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A NEW SINGLE-ROLLER BURNISHING TECHNIQUE DECREASING ROUGHNESS OBTAINED

J. T. MAXIMOV[1], G. V. DUNCHEVA[2], I. M. AMUDJEV[3], K. K. KRUMOV[4] and T. V. KUZMANOV[4]

[1]Department of Applied Mechanics
Technical University of Gabrovo
Bulgaria
e-mail: maximov@tugab.bg

[2]Department of Machine Elements
Technical University of Gabrovo
Bulgaria

[3]Department of Mechanical Engineering Equipment and Technologies
Technical University of Gabrovo
Bulgaria

[4]Department of Mechanical Engineering Equipment and Technologies
Technical University of Sofia
Bulgaria

Abstract

This article presents outcomes from comprehensive study of a new single-roller burnishing technique of external cylindrical surfaces, directed to achieving smaller roughness of workpieces made of low alloyed constructional steel. The method differs from the conventional roller burnishing because it is performed in conditions of tangential and axial skid between the deforming roller having toroidal operating surface and the workpiece being burnished. This positive effect for roughness has been achieved by a single-roller burnishing device, allowing crossing of the roller and the burnished workpiece axes, as well as adjusting the

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crossing angle. The process has been studied experimentally by an optimal composed-second-order experimental design. The levels of the burnishing parameters have been determined by means of a preliminary experiment and a one-factor-at-a-time method has been employed to this purpose. On the basis of a conducted analysis of variance (ANOVA) and analysis of regression, the optimal burnishing parameters for obtaining minimal roughness have been determined. Using the obtained optimum parameters, an additional experiment has been carried out with 10 types of lubricants. It has been found that the roughness obtained is minimum when the liquid lubricants Blasocut 2000 and kerosene were used. By means of an additional experiment conducted with the optimum burnishing parameters and using Blasocut 2000, it has been found that the optimal number of passes is three, and the minimum roughness $R_a = 0.1\mu m$ has been obtained.

1. Introduction

The set of characteristics (roughness, micro-hardness, residual stresses, micro-structure), determining the condition of the superficial layer of the structural components, is known in publications as surface integrity [13]. The latter affects directly the function performance of the components and has a significant effect on their properties as fatigue strength, load-carrying capacity, wear resistance, and corrosion resistance. For a certain material, the surface integrity depends to a great extent on the type of the surface finish-by cutting or by plastic deformation of the superficial layer, known as *burnishing*. The advantages of burnishing technologies regarding the superficial layer quality were established by many authors. Jujerm and Altenberger [8] demonstrated the effectiveness of the deep rolling process for enhancement of the fatigue life of cylindrical specimens made of austenitic stainless steel AISI 304 and normalized plain carbon steel SAE 1045 in the conditions of high cycle fatigue regime. Zhang and Lindemann [22] investigated the effect of applying roller burnishing to high cycle fatigue strength of wrought magnesium alloy AZ80. They found the optimal rolling force and achieved improvement of fatigue strength by about 110%. A new burnishing method based on a spherical motion of the deforming tool having internal toroidal working surface has been developed by Maximov et al. [11]. Yeldose and Ramamoorthy [21] demonstrated the benefit from using TiN-coated rollers in the burnishing process. A comprehensive study of ball and roller burnishing and the influence of the quality of the surface treated on the fatigue life of the corresponding structural component has been carried out by Suchkov [18]. Significant research work in the field of burnishing technologies has been carried out by Ecoroll-AG, Germany, as well as at the laboratory WZL/RWTH, Aachen, under the guidance of Klocke [9].

According to the classification made by Korzynski [10], the burnishing methods can be classified as smoothing, dimensional, hardening or mixed. This paper considers the first group. By burnishing, has been achieved roughness within $R_a = 0.2 \div 0.6 \mu\text{m}$ depending on the adopted method. Smaller roughness is achieved by combined and special burnishing methods. Tian and Shin [19] developed a novel laser-assisted burnishing method applied to hard materials. Ultra-precision surface finish of mould tool steel by using sequential ball burnishing and ball polishing processes has been proposed by Shiou and Cheng [15]. Surface finishing of hardened and tempered stainless tool steel by using sequential ball grinding, ball burnishing, and ball polishing processes on a machining centre has been developed by Shiou and Hsu [16]. Bozdana et al. [1] developed a new ultrasonic deep rolling technique for treating thin components. Shiou and Ciou [14] introduced a new vibration-assisted spherical polishing system to improve the burnished surface roughness of hardened stainless mold steel. A roughness of $R_a = 0.045 \mu\text{m}$ is achieved. A new hybrid burnishing method was developed by Radziejewska et al. [12]. Ebejd and El-Taweel [2] developed a nowel combined process including electrochemical turning and roller burnishing.

One of the most widely used methods for mechanical surface treatment of external cylindrical surfaces is roller burnishing, studied by a lot of authors. Most of the publications study the effect of the major factors (speed, burnishing force, feed rate, and number of passes) on the burnishing process [3-6]. Relatively few publications refer to the effect of several types of lubricants on the roughness and microhardness obtained [7, 17].

Roller burnishing is a cheap cold working process. For instance, deep rolling and low plasticity burnishing work similarly to roller burnishing, but solving different tasks requires dynamic adaptive control of all process parameters, and especially of the burnishing force.

Roller burnishing, especially carried out by a single-roller tool, has a limit for achieving minimal roughness. Additional decrease in the roughness obtained can be sought in the following directions:

● Kinematics ensuring skidding between the deforming roller and the burnished surface not only in tangential direction, but both in tangential and axial direction and the presumption is that axial skid is not caused only by the burnishing feed;

● For each material being processed, the most suitable lubricant is used;

● Optimization of the number of passes in correlation with the respective appropriate lubricant.

For the conventional roller burnishing of external cylindrical surfaces from the point of view of rigid body kinematics, the deforming roller motion with respect to the workpiece is reduced to adding rotation around parallel axes (of the workpiece and roller) and translation in the direction of these axes. In this case, insignificant skidding in axial direction caused by feed rate exists between the deforming roller and the workpiece.

However, if the axes of the roller and workpiece cross at an angle α, the movement of the roller with respect to the workpiece is a superposition from adding rotation around crossing axes and translation along to workpiece axis. In this case, a skidding between the roller and workpiece will arise simultaneously in tangential and axial directions caused by the specific kinematics. Total results from theoretical and experimental studies and from performing of such a process have not been published.

The main objective of this study is to investigate by experiment in terms of roughness obtained, roller burnishing process of external cylindrical surfaces of workpieces made of 38Cr4 steel, whereas the axes of the toroidal deforming roller and workpiece are crossed.

2. Theoretical Background

2.1. Roller motion in the workpiece coordinate system

To clarify the kinematics of the method, it is necessary to study the movement of the deforming roller in the coordinate system of the workpiece. It is expedient this movement to be treated as a kinematic screw on the analogy of statics.

The static axes of the workpiece 1 and deforming toroidal roller 2 (Figure 1), rotating, respectively, at angular velocities $\vec{\omega}_w$ and $\vec{\omega}_t$, cross at an angle α, and their transversal has a length of $a = R_w + R_t$, where R_w and R_t are radii of the workpiece and roller, respectively. At the same time, the roller moves at linear velocity $\vec{v}_f$, parallel to workpiece axis. The whole system is given angular velocity $\vec{\omega}_{\text{rev}} = -\vec{\omega}_w$, whose vector lies on the static axis x_1. In this way, the workpiece is converted into static, and the deforming roller performs rotations around crossing axes, as its axis x_2 describes a hyperboloid. The roller kinematic characteristics are angular velocities $\vec{\omega}_t$ and $-\vec{\omega}_w$ and translational velocity $\vec{v}_f$.

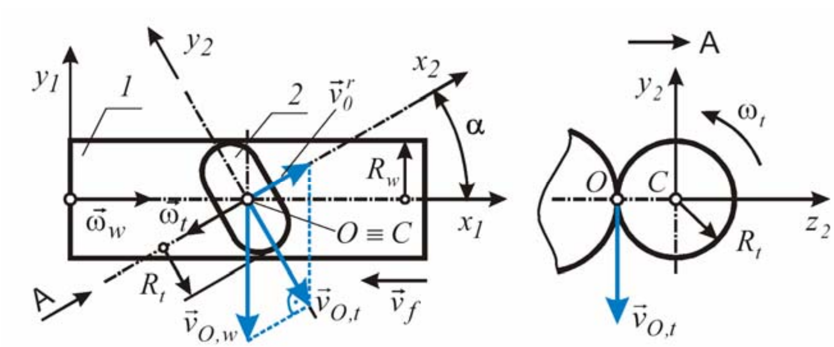
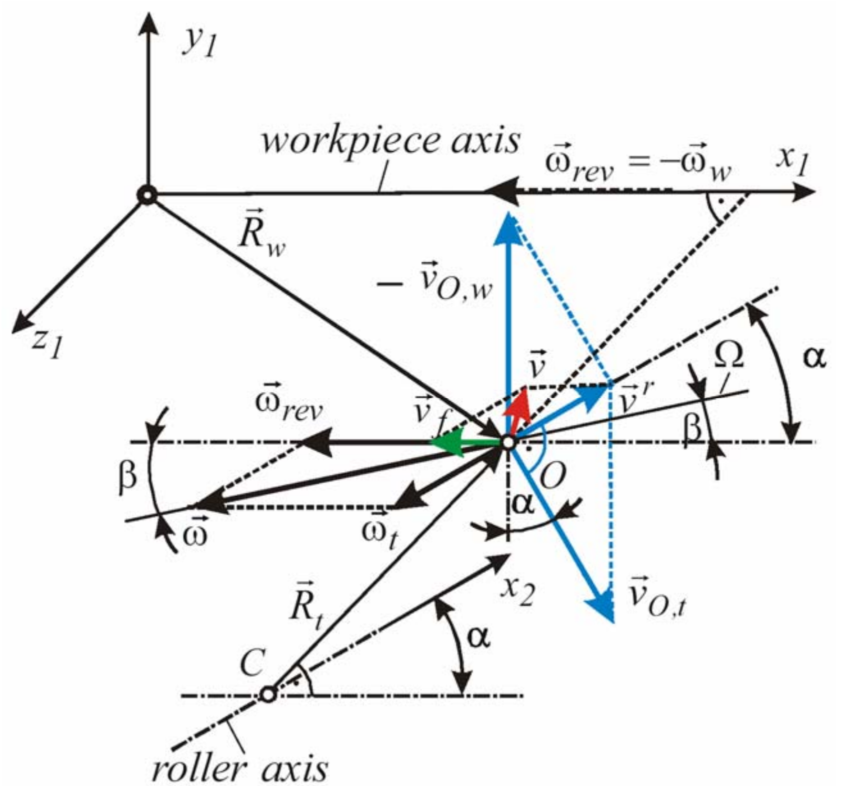


Figure 1. Kinematic scheme of the roller burnishing method.

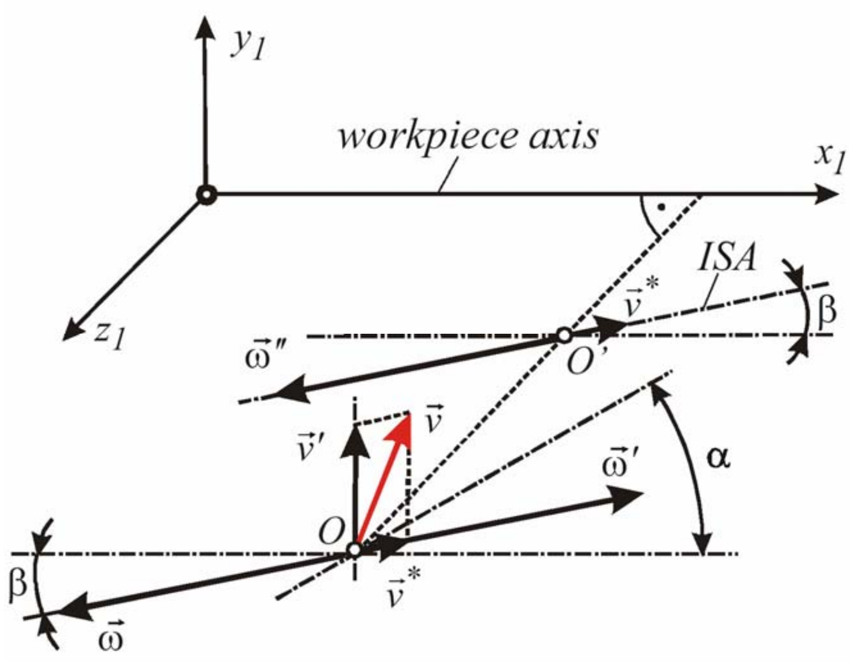
Both angular velocities which are sliding vectors are transferred parallel to themselves to the centre point O (Figure 2(a)), which is a contact point between the workpiece and the roller, and at the same point, the translational velocities are placed as well:

$$-\vec{v}_{O,w} = \vec{\omega}_{\text{rev}} \times \vec{R}_w = -\vec{\omega}_w \times \vec{R}_w; \quad \vec{v}_{O,t} = \vec{\omega}_t \times \vec{R}_t,$$

where $\vec{v}_{O,w}$ and $\vec{v}_{O,t}$ are velocities of the contact point O, respectively, of the workpiece and roller.



(a)



(b)

Figure 2. Kinematic dependences: (a) kinematic parameters in contact point O; (b) kinematic screw of the deforming roller.

Velocity $\vec{v}_f$ is placed at the same point. The movement is reduced to translation at velocity (Figure 2(a)):

$$\vec{v} = \vec{v}_f - \vec{v}_{O,w} + \vec{v}_{O,t},$$

and rotation around instantaneous axis of rotation (IAR) Ω at angular velocity:

$$\vec{\omega} = \vec{\omega}_{\text{rev}} + \vec{\omega}_t = \vec{\omega}_t - \vec{\omega}_w.$$

The two kinematic characteristics $\vec{v}$ and $\vec{\omega}$ are placed in reduction centre point O (Figure 2(a)). Obviously, $\vec{v}$ and $\vec{\omega}$ have different directions and Ω is not an instantaneous screw axis (ISA). Therefore, IAR is not tangent to the workpiece surface, as it is in conventional roller burnishing.

The roller motion in the workpiece coordinate system is determined by the pole velocity $\vec{v}$ and the angular velocity $\vec{\omega}$ around IAR Ω. This motion is reduced to kinematic screw (Figure 2(b)) at angular velocity $\vec{\omega}'' = \vec{\omega}$ and sliding velocity $\vec{v}^*$. Obviously, ISA crosses the workpiece. ISA describes a hyperboloid, since it crosses the static axis x_1 at angle $\beta < \alpha$ and rotates around x_1 at angular velocity $-\vec{\omega}_w$.

2.2. Burnishing parameters

Burnishing parameters are the following (Figure 3):

Geometrical parameters:

- workpiece diameter D_w;
- initial roughness R_a^{init};
- roughness obtained R_a;
- diameter of the deforming toroidal roller equator d_t;
- roller radius r;
- cross angle α between the axes of the roller and workpiece.

Manufacturing parameters:

- burnishing speed n_w, rpm;
- burnishing feed rate f, mm / rev;
- number of passes N.

Physical parameters:

- yield limit of the workpiece material σ_Y;
- depth of penetration d_p.

Power parameters:

- burnishing force F_b;
- axial force P_a;
- rotating moment M_e.

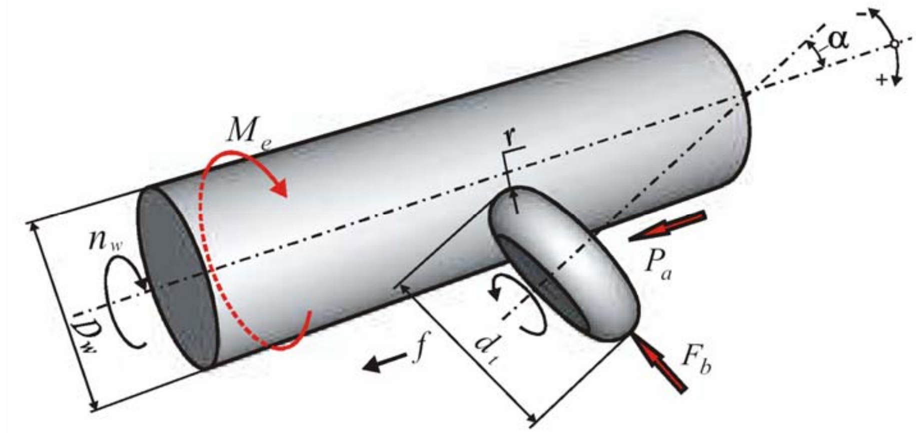


Figure 3. Scheme for defining the roller burnishing parameters.

The process parameters are classified into three groups (Table 1).

Table 1. Parameters of the process

Assigned	D_w, R_a, σ_Y
Independent	R_a^{init}, d_t, r, α, n_w, f, N, F_b
Dependent	d_p, P_a, M_e

2.3. Velocity analysis

In order to evaluate and make an optimal choice of the governing factors (independent parameters of the process), it is necessary to analyze the velocities of contact point O between the workpiece and deforming toroidal roller, whose axis crosses the workpiece axis at angle α (Figure 3). The magnitude of velocity of point O, related to the workpiece is:

$$v_{O,w} = \frac{\pi n_w D_w}{60}, \text{ mm / s,} \tag{1}$$

where n_w is burnishing speed in $\min^{-1}$, and D_w is workpiece diameter in mm.

The magnitude of velocity of the same point, but related to the deforming roller is:

$$\nu_{O,t} = \frac{\pi n_w D_w}{60} \cos\alpha, \text{ mm / s.} \tag{2}$$

In vector form:

$$\vec{\nu}_{O,t} = \vec{\nu}_{O,w} + \vec{\nu}^{r}, \tag{3}$$

where $\vec{\nu}^{r}$ is relative velocity, i.e., the velocity of point O of the roller in relation to point O of the workpiece. The magnitude of $\vec{\nu}^{r}$ is:

$$\nu^{r} = \frac{\pi n_w D_w}{60} \sin\alpha, \text{ mm / s.} \tag{4}$$

The presence of relative velocity $\vec{\nu}^{r}$, as a result of the crossing axes, is the reason for axial and tangential skidding between the roller and workpiece.

From the translational movement of the roller in relation to workpiece, velocity $\vec{\nu}_f$ of point O of the roller is got and its magnitude is:

$$\nu_f = \frac{n_w f}{60}, \text{ mm / s.} \tag{5}$$

The absolute velocity $\vec{\nu}$ of point O of the roller in the workpiece coordinate system is:

$$\vec{\nu} = \vec{\nu}_f + \vec{\nu}^{r}, \tag{6}$$

and its magnitude is:

$$\nu = \frac{n_w}{60} \sqrt{(-f + 0.5\pi D_w \sin 2\alpha)^2 + \pi^2 D_w^2 \sin^4\alpha}, \text{ mm / s.} \tag{7}$$

If $\nu_f = \nu^{r}\cos\alpha$, then vector $\vec{\nu}$ will be orthogonally crossing the workpiece axis and there will be only tangential skidding (Figure 2(a)).

Figure 4 shows a plot of $\frac{\nu_f}{\nu^r} = \frac{\nu_f}{\nu^r}(\alpha)$. Typical values of feed are within $0.05 \div 0.2\text{mm / rev}$. It can be seen from the plot that the cross angle α should be smaller than $0.1 \div 0.2°$, so that vector $\vec{\nu}$ can be orthogonally crossed with the workpiece axis, i.e., this case is practically groundless. Obviously, for $|\alpha| > 1°$, it can be assumed that $\nu \approx \nu^r$, i.e., correlation between ν and *f* is very feebly displayed.

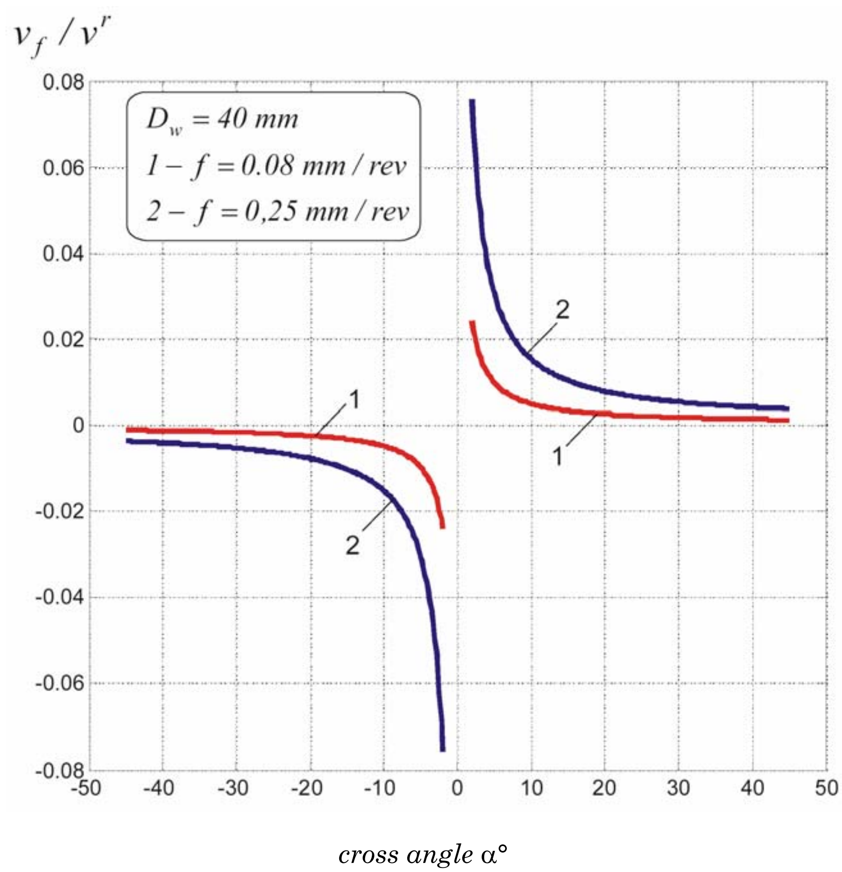


Figure 4. Graphics of the function $\frac{\nu_f}{\nu^r} = \frac{\nu_f}{\nu^r}(\alpha)$.

Velocity analysis shows that the burnishing speed n_w, the burnishing feed rate *f*, and the cross angle α can be assumed as independent parameters having kinematic character in the experimental study.

3. Experimental Study

3.1. Experimental design for roughness investigation

3.1.1. Formulation of the study

Figure 5 shows an especially designed burnishing device, which performs the process. It is fixed in the tool post of a conventional lathe or in the turret of an NC lathe. The device belongs to the group of single-roller tools with elastic operation. Spring deformation provides an elastic contact between the roller and workpiece. Deformation force can be specified by a radial displacement of the device at the expense of a relative displacement of the movable parts in relation to the body. Flat ended spring having a stiffness of $6.25\text{kg}/\text{mm}$ has been used in the device.

Figure 5. Roller burnishing device.

Tangential and axial skidding in the contact zone between the deforming roller and the workpiece takes place by crossing their axes. Angle α is set by rotating the roller around the body axis of the device.

The process is carried out on conventional lathe C11. The specimens are fixed between rotating centres (Figure 6).

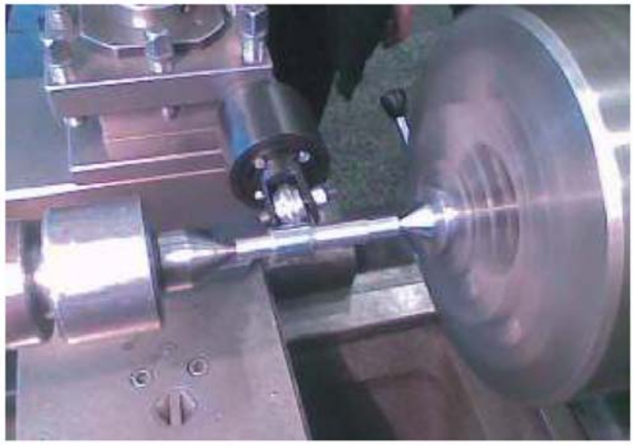


Figure 6. Roller burnishing process.

The specimens are made of low-alloy structural steel 38Cr4. The percentage of its chemical composition is given in Table 2. It has been selected because of its importance in industry and due to its specific application. The nominal diameter and length of the part of specimens being treated are, respectively, 20mm and 40mm. Semi-organic grease has been used between tools and specimens.

Table 2. Chemical composition of the 40X steel

C	Si	Mn	P	S	Cr	Mo	Ni	Al
%	%	%	%	%	%	%	%	%
0.374	0.198	0.62	0.018	0.016	0.89	0.013	0.052	0.019

The roughness of each specimen has been measured by means of Mitutoyo Surftest–4 along two generating lines and the arithmetical mean has been taken. Each point from the experimental design has been under three observations and the final result is an arithmetic mean of the three.

Multiple factorial analysis of variance has been made in order to evaluate the effect of the factors, followed by an analysis of regression of the experimental results obtained from the experimental design. Using the optimum parameters obtained, the effect of the lubricant type on the roughness obtained has been studied. Finally, by means of the optimum parameters and the lubricant selected, the effect of the number of passes on the roughness obtained has been studied.

3.1.2. Objective function, factors and levels

The objective function is the roughness obtained R_a. It depends on: R_a^{init}, d_t, r, α, n_w, f, N, F_b, mechanical properties of the workpiece material, lubricant between the workpiece and roller. Related to the target function all factors involve huge experimental work. Since a particular burnished material and roller diameter d_t, have been selected the experimental design is made with seven factors. On this basis, the optimum burnishing parameters have been determined and with them the effect of 10 types of lubricants on the roughness obtained has been studied.

The levels of variance of the governing factors are shown in Table 3 and they have been chosen on the basis of experimental results from a preliminary (eliminating) experiment. It has been carried out by means of one-factor-at-a-time method. Great attention was paid to the effect of the cross angle α on the roughness obtained.

Table 3. Burnishing conditions

Parameters		Levels of the parameters		
		code		
		−1	0	+1
actual	code	actual		
Roller radius r, mm	x_1	5	10	15
Burnishing force F_b, N	x_2	100	300	500
Burnishing feed rate f, mm / rev	x_3	0.07	0.21	0.35
Cross angle α	x_4	−30	0	30
Burnishing speed n_w, rpm	x_5	250	500	750
Number of passes N	x_6	1	2	3
Initial roughness R_a^{init}, μm	x_7	1	3	5

Table 4 shows the conditions of this part of the preliminary experiment. The initial roughness R_a^{init} of the specimens is within $5.8 \div 7.1\mu$m.

Table 4. Burnishing conditions for one-factor-at-a-time experiment for influence of α

№	α, deg	n_w, rpm	f, mm / rev	F_b, N	r, mm	R_a^{init}, μm	N
1	– 45						
2	– 30						
3	– 15						
4	0	355	0.07	312	10	6.3	1
5	15						
6	30						
7	45						

Three observations were made for each experimental point, i.e., three specimens for each point were subjected to roller burnishing. Roughness for each point was obtained as arithmetic mean of the three observations. The results are illustrated in Figure 7. Obviously, the lowest roughness was obtained for $\alpha = -30°$. At the same time, for this value of α, the largest coefficient of reduction $k_{red}^{R_a}$ of the initial roughness was obtained. The plot shows that when the absolute value of α rises over $30°$, the obtained roughness deteriorates. For this reason, $-30° \le \alpha \le 30°$ is adopted in the experimental design.

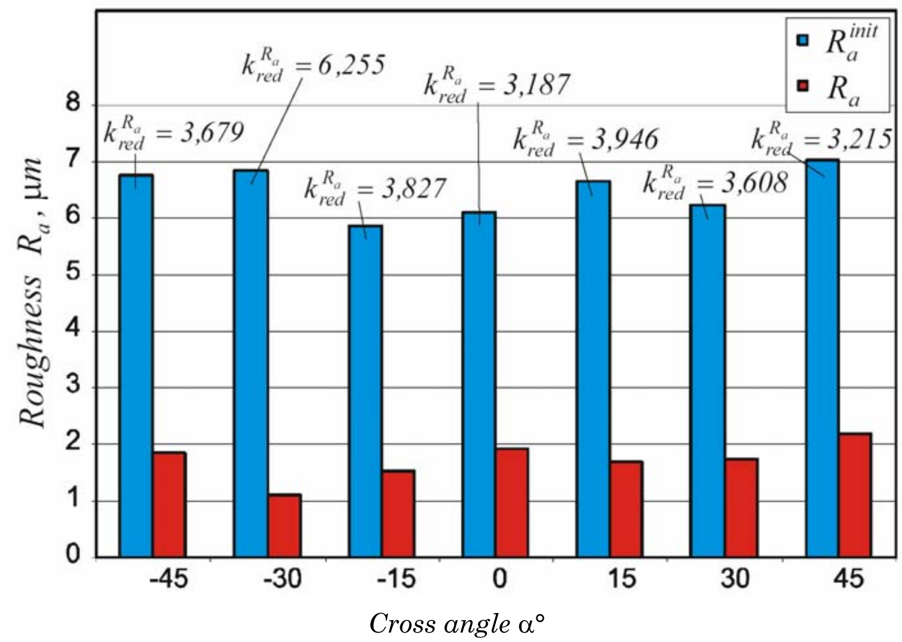


Figure 7. Effect of cross angle α on roughness.

Similar studies have been conducted with the remaining factors and on this basis, their levels of variation have been determined in the experimental design.

3.1.3. Experimental design

An optimal composed-second-order design (Table 5) has been chosen. Since the factors are 7, the number of experimental points (number of combinations) rises to $N = 2^7 + 2 \times 7 = 142$ and is too high to be logistically feasible. To reduce the number of combinations, the nucleus of the composed design is chosen to be fractional factorial design with a size of the fraction $t = 3$, i.e., the number of the experimental points in the design nucleus is $N_{nuc} = 2^{7-3} = 16$. By means of specialized software QStatLab [20], an optimal composed design with one central point is synthesized (Table 5). Averaged measured values of roughness $\{R_{a,u}\}$ from three repetitions at each experimental point are shown in Table 5.

Table 5. Experimental design and results

№	x_1	x_2	x_3	x_4	x_5	x_6	x_7	$R^{init}_{a, measured}$, μm	R_a
1	−1	−1	−1	−1	−1	−1	−1	1.29	0.31
2	1	−1	−1	−1	1	−1	1	5.01	1.52
3	−1	1	−1	−1	1	1	−1	1.41	0.15
4	1	1	−1	−1	−1	1	1	5.05	0.20
5	−1	−1	1	−1	1	1	1	5.08	2.16
6	1	−1	1	−1	−1	1	−1	1.28	0.62
7	−1	1	1	−1	−1	−1	1	5.14	1.39
8	1	1	1	−1	1	−1	−1	1.34	0.48
9	−1	−1	−1	1	−1	1	1	5.31	1.09
10	1	−1	−1	1	1	1	−1	1.22	0.36
11	−1	1	−1	1	1	−1	1	5.24	0.93
12	1	1	−1	1	−1	−1	−1	1.26	0.52
13	−1	−1	1	1	1	−1	−1	1.11	0.51
14	1	−1	1	1	−1	−1	1	4.98	3.23
15	−1	1	1	1	−1	1	−1	1.07	0.39
16	1	1	1	1	1	1	1	5.02	1.36
17	0	0	0	0	0	0	0	3.03	0.83
18	−1	0	0	0	0	0	0	2.90	0.81
19	1	0	0	0	0	0	0	3.28	0.88
20	0	−1	0	0	0	0	0	2.90	2.50
21	0	1	0	0	0	0	0	3.41	0.64
22	0	0	−1	0	0	0	0	3.31	0.59
23	0	0	1	0	0	0	0	3.36	0.96
24	0	0	0	−1	0	0	0	2.98	0.37
25	0	0	0	1	0	0	0	3.43	0.40
26	0	0	0	0	−1	0	0	3.37	0.83
27	0	0	0	0	1	0	0	3.32	0.71
28	0	0	0	0	0	−1	0	3.22	1.15
29	0	0	0	0	0	1	0	2.96	0.70
30	0	0	0	0	0	0	−1	1.08	0.35
31	0	0	0	0	0	0	1	5.08	1.39

3.1.4. Analysis of variance

Analysis of variance (ANOVA) was conducted by using the results given in Table 5 to study the effect of factors on the roughness obtained in quality aspect by QStatLab. Figure 8 shows a graphic interpretation of the main effects. The factors x_7 (initial roughness), x_2 (burnishing force), and x_3 (feed rate) are highly influential. The effect of x_4 (cross angle) and x_6 (number of passes) is significant and relatively equal. The factor x_5 (burnishing speed) is the least significant. It follows from Figure 8 that, it is necessary the 7 factors to be maintained at certain levels shown in Table 6 in order to obtain minimum roughness. Obviously, crossing the axes at angle $\alpha = -30°$ leads to decreasing roughness.

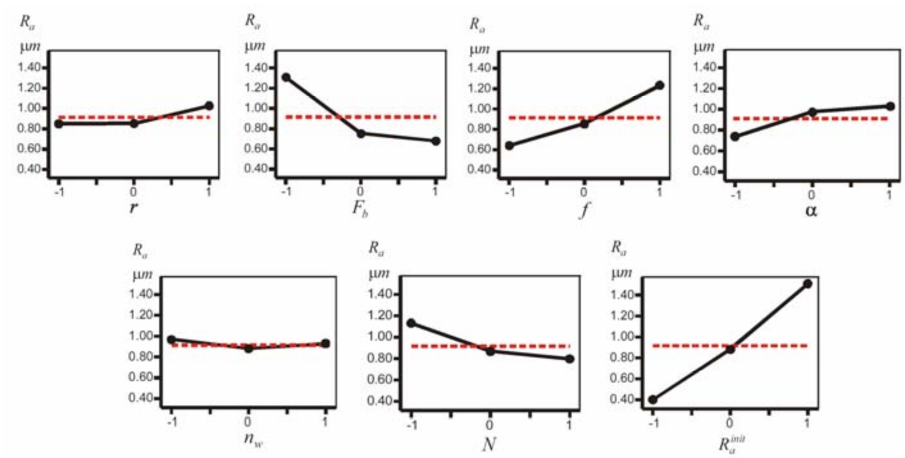


Figure 8. Visualization of main effects.

Table 6. Optimal levels of the factors

Factor	x_1	x_2	x_3	x_4	x_5	x_6	x_7
Level	– 1	1	– 1	– 1	0	1	– 1

3.1.5. Analysis of regression

In view of the fact that optimal composed-second-order design has been employed, the model of regression has to be second-order polynomial, whose coefficients should not be more than 31, so that correct statistical analysis can be made. Visualization of the main effects (Figure 8), however, shows that the influence of each factor can be linearized, and the fifth factor (frequency of rotation) can be ignored. Another reason for this assumption is the great number of independent factors and very often, it results in intolerable “shaking” of the target function between the experimental points, even in second-order polynomials. Analysis of regression was done by QStatLab. The approach of consecutive entry of coefficients and statistic evaluation of the current model was adopted. The following model of regression is obtained in which all coefficients are significant:

$$\begin{aligned} Y_{R_a} = {} & 0.952 + 0.122x_1 - 0.222x_2 + 0.26x_3 + 0.048x_4 - 0.14x_6 \\ & + 0.536x_7 + 0.079x_1x_4 + 0.07x_1x_7 - 0.09x_2x_3 + 0.076x_2x_4 \\ & + 0.048x_2x_6 - 0.144x_2x_7 - 0.105x_3x_4 + 0.152x_3x_7 - 0.075x_6x_7. \quad (8) \end{aligned}$$

The graphic visualization of the roughness model (Figure 9) confirms the conclusions made in Subsection 3.1.4 about the influence, the significance, and the factor levels on the roughness. For each plot in Figure 9, the remaining factors are kept at average levels. Crossing the axes of the roller and workpiece at negative angle ($\alpha = -30°$) significantly decreases roughness. Smaller feed, higher burnishing force and number of passes, smaller initial roughness lead to low roughness obtained.

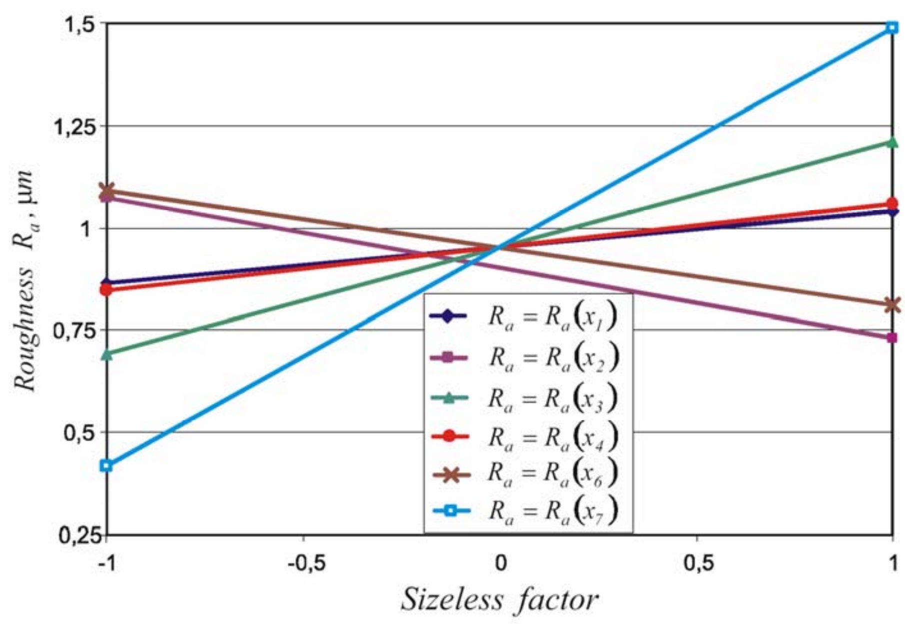


Figure 9. Sections of the roughness hypersurface with hyperplanes.

Detailed scanning of the regression model made, shows that there are no areas in factor space with negative values of the target function. By means of QStatLab, a minimum of the roughness function has been found. Genetic algorithm based on NSGA2 algorithm, developed by Prof. Deb Kalmonoy [20] was made use of. The minimum of the mathematical model of roughness is $\min R_a = 0.05\mu\text{m}$ and it is obtained for the following values of the governing parameters:

$$r = 10\text{mm};\ F_b = 500\text{N};\ f = 0.07\text{mm / rev};\ \alpha = -30°;$$

$$n_w = 350\text{rpm};\ N = 3;\ R_a^{init} = 1\mu\text{m}.$$

The first four of them were used in the next experiments.

3.2. Effect of the type of lubricant on the roughness obtained

The experimental design was not used during this study. The experimental investigation has been carried out with the following parameters: $r = 10\text{mm}; F_b = 500\text{N}; f = 0.07\text{mm/rev}; \alpha = -30°; n_w = 750\text{rpm};$ $N = 1$ and $N = 3$; $R_a^{init} = 1.5 \div 2\mu\text{m}$.

Ten types of lubricants were used shown in Table 7. The number of observations at each experimental point is 3. When the number of passes is $N = 3,$ the operating scheme is without separating the roller from the workpiece, i.e., for the first and third passes, the feed direction is the same and for the second pass, it is opposite. The outcomes are shown in Table 7. The following conclusions can be made:

● For both types of number of passes, liquid lubricants result in lower roughness. Therefore, this method is very suitable for NC lathes.

● When for one reason or another, it is necessary to use one pass $(N = 1),$ the lowest roughness is obtained by using Vaskomill 42 as a lubricant.

● When $N = 3,$ the lowest roughness is obtained by kerosene and in the second place−Blasocut 2000. Of course, for environmental and esthetic reasons, it is expedient to use Blasocut 2000 or Hocut 1033.

To find out the effect of N on the roughness obtained when using Blasocut 2000 as lubricant, more experiments were conducted. The process was performed with its optimum parameters as $N = 2 \div 7$ and $R_a^{init} = 1.5 \div 2\mu\text{m},$ following two schemes:

● without separating the roller (multidirectional passes);

● separating the roller after each pass (unidirectional passes).

Table 7. Lubricants and results for roughness obtained

№	Lubricant	Roughness R_a, μm					
		$N = 1$			$N = 3$		
		Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1	Hocut 1033	0.31	0.30	0.32	0.15	0.17	0.14
2	Blasocut 2000	0.32	0.33	0.33	0.11	0.15	0.10
3	Kerosene	0.30	0.24	0.34	0.08	0.10	0.11
4	Vaskomill 42	0.18	0.16	0.15	0.16	0.12	0.19
5	Vaskoform 110	0.67	0.59	0.60	0.17	0.13	0.14
6	Bisol 10w-40	0.36	0.34	0.31	0.18	0.19	0.16
7	Lard	0.47	0.52	0.55	0.23	0.26	0.29
8	Lithium grease GP-3	0.70	0.73	0.65	0.24	0.27	0.22
9	Graphite	0.45	0.56	0.45	0.24	0.24	0.33
10	Semi-organic grease	0.44	0.47	0.50	0.26	0.28	0.25

The number of observations per experimental point is 3. The obtained results have shown that for $N > 3$, the roughness obtained practically has a constant value $(R_a \approx 0.12 \mu\text{m})$ for both schemes, i.e., the optimum number of passes is $N = 3$.

To find out the process stability in aspect of roughness obtained when using Hocut 1033 as lubricant, additional experiments were carried out for three characteristic values of α and for each of them 12 observations were made. The process was performed with its optimum parameters as $N = 3$ (multidirectional passes) and $R_a^{init} = 1.5 \div 2 \mu\text{m}$. The results obtained (Table 8) prove the process stability.

Table 8. Stability of the roughness obtained

№	α	Roughness R_a, μm											
		1	2	3	4	5	6	7	8	9	10	11	12
1	$-30°$	0.13	0.17	0.12	0.15	0.14	0.16	0.16	0.14	0.13	0.17	0.16	0.14
2	$0°$	0.22	0.20	0.23	0.25	0.21	0.20	0.24	0.22	0.23	0.25	0.24	0.22
3	$+30°$	0.21	0.22	0.21	0.24	0.24	0.23	0.22	0.25	0.23	0.24	0.24	0.25

4. Conclusion

● A new single-roller burnishing technique has been developed and extensive investigated experimentally in an aspect of roughness obtained. The results from the conducted experimental study confirm the greater manufacturing capacity in terms of roughness obtained by proposed single-roller burnishing technique in comparison to conventional roller burnishing. The process is performed when the axes of the deforming roller with external toroidal working surface and the workpiece being processed cross by means of a relatively simple single-roller burnishing device. It can be applied to conventional lathes and NC lathes. This kinematics provides both tangential and axial skidding between the deforming roller and the workpiece being processed. The relation between them depends on the size and direction of the cross angle and in this way affects the roughness. It has been established that a minimum roughness is obtained when the angle between the vectors $\vec{v}$ and $\vec{v}_f$ is obtuse (see Figure 2(a)).

● By means of ANOVA and analysis of regression, optimum burnishing parameters have been found providing minimum roughness. They were determined quantitatively by minimizing the regression model by using a genetic algorithm. It has been found that minimum roughness is achieved when the cross angle $\alpha = -30°$. The initial roughness, burnishing force, and burnishing feed rate have the strongest effect on roughness. The influence of the cross angle and the number of passes is significant and relatively equal. The least significant factor is burnishing speed.

● By the optimum burnishing parameters, the effect of the type of lubricant on the roughness obtained has been studied. It has been found that liquid lubricants contribute to lower roughness, which makes the method very suitable for NC lathes. When it is expedient to apply one pass, the most suitable lubricant is Vaskomill 42. In case of more passes, the lowest roughness is obtained when we use kerosene or Blasocut 2000.

● By an additional experiment conducted with the optimum burnishing parameters and lubricant Blasocut 2000, it has been found that the optimum number of passes is three.

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