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PARTIAL EFFECT OF CUTTING PARAMETERS ON ENGAGED POWER AND ENERGY CONSUMPTION: THE CASE OF EXTERNAL TURNING OF AN AISI1045 STEEL WORKPIECE

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Abstract. *With the ever-growing interest in energy saving during machining processes, it is important to be able to assess energy consumption for various machining conditions. The paper presents results on measuring of engaged power and energy consumption for external turning of an AISI1045 steel part. A series of experiments were conducted in which the values of cutting speed, depth of cut and feed rate were changed within their selected range. The measurement was performed using an advanced energy sensor that allows detailed monitoring of the engaged power and energy in real time. The measurement results draw out the partial effect of each of the parameters on the increase in the engaged power and the consumed energy. In addition, the measurement results enable the development of a prediction model that can be useful for making the optimal choice of machining parameters regarding energy consumption, especially for the cases of high-volume manufacturing.*

Key words: *Turning, Machining energy, Machining power, AISI 1045, In situ measurement*

1. INTRODUCTION

Usually, the ultimate business imperative for a micro or small enterprise, which is involved in metal machining, is to keep its production resources fully engaged all the time. The simplest way to ensure a high level of employment of the equipment and people is to use batch production where a set of machining operations are repeated. In such circumstances, careful planning of every machining operation regarding energy saving and reducing the engaged machine power becomes very important, because even small savings for one component may result in significant cumulative savings for a large number of components. For a small company, production equipment (e.g., machine tools) is something which is usually a given state, and it is not easy to replace the existing machine

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tools with more efficient or productive ones. In addition, the machining process technology for a specific product imposes the selection of the cutting tools that should be used as well as the cutting parameters (depth of cut, cutting speed and feed rate) that should be applied. Yet, the machining plan designer is expected to select a proper combination of values for machining parameters within their recommended ranges trying to ensure minimal energy consumption and engaged power. To be able to make an optimal choice on these cutting parameters, the machining plan designer should explore the partial influence of each parameter on energy consumption and engaged power. Even for common material such as unalloyed steel, to make an optimal selection of cutting parameters in terms of energy savings while preserving the required productivity of the specific machining operation at the same time, there is a need to conduct an experiment to determine how each cutting parameter affects the energy consumption and engaged power. Besides calculating the energy consumption during machining based on measured cutting forces, from the perspective of the machining plan designer who searches for an optimal combination of cutting parameters that will make the highest possible productivity while keeping energy consumption and engaged power to a minimum at the same time, it is more accurate and comprehensive to directly measure the electric current and voltage during the machining process. Thus, it is easy to measure the portion of energy being consumed for the idle state (when the machine tool is turned on), for rotating the workpiece, for cutting fluid supply and finally for pure machining. This paper presents the procedure for measuring the energy and the engaged power by using modern IIOT equipment for measuring electrical quantities. Before presenting the measurement procedure and the results obtained, a brief overview of the related research is presented.

2. RELATED WORK

Since energy is becoming increasingly precious as a result of its depletion, and pollution being one of today's primary global worries, everyone should help in reducing the pollution in the world we live in. One of the major polluters is the manufacturing industry. The scientific society has been searching for means to reduce the environmental impact of manufacturing processes. Machining is also being thoroughly explored, as it is one of the most widely used manufacturing processes. Gutowski et al. [1] established the groundwork for mathematical models of power and energy consumption, which were then upgraded by many different researchers. Balogun and Mativenga [2] proposed a novel mathematical model for estimating direct electrical energy requirements for various machining tool paths. Xie et al. [3] developed a model for estimating specific energy consumption (SEC) in manufacturing processes under various conditions, with a focus on spindle system energy consumption. Validation trials revealed that the created model predicts SEC with less than 10% inaccuracy. Zhou et al. [4] and Zhao et al. [5] provided a comprehensive research review in the field of energy consumption modeling, using examples of mathematical models from the reviewed literature.

As AISI 1045 is one of the most widely used materials, research regarding parameter optimization of turning processes with this material has already been done to some extent. Senthilkumar et al. [6] investigated the influence of cutting parameters and cutting-edge angle on material removal rate, surface roughness and tool wear. They used a hybrid grey-fuzzy algorithm to find optimal conditions. Iqbal et al. [7], [8] investigated the effects of cutting speed on tool rake face contact length, friction, contact area, surface roughness. Flow stress models were also introduced, but no energy consumption was analyzed. Qasim et al. [9] used the general purpose ABAQUS finite element code to study the effects of cutting speed, feed rate, depth of cut and rake angle in orthogonal cutting processes with regards to surface roughness, shape of chips, temperature and energy consumption, with multiple cutting tools. Results of the simulation were compared with experimental results from the reviewed literature. Sangwan and Kant [10], through the use of response surface methodology (RSM) and generic algorithm (GA), developed a predictive and optimization model used for determining minimal power consumption based on cutting speed, feed rate and depth of cut. However, they did not measure energy consumption directly, rather through measuring of cutting forces (with a Kistler Type 9272 dynamometer), as in their previous work done on the same topic [11]. It is interesting that both papers analyzed same machining parameters with regards to power consumption, but the authors came to different conclusions. In [10] the authors conclude that depth of cut has the greatest influence on power consumption, followed by cutting speed and feed rate, but in [11] the conclusion was that feed rate has the greatest influence, followed by depth of cut and cutting speed. It may be the case that by only looking at power consumption as an output parameter of the optimization (as in [11]) the results differ from those looking at both power consumption and surface roughness (as in [10]). Abbas et al. [12] studied the effects of different cooling and lubrication strategies on surface roughness and power consumption of the turning process and used optimization methods to determine the best parameter combination for each defined cooling and lubrication strategy. Pimenov et al. [13] did a thorough investigation on surface quality and energy consumption, but for face milling of parts. Bhattacharya et al. [14] estimated the effects of cutting speed, feed rate and depth of cut on surface roughness and power engagement. The authors concluded that cutting speed has the most significant effect on the power engagement level. Contrary to the results obtained in this research, which will be discussed later, research [14] pointed out that the impact of feed rate on the engaged power is the smallest. Concerning the surface roughness, the authors claimed that the greatest effect is exerted by cutting speed, and then feed rate and depth of cut both similarly.

From the reviewed literature, it can be concluded that the majority of the research done for cutting parameter influences on machining performances in turning of AISI 1045 steel was focused on surface roughness, costs, power consumption, lubrication, etc., but few have studied the influence of cutting parameters on energy consumption. Even if energy consumption was studied, it was not empirically measured, but calculated through power consumption, and often was combined with some other machining performance characteristic (such as surface roughness) and then optimized.

3. Research Goal

The research goal was to empirically determine the partial effect of each machining parameter: depth of cut, feed rate and cutting speed on engaged power and energy consumption while external rough turning a workpiece of AISI 1045 steel. The purpose was to use measurement results for creating a power and energy consuming prediction model, which would be used for the optimal choice of machining parameters regarding energy consumption, especially for the large production volume cases. In a case where a similar machining operation, e.g., external rough turning should be repeated for 10^5 times per year on a specific machine to meet the required production volume in a given period, the ability to select the optimal combination of these parameters regarding energy consumption becomes very relevant since even a small energy saving yields a large final amount.

4. EXPERIMENT – TEST SETUP

The experiment involves three workpieces (bars) with the initial diameter of 60 mm and length of 500 mm. Pre-machining was applied to ensure a proper cylindrical shape and to create a tailstock center support area. To provide regular and uniform working conditions, the geometric and dimensional tolerances of workpieces were checked after pre-machining.

Table 1 The workpiece features

Workpiece Material	HB	$k_{c1.1}$ [N/mm2]	m_c	Starting diameter [mm]	Length [mm]
AISI 1045	206	2000	0.15	58	500

The cutting tool was selected in accordance with a given tool system, which was selected to be used for external rough turning operation for this specific case.

Table 2 The tool system features

Toolholder	Insert	Grade	Insert manufacturer
DCLNL 2020K 12	CNMG120408-PM	YBC252*	ZCC CT
Cutting edge angle 95°	L_e=12 [mm] r_e =0.8 [mm]	(P10-P35)**	

*YBC252 comprises a thick layer of TICN and Al2O3 in CVD
**(P10-P35) is written on the tool manufacturer's box, but does not fully comply to the ISO standard mark (P20-P35)

The machine tools that were selected for turning operations for this case are very similar to the one in the Laboratory for Machine tools at the Faculty of Mechanical Engineering in Niš.

Table 3 The turning machine features

Machine tool	Power [kW]	Max. spindle speed [rpm]	Control Unit
Gildemeister NEF 520	12	3000	Heidenhain Manual Plus 4110

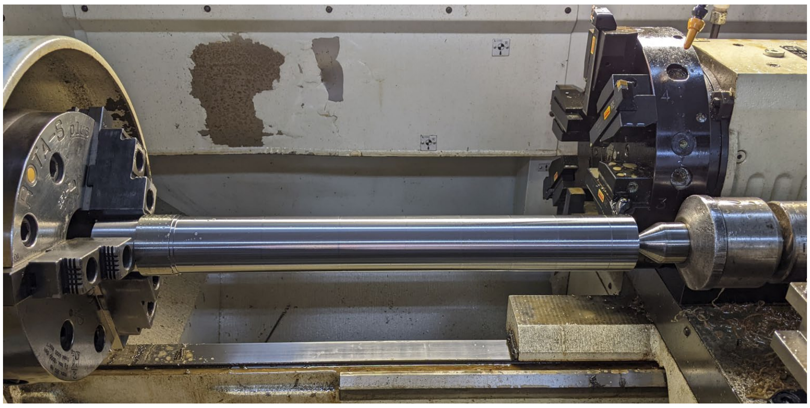

Fig. 1 Setup of the workpiece in the lathe.

The total engaged power and total energy consumption were measured by an IIOT measuring device - NTPM smart sensor of Netico Solutions (https://netico-group.com/energy-management/ntpm-100-series/).

Fig. 2 NTPM smart sensor aimed for measuring electric magnitudes

The NTPM sensor is used for measuring electric current and voltage at a sampling rate of 60 ms. The energy is calculated and cumulatively added to the energy balance per second. The engaged power is also calculated based on the measured values of the electric current and voltage, but it is sampled discretely, also per second.

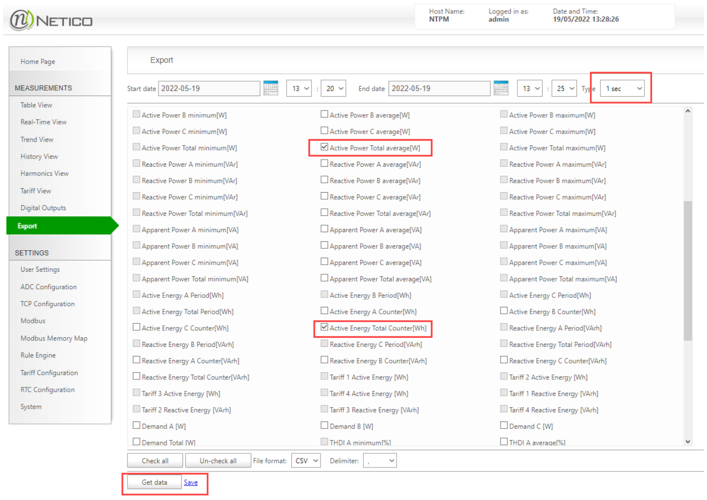

Fig. 3 Selection of the values to be recorded from the control panel of the NTPM Sensor: Active Energy Total [Wh] Active Power Total Average [W]

4.1 Experiment conduction method

For the experiment it was decided to change depth of cut (a_p), feed rate (f) and cutting speed (v_c) within recommended ranges at three levels.

$\boldsymbol{a_p}$ = {1, 1.675, 2.5} [mm];

$\boldsymbol{f}$ = {0.1, 0.2, 0.3} [mm/rev];

$\boldsymbol{v_c}$ = {240, 270, 300} [m/min].

Table 4 lists all the combinations (27) of these parameters that are involved in the experiment.

Table 4 Parameter combinations involved in the experiment

#	a_p [mm]	f [mm/rev]	v_c [m/min]	#	a_p [mm]	F [mm/rev]	v_c [m/min]	#	a_p [mm]	f [mm/rev]	v_c [m/min]
1	1	0.1	240	10	1.675	0.1	240	19	2.5	0.1	240
2	1	0.1	270	11	1.675	0.1	270	20	2.5	0.1	270
3	1	0.1	300	12	1.675	0.1	300	21	2.5	0.1	300
4	1	0.2	240	13	1.675	0.2	240	22	2.5	0.2	240
5	1	0.2	270	14	1.675	0.2	270	23	2.5	0.2	270
6	1	0.2	300	15	1.675	0.2	300	24	2.5	0.2	300
7	1	0.3	240	16	1.675	0.3	240	25	2.5	0.3	240
8	1	0.3	270	17	1.675	0.3	270	26	2.5	0.3	270
9	1	0.3	300	18	1.675	0.3	300	27	2.5	0.3	300

The external rough turning for one value of depth of cut was planned to be done with one workpiece. The cutting speed changed from 240, over 270 to 300 m/min, while feed rate was kept constant at one value (initially 0.1 mm/rev). For each combination of cutting parameters, the cutting lengths were set so that machining took 9 seconds, in order to enable power and energy sensor to sample sufficient set of values. The first three machined cylindrical surfaces, as can be seen in Fig. 4, had different cutting lengths (L1, L2, L3) since each of them was machined with a different cutting speed. Between these surfaces, there were so-called transition segments which were machined during the change of cutting speed to the next discrete value (e.g., from 240 to 270 m/min). For these toolpath segments, the feed was set to 0.02 mm/rev in order to make these segments short (I1, I2, I3) and keep the machining time below 3 sec. Then, the machining continued with the same depth of cut, but now with the next discrete value of feed rate, i.e., 0.2 mm/rev, and again with three different cutting speed values. The tool was kept plunged in the workpiece material during the whole experiment.

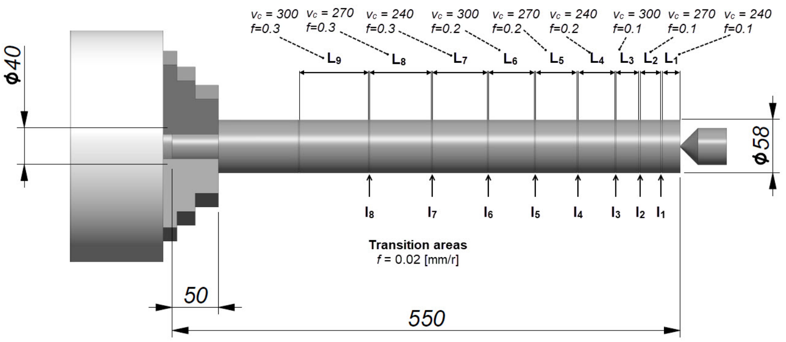

Fig. 4 The machining segments' disposition along the workpiece for the experiment

During machining, the cutting oil flooded the tool, workpiece and cutting zone. Cutting oil - FAM SG 15 N (ISO 6743-7, L-MHE; ISO/TS 12927) was supplied through the turret and through the flexible oil coolant pipe hose (Fig. 5).

5. Measurements and Results

The measurements of engaged power and energy consumption were performed in three phases:

1. Idle state – the machine tool is turned on, but is without movements (no cutting oil supply, also).
2. Air machining - the workpiece rotates, the tool moves, the cutting fluid floods the tool and the workpiece, but there is no material removal. The tool is offset for 0.5 [mm] from the workpiece boundary.
3. Machining – the workpiece rotates, the tool moves, the cutting fluid floods the tool, workpiece and cutting zone, the material is removed.

This measuring approach allows one to separately determine energy (and power), which is used while the machine tool is in the so-called idle state (Fig. 6), then while it performs air machining, and finally while it cuts the workpiece material. Thus, it was possible to identify the difference between so-called air-machining and real machining, and to calculate the effect of each cutting parameter on engaged power and energy consumption while the material cutting was being done (Fig. 7) and to perform further analysis and optimization.

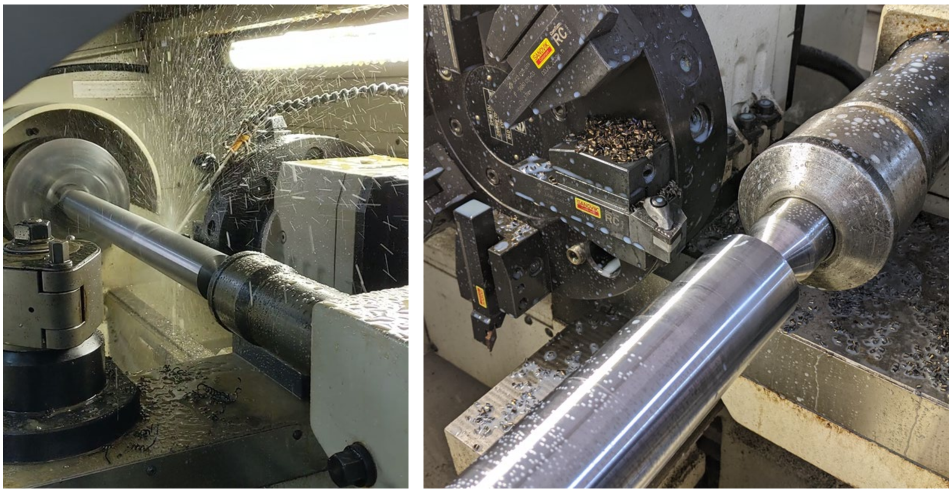

Fig. 5 Machining in wet conditions

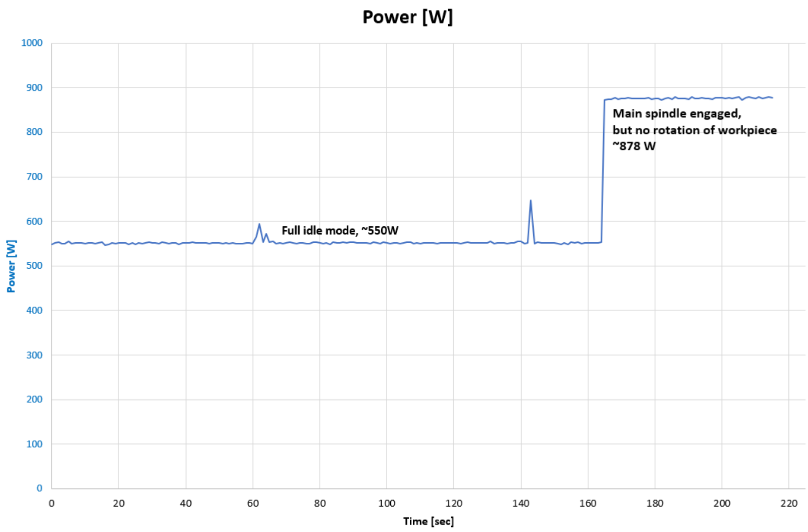

Fig. 6 Engaged power in idle mode

The diagram in Fig. 7 indicates an increase in the power engagement and energy consumption with an increase in cutting speed and feed rate. Also, one can notice that the machine tool engages a significant portion of power and energy just to rotate the workpiece.

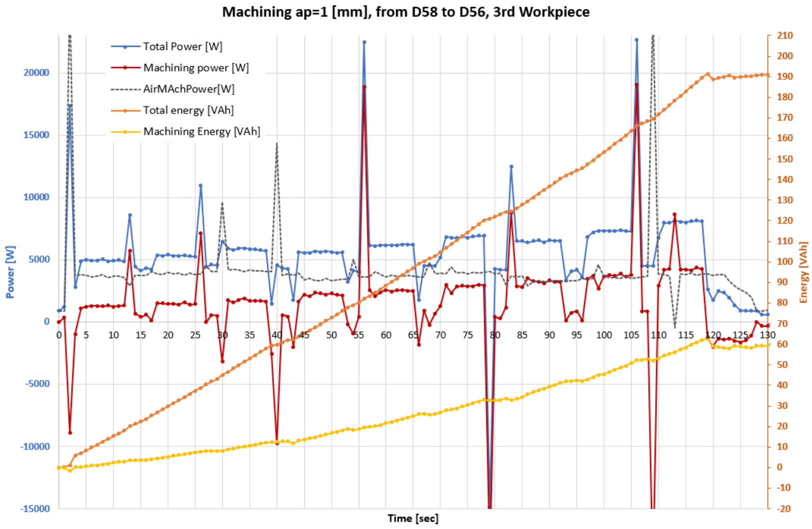

Fig. 7 Differential diagram of engaged power and energy consumption for the case of a_p=1 [mm] and D_o=58 [mm] (3rd workpiece)

6. THE MEASUREMENT RESULTS

The results include engaged power [W], specific energy consumption [VAh/s] and material removal rate [mm^3/s]. The cumulative results are shown below (Fig. 8):

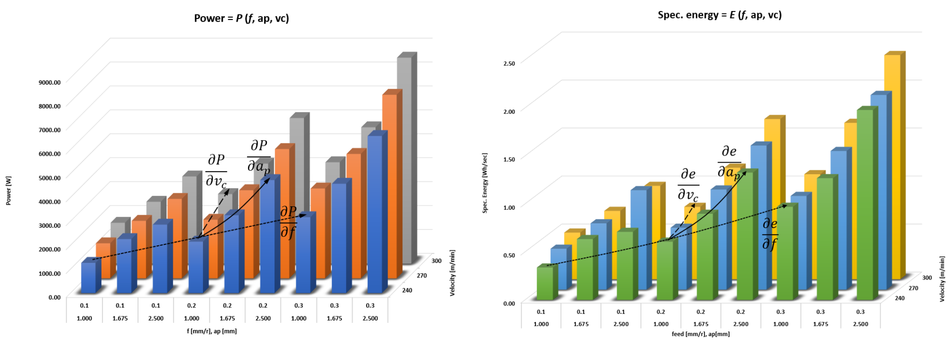

Fig. 8 Change in engaged power and specific energy consumption with respect to the cutting parameters change

The following sets of *box plots* show the effect of each different cutting parameter on engaged power and specific energy consumption for the specific machining conditions (while performing external rough turning of a cylindrical workpiece made of AISI 1045 steel on a NEF520 Gildemeister turning machine).

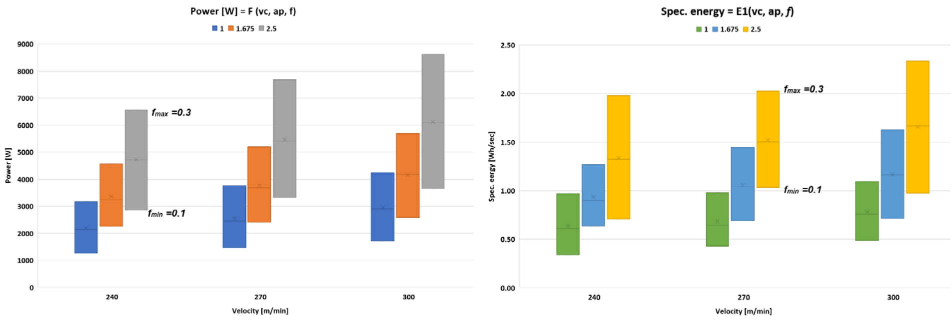

Fig. 9 Effect of feed rate on P and E_{spec}

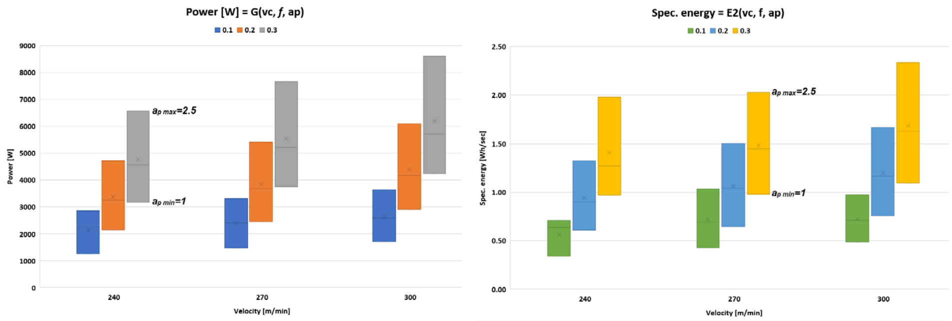

Fig. 10 Effect of depth cut on P and E_{spec}

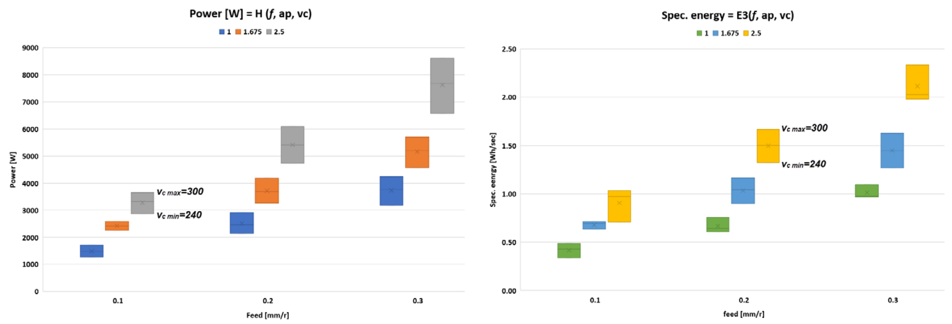

Fig. 11 Effect of cutting speed on P and E_{spec}

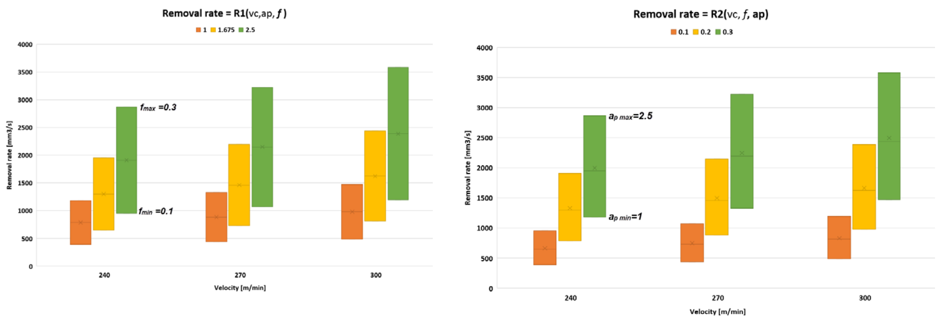

Fig. 12 Effect of feed rate on material removal rate (left) and effect of depth of cut on material removal rate (right)

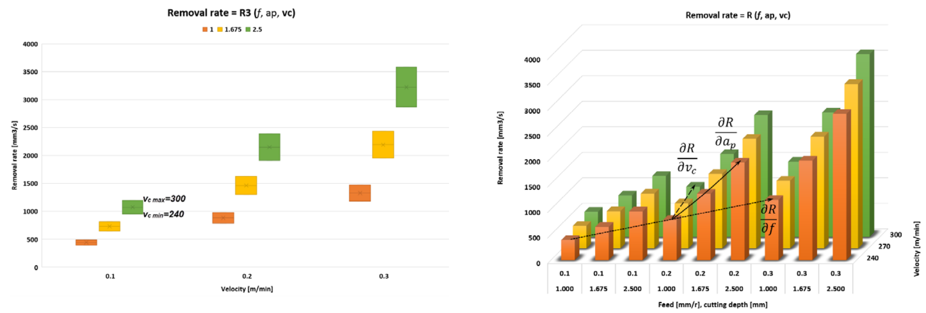

Fig. 13 Effect of cutting speed on material removal rate (left) and change in material removal rate with respect to cutting parameters change (right)

6. Discussion

Before discussing the results obtained through measuring, it should be noted that cutting parameters were changing within their selected limits for the specific application (external rough turning of AISI 1045 on a Gildemeister NEF 520 machine tool). The results show that feed rate and depth of cut have a similar influence on engaged power and energy consumption increase. At the same time, by comparing the charts shown in Figs. 9, 10 and 11, it is obvious that the cutting speed change within the selected range has a significantly smaller effect on energy and engaged power compared to feed rate and depth of cut. The same applies to the material removal rate (Figs. 12 and 13). From the machining plan designer's perspective, the optimal solution regarding energy and power savings can be obtained most easily by choosing the appropriate combinations of depth of cut and feed rate from the selected ranges.

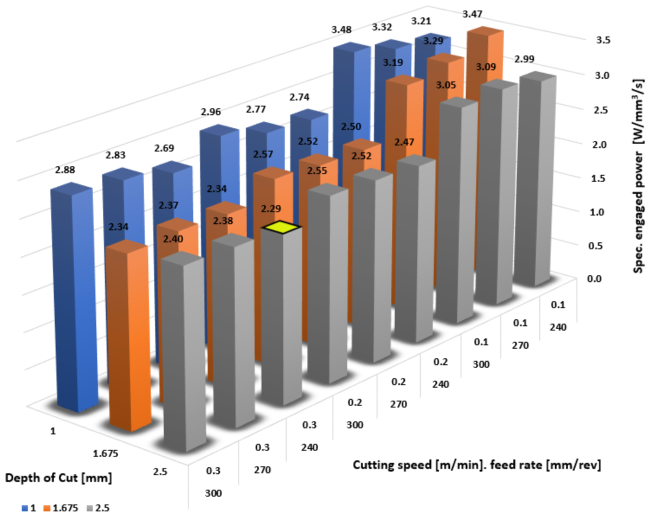

Fig. 14 The engaged power with regard to material volume removal rate.

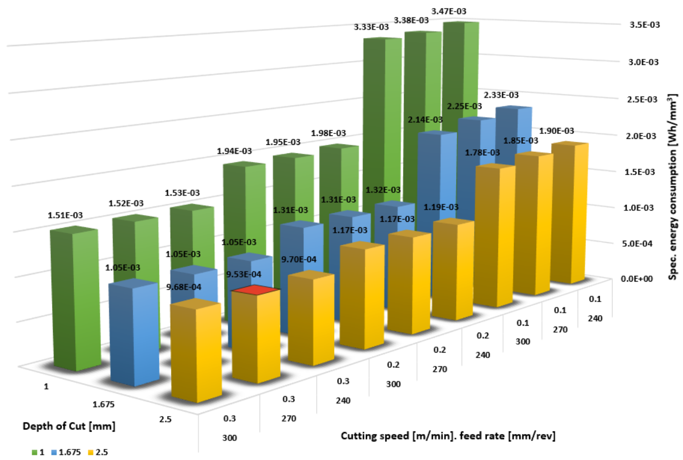

Fig. 15 The specific energy consumption with regard to material volume removal rate.

The diagram presented in Fig. 14 shows the engaged power per material volume removal rate depending on the cutting parameters combination. It turns out that the most effective combination in terms of engaged power is $\boldsymbol{a_p}$ = 2.5 mm, $\boldsymbol{f}$ = 0.3 mm/rev, $\boldsymbol{v_c}$ = 240 m/min. Similarly, the diagram in Fig. 15 shows specific energy consumption per material removal rate where the combination of cutting parameters: $\boldsymbol{a_p}$ = 2.5 mm, $\boldsymbol{f}$ = 0.3 mm/rev, $\boldsymbol{v_c}$ = 270 m/min ensures the most effective performance.

7. Conclusion

The paper presents a measuring procedure whose results can be used for creating appropriate models and subsequently determining the optimal cutting parameter values that can provide maximal savings regarding energy consumption and engaged power. This kind of experiment should be conducted for every single machining operation or at least for those machining operations for which it is expected to take a lot of energy, before getting into a large batch production. In addition, the paper presents the measuring results showing how each of the cutting parameters affects the electric energy consumption, engaged power and material removal rate. The collection of measured data can be used for the development of prediction models that can help a machining plan designer to anticipate the energy savings for each combination of machining parameters values.

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