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Optimization Of Multi-Tool Machining Process

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Abstract: Optimization of the machining modes for machine tools by criterion of the maximum productivity rate is complex and in many cases an unresolved problem. Increasing of machining modes leads to change the productivity rate. In the case of multi-tool machining processes, when cutters are engaged simultaneously or sequentially to define the optimal machining mode that gives the maximum productivity rate is an important problem. The present paper formulates a mathematical model based on maximum productivity rate by criterion for optimization of machining mode on machine tools. This case study represents a new mathematical model of the productivity rate of machine tools for multi-cutting processes with changes in machining modes. Practical application of new equations of the productivity rate for a machine tool with changes in the machining mode for the optimal multi-cutting operations is presented.

Key words: machining, productivity, optimization.

INTRODUCTION

The two most important parameters of the economics of machining are the minimum machining cost per part and the maximum production rate of machine tools. Which of those parameters is more important depends on many factors. Manufacturers are struggling to increase of productivity of machining processes and to put more products on the market. Increasing of productivity rate is reached by increasing of machining modes, which leads to increasing of the costs of machining processes and to increasing of the cost of products. This last leads to decreases in the sale of products due to its expensiveness (Tlusty and Tlusty, 1999; Kalpakjian, 2006; Volchkevich, 2005; Freiheit and Hu, 2002; Isakov, 2004). However, the marketing process shows a different picture of sales. If a product is requested by customers, manufacturers can sell at high prices. In this case, the index of minimum machining cost moves away from its first position and the index of the productivity rate comes to the first level. When a market comes to be saturated by products, the sales of a product decrease; in such a case, the product should be manufactured by using the minimum machining cost.

Different researchers have proposed numerous models, which underline the importance of optimization of machining parameters. In literature, there are many research papers dedicated to different aspects of optimization of machining processes. Many researchers have proposed solutions as an effective tool for dealing with such difficult problems (Kountanya and Boppana, 2008; Onwubolu, 2005; Chan *et al.* 2003). Some of them consider optimization of multi cutting machining modes with some constrains (Hägglund, 2003; Agapiou, 1992; Chen M.C. and Su, 1998; Kumar *et al.,* 2006; Amiolemhem *et al.,* 2004; Kim Sung Soo *et al.,* 2008). Other papers represent optimization of the single and multiple passes turning operations (Wang S-G and Hsu, 2005; Gupta *et al.,* 1995; Naik *et al.,* 1998; Abburi *et al.,* 2007; Zhang Lee Yi *et al.,* 2010). There are mathematical models that enable the calculating of the minimum machining cost depending on the changes in the machining modes and the optimization of the machining process (Tlusty and Tlusty, 1999; Kalpakjian, 2006; Volchkevich, 2005). However, the criterion of the maximum productivity rate of machinery prevails in many cases of industrial production. Practice shows no great difference in the values of optimal machining modes calculated by the criterions of the minimum cost and the maximum productivity rate (Tlusty and Tlusty, 1999; Kalpakjian, 2006; Volchkevich, 2005). Unsolved problems of optimization of machining modes are corrected practically that paths long process of analysis by both criterions. The lack of mathematical models, which give correct results of optimization of machining parameters, is reveals itself in numerous publications that show this difficult problem is still a debated topic. However, in literature there are not many mathematical models that combine general parameters of machining processes, which can develop a generalized mathematical model. This paper represents the mathematical models of the optimal machining modes for multi-cutting machining processes with different cutters involved simultaneously and separately in processes. Mathematical models of optimization of machining mode considering maximum productivity rate criterion.

Analytical Approach:

Demand to increase the productivity rate of the machine tools leads to intensification of the machining process, which reflects on the reliability parameters of the machine tool components. Hence, increase of machining modes of industrial machine tools leads to an increase in the productivity rate on one side and on the

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other side leads to an increase in the failure rates of the machine tool components. The failure rates increase due to the increase of the dynamic loads on the components, increases in the wearing process, etc., hence machine tools need to be stopped and tuned, which decreases the primary productivity rate. These circumstances show that machine tools should have optimal machining modes that can give a maximal productivity rate. The dependency of the productivity rate with the change of machining modes should be described analytically to enable the prediction of the real output of machine tools. To find such mathematical dependency it is necessary to conduct analyses of all parameters of the machine tool work with the change of machining modes.

Machining processes comprise many unsolved problems that should be resolved in order to get reliable data with respect to manufacturing economics. Some analytical models are able to predict machine tool output through changes of the tool life (Tlusty and Tlusty, 1999; Kalpakjian, 2006; Volchkevich, 2005). Known equations of machining modes are quite poor in expressing the productivity rate and do not have analytical functions on reliability for machine tool mechanisms (Kountanya and Boppana, 2008; Onwubolu, 2005; Chan *et al.* 2003; Hägglund, 2003; Agapiou, 1992). The analytical expressions of the productivity rate that include all parameters of the machining mode are very important in manufacturing areas to enable the predicting of the output of machinery with high accuracy.

A machining mode is characterized by the following parameters: the cutting speed, the feed rate and the depth of cut. Feed rate and depth of cut cannot be changed in large scale operations due to limitations in the quality of the surface and the accuracy of the machining process. However, the cutting speed can be changed over quite a large range. With the increase in cutting speed comes the reduced surface roughness of a machined part, the increased accuracy of machining and also the increase in the productivity rate of the machining process. Also, it is known that the intensification of machining modes reflects on the more intensive wear process of machine tool units as a result of the increase in the dynamic forces and speed of primary motions. As a result, machine tools have to go through more maintenance and repairing processes that ultimately result in the decrease of its output and economic efficiency.

The fundamental basis of the calculation of the productivity rate for machine tools as a function of the intensification of machining regimes can be presented by the following equation (Volchkevich, 2005).

$$Q = \frac{1}{t_m + t_a + \sum_{i=1}^{k} t_{ci} + \sum_{j=1}^{p} t_{ej}} \tag{1}$$

where Q is the productivity rate of a machine tool (parts/min), t_m is the duration of the machining time spent in the feed mode or cutting and removing chips (min/parts), t_a is the duration of auxiliary time spent to load and unload the work-piece, advance and retract the tool and occasional dimensional inspection of the part (min/parts), $\sum_{i=1}^{k} t_{ci}$ is the time losses referred to one part due to reliability of cutting tools that are changed after some limit of wearing or occasional breakage, then cutters set up and tuning and so forth (min/parts), $\sum_{j=1}^{p} t_{ej}$ is time losses referred to one part due to the reliability of machine tool units containing mechanical, or electrical, or hydraulic units, etc. (min/parts).

For the analysis of the influence of change of machining modes on the productivity rate of machine tools, it is grouped by mechanisms for machining motions and auxiliary motions. Industrial practice and theory of machining processes show that increase in the cutting speed leads to decrease of the machining time, and to increase the productivity losses due to reliability of machine tool components. It is necessary to consider each component of the equation of machine tool productivity with the change in cutting speed on the machine tool.

The change of the machining time with change in machining mode:

The machining time can be expressed by the ratio of the sum of the number of the spindle revolutions, which is necessary for fulfillment of all uncombined operations (Σn_i) to the number of revolutions of the spindle per minute n_s. This machining time has the following equation

$$t_m = \frac{\sum_{i=1}^{g} n_i}{n_s} \tag{2}$$

where $\sum_{i=1}^{g} n_i$ is the sum of the number of the spindle revolutions for fulfillment of g uncombined i operations.

The number of the spindle revolutions per each operation can be expressed by the following equation

$$n_1 = l_1/f_1;\; n_2 = l_2/f_2;\; n_3 = l_3/f_3;\; \ldots\; n_g = l_g/f_g; \tag{3}$$

where l_1; l_2; l_3; … l_g are the lengths of the part to be machined, f_1; f_2; f_3; … f_g are feed rates of cutters per one revolution of the spindle.

Hence $$\sum_{i=1}^{g} n_i = \sum_{i=1}^{g} \frac{1}{n_s}\frac{l_i}{f_i} \tag{4}$$

The number of the revolutions of the spindle per minute n_s has the following expression

$$n_s = \frac{V}{\pi d} \tag{5}$$

Where V is the cutting speed (m/min), d is the diameter of the part surfaces to be machined (m).

Substituting expressions (4) and (5) into Eq. (2), and after the transformation, the machining time will have the following equation

$$t_m = \sum_{i=1}^{g} \frac{\pi d_i}{V_i}\frac{l_i}{f_i} \tag{6}$$

where all parameters are as specified above.

In the case of combined operations, machining time is chosen by the constraints of machining modes for each operation based on the indices of machining quality. Constraints of machining modes concern mainly the feed rates f_i and depth of the cut of machining process. For multi-tool machining mode the choice was the minimum feed rate f_{min} for some operations, with the ability to change the cutting speed V. Other parameters like length of the cut $l_{i,}$, the diameter and the cutting speed are chosen for the operation with maximum duration of machining process. Hence, the equation of the machining time will have the following expression:

$$t_m = \frac{\pi d_{\max}}{V_i}\frac{l_{\max}}{f_{\min}} \tag{7}$$

where all parameters as specified above.

The Change Of The Auxiliary Time With Change In Machining Mode:

Most modern designs of the machine tools do not have kinematic functions between mechanisms of machining and auxiliary motions. The changes of the machining modes in the mechanism of the machining motions do not reflect on the regime of work for the mechanisms of the auxiliary motions. Hence, for this type of machine tools the auxiliary time is not changed because the part feeding, fast motions of the tool holders to machining area and back, handling motions, etc., are presented the auxiliary time. This time is outside the machining processes and changes of machining mode do not reflect on the time of auxiliary motions. Based on these circumstances, the time of auxiliary motions is accepted as constant for manufacturing machines, i.e. t_a = const.

In the case where the machine tool designs have the kinematic function between mechanisms of the machining and auxiliary motions, the auxiliary time has the proper function on the change of machining modes. Most of these type machine tools are rare designs and the amount of them in manufacturing area is small and does not play a big role. So for further analysis these types of machine tools are not considered.

The Change Of The Time Losses Due To Reliability Of Cutters With Change In Machining Mode:

The mathematical function of the increase in productivity losses due to intensive wear process and reliability of cutting tool with an increase of cutting speed can be found by the following approach.

The index $\sum_{i=1}^{k} t_{ci}$ of time losses due to reliability of k cutters with an intensification of machining modes is not analytically dependent and it is a subject for analysis (Volchkevich, 2005) This index has the following expression:

$$\sum_{i=1}^{k} t_{ci} = \frac{\sum_{i=1}^{k} \theta_{ci}}{z}, \tag{8}$$

where $\sum_{i=1}^{k}\theta_{ci}$ = $\theta_1 + \theta_2 + \theta_3 +... + \theta_k$, and $\theta_{1,}$ θ_2, etc., is the average random individual idle time due to change of the cutters of a machine tool, z is the quantity of machined parts per a considered time interval.

Time losses due to the cutter i has the following expression:

$$t_{ci} = \frac{\theta_i}{z} \tag{9}$$

The time losses (θ_{i}) due to change of the cutter i can be presented in the average parameters of reliability, i.e., by the index of the mean time τ, of the change of the cutter i, and by the number of change cutters r or $\theta_{\mathrm{i}} = \tau r$ is product of τ and r.

The number of machine parts produced per observation time, and therefore by the cutter i, can be expressed by the following equation:

$$z = z_i r = \left(\frac{T_i}{a_i}\right) r \tag{10}$$

where z_i is the average number of parts machined between two replacements of the cutter i, T_i is the tool-life, a_i is time of machining by the cutter i of the one part, other parameters as specified above.

The time of machining of the one part a_i by the cutter i can be expressed by Eqs. (6) and (7), but there is one difference. The difference is the time of machining a_i does not include the time, which is necessary to pass the safety distances between the cutter and the part. These safety distances are necessary to avoid the occasional hits of the cutter to the part at the beginning of the machining process and to guarantee finishing machining the surfaces.

The machining length and the length of part to be machined have the following expression, $l_i = l_{ai} + l_{si}$, where l_{ai} is the length of the part to be machined, $l_{si} = 2…4$mm is the safety distance, all other parameters as specified above. Hence, the time a_i of machining of a single part will have the following expression:

$$a_i = \frac{\pi d_i}{V_i}\frac{l_{ai}}{f_i} \tag{11}$$

Substituting expressions $\theta_{\mathrm{i},}$ (10) and (11) into Eq. (9), and after transformation, the time losses due to the cutter i will have the following expression:

$$t_{ci} = \frac{\tau}{T_i} * \frac{\pi d_i}{V_i} * \frac{l_{ai}}{f_i} \tag{12}$$

where all parameters are as specified above.

The equation of the Taylor tool-life of the cutter i has the expression (Tlusty and Tlusty, 1999; Kalpakjian, 2006; Volchkevich, 2005; Freiheit and Hu, 2002; Isakov, 2004):

$$T_i = \left(\frac{C_i}{V_i}\right)^{1/b_i}, \tag{13}$$

where T_i is the tool-life in minutes, C_i is empirical constants resulting from regression analysis and field studies and depends on many factors: geometry of the tool, cooling process, cutting speed, surface hardness of the work-piece, etc., V_i *is* the cutting speed in m/min of a machining process, and b_i is empirical constants that depend in general on the cutter tool material.

After substituting defined parameters into Eq. (11), following transformations and simplification, the expression of the time losses due to change of the cutter i will have the following equation:

$$t_{ci} = \frac{\pi\tau d_i l_{ai}}{f_i}\left(\frac{V_i^{(1-b_i)/b_i}}{C_i^{1/b_i}}\right) \tag{14}$$

In common cases, the machine tool can have different cutters with different properties b_i and $C_{\mathrm{i},}$, then the sum of time losses due to different k cutters can be expressed by the following equation:

$$\sum_{i=1}^{k} t_{ci} = \sum_{i=1}^{k}\frac{\pi\tau d_i l_{ai}}{f_i}\left(\frac{V_i^{(1-b_i)/b_i}}{C_i^{1/b_i}}\right) \tag{15}$$

where all parameters are as specified above.

The change of the time losses due to reliability of machine tool units with change in the machining mode:

The mathematical function of productivity losses due to reliability of machine tool units with increase of cutting speed is the subject of special investigations. Definitely, there are some functions that can be described mathematically. However, most primary machine units like spindles, supports, mechanisms of machining motions, etc., have reliability levels that are many times higher than the reliability of the cutters.

The practice shows the intensification of machining processes does not reflect too much on the reliability of machine tool mechanisms. This result is based on data that the failure rate of the cutters is prevalent many times over the failure rates of the other machine units (Tlusty and Tlusty, 1999; Kalpakjian, 2006; Volchkevich, 2005). In such circumstances, time losses due to machine units do not give sensitive results on the drop in the productivity rate of the machine tool. Hence, the time losses of primary machine tool units with change in the processing modes for common cases of machining processes is accepted as constant, i.e., $\sum_{j=1}^{p} t_{ej}$ = const.

It is necessary to mention that the modern tendency in manufacturing areas is the use of new types of cutter materials, whose properties are close to the diamond-type cutters. New cutter materials have the high reliability level that can be commensurable to the reliability level of primary machine units. In such cases, to derive the mathematical dependency mentioned above is crucial (Tlusty and Tlusty, 1999; Kalpakjian, 2006; Volchkevich, 2005; Freiheit and Hu, 2002).

Productivity rate of the machine tool with change in multi-tool machining mode:

Defined expressions of changes in the parameters of the productivity rate enable derivation of the equation of the productivity rate for machine tools with change in multi-tool machining mode when cutters imply simultaneous operations. Substituting defined expressions (9) and (16) into Eq. (3), and after following transformations and simplifications, the equation of the productivity rate will become the following equation:

$$Q = \frac{1}{\dfrac{\pi d_{\max}}{V_i} * \dfrac{(l_{a\max} + l_{si})}{f_{\min}} + t_a + \sum_{i=1}^{k} \dfrac{\tau \pi d_i l_{ai}}{f_{\min}} \left(\dfrac{V_i^{(1-b_i)/b_i}}{C_i^{1/b_i}} \right) + \sum_{j=1}^{p} t_{ej}} \tag{16}$$

where all parameters are as specified above. Eq. (16) can be solved by numerical methods and software.

Productivity Rate Of The Machine Tool With Change In Multi-Tool Machining Mode When Tools Imply Separately:

The equation of the productivity rate when a single tool *i* cuts separately is derived from Eqs. (1), (7), and (14), which after substituting and simplification will have the following equation:

$$Q = \frac{1}{\sum_{i=1}^{k} \dfrac{\pi d_i}{V_i} * \dfrac{(l_{ai} + l_{si})}{f_i} + t_a + \sum_{i=1}^{k} \dfrac{\tau \pi d_i l_{ai}}{f_i} \left(\dfrac{V_i^{(1-b_i)/b_i}}{C_i^{1/b_i}} \right) + \sum_{j=1}^{p} t_{ej}} \tag{17}$$

where parameters are all as specified above.

The optimum cutting speed by use of the criterion of the maximum productivity rate for each operation is derived by taking the first derivative of Eq. (17) with respect to cutting speed V_i and set it to zero. In this case, Eq. (17) should be represented for a single cutter by the following expression where $f_i = f_{min}$:

$$Q = \frac{1}{\dfrac{\pi d_i}{V_i} * \dfrac{(l_{ai} + l_{si})}{f_i} + t_a + \dfrac{\tau \pi d_i l_{ai} V_i^{(1-b_i)/b_i}}{f_i C_i^{1/b_i}} + \sum_{j=1}^{p} t_{ej}}$$

Then the first derivative is

$$\frac{dQ}{dV_i} = -\left[-\frac{\pi d_i (l_{ai} + l_{si})}{V_i^2 f_i} + \frac{\tau \pi d_i (1-b_i) V_i^{(1-2b_i)/b_i}}{b_i f_i C_i^{1/b_i}} \right] = 0$$

$\dfrac{1}{V_i^2} - \dfrac{\tau (1-b_i) V_i^{(1-2b_i)/b_i}}{b_i (l_{ai} + l_{si}) C_i^{1/b_i}} = 0$, giving

$$V_{opt.i} = \left(\frac{(l_{ai} + l_{si}) C_i^{1/b_i}}{\tau[(1/b_i) - 1]} \right)^{b_i} \tag{18}$$

Where $V_{opt.i}$ is the optimal cutting speed for single cutter i giving the maximum productivity rate and other parameters are as specified above.

The expression for the maximum productivity rate for multi-tool machining process with sequential use of cutters can be found by substituting Eq. (18) into Eq. (17). After the transformation and simplification the equation becomes:

$$Q_{\max} = \frac{1}{\sum_{i=1}^{g} \frac{\pi d_i}{\left(\frac{(l_{ai} + l_{si}) C_i^{1/b_i}}{\tau[(1/b_i) - 1]} \right)^{b_i}} * \frac{(l_{ai} + l_{si})}{f_i} + t_a + \sum_{i=1}^{k} \frac{\tau \pi d_i l_{ai} \left(\frac{(l_{ai} + l_{si}) C_i^{1/b_i}}{\tau[(1/b_i) - 1]} \right)^{1-b_i}}{f_i C_i^{1/b_i}} + \sum_{j=1}^{p} t_{ej}} \tag{19}$$

where all parameters are as specified above.

3. A working example:

3.1. The multi-tool simultaneous machining process:

The carbon steel part is machined by the two cutters and one drill bit simultaneously on the turning machine tool. The sizes of the part surfaces are presented in Fig. 1. The recommended machining modes for the tools are presented in Table 1 (Freiheit and Hu, 2002).

Table 1: Machining mode and tool parameters

Tool	Material	Feed rate f, mm/rev	Cutting speed V, m/min	Tool life, min	C_b tool constant	b tool constant
Cutter 1	Carbide	0.2	75	100	300	0.3
Cutter 2	Cemented carbide	0.25	90	110	590	0.4
Drill bit	High speed steel	0.15	30	60	55	0.15

Cutting speeds for all tools should be optimized by using the criterion of maximum productivity rate.

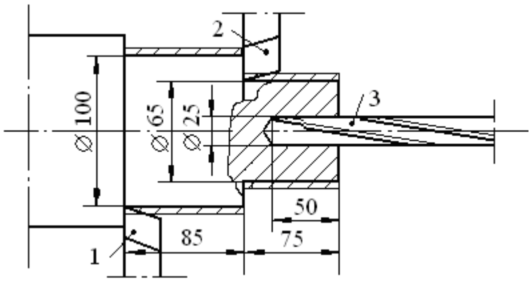

Fig. 1: the part surfaces machined by the three cutters simultaneously

Solution:

Analysis of machining operations shows that the cutting speeds and feed rates for different surfaces of the part are different. All tools are cutting simultaneously and the spindle has one number of revolutions per time for all tools. The drill bit has a minimum feed rate f_3 = 0.15 mm/rev, which is constrained by the quality of the hole surface. This feed rate should be used for other cutters. Cutter 1 has a maximum length l = 85 mm and diameter of 0.1 m of the machining surface. The length of drilling is defined according to the geometry of the drill bit. This data should be used for the following calculations. Geometry of machining processes of the part surfaces is represented in Table 2.

Table 2: Geometrical parameters of the part surface to be machined by the tools

Tool	Diameter, m	Length, mm	Depth of the cut, mm
Cutter 1	0.1	85	2.0
Cutter 2	0.065	75	1.5
Drill bit	0.025	$50 + 12.5\tan 30^0 = 57.2$	12.5

Optimal cutting speed by using the criterion of the maximum productivity rate of multi-tool machining processes is defined by Eq. (16). where $d_{\max} = 0.1$ m, $l_{a\max} = 85$ mm, $l_{si} = 2$ mm, $f_{\min} = 0.15$ mm/rev, $t_a = 0.3$ min, $\tau = 2$ min, $d_2 = 0.065$ m, $d_3 = 0.025$ m, $l_{a1} = 85$ mm, $l_{a2} = 75$ mm, $l_{a3} = 57.2$ mm, $\sum_{j=1}^{p} t_{ej} = 0.005$ min/part, other parameters represented in the Table 1. Substituting all defined parameters into Eq. (16) and calculating, the result is represented in Fig 2. of the productivity rate of multi-tool machining processes versus cutting speed.

$$Q = \frac{1}{\frac{\pi d_{\max}}{V_i} * \frac{(l_{a\max} + l_{si})}{f_{\min}} + t_a + \sum_{i=1}^{k} \frac{\tau \pi d_i l_{ai}}{f_{\min}} \left(\frac{V_i^{(1-b_i)/b_i}}{C_i^{1/b_i}} \right) + \sum_{j=1}^{p} t_{ej}}$$

$$Q = \frac{1}{\frac{\pi 0.1}{V} * \frac{87}{0.15} + 0.3 + 31.4 \left[\begin{array}{l} \left(\frac{0.1*85*V^{(1-0.3)/0.3}}{300^{1/0.3}} \right) + \left(\frac{0.065*75*V^{(1-0.4)/0.4}}{590^{1/0.4}} \right) \\ + \left(\frac{0.025*57.2*V^{(1-0.15)/0.15}}{55^{1/0.15}} \right) \end{array} \right] + 0.005} =$$

$$Q = \frac{1}{\frac{182.166}{V} + 0.3 + 31.4 \left(4.703*10^{-8} V^{2.333} + 5.765*10^{-7} V^{1.5} + 3.581*10^{-12} V^{5.666} \right) + 0.005}$$

The diagram (Fig. 2) shows the maximum productivity rate is $Q = 0.217$ parts/min, when cutting speed is $V = 50$ m/min, which is optimal.

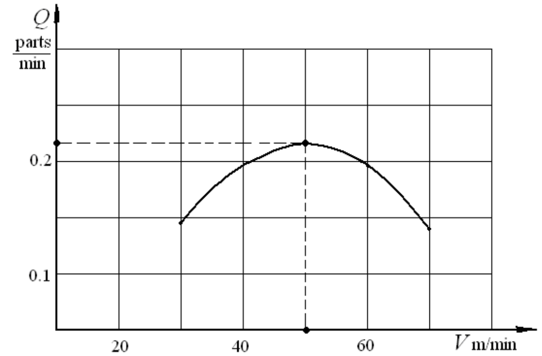

Fig. 2: Productivity rate of multi-cutting process versus cutting speed

The multi-tool consequence machining process:

The part is machined by the two cutters and one drill bit consequentially on the turning machine tool. All parameters of the part to be machined are presented above for the case of the multi-tool simultaneous machining process. The optimal cutting speed for multi-tool machining processes of the part when tools cut separately is calculated by Eq. (18), which gives the maximum productivity rate.

Solution All tools are cutting separately and the spindle should have a different angular velocity for all tools. Optimal cutting speed and the spindle angular velocity for each surface by using the criterion of the maximum productivity rate of multi-tool consequential machining processes is defined by Eqs. (18) and (19).

(a) cutter 1: $V_{opt.i} = \left(\frac{(l_{ai} + l_{si}) C_i^{1/b_i}}{\tau[(1/b_i) - 1]} \right)^{b_i} = \left(\frac{(85+2)300^{1/0.3}}{2[(1/0.3) - 1]} \right)^{0.3} = 720 m/\min$

(b) cutter 2: $V_{opt.i} = \left(\frac{(l_{ai} + l_{si}) C_i^{1/b_i}}{\tau[(1/b_i) - 1]} \right)^{b_i} = \left(\frac{(75+2)590^{1/0.4}}{2[(1/0.4) - 1]} \right)^{0.4} = 2160 m/\min$

(c) the drill bit 3: $V_{opt.i} = \left(\frac{(l_{ai} + l_{si}) C_i^{1/b_i}}{\tau[(1/b_i) - 1]} \right)^{b_i} = \left(\frac{(57.2+2)55^{1/0.15}}{2[(1/0.15) - 1]} \right)^{0.15} = 70 m/\min$

Substituting all defined parameters into Eq. (19) is defined as the maximum productivity rate of the multi-tool consequence cutting process.

$$Q_{\max} = \frac{1}{\sum_{i=1}^{g} \frac{\pi d_i}{V_{opt.i}} * \frac{(l_{ai} + l_{si})}{f_i} + t_a + \sum_{i=1}^{k} \frac{\tau \pi d_i l_{ai} V_{opt.i}^{(1-b_i)/b}}{f_i C_i^{1/b_i}} + \sum_{j=1}^{p} t_{ej}} =$$

$$\frac{1}{\frac{0.1\pi}{720} * \frac{87}{0.2} + \frac{0.065\pi}{2160} * \frac{77}{0.25} + \frac{0.025\pi}{70} * \frac{59.2}{0.15} + 0.3 + 2\pi\left(\frac{0.1 * 85 * 720^{(1-0.3)/0.3}}{0.2 * 300^{1/0.3}} + \frac{0.065 * 75 * 2160^{(1-0.4)/0.4}}{0.25 * 590^{1/0.4}} + \frac{0.025 * 57.2 * 70^{(1-0.15)/0.15}}{0.15 * 55^{1/0.15}}\right) + 0.005} =$$

$= 0.064$ parts/min

The productivity rate of machining process when cutters imply consequently with optimal cutting speeds for each operations, gives maximum productivity rate $Q = 0.064$ parts/min.

RESULTS AND DISCUSSION

The mathematical models of the productivity rate of a machine tool for multi-tool machining processes have been derived. The new equations enable the calculation of output of a machine tool in the cases of multi-tool machining for simultaneous and separate processes. Equations include reliability indices of its primary mechanisms and reliability of the cutters. Based on the new equations, the productivity rate of multi-tool processes for a machine tool is calculated as a function of the cutting speed changes. The new equations for the productivity rate enable the finding of the correct optimal machining modes that can give the maximum productivity rate of a machine tool.

In case of the multi-tool simultaneous machining process the optimal cutting speed is 50 m/min for all cutters gives the productivity rate 0.217 parts/min.

For the multi-tool separate machining process, each cutter has optimal cutting speed: the cutter 1, $V_1 = 720$ m/min, the cutter 2, $V_2 = 2160$ m/min and the cutter 3, $V_3 = 70$ m/min. This process gives the productivity rate 0.064 parts/min.

Summary:

The tendency for intensification of manufacturing processes created problem of finding the mathematical model of the optimal productivity rate for machine tools. Optimization of machining mode by criterion of maximum productivity rate in case of multi-tool machining processes of parts is crucial. These mathematical models have a more complex character than are known primarily for single cutter use in conditions of intensification of machining modes. Solutions of these problems will be very important for the manufacturing industry.

The new mathematical models of the productivity rate of a machine tool for multi-tool machining processes with change in processing mode are derived. New equations include basic parameters of machining processes, reliability indices of mechanisms and cutters of a machine tool. The new equations represent output of a machine tool in the cases of multi-tool machining processes when cutters implied simultaneously and separately. The represented equation for the calculation of the productivity rate of a machine tool as a function of the cutting speed change enables the prediction of more authentic results. Equations can be used in preparing economically effective multi-tool manufacturing processes of parts.

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