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ANALYSIS AND COMPARATIVE DESCRIPTION OF PREPARATION METHODS OF SMALL CYLINDRICAL CONNECTIONS PRECISION SURFACES TO THE ASSEMBLY

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Abstract: *The article describes the methods of finishing precision surfaces of small cylindrical connections.*

Keywords: precision surface, confidence limit, wear resistance of surface, finishing, spinning

1. INTRODUCTION

Surface preparation methods of small cylindrical connections to the assembly of high accuracy have its specialty. All finishing operations on the seating surfaces are performed on the almost ready, highly complex parts or the whole subassembly, the cost of which at this stage of the process is very high. It currently used methods are primarily lapping and machining of parts by plastic surface deformation (PSD).

Lapping provides surfaces precision in grade 6 and above and roughness to Ra = 0.063 microns. Available literature data about lapping (including the equipment, tools, modes) are mainly cases of finishing medium and higher size parts [1, 2]. So in this work we paid attention to the small (up to 8 microns) diameter surfaces lapping.

The purpose of the article is a comparative evaluation of surface preparation for assembly methods of small cylindrical connections increased accuracy.

2. THE MAIN CONTENT AND RESULTS

Processing parts by PSD method is used to improve the microhardness, increase surfaces and improve the wear resistance of surfaces [3, 4]. Precision machining for PSD-hanging depends on the design features of parts, shape and quality of the original surface, tools, modes of processing, precision size. Original surfaces with 5...7 accuracy degree are subjected of burnishing and spinning, so that allows to advance dimensional accuracy to 10...20% and to reduce the shape deviations to 10... 30 microns.

Finishing allowance can reach relatively large quantities. Figure 1 shows the allowances Z landfill distribution, skimmed in finishing micromachines shafts trunnions diameter 4...6 microns (Fig.1,a), and holes with diameter 11...15 microns (Fig.1,b) made of material 14X17H2 and 17X18H9. Pretreatment is a grinding to Ra = 3.2 ... 1.6 microns.

Confidence limits for the mean values are built on t - t-test with a confidence level of 0.95 [3].

To investigate the intensity of material removal during lapping, a number of statistical tests were made. Size measurements were made with optimeter ICG. The test results were summarized in the correlation table 1. Further calculations were carried out in accordance with [3].

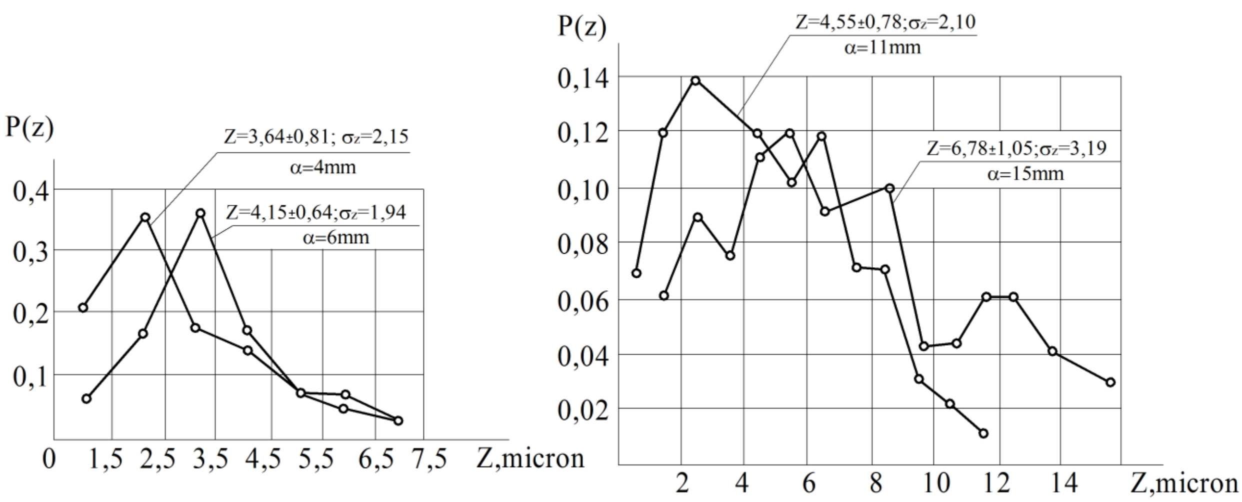

Fig. 1: Allowances allocation polygons for finishing

Table 1: Correlation table of test results

Time of grinding t, sec		Allowance of Z, micron									Numbers of columns		
		0,5	1	2	3	4	5	6	7	8	1	2	3
											m_t	$m_t \cdot t$	$m_t \cdot t^2$
2		1	-	-	-	-	-	-	-	-	1	2	4
4		1	1	1	1	-	-	-	-	-	4	16	64
6		-	2	3	-	1	-	-	-	-	6	36	216
8		-	-	1	1	-	-	-	-	-	2	16	128
10		-	-	-	-	1	1	1	-	1	4	40	400
12		-	-	-	-	1	1	1	-	2	6	72	864
14		-	-	-	-		-	1	1	-	2	28	392
16		-	-	-	-	2	-	-	-	-	2	32	512
18		-	-	-	-	-	-	1	-	-	2	36	648
20		-	-	-	-	-	-	-	-	1	1	20	400
1	n_z	2	3	5	3	5	2	4	1	4	$\sum_{(1)}=29$	$\sum_{(2)}=298$	$\sum_{(3)}=3628$
2	$n_z \cdot z$	1	3	10	9	20	10	24	7	32	$\sum (2) = 116$		
3	$n_z \cdot z^2$	0.5	3	20	27	80	50	144	49	144	$\sum (3) = 522.5$		
4	$\sum n_{zt} \cdot t$	6	16	30	24	60	22	54	14	54	$\sum (4) = 280$		
5	$Z \sum n_{zt} \cdot t$	3	16	60	72	240	110	324	98	432	$\sum (5) = 1355$		
6	$\overline{t_z}$	3	5.34	6	8	12	11	13.5	14	13.5			

Using data from Table 1 we find the average values of Z and removes the allowance of time for this procedure t, correlation Czt, average square deviations σz and σt, as well as the correlation coefficient Rzt.

$$\bar{z} = \frac{\sum n_z \cdot z}{\sum n_z} = \frac{115}{29} = 3{,}96 \text{microns}; \qquad \bar{t} = \frac{\sum m_i \cdot t}{\sum m_y} = \frac{298}{29} = 10{,}25 \text{sec};$$

$$C_{zt} = \frac{\sum \left(z \sum n_{zt} \cdot t \right)}{\sum n_z} - \bar{Z} \cdot \bar{t} = \frac{1355}{29} - 3{,}96 \cdot 10{,}25 = 6{,}3$$

$$\sigma_z = \sqrt{\frac{\sum n_z \cdot Z^2}{\sum n_z} - Z^2} = \sqrt{\frac{522{,}5}{29} - 3{,}96^2} = 1{,}55;$$

$$\sigma_z = \sqrt{\frac{\sum m_t \cdot t^2}{\sum m_t} - t^2} = \sqrt{\frac{3628}{29} - 10{,}25^2} = 4{,}70$$

$$R_{zt} = \frac{C_{zt}}{\sigma_z \cdot \sigma_t} = \frac{6{,}3}{1{,}55 \cdot 4{,}70} = 0{,}86$$

The correlation coefficient characterizing the relationship between the lapping machine time and allowance is not equal to one. This is due to the variation of finishing details microhardness and the operator's fear to remove too much envelop of metal. According to the industry, which produces equipment for shipbuilding, attempts to mechanize the process did not lead to positive results due to weak coupling Z and t.

Due to the fact that the ratio of t and Z isn't straight, we need to verify a process to the presence of the curvilinear link. Suppose there is a parabolic relationship, described by the equation:

$$\bar{Z} = a_0 + a_1 t + a_2 t^2 \qquad (1)$$

where: a_0, a_1, a_2 – constant coefficients.

To find the unknown parameters of equation (1) - a_0, a_1, a_2 we use the Chebyshev interpolation formula, where the argument is the value: $\chi = t - \bar{t}$, где $\bar{t}_i = \frac{\sum t_i}{n}$ (n - the number of tests):

$$y = k_0 q_0(x) + k_1 q_1(x) + k_2 q_2(x) + \ldots \qquad (2)$$

Experimental data for the calculation and preliminary calculations are summarized in Table 2.

The definition of a zero degree parabola is:

$$k_0 = \frac{\sum Z_i}{n} = \frac{42{,}3}{11} = 3{,}85 \qquad q_0(x) = x^0 = 1, \text{ o}f(x) = k_0 q_0(x) = 3.85$$

The fundamental error of σ_0 is:

$$\sum = \sum \cdot Z^2 - \frac{\left(\sum \cdot Z_i\right)^2}{n} = 235{,}71 - \frac{42{,}3^2}{n} = 72{,}71 \qquad \sigma_0 = \sqrt{\frac{\sum_0}{n-1}} = \sqrt{\frac{72{,}71}{11-1}} = 2{,}67$$

Parameter determination of the first degree parabola:

$$\bar{t}_i = \frac{\sum \cdot t_i}{n} = \frac{110}{11} = 10;; \qquad k_1 = \frac{\sum \cdot Z_i \cdot \chi_i}{\sum \cdot \chi_i^2} = \frac{150}{440} = 0{,}35;$$

$$q_1(\chi) = \chi^1 = \chi; \qquad 1f(\chi) = 0f(\chi) + k_1 q_1(\chi) = 3.85 + 0.35\,\chi$$

The fundamental error σ_1 is:

$$\sum_1 = \sum_0 - k_1^2 \sum \chi_i^2 = 72.71 - 0{,}35^2 \cdot 440 = 18.71 \qquad \sigma_1 = \sqrt{\frac{\sum_1}{n-2}} = \sqrt{\frac{18{,}71}{11-2}} = 1{,}44$$

Due to the fact that σ0 considerably exceeds σ1, we'll continue interpolation.
The definition of the second degree parabola is:

$$A_2 = \frac{\sum \chi_i^2}{n} = \frac{440}{11} = 40; \quad b_2 = \frac{\sum \chi_i^3}{\sum \chi_i^2} = \frac{0}{440} = 0;$$

$$C_2 = \sum \chi_i^4 - b_2 \sum \chi_i^3 - A_2 \sum \chi_i^2 = 31328 - 0 - 40 \cdot 440 = 13728$$

$$k^2 = \frac{\sum \cdot \chi_i^2 z - k_0 \sum {}_i^2 - k_1 \sum {}_i^3}{C_2} = \frac{1579{,}2 - 3{,}85 \cdot 440 - 0}{13728} = 0{,}00845$$

$$q_2(x) = x^2 - b_2 x - A_2 = x^2 - 40; \qquad k_2 q_2(x) = 0.00845(x^2 - 40)$$

Table 2: Test data

Time of grinding t, sec	Allowance of Z, micron									m_t	$\overline{Z}$
	0.5	1	2	3	4	5	6	7	8		
2	1	-	-	-	-	-	-	-	-	1	0,5
4	1	1	1	1	-	-	-	-	-	4	1,4
6	-	2	3	-	1	-	-	-	-	6	2,0
8	-	-	1	1	-	-	-	-	-	2	2,5
10	-	-	-	-	1	1	1	-	1	4	5,7
12	-	-	-	1	1	1	1	-	2	6	5,7
14	-	-	-	-	-	-	1	1	-	2	6,5
16	-	-	-	-	2	-	-	-	-	2	4,0
18	-	-	-	-	-	-	1	-	-	1	6,0
20	-	-	-	-	-	-	-	-	1	1	8,0
n_z	2	3	5	3	5	2	4	1	4	29	
$\sum n_z \cdot t$	6	16	30	24	60	22	54	14	54	280	
$\overline{t_z}$	3.0	5.34	6.0	8.0	12.0	11.0	13.50	14.0	13.5		

Make the substitution in accordance with (2) to find f(x). After transformations we obtain:

$$_2 f(x) = 4.188 + 0.35x - 0.00845x^2 \qquad (3)$$

The fundamental error σ2 is:

$$\sum_2 = \sum_1 - k_2^2 C_2 = 1871 - (-0.00845)^2 \cdot 13728 = 17.735 \qquad \sigma_2 = \sqrt{\frac{\sum_2}{n-3}} = \sqrt{\frac{17{,}735}{11-3}} = 1{,}42$$

Carry out replacing x = t-10 in the equation (3) to find Z (t). After conversion, we get:

$$Z(t) = -0.157 + 0.52t + 0.00845t^2 \qquad \begin{cases} 1; t < 20 \\ 0; t > 10 \end{cases} \qquad (4)$$

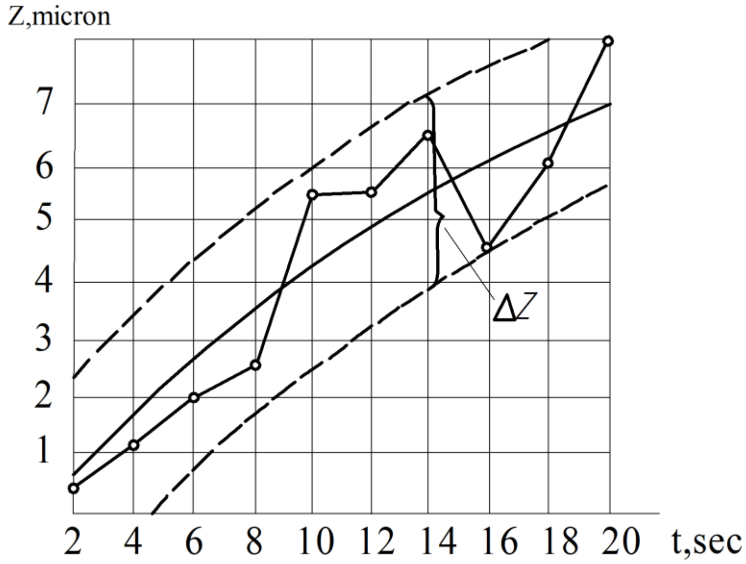

Fig. 2: The material removal rate during lapping

Graphical interpretation of Table 3 is shown in Fig. 2.
Table 3 shows the comparison of experimental and calculated values of Z.

Table 3: The experimental and calculated values of Z

t	2	4	6	8	10	12	14	16	18	20
z_{exp}.	0,5	1,4	2,0	2,5	5,7	5,7	6,5	4,0	6,0	8,0
z_{calc}.	0,85	1,79	2,66	3,49	4,20	4,86	5,48	6,00	6,45	6,86
$\frac{z_{\exp} - z_{calc.}}{z_{\exp.}}$	-0,7	-0,2	-0,33	-0,4	0,26	0,15	0,15	-0,5	-0,08	0,14

Figure 2 shows the removal stock swings ΔZ at fixed values of time t with a confidence level of 0.95.

$$\Delta Z = C \cdot \sigma^2 \qquad (5)$$

where: ΔZ is a deviation of the average values of the removed metal in the interest intervals, C - ratio of the average square deviation to the interval swing (in connection with the fact that in some cases the number of intervals is less than 6, then C = 2,3), σ^2 - average square deviation counted in equation (4) development.

The wide confidence zone indicates instability of the lapping process in time. This requires operator great skill and greatly complicates the process of mechanization.

Similar experiments were carried at the facility for finishing and restoration rotors pins developed at the Department of Manufacturing Engineering FSFEI HPE "Sevastopol State University" (Fig.3) PSD was using as reworking operation.

Chiseled and polished pins Ø4 ... 6 mm, a length of 4...5 mm of material 30X13, 14X17H2, 17X18H9 (HRC = 26...30) with the initial roughness Rz = 3,2 ... 1,6 microns were chosen for the experimental spinning. A total number of 2,000 pins was spinned, at the rate of

27 ... 30 pins on one mode of the spinning, which corresponds to a confidence level of β = 0,95.

By analogy with the lapping amount of the diameter change in a spinning was conditionally named removable allowance.

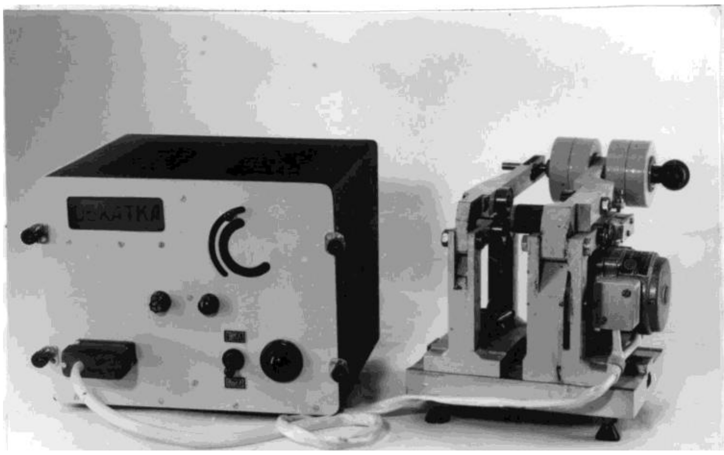

Fig. 3: General view of the complex for finishing and restoration micromachines rotors pins by plastic deformation

Spinning sharpened pins. Correlation evaluation such as the above was made. It was found that the value of the allowance Z and the spinning time t are related with curvilinear relation. Moreover, the maximum correlation coefficient is observed when spinning force is P = 60...90N.

Table 4: The average experimental Z (microns) allowance removed values for spinning sharpened pins Ø4 ... 6 mm

t, sec / P, N	0	3	6	9	12	15	20	25	40	60	r_{zt}	confidence limit at β=0,9
30	0	0,5	0,8	0,9	1,0	1,1	1,2	1,2	1,2	1,2	0,52	0,57÷0,85
60	0	1,2	1,5	2,0	2,1	2,3	2,3	2,3	2,3	2,3	0,78	
90	0	1,5	1,8	2,1	2,5	2,9	3	3	3	3	0,71	
120	0	1,9	2,6	3,3	3,5	3,9	4,0	4,0	4,0	4,0	0,58	
150	0	2,1	3,5	3,9	4,7	5,0	5,1	5,1	5,1	5,1	0,56	
300	0	5,5	6,0	9,0	10,0	10,0	10,0	10,0	10,0	10,0		
400	0	11	11,5	12,0	12,0	12,0	12,0	12,0	12,0	12,0		
500	0	12,5	12,7	12,7	12,7	12,7	12,7	12,7	12,7	12,7		

Table 4 shows the average experimental Z allowance removed values for spinning, correlation coefficients r_{zt} and confidence limit for the maximum r_{zt}, calculated in accordance with [3].

Table 4 shows that Z allowance taken from the operating force P <300N depends on the spinning duration only the first 15 seconds. After this period Z allowance is almost unchanged. Due to the fact that, for t> 15 sec. Z and t values are uncorrelated, the rzt correlation coefficients were found for spinning process with t≤ at 15 seconds. Allowance are removing almost in the first 3 ... 6 seconds if the rollers pressing efforts was above 300N. Calculations of rzt correlation coefficients of confidence limits for the allowance Z are similar to the previous estimates.

Fig. 4 is a graphical depiction of relation Z with the spinning time, and confidence limits for the Z allowance are shown for spinning force 60N.

Further analysis of the experimental data from table 4 makes possible to calculate the dependence of Z (P) for the duration of the spinning t = 15 sec and allowance confidence limits with the method of calculation used above.

$$Z(t) = 0.35t - 0.015t^2 \quad (6)$$
$$\begin{cases} 1; t < 15\,\mathrm{sec}; P = 60N \\ 0; t > 15\,\mathrm{sec} \end{cases}$$

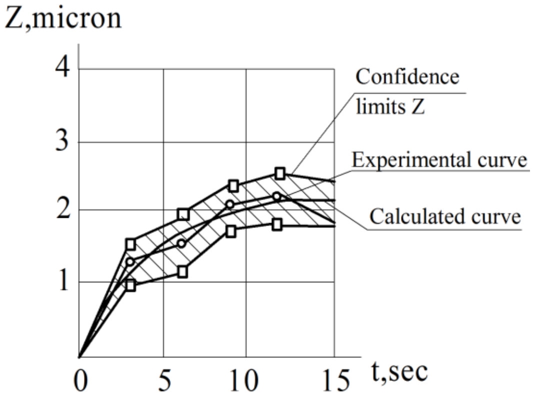

Fig. 4: Comparison data of experimental and calculated by the formula (6) values of removed during spinning allowance Z microns

Fig. 5 is a graphical interpretation of the calculated dependence Z (P), and average experimental values and confidence limits for the allowance Z are applied.

$$Z(P) = 0.18+0.0323P \quad (7)$$
$$\begin{cases} 1; & 30 \le P \le 300N; t = 15\,\mathrm{sec} \\ 0; & other \end{cases}$$

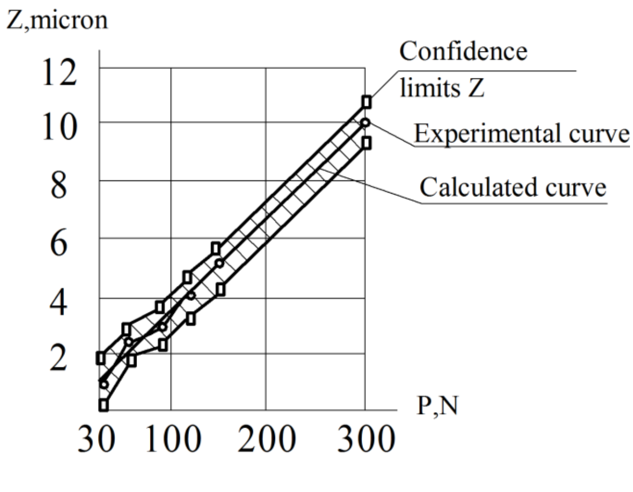

Fig.5: Comparative data of experimental and calculated according to the formula (7) value of removed during spinning allowance Z microns

Based on the deduced data (in) we could build a multiple regression equation:

$$z=a_1t+a_2P+a_3t\cdot P+a_4t^2+a_5P^2$$

where: a_1, a_2, a_3, a_4, a_5 – regression coefficients; t – machining time; P – spinning effort.

Regression coefficients are found by the least squares method:

$$U=\sum_{i=1}(Z-Z_i)^2=U_{min}$$

where: Zi - the Z experimental value.

The first derivatives for this equation are zero.

We could write the last expression in the following form:

$$U=\sum(a_1t+a_2P+a_3tP+a_4t^2+a_5P^2-Z)^2=U_{min}$$

We find the partial derivatives of functions on a_1, a_2, a_3, a_4, a_5 and equate them to zero.

$$\begin{cases}\frac{\partial U}{a_1}=2\sum(a_1t+a_2P+a_3tP+a_4t^2+a_5P^2-Z)t=0\\ \frac{\partial U}{a_2}=2\sum(a_1t+a_2P+a_3tP+a_4t^2+a_5P^2-Z)P=0\\ \frac{\partial U}{a_3}=2\sum(a_1t+a_2P+a_3tP+a_4t^2+a_5P^2-Z)P\cdot t=0\\ \frac{\partial U}{a_4}=2\sum(a_1t+a_2P+a_3tP+a_4t^2+a_5P^2-Z)t^2=0\\ \frac{\partial U}{a_5}=2\sum(a_1t+a_2P+a_3tP+a_4t^2+a_5P^2-Z)P^2=0\end{cases}$$

Reducing equations system to the normal form and solving it, we could find the values of the regression coefficients.

Multiple regression equation is as follows:

$$Z\cdot10^3 = 96t+7P+1,5t\cdot P-5.5t^2+0.02P^2 \quad (8)$$

$$\begin{cases}1; & t\le15 сек; & P\le150H\\ 0; & t\ge15 сек; & P\ge150H\end{cases}$$

Figure 6 shows the graphical interpretation of the expression (8) and Z experimental points.

Polished trunnions spinning. Correlation analysis reveals a curvilinear relationship between the spinning time t and removes oversize Z. Moreover, the maximum correlation coefficient is observed at spinning force P = 120N. For this case the dependence removed allowance Z from duration of spinning was found using the Chebyshev method. In Table 5, Figure 7 and Figure 8 the results of investigations carried out by the above procedure are shown.

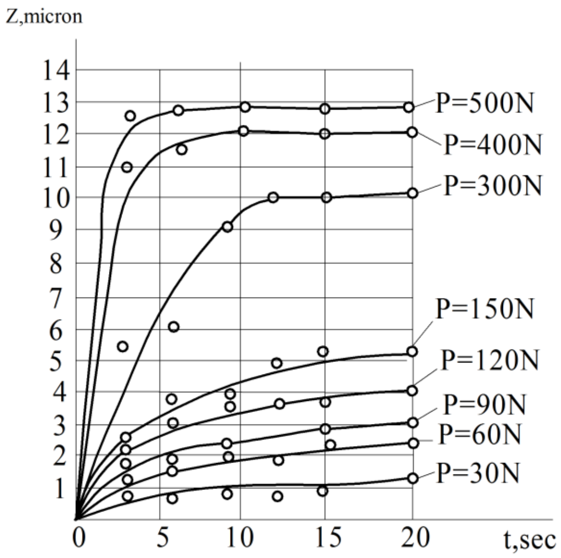

Fig.6: Theoretical and experimental Z (t, P) dependences during sharpened samples machining

Table 5: The average experimental values of remove oversize Z microns during spinning polished pins Ø4 ... 6 mm

Spinning force P, H	Spinning time t, sec			r_{zt}	confidence limit at β=0,9
	5	10	15		
90	0,9	1,2	1,35	0,7	0,34÷0,93
120	1,2	1,35	1,4	0,77	
150	1,35	1,5	1,5		
300	3,00	3,00	3,00		

$$Z(t) = 1.04+0.02t \tag{9}$$

$$\begin{cases} 1; & 5 \le t \le 15 \sec; P = 120\,N \\ 0; & other \end{cases}$$

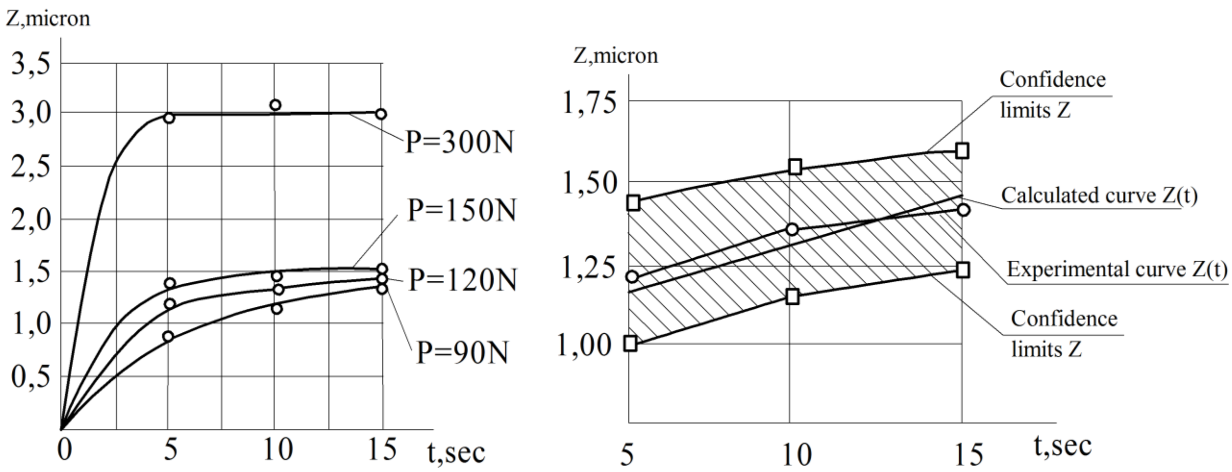

Fig.7: Comparative data of dependence experimental and calculated values of the spinning removed allowance to the duration of this process

$$Z(P) = 0.04+0.011P \qquad (10)$$

$$\begin{cases} 1; & 90 \le P \le 300N; \quad t = 10\,sec \\ 0; & other \end{cases}$$

The Z (P) dependence is calculated for the case when the maximum force of rollers pressing during spinning does not exceed 300 ... 400N. When P≥500N some deteriorations of trunnions macrogeometry and parts straightness exceeds the allowance for this parameter are observed.

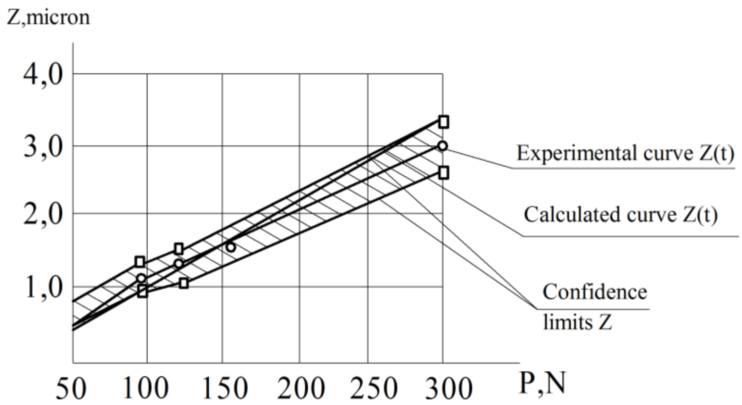

Fig.8: Comparative data of experimental and calculated according to the dependence (10) values of removed allowance Z during spinning with various efforts P.

3. CONCLUSION

Firstly, researching of finishing methods entering to the assembly parts of small diameters precision pairs have showed that rollers spinning should be encouraged as a reworking operation. Of all others this method allows to get the items that provide higher performance characteristics using a similar amount of efforts. *Secondly*, elucidated that spinning finishing is a more controlled process than grinding (correlation coefficients values are larger). *Thirdly*, the analytical expressions depending value of the removed allowance from the mode finishing were elucidated.

Presented in this work results are valid for steel 14X17H2 and 17X18H9, using other materials more research is needed, which is a further object of research in this area.

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