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Qualimetry as productivity criteria in metal-cutting operations

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Abstract. The qualimetry method will allow an objective assessment of the performance of metal-cutting machines and the production capacity of machinery, as well as an objective assessment of their use in multi-product manufacturing, applying the qualimetry approach and qualimetry indicators, which are based on the concept of qualification of metal removing during machine operations. The aim of the study is to develop methods for measuring the performance of metal-cutting machines and open the way to create a regulatory framework based on quantitative indicators of the equipment quality. Qualimetry measured volume of metal removing allows setting the maximum possible productivity (quali-power) of metal cutting machinery, based on a small number of basic quality indicators contained in the machinery data sheets. It is essential that the quali-power of the machinery is an objective indicator of its quality, independent of the specific conditions of its operation at any given time. Hence the productivity criteria in metalworking cutting operations can be measured.

Key words: qualimetry, ergonomics, quantitative, manufacturing, equipment.

INTRODUCTION

The results of scientific and practical activities of the American engineer F.W. Taylor are classical in enterprise management and organization. His methods constituted an essential scientific and practical part of the global system of economic measurements (Taylor, 1923). More than 120 years have passed since Taylor presented his conclusions on the theory of metal-cutting. Since then it has remained basically unchanged, and we cannot imagine the management of industry around the world without it.

It is worth noting that from the standpoint of the modern development of economy, the experiments conducted by Taylor on metal-cutting are the beginning of a qualitative modeling of the production of machine parts called ‘qualimetry’ (Azgaldov et al., 1968). It is important since one of the main components of the production potential in mechanical engineering is the technological machinery, a significant part of which falls on the share of metal-cutting machinery (Smailovskaya et al., 2011; Gardner Intelligence, 2018).

Labour productivity (Thomson & Webster, 2013; Yi & Chan, 2014) has been studied sufficiently in many industries both from the perspective of ergonomics (Orefkov & Perevoschikov, 2007; Maksimov & Kalkis, 2018), microelement rationing (Maynard et al., 1948; Golabchi et al., 2016; Koptak et al., 2017), and a subjective assessment of the time for completion of the work (Chan et al., 2017). However, the productivity of machines, in particular, metal-cutting equipment, from the qualitative side has been poorly studied.

Currently, the overage machine shift is the indicator that determines the use of equipment. This term refers to the average operating time of an equipment element at a site or enterprise (Podzorov, 2018). However, it does not fully characterize the equipment used, since it does not consider the technological capabilities of metal-cutting machines. In other words, qualitative characteristics are not considered in accordance with the purpose of the machines.

The purpose of the qualimetry analysis of the machine parts production is to develop methods for measuring the performance of metal-cutting machines and the production capacity of machine shops, as well as to create a regulatory framework for such a measurement based on quantitative indicators of equipment quality and processing technology conditions.

This work is part of a study conducted in the framework of economic metrology (Pevoshchikov et al., 2005; Perevoshchikov, 2015) using qualimetry methods. The first part is dedicated to creating an ergonometric workplace passport (Maksimov & Kalkis, 2018). The second one deals with the complexity of product manufacturing (Ermilov & Perevoshchikov, 2018; Maksimov et al., 2019). The aim of study is to develop methods for measuring the performance of metal-cutting machines, and, in the future, to create a regulatory framework based on quantitative indicators of the equipment quality. The beginning of the study is presented in the work of Perevoshchikov (Per, 2019).

MATERIALS AND METHODS

The application of the concept of 'productivity' in relation to machine tools, used in the production of different types of products, is impossible since it is different for different types of products and operations. This value is inversely proportional to time per a piece, and therefore cannot serve as objective characteristics of the capability of metal-cutting machinery.

The methods currently used for calculating production capacities do not consider the capabilities of technological machinery determined by its qualitative composition, but consider the amount of equipment only (Liang & Shin, 2016).

In metal-cutting machinery, it is necessary to introduce a new, universal, concept of 'machine production capacity', which is not related to the manufacture of one particular product and is determined by the maximum productivity of the equipment. The production capacity of the site in which this equipment is used is defined as the sum of the production capacities of all metal-cutting machinery used.

The production capacity of the machine should be determined based on the indicators given in the equipment certificate, since they characterize maximum possibilities and do not depend on the characteristics of the workpiece. It should also be noted that metal-cutting machines are subdivided according to the degree of accuracy and the type of surface treatment performed – finishing and roughing. The maximum productivity of the machine during the initial roughing should be measured by the maximum possible amount of metal that can be 'removed' in a certain unit of time under the established reference conditions for this type of equipment.

As the basic unit of measurement of the machine's operating time, the operating time for one minute will be used.

Production capacity per minute of the studied metal cutting section can be determined using the formula (Per, 2019)

$$Q_{max} = \sum_{i=1}^{n} q_{max_i} \tag{1}$$

where i– the serial number of the machine; n – number of machines; q_{max} – maximum amount of chips to be removed in one minute on a metal cutting machine.

The power utilization factor can be represented in the form of the following formulas:

– for one machine

$$\eta_{M_i} = \frac{q_{M_i}}{q_{max_i}} \tag{2}$$

where η_{Mi} – capacity factor by one machine; q_{Mi} – the amount of metal to be removed per one machine in 1 minute

– for the workshop (site)

$$\eta_{M_i} = \frac{Q_{\ M}}{Q_{\ max}} \tag{3}$$

where η_M – capacity factor by all machines; Q_M – the amount of metal, removed by all machines of the workshop or site in 1 min.

$$Q_M = \sum_{i=1}^{n} q_{M_i} \tag{4}$$

$$Q_M = nq_{Mavr} \tag{5}$$

where q_{Mavr} – the amount of metal removed per 1 minute per one machine on average.

However, the use of the above formulas (formula 1–5) is difficult, since for their application it is necessary to take into account a large number of processing conditions, which are determined by the quality of the tool, the material being processed and the quality of the internal mechanisms of the machine.

The quality of the material to be treated is characterized by hardness, strength, chemical composition, surface condition and ductility. During final processing, it is also necessary to take into account surface roughness and dimensional accuracy of the part. The quality of the tool used in the treatment is characterized by its material and geometry. The environmental quality of the machine, that is, the lubricating and cooling agents, is characterized by their composition and quantity.

Record of the variety of processing conditions presented above is possible based on the qualimetry assessment of productivity of the machine. For the qualimetry analysis of the production capacity of the machine it is necessary to establish its maximum qualimetry productivity (qualimetry production capacity – quali-power), determined by the maximum possible amount of metal that can be removed by this machine under reference conditions in 1 minute of the cutting process. This value should not depend on the conditions of the product treatment, but is determined by the limiting parameters of the machine only which are constant.

The main task in this case is the development of methods for determining the maximum productivity of machines. To solve this problem, it is necessary to determine the maximum parameters of the removed chip volume for a certain period of time. The following conditions are set as limitations (Per, 2019):

– the power of the cutting process N_p should not exceed the power of the drive of the main movement N_{np}, taking into account the efficiency of the machine;

– the forces P and the rotational force M_{rf} arising during the cutting process should not exceed the forces P_c and the rotational force M_c allowed by the machine;

– the dimensions of the processed products G should not exceed those allowed by the machine G_k;

– speeds of displacements (feeds) S and speeds of rotation n of the working parts of the machine must not be less than the minimum speeds allowed by the machine S_{min} and speeds n_{min}, and not greater than the maximum allowed by the machine S_{max}, n_{max};

– the dimensions of the cutting tool L_i must be neither smaller nor bigger than the sizes allowed by the machine L_{min} and L_{max}. Symbolic record of the task in the general statement is:

$$V_M = f(v, s, t) \rightarrow (efficiency\ function) \tag{6}$$

$$\begin{cases} N_p = \varphi_N(v, s, t, r^{st}) \le N_{\text{пр}} \\ P = \varphi_P(v, s, t, r^{st}) \le P_c \\ M_{rf} = \varphi_M(v, s, t, r^{st}) \le M_c \\ G \le G_c \\ S_{min} \le S \le S_{max} \\ n_{min} \le n \le n_{max} \\ L_{min} \le L \le L_{max} \end{cases} \tag{7}$$

where v – cutting speed; t – cutting depth; r^{st} – factors taking into account standard conditions.

Using this method for specific machines and the necessary types of processing, it should be noted that the desired maximum quali-power of the machine will be obtained with certain combinations of cutting conditions. But it should be kept in mind that parameters that are not acceptable in practice from an economic and operational point of view may be calculated.

Based on the analysis of the machines, the following types of machine qualifications were identified:

– theoretical quali-power of the machine tool;

– real quali-power of the machine tool;

– actual quali-power of the machine tool;

– minute quali-power.

By theoretical power (quali-power) of a machine is meant its maximum productivity (quali-production) in one minute. In this work it is denoted by the symbol V_m.

The actual quali-power of the machine tool differs from the theoretical one in the fact that it takes into account the limited maximum treatment length on each particular machine and the corresponding additional costs of time during which the treatment process does not occur.

The actual quali-power is determined with the formula

$$V_a = \frac{V_M \cdot t_{o\,max}}{t_{o\,max} + t'_a} \tag{8}$$

where t'_a is conditional auxiliary time, taking into account the change of products with the maximum possible processing length; t_o – direct manufacturing time.

At present, the determination of the conditional auxiliary time (t'_a) is a problem, since it should not depend on the specific products processed on this machine. To solve this issue, further theoretical research is needed.

By minute quali-power of a machine we mean a qualitatively measured volume of metal (metal quali-volume) removed in 1 minute of the treatment process.

The actual qualification productivity of the machine takes into account the necessary costs of auxiliary time and is determined with the formula

$$V_a = \frac{V_k \cdot t_o}{t_b} \tag{9}$$

where t_b – basic cycle time.

The utilization rate of the theoretical quali-power of the machine is determined by the ratio of actual productivity to the quali-power of the machine in the reference conditions:

$$\eta_t = \frac{V_k}{V_m} \tag{10}$$

The amount of metal being removed is measured by its corresponding volume of metal removed under reference processing conditions. The transformation of the real volume of metal removed under certain specific conditions into the quali-volume is a problem and the solution for practical application will be the next stage of this research in future.

RESULTS AND DISCUSSION

As an example of the application of this methodology, we will consider the processing of a product on a 16K25 lathe (SCL, 1975).

Workpiece material – steel 20XM, rolled steel.

The diameter of the workpiece is 100 mm. The workpiece is fixed in the chuck, the part is treated from the loose side, the diameter after the workpiece is 92 mm, and treatment is performed with one tool. As a tool, a straight cutter with a hard alloy plate is used, and the main angle in the bar is 75°.

To calculate the data, we accept the following parameters (HME, 1985; Liang & Shin, 2016):

– feed (s) 1 mm rev^{-1}
– cutting depth (t) 3 mm
– cutting speed.

$$v = \frac{C_v}{T^m \cdot t^x \cdot s^y} \cdot k_v \tag{11}$$

where $C_v = 338$; $x = 0.15$; $y = 0.45$; $m = 0.20$.

Tool life (T) is set to 60 minutes

$$k_v = k_{mv} \cdot k_{nb} \cdot k_{ub} \cdot k_\varphi \tag{12}$$

where $k_{mv} = 0.87$; $k_{nb} = 0.86$; $k_{ub} = 1$; $k_\varphi = 0.8$; $k_v = 0.599$; $v = 75.7$ m minute^{-1}.

$$t_o = \frac{l}{s \cdot n} = \frac{150}{1 \cdot 276} = 0.54\, minute$$

where t_o – direct manufacturing time.

For reference conditions $k_v = 1$; $t_{st} = 3$; $s_{st} = 1$; $v_{st} = 122$ m minute^{-1}.

$$n_э = \frac{1{,}000 \cdot 122}{3.14 \cdot 100} = 388\, rpm$$

$$V_t = V_k \cdot t_o = \pi \cdot d \cdot t \cdot s \cdot n \cdot t_o (mm^3)$$

where V_t – quali-volume of the removed metal in time t_o;

$V_k = 3.14 \cdot 100 \cdot 3 \cdot 1 \cdot 388 = 365{,}496$ mm^3 minute^{-1}.

$V_t = 365{,}496 \cdot 0.54 = 197{,}368$ mm^3 = 197,4cm^3.

Machine quali-power 16K25 is $V_m = 668$ cm^3 minute^{-1}.

The utilization factor of the theoretical power in this case will be:

$$\eta_t = \frac{365.6}{668} = 0.55$$

The described method shows the possibility of applying the qualimetry analysis for an objective assessment of the use of metal-cutting equipment.

Improvement of machine productivity is discussed also in other findings and some of them are 'based on registering the moment when the cutting tool touches the workpiece during a machining operation' (Nenov et al., 2002). The performance of machines to a large extent depends on their mechatronic behavior (Frieß et al., 2014), but does not provide information on the maximum of the equipment capacity. At the same time it is noted by other authors that the need for accessing the machine tool performance and not relay solely only on the specifications was considered by Deshpande (2012).

Considering the research results, the most common indicators of social labour costs per a production unit are the cost price and reduced costs. But to obtain accurate workpieces, expensive technological equipment is needed, which, with production of small-scale and single-type workpieces, increases their cost so much that often this increase is not covered by a reduction of expenses for metal cutting and economy of metal. And since in the near foreseeable future, it is likely that these types of production will remain rather common in mechanical engineering, in many relevant cases the most representative and logically justified will be the determination of the productivity of metal cutting machines by the amount of metal chips cut per unit of time.

This article presents part of the study, which describes only the preliminary treatment of products, but at the same time, it would be the final treatment, if it is consistent with the process. Here we need to once again return to the issue measuring productivity, because, in the area of treatment technology, such directions as application of precision blanks and low-waste technologies can lead to the fact that the problem of the objective use of the production capacity of metal-cutting sections in preliminary procession is outdated and does not require attention.

CONCLUSIONS

In conclusion it should be noted that qualimetry, used for measuring the amount of chips removed, allows setting the maximum productivity of metal-cutting equipment basing on the quantitative indicators given in the machine passport. The energy power of the main movement drive appears to be the main indicator. It should be noted that the quali-power of the machine is an objective indicator of its quality, which does not depend on specific working conditions at any given time.

For the practical application of the theoretical foundations given in this study, further development of the appropriate methodology for the application of qualimetry analysis of the production capacity of metal-cutting equipment is required.

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