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A BURNISHING PROCESS BASED ON THE OPTIMAL DEPTH OF WORKPIECE PENETRATION

POSTOPEK GLADILNEGA VALJANJA NA OSNOVI OPTIMALNE GLOBINE PRODIRANJA V OBDELOVANEC

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This paper deals with the problem of defining the trajectory of a stiff burnishing tool that would be optimal from the point of view of surface quality. The basic goal of this work is to gain an insight into the very process from the microscopic aspect, with the primary focus on material flow and roughness variations. Based on theoretical considerations, we planned an experiment with the aim to verify the initial hypotheses about the analysis of roughness change and a determination of the optimal depth of the workpiece penetration. Through matching and the superposition of surface profiles formed at various contact pressures, i.e., various burnishing forces and various penetration depths of the burnishing ball into the profile roughness, the phenomenon of roughness change was explained. Theoretical assumptions related to a determination of the optimum tool trajectory have largely been confirmed from the point of view of surface quality. The balls within the stiff tool system, which follow a predetermined depth of penetration into the roughness profile, very likely provide optimum surface quality, regardless of the initial machining. Based on experimental results, it is highly possible that the depth of the penetration of tool (burnishing ball) should equal the roughness profile height of the previously machined surface. The analysis of results obtained by the measurement of the surface roughness and the super-positioning of the profiles obtained by burnishing with various burnishing forces, significantly contributed to the explanation of the roughness peaks' deformation phenomenon. The proposed burnishing method could be of special importance in the burnishing of roughly machined surfaces, where R_p reaches high values. Investigations presented in this paper open a number of new directions, such as the testing of a stiff tool system with various workpiece materials and burnishing regimes, with different surface roughnesses as the result of the initial machining. We believe that the proposed model can significantly improve our present knowledge of the burnishing process.

Keywords: burnishing, surface quality, stiff tool system, profile peaks, profile valleys

Članek obravnava problem določanja optimalne trajektorije togega gladilnega orodja glede na kvaliteto površine. Osnovni cilj tega dela je vpogled v postopek obdelave na mikroskopskem nivoju, osredinjen na tečenje materiala in spreminjanje hrapavosti površine. Na osnovi teoretičnega raziskovanja so avtorji pripravili preizkus za potrditev začetne hipoteze o spremembi hrapavosti in določanju optimalne globine prodiranja v obdelovanec. Z usklajevanjem in predpostavljanjem profila površine, ki nastane pri različnih pritiskih, to je z različnimi silami pri gladilnem valjanju in za različne globine prodiranja gladilnih kroglic na profil hrapavosti, je bil pojasnjen pojav spreminjanja hrapavosti. Teoretične predpostavke za določanje optimalne poti orodja so bile potrjene s stališča kvalitete površine. Kroglice v togem orodju, ki sledijo vnaprej določenemu prodiranju v profil hrapavosti, zelo verjetno zagotavljajo optimalno kvaliteto površine, ne glede na predhodno obdelavo površine. Na osnovi eksperimentalnih rezultatov je najbolj verjetno, da naj bi bila globina prodiranja orodja (gladilne kroglice) enaka višini profila hrapavosti predhodno obdelane površine. Analiza rezultatov, dobljenih z meritvami hrapavosti površine, dobljene pri gladilnem valjanju z različnimi silami gladilnega valjanja, je pomembno prispevala k razjasnitvi pojava hrapavosti. Predlagana metoda glajenja je lahko pomembna pri gladilnem valjanju grobo obdelanih površin, kjer R_p dosega velike vrednosti. Raziskave, predstavljene v tem prispevku, odpirajo številne nove smeri, kot so preizkušanje sistemov togih orodij z različnimi materiali obdelovancev in režimi gladilnega valjanja pri različnih hrapavostih iz predhodne obdelave. Avtorji menijo, da predlagani model lahko pomembno prispeva k sedanjemu poznanju postopkov glajenja površin.

Ključne besede: gladilno valjanje, kvaliteta površine, sistem togega orodja, profil vrhov, profil dolin

1 INTRODUCTION

In manufacturing industry, surface roughness plays a vital role in product performance. Regardless of whether a product is shaped with or without chip removal, there are a number of factors that influence workpiece surface roughness, such as workpiece characteristics (physical and mechanical properties, chemical composition, micro-geometry, macro-geometry, etc.), machining equipment (stiffness, kinematics, sensitivity to heat transfers, etc.), tool (material, shape, surface quality, rigidity, wear, etc.), cooling and lubricating agent (chemical composition, viscosity, method of application, etc.), as well as the characteristics of the machining or forming process (strain, strain rates, stress distribution inside a workpiece, heat generation, etc.).[1–3] In addition to numerous machining processes (milling, grinding, polishing, honing, lapping) which contribute to a lower surface roughness,[4] there is also the burnishing process.

Ball/roller burnishing is a cold-finishing process without chip removal that plastically forms the surface layer of a workpiece. The purpose of this finishing process is not to achieve a dimensional accuracy but a surface quality with appropriate roughness,[5–10] microhardness,[11–13] wear and corrosion resistance,[14–16] fatigue- and tensile strength.[14,15,17] Furthermore, residual tensile surface stresses, which are the result of previous machining (turning, milling, etc.), are transformed by burnishing into compressive stress, thus improving several mechanical properties.[17–20] The penetration depth of compressive stresses as well as the thickness of hardened surface layer depend on the workpiece material and the applied loads. Compressive stresses decrease from the workpiece surface to the interior, while the penetration depth can reach up to 1 mm, depending on the workpiece material and the loads. Such a treatment achieves a smooth surface with a hard layer on the workpiece surface, which is the result of the deformation strengthening caused by intensive plastic deformation of the surface layer. It also diminishes the surface defects (as the result of surface plastic deformation) and modifies the surface microstructure.[21–23] Among the advantages of ball/roller burnishing are flexibility, cost-effectiveness and the possibility to use simple machining equipment.

In burnishing, the working part of the tool (hard ball or roller) is rolled over workpiece surface. As the result of rolling over the surface, high contact (Hertz) pressures occur, which overstep the yield stress, leading to plastic forming of the surface layer. Roughness peaks are deformed, and through plastic flow we begin to fill the roughness valleys between them, evening out the texture of the surface roughness.

Burnishing can be used on workpieces of various materials, such as the bronze,[24] aluminum[5,17,18,25–27] and various steels.[7,9,10,16,20–23] Brinksmeier et al.[21] showed that the burnishing of workpieces with a large content of unstable austenite can lead to a deformation-induced martensitic transformation. This proved that it is possible to include martensitic transformation in a mechanical surface treatment without introducing additional thermal processes. Besides using burnishing on various material workpieces, this process can also be applied on workpieces of various geometries, which makes it practical for treating outer and inner cylindrical surfaces as well as small- and large-area flat surfaces.

The tools that are used in this process feature a ball or a roller as the working element whose design should provide smooth rolling over the workpiece surface, without sliding and the occurrence of adhesive bonding during work. There are various design solutions that provide the free rolling of the working element, using backing-up balls[17,24] or roller bearings, as is the case in this work. The force with which the ball presses against the workpiece surface is most often regulated by calibrated springs,[24–27] although different solutions also exist, featuring pressurized fluid,[21–23,28] flexible tool holders,[29] etc. In addition, there are tool carriers that are specially designed for application on large-area flat surfaces, which reduce the processing time while being able to accommodate several simple burnishing tools.[17,30]

Numerous researchers have studied this process, investigating the influence of ball/roller material and dimensions, workpiece material, tool geometry, and process parameters, i.e., the burnishing speed, feed, pressure force, and number of passes. There are a number of papers that investigate the optimization of process parameters.[10,12,18,19,24–26] However, achieving an optimum set of burnishing parameters for a specific workpiece material requires a large number of experiments. In order to limit that number, Response Surface Methodology (RSM)[17] and the Taguchi method[24] are employed. For this reason it is very important to develop an appropriate mathematical model that predicts the surface-quality parameters with the required accuracy.[17,30,31]

Furthermore, there are a number of papers that compare burnishing to alternative processes that provide similar output results.[9,14,32–34] Also, some authors have investigated the surface quality achieved by burnishing, considering previous machining. For example, Bouzid et al.[35] have established that the best burnishing results are achieved with grinding as the initial machining. There are some authors who used finite-element analyses (FEA) to model the burnishing process, achieving satisfactory results.[34,36]

The papers analyzed in this section allow us to conclude that the burnishing force is the most influential parameter regarding surface roughness, hardness, thickness of the hardened layer, as well as the likelihood of surface damage (layer peeling) during processing. Gharby et al.[30] have investigated the burnishing of AISI 1010 steel plates and established a limit of 400 N burnishing force, stating that above this limit the workpiece surface layers begin to peel off. The same author[17] conducted experiments on 1050A aluminium and established an optimal burnishing force of 115 N, pointing out that a combination of large burnishing forces and large feeds deteriorates the surface roughness. Most of the investigations dealing with this subject varied the burnishing force within the range 0–400 N. In this paper we focused on the influence of the burnishing force on the surface roughness, while the force was varied within the range 0–450 N.

The optimal forces are determined for specific workpiece material types and their characteristics. From the reviewed literature it can be concluded that the burnishing force is used as an optimization parameter. However, considering the very burnishing process (surface strengthening and surface quality), it is better to consider the magnitude of the contact pressure between the burnishing ball and the workpiece surface as an optimization parameter. A numerical determination of the magnitude and the distribution of contact pressures requires data on the ball/roller radius, the radius of workpiece surface curvature (in the case that the burnishing is performed on a lathe, it is the billet radius, otherwise, for flat surfaces, an infinite radius of curvature is assumed), and the data on the module of elasticity and the Poisson coefficient for the workpiece and the ball/roller material. However, most often the available literature on the subject of burnishing does not provide these data. Bearing in mind that the profiles of the machined surfaces are inherently stochastic, it is extremely difficult to determine the values of the contact pressures with the required certainty. All this considered, most investigators of burnishing process choose to consider the burnishing force as the parameter of influence, rather than the more relevant contact pressure.

Considering the large number of material types in industrial applications and the wide range of their properties, the broader application of the burnishing process would require an extensive database with the optimal contact pressures for all types of materials. This is especially true if one considers that the optimal contact pressure is not only related to the workpiece material characteristics but also to the process parameters (feed, number of passes, initial surface quality, etc.).

For that reason, the focus of this investigation is placed on establishing the depth to which the stiff burnishing tool penetrates the roughness valleys, i.e., the optimal value for this depth which, considering the force magnitude and other process parameters, provides near-optimal surface quality.

The available references mostly agree on ranking the influential parameters (burnishing force, feed, number of passes and other factors) based on their relative impact on the surface quality. However, an optimal surface roughness can be achieved at various levels of burnishing forces. Therefore, optimal burnishing forces depend on the workpiece material properties and the ball/roller diameter, the burnishing parameters and the initial surface quality. It is worth noting that the investigations published so far have not looked into the phenomenon of roughness peaks, which leaves space for an investigation into the changes that take place in the surface roughness during the burnishing.

The initial hypothesis in this investigation supposes that it is possible to define a near-optimal penetration depth of the burnishing tool into the workpiece roughness profile, which would result in a near-optimal surface quality, depending on the magnitude of the burnishing force and other burnishing parameters.

Within this investigation, experiments were conducted with the aim to verify the initial hypotheses pertaining to an analysis of the surface topography changes and a determination of the near-optimal tool trajectory. By monitoring the changes that take place in the roughness profiles at various depths of tool penetration into the roughness valleys, an optimal penetration depth was determined that corresponds to the minimal surface roughness (R_a). In these experiments a specially designed stiff tool system was employed. It should be noted that the phenomenon of workpiece surface strengthening was not within the scope of this investigation. As previously discussed, this study is dealing primarily with the problem of workpiece surface quality in burnishing, and also looks into the problem of optimizing the surface quality as a function of tool (ball) penetration depth into the workpiece surface roughness profile. Finally, experimental investigations were performed on a tempered steel.

2 THEORETICAL CONSIDERATIONS

In this section theoretical considerations of the burnishing process are presented as the rolling of a ball over the roughness peaks on the previously machined workpiece (**Figure 1**). The burnishing is performed with a tool system of high stiffness, consisting of a ball with a defined radius *R*, mounted on a carrier that provides free rolling.

During the burnishing process the burnishing ball is also exposed to lateral forces. The theoretical model proposed in this paper does not consider these forces for the following reasons:

- The rolling resistance of the ball during relative motion over the workpiece surface represents the lateral force. This force can be neglected, considering the 0.001 order of magnitude of the rolling resistance coefficient, as well as the relatively high ratio between the normal (vertical) load and the rolling resistance.
- The remaining lateral forces can also be neglected if one considers the exclusively large ratios between the ball radius and the maximum surface profile peak height, which is often the case in ball burnishing. In such conditions the angle between the lines drawn from the ball centre, connecting the two points of ball/profile contact, is very small, which means that the vertical load on the burnishing ball is predominant, as illustrated in **Figure 2**.

The considered model pertains to static loads, neglecting the dynamic force component. This is justified in cases when burnishing is performed at relatively low

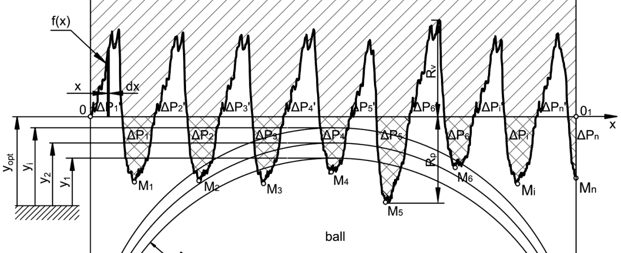

Figure 1: Theoretical analysis of the burnishing process based on a stiff tool system

Slika 1: Teoretična analiza postopka gladilnega valjanja, zasnovanega na sistemu togega orodja

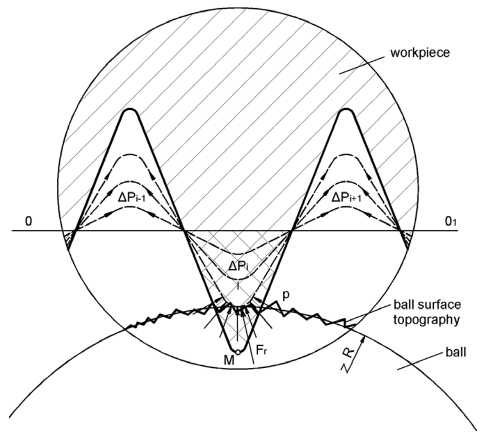

Figure 2: The contact zone during ball burnishing and the supposed directions of material flow

Slika 2: Kontaktno področje med procesom gladilnega valjanja in predvidena smer toka materiala

speeds, which is the case in this experimental investigation. The authors maintain that, given the discussed restrictions, the developed model can prove useful in clarifying the phenomenon of workpiece surface profile variations at various penetration depths of a stiff tool system.

Depending on the ball radius, the roughness pitch and the roughness form, the contact between the ball and the workpiece is established over one or more roughness peaks (neighbourhood of points M_1, M_2, ... M_n). In the course of the ball's penetration into the roughness profile, over the planes parallel to OO_1 axis, the area of the contact surface between the ball and the roughness peaks increases. For a predefined tool displacement, y_i, (tool movement into roughness profile, from a reference point) there follows: $F(y_1) \geq F(y_2) \geq ... \geq F(y_i)$, where $F(y_i)$ is the force corresponding to the y_i coordinate.

If the goal is to achieve the maximum surface quality, it is essential to establish the depth, y_{opt}, which represents the optimal tool penetration into the roughness profile.

One of the possible models of material flow in the contact zone during burnishing is presented in **Figure 2**. Due to the high contact pressures that exceed the yield stress, roughness peaks begin to flow and gradually fill the valleys. It is well known that surface strengthening should be the most pronounced in the layers closer to the profile peaks. In other words, the intensity of the surface strengthening drops towards the profile valleys. This results in the fewer hard material layers being suppressed towards the profile valleys by the layers of greater hardness.

As the tool penetration depth, y, increases, the roughness valleys are filled. We supposed in this work that the tool penetration depth y should be determined based on the recorded surface roughness profile prior to burnishing, according to:

$$y \approx R_p \tag{1}$$

where: R_p is the maximum height of the surface roughness profile before burnishing. The resulting equality is:

$$\sum_{i=1}^{i=n} \Delta P_i \cong \sum_{i=1}^{I=n} \Delta P_i' \tag{2}$$

where ΔP_i is the surface area of i-th peak relative to the mean profile line, $\Delta P_i'$ is the surface area of i-th valley relative to mean profile line, that is:

$$\int_0^L f(x)\mathrm{d}x \bigg|_{f(x)<0} \cong \int_0^L f(x)\mathrm{d}x \bigg|_{f(x)>0} \tag{3}$$

Evidently, the roughness profile curve of the previously machined surface (prior to burnishing) does not have an analytical function, $f(x)$. However, based on the numerical data obtained by modern devices for surface-roughness measurements it is possible to check whether the condition of approximate equality between the surface areas of the profile peaks and the valleys processed by burnishing. This should require dedicated software, which is one of the goals for future investigation. The assumptions made in this work claim that the optimal surface quality in burnishing of previously machined surfaces is achieved for a tool penetration depth that equals the maximum peak height, R_p, which roughly conforms with the condition of equality between the surface areas of the roughness peaks and valleys. These assumptions are based on the following facts:

- The material which flows along the surface roughness peaks should be allowed some space to deposit (**Figure 2**). The condition of equality between the surface areas of the peaks and valleys theoretically allows a simultaneous decrease of the roughness peaks, R_p, and the roughness valleys, R_v.
- When the tool (ball) is displaced for y_{opt} relative to some reference location into the roughness profile, the material will flow from the peaks, filling the valleys and leaving the profile without additional peaks.
- Presumably, the flow of material in the surface peaks predominantly occurs through the widening and narrowing of peak profiles. This claim is supported by assumption that, due to the large ratio of the ball radius (R) and the relatively small feeds used in the initial machining, the resulting contact force that compresses the profile peaks probably assumes a direction normal to the mean profile line (**Figure 2**). Thus, regardless of the stochastic nature of the initial surface roughness profile, it is realistic to expect that the proposed burnishing method, based on a stiff tool system, will yield a better surface quality compared to the burnishing tools that operate with a constant force (provided by spring mechanisms). Due to variations in the material resistance, such tools oscillate considerably, which represents the source of the additional roughness and profile waviness.

To confirm the theoretical assumptions, **Figure 3** presents the results of preliminary investigations that

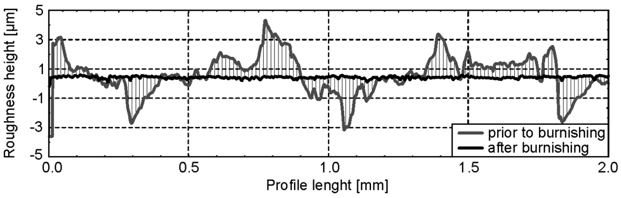

Figure 3: Superimposed recordings of the surface profiles
Slika 3: Prekrivanje meritev hrapavosti površine

involved a stiff tool system with the ball penetration depth limited to the maximum peak height. The same scale was used to represent the superimposed surface roughness profiles before and after the completion of the burnishing process. The finished surface of very small roughness, R_a = 0.061 µm (**Figure 3**), was obtained with a 5 µm penetration depth, which approximately corresponds to a maximum profile peak height, R_p = 4.3 µm, of the same surface prior to burnishing.

3 EXPERIMENTAL INVESTIGATION

The experimental investigation included burnishing of the cylindrical surface. The burnishing was performed on a specimen (billet) of tempered steel, 36CrNiMo4, hardness 42 HRC. The specimen dimensions were d = 50 mm and L = 400 mm. The burnishing was performed on a universal lathe (**Figure 4**) with a specially designed stiff tool system, a technical drawing of which is shown in **Figure 5**. The system was designed with three roller bearings that support the burnishing ball at the areas defined by the neighbourhoods of three points, ensuring that the ball rolls in a plane. The burnishing ball featured a 7 mm diameter and was made of steel, A 295 52100 (USA/ASTM). The ball hardness was 65 HRC, while its surface roughness was equal to R_a = 0.02 µm.

Figure 4: Photograph of burnishing tool in operation
Slika 4: Posnetek orodja med gladilnim valjanjem

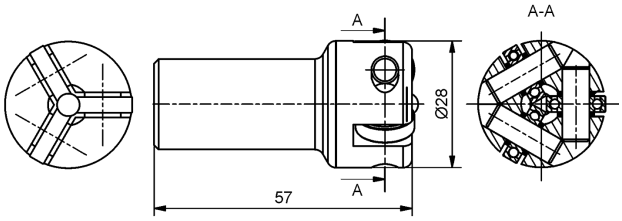

Figure 5: Technical drawing of burnishing tool system
Slika 5: Tehnična risba orodja

Considering the burnishing ball, it should be noted that, due to the limited load capacity of the small roller bearings (**Figure 5**), the maximum allowed force on the ball is limited to F = 600 N. Thus, it is important to emphasize that it was not possible to perform burnishing with penetration depths above the maximum peak height on the previously machined surface.

The burnishing was performed in a single pass, with a feed rate f = 0.05 mm/r and the number of revolutions n = 45 r/min. A small number of revolutions was selected in order to eliminate the negative thermal and dynamic effects. Considering the initial hypotheses and the goal of this investigation, the tendency was towards avoiding intensive heating of the burnishing ball, as well as any significant vibrations of the tool system and the workpiece. All this allowed a deeper insight into the very process, as well as a more realistic comparison between the proposed theoretical model and the experimental results. Loads were applied using a cross slide on a universal lathe. Mounted on the lathe was a dynamometer, Kistler 9265A, which supported the tool system. The level of loading was determined by this dynamometer prior to the initiation of the burnishing process. Also, during the burnishing process, the Kistler 9265A dynamometer was used for continuous monitoring of the burnishing force used in the process. Both workpiece sections were previously lathed to different surface roughness and subsequently burnished with six different burnishing forces. Upon completion of the burnishing process, a Talisurf 6 was used to measure the burnished surface roughness parameters (R_a and R_p). Measurements were taken in both sections (initial machining 1, and initial machining 2), along the contour lines on the workpiece, in three radial directions oriented at 120° relative to the axis of the workpiece. **Figure 6** shows a

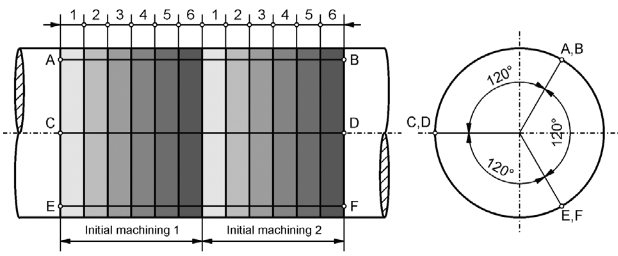

Figure 6: Schematic drawing of the fields in which the burnishing forces were measured, and the locations of the contour lines along which the roughness measurements were taken
Slika 6: Shematičen prikaz polj, na katerih so bile izmerjene sile med gladilnim valjanjem, in položaj linij, vzdolž katerih je bila izmerjena hrapavost

drawing with the marked sections used to measure the burnishing forces, showing the locations of the contour lines along which the roughness measurements were taken. The referential length for taking the roughness measurements equalled 3 × 0.8 = 2.4 mm. Burnishing was performed on two previously machined surfaces with different roughness (initial machining 1, and initial machining 2 – **Figure 6**). The first initial machining was performed with the following parameters: feed rate f = 0.5 mm/r, depth of cut d = 1 mm, and number of revolution n = 710 r/min. The second initial machining was performed with f = 0.1 mm/r, while the rest of parameters were identical to the first initial machining.

4 RESULTS

The experimental results encompass the data on the burnishing forces that were used in the process as well as the data on the roughness parameters of the burnished surfaces.

Table 1 presents the mean values of the burnishing force, the standard deviations, the minimum and maximum burnishing forces generated during the process, and the surface-roughness parameters (arithmetic mean surface roughness, R_a, maximum peak height, R_p, and maximum valley height, R_v). Based on the maximum peak height on the profile of the previously machined surfaces, $R_{p(init)}$, as well as the maximum peak height, $R_{p(F)}$, measured upon completion of the burnishing process in a particular section and along a particular contour line, the ball penetration depths were calculated according to:

$$y = R_{p(init)} - R_{p(F)} \quad (4)$$

Thus, the values of y represent the real ball-penetration depths into the roughness profile. These values were measured after the completion of the burnishing process, which eliminated the errors due to the elastic deformations of the workpiece, tool system, and support.

We believe that measurements of the maximum peak heights along the three profile lines helped mitigate the negative influence of technological errors (deviation from circularity during the workpiece rotation and the workpiece elasticity). This influence is manifested through a more or less pronounced dispersion of the burnishing force within particular sections. It is not only a logical assumption, but was actually observed in the experiment, that each variation in the burnishing force within a burnishing section, resulted in a roughness

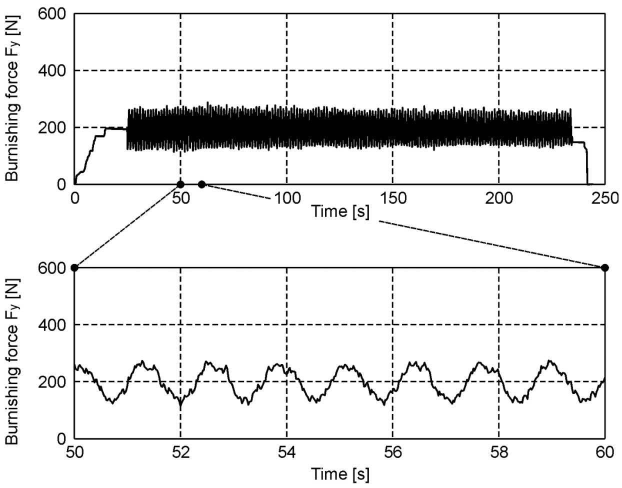

Figure 7: Typical recording of the burnishing force signal
Slika 7: Značilen zapis signala sile pri gladilnem valjanju

Table 1: Results of the experimental investigation
Tabela 1: Rezultati preizkusov

Forces and roughness parameters			Initial machining 1						Initial machining 2					
			R_a [µm]		R_p [µm]		R_v [µm]		R_a [µm]		R_p [µm]		R_v [µm]	
			7.3 ÷ 7.53		15 ÷ 16		–13 ÷ –14		4.5 ÷ 5.4		14 ÷ 17		–16 ÷ –19	
			Number of measurement – force variation –						Number of measurement – force variation –					
			1	2	3	4	5	6	1	2	3	4	5	6
Forces and dispersion of forces		F_{ysr} [N]	47.98	67.41	32.30	55.53	213.28	320.70	81.75	166.08	194.86	322.37	305.21	444.28
		σ_{Fn} [N]	25.21	36.32	26.05	40.51	103.20	103.46	34.71	52.74	39.88	47.98	38.31	56.77
		F_{ymin} [N]	8.14	16.74	0	3.16	74.32	125.57	21.31	83.00	113.49	216.88	220.71	318.03
		F_{ymax} [N]	111.68	169.94	103.88	169.23	432.60	577.61	182.97	289.21	287.77	428.39	389.76	569.26
Profile line on workpiece	AB	R_a [µm]	6.6	6.9	6.6	6.9	4.1	1.04	0.84	1.33	1.05	0.49	0.85	0.774
		R_p [µm]	13	15	13	15	9	1.9	3.6	3.5	2.5	1.3	2	2.27
		y [µm]	3	1	3	1	7	14.1	13.7	13.8	14.8	16	15.3	15.03
	CD	R_a [µm]	5.7	5.06	3.69	4.31	0.57	0.84	1.82	0.627	0.51	0.41	0.5	0.52
		R_p [µm]	12	8.8	7.8	8.6	1.3	1.8	5	2.02	1.4	1.5	1.2	1.3
		y [µm]	4	7.2	8.2	7.4	14.7	14.2	12	14.89	15.6	15.5	15.8	15.7
	EF	R_a [µm]	6.59	6.85	6.1	6.35	2.75	1.2	1.89	0.88	0.76	0.54	1.01	0.55
		R_p [µm]	13.1	14.3	12.3	12.6	4.3	2.3	6.1	2.4	2.4	1.5	2	2.8
		y [µm]	1.9	0.7	2.7	2.4	10.7	12.7	7.9	11.6	11.6	12.5	12	11.2

deviation (see the measurement results for R_p, along profile lines AB, CD, and EF – **Table 1**).

A typical example of a burnishing-force signal recording is shown in **Figure 7**. In the burnishing force signal pattern one clearly distinguishes near-periodic variations within a single revolution. Namely, the force variations repeat every 1.33 s, which approximately corresponds to n = 45 r/min. This indicates that variations in the burnishing-force magnitude, and, consequently, variations in the surface quality, occur due to errors in the number of workpiece revolutions degrees of its elastic deformations in particular sections, which inevitably leads to variations in the contact pressure between the tool and the workpiece surface. Since the experiment was performed with an extremely stiff tool system, minor errors in the circularity of rotation and small deviations in the workpiece elastic deformations were sufficient to generate a significant dispersion of the burnishing force.

Through the processing of measurement signals acquired with the Talisurf 6 profilometer, the profiles of treated surfaces were superimposed for a visual analysis of the changes in the surface roughness due to a varied burnishing force. **Figures 8** and **9** show the superimposed profiles generated by applying different burnishing forces on two surfaces previously machined to various surface-roughness values. These diagrams (**Figures 8** and **9**) pertain to the first initial machining, with the surface roughness ranging within the R_a = 7.3–7.53 μm interval. From the diagrams in **Figures 8** and **9** we can see that the increase of the burnishing force gradually leads to a significant reduction of the surface roughness.

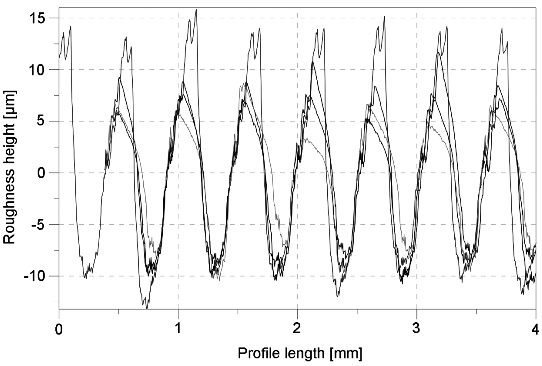

Figure 8: Superimposed profiles generated by burnishing after the first initial machining, with F = 32 N, F = 47 N and F = 67 N
Slika 8: Prekrivanje profilov, dobljenih pri glajenju s silo F = 32 N, F = 47 N in F = 67 N, na predhodno obdelani površini

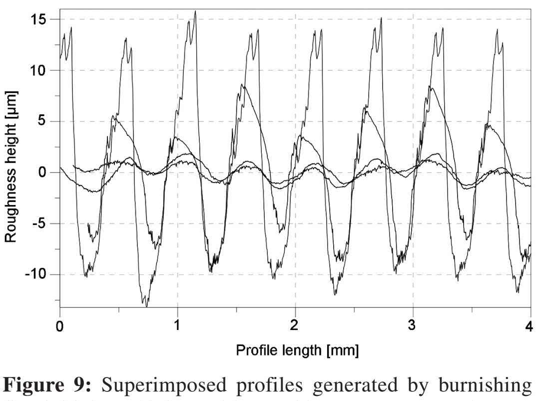

Figure 9: Superimposed profiles generated by burnishing after the first initial machining, with F = 55 N, F = 213 N and F = 320 N
Slika 9: Prekrivanje profilov, dobljenih pri glajenju s silo F = 55 N, F = 213 N in F = 320 N, na predhodno obdelani površini

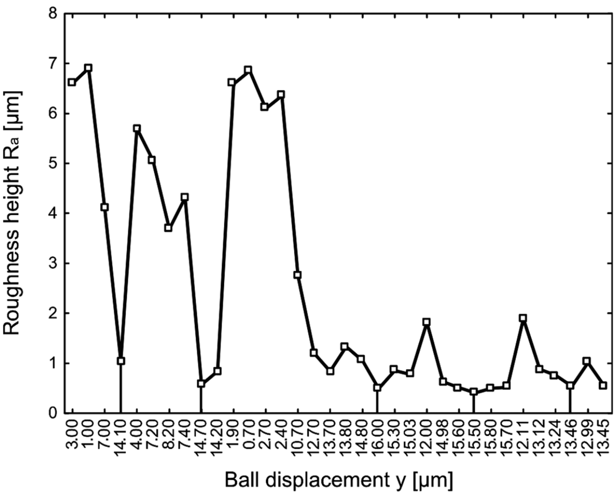

Figure 10: Dependence of the surface roughness R_a, on the depth of the ball penetration into the roughness profile
Slika 10: Odvisnost hrapavosti površine R_a od globine prodiranja kroglic v profil hrapavosti

It is interesting to note that for both initial machinings, the ball penetration depths that are close to the maximum peak height of the previously machined surface correspond to lowest R_a values (**Table 1**).

Based on the data from **Table 1** the diagram in **Figure 10** shows, for both initial machinings, the dependence between the roughness, R_a, and y, which represents the ball penetration depth. For both initial machinings, the diagram shows an obvious trend of the surface roughness (R_a) variations as a function of the ball penetration depth. Evidently, for both initial machinings, the surface roughness drops sharply until it reaches the maximum peak height of the previously machined surface roughness profiles, i.e., $y = R_p$ = 14–17 μm. After that point, the surface roughness decreases very slightly.

5 DISCUSSION

Numerous authors have focused their investigations on defining the optimal burnishing force. As previously discussed, the widespread and efficient application of burnishing should require an extensive database containing optimal values for the burnishing forces that are a function of a number of parameters (workpiece material, burnishing feed, number of passes, and quality of surface prior to burnishing). In this work the focus is placed on defining the appropriate penetration depth of a stiff burnishing tool system, i.e., the depth that will provide an optimal surface roughness, regardless of the force magnitude and the other parameters of the burnishing process. Discussed were the basic theoretical considerations according to which the rolling of a ball within a stiff tool system, and the penetration into the roughness profile up to the predefined depth, are very likely to provide near-minimal surface roughness, where equalities (1) and (3) apply.

The basic assumptions in this paper were largely confirmed by the results of the experimental investigation. The diagram in **Figure 10** clearly indicates that the displacement of the burnishing ball into the roughness profile, *y*, which is close to the maximum peak height of the previously machined surface-roughness profiles, provides the lowest surface roughness, R_a. For the first initial machining (**Table 1**) the maximum peak height is in the range R_p = 15–16 μm. From the diagram in **Figure 10** it is evident that y = 14.7 μm (measured along the profile line CD – **Table 1**), which corresponds to R_p = 15–16 μm in the case of first initial machining, results in the near-minimal surface roughness, R_a = 0.57 μm (see **Figure 10** and **Table 1**).

Considering the second initial machining (**Table 1**), the maximum peak height is in the range R_p = 14–17 μm. The diagram shown in **Figure 10** clearly indicates that y = 15.5 μm (measured along the profile line CD – **Table 1**), which corresponds to the maximum peak height, R_p = 14–17 μm, results in a near-minimal surface roughness, R_a = 0.41 μm. It should be noted that in the case of the second initial machining (**Table 1**) on the profile lines AB and CD there are a number of y values that are approximately equal to R_p = 14–17 μm, and which correspond to a near-minimal surface roughness, as shown in **Figure 10**. Based on the previous discussion, and the diagram in **Figure 10**, it is logical to suppose that the optimum ball-penetration depth equals the maximum peak height, R_p, of the previously machined surface. This claim is also supported by the trend of the change of surface roughness R_a depending on the ball-penetration depth (**Figure 10**). Based on the diagram shown in **Figure 10** it is obvious that, for both initial machinings, the surface roughness, R_a, drops significantly until the ball-penetration depth reaches the maximum peak height achieved with the previous machining. After that, the decrease of R_a is significantly milder. With the first initial machining (higher surface roughness) the percentage change of the surface roughness, R_a, is significantly higher. Thus, regardless of the surface quality obtained with the previous machining, the values of y that are close to the maximum peak height, result in the lowest values of surface roughness. This fact can be valuable when applying burnishing on surfaces with a rough previous machining.

Therefore, a high surface quality can be achieved with a tool displacement that corresponds to the maximum peak height, R_p, of the previously machined workpiece surface. It is evident that the material flowing from the profile peaks should be allowed allocation space (**Figure 2**). Besides, the condition of equality of the cross-section surface areas of the roughness peaks and valleys theoretically allows the simultaneous decrease of the peak, R_p, and the valley height, R_v. The material which flows from the profile peaks fills up the valleys leaving the profile without additional peaks. The theoretical claim that material flow from the peaks mostly manifests as their widening, is convincingly illustrated by the experimental results (**Figures 8** and **9**). Experimental investigations were conducted on a universal lathe and it was not possible to precisely define the depth of the ball penetration into the roughness profile. In other words, the limited accuracy of the lathe slide ways, the presence of clearances and the system compliance prevented the burnishing ball from moving exactly along the direction defined by the theoretical considerations. For that reason, we determined the required displacement in an indirect way, monitoring the variation of the forces during burnishing. Thus, the forces were periodically increased in order to achieve a penetration depth that approximately equals the maximum peak height of the previously machined surface, R_p. The diagrams in **Figures 8** and **9** clearly show a gradual decrease of the roughness over the 32–320 N force interval. One of the basic goals was to visually identify the oscillation of the profile curve of the burnished surface, around the line that divides the profile of the previously machined surface into two, approximately equal, surface areas of peaks and valleys (**Figure 9**).

6 CONCLUSIONS

Theoretical assumptions pertaining to defining an optimal tool trajectory that results in the best surface quality were largely confirmed in this experiment. A ball rolling within a high-stiffness tool system, according to a predefined penetration depth, provides a near-optimal condition, i.e., minimal surface roughness, regardless of the quality of the initial machining. Based on the experimental results, the ball should penetrate the surface roughness profile up to a depth that approximately equals the maximum peak height achieved by the initial machining. The results of this study allow the assumption that ball-penetration depths beyond R_p do not significantly contribute to the surface quality, primarily because the displaced material should create new, probably higher profile peaks. According to the results of the measurement, regardless of the surface quality on a previously machined surface, the value of y that is close to the maximum peak height results in the lowest R_a. This could be especially valuable when burnishing relatively rough surfaces.

An analysis of the surface-roughness measurement results and the super positioning of the profiles generated using various burnishing forces and tool displacements, largely explained the phenomenon of the roughness peaks' deformation. Having this and the theoretical considerations in mind, we can conclude that the defined penetration depth, $y \approx R_p$, satisfies the condition of approximate equality of surface areas defined by the roughness profile peaks and valleys. The proposed burnishing methodology could be especially valuable when dealing with roughly machined surfaces with significant R_p.

The research reported in this paper opens up a number of new, interesting directions for research, such as the testing of a stiff tool system with various workpiece materials, different burnishing regimes, and various surface roughnesses as a result of the initial machining. We believe that the proposed model casts new light on the burnishing process. It opens up new directions of research involving stiff tool systems and penetration depths that yield a near-minimal surface roughness, regardless of the workpiece material, the burnishing parameters, and the initial surface roughness. Future work should involve an investigation of surfaces that drastically differ from the aspect of the surface roughness achieved by previous machining. They should be penetrated by a burnishing ball beyond the maximum profile peak height. In this way it would be possible to verify the results obtained in this study as well as open up new directions for research on the burnishing process.

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