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Optimization of Machine Tools by Using the Maximum Productivity Rate

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Abstract: Calculation of the productivity rate and optimization of the operating modes for automatic machine tools today is complex, and in many cases, an unresolved problem. Most equations for calculating the optimal machining processes with the changes in operating modes consider the change of machining mode by using the minimum cost These equations do not reflect changes in the productivity rate due to the changes in the failure of cutters with the change in operating mode. In manufacturing areas, it is necessary to have mathematical dependency of the productivity rate of machine tools on the function of change in machining modes. In some cases of marketing environments, the maximum productivity rate is more preferable than the minimum cost of the machining process. The present paper has discovered a new analytical dependency of the productivity rate for automatic machine tools that includes the changes in the failure of cutters with the change in operating modes.

Key words: productivity, optimization, machining mode, machine tools.

INTRODUCTION

Metal cutting machining processes comprise many unsolved problems that should be resolved in order to obtain reliable data with respect to the economics of manufacturing. Some analytical models that are well-described were able to predict the tool life through changes in the machining. There are also well-known mathematical equations that calculate the minimum machining cost depending on the changes in the machining regimes, thereby optimizing the machining process (S. Kalpakjian, 2006). However, known equations of metal cutting processes, tool life and minimum machining cost have no dependency on the productivity rate of the machine tool, which is one of the main indices of machining economics (M.P., groover, 2006; E.P. DeGarmo, 2002; J. Beddoes, 1999; J. G. Bralla, 2007; V. Flores, 2007).

Researchers do not consider the very important aspects of machine tool output that are influenced by the change in machining regimes. However, indices of the productivity rate of machine tools and machining costs logically depend on the failures of cutters, which are changeable in the intensification of any machining processes (T. Freiheit and S. J. Hu, 2002; P. Jones, 2004; Isakov, 1996).

It is known that the intensification of operating modes reflects on the more intensive wear process of machine tool cutters as a result of the increase in dynamic forces, speed of the cutting process, magnitudes of feed rates and depth of cut (E.A. Elsayed, 1996). As a result, machine tools have to go through many cutter replacement processes that ultimately result in the decrease of its output and economical efficiency. The absence of the mathematical dependency of machine tool output versus the intensification of machining process does not allow efficient results from production processes. The cutters are the most unreliable elements of machining tools and to have mathematical equations of the productivity rate with changes in the processing mode is very important for manufacturing industries. The known results of research in the area of metal cutting processes are based on the theory of reliability, the theory of industrial productivity, and the mathematical methods of analysis with complex variable processes, which enables researchers to solve these problems.

Any machine tool consists of many mechanical arrangements and components that have reliability dependency on the intensification of processing modes. Descriptions of the dependency of tool life on the change in processing modes is explained. in that metal cutters are the most unreliable elements of machining tools, which should at a proper time be replaced to support metal cutting machining processes (R. Usubamatov, 2004). Other components of machine tools like spindles, bearings, sliders, etc. are many times more reliable relative to metal cutters.

Manufacturers are focusing their attention on increasing productivity of machine tools and primarily by intensification of the processing mode. Use of new materials for metal cutters that have a longer tool life and can work under intensive conditions of machining processes allow an increase in the productivity rate by the increase in operating modes. However, the intensification of machining processes is reflected in the growth of failure of cutters due to increasing dynamic loads, wearing of surfaces, decreasing accuracy of machining processes, necessity of tuning machine tool units, etc., (J.G. Bralla, 2007; P. Jones, 2004; Isakov, 2004). Hence,

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the intensification of the machining processes leads to a decrease in the machining time and an increase in the failure rate or time loss from machine arrangements, mechanisms and cutters.

All these circumstances lead to a drop in the productivity rate of machine tools and a drop in the effectiveness of machining processes. These conditions oblige the researcher to find the correct mathematical dependencies between intensification of the machining mode and the productivity rate of machine tools based on the change in the reliability of cutters.

Results of research for different machine tools on the change in the processing mode show that the failure of cutters changes progressively (G. Tlusty, 1999; M.P. Groover, 2006; R. Usubamatov, 2004; Glyn Games. 2001; Daniel T. 2007). The well-known equation of the tool life versus the change of machining mode enables the solving of mathematical problems of the productivity rate and optimization processing modes of machine tools.

Manufacturing practice shows that the normal processing modes in manufacturing have not differed much from the analytically defined optimal parameters that can give the maximum productivity for machine tools. Also, the optimal processing modes for metal cutters by using the criterion of the minimum machining cost shows that practical recommendations of manufacturing companies have some differences in the relative optimal machining regimes by using the criterion of maximum productivity. These differences, of about 10%-30%, can be solved by looking at the mathematical dependencies of the optimal processing modes on the marketing policies of a company. The solution to this problem is outside the consideration of this article and should be presented in other research.

Analytical Approach:

The productivity rate of machine tools is presented by the following equation (G. Tlusty, 1999).

$$Q = \frac{z}{\theta} = \frac{z}{\theta_w + \theta_i} \text{ Product/time} \tag{1}$$

Where Q (product/time) is the productivity rate of an automatic machine tool; z is the number of products machined per observation time θ, which magnitude is expressed in minutes for high production machines.

The observation time θ can be presented as the sum of the machine work time (θ_W) when the machine produces products and the idle time as (θ_i) when the machine stops for reasons of repair, tuning, etc. The following equation is the transformation of the Eq. (1) giving.

$$Q = \frac{1}{\theta_w / z + \theta_i / z}, \text{ product/min} \tag{2}$$

where $\theta_w / z = T$ (min) is the cycle time of the machining of one product;

$\theta_i / z = \sum_{i=1}^{n} t_i$ (min/product) is the time loss referred to one product due to repair, tuning, etc of components and mechanisms of the machining tool.

Generally, these indices present reliability parameters of a machine tool and can be expressed by standard indices of reliability theory. The idle time of machine tools can include the time losses due to organizational and managerial aspects. However, these indices are omitted from consideration of the machining mode and idle time losses, as organizational and managerial aspects do not have a proper relation to the machining process.

In industrial areas most machining processes are discrete, i.e., for machining of one product is spent machining time t_m and auxiliary time t_a on loading and removing a part, clamping and releasing of a work-piece in the machining area, and other actions before and after the machining processes. These times are presented in the cycle time T of machining of one product, which is expressed by the following equation:

$$T = t_m + t_{a.} \text{ min} \tag{3}$$

The time losses due to repair, tuning, etc., of components and mechanisms of the machining tool are presented by the following expression:

$$\sum_{i=1}^{n} t_i = t_c + t_e, \text{ min/product} \tag{4}$$

where t_c (min/product) is time losses referred to one product due to failures of the cutter; t_e (min/ product) is time losses referred to one product due to the reliability of the machining tool mechanisms and devices containing mechanical, electric, or hydraulic units.

Substituting the definition of Eqs. (3) and (4) into Eq. (2), then the expression of the productivity rate of a machine tool will have the following equation:

$$Q = \frac{1}{t_m + t_a + t_c + t_e} \text{, product/min} \tag{5}$$

where all parameters have been specified above.

For further analysis, it is necessary to mathematically express the time components of Eq. (5) using indices of machining mode, which includes the standard dimensions of the cutting speed V (m/min), depth of cut d (mm), feed rate f (mm/min) and the tool life T_c (min) of the cutter.

The machining time with the definition of the feed rate and depth of cut is calculated typically by the following equation:

$$t_m = \frac{l}{V} \text{, min/product} \tag{6}$$

where l is the length of the machining process, and V is the cutting speed.

For the turning operation $t_m = \frac{\pi D(l_p + a)}{Vf}$ (7)

where D, expressed in mm, is the diameter of the part to be machined, and f (mm/rev), is the feed rate of the turning operation.

Analysis of other components of Eq. (5) and the dependency on machining mode shows the following results. The auxiliary time t_a of the machine work is the index that expresses the technical characteristics of the machining tool and does not have any relation to the cutting process. The magnitude of the auxiliary time t_a is accepted as a constant t_a = const for the majority of types of machining tools. The time losses t_e due to failures of the machine tool mechanisms and devices has some dependency on machining modes. However, due to high reliability of the main components of a machining tool (spindle unit, supports, etc.) compared with the failure rate of cutters, and due to the absence of initial data of component reliability, this index does not consider this and accepts t_e as a constant (t_e = const). Also, this problem is outside the scope of this article because the many reliability indices of machining tool mechanisms are still unsolved problems and there is a need to conduct analytical and practical studies.

The time losses t_c due to failure of the cutter has definite dependency with machining modes and is presented by the following equation.

$$t_c = \frac{\theta_c}{z} = \frac{mn}{T_c n / t_{cut}} \text{, min/product} \tag{8}$$

where θ_c is the idle time due to replacement of the cutter, its tuning, test cutting, etc.; m is average time of cutter replacement, n is the number of cutter replacements; $t_{cut} = \frac{\pi D l_p}{Vf}$ is the time of the cutting process for machining of one product, where l_p is the length of the part being machined.

The length of machining is always more than the length of the part being machined ($l > l_p$) because between the cutter and the part it is necessary to have a safety distance a = 2…5 mm to avoid casual hitting of the cutter after fast motion of the part and to have space after the cutting process that guarantees finishing of the cutting process. Hence, $l = l_p + a$ (mm).

Most companies that produce and use machine tools are monitoring failure rates of machine tools and have recorded data. Practically, the average time of cutter replacement of m is normative data that has the magnitude m = 2…3 min and can be used for calculation of the time losses index t_c of machine tools by Eq. (7).

The equation for the tool life has the following empirical expression

$$T_c = \left(\frac{C}{V}\right)^{1/N} \text{, min} \tag{9}$$

where C is the coefficient of the cutter work that expresses the conditions of cutting process, cooling, geometry of the cutter, types of work-piece material, hardness of cutting materials; N is the index of the type of cutter material (HSS, HS, etc); V is cutting speed.

Substituting defined parameters into Eq. (7) and after transformation, the time losses due to the cutter will have the following expression:

$$t_c = \frac{m\pi D l_p V^{(1/N)-1}}{C^{1/N} f} \text{ Min/product} \tag{10}$$

Many researches express the dependency of total life of the cutter on the cutting speed, feed rate and depth of cut. For simplicity of consideration the cutting speed parameter V of Eqs. (9) and (10) is accepted as variable only because the feed rate and depth of cut are variable in a narrow range due to restrictions of surface roughness and accuracy of the machining process. The feed rate f and the depth of cut d for machining processes is accepted as constant.

Substituting all defined components of Eqs. (6) and (9) into Eq. (5) the equation of the productivity rate of a machine tool will have the following expression:

$$Q = \frac{1}{\frac{\pi D}{f}\left(\frac{l_p + a}{V} + \frac{m l_p V^{(1/N)-1}}{C^{1/N}}\right) + t_a + t_e} \tag{11}$$

Eq. (10) contains geometrical parameters of the part being machined l, l_p, cutting speed V, parameters of the cutter C, N, reliability index of the cutter m, and other parameters specified above. Analysis of Eq. (9) shows that a possible increase of cutting speed V leads to a decrease of machining time ($t_m = l/V$), and will increase the time losses in Eq. (9) due to cutter replacement and tuning, etc. The change of the cutting speed will not affect the duration of auxiliary time and on time losses due to reliability of the machine tool component as accepted earlier.

Eq. (11) is for the productivity rate of a machine tool depending on the change of processing mode having the extreme limits of function. In such case, it is possible to decide the mathematical task of optimization of processing mode by criterion of the maximum productivity rate. This task can be solved by the first derivative of Eq. (11), that of equating to zero. Since there is one variable V it is necessary to find the first derivative of Eq. (10) with respect to parameter V, when other parameters are constants. This approach can give the decision of the optimal machining mode by using the criterion of the maximum productivity rate of the machine tool.

Differentiating Eq. (11) with respect to the variable of the cutting speed V when other Parameters are constant and equating to zero, gives:

$$\frac{dQ}{dV} = \frac{d}{dV}\left(\frac{1}{\frac{l}{V} + t_a + \frac{m l_p V^{(1/N)-1}}{\sqrt[N]{C}} + t_e}\right) = 0$$

giving

$$-\frac{l}{V^2} + [(1/N) - 1]\frac{m l_p V^{(1/N)-2}}{\sqrt[N]{C}} = 0$$

After transformation of this equation, the optimal cutting speed by the criterion of productivity is given by the following expression:

$$V_{opt} = C\left\{\frac{(1 + a/l_p)}{[(1/N) - 1]m}\right\}^N \tag{12}$$

with all parameters specified above.

Substituting the expression of the optimal cutting speed Eq. (12) into Eq. (11), and after transformation of the equation, the maximum productivity rate of the machine tool will have the following expression:

$$Q_{\max} = \frac{1}{\dfrac{[l_p(1+m)+a]}{C}\left\{\dfrac{[(1/N)-1]m}{1+a/l_p}\right\}^N + t_a + t_e}$$

with all parameters specified above.

There is a well-known equation of the cost of machining process versus the cutting speed. This equation can give the answer for the minimum cost of the machining process that gives the optimal machining mode by the following expression:

$$V_{opt} = \frac{C(L_m + B_m)^N}{\{[(1/N)-1][t_a(L_m+B_m)+T_g(L_g+B_g)+D_c]\}^N} \qquad (13)$$

where L_m is the labor cost of production operator per hour, B_m is the overhead charge of the machine, including depreciation, maintenance, indirect labor, etc.; T_g is the time required to grind the tool, L_g is the labor cost of the tool grinder operator per hour, B_g is the overhead charge of the tool grinder per hour, D_c is the depreciation of the tool in dollars per grind, and other parameters specified above.

Eq. (13) consists of the components of the cost of machining process due to failure rate of machine tool cutters that shows dependency on the change of processing mode. Compared to mathematical approaches of optimal machining modes that show maximum productivity and minimum cost, what type of optimization is preferable depends on the economic policy of a company.

A Working Example:

Assume the automatic turning machine works with one cutter and the technological process for processing 1000 parts has the following parameters: Diameter of the part D = 50 mm of AISI 4140, the length of the part to be machined l_p = 250 mm; the depth of cut = 1.5 mm, the feed rate = 0.2 mm/rev, the cutter safety distance a = 3 mm; auxiliary time is t_a = 0.2 min/part, time losses (idle time) due to reliability of the machine tool t_e = 0.05 min/part, tool change time m = 2 min, loading &unloading time Tl=0.25min.

The following data is applicable for machining the part: labor cost per hour = 15$, machine overhead charge per hour = 50$, grinding cost per hour = 20$, grinding machine overhead charge per hour = 60$. Taylors' tool life equation is given by $VT^{0.25} = 150$, i.e., N = 0.25, C = 150. The operation is carried out using the brazed tool with the following data: initial cost = 70$, grinding time of the tool = 3 min, the depreciation of the tool per grind = 4$. It is necessary to find the optimal cutting speed using the criteria of the maximum productivity rate and the minimum production cost.

The machine tool productivity rate with change of the processing mode at given technical and technological parameters has been calculated on the basis of Eq. (10) and (12). Figure 1 represents the graphs of dependency of productivity rate for the automatic machine tool as a function of the cutting speed V calculated by Eq. (10), and by Eq. (12).

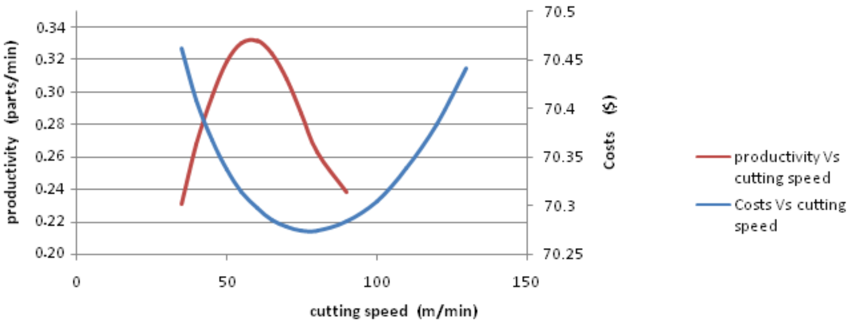

Fig. 1: The productivity rate of an automatic machine tool and the machining cost versus the cutting speed change, for cemented carbide.

Fig. 1 shows the maximum productivity rate of the machine tool that occurs, where the optimal cutting speed of the machining process is V_{opt} = m/min, and the minimum cost of the machining process when the optimum cutting speed is V_{opt} = m/min. The new equation shows that the magnitude of the productivity rate is variable. It grows with the increase in the cutting speed at the beginning, reaches maximum, and then decreases. The optimal speed of the cutting process by using the two criteria of the maximum productivity and the minimum cost is differed. The optimal cutting speed for minimum machining cost should be less than by the criteria of the maximum productivity rate.

Solution of the optimal machining mode should be solved on the basis of macro-economic criterion that should include variable parameters of long-term machining processes of products that depend on the marketing environment.

RESULTS AND DISCUSSION

Equation for the productivity rate of an automatic machine tool depending on the change of processing mode for an automatic machine has been obtained. The new equation enables the calculation of the productivity rate with known technical and technological parameters of machine tool and machining processes. On the basis of the new equation we have calculated the productivity rate for an automatic machine tool that works with one cutter. The obtained equation of the productivity rate enables the finding of the optimal processing mode that can give the maximum productivity rate of a machine tool and compare that with the optimal machining mode obtained by the criteria of the minimum machining cost.

Summary:

The new equation for the productivity rate for a machine tool includes dependencies on technical and technological parameters of a machine tool and the machining process. The equation will be useful in modeling the output of an automatic machine tool and calculating the meaning of the processing mode that gives the maximum productivity rate of a machine tool. The represented equation of the productivity rate for automatic machine tool is a function of cutting speed and parameters of the tool life, which enables calculations at the project stage of preparing economically effective manufacturing processes for products.

The manufacturing industry has accumulated much useful information in the area of machine reliability and productivity, and has also many unsolved problems in the area of productivity rate of machine tools. Tendency of intensification of manufacturing processes sets problems finding dependencies of the productivity rate on the reliability of primary mechanisms of machine tools that have more complex character with the change of processing mode. Solutions of these problems will be very important for the manufacturing industry.

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