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Original scientific paper

ON ONE ASPECT OF SUSTAINABLE MANUFACTURING
Power Consumption vs Productivity

Edin Begović, Ibrahim Plančić, Sabahudin Ekinović, Vedran Mizdrak[1]

[1]The University of Zenica, Faculty of Mechanical Engineering

ABSTRACT

The paper presents one aspect of the analysis of energy consumption and productivity of the manufacturing operation. As an example of the operation, the operation of turning with a single-blade tool was taken. Sustainable development in its general concept implies sustainable materials, sustainable design, and sustainable manufacturing. This paper presents an analysis of one important part of sustainable manufacturing, and that is energy saving. The experimental study was conducted as follows. In laboratory conditions, an experimental-mathematical regression model of the relationship between cutting force and processing conditions was defined. Machining experiments were performed under ECO-friendly conditions with technology known as MQCL (Minimum Quantity Cooling Lubrication) machining. The obtained mathematical model was used to calculate the energy consumption and the workpiece material removal rate (MRR, productivity). The results of the analysis showed that there is a lot of space for optimization of machining conditions from the aspect of power consumption, with mandatory calculation and other machining costs, above all, the cost of tools and machine tools. In this regard, recommendations for analysis with the aim of power saving are given.

Keywords: sustainable manufacturing; MQCL machining; power saving; design of experiment; cutting force measurement, power consumption, productivity

Corresponding Author:
Sabahudin Ekinović,
The University of Zenica, Faculty of Mechanical Engineering
Fakultetska 1., 72000 Zenica, Bosnia and Herzegovina
Tel.: ++ 387 61 477 570
E-mail address: sabahudin.ekinovic@unze.ba

1. INTRODUCTION

To achieve the concept of sustainable manufacturing, which is a very complex problem, it is necessary to consider three integral levels of interaction, namely: products, processes, and systems [1,2], Figure 1. There is no universal or generally accepted definition of sustainable manufacturing in the literature and practice [1]. However, it must be said that there are many insufficient attempts, including a partially integrated approach. Almost all of these attempts are flawed because they mainly deal only with products and processes, but do not emphasize the interconnectedness between the three constituent elements involved in manufacturing (products, processes, and systems). In line with the basic concept, sustainable manufacturing offers a new way of producing functionally sustainable products using sustainable technologies and advanced manufacturing methods. This is only possible if product design, production, supply chain design and management, and logistics at the manufacturing enterprise level can be understood, developed, and managed in an integrated way.

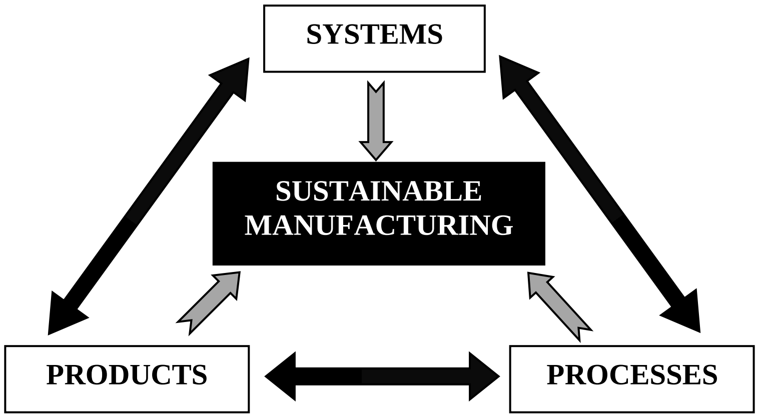

Figure 1. Integrated elements of sustainable manufacturing [1]

The interaction between the levels of the elements shown in Figure 1 gives the desired sustainable goal.In terms of products (Figure 1), a new 6R approach (i.e. re-duce, re-design, re-use, re-cover, re-manufacture, and re-cycle) has been established instead of the 3R

Regarding the process (Figure 1), the reduction of energy consumption, hazards, and toxic waste is achieved by using an optimized technological process. This technological process is associated with an efficient process planning methodology, with the use of an efficient supply chain system that takes into account all stages of the life cycle (i.e. pre-manufacturing, manufacturing, u,se and post-use) ensures an effective sustainable system [5]. The expectations of a sustainable manufacturing process are concluded as follows [3,4,5]:

- Energy consumption reduction
- Waste elimination/reduction
- Product durability improvement
- Health hazards and toxic dispersion elimination
- Higher quality of manufacturing
- Recycling, reuse, and remanufacturing enhancement
- Development of renewable energy resources.

On the other hand, the analysis of each of the elements shown in Figure 1 should be approached from a comprehensive point of view. In this paper, special attention is put to the process. The manufacturing process observed in a cybernetic way can be represented in the way that Figure 2 shows. The clear position of the so-called internal factors can be seen, among which are the cutting forces. This is especially important from the aspect of energy saving or energy consumption reduction to achieving sustainable manufacturing. So, technologically speaking, there are large reserves in the segment of energy consumption. In this paper, the example of a turning operation shows how energy can be saved. Previously, the relationship between the cutting forces and the elements of the cutting regime was experimentally modeled, and later this mathematical model was used for the analysis and calculation of energy/power consumption.

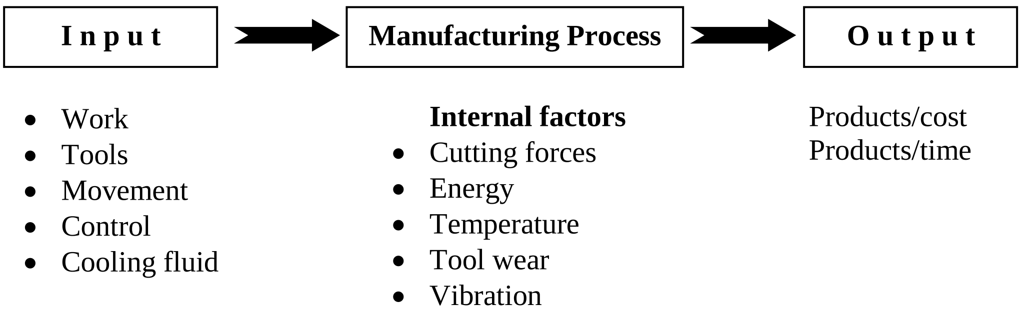

Figure 2. Machining process

2. EXPERIMENTAL SETUP

Turning is one of the most widely applied production technologies in industrial practice [6]. As with any other production technology by removing workpiece material, the presence of cutting forces is bound to take place. Greater magnitudes of the resulting cutting force in production processes cause higher wear of cutting tools, higher probability of tool breakage, higher cutting temperature, as well as lower quality of the machined surface and dimensional accuracy of the machined product [7]. Since all of the aforementioned are important factors from the aspects of both productivity and costs, finding ways to predict the magnitude of the resulting cutting force for a given machining condition is of paramount importance. One way to obtain a reliable mathematical model describing the relationship between cutting forces and machining conditions is the experimental method. This is meant the conduct of experiments, and the use of appropriate statistical methodologies, primarily regression analysis and analysis of variance.

The experiment has been performed at the Laboratory for Metal Cutting and Machine Tools, at the Faculty of Mechanical Engineering, University of Zenica. The experiments were conducted under ECO-friendly conditions, so-called MQCL (Minimum Quantity Cooling Lubrication) machining. Figure 3 shows the experimental setting of the turning operation. Cooling and lubricating media is an aerosol that represents water droplets with such an oil film carried by a stream of compressed air. This aerosol is not harmful to the environment at all, it is composed of water and vegetable oil. The following volume ratio was used in the experiment: 0.9 liters per hour of water and 30 ml per hour of oil. Aerosol production (atomization) is done in a nozzle that directs it to the cutting zone.

The conventionally operated lathe is a Potisje PA501M model. The cutting tool used in all of the experimental runs was Mitsubishi SNMG120408-MA inserts. The material of the workpiece is steel C45 (EN). The magnitude of the resulting cutting force was calculated based on measurements of the cutting force components, which were performed using a Kistler dynamometer 5070 type.

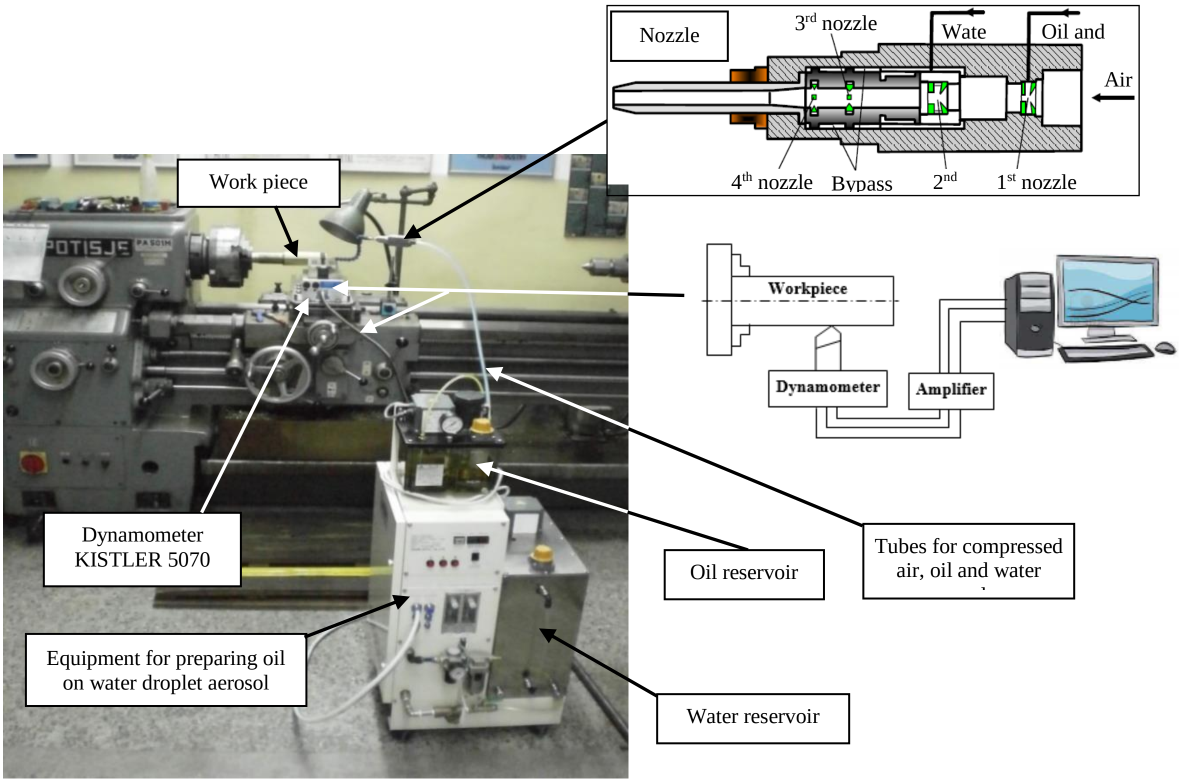

Figure 3. Experimental setup

The three most important machining conditions were selected for the factors: cutting speed, *v*, (or, rpmin of the workpiece), feed, *f* (mmpr,) and depth of cut, *d* (mm). Factor levels with natural and coded values are shown in Table 1.

Table 1. Factor levels with natural and coded values

Factors levels	Workpiece revolution per minute		Feed		Depth of cut	
	n, rpmin Natural	x_1 Coded	*f*, mmpr Natural	x_2 Coded	*d*, mm Natural	x_3 Coded
Upper	265	+1	0.049	+1	0.5	+1
Medium	600	0	0.124	0	1.0	0
Lower	910	-1	0.196	-1	1.5	-1

3. RESULTS AND DISCUSSION

Table 2 shows the plan-matrix of the experiment with measurement results, namely: main cutting force *Fz*, thrust forces, *Fy* and feed forces *Fx*, as well as calculated values of the overall (resulting) cutting force *F*. Overall force is calculated according to the expression:

$$F = \sqrt[2]{F_x^2 + F_y^2 + F_z^2}, \text{N}, \quad (1)$$

Figure 4 shows the measurement results of the cutting force components for experimental runs 2 and 7.

Table 2. Plan-matrix of experiment and measurement results

Experi-mental runs	Plan – matrix of experiment								Measurement results, N			
	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	*Fx*	*Fy*	*Fz*	*F*
1	+1	-1	-1	-1	+1	+1	+1	-1	41	44	91	109
2	+1	+1	-1	-1	-1	-1	+1	+1	45	54	92	116
3	+1	-1	+1	-1	-1	+1	-1	+1	75	96	239	268
4	+1	+1	+1	-1	+1	-1	-1	-1	92	124	240	285
5	+1	-1	-1	+1	+1	-1	-1	+1	105	102	236	277
6	+1	+1	-1	+1	-1	+1	-1	-1	156	154	241	326
7	+1	-1	+1	+1	-1	-1	+1	-1	269	262	695	790
8	+1	+1	+1	+1	+1	+1	+1	+1	255	263	609	711
9	+1	0	0	0	0	0	0	0	153	163	314	386
10	+1	0	0	0	0	0	0	0	157	169	327	400
11	+1	0	0	0	0	0	0	0	177	186	367	448

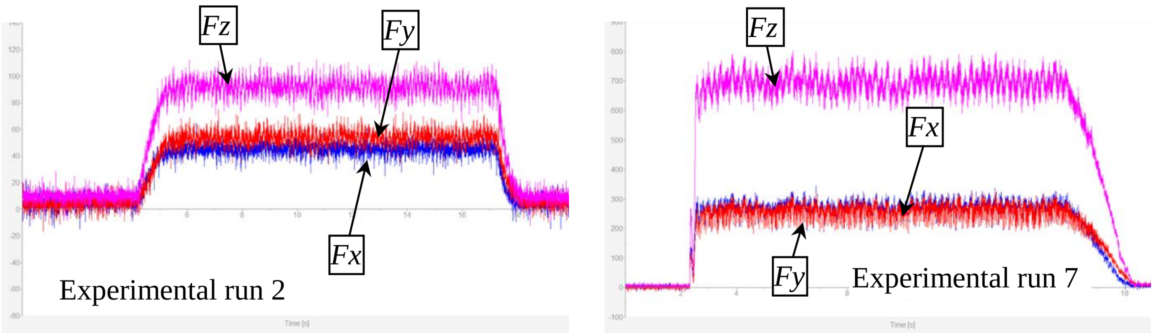

Figure 4. Measurement results of the cutting force components for experimental runs 2 and 7 (Table 2)

The task of experimental research is to determine the mathematical model of the function of the dependence of the overall cutting force on the number of revolutions, *n*, feed, *f,* and depth of cut, *d*. If a mathematical form is assumed as:

$$\emptyset = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3 + \beta_{12} \cdot X_1X_2 + \beta_{13} \cdot X_1X_3 + \beta_{23} \cdot X_2X_3 + \beta_{123} \cdot X_1X_2X_3, \quad (2)$$

then the parameters of models β_0, β_1, β_2, β_3, β_{12}, β_{13}, β_{23}, and β_{123} are called theoretical regression coefficients. Their values can only be statistically estimated on the basis of experimental results and through the regression coefficients b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, and b_{123} in the multiple regression equation (3). For the assumed linear regression model without interactions (interaction effect of factors), based on the results from Table 2, a regression model is obtained in coded values, Eqn. (3), and (4), and in natural values by equation (5). For the assumed linear regression model with interactions, a regression model in coded values is given by equation (6), or in natural values by equation (7).

$$y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_{12} \cdot x_1x_2 + b_{13} \cdot x_1x_3 + b_{23} \cdot x_2x_3 + b_{123} \cdot x_1x_2x_3, \quad (3)$$

$$y = 360.28 - 0.831 \cdot x_1 + 153.31 \cdot x_2 + 165.7 \cdot x_3, \quad (4)$$

$$F = -225.12 - 0.0026 \cdot n + 2085.85 \cdot f + 331.4 \cdot d. \quad (5)$$

$$\begin{aligned} y = 360.28 - 0.831 \cdot x_1 + 153.31 \cdot x_2 + 165.7 \cdot x_3 - 14.71 \cdot x_1x_2 - \\ -6.8 \cdot x_1x_3 + 71.05 \cdot x_2x_3 - 17.33 \cdot x_1x_2x_3 \end{aligned} \quad (6)$$

$$\begin{aligned} F = 46 - 0.0026 \cdot n - 341.93 \cdot f + 14.125 \cdot \mathrm{d} + 0.841 \cdot n \cdot f + \\ +0.137 \cdot n \cdot d + 2792.25 \cdot f \cdot d - 1.46 \cdot n \cdot f \cdot d \end{aligned} \quad (7)$$

Statistical analysis, i.e. regression analysis, and analysis of variance was conducted using Minitab software. Graphical interpretation of individual factors and their interactions influence the overall cutting force is shown in Figure 5. The analysis of the significance of the influence of individual factors showed, as the diagram in Figure 5 clearly shows, that the feed, *f,* depth of cut, *d,* and their induction significantly affect the overall cutting force. All other factors can be excluded from the model (7) so that it can finally be written by equation (8).

$$F = 46 - 341.93 \cdot f + 14.125 \cdot d + 2792.25 \cdot f \cdot d. \quad (8)$$

The metal cutting process is a process that has the following physical and production characteristics from a power consumption and productivity point of view. The cross-section of the chip is the product of the feed, *f*, mmprev, and the depth of cut, *d*, mm, and is equal to $A = f \cdot d$, mm^2. The product of this area and the cutting speed *v*, mpmin, gives the material.

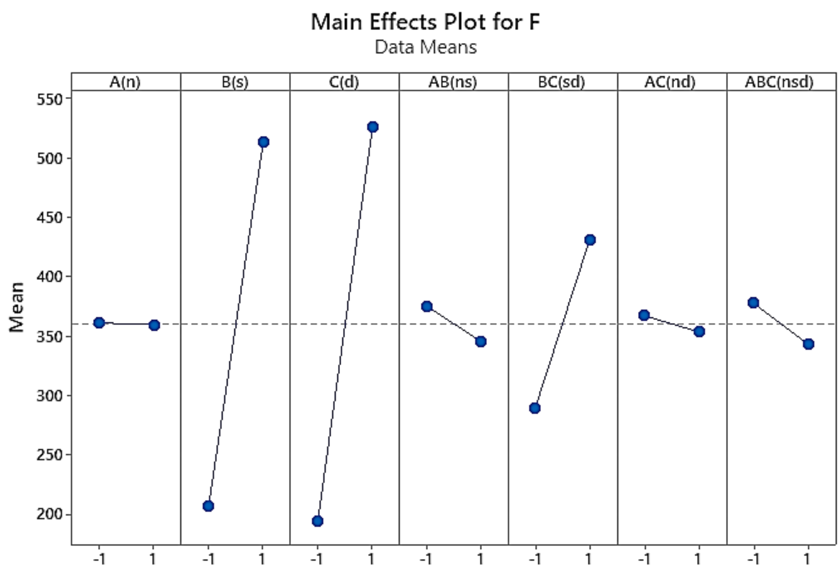

Figure 5. Main Effects Plot for the magnitude of the overall cutting force F

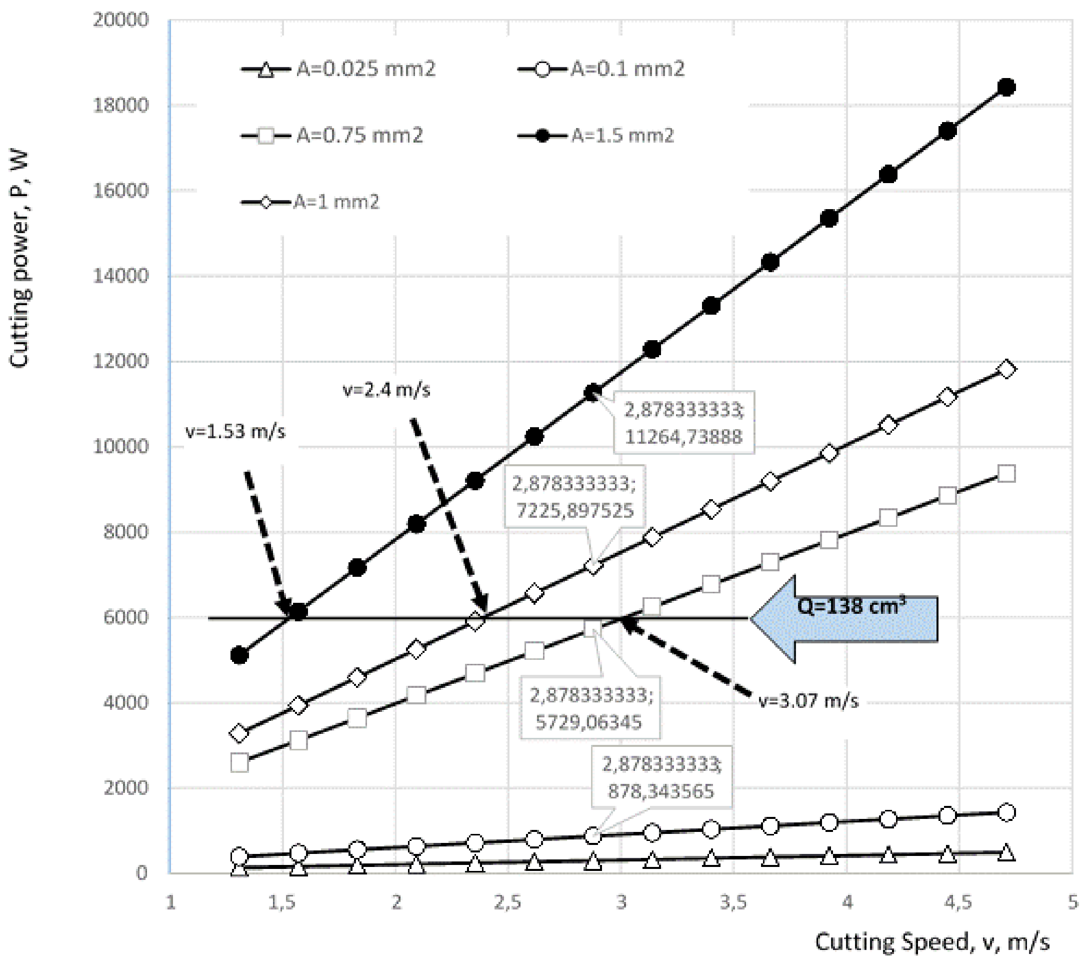

Figure 6. Relationship between cutting power and cutting speed for a different cross-section of the chip and productivity

removal in a unit of time (MRR, material removal rate) or, in short, productivity, i.e. $Q = A \cdot v$, mm^{3}pmin. On the other hand, the cutting power is equal to the product of the total cutting force F, N, and the cutting speed, v, mpmin, i.e. $P = F \cdot v$, W.

Analysis of power consumption and productivity of the cutting process in terms of achieving sustainable manufacturing, expression (8) will be used. This refers to the integrated elements of sustainable manufacturing shown in Figure 1. It is clear that the analysis of power consumption and productivity refers to the element "process", Figure 1. For a constant workpiece diameter D = 100 mm, Figure 6 shows the lines of constant cross-section area; from A = 0.025 mm^2 to A = 1.5 mm^2. Furthermore, for different cutting speeds, different productivity of manufacturing processes are obtained (Material removal rate, MRR), which ultimately gives different cutting powers, Figure 6. The goal is to power saving and thus bring the cutting process to the level of sustainable manufacturing.

From the diagram in Figure 6, it is clear that power can be saved with machining conditions that give a smaller cross-section of the chip. For example, for a cutting speed of 2.88 mpsec for the largest value of chip cross-section, a maximum cutting power of 11264 W is required. However, the power-saving calculation can be done as follows. Reducing the cross-section of the chip reduces productivity, but significantly reduces power. Thus, for the smallest value of chip cross-section A = 0.1 mm^2, this power is only 878 W, and for the value A = 0.025 mm^2, the power is even lower and amounts to only 304 W. With the appropriate calculation of the required machining time, the optimal cutting power can be achieved.

Also, the following analysis can be performed in another way, and thus the calculation. For constant productivity, for example, Q = 130 cm^{3}pmin, for the same cutting power of P = 6000 W, machining can be performed with different cutting speeds from v = 1.53 mpsec to v = 3.07 mpsec. The corresponding values of the chip cross-section are reduced from A = 1.5 mm^2 to A = 0.75 mm^2. A higher value can be adopted for rough machining and a lower value for finish machining. The cost of tools is also introduced into the analysis. Namely, it is a known fact that the tool life and the cutting speed are inversely proportional. As the speed increases, the cost of the tool increases, but the machining takes less time.

4. CONCLUSION

Based on the conducted research, the following conclusions can be made:

- One of the ways to approach the concept of sustainable production is energy savings, which can be implemented in several ways. In the paper, this is shown in the example of a turning operation.
- This paper presents an example of how an experimental measure of the cutting force can lead to a mathematical model of the dependence of the overall cutting force on the machining conditions (cutting speed, feed, and depth of cut). The obtained mathematical model can be used to calculate cutting power control (saving) and productivity calculation.
- Optimal solutions must include the calculation of cutting power consumption savings.

Conflicts of Interest

The authors declare no conflict of interest.

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