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ASSESMENT OF ENERGY CONSUMPTION BY MACHINE TOOLS

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ABSTRACT: The aim of the study was to determine the energy required to perform the machining of selected parts, and then to assess the quality of the machine tools from the point of view of their energy consumption. A method for determining and assessing energy consumption was developed. Test workpieces, tools and cutting parameters for lathes and milling machines were proposed. Specific cutting tests for different cutting speeds, feed rates and depths of cut were carried out. On the basis of the instantaneous values of the power consumed by the machines in idle operating conditions and during the cutting process, their cutting energy consumption indices were determined.
KEYWORDS: machine tool, energy consumption, cutting tests, assessment

INTRODUCTION

Despite the fact that problems relating to energy consumption by machine tools are investigated by many research centres [2-3,5-10], the introduction of energy consumption indices encounters difficulties arising from the peculiar nature of such machines. Machine tools are highly complex and consist of a large number of different modules of different size, performing different functions. Since machine tools are universally used in manufacturing processes, measures aimed at introducing energy-efficient solutions can lead to a reduction in manufacturing costs.

The European Machine Tool Industry Association (CECIMO) has undertook action to develop high and competitive standards for energy-efficient machine tools [1] according to EU directive [4]. As a result, procedures and methods enabling machine tool manufacturers to determine environmental impact on the basis of energy consumption will be developed. Both relative and absolute energy-saving values are used to show clients that the additional investment into energy-efficient machine tool solutions can be profitable, particularly in the context of the increasing prices for energy carriers. Also in Poland almost 90% of the manufacturers declare that they make attempts to minimize energy consumption [5]. This means that this problem is perceived as crucial for reducing production costs and for the proper operation of industrial enterprises.

The aim of this research was to determine the amount of energy required to machine selected parts and to assess the quality of the machine tools with regard to energy consumption. The research was limited to the assessment of the energy consumption by selected types of cutting machine tools (milling machines and lathes) in idling conditions and during the machining of test workpieces. The advantage of this paper over other similar studies is the application of instantaneous power to the calculation of the energy consumption during the processing of the test workpieces, instead of average power of machine tools. For the assessment of the energy consumption by machine tools, energy consumption index was introduced as the relative average measure.

FACTORS HAVING BEARING ON ENERGY CONSUMPTION BY CUTTING MACHINE TOOLS

Constant factors, which are independent of the particular machining process, and variable factors, which depend on the type and course of the manufacturing process have a bearing on energy consumption by machine tools (Figure 1).

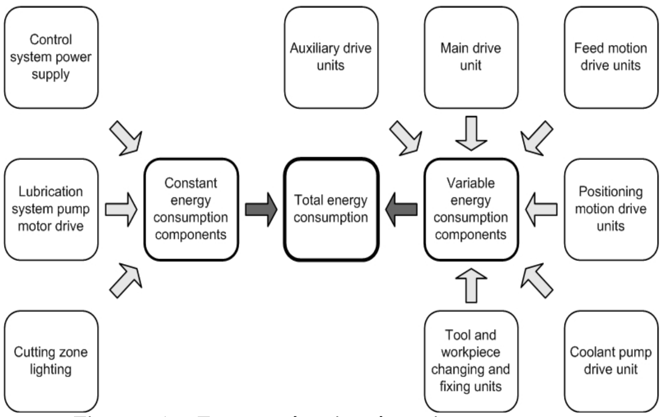

Figure 1 - Factors having bearing on energy consumption by machine tools.

Most of the energy consumed by a machine tool is consumed by its drive system. The latter usually consists of several drive units ensuring the execution *of the motions involved in the shaping of a product. Such a drive system incorporates:*

- *drive units for main motions (e.g. of lathe spindles),*
- *feed drive units,*
- *tool and workpiece changing and fixing units,*
- *positioning drive units,*
- *auxiliary drive units (for, e.g., the chips conveyor and the coolant pump).*

Regardless of the type of machining, energy is also needed to power other systems, such as the control system, the cutting zone lighting, the lubrication system pump motor drive and so on.

ASSESSMENT OF ENERGY CONSUMPTION BY MACHINE TOOL

The amount of energy consumed to remove machining allowance is considered to be independent of the machine tool which is used for this task. In the literature one can find theoretical relations for calculating the amount of this energy [6]. However, this is only a part of the energy actually consumed in the manufacture of a product – the other part of this energy depends on the machine tool used in the machining process. In order to take the latter part of the energy into account it is proposed to the determine the average power used for the machining of a representative workpiece by a given machine [9,10]. Then energy E_{mt} consumed to perform a single machining operation is:

$$E_{mt} = E_c + P_{av} t_g \tag{1}$$

where: E_{mt} [J] - the total energy consumed during machining, E_c [J] - cutting energy, P_{av} [W] - average power of the machine tool, t_g [s] - the main machining time.

The definition of a representative test workpiece and how to use the average power determined in this way as a representative power remain an open question. It should be noted that the total energy calculated in this way does not take into account many auxiliary operations.

Electric power P_{el} drawn from the mains is not only used to overcome the machining resistances and the resistance of all the units along the power transmission path from the motor to the executing unit, but also to power all the peripheral devices. It is assumed that this power can be divided into three components: effective power P_{ef} needed to perform machining work, power ΔP_{bo} consumed by the machine tool when running idle and additional power losses ΔP_o under drive system load. Thus the electric power is the sum of the three components, as formulated below:

$$P_{el} = P_{ef} + \Delta P_{bo} + \Delta P_o \tag{2}$$

where: P_{el} [W] - electric power, P_{ef} [W] - effective power, ΔP_{bo} [W] - power consumed during idle runing, ΔP_o [W] - additional power lost under load.

In this research an attempt was made to analyze energy consumption E in turning and milling, by discretely measuring, at constant time intervals Δt, instantaneous power P_i drawn from the mains by a machine tool not loaded with cutting forces and during the machining of selected test workpieces. The energy was calculated from the relation:

$$E = \sum_{i=1}^{n} P_i \Delta t \tag{3}$$

where: $\Delta t = 1/f_p$ (f_p - power signal sampling frequency), $n = t_g/\Delta t$.

For assessing the energy consumption by machine tools, energy consumption index W_e expressed as the ratio:

$$W_e = \frac{E_{el} + E_{bo}}{E_{el}} = 1 - \frac{E_{bo}}{E_{el}} \tag{4}$$

where: E_{el} - total energy calculated on the basis of power P_{el} consumed during machining, E_{bo} - energy determined on the basis of power ΔP_{bo} consumed during idle running,

is proposed. Its value may range from 0 to 1.

INVESTIGATIVE METHODOLOGY

For the assessment of machine tools with regard to their energy consumption three lathes (one conventional – TUR50 and two numerically controlled – TUR MN560 and HAAS) and two milling machines (one conventional – FWD32J and one numerically controlled – HAAS Mini Mill) were selected. Two different test workpieces were proposed for the machines and proper tools and machining parameters were chosen.

The choice of a shaft as the workpiece for the lathes was dictated by the possibility of attaining proper cutting speeds. The shaft diameter of 125 mm (Figure 2) and steel C45 (commonly used in machining tests) were adopted. Two grooves were cut in the shaft so that at least two surfaces could be machined in one clamping. The grooves enabled machining at three different depths of cut. For example, the shaft's right segment was machined at a cut depth of 0.4 mm, then the tool was brought back to its initial position and the same segment was machined at a cut depth of 1 mm. Subsequently the middle segment was machined at a cut depth of 1.4. A short workpiece (L/D<3) required only one-sided clamping in the lathe chuck without lathe centre support.

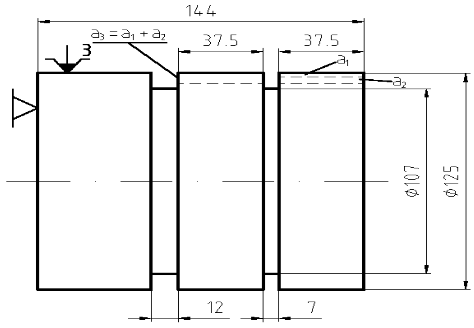

Figure 2 - Test workpiece used in turning operations

The choice of lathe tools was dictated by the possibility of fixing them in the engine lathe's tool block or in the tool head of the NC lathes. Also the possibility of setting a spindle rotational speed which would make it possible to attain the recommended cutting speed was taken into account. Lathe tool MWLNR 2020K06 with a WNMG060408N-GE insert made of carbide AC820P met all these requirements whereby the shaft could be machined on all the three lathes. The recommended cutting speeds ranged from 210 m/min for roughing to 440 m/min for finishing.

Power on the TUR-50 lathe was measured at a spindle rotational speed of 900 or 1120 rpm, whereby a cutting speed of 350 m/min or 440 m/min could be attained. In the case of the other lathes, the speeds were attained using an infinitely variable drive. Depths of cut a_p and feed rates f are shown in Table 1.

The consumption of power P_{el} during milling was studied for the face milling of a 170 x 100 x 40 mm prismatic workpiece (Figure 3). The workpiece's dimensions were such that it could be secured in a precision vice fixed to the milling table. In conformance with the tool manufacturer recommendation, the milled surface width was about 1.6 smaller than the cutter diameter. Machining was done at longitudinal milling table feed parallel to the workpiece's longest edge while the face milling cutter axis was perpendicular to its longitudinal axis.

Table 1. Machining parameters used for shaft turning

	n = 900 rpm			n = 1120 rpm		
f [mm/rev.]	a_p [mm]			a_p [mm]		
0.1	0.4	1	1.4	0.4	1	1.4
0.22	0.4	1	1.4	0.4	1	1.4
0.4	0.4	1	1.4	0.4	1	1.4

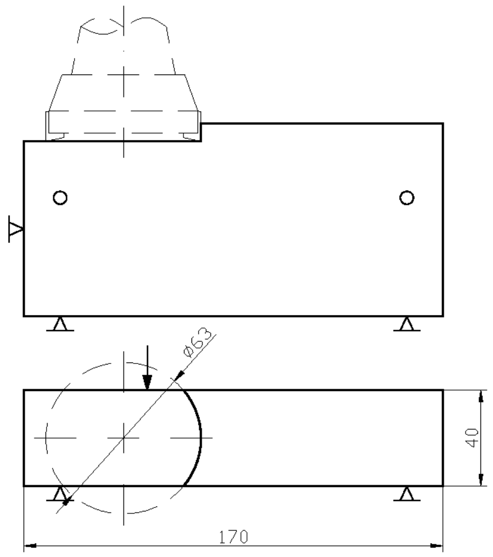

Figure 3 - Test workpiece used in milling operations

Face milling cutter 20.699-063/R610.21-063 (63 mm in diameter) made by DOLFAMEX, with six APKT 160416ER-46 SP6564 inserts (bit material SP6564) was used for milling. The choice of the cutter and the cutting parameters was based on the milling machine capability determined by the power of the machine's motors and its stiffness. In the case of the HAAS Mini Mill, power P_{el} was measured at milling rates v_c=80, 140 or 200 m/min.

Similar milling rates were used for the FWD32J miller. The rates in this case were determined by the sequence of spindle rotational speeds and amounted to 90, 140 and 220 m/min. The machining parameters are shown in Table 2. The differences in feed rates f between the conventional miller and the NC miller are due to the fact that in the former only feed rates expressed in mm/min can be selected, whereas in the latter there more options available.

Table 2 - Machining parameters used for flat surface milling

	FWD32J miller		
depth of cut a_p [mm]	cutting speed v_c [m/min]		
	90	140	220
	feed rate f [mm/min]		
0.5	112	224	355
1.0	112	224	355
1.5	112	224	355
	HAAS miller		
depth of cut a_p [mm]	cutting speed v_c [m/min]		
	80	140	180
	feed rate f_z [mm/tooth]		
0.5	0.04	0.08	0.12
1.0	0.04	0.08	0.12
1.5	0.04	0.08	0.12

MEASURING SETUP

In order to asses the energy consumption by the machine tools it was necessary to measure the electric power drawn by them during the different stages of the machining process. Wattmeters connected into the Aron circuit, forming the measuring set made by LUMEL, were used for this purpose. The measuring set was equipped with a digital display of consumed power and the latter could be recorded as a function of time (at a programmed measuring signal sampling frequency) by a PC. A scheme showing the location of the wattmeter between the power supply and the machine tool, and the transmission of the measuring signal via a converter to the PC is shown in Figure 4. The measuring setup enabled the measurement of a.c. active power from -50 to + 50 KW at a supply current frequency of 45-65 Hz.

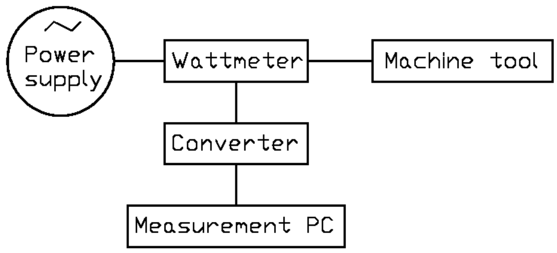

Figure 4 - Wattmeter-converter-PC connection scheme

Consumed power P_{el} was recorded as a function of time by the PC in order to determine the energy consumed by the machine tool during no-load operation and while carrying out the machining tests. The averaged energy value was calculated from relation 3.

TEST RESULTS

In order to determine machine tool energy consumption the electric power take-off from the mains was determined for the different machine operating conditions. A typical work program consisted of turning machine tool power on, turning spindle rotational motion on, no-load feed motion and machining at different speeds, feed rates or cut depths. Typical power waveforms recorded for the HAAS lathe according to the above scheme are shown in Figure 5.

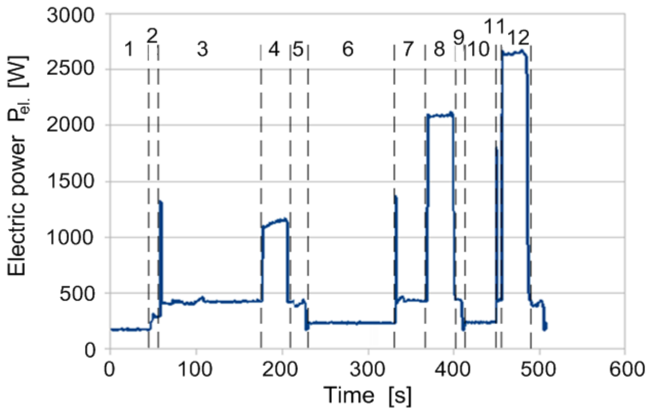

Figure 5 - Course of the power consumption P_{el} for straight turning on HAAS NC lathe at cutting speed v_c = 270 m/min, feed rate f = 0.1 mm/rev. and depth of cut a_p = 0.4, 1.0 or 1.4 mm (MWLNR 2020K06 tool with WNMG060408N-GE insert).

In the above figure, the following stages in the operation of the lathe can be distinguished: 1 – only the machine tool supply circuit switched on, 2 – the spindle rotational motion drive switched on, 3 – the feed drive motor additionally switched on, 4 – machining at depth of cut a_p = 0.4 mm, 5 – the feed and the spindle drive remain switched on after machining, 6 – the spindle drive switched on, the tool brought back to the initial position, 7 – feed switched on, 8 – machining at depth of cut a_p = 1.0 mm, 9 – the same state as in pt. 5, 10 – only the spindle drive switched on, 11 – the feed additionally switched on, 12 – machining at a cut depth of 1.4 mm. The instantaneous increases in power consumption between, e.g., stages 2 and 3, or 6 and 7 are connected with the starting currents and are due to the inertia of the machine's mechanisms whose speed had to increased to the speed required in the given machining stage.

Similar measurements of the power drawn by machine tool drive units were carried out for machining on the FWD32J and HAAS Mini Mill milling machines. Figure 6 shows the results obtained for the FWD32J miller at a cut depth of 0, 0.5, 1.0 and 1.5 mm.

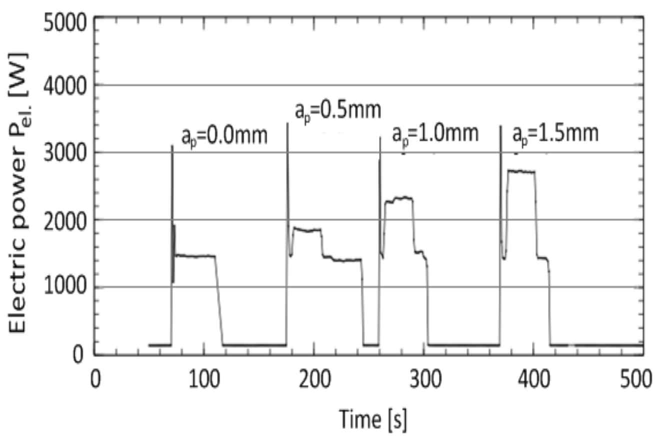

Figure 6 - Power P_{el} measured for flat surface milling on miller FWD 32J at cutting speed v_c = 140 m/min, feed rate f = 355 mm/min and depth of cut a_p = 0-1.5 at every 0.5 mm (milling cutter 20.699-063/R610.21-063 with six inserts APKT 160416ER-46 SP6564)

In each of the three diagram parts for milling at depth of cut a_p other than zero one can notice an instantaneous increase in power consumption, due to the switching on of the feed drive, an increase in power consumption until the milling cutter begins cutting along the full workpiece width, an almost constant power value during machining along the full workpiece width, a decrease in power as the tool leaves the workpiece and a constant power value as the tool moves above the already machined workpiece. A similar pattern of power consumption was obtained for the HAAS lathe. But the power values for machining were in this case much lower despite the same machining parameters and only slightly different feed rates. The differences were mainly due to the much lower power consumed by the HAAS lathe during idle running.

The recorded power measurement data were used to determine the energy consumed in order to remove a material allowance from the workpiece. For the turning of the shaft, the energy was calculated assuming that straight turning proceeded along a length of 37.5 mm. For machining along this length one had to determine the tool-workpiece contact time and multiply it by the average measured power. In the case of facing, especially at a constant cutting speed, one had to determine the area under the power graph through integration since this power was subject to considerable variation. Exemplary values of energy [in Wh] consumed for turning using the HAAS and TUR MN 560 lathes are shown in Figure 7.

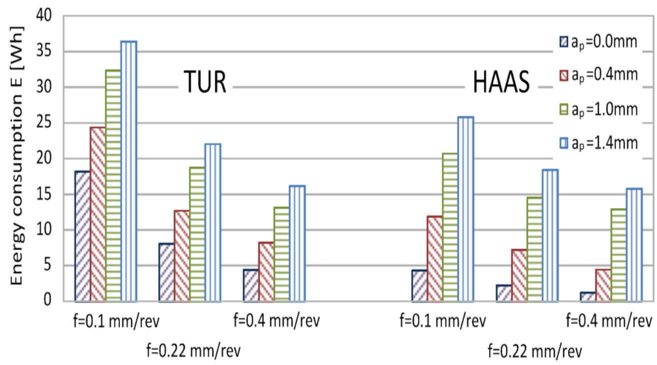

Figure 7 - Energy consumed during straight turning of shaft on TUR MN 560 and HAAS lathes (at different feed rates f and depths of cut a_p) at cutting speed v_c = 270 m/min

From the above diagrams one can draw some conclusions about turning using the TUR MN 560 lathe and the HAAS lathe. As the depth of cut increases so does the amount of energy consumed for removing of a material allowance. This is obvious since the greater the depth of cut, the larger the cross section of the material layer being removed. The cutting forces are then greater and the machining power is higher whereby at the unchanged machining time, energy consumption increases. However, when one increases the feed rate, this results in a reduction in energy consumption. Although as the feed rate is increased, power P_{el} drawn by the machine tool also increases, the time of the operation is then shorter and consequently less energy is consumed for removing the material allowance. Also cutting speed *has a beneficial effect on energy consumption. As the cutting speed increases so does the feed per minute whereby the time of machining the given part of the shaft is reduced. Thus in order to reduce the amount of energy consumed for removing a given material layer one should use the parameters recommended for roughing, i.e. large depths of cut and high feed rates. Although lower feed rates are recommended for roughing (because of tool durability), high-speed machining is advantageous from the energy consumption point of view.*

The power consumption coefficient increases with the depth of cut and the feed rate. Therefore as more energy is consumed for machining work, the index also assumes higher values when the machine drive system consumes less power during no-load operation. In the presented cases, W_e assumes higher values for the HAAS lathe and lower values for the TUR MN 560 lathe. As it appears from the bar charts shown in Figure 8, the values of power ΔP_{bo} drawn during no-load operation are lower in the former case. Generally speaking, the higher the power consumption coefficient W_e, the less energy-intensive the cutting process executed using a machine tool.

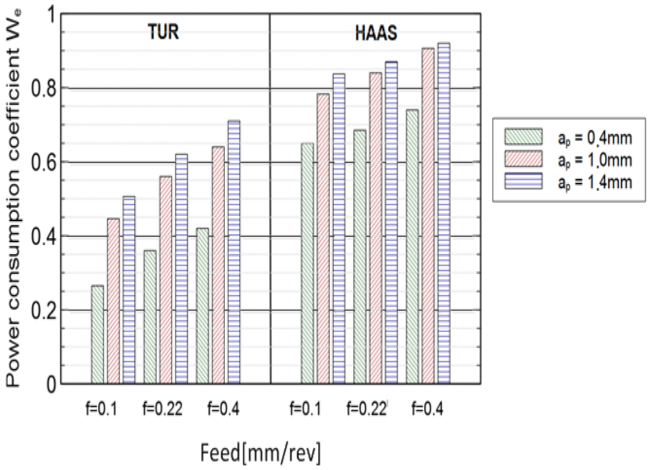

Figure 8 - Energy consumption coefficient for straight turning of shaft on TUR MN 560 and HAAS lathes (at different feed rates f and depths of cut a_p) at cutting speed v = 180 m/min.

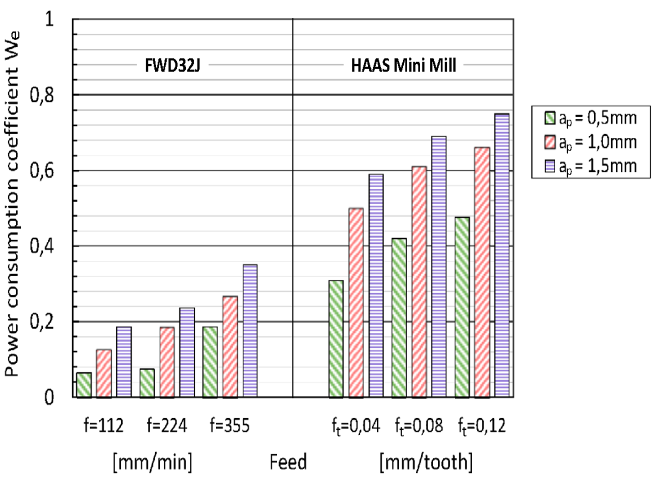

Figure 9 - Energy consumption coefficient for flat surface milling on FWD32J and HAAS Mini Mill millers (at different feed rates f and depths of cut a_p) at cutting speed v = 140 m/min

Conclusions similar to the turning process can be confirmed for the milling process, analyzing characteristics from Figure 9. Energy consumption coefficient W_e value increases with milling depth and feed rate, just like in the turning process. When milling on CNC miller - HAAS Mini Mill, its value is considerably larger than on conventional milling machine FWD32J. The main reason for differences in both millers energy consumption is the extensiveness of the FWD32J main and feed drive systems. This machine tool draws more power when running idle due to the greater power loss in both drive systems. This results in higher energy consumption.

CONCLUSIONS

The costs of energy consumption in the production process become an increasingly critical component of the total production costs. Therefore attempts at reducing them are economically imperative. One should also take into account the fact that electric energy is usually produced by combusting natural fuels, which is one of the main causes of environmental degradation. The above factors make it necessary to economically manage the national energy resources. Also in the sphere of machines production and operation one can find possibilities of reducing energy consumption.

The preliminary studies presented in this study show that even in the case of simple machining operations performed on manually or numerically controlled universal machine tools there are possibilities of reducing energy consumption. The amount of energy consumed for the turning of a cylindrical surface using the TUR MN 560 lathe and the HAAS lathe differs significantly between the two lathes.

The following conclusions (which need to be verified by further research) emerge from the studies:

- *the amount of energy needed to perform the same machining operation to a large extent depends on the design of the drive units of the machines on which the operation is performed;*
- *the differences in the amount of energy consumed for performing the same machining operation are mainly due to the differences in power ΔP_{bo} consumed by the machine during no-load operation;*
- *the process parameters have an influence on the amount of energy consumed for machining: the amount of this energy decreases as the cutting speed and the feed rate increase and increases with the depth of cut;*
- *having in mind energy consumption, one should use large depths of cut and single-pass machining instead of a larger number of passes at a smaller depth of cut;*
- *dimensionless index W_e is recommended to be used for assessing machine tool energy consumption; the magnitude of the index depends on the amount of energy consumed during the no-load operation of the machine and during machining;*
- *in order to determine the energy consumption index one should determine the course of the power consumed by the machine tool during no-*

load operation and during machining and measure the machine tool operation time;

- *the energy consumption index may assume values from 0 to 1. The higher the index, the less energy will be consumed for the machining process.*

The studies have an exploratory character. They were carried out on machine tools with simple drive units, performing only simple machining operations. Nevertheless, it emerges from the obtained results that the energy consumption by a machine tool can be assessed on the basis of the power drawn by it during machining and during no-load operation. The energy consumption can be expressed by dimensionless energy consumption index W_e.

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