnishing tool, traces of deformation of the plastically deformed material were revealed, with intervals resulting from the distance of the roughness of the preceding processing (turning). These traces, due to deformations occurring in the area where the tool exited the machining zone, were no longer visible in the area of the burnished surface (Figure 1b and the right side in Figures 16–20). At this point, complete plastic deformation and over-forming of the irregularities occurring before burnishing have already occurred. A new geometric structure of the material was created. The analysis of the deformation zones obtained for ball burnishing with varying burnishing feed rates (Figures 16–18) allowed for the conclusion that the increase in feed rate causes a significant increase in the geometric dimensions and depth of the deformation zone obtained as a result of burnishing. The direction of movement of the material wave has changed. The use of a disc as a burnishing tool (Figures 19 and 20) led to the formation of a deformation zone with a shape that was different from the zones obtained in the ball burnishing process. The deformation zone was noticeably longer, and its depth was smaller (Figures 18 and 19). The increase in the feed resulted in a significant increase in the height and direction of growth of the accumulated wave of material in front of the tool. Microscopic observations described in this article completely confirmed both, the previously obtained measurement results and the proposed methodology for analysing computer images.

5. Conclusions

The subject of the research was a computer-aided analysis of the focus of deformation in the mechanical burnishing process. The topics resulted directly from the industry needs. Burnishing is commonly used to change the properties of the surface layer, with particular emphasis on its strengthening. As the research has shown, the geometric parameters of the deformation centre are influenced by the conditions related to the processed material and the surface roughness parameters prior to processing, as well as the shape (type of tool) and technological parameters of the burnishing treatment process. The deformed material is displaced both in the axial direction (in the direction of feed of the burnishing element and in the direction opposite to it) and in the circumferential direction. In accordance with computer-aided analyses, the most important factor for the final effects of the tested process is the flow of the material in the axial direction, which determines the final stereometry of the surface obtained as a result of burnishing. The measurement results showed that the deformation process can occur in the part of the material covering only the roughness peaks remaining after the previous processing (which leads only to partial smoothing of the roughness peaks). When the burnishing forces are further increased, a material wave appears and grows, which (after reaching a certain force value depending on the material and burnishing parameters) exceeds the height of the roughness peaks remaining after the previous processing. In these conditions, a typical deformation centre (so-called type III deformation centre) for stable burnishing conditions, described in the literature, is created [3,4,32]. Achieving this type of deformation focus is the most appropriate process to obtain the correct properties of the surface layer obtained as a result of burnishing. This is the most important goal of properly performed burnishing. A further increase in the burnishing force and the associated increase in the growing wave of deformation leads to damage to the formed surface layer and disruption of the degree and uniformity of microhardness. Therefore, it should not be used in practice. Unfortunately, in industrial conditions, the "trial and error" method is used to determine the correct technological parameters of the burnishing process. The considerations presented in the article and the use of computer technology will contribute to the optimization of machining.

The analysis of many images and charts obtained using several methods (profilographometer, microscope, roundness gauge) of the stereometry of the deformation centre and machining burnished surfaces with various processing parameters allowed for tracing the process of shaping the deformation zone. The research results clearly show that the parameter that best describes the nature of the changes in the geometry of the deformation zone is the height of the deformation wave (h_f) determined in the axial cross-sectional plane and the size of the tool cavity in relation to the surface of the raw material (h_{fo}). These parameters are relatively easy to determine in industrial conditions. Their determination is even possible directly on the machine tool using portable roughness measuring equipment. This allows not only the proper selection of burnishing parameters, which do not lead to excessive shape errors of the obtained surfaces, but also, as a result, the elimination of the "trial and error" method from the industry.

The practical use of computer-aided measurement methods for the analysis of selected stereometric parameters and the shapes of the deformation zone of burnished surfaces, presented in the study, allows for a significant increase in the amount and transparency of information that can be obtained. It becomes possible to precisely determine the area of contact between the burnishing tool and the processed material. Thanks to this, the values of actual contact stresses in the contact zone are known. It is also possible to trace the shape changes occurring within the deformation formation zone, both in axial and circumferential cross-sections. This enables the proper selection of burnishing parameters that eliminate shape errors on the obtained surfaces and improve their microhardness characteristics.

Author Contributions: Conceptualization, A.P. and A.Z.; Validation, A.Z.; Formal analysis, A.P., A.Z. and A.T.; Investigation, A.P. and A.Z.; Data curation, A.P.; Writing—original draft, A.P.; Supervision, A.T.; Funding acquisition, A.T. All authors have read and agreed to the published version of the manuscript.

Funding: Statutory funds of the Częstochowa University of Technology BS/PB-1-100-301/2024/P.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Przybylski, W. *Low Plasticity Burnishing Processes: Fundamentals, Tools and Machine Tools*; Institute for Sustainable Technologies, National Research Institute in Radom: Radom, Poland, 2019.
2. Korzyński, M. *Sliding Burnishing*; WNT: Warsaw, Poland, 2007.
3. Tubielewicz, K. *Analysis of Stresses Arising in the Surface Layer during the Burnishing Process*; Wydawnictwo Politechniki Częstochowskiej: Częstochowa, Poland, 1993.
4. Tubielewicz, K. *Analysis of Phenomena Accompanying the Deformation of the Surface Layer in the Burnishing Proces*; Seria Monografie nr 13; Wydawnictwo Politechniki Częstochowskiej: Częstochowa, Poland, 1990.
5. Balland, P.; Tabourot, L.; Degre, F.; Moreau, V. Mechanics of the burnishing process. *Precis. Eng.* **2013**, *37*, 129–134. [CrossRef]
6. Hassan, A.M.; Al-Bsharat, A.S. Influence of burnishing process on surface roughness, hardness, and microstructure of some non-ferrous metals. *Wear* **1996**, *199*, 1–8. [CrossRef]
7. Malleswara Rao, J.N.; Chenna Kesava Reddy, A.; Rama Rao, P.V. The effect of roller burnishing on surface hardness and surface roughness on mild steel specimens. *Int. J. Appl. Eng. Res.* **2011**, *1*, 777–785.
8. Raza, A.; Kumar, S. A critical review of tool design in burnishing process. *Tribol. Int.* **2022**, *174*, 107717. [CrossRef]
9. Kułakowska, A.; Kukiełka, L. Numerical analysis of the influence of deviations of the surface roughness outline after turning on selected properties of the surface layer of a burnished product. In *Współczesne Problemy w Technologii Obróbki przez Nagniatanie*; Praca Zbiorowa pod Redakcją Włodzimierza Przybylskiego; Wydawnictwo Politechniki Gdańskiej: Gdańsk Poland, 2008; Volume 2, pp. 127–134.
10. Zaleski, K.; Skoczylas, A. Effect of slide burnishing on the surface layer and fatigue life of titanium alloy parts. *Adv. Mater. Sci.* **2019**, *19*, 35–45. [CrossRef]
11. Grzesik, W.; Żak, K. Modification of surface finish produced by hard turning using superfinishing and burnishing operations. *J. Mater. Process. Technol.* **2012**, *212*, 315–322. [CrossRef]
12. Korzyński, M. Modeling and experimental validation of the force-surface roughness relation for smoothing burnishing with a spherical tool. *Int. J. Mach. Tools Manuf.* **2007**, *47*, 1956–1964. [CrossRef]
13. Korzyński, M.; Lubas, J.; Świrad, S.; Dudek, K. Surface layer characteristics due to slide diamond burnishing with a cylindrical-ended tool. *J. Mater. Process. Technol.* **2011**, *211*, 84–94. [CrossRef]
14. Lin, Y.C.; Wang, S.W.; Lai, H.Y. The relationship between surface roughness and burnishing factor in the burnishing process. *Int. J. Adv. Manuf. Technol.* **2004**, *23*, 666–671. [CrossRef]
15. Sagbas, A. Analysis and optimization of surface roughness in the ball burnishing process using response surface methodology and desirabilty function. *Adv. Eng. Softw.* **2011**, *42*, 992–998. [CrossRef]
16. Oliveira, D.A.; Martins, A.M.; Magalhaes, F.C.; Abrao, A.M. Characterization of the topography generated by low plasticity burnishing using advanced techniques. *Surf. Coat. Technol.* **2022**, *448*, 128891. [CrossRef]
17. Swirad, S.; Wdowik, R. Determining the effect of ball burnishing parameters on surface roughness using the Taguchi method. *Procedia Manuf.* **2019**, *34*, 287–292. [CrossRef]

18. Cagan, S.C.; Pruncu, C.I.; Buldum, B.B. An investigation into ball burnishing process of magnesium alloy on CNC lathe using different environments. *J. Magnes. Alloys* **2020**, *8*, 1061–1070. [CrossRef]
19. Saldana-Robles, A.; Plascencia-Mora, H.; Aguilera-Gómez, E.; Saldana-Robles, A.; Marquez-Herrera, A.; Angel Diosdado-De la Pena, J.A. Influence of ball-burnishing on roughness, hardness and corrosion resistance of AISI 1045 steel. *Surf. Coat. Technol.* **2018**, *339*, 191–198. [CrossRef]
20. El-Tayeb, N.S.M.; Low, K.O.; Brevern, P.V. Enhancement of surface quality and tribological properties using ball burnishing process. *Mach. Sci. Technol.* **2008**, *12*, 234–248. [CrossRef]
21. El-Tayeb, N.S.M.; Low, K.O.; Brevern, P.V. Influence of roller burnishing contact width and burnishing orientation on surface quality and tribological behaviour of Aluminium 6061. *J. Mater. Process. Technol.* **2007**, *186*, 272–278. [CrossRef]
22. El-Tayeb, N.S.M.; Low, K.O.; Brevern, P.V. On the surface and tribological characteristics of burnished cylindrical Al-6061. *Tribol. Int.* **2008**, *42*, 320–326. [CrossRef]
23. Tubielewicz, K.; Zaborski, A. The course of the burnishing surface layer wear proces. *Tribologia* **2008**, *4*, 165–174.
24. Zaborski, A.; Tubielewicz, K. Analysis of the wear course of the surface layer after burnishing. In *Współczesne Problemy w Technologii Obróbki przez Nagniatanie*; Praca Zbiorowa pod Redakcją Włodzimierza Przybylskiego; Wydawnictwo Politechniki Gdańskiej: Gdańsk, Poland, 2005; pp. 255–264.
25. Zaborski, A. Analysis of the Wear Process of Surface Layers after Burnishing. *Tribologia* **2022**, *1*, 97–109. [CrossRef]
26. Kovács, Z.F.; Viharos, Z.J.; Kodácsy, J. Determination of the working gap and optimal machining parameters for magnetic assisted ball burnishing. *Measurement* **2018**, *118*, 172–180. [CrossRef]
27. Kovacs, Z.F.; Viharos, Z.J.; Kodacsy, J. Improvements of surface tribological properties by magnetic assisted ball burnishing. *Surf. Coat. Technol.* **2022**, *437*, 128317. [CrossRef]
28. Kovacs, Z.F.; Viharos, Z.J.; Kodacsy, J. Surface flatness and roughness evolution after magnetic assisted ball burnishing of magnetizable and non-magnetizable materials. *Measurement* **2020**, *158*, 107750. [CrossRef]
29. Frihat, M.H.; Al Quran, F.M.F.; Al-Odat, M.Q. Experimental Investigation of the Influence of Burnishing Parameters on Surface Roughness and Hardness of Brass Alloy. *J. Mater. Sci. Eng.* **2015**, *5*, 216.
30. Saini, D.; Kapoor, M.; Jawalkar, C.S. Parametric Analysis of Mild steel specimens using roller burnishing process. *Int. Ref. J. Eng. Sci.* **2017**, *6*, 45–51.
31. Dix, M.; Posdzich, M. Force-controlled burnishing process for high surface integrity on additive manufactured parts. *Procedia CIRP* **2022**, *108*, 642–647. [CrossRef]
32. Zaborski, A. *Analysis of Deformation Zone Formation in the Burnishing Proces*; Seria Monografie nr 260; Wydawnictwo Politechniki Częstochowskiej: Częstochowa, Poland, 2013.
33. Zaborski, A. Computer-aided measurement of geometrical parameters of the deformation zone in the burnishing proces. *Mechanik* **2019**, *8–9*, 548–550. [CrossRef]
34. *EN ISO 683-17:2015*; Heat-Treated Steels, Alloy Steels and Free-Cutting Steels—Part 17: Ball and Roller Bearing Steels. ISO: Geneva, Switzerland, 2015. Available online: https://sklep.pkn.pl/pn-en-iso-683-17-2015-01e.html (accessed on 20 January 2024).
35. Zaborski, A.; Winczek, J. Imaging and computer analysis in the shape error measurements and in the cylindrical object's stereometry. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *776*, 012077. [CrossRef]