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Study of the Quality Iindicators of the Surfaces of Gear Blankets After Combined Processing by Cutting and Surface Plastic Deformation

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Abstract— **The continuous increase in the requirements for the quality of surface treatment of elements of mechanical engineering products from gears requires the improvement of processing and control methods. The main influence on the smoothness and noiselessness of power transmissions is exerted by the correct choice of the method for processing the base holes of the gears. The currently known methods for final processing of holes such as: countersinking, reaming, grinding, etc., do not guarantee high wear resistance, and hence, when assembling them to the journal of the shafts transmitting torque, they do not provide the prescribed kinematic accuracy in the gears. This requires conducting research on combined processing of holes in gear blanks, as well as obtaining the corresponding processing modes and their influence on roughness and microhardness.**

Keywords— kinematic accuracy, machining quality, surface machining, superficial plastic deformation (SPD).

I. Introduction

A significant increase in the productivity and economy of mechanical processing during boring can be achieved if the errors caused by the dissipation of elastic deformations of the technological system are reduced. In existing systems for controlling elastic displacements during boring, accuracy is increased by stabilizing the deformations of the support, which to the greatest extent determine the size and nature of the change in the total deformation of the system. To determine the limiting element of the system during boring, which significantly affects the deformation, it is necessary to carry out studies to determine the stability of the technological system [1] – [3].

Here, a combined approach is applied, based on the synthesis of results from real and numerical experiments. In practice, the same approach has been applied repeatedly when studying the process of surface plastic deformation (SPD).

The change in surface microhardness, as a result of mechanical impact, is due to the strengthening of the material that occurs after its drawing [4]. Given the fact that even for a one-dimensional stressed state, the deformed state is three-dimensional, the elongation is characterized by equivalent plastic deformation, i.e. there is a direct correlation between the equivalent plastic deformation and the microhardness [5], [6].

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Experimentally, based on a planned experiment, the microhardness of machined internal cylindrical surfaces is measured. The same experimental plan is used. In this way, qualitative information is obtained about the machined surface from the point of view of „microhardness of the surface layer“ [7].

Numerical modeling was performed to determine the equivalent plastic deformation of the surface layer and the depth of the reinforced layer – the layer with equivalent plastic deformation. In this way, quantitative information is obtained about the machined surface from the point of view of, respectively, „microhardness of the surface“ and „depth of the reinforced layer“ [8].

II. MATERIALS AND METHODS

Experimental setup

Technical equipment of the experiment

The figures below show the implementation, the tool used in the combined machining of holes in hydraulic cylinders.

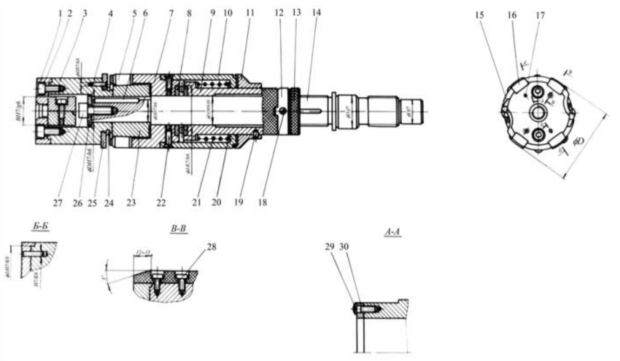


Fig. 1. Combined tool for machining a hole.

To study the roughness of the workpiece, the change in the inner and outer diameter obtained after machining by cutting and superficial plastic deformation (SPD), the based and established workpiece is machined with a pre-set tool. After machining the test specimens, we conduct measurements in three sections, equally spaced along the length (Fig. 2).

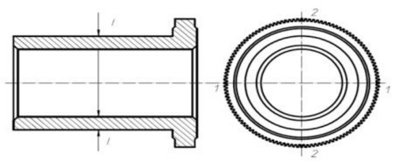


Fig. 2. Scheme for conducting control measurements.

A planned experiment was conducted to study the influence of technological parameters on the quality of the processed surfaces. The roughness measurements were performed with a Mitutoyo Surftest device, using three forming surfaces and an average value was determined [9].

The following factors were studied:

A total of 27 experiments were conducted, which corresponds to an optimal compositional plan.

Planning of experiments experimental results

Essence of planning

The purpose of planning the studied process is to solve the following main tasks [10], [11]:

- Selection of an objective function.
- Selection of the factors determining the nature of the studied process.
- Selection of the type and number of functions of the input factors that determine the actual structure of the mathematical model.

Fig. 3. Mitutoyo Suftest – 4.

Selection of an objective function

The following objective functions are selected: $Y_i\ i = 1{,}2$:

- Obtained roughness R_a;
- Microhardness of the surface layer HV.

Selection of factors

The following factors influencing the roughness in the spherical mandrel process are the subject of research:

- Tightness - i,$[mm]$;
- Machine spindle speed - $n_e[min^{-1}]$;
- Tool feed – $f\,[mm/min]$;
- Initial roughness -R_a^{init};
- Number of transitions – n;
- Physical and mechanical properties of the material;
- Lubrication between the tool and the workpiece.

Physico-mechanical properties of the material and the lubricant between the tool and the workpiece will not be taken into account. The main reason for this is the fact that the research is carried out on only one type of material: Steel E410. The lubricant used was selected based on research conducted during the superficial plastic deformation (SPD) research process [12].

A planned experiment was conducted. The height of the roughness was measured by two forming, and an arithmetic mean value was taken. Multifactorial variance analysis was performed sequentially for the purpose of qualitative assessment of the influence of the factors and regression analysis for the purpose of the obtained experimental results [13].

Microhardness study

The planned experiment was carried out with 5 factors, and the levels of variation are presented in Table 1.

TABLE 1 GOVERNING FACTORS AND THE LEVELS OF VARIATION

Governing factors		*Coding of factor levels*		
		-1	*0*	*1*
Natural	***Coded***	***Natural***		
Tightness - i, [mm]	x_1	*0,10*	*0,22*	*0,32*
Submission - f [mm/min]	x_2	2000	2500	2800
Machine spindle speed - n_e, [min^{-1}]	x_3	*800*	*1100*	*1400*
Number of transitions - n, [бр]	x_4	*1*	*2*	*3*
Initial roughness - R_a^{init}, [μm]	x_5	*1*	*3*	*5*

Table 2 shows the experimental design. Since the factors are 5, the number of experimental points is 27. An optimal compositional plan with one central point was synthesized with QStatLab.

TABLE 2 EXPERIMENTAL DESIGN

№	x_1	x_2	x_3	x_4	x_5	R_a^{init}, μm	$R_{a,measured}^{init}$, μm	$\{R_{a,u}\}$
1	-1	-1	-1	-1	-1	1	1,24	0,36
2	-1	-1	1	-1	1	5	4,73	1,34
3	1	-1	1	1	-1	1	1,27	0,22
4	1	-1	-1	1	1	5	5,01	0,41
5	-1	1	1	1	1	5	5,04	2,32
6	-1	1	-1	1	-1	1	1,36	0,67
7	1	1	-1	-1	1	5	5,30	1,40
8	1	1	1	-1	-1	1	1,38	0,55
9	-1	-1	-1	1	1	5	5,44	1,10
10	-1	-1	1	1	-1	1	1,22	0,49
11	1	-1	1	-1	1	5	5,17	1,01
12	1	-1	-1	-1	-1	1	1,21	0,57
13	-1	1	1	-1	-1	1	1,18	0,53
14	-1	1	-1	-1	1	5	5,14	3,12
15	1	1	-1	1	-1	1	1,42	0,62
16	1	1	1	1	1	5	5,04	1,48
17	0	0	0	0	0	3	3,01	0,81
18	-1	0	0	0	0	3	2,94	1,68
19	1	0	0	0	0	3	3,16	0,79
20	0	-1	0	0	0	3	3,25	0,63
21	0	1	0	0	0	3	3,54	1,02
22	0	0	-1	0	0	3	3,22	0,84
23	0	0	1	0	0	3	3,36	0,77
24	0	0	0	-1	0	3	3,39	1,20
25	0	0	0	1	0	3	3,01	0,76
26	0	0	0	0	-1	1	1,18	0,48
27	0	0	0	0	1	5	5,23	1,29

Microhardness was measured with a Leica VMHT Auto instrument using the Vickers method.

The change in microhardness is determined by the ratio:

$$К_н = \frac{HV_{after}}{HV_{before}} \quad (1)$$

The increase in microhardness is due to strengthening of the surface layer due to plastic deformation.

III. RESULTS AND DISCUSSION

The analysis of the regression model was performed with QStatLab in two aspects: by sections of the hypersurface of the modeled roughness using hyperplanes and by scanning the resulting linear regression model [14].

Given the fact that the design is of the second order (optimal compositional), the regression model was chosen to be a second order polynomial, whose coefficients should not be more than 27 in order to perform a correct statistical analysis [15]:

$$Y_{Ra}(x_1, \dots, x_4) = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \sum_{i=1}^{k} b_{ii} x_i^2 \quad (2)$$

Where:

Y_{Ra} the objective function of the resulting roughness R_a with arguments the encoded factors.

The coefficient estimates $b_0, b_1, \dots, b_{44}, \dots$ are obtained from the matrix products:

$$\{b\} = ([F]^T[F])^{-1}[F]^T\{R_{a,u}\} \quad (3)$$

$$Y_{Ra} = 0.874 - 0.372x_1 + 0.323x_2 - 0.023x_3 - 0.179x_4 + 0.571x_5 + 0.519x_1x_1 - 0.336x_2x_2 - 0.095x_1x_2 + 0.074x_1x_3 + 0.008x_1x_4 - 0.259x_1x_5 \quad (4)$$

Testing the hypothesis of significance of the coefficients in the regression model

To test the hypothesis of significance of the uncorrelated coefficients, the Student distribution is used.

The magnitude is calculated $\hat{t}_k$.

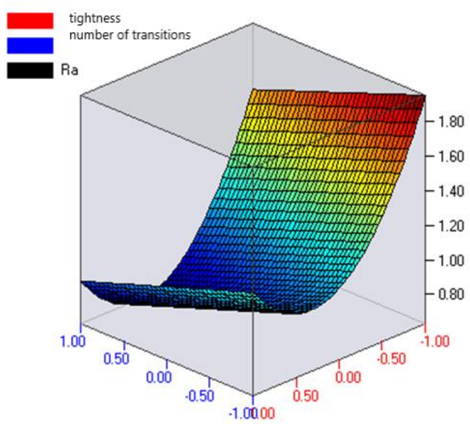


Fig. 4. Tightness, Number of transitions, R_a.

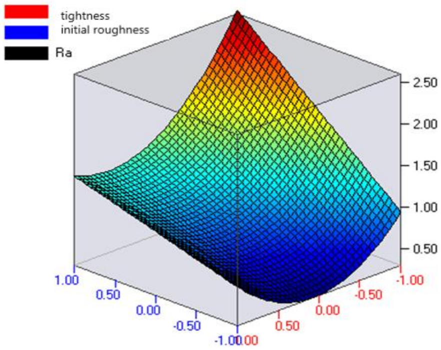
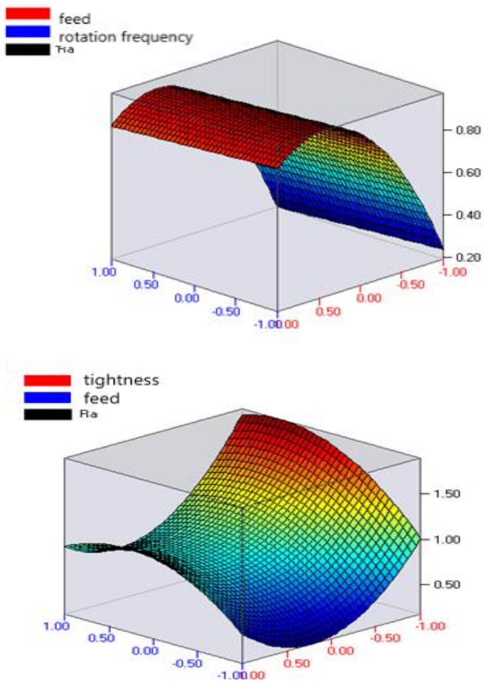


Fig. 5. Tightness, Initional roughness, R_a.

$$\hat{t}k = \frac{|b_k|}{\sqrt{c_{kk}s_\varepsilon^2}} \quad (5)$$

Since the regression analysis was performed with QStatLab in iterative mode, the significant coefficients were determined for each iteration using the above methodology.



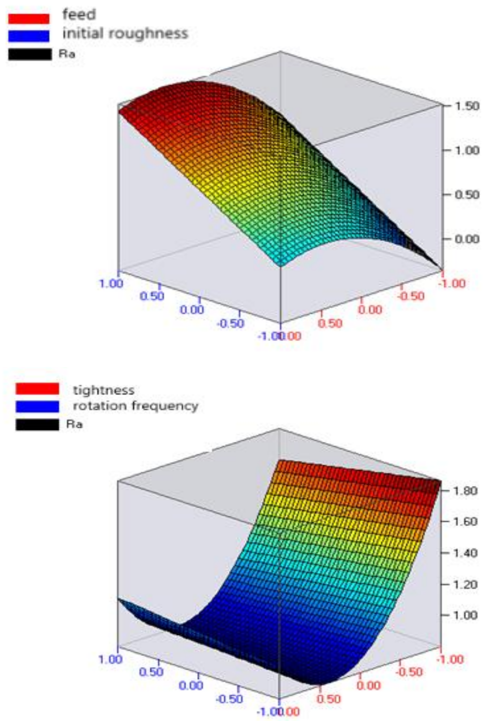


Fig. 6. Three-dimensional graphs of dependence between processing factors.

The graphical visualization of the roughness model (Fig. 5) confirms the conclusions made about the influence, significance and levels of factors on roughness. Small feeds, medium levels of tightness, and lower initial roughness lead to low obtained roughness. A detailed scan of the resulting linear regression model shows that there are no areas with negative roughness values. Using the genetic algorithm in QStatLab, the minimum of the roughness function in the full factor space was found.

Analysis of the roughness reduction coefficient

In order to study the influence of individual factors in the processing of the obtained results, a roughness reduction coefficient is introduced $K_{red}^{R_a}$.

The reduction factor is determined by the ratio between the initial and the roughness obtained after processing.

$$K_{red}^{R_a} = \frac{R_a^{init}}{R_{a,и}} \quad (6)$$

The results for the roughness reduction factor are shown in Table 3.

A graphical comparison between the reduction factor and the initial roughness was also performed.

A graphical comparison between the reduction coefficient $K_{red}^{R_a}$ and the initial roughness $R_{a,и}$ for each of the controlling factors has also been made. The values in the graphs are averages.

TABLE 3 EXPERIMENTAL DESIGN

№	1	2	3	4	5	6	7	8	9
$R^{init}_{a,measured}$ μm	2,24	4,73	1,27	5,01	5,04	2,56	5,30	1,38	5,44
$\{R_{a,u}\}$	0,36	1,34	0,22	0,41	2,32	0,67	1,40	0,55	1,10
K^{Ra}_{red}	6,22	3,52	5,77	12,2	2,17	4,00	3,7	2,5	4,9
№	10	11	12	13	14	15	16	17	18
$R^{init}_{a,measured}$ μm	2,22	5,17	1,21	1,18	5,14	1,42	5,04	3,01	2,94
$\{R_{a,u}\}$	0,49	1,01	0,57	0,53	1,12	0,62	1,48	0,81	1,68
K^{Ra}_{red}	4,53	5,1	2,1	2,2	4,58	2,3	3,4	3,7	1,8
№	19	20	21	22	23	24	25	26	27
$R^{init}_{a,measured}$ μm	3,16	3,25	3,54	3,22	3,36	3,39	3,01	1,18	5,23
$\{R_{a,u}\}$	0,79	0,63	1,02	0,84	0,77	1,20	0,76	0,48	0,8
K^{Ra}_{red}	4,0	5,2	3,5	3,8	4,40	2,8	3,9	2,5	6,53

Experimental results regarding the influence of tightness on the resulting roughness are illustrated in Fig. 7.

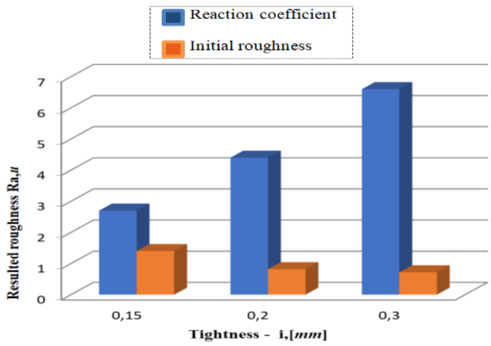


Fig. 7. Graph of K^{Ra}_{red} and $R_{a,u}$. versus factor values Tightness, i.

From the above graph it can be seen that the highest values of the reduction factor K^{Ra}_{red}, combined with the lowest values of roughness heights, are observed at a tightness of 0.32 mm. Therefore, we can define the tightness factor as significant in the formation of roughness on the surface layer.

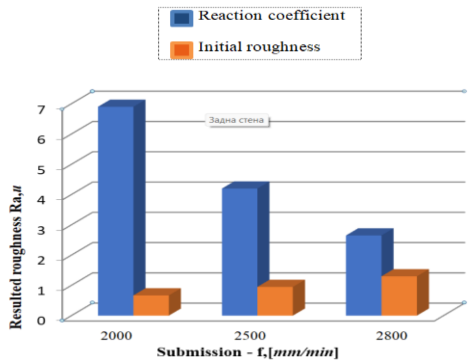
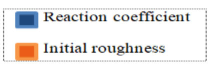


Fig. 8. Graph of K^{Ra}_{red} and $R_{a,u}$. versus factor values Submission, f.

Optimal results are observed at a feed rate of 2000 $[mm/min]$. The reduction factor K^{Ra}_{red} increases significantly at lower feed rates.



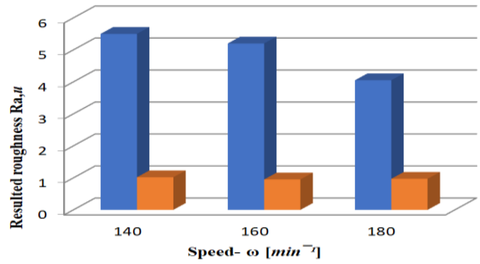


Fig. 9. Graph of K^{Ra}_{red} and $R_{a,u}$ versus factor values Speed, ω.

It is clearly seen from Figure 9 that the values of the initial roughness $R_{a,u}$ are close. Although the highest values of are $R_{a,u}$ observed at a rotation frequency of 800 min^{-1}, the lowest values of K^{Ra}_{red} are observed at a value of 1400 min^{-1}. The rotation frequency factor can be defined as a factor with low influence.

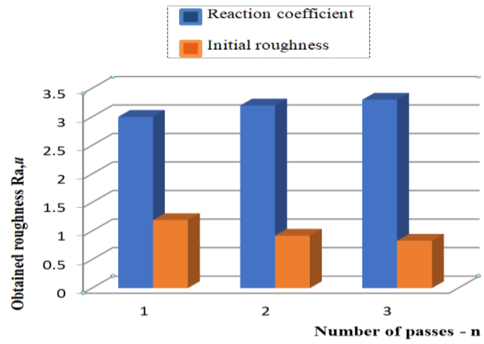


Fig. 10. Graph of K^{Ra}_{red} and $R_{a,u}$ versus factor values Number of passes.

As the number of transitions increases, K^{Ra}_{red} increases with low values.

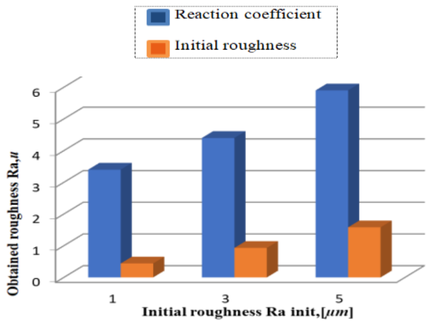


Fig. 11. Graph of K^{Ra}_{red} and $R_{a,u}$ versus factor values R^{init}_{a}.

It is known that the quality of machining is largely determined by the previous operation. The initial roughness is an essential parameter in determining the output roughness. Low initial roughness leads to low values of both $R_{a,u}$ and K^{Ra}_{red}.

IV. Conclusions

The experimental results show that maximum values of k^{Ra}_{red} are obtained at a tightness of 0,32 mm. This gives us reason to believe that tightness is of great importance for the combined hole machining process.

Small feeds lead to improved roughness indicators. Optimal roughness is observed at a feed of f = 10 [mm/min].

The machining speed is an insignificant factor for the obtained roughness of the machined surfaces.

The initial roughness R_a^{init} a factor of decisive importance for the obtained roughness. This is explained by the so-called technological heredity. The higher R_a^{init}, the lower $k_{red}^{R_a}$.

The number of passes does not significantly affect $R_{a,u}$.

Regression analysis shows that:

- increasing tightness leads to an increase in microhardness;
- small feeds give better results;
- initial roughness has a significant impact;

Graphical analysis confirms that optimal values are achieved at:

- medium tightness values;
- low feed;
- low initial roughness.

The adequacy of the regression model was checked using the Fisher test. The results show that the model is adequate and can be used to predict the results.

As a result of the conducted research, the following statements can be defined:

1. Combined processing by cutting and SPD significantly improves the quality of surfaces.
2. The most significant factors are tightness, feed and initial roughness.
3. The microhardness of the surface layer increases due to plastic deformation.
4. The developed regression models allow optimization of the technological process.
5. The method is applicable in the production of gears with high requirements for accuracy and wear resistance.

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