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OPTIMIZATION OF CUTTING FORCES DURING PLUNGE TURNING OF HARDENED 18CrMo4 STEEL

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Summary

The paper investigates the influence of cutting parameters (v_c, f, m) on the main cutting force F_c and the feed force F_f during finish plunge hard turning of hardened 18CrMo4 steel with the use of Cubical Boron Nitride (CBN) inserts. The experimental research was conducted according to the Taguchi methodology. On the basis of the research results obtained, optimal values of cutting parameters were determined, for which the cutting forces F_c and F_f are minimal. Next, the analysis of variance ANOVA was performed in order to determine the significance of the impact of particular cutting parameters on the optimized criteria. Verification tests which were carried out confirm the conclusions drawn that the greatest influence on cutting forces F_c and F_f has the cutting speed v_c which should be the greatest and feed f which should be the lowest.

Keywords: plunge hard turning, cutting forces, optimization, Taguchi method

Optymalizacja sił skrawania podczas wgłębnego toczenia zahartowanej stali 18CrMo4

Streszczenie

W pracy określono wpływ parametrów skrawania (v_c, f, m) na składową główną siły skrawania F_c i składową posuwową F_f podczas wykończeniowego wgłębnego toczenia na twardo stali 18CrMo4 w stanie zahartowanym. Stosowano płytki z regularnego azotku boru (CBN). Badania eksperymentalne prowadzono przy użyciu metodyki Taguchi'ego. Analiza uzyskanych wyników badań była podstawą do ustalenia optymalnych wartości parametrów skrawania, dla których siły skrawania F_c i F_f, przyjmują wartości najmniejsze. Wykonano również analizę wariancji ANOVA w celu określenia istotności wpływu poszczególnych parametrów skrawania na optymalizowane kryteria. Prowadzono badania weryfikujące, których wyniki potwierdziły przyjętą hipotezę, że największy wpływ na siły skrawania F_c i F_f ma prędkość skrawana v_c. Stąd należy stosować dużą prędkość skrawania, natomiast minimalny posuw.

Słowa kluczowe: wgłębne toczenie na twardo, siły skrawania, optymalizacja, metoda Taguchi'ego

1. Introduction

The increase in popularity of hard turning in recent years has brought many interesting variations of the plunge turning method [1]. The most important advantage of this machining method is the reduction of machining time of approx. 75-90% as compared to straight hard turning, even using the Wiper geometry

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inserts. This is a significant advantage in the current pressure to reducing the manufacturing time and production costs. Another advantage of hard turning with plunge feed is distribution of the cutting process over a considerable length of the cutting edge of the insert, which in combination with the short contact time of the stock with the tool results in extension of the tool life [2, 3]. Other benefits include the elimination of coolant and helical machining marks. Of course, hard turning with plunge feed has several drawbacks. The main one is the occurrence of increased cutting forces resulting from the distribution of the cutting process over a considerable length of the cutting edge. In addition, the quality of the finish, as well as the strength of the cutting edge of the insert must be high [2].

The width of the machined surface during plunge turning is limited to the length of the cutting edge of the insert. However, if the machining surfaces mating with sealing rings, this restriction is not an obstacle, because the contact of the sealing ring with the shaft surface occurs on a very small width. The results of preliminary research presented in paper [4] indicate that the surface of the steel 18CrMo4 after plunge hard turning perfectly meets the requirements for suitable geometrically-dimensional accuracy and surface layer properties [5-7]. Chromium-manganese steel 18CrMo4 is a common material for gear parts, for example for toothed shafts mating with the sealing rings. So far, the most common in industrial practice as finishing operation of surfaces mating with the sealing rings is used plunge grinding with a sufficiently long time of sparking-out, recommended by most manufacturers sealing rings. The problem of alternative methods of finishing surfaces mating with the sealing rings was raised, among others in the papers [8-10].

2. Methodology

The paper investigates the influence of the cutting speed v_c, plunge feed f and displacement m on the criteria of the main cutting force F_c and feed force F_f. The following measurements were performed during the research: mean values of the main cutting force $F_{c\,avg}$ and the feed force $F_{f\,avg}$, maximal values of this forces $F_{c\,max}$ and $F_{f\,max}$. The mean value of cutting forces $F_{c\,avg}$ and $F_{f\,avg}$ was determined only for the time period in which the values of these forces exceed the level of at least 50 N. The displacement parameter m consists in a small movement of the insert along its cutting edge, the purpose of which is the elimination of the effects of profile roughness of the cutting edge on the machined surface [2]. It occurs after the completion of the plunge feed movement of the cutting insert.

The experimental study was performed with the use of the Taguchi methodology. This methodology allows a simple, efficient, and systematic improvement of product quality and/or a reduction of its machining costs by using experimental research. Traditional designs of the experiment are complicated and difficult to use. Additionally, when the number of input parameters increases it is necessary to perform a large number of experiments [11]. Orthogonal arrays designed by Taguchi allow for simultaneous and independent assessment of the influence of two or more input parameters on the output parameter when the minimal number of experiments is performed. In the Taguchi methodology, the lost function is defined which is the difference between the desired value and the experimental value. In turn, the lost function can be transformed to the signal-to-noise *S/N* ratio, which, depending on the characteristic of the examined quantity can be: the smaller-the better, the bigger-the better, and the nominal-the better. Values of the signal-to-noise *S/N* ratio for the cutting forces F_c and F_f were calculated adopting the smaller the better criterion (SB), with the use of the following equation:

$$S/N_{SB} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

where: n – number of the measurements for a given layout of the experimental design, y_i – measured value of the investigated parameter. Regardless of the type of the optimized size, the largest value of the *S/N* coefficient corresponds to the optimal levels of the cutting parameters.

Three setting values of the cutting parameters were used in the experimental research v_c = 100, 200, 300 m/min, f = 0.02, 0.04, 0.06 mm/rev and m = 0, 0.025, 0.05 mm, successively referred to as level 1, 2 and 3. The experimental research was conducted according to the experimental design based on the orthogonal array L_9 (Table 1). For each layout of the experimental design 3 repetitions were performed. During the research, the following initial levels of the cutting parameter are assumed v_c = 200 m/min, f = 0,02 mm/rev, m = 0.025 mm labeled as: v_c2, $f1$, $m2$.

Table 1. Setting levels and the corresponding values of the cutting parameters for particular layouts of the experimental design based on the orthogonal array L_9

Layout No.	v_c	f	m	v_c**, m/min**	f**, mm/rev**	m**, mm**
1	v_c1	$f1$	$m1$	100	0.02	0
2	v_c1	$f2$	$m2$	100	0.04	0.025
3	v_c1	$f3$	$m3$	100	0.06	0.05
4	v_c2	$f1$	$m2$	200	0.02	0.025
5	v_c2	$f2$	$m3$	200	0.04	0.05
6	v_c2	$f3$	$m1$	200	0.06	0
7	v_c3	$f1$	$m3$	300	0.02	0.05
8	v_c3	$f2$	$m1$	300	0.04	0
9	v_c3	$f3$	$m2$	300	0.06	0.025

For each attempt at a final stage of the machining, a dwell is performed which is equal to two shaft rotations, aimed at assuring adequate dimensional accuracy of the machined surface. The research was conducted on the shaft having dimensions of Ø60×300 mm, made from 18CrMo4 steel. 27 grooves were cut on the shaft with dimensions of 4×4 mm, which created 27 cylindrical surfaces with the width 6 mm (9 layouts of the design × 3 repetitions), used in the course of the research. In the next step, the shaft underwent the following thermo-chemical treatments: carburizing to the depth of 2 mm, hardening and tempering to the hardness of 60±2HRC. The machining was carried out on the CNC lathe TUG 56-MN. Monolithic inserts TNGX1103085S-R-WZ of CBN100 grade which consisted of 50% CBN (grain size 2 µm) and 50% TiC used as the binder were used for finishing hard turning. The inserts were clamped in the tool holder CTJNR 2525 M11. During the research, a 0.2 mm-thick layer of the material was removed for each attempt. The test stand with the fixed testing shaft is shown in Figure 1.

Fig. 1. View of the test stand

The measurements of cutting forces F_c and F_f were performed using a Kistler dynamometer type 9272 connected to the charge amplifier, type 5070. The measured data were acquired using an A/C card type 2855A4 and software DynoWare. Statistical analysis of the results was performed using the software package Statistica v.12.

3. Results and their analysis

Values obtained from the measurements (mean from 3 repetitions) of the main cutting forces $F_{c\,avg}$, $F_{c\,max}$ and feed cutting forces $F_{f\,avg}$ and $F_{f\,max}$ with the corresponding S/N_{SB} ratio after turning with the plunge feed are presented in Table 2.

Table 2. The values of the main cutting forces $F_{c\ avg}$, $F_{c\ max}$ and feed cutting forces $F_{f\ avg}$ and $F_{f\ max}$ with corresponding S/N_{SB}

Layout No.	$F_{c\ avg}$, **N**	S/N_{SB}, **dB for** $F_{c\ avg}$	$F_{c\ max}$, **N**	S/N_{SB}, **dB for** $F_{c\ max}$	$F_{f\ avg}$, **N**	S/N_{SB}, **dB for** $F_{f\ avg}$	$F_{f\ max}$, **N**	S/N_{SB}, **dB for** $F_{f\ max}$
1	276.0	-49.132	457.3	-54.065	499.6	-53.587	749.5	-57.579
2	388.0	-51.782	691.6	-55.447	591.8	-56.813	898.9	-59.083
3	351.3	-51.067	623.0	-55.403	587.5	-56.072	880.2	-58.916
4	248.1	-47.922	436.4	-54.264	515.2	-52.858	772.3	-57.779
5	269.1	-48.600	549.3	-55.173	573.5	-54.817	884.8	-58.940
6	268.5	-48.695	513.5	-55.402	586.8	-54.319	881.0	-58.924
7	189.7	-45.613	364.1	-53.248	458.7	-51.260	677.8	-56.625
8	233.0	-47.351	489.3	-54.956	559.4	-53.793	764.1	-57.664
9	239.4	-47.582	546.6	-55.646	605.3	-54.759	825.0	-58.330

Table 3. The mean values of the S/N_{SB} ratio for particular setting levels of cutting parameters for the mean value $F_{c\ avg}$ and the maximum value $F_{c\ max}$ of the main cutting force

Cutting parameter	$F_{c\ avg}$				$F_{c\ max}$			
	Mean value S/N_{SB}, **dB**			$S/N_{SB\ max}$–$S/N_{SB\ min}$	**Mean value** S/N_{SB}, **dB**			$S/N_{SB\ max}$–$S/N_{SB\ min}$
	level 1	**level 2**	**level 3**		**level 1**	**level 2**	**level 3**	
v_c, m/min	-50.660	-48.406	-46.849	3.812	-55.491	-53.998	-53.270	2.220
f, mm/rev	-47.556	-49.244	-49.115	1.689	-52.568	-55.141	-55.050	2.573
m, mm	-48.393	-49.095	-48.427	0.703	-53.900	-54.810	-54.050	0.910
	Total mean ratio η=-48.638 dB; – optimal level				Total mean ratio η=-54.253 dB; – optimal level			

Table 4. The mean values of the S/N_{SB} ratio for particular setting levels of cutting parameters for the mean value $F_{f\ avg}$ and the maximum value $F_{f\ max}$ of the feed cutting force

Cutting parameter	$F_{f\ avg}$				$F_{f\ max}$			
	Mean value S/N_{SB}, **dB**			$S/N_{SB\ max}$–$S/N_{SB\ min}$	**Mean value** S/N_{SB}, **dB**			$S/N_{SB\ max}$–$S/N_{SB\ min}$
	level 1	**level 2**	**level 3**		**level 1**	**level 2**	**level 3**	
v_c, m/min	-54.972	-54.946	-54.617	0.355	-58.526	-58.548	-57.539	1.008
f, mm/rev	-53.859	-55.192	-55.484	1.625	-57.328	-58.562	-58.723	1.395
m, mm	-54.808	-55.119	-54.608	0.511	-58.056	-58.397	-58.160	0.342
	Total mean ratio η=-54.845 dB; – optimal level				Total mean ratio η=-58.204 dB; – optimal level			

In Tables 3 and 4 and Fig. 2 and 3, mean values of the S/N_{SB} ratio are presented for particular set-up levels of cutting parameters for the cutting forces

$F_{c\,avg}$, $F_{c\,max}$ and $F_{f\,avg}$, $F_{f\,max}$. In addition, these tables comprise the difference between maximum and minimum value of the $S/N_{SB\,max} - S/N_{SB\,min}$ ratio calculated for each cutting parameter and the total mean value η of the S/N_{SB} ratio.

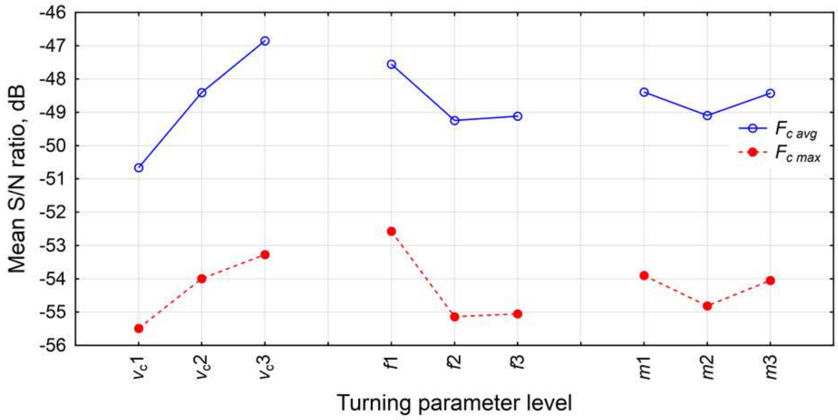

Fig. 2. The graph of mean values of the S/N_{SB} ratio for mean value $F_{c\,avg}$ and maximum value $F_{c\,max}$ of the main cutting force

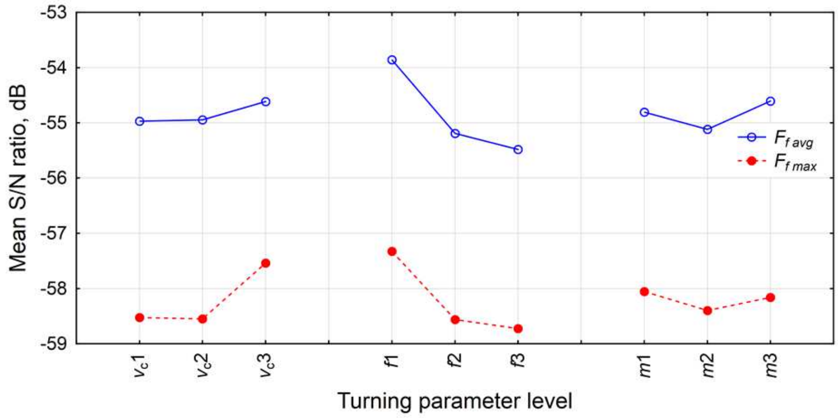

Fig. 3. The graph of mean values of the S/N_{SB} ratio for mean value $F_{f\,avg}$ and maximum value $F_{f\,max}$ of the feed cutting force

Analysis of Tables 3 and 4 and Fig. 2 and 3 shows that in most cases the optimal levels of cutting parameters (the highest values of S/N_{SB}) are as follows: v_c3, $f1$, $m1$. Only for $F_{f\,avg}$ the optimal value of displacement m is at a level of $m3$, i.e. m = 0.05 mm. Summarizing the above experimental results, the most significant effect on the components of the cutting force F_c and F_f is the cutting speed v_c and feed f (the largest differences of the $S/N_{SB\,max} - S/N_{SB\,min}$). The increase in the cutting speed v_c, and the decrease in the feed f value reduces the components of cutting force. The displacement m has practically no effect on the value of the components of the cutting force, because it does not change the cut of an undeformed chip. This is confirmed by the smallest differences between $S/N_{SB\,max} - S/N_{SB\,min}$ for this parameter.

Figure 4 shows an example chart of the main component F_c and the feed component F_f of the cutting force for the optimal values of the cutting parameters: $v_c = 300$ m/min, $f = 0.02$ mm/rev, $m = 0$ mm.

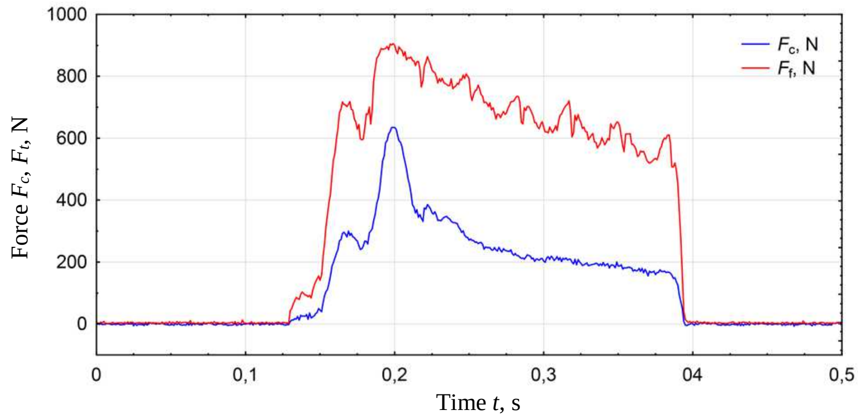

Fig. 4. An example chart of the main component F_c and feed component F_f of cutting force for the optimal values of the cutting parameters: $v_c = 300$ m/min, $f = 0.02$ mm/rev, $m = 0$ mm

An almost 2-times higher value of the feed cutting force F_f (Fig. 4, Table 2) results from the fact that the insert TNGX1103085S-R-WZ has a protective chamfer of the cutting edge with a width of 0.1 mm, an angle of 20° relative to the rake face. Thus, the whole cutting process takes place within the chamfer.

At the next stage of the research, analysis of variance ANOVA was performed to determine which particular cutting parameters v_c, f, m significantly influences the components of the cutting force F_c and F_f. The analysis was performed at the significance level of 1% (99% confidence level). The results of the ANOVA for the cutting forces $F_{c\,avg}$, $F_{c\,max}$ and $F_{f\,avg}$, $F_{f\,max}$ are given in Tab. 5 and 6.

Analysis of variance ANOVA for the mean value of the main cutting force $F_{c\,avg}$ (Table 5) indicates the greatest impact is the cutting speed v_c – 77.41%, followed by the feed f – 18.61%. However, as regards the maximum value of the main cutting force $F_{c\,max}$, the feed f – 58.11% has the greatest influence, and next the cutting speed v_c – 34.94%. Reasons for this situation should be sought in a large negative angle of the rake face of the insert (working in the area of protective chamfer) and in the fact that the maximum value of the force determines only the highest and usually short-lasting moment of the cutting force (Fig. 4) which occurs the moment the insert enters the stock, and therefore the impact of the feed f is more important. Consideration of the mean value of the main cutting force $F_{c\ avg}$ gives a more general picture of the participation of each cutting parameter in the total variance of this force. Therefore, the final conclusion should be drawn that the cutting speed v_c has a greater impact on the main cutting force F_c, than the feed f. Analysis of variance ANOVA for the feed cutting force F_f (Table 6) in both cases of the mean value $F_{f\ avg}$ and the maximum value $F_{f\ max}$ reveals that the feed f has the greatest impact on this force. This contribution amounts to 85.89% and 61.22%, respectively. Next is the cutting speed v_c, which accounts for 4.48% and 34.86% of total variance of the feed cutting force F_f, respectively. While the displacement parameter m for the cutting force F_c and F_f has minimum impact. The contribution of the order of a few percent in practice should be considered negligible.

Table 5. Results of the analysis of variance ANOVA for the mean value $F_{c\ avg}$ and the maximum value $F_{c\ max}$ of the main cutting force

Cutting parameter	**Degrees of fredom**	**$F_{c\ avg}$**				**$F_{c\ max}$**			
		Sum of squares	**Mean square**	**F**	**Contribution, %**	**Sum of squares**	**Mean square**	**F**	**Contribution, %**
v_c	2	22.039	11.019	115.453	77.41	7.688	3.844	76.935	34.94
f	2	5.300	2.650	27.763	18.61	12.787	6.394	127.964	58.11
m	2	0.943	0.471	4.938	3.31	1.429	0.714	14.300	6.49
Error	2	0.191	0.095		0.67	0.100	0.050		0.45
Total	8	28.472			100.00	22.005			100.00

Table 6. Results of the analysis of variance ANOVA for the mean value $F_{f\ avg}$ and the maximum value $F_{f\ max}$ of the feed cutting force

Cutting parameter	**Degrees of fredom**	**$F_{f\ avg}$**				**$F_{f\ max}$**			
		Sum of squares	**Mean square**	**F**	**Contribution, %**	**Sum of squares**	**Mean square**	**F**	**Contribution, %**
v_c	2	0.235	0.117	2.197	4.48	1.991	0.995	49.551	34.86
f	2	4.502	2.251	42.102	85.89	3.496	1.748	87.037	61.22
m	2	0.398	0.199	3.719	7.59	0.184	0.092	4.576	3.22
Error	2	0.107	0.053		2.04	0.040	0.020		0.70
Total	8	5.242			100.00	5.711			100.00

After determining the optimal levels of the cutting parameters, in the next step, a verification experiment is performed that in a practical way confirms the improvement of the optimized criteria. For optimal values of cutting parameters due to the cutting forces, the value of the S/N ratio was determined labeled as η_{opt} [12]:

$$\eta_{opt} = \eta + \sum_{i=1}^{n} (\eta_i - \eta) \tag{2}$$

where: η_i – value of the *S/N* ratio for the optimal level of the cutting parameter, *i* – number of parameters affecting the optimized criterion in a significant way.

Table 7 shows the results of the confirmation experiment using the optimal cutting parameters based on the criteria of cutting forces.

Table 7. The results of the confirmation experiment for the optimal values of the cutting parameters based on the criteria of cutting forces

	Initial cutting parameters		**Optimal cutting parameters**	
			Prediction	**Experiment**
Force	Level	v_c2, *f*1, *m*2	v_c3, *f*1, *m*1	v_c3, *f*1, *m*1
	$F_{c\ avg}$, N	263		215
	$F_{c\ max}$, N	397		415
	$F_{f\ avg}$, N	543		508
	$F_{f\ max}$, N	827		720
	VB_B, µm	152		148
$F_{c\ avg}$	*S/B* ratio, dB	-48.419	-45.520	-46.649
	Improvement of *S/B* ratio, dB		1.750	
$F_{c\ max}$	*S/B* ratio, dB	-51.976	-51.232	-52.361
	Improvement of *S/B* ratio, dB		-0.385	
$F_{f\ avg}$	*S/B* ratio, dB	-54.696	-53.594	-54.117
	Improvement of *S/B* ratio, dB		0.579	
$F_{f\ max}$	*S/B* ratio, dB	-58.350	-56.514	-57.147
	Improvement of *S/B* ratio, dB		1.203	

Table 7 shows, that the average improvement in the *S/N* ratio is 0.787 dB. Thus, a change in the cutting of the initial level to the optimal level allowed a visible reduction of the value of the cutting forces. It should be noted that the optimal value of the cutting speed v_c for optimization criteria is 300 m/min. As a final optimal cutting parameters values are proposed v_c = 300 m/min, *f* = 0.02 mm/rev, *m* = 0.025 mm (v_c3, *f*1, *m*2), as this will allow the reduction of cutting forces by 20%. This, in turn, will provide more stable cutting conditions, minimizing the chance of vibrations, which have a very damaging effect on the CBN inserts. The proposed displacement level *m*2 has no significant impact on the value of cutting forces.

For the proposed optimal cutting parameter levels v_c3, *f*1, *m*2, parameters of surface roughness were measured, which are as follows: *Ra* = 0.058 µm, *Rz* = 0.42

µm, *Rmax* = 0.61 µm. These parameters fulfill the requirements for the properties of the surface layer as recommended by manufacturers of sealing rings.

4. Conclusions

The paper presents the results of the optimization of cutting parameters due to the criteria of occurring cutting forces F_c and F_f using the Taguchi methodology. This made it possible to reduce the number of experiments carried out to determine the optimal levels of cutting parameters (v_c, f, m). Summarizing the above results, the following conclusions can be drawn:

- On the basis of the mean value of the *S/N* ratio, the optimal cutting parameters levels for cutting forces F_c and F_f – v_c3, f1, m1 (v_c = 300 m/min, f = 0.02 mm/rev, m = 0 mm) can be determined.
- On the basis of a subsequent analysis of variance ANOVA, it can be seen that the cutting speed v_c accounts for 77.41%, and the feed f – for 18.61% of total variance of the main cutting force $F_{c\,avg}$. For the feed cutting force F_f, in both cases, and $F_{f\,avg}$ and $F_{f\,max}$ revealed a greater impact feed f, this proportion is 85.89% and 61.22%, respectively. The contribution of the cutting speed v_c, amounts to 4.48% and 34.86%, respectively. Displacement m for cutting forces has a practically negligible impact on these quantities.
- For optimal cutting parameter levels, the results of the confirming experiments confirmed the above conclusions. It was possible to obtain a decrease in cutting forces by 20%, as compared to the initial cutting parameters.
- The proposed final optimal cutting parameters levels are as follows: v_c3, f1, m2 (v_c = 300 m/min, f = 0.02 mm/rev, m = 0.025 mm).

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