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THE ESTIMATION OF POSSIBILITIES OF THE TURNING PRODUCTIVITY RISE WITH THE USE OF COATED CARBIDE CUTTING TOOLS AND TECHNOLOGICAL CUTTING FLUID

An optimization method for selecting turning parameters based on the maximum productivity criterion has been developed for machining with coated carbide cutting tools and technological cutting fluids. A mathematical model of the turning process was formulated, incorporating constraints related to the permissible cutting temperature. Using linear programming techniques, analytical relationships describing the optimal cutting conditions as functions of the principal turning parameters were obtained. A productivity growth factor was introduced to account for the increased service life of coated carbide tools as well as the cooling and lubricating performance of the technological cutting fluid. On the basis of this factor, the potential for productivity improvement under various turning conditions with the application of coated tools and cutting fluids was evaluated.

Keywords: turning, optimization, cutting temperature, coated tools, cutting fluid, productivity.

Т. Г. Ивченко**ОЦЕНКА ВОЗМОЖНОСТЕЙ ПОВЫШЕНИЯ ПРОИЗВОДИТЕЛЬНОСТИ ТОЧЕНИЯ ПРИ ПРИМЕНЕНИИ ТВЕРДОСПЛАВНОГО РЕЖУЩЕГО ИНСТРУМЕНТА С ПОКРЫТИЕМ И ТЕХНОЛОГИЧЕСКОЙ СМАЗОЧНО-ОХЛАЖДАЮЩЕЙ ЖИДКОСТИ**

Разработан метод оптимизации режимов резания при точении по критерию максимальной производительности с применением твердосплавного режущего инструмента с покрытием и технологической смазочно-охлаждающей жидкости. Сформирована математическая модель процесса точения с учетом ограничений по допустимой температуре резания. С использованием методов линейного программирования получены аналитические зависимости оптимальных режимов резания от основных параметров точения. Введен коэффициент роста производительности, учитывающий увеличение стойкости твердосплавного инструмента с покрытием, а также охлаждающие и смазывающие свойства технологической смазочно-охлаждающей жидкости. На основе данного коэффициента выполнена оценка возможностей повышения производительности при различных режимах точения с применением инструмента с покрытием и смазочно-охлаждающей жидкости.

Ключевые слова: точение, оптимизация, температура резания, инструмент с покрытием, смазочно-охлаждающая жидкость, производительность.

1. Introduction

The intensification of the cutting process remains a central challenge in the machining of mechanical components. At present, the most effective approach to increasing machining efficiency involves the use of coated carbide cutting tools (CCT) in combination with technological cutting fluids (CF) [1]. These technological solutions enable higher cutting speeds and feeds while maintaining acceptable tool life and surface quality.

To achieve maximum benefit from their application, it is necessary to implement optimization procedures for selecting cutting parameters based on criteria such as maximum productivity or minimum production cost [2]. Among the available optimization techniques, linear programming is widely employed for determining optimal cutting speed and feed rate under operational constraints when maximizing productivity.

However, intensification of the cutting process inevitably leads to a significant increase in cutting temperature. This necessitates the incorporation of thermal constraints into optimization models. The studies presented in [3] provide methods for calculating heat flows and cutting temperatures during turning with the use of cutting fluids, enabling the solution of

optimization problems with explicit consideration of temperature limitations under various machining conditions.

Optimization problems for turning operations with the use of cutting fluids have been successfully addressed in previous studies [4, 5]. Nevertheless, the obtained results cannot be directly extended to coated carbide cutting tools, whose performance characteristics – particularly tool life – are substantially influenced by coating properties and thermal effects. Therefore, further development of optimization methods that account for the increased durability of coated carbide tools is both relevant and necessary. Such an approach makes it possible to justify higher cutting parameters and achieve a significant rise in machining productivity.

The objective of the present study is to refine the method for optimizing turning conditions and to evaluate the potential for productivity enhancement, taking into account the combined influence of cutting fluid and coated carbide cutting tools.

2. The main contents and outcomes of activity

By optimization of cutting regimes, productivity is accepted as an objective function of the machining which maximum is reaching at a minimum of basic time at rough turning limitations on possibilities of the cutting tool (1); on the maximum permissible cutting power N (2); on maximum permissible of cutting temperature Θ (3); on maximum permissible cutting tool strength (4); on maximum permissible ranges of a rotational speed n_{\min} (6), n_{\max} (7) and the feed S_{\min} (8), S_{\max} (9) operate, at finish turning on maximum permissible of machined surface roughness R_a (5), additionally operates in place of limitation on maximum permissible cutting tool strength. As a result of linearization of objective function and limitations by taking the logarithm the mathematical model of the cutting process expressed by system of the linear inequalities is defined ($X1 = \ln n$; $X2 = \ln S$):

At rough turning

$$\begin{cases} X1 + y_V X2 \leq b_1, \\ (n_p + 1)X1 + y_P X2 \leq b_2, \\ z_t X1 + y_t X2 \leq b_3, \\ y_P X2 \leq b_4, \\ X1 \geq b_6, X1 \leq b_7, \\ X2 \geq b_8, X2 \leq b_9, \\ (X1 + X2) \rightarrow \max, \end{cases}$$

(1)

at finish turning

$$\begin{cases} X1 + y_V X2 \leq b_1, \\ (n_p + 1)X1 + y_P X2 \leq b_2, \\ z_t X1 + y_t X2 \leq b_3, \\ k_3 X1 + k_2 X2 \leq b_5, \\ X1 \geq b_6, X1 \leq b_7, \\ X2 \geq b_8, X2 \leq b_9, \\ (X1 + X2) \rightarrow \max, \end{cases}$$

$$\begin{aligned}
 b_1 &= \ln(1000C_VK_VK_T^m/\pi DT^m t^{(x_v)}); \\
 b_2 &= \ln(6 \cdot 10^{3(n_p+2)}N\eta/C_PK_PK_{MP}(\pi D)^{(n_p+1)}t^{x_p}); \\
 b_3 &= \ln(1000^{z_t}\Theta/\tilde{N}_\Theta K_\Theta K_O(\pi D)^{z_t}); \\
 b_4 &= \ln(34\tilde{n}^{1,35}K_\Phi/C_PK_PK_{MP}t^{(x_p-0,77)}); \\
 b_5 &= \ln(R_a(\pi D/1000)^{k_3}/k_oK_RK_{MR}); \\
 b_6 &= \ln n_{min}; b_7 = \ln n_{max}; b_8 = \ln S_{min}; b_9 = \ln S_{max}.
 \end{aligned}$$

where T – tool life; t – depth of cut; D – diameter of machining; C_v, K_v and x_v, y_v, m – factors and the indexes characterizing degree of influence of depth, feed and tool life for cutting speed; K_T – factor, which takes into account the increase of coated carbide cutting tool life; n – synchronous speed; C_p, K_p, x_p, y_p, n_p – factors and the indexes characterizing degree of influence of depth, feed and cutting speed for cutting force P_z ; K_{MP} – factor, which takes into account the oiling properties of CF for cutting force; η – efficiency of transmission of machine tool; k_o, K_R, k_2, k_3 – factors and the indexes characterizing degree of influence of feed and cutting speed; K_{MR} – factor, which takes into account the oiling properties of CF for treated surface roughness; C_Θ, K_Θ and z_t, y_t – factors and the indexes characterizing degree of influence of cutting speed and feed for cutting temperature; K_O – factor of temperature lowering, which takes into account the cooling properties of CF.

The example of definition of optimum of cutting regimes at rough and finish turning of steel 45 is reduced on a figure 1.

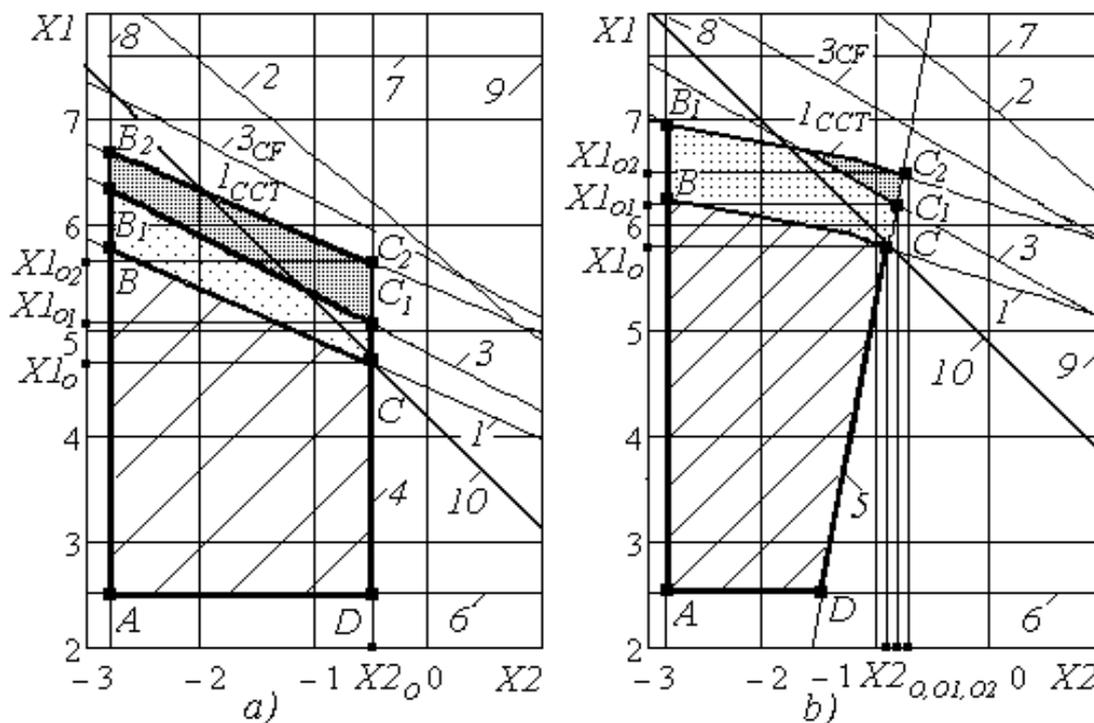


Figure 1. Graphs of determination of the optimum regimes at rough turning ($t=3mm; T=30min; c=5mm$) – a) and finish turning ($t=1mm; T=60min; R_a=3,2mkm$) – b) with use of CCT and CF

Polygon ABCD on reduced figure 1 represents the area of possible decisions at turning without CCT and CF. The objective function accepts the maximum value to a point C, for

which the sum of distances to shafts (X1+X2) is maximum to what the extremely possible position of the line 10 characterizing objective function testifies. The point C is a cross point of limitations on possibilities of the cutting tool (1) and cutting tool strength (4) at rough turning and on a roughness of machined surface (5) at finish turning. Coordinates of a point C (X1_o, X2_o) are required the best values of parameters.

The use of CCT increases tool life and changes limitations on possibilities of the cutting tool (1_{CCT}). However, the presence of temperature limitation does not allow realizing the possible of the cutting regimes increase. The point C₁ is a cross point of limitations on maximum permissible temperature of cutting (3) cutting tool strength (4) at rough turning and on a roughness of machined surface (5) at finish turning. Coordinates of a point C₁ (X1_{o1}, X2_{o1}) are required the best values of parameters.

The use of CF deletes temperature limitation and increases the cutting regimes. The point C2 is a cross point of limitations on possibilities of the cutting tool (1_{CCT}) and cutting tool strength (4) at rough turning and on a roughness of machined surface (5) at finish turning. Coordinates of a point C₂ (X1_{o2}, X2_{o2}) are required the best values of parameters.

Optimum cutting regimes – feed S_o and cutting speed V_o can be define analytically:

At rough turning:

$$S_{i1} = (34c^{1,35}t^{(0,77-x_p)}K_\phi/C_pK_PK_{MP})^{1/y_p} \tag{2}$$

$$V_{i1} = \begin{cases} (\Theta/C_\theta K_\theta K_o t^{x_t} S_{o1}^{y_t})^{1/z_t}, & \text{if } \Theta < \Theta_{o1} \\ C_V K_V K_T^m / T^m t^{x_v} S_{o1}^{y_v}, & \text{if } \Theta \leq \Theta_{o1} \end{cases} \tag{3}$$

At finish turning:

$$S_{o2} = \begin{cases} \left(\frac{\Theta(k_o K_R K_{MR})^{z_t/k_3}}{C_\theta K_\theta K_o R_a^{z_t/k_3} t^{x_t}} \right)^{\frac{k_3}{y_t k_3 - z_t k_1}}, & \text{if } \Theta < \Theta_o; \\ \left(\frac{R_a T^{m k_3} t^{k_3 x_v}}{k_o K_R K_{MR} (C_V K_V K_T^m)^{k_3}} \right)^{\frac{1}{k_1 - y_v k}}, & \text{if } \Theta \geq \Theta_o; \end{cases} \tag{4}$$

$$V_{o2} = \begin{cases} (R_a/k_o K_R K_{MR} S_{o2}^{k_1})^{1/k_3}, & \text{if } \Theta < \Theta_o; \\ C_V K_V K_T^m / T^m t^{x_v} S_{o2}^{y_v}, & \text{if } \Theta \geq \Theta_o. \end{cases} \tag{5}$$

where Θ_{o1}, Θ_{o2} – boundary value of cutting temperatures for which it is necessary to consider temperature limitation:

$$\Theta_{o1} = C_\theta K_\theta t^{x_t} \left(\frac{C_V K_V K_T^m}{T^m t^{x_v}} \right)^{z_t} \times \left[\frac{R_a T^{m k_3}}{k_o K_R (C_V K_V K_T^m)^{k_3}} \right]^{\frac{y_t - y_v z_t}{k_1 - y_v k_3}}$$

$$\Theta_{o2} = C_\theta K_\theta t^{x_t} \left(\frac{C_V K_V K_T^m}{T^m t^{x_v}} \right)^{z_t} \times \left[\frac{340c^{1,35}t^{(0,77-x_p)}K_\phi}{C_p K_P} \right]^{\frac{y_t - y_v z_t}{y_p}}$$

The results of analysis of cooling and oiling proper-ties for different CF are presented on table 1, 2, 3 [3].

The analysis for followings most widespread CF: Akvol-2 (CF, which owns the most expressed cooling properties); Ukrinol-1 (CF, which owns the most expressed cooling proper-ties and partly oiling properties); MR-1y (CF, which owns the most expressed oiling proper-ties and partly cooling properties) is carried out. MR-1y has the minimal factors of tempera-ture lowering K_O , factors cutting force at rough turning K_{MP} and machined surface roughness at finish turning K_{MR} .

The use of CF ensures possibility of optimum feeds S_{oCF} and cutting speed V_{oCF} rise in comparison with optimum cutting regimes S_o and V_o at machining without CF.

Table 1. Factors of temperature lowering K_O for different CF

Machining material	Factors of temperature lowering K_O for different CF:		
	Acvol-2	Ukrinol-1	MR-1y
Constructional steel	0,85	0,82	0,78
Stainless steel	0,80	0,76	0,73

Table 2. Factors K_{MP} of cutting force lowering at rough turning for different CF

Machining material	Factors of t cutting force lowering K_{MP} for different CF:		
	Acvol-2	Ukrinol-1	MR-1y
Constructional steel	1	0,95	0,85
Stainless steel	1	0,9	0,8

Table 3. Factors K_{MR} of machined surface roughness lowering at finish turning for different CF

Machining material	Factors of machined surface roughness lowering K_{MR} for different CF:		
	Acvol-2	Ukrinol-1	MR-1y
Constructional steel	1	0,97	0,9
Stainless steel	1	0,95	0,85

Quantitatively the rise of machining productivity can be justified based on factor $K = S_{oCF}V_{oCF}/S_oV_o$. Ground fixed analytical dependences of optimum feeds S_o and cutting speed V_o on machining conditions, the factor of machining productivity rise at the expense of use CF for rough turning K_1 and finish turning K_2 is defined:

$$K_1 = \begin{cases} K_O^{-n_1} K_{MP}^{n_2} K_T^m, & \text{if } K_O \geq K_{O1}; \\ \left(\frac{C_V K_V K_T^m}{T^m t^{x_v}} \right) \left(\frac{C_\theta K_\theta}{\theta t^{-x_t}} \right)^{n_1} \left(\frac{C_P K_P t^{(x_p - 0,77)}}{34 C^{1,25} K_\phi^{0,8}} \right)^{n_3} \end{cases} \quad (6)$$

$$n_1 = \frac{1}{z_t}; \quad n_2 = \frac{y_t - z_t}{y_p z_t};$$

$$n_3 = \frac{y_v z_t - y_t}{y_p z_t}$$

$$K_2 = \begin{cases} K_O^{n_4} K_{MR}^{n_5} K_T^m, & \text{if } K_O \geq K_{O2} \\ \left(\frac{C_V K_V K_T^m}{T^m t^{x_v}} \right)^{n_6} \left(\frac{C_\Theta K_\Theta}{\Theta t^{-x_t}} \right)^{n_7} \left(\frac{R_a}{k_0 K_R} \right)^{n_8} \end{cases} \quad (7)$$

$$n_4 = \frac{k_1 - k_3}{y_t k_3 - z_t k_1}; \quad n_5 = \frac{y_t - z_t}{y_p z_t};$$

$$n_6 = \frac{k_1 - k_3}{k_1 - y_p k_3}; \quad n_7 = \frac{k_3 - k_1}{y_t k_3 - z_t k_1};$$

$$n_8 = \frac{(y_p z_t - y_t)(k_1 - k_3)}{(y_t k_3 - z_t k_1)(k_1 - y_p k_3)}.$$

where $K_{O1} = \Theta/\Theta_{o1}$, $K_{O2} = \Theta/\Theta_{o2}$ – the factor considering cooling action of CF, which defines a limiting value for which it is necessary to consider temperature limitation.

Graphs of dependence of factors K_{O1} and K_{O2} on cutting feed t and machined surface roughness R_a (in the conditions of the machining, specified earlier) for different values tool life T are reduced on figure 2.

The factors considering cooling action of CF, which defines a limiting value, for which it is necessary to consider temperature limitation, are higher than cutting depths at rough turning (figure 2, a) and machined surface roughness at finish turning (figure 2, b) are higher.

With the use of the known normative information [6] the factors of machining productivity rise for different steels: steel 45, steel 30XГC, stainless steel X18H9T can be presented:

$$K_{1st45} = \begin{cases} K_O^{-2,6} K_{MP}^{-0,17} K_T^{0,2}, & K_O \geq K_{O1st45}; \\ 2,6 K_T^{0,23} / T^{0,2} t^{0,28}, \end{cases}$$

$$K_{2st45} = \begin{cases} K_O^{-3,0} K_{MR}^{-0,06} K_T^{0,2}, & K_O \geq K_{O2st45}; \\ 1,24 K_T^{0,23} R_a^{0,9} / T^{0,2} t^{0,15}, \end{cases}$$

$$K_{1st30XGC} = \begin{cases} K_O^{-2,6} K_{MP}^{-0,17} K_T^{0,2}, & K_O \geq K_{O1st30XGC}; \\ 3,4 K_T^{0,23} / T^{0,2} t^{0,28}, \end{cases}$$

$$K_{2st30XGC} = \begin{cases} K_O^{-3,0} K_{MR}^{-0,06} K_T^{0,2}, & K_O \geq K_{O2st30XGC}; \\ 2,14 K_T^{0,23} R_a^{0,9} / T^{0,2} t^{0,15}, \end{cases}$$

$$K_{1stX18H9T} = \begin{cases} K_O^{-2} K_{MP}^{-0,5} K_T^{0,25}, & K_O \geq K_{O1stX18H9T}; \\ 4,4 K_T^{0,29} / T^{0,25} t^{0,2}, \end{cases}$$

$$K_{2stX18H9T} = \begin{cases} K_O^{-2} K_{MR}^{-0,17} K_T^{0,25}, & K_O \geq K_{O2stX18H9T}; \\ 3,25 K_T^{0,29} R_a^{0,3} / T^{0,25} t^{0,3}. \end{cases}$$

The results of estimation of possibilities of the turning productivity rise with the use of technological cutting fluid based on presented method are reduced on figure 3-5.

Graphs of dependence of factors of machining productivity rise K_1 and K_2 on factor of temperature lowering K_0 considering cooling action of CF at rough and finish turning of different steels are reduced on figure 3.

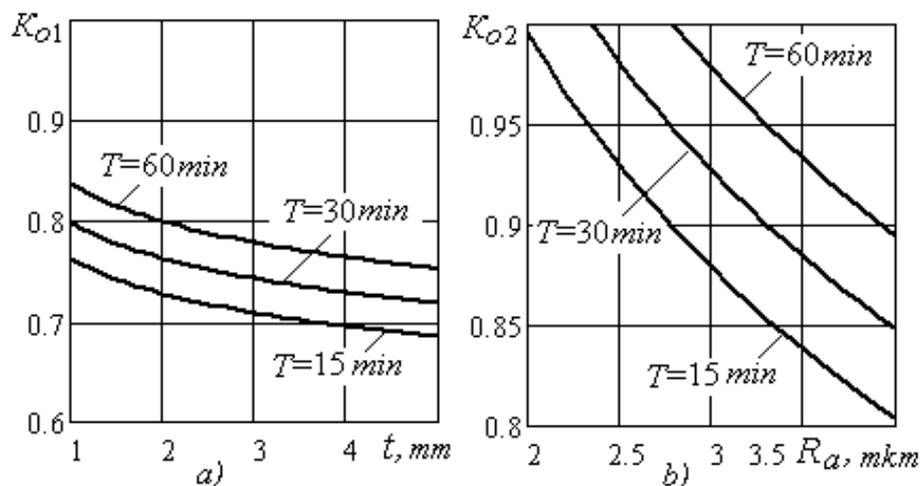


Figure 2. Graphs of dependence of factor K_{O1} and K_{O2} on cutting feed t at rough turning – a) and on machined surface roughness R_a at finish turning – b)

The machining productivity with use of CF rises in connection with reduction of factor of cutting temperature lowering to the level defined by removal of temperature limitation and then productivity remains constant. The subsequent change of factor of cutting temperature lowering becomes inexpedient from the point of view of machining productivity rise.

The greatest increasing of the productivity can be reached for stainless steel X18H9T at finish turning. Graphs of dependence of factor of machining productivity rise K_1 and K_2 on factor of temperature lowering K_0 for different factors K_{MP} and K_{MR} which takes into account the oiling properties of CF for cutting force at rough turning and machined surface roughness at finish turning are reduced on figure 4.

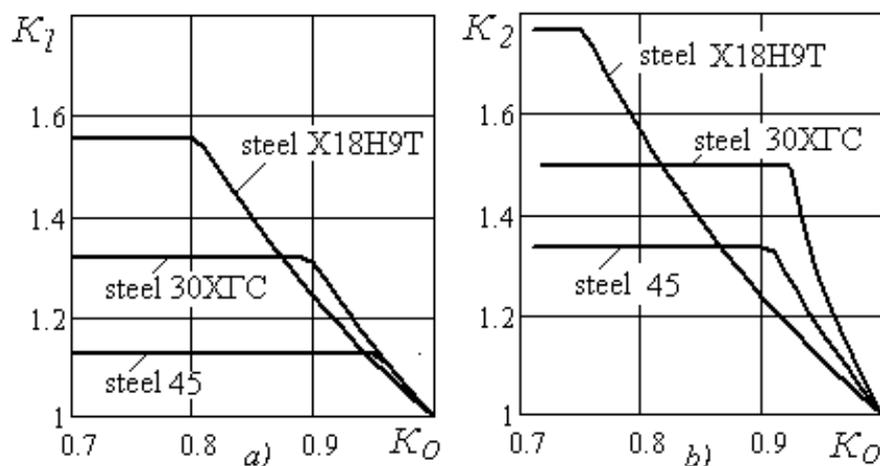


Figure 3. Graphs of dependence of factors of machining productivity rise K_1 and K_2 on factor of temperature lowering K_0 for different steels at rough turning – a) and finish turning – b)

Machining productivity is higher than factors K_{MP} and K_{MR} are less that corresponds to higher oiling properties CF. The greatest increasing of the productivity can be reached at value factors K_{MP} which takes into account the oiling properties of CF for cutting force at rough turning (figure 4, a) and small value factors K_{MR} which takes into account the oiling properties of CF for machined surface roughness at finish turnings (figure 4, b).

Graphs of dependence of factor of machining productivity rise K_1 and K_2 on factor of temperature lowering K_O for different cutting depth at rough turning and machined surface roughness at finish turning are reduced on figure 5.

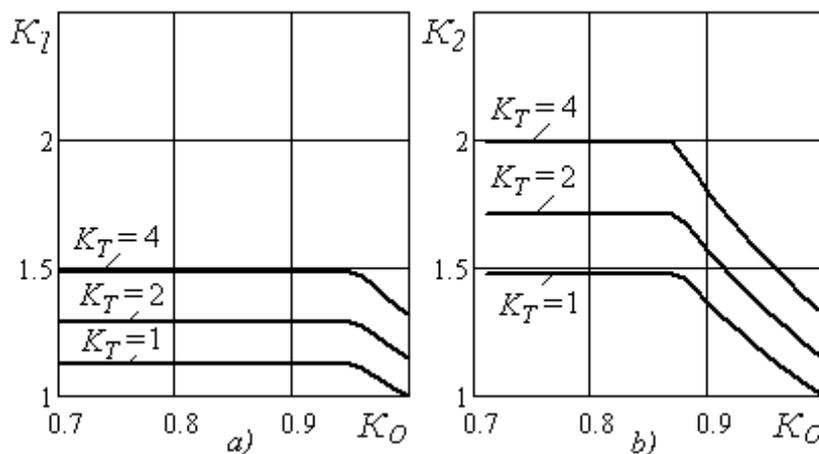


Figure 4. Graphs of dependence of factors of machining productivity rise K_1 and K_2 on factor of temperature lowering K_O for different factors K_T , which takes into account the increase of coated carbide cutting tool life at rough – a) and finish – b) turning steel 45

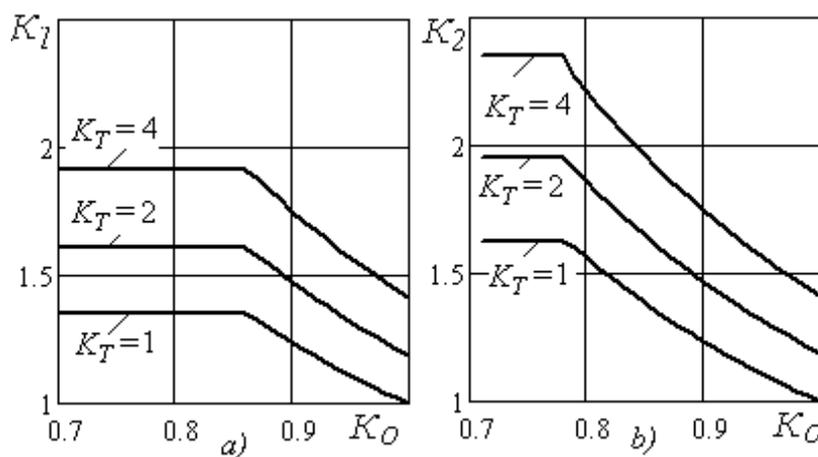


Figure 5. Graphs of dependence of factors of machining productivity rise K_1 and K_2 on factor of temperature lowering K_O for different factors K_T , which takes into account the increase of coated carbide cutting tool life at rough – a) and finish – b) turning steel X18H9T

Machining productivity is higher than cutting depths at rough turning and machined surface roughness at finish turning are higher. The greatest increasing of the productivity can be reached at great values of cutting depth (figure 5, a) and great values of the machined surface roughness (figure 5, b).

The results of estimation of possibilities of the turning productivity rise with the use of coated carbide cutting tools based on the presented method for different steels are reduced on

figure 6 and figure 7.

Machining productivity is higher than factors K_T , which takes into account the increase of coated carbide cutting tool life, are higher. The greatest increasing of the productivity can be reached at finish turning.

3. Conclusion

As a result of the conducted research, a methodology for optimizing turning parameters based on the criterion of maximum productivity has been developed. The approach incorporates the application of coated carbide cutting tools and technological cutting fluids. A mathematical model of the turning process was formulated, accounting for constraints imposed by permissible cutting temperature. Using linear programming techniques, analytical relationships describing the optimal cutting conditions as functions of the principal turning parameters were derived.

A productivity enhancement factor was introduced to quantitatively reflect the combined effects of increased tool life of coated carbide inserts, as well as the cooling and lubricating performance of technological cutting fluids. The influence of temperature reduction – considering both the thermo-physical properties of the cutting fluid and the characteristics of coated carbide tools for different steel grades – on the productivity growth factor was established.

An assessment of the potential productivity gains achievable through the application of coated carbide tools and cutting fluids under various turning conditions was performed. The results demonstrate that productivity improvements for all investigated steels are more significant in finish turning than in rough turning, reaching up to 30%. Moreover, greater productivity growth was observed in machining stainless steel X18H9T compared to structural steel 45, with increases of up to 25% under both rough and finish turning conditions.

The maximum productivity gain was achieved in finish turning operations with the combined use of coated carbide tools and technological cutting fluids: up to 2.5-fold for stainless steel X18H9T and up to twofold for structural steel 45.

The proposed method can be applied to evaluate the potential for productivity enhancement across various machining scenarios involving coated carbide cutting tools and technological cutting fluids.

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