INVESTIGATION OF THE INFLUENCES ON ENERGY CONSUMPTION DURING TURNING AND ITS MODELLING

Ilgar Abbasov[1], Rezo Aliyev[2], Arastun Mammadov[3], Mahabbat Suleymanov[1], Huseyn Mammadov[1]

•

[1]Brandenburg University of Technology Cottbus-Senftenberg, Platz der deutschen Einheit 1, 03046 Cottbus, Germany.
[2]TU Bergakademie Freiberg, Agricolastrasse 1,09599 Freiberg, Germany
[3]Azerbaijan Technical University, Huseyn Cavid pr.25, Baku, AZ1073
Ilgar.Abbasov@b-tu.de, rezo.aliyev@imkf.tu-freiberg.de, arastun.mammadov@aztu.edu.az
Mahabbat.Suleymanov@b-tu.de, huseyn.mammadov@b-tu.de

Abstract

This article examines the interrelationships between technological parameters, including cutting speed, feed rate, and depth of cut, and their influence on average power consumption. A statistical design of experiments was employed with the objective of developing a model that would enable a quantitative and qualitative description of the interactions in question. The insights yielded by these analyses facilitate the optimisation of energy consumption during the turning process, thereby reducing the environmental impact of the manufacturing process. In order to identify the optimal process parameters, preliminary experiments were conducted under three distinct conditions: dry, coolant lubricants, and idle. Furthermore, restrictions were defined with regard to rough and finish turning. At the same time the study examines the influence of minimum quantity lubrication on energy consumption, thus providing further insights into the domain of energy-efficient machining.

Keywords: energy efficient, turning, cutting parameter, restriction, design of experiments, coolant lubricants.

I. Introduction

Optimizing energy consumption in the engineering industry, as in other advanced manufacturing fields, is one of the important issues for increasing productivity and efficient use of resources. So far, various studies have been conducted to measure the effect of various parameters—for example, cutting speed, feed rate, and material removal rate—on energy consumption [1,2,3,4].

In order to develop effective strategies for improving energy efficiency, it is necessary to take a differentiated look at the interactions between the various process parameters and energy consumption. It is only through a comprehensive understanding of the interrelationships that targeted optimisation measures can be derived, which help to minimise energy consumption and enhance the sustainability of the turning process. It is of the utmost importance to adopt a systematic approach to the analysis of process parameters. It is well known in industry that the same process results can be achieved with different energy consumption [5]. This is made possible by varying process parameters and components. In order to successfully implement this constellation, it is necessary to employ an energy-based process model. Nevertheless, the construction of an analytical model is a challenging endeavour, due to the multitude of systematic and random factors that exert influence. A practical solution to this problem is to use statistical experimental design methods. These methods make it possible to mathematically describe the relationship between the input and output variables of the process. Complex relationships between process parameters and energy consumption can be modelled using polynomials [6,7]. In this way, optimum constellations of process parameters can be identified in order to achieve the desired process results while minimising energy consumption.

The influences of different cooling lubricants on energy consumption were also investigated as part of this work. Although cooling lubricants fulfil important functions with regard to improving tribological phenomena in the cutting zone, they do not always lead to optimum results in terms of energy consumption [8].

II. Experimental setup and equipment description

The experimental investigations were conducted using a CTX 310 ecoline lathe from DMG Mori (Fig. 1). The DMG Mori CTX 310 ecoline is a computer numerical control (CNC) lathe that has been designed with the objective of facilitating precise and efficient turning operations. The machine is distinguished by its versatility, accuracy and reliability, rendering it suitable for processing a diverse range of workpieces within the manufacturing industry. The machine is equipped with a turret head, which enables the rapid and precise modification of the tools in use, thereby facilitating the overall process and allowing for greater efficiency. In addition, the CTX 310 ecoline offers options such as driven tools, programmable tailstock functions and advanced control to meet the needs of a wide range of turning operations.

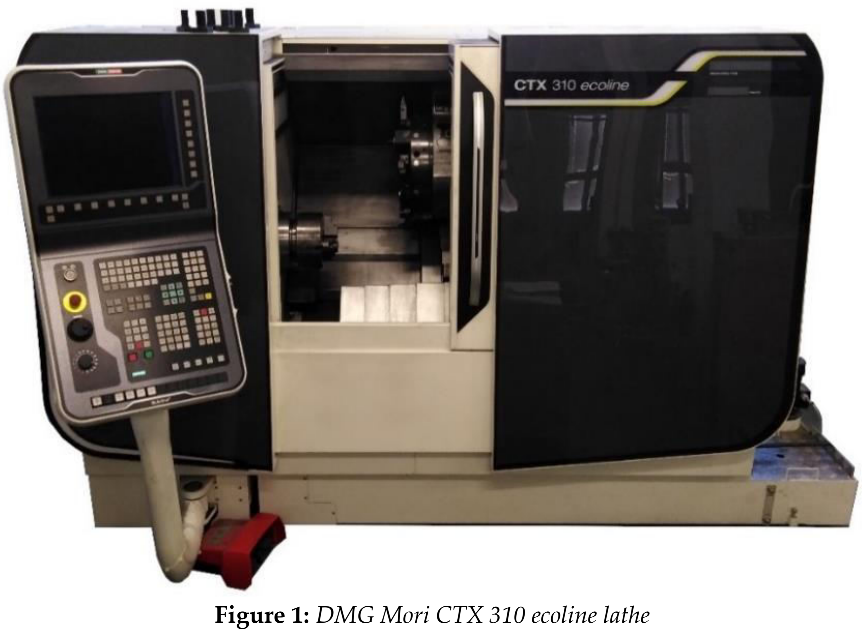

Figure 1: *DMG Mori CTX 310 ecoline lathe*

Fluke 434 Series II instrument was utilised for the purpose of measuring power. In accordance with the instructions provided, the Fluke 434 power quality analyser was connected to the three live conductors and the neutral conductor. These conductors and the neutral conductor supply power to the machine tool from the power grid. In order to facilitate the downloading and subsequent analysis of the data obtained from the Fluke 434 power quality analyser, the Power-Log software was employed as the appropriate tool for this purpose, given its suitability for the task.

III. Influence of cooling lubricants on energy requirements

Figure 2. illustrates the effects of various cooling lubricants on the average power. There are only minor differences among the cooling lubricants in terms of their impact on the average power. This suggests that the performance of the lubricants in preventing wear and adhesion may be similar.

Since there are only very small differences between these cooling lubricants, OZ 33 CBF was selected for comparison with dry machining due to its physical and chemical properties such as pH value, corrosion protection, and biocompatibility (Figure 3).

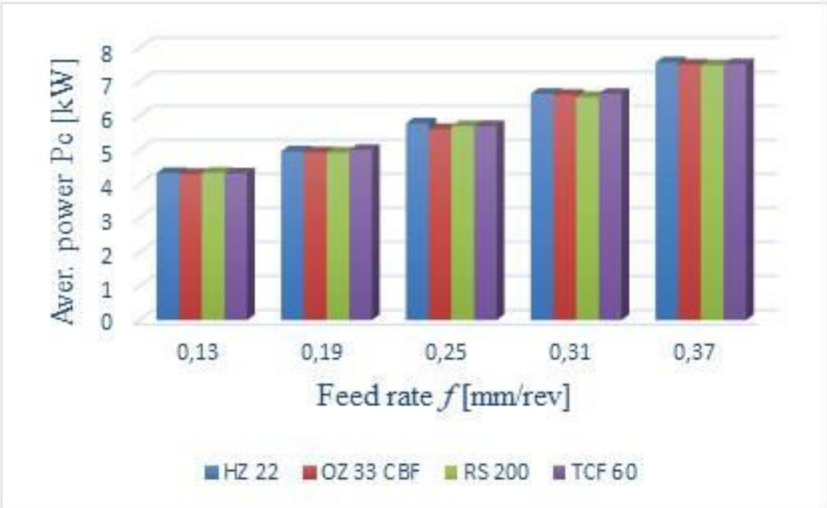

Figure 2: *The effect of feed rate on the average power at a cutting speed of V_c=200 m/min and a depth of cut a_p=2 mm in various coolants lubricants*

The observation from the experiments revealed that there was no significant difference in the average power between the use of cooling lubricants and dry machining (Figure 3).

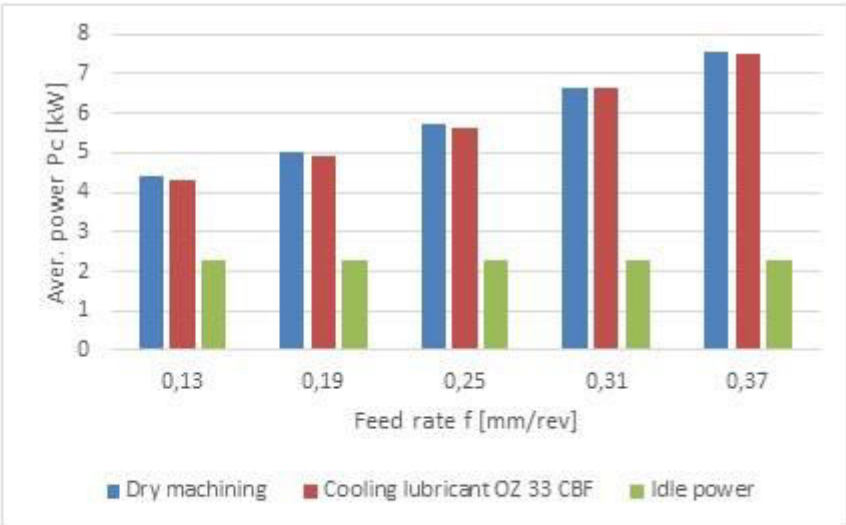

Figure 3: *The influence of feed rate on the average power at a cutting speed V_c=200 m/min and a depth of cut a_p=2 mm in dry machining, cooling lubricant and idle power*

In addition, there are very slight changes in the average idle power (no load power) when the cutting parameters change. Pumps for minimum quantity lubrication (MQL) systems typically require electrical energy to deliver and spray the lubricant into the cutting zone. The operation of pumps can therefore lead to additional energy consumption, impacting overall operating costs and environmental performance. In the experiments conducted, one liter of cooling lubricant costs nearly €18, making it relatively expensive. During the trials, the flow rate of cooling lubricants was also measured (Figure 4). In total, almost 1000 ml/s of cooling lubricant was used in each experiment. Typically, with minimum quantity lubrication (MQL), less than 50 ml of lubricant is used per hour, representing a significantly reduced amount compared to conventional methods such as flood cooling or spray cooling [9]. After each experiment, traces of cooling lubricant appeared on the tool and workpiece.

In conclusion, the minimum quantity lubrication (MQL) device may not be suitable for the MQL task, as the amount of cooling lubricant used significantly exceeded the typical value. The results also show that there was no significant difference between the use of cooling lubricants and dry machining. This suggests that, in this case, the minimum quantity lubrication was not effective and may not have provided the intended benefits.

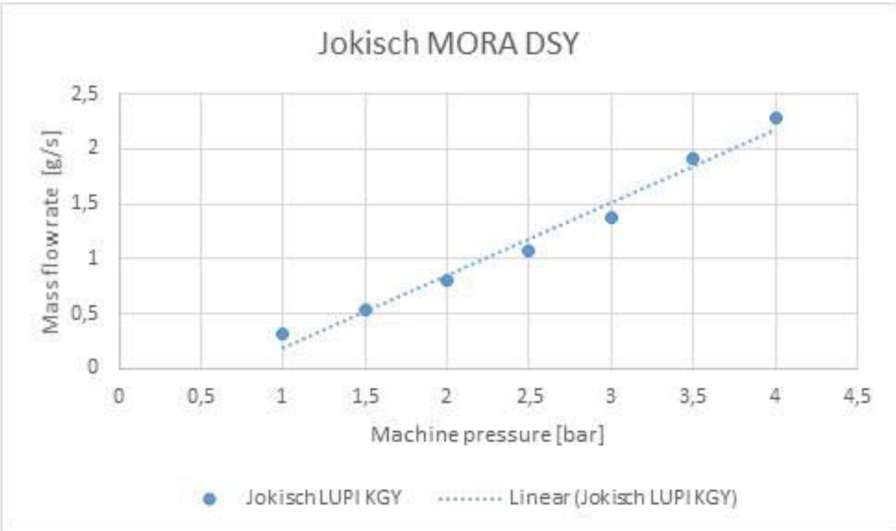

Figure 4: *Determination of the flow rate of cooling lubricants (OZ 33 CBF Jokisch)*

IV. Experimental design and methodology

Due to the non-linear nature of the parameter influences, employing a second-degree model is essential for accurate analysis. To achieve precise and reliable insights into the relationships defined in the statistical experiment design, centralized approaches such as the Central Composite Design (CCD plan) are recommended. This method offers a balance between efficiency and accuracy by requiring a limited number of test points while enabling clear and straightforward calculations to interpret the results effectively. These features contribute to its widespread adoption as a preferred second-order planning method [6,7,10]. The cutting parameter and other conditions values applied during the experiments are detailed in Table 1. The experimental design includes eight factorial points, six axial points, and ten center points. To assess the consistency and reliability of the process, repeated trials were conducted at the center points, ensuring robust conclusions regarding process stability.

Influencing variable		Dimension	-a	-1	0	+1	+a
1	Feed rate f	mm	0,0785	0,1	0,2	0,3	0,3215
2	Cutting speed V_c	mm	140,33	150	195	240	249,675
3	Depth of cut a_p	mm	1,34	1,5	2,25	3	3,16

V. Determination of restrictions for roughing

The process parameters in roughing are limited by machine and tool parameters. Roughing in machining is the process of removing large amounts of material from a workpiece in preparation for semi-finishing and finishing operations. High feed rates and large depths of cut are used to remove the excess material as quickly and efficiently as possible. On the other hand, as the feed rate and depth of cut increase, the mechanical load on the insert and the required power $P_c$increase. These process parameters are limited by the machine parameters. Therefore, power is one of the most important parameters for limiting the work value range.

When machining steel with an indexable insert, the maximum possible feed rate given by the technical limits of the machine tool can be utilized. Therefore, the technically maximum permissible cutting depths and cutting speeds were adopted to carry out the roughing process. Figure 5 shows a graphical representation of the restrictions when roughing with indexable inserts on the machine tool to determine the cutting parameters.

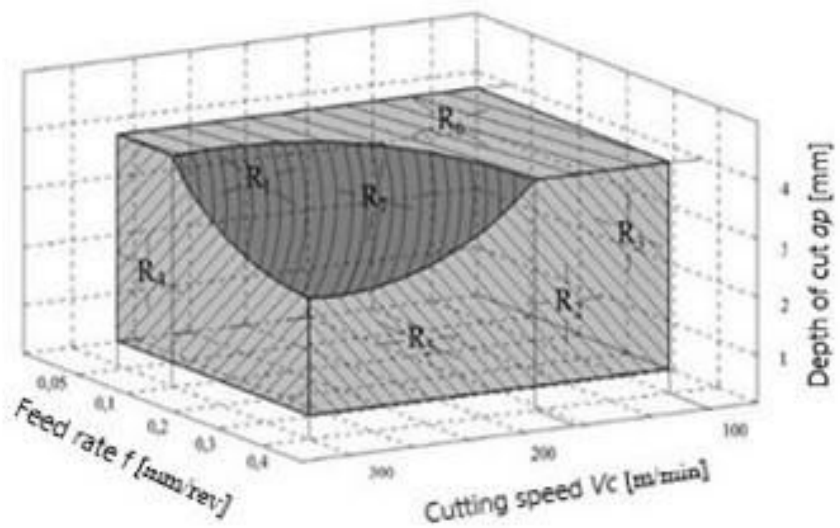

Figure 5: *Solution space for roughing with power restriction (P_c= 11 kW)*
The restrictions of the solution space presented here are determined according to the maximum possible parameter values: feed rate, depth of cut and cutting speed (Table 2)

Table 2: *Restrictions for roughing*

Restriction system		
Feed rate	$R_1: f \geq 0{,}05\ mm/rev$	$R_2 : f \leq 0{,}4\ mm/rev$
Cutting speed	$R_3: V_c \geq 100\ m/min$	$R_4 : V_c \leq 0{,}4\ mm/rev$
Depth of cut	$R_5: a_p \geq 1\ mm$	$R_6 : a_p \leq 4\ mm$
Power	$R_7: f \cdot a_p \cdot V_c \leq (P_c \cdot 60000/k_c)$	

VI. Determination of restrictions for finishing

In the context of finish turning, permissible surface roughness is typically specified alongside limits for positional deviations of the workpiece. The working value limits, which must ensure the permissible roughness of the workpiece surface, already achieve satisfactory accuracy when the influence of the secondary cutting edge and the minimum chip thickness are taken into account [10, 11]. The primary cause of surface roughness lies in the imprint of the cutting edge or adjacent parts of the cutting edge on the workpiece surface. From this, geometric relationships can be derived, which are primarily dependent on the feed rate. In finishing operations, low feed rates are used to match the surface's form deviation. Regarding surface quality, the roughness limits of the feed rate must be considered during process optimization. The restriction on roughness in the feed direction can be derived based on geometric relationships [10].

The restriction of the feed rate is determined by the permissible roughness depth of the required workpiece surface. According to BAUER, the boundary equation for machining provides a good approximation for this purpose [11]:

$$f \leq \sqrt{8 \cdot r_\varepsilon \cdot R_{th}} \tag{1}$$

Here r_ε – is tool corner radius, which influences the surface finish and cutting stability and R_{th} is allowable surface roughness threshold, which defines the maximum roughness acceptable for the machined surface. The roughness restriction (Eq. 1) limits the solution space for optimal parameters. Figure 6 illustrates this using the example of machining with tool having r_ε = 0,4 mm and R_{th} = 0,02 mm. The calculation of the feed rate according to Eq. (1) results in a value of ffinish = 0,25 mm.

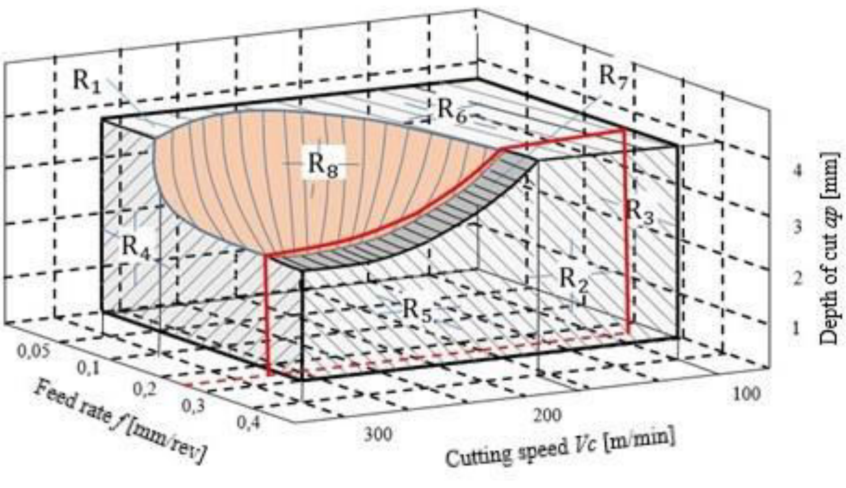

Figure 6: *Solution space for finishing with roughness restriction (red line)*

In this solution space, the relationship between the optimal feed rate and other machining parameters is shown to achieve the desired surface quality. The graphical representation of the solution space, based on previous systematic investigations, provides a visual depiction of potential settings and aids in selecting optimal parameters for the finishing process.

Another restriction in finishing is the deformation of the component. This requires defining the solution space in the optimization model while considering the permissible deflection of the workpiece. When machining workpieces with low stiffness, high cutting parameters can lead to elastic deformations, as these workpieces tend to deform more under load compared to stiffer ones. High cutting forces, particularly at high feed rates and/or cutting depths, can significantly increase the deformations, affecting the dimensional accuracy and surface quality of the machined part [10]. Using Eqs. (2), the restrictions due to elastic deformation of workpieces can be derived [10]:

$$f \leq \sqrt[1-m]{\frac{\Delta \cdot (\sin\gamma)^m \cdot 3E \cdot I}{a_p \cdot k_{c1.1} \cdot l^3}} \quad (2)$$

Here E – modulus of elasticity of the material, reflecting stiffness and I is moment of inertia of the workpiece cross-section, indicating resistance to bending. Besides that l is length of the workpiece and $k_{c1.1}$ is specific cutting force, often used to describe material resistance to cutting.

To keep deviations during finishing within the permissible range, the deflection of the shaft, which can lead to a form deviation, must be calculated. Since the feed rate is fixed, the deflection is calculated for various combinations of cutting depth and cutting speed according to Equation 2 and is presented in Figure 7.

As demonstrated in Figure 7, the deviations are less than 0.018 mm, which can be attributed to the high rigidity of the workpiece. This value is within the tolerance range for turning operations. Consequently, the restriction concerning positional deviation cannot be considered when searching for optimal cutting parameters in the examined case. However, this does not exclude its influence on process optimization. For machining less stable workpieces, considering this restriction is essential.

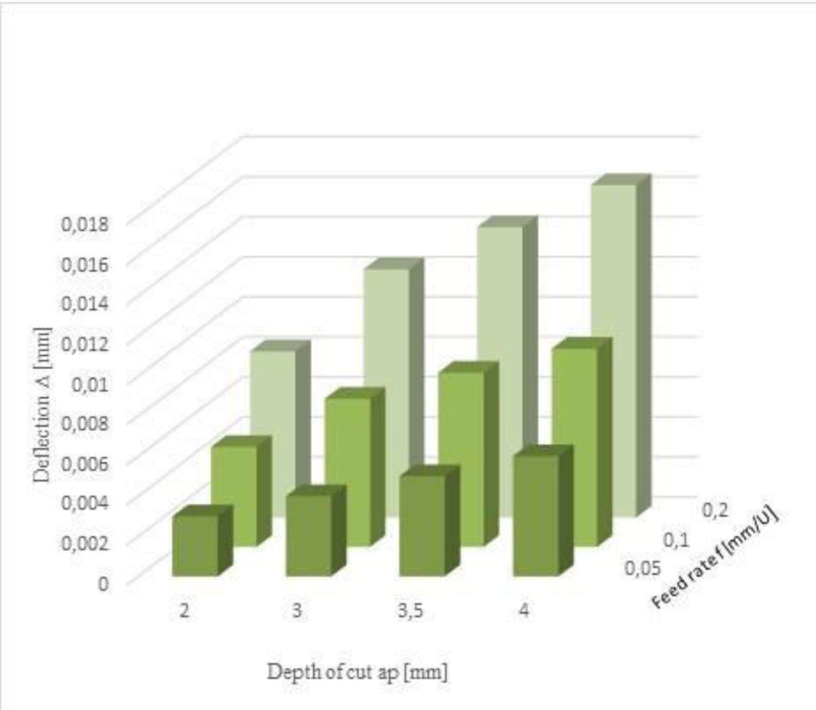

Figure 7: *Strength-related restriction of the feed rate*

Technological influences on power consumption

Using statistical experimental design, a model was created that describes the relationship between average power and the process parameters f, V_c and a_p in both numerical and analytical terms.

MODELL: $y = 0{,}89 - 20{,}04 \cdot f - 4{,}24 \cdot a_p + 0{,}0474 \cdot V_c + 8{,}533 \cdot f \cdot a_p + 0{,}08 \cdot f \cdot V_c + 0{,}0083 \cdot a_p \cdot V_c + 0{,}604 \cdot {a_p}_2^2 - 0{,}000158 \cdot {V_c}_2^2$

The significance of this polynomial is highlighted by displaying the results of the y-model as a response surface. The results show that the main quantitative factor influencing the average power is the cutting speed and its interaction with the feed rate and depth of cut [12]. Additionally, the required average power and other key optimization parameters, such as cutting speed, play a critical role in determining processing time. For this reason, it is essential to ensure that these parameters are carefully optimized and kept within an ideal range to achieve efficient machining while maintaining desired performance outcomes.

VII. Conclusions

The study investigates the impact of technological and non-technological factors on the energy consumption in machining processes, focusing specifically on turning operations. A comprehensive methodology was developed to quantitatively and qualitatively evaluate these influencing factors. Experimental verification was conducted to measure the effect of individual input parameters on process outcomes, laying the foundation for identifying technological and technical constraints within the machining system. Using statistical experimental design, systematic data collection facilitated the development of mathematical models that elucidate the relationship between process parameters and average power consumption. This approach ensures a robust understanding of parameter influence, enabling targeted optimization of the turning process for improved energy efficiency and reduced manufacturing costs.

Besides that the experiments revealed no significant differences in average power between the use of cooling lubricants and dry machining, indicating that the cooling lubricants tested offered no substantial advantage in this case. Furthermore, the minimum quantity lubrication (MQL) system used excessive amounts of lubricant, far exceeding typical values, which undermines its effectiveness and cost-efficiency. These findings suggest that MQL was not suitable for the task and did not deliver the expected benefits.

References

[1] Zhang, Y.; Liu, Q.; Zhou, Y.; Ying, B.: Integrated optimization of cutting parameters and scheduling for reducing carbon emissions. J Clean Prod 149, 886-895. (2017)

[2] Qianqian, Z.; Renzhong, T.; Tao, P.: Decision rules for energy consumption minimization during material removal process in turning. Journal of Cleaner Production 140, 1819-1827, Elsevier, (2017)

[3] Kant, G.; Sangwan, K.S.: Prediction and optimization of machining parameters for minimizing power consumptions and surface roughness in machining. J.Clean. Prod. 83, 151-164, (2014)

[4] Camposeco-Negrete, C.: Optimization of cutting parameters for minimizing energy consumption in turning of AISI 6061 T6 using Taguchi methodology and ANOVA. K. Clean. Prod. 53, 195-203. (2013)

[5] Aliyev R., Hentschel B.: HSC – Fräsen von stäubenden Werkstoffen. Strategien zur Auslegung von Prozess und Komponenten. ISBN 978-3-662-63692-3. https:/doi.org/10.1007/978-3-662-63693-0. Springer Vieweg Berlin, Heidelberg, (2021)

[6] Siebertz, K.; Bebber, D.V.;Hochkirchen, T.: “Statistische Versuchsplanung”, 2. Auflage,

Achen: Springer Vieweg, (2017)

[7] E. Scheffler.: "Einführung in die Praxis der statistischen Versuchsplanung", VLN 152-915/49/74, (1974)

[8] Jersak, J.; Simon, S.: Influence of cooling lubricants on the surface roughness and energy efficiency of the cutting machine tools. Int. J. of Applied Mechanics and Engineering, vol 22, No.3, S.779-787, DOI: 10.1515. (2017)

[9] Ramazan, H.N.; Sadık, E.K.; Bahram, L.S.: Investigation of the effect of minimum quantity lubrication technique on cutting forces in rough machining of Ti-6Al-4V alloy. Machine design and manufacturing magazine, Volume 17, Issue 2, (2020)

[10] Jacobs, H.J.: Spanungsoptimierung. VEB Verlag Technik Berlin. (1977)

[11] Jacobs, H.J.; Dürr, H.: Entwicklung und Gestaltung von Fertigungsprozessen. Planung und Streuung der spanenden Teilefertigung. Fachbuchverlag Leipzig im Carl Hanser Verlag. (2002)

[12] Abbasov I.; Suleymanov I.; Mammadov A.: Modelling of turning process for prediction of energy consumption. Key Engineering Materials, ISSN: 1662-9795, Vol. 979, 19-25 (2024)