ISSN 2831-1434

Journal homepage: https://jem.fpm.ues.rs.ba/index.php/journal

Journal of Engineering and Management

Volume 2 / No 1 / March 2024 / 1 - 7

UDK 621.311.22:66.012.3

DOI http://dx.doi.org./10.7251/JEM2402001S

Original Research Paper

Modelling and optimisation of power consumption and productivity in milling of thin-walled parts

Modelovanje i optimizacija potrošnje energije i produktivnosti u glodanju tankozidnih dijelova

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Abstract: *A high percentage of mechanical parts in the metalworking industry (automotive, medical, energetic sector, and etc.), refers to thin-walled structures with optimized shapes and dimension, which produce on high or semi batch production principle. Production processes management, in mentioned industry and production systems, requires the development of appropriate information technologies based automatic systems. Planning and control systems are based on computer-aided technologies. Basis of this system are mathematical-logical models commonly, which is quantitatively link between input process parameters and process performance indicators (output parameters). In this study, modelling of total power consumption and process productivity was performed. Total power consumption and the process productivity were modelled, as very important output indicators in efficient and sustainable production. The modelling is based on the experimental analysis of the machining process during machining of thin-walled parts made of C45E (AISI 1045) carbon steel. Modelling was performed using the least squares method, with the use of ANOVA statistical analysis for the purpose of defining the input factors significance. Depth of cut, milling width and feed per tooth were used as input cutting parameters. Input cutting parameters combined experimental analysed according to Taguchi experimental plan. Based on developed adequate and sufficiently accurate mathematical models, optimization procedure was performed. The goal of optimisation was to minimize the power consumption and maximise productivity.*

Key words: *milling, power consumption, modelling, optimisation*

Apstrakt: *Veliki procenat mehaničkih dijelova u metalskoj industriji (automobilskoj industriji, u medicini, energetskom sektoru, itd.) čine tankozidne strukture optimizovanih oblika i dimenzija, koje se proizvode po prinicpu visoke ili poluserijske proizvodnje. Upravljanje proizvodnim procesima u pomenutoj industriji i proizvodnim sistemima zahtijeva razvoj odgovarajućih informacionih tehnologija zasnovanih na automatizovanim sistemima. Sistemi planiranja i kontrole se zasnivaju na kompjuterski podržanim tehnologijama. Osnova tih sistema su obično matematičko-logički modeli koji predstavljaju kvantitativno izraženu vezu između ulaznih procesnih parametara i indikatora performansi procesa (izlazni parametri). U ovom istraživanju izvršeno je modelovanje ukupne potrošnje energije i produktivnosti procesa. Ukupna potrošnja energije i produktivnost procesa su modelovani kao veoma bitni izlazni indikatori efikasne potrošnje energije. Modelovanje je izvršeno eksperimentalnom analizom tokom procesa mašinske obrade tankozidnih dijelova napravljenih od C45E (AISI 1045) ugljeničnog čelika. Modelovanje je izvršeno metodom najmanjih kvadrata, korištenjem ANOVA statističke analize sa ciljem definisanja važnosti ulaznih faktora. Dubina rezanja, širina glodanja i korak su uzeti za ulazne parametre rezanja. Ulazni parametri rezanja su kombinovani sa eksperimentalnom analizom prema Taguchi eksperimentalnim planu. Na osnovu razvijenih odgovarajućih i dovoljno preciznih matematičkih modela, izvršena je optimizacija. Cilj optimizacije je bio minimiziranje potrošnje energije i maksimizacija produktivnosti.*

Ključne riječi: *glodanje, potrošnja energije, modelovanje, optimizacija*

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1 INTRODUCTION

Thin-walled parts with complex forms are widely present in almost all fields of the metalworking industry. Thin-walled structures are most often used for the production of housings parts, base support part for other elements in the assembly. Due to their complex geometry, they are technologically extremely complex. More problems comes in especially if structures are made by stronger and harder materials. The most common technologies for the production of thin-walled structures are: casting, printing, joining and cutting technologies [1]. Casting and joining technologies are used in case production of structures with non-functional surfaces. Cutting technologies used in case if there are complex or functional surfaces on the structures. Metal cutting is one of the most dominant production technologies, and very common used in the machining of thin-walled structures. However, the production of thin-walled structures by cutting technologies is performed by mechanical removing material by cutting tool from bulk parts, where up to 95% of the mass of the preparation must be removed [1, 2]. Regard to this, there are neediness to achieve high productivity. The power and energy invested in removing such a large amount of material contributes significantly to the final production cost, and product cost at least.

In order to establish a sustainable, manageable and highly efficient production, it is necessary to create a base for the development of a process planning system and process controlling system [3]. Today, production process planning and control systems are based on information technologies, which include CAx systems [3]. In CAPP and CAM systems, the knowledge databases are incorporated. This is base of efficient production processes. Mathematical-logical models, which describe the relations between input and output process parameters, are the basis of modern process control development, and raising the production efficiency. Based on them, it is possible to predict the behaviour of the machining system, optimize the process, and perform the necessary corrections of input process parameters.

The main problem is the establishment of efficient production of thin-walled parts, which includes achieve of high productivity and minimization of power consumption. In this study, the milling process of a thin-walled tubular part and made of carbon steel, is analysed. An experimental and statistical analysis was carried out, after which the process performance indicators were modelled. In [4] authors were presented method to compensate deformation errors in five-axis flank milling based on tool path optimization, in milling of thin-walled parts. The optimization of the milling process of thin-walled aluminum parts is presented in paper [5]. The study used experimental data and the influence of the tool path strategy, wall thickness and feed rate on the machining time, dimensional accuracy deviation, shape and position accuracy deviation, and surface roughness. Bolar et al. analysed energy efficiency, product quality, and productivity have become crucial requirements in thin-wall machining [6]. They examined the impact of axial depth of cut, radial depth of cut, feed per tooth, and tool diameter on process performance. In [7], authors presented optimization method for maximize the material removal rate in milling of thin-walled. Optimisation was based on cost function, and shown very effectively in optimum conclunding

2 EXPERIMENTAL SETUP

The experiment runs were performed on three-axis milling machining centre Emco Concept MILL 450 (Fig. 1). Maximum power is 11 kW, maximum main spindle speed is 11000, and linear axis motors has acceleration of 2 m/s². Machining centre is equipped with Sinumerik 810D/840D control unit, which programmed by using the SolidCAM software. For experimental machining runs, *Dormer* S814HA four teeth milling cutter is used, was used to machining the experimental samples. It is sintered carbide tool with *Alcrona* coating. The milling cutter diameter is d_c = 16 mm, body length is l_1 = 92 mm, active cutting length is l_2 = 32 mm. The tool mounted on overhang of l_3 = 40 mm, with an ER32 elastic chuck with an axial nut, adapted to ISO 40 tool holder.

Fig. 1. Experimental setup

Workpiece material is carbon steel C45E (Č.1530, DIN 17200, EN 10083). It has adequate wear resistance and strength. This structural steel can be used for the production of responsible parts in machines. It can be heat treated by hardening and annealing, and used in mould and die industry. Workpiece was tubular shaped, with basis for fixturing. Outer diameter is 40 mm, height is 40 mm, and wall thickness 1.5 mm (Fig. 2).

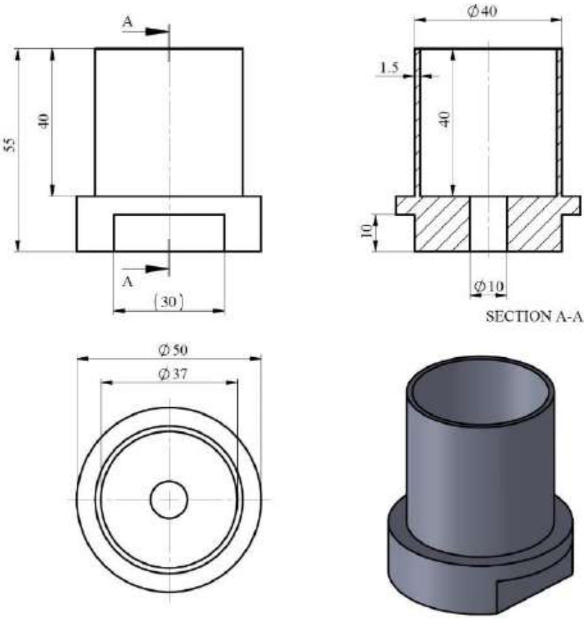

Fig. 2. Workpiece geometry

The measurement of tool machine and machining process power and energy consumption, and machining time was measured by Mavowatt 30 device. This three-phase device for measuring electrical energy meets the relevant standards for electrical energy measuring: EN50160, EN61000-4-7, and EN61000-4-15. It provides a visual display with RMS values, harmonic oscillations, flicker and transient processes up to a time range of 80 µs. The device is connected to the tool machine electrical lines by appropriate electrical instruction.

For experimental runs of cutting parameters combinations, Taguchi's orthogonal experimental plan L9 was used. This experimental plan contains nine combinations of cutting parameters variation. Input cutting parameters: P1 as depth of cut a_p (mm), P2 as feed per tooth f_z (mm/tooth), and P3 milling width *ae* (mm) were varied on three value levels (up level 1, middle level 0, and low level -1). Parameter level variation is given in Table 1, with experiments results. The cutting speed was constant on v_c = 120 m/min. Cooling and lubrication was performed by flooding technique. A synthetic water emulsion with content of 5% oil, was used fluid. It was supplied through two nozzles on outside of cutting tool, under pressure of 5 bar, and the flow rate of 40 l/min.

3 RESULTS AND DISCUSION

The Fig. 3 shows a diagram of power consumption during the machining time, which was taken from the interface of the software for measuring physical quantities related to electrical current consumption. The diagram shows the stages in the machining process, such as: tool changing, cooling turning, cutting tool entering, and the end of the machining. There can be noted the increase in electrical energy consumed during machining time.

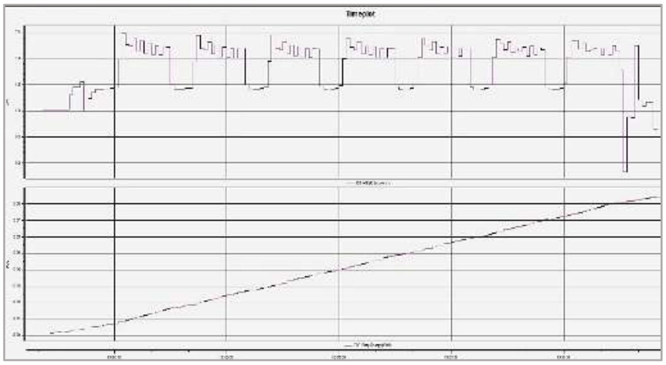

Fig. 3. Interface of energy measuring software

In Table 1 are given results of measured total power consumption of machining *P* (kW), as total power consumption of tool machine, and calculated material removal rate *MRR* (mm³/min) for experimental runs.

Table 1. Results of experiments

Exp	P1	P2	P3	a_p (mm)	f_z (mm/ tooth)	a_e (mm)	*MRR* (mm³/ min)	*P* (kW)
1	-1	-1	-1	2.0	0.06	0.5	573	1.54
2	-1	0	0	2.0	0.12	1.0	2292	1.66
3	-1	1	1	2.0	0.18	1.5	5157	1.82
4	0	-1	0	4.0	0.06	1.0	2292	1.69
5	0	0	1	4.0	0.12	1.5	6875	1.99
6	0	1	-1	4.0	0.18	0.5	3438	1.75
7	1	-1	1	6.0	0.06	1.5	5157	1.89
8	1	0	-1	6.0	0.12	0.5	3438	1.77
9	1	1	0	6.0	0.18	1.0	10313	2.20

Total power consumption values for different experimental run is shown on diagram in Fig. 4. It can be concluded that with increase of cutting parameters, the total power consumption increase also. The highest total power consumption value of P = 2.2 kW is obtained when using the cutting parameters a_p = 6.0 mm, f_z = 0.18 mm/tooth and a_e = 1.0 mm, while the lowest value of P = 1.54 kW is obtained with the cutting parameters a_p = 2.0 mm, f_z = 0.06 mm/tooth and a_e = 0.5 mm. Higher total power consumption values were obtained for larger depth of cuts and milling widths.

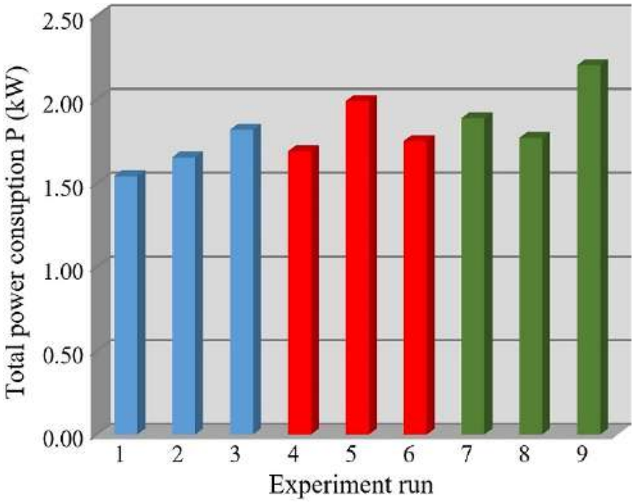

Fig. 4. Total power consumption values

Least square method was employed for modelling of total power consumption. For this procedure, the linear model with the interaction of two parameters versus to simple linear model (2FI vs Linear) were proposed and analysed. After the statistical analysis of model response and experimental obtained data by ANOVA, linear model with the interaction of two parameters was chosen. Based on the statistical indicators P and F values, it can be concluded that the model is significant. The values of the varied all cutting parameters have high influence on the total power consumption, which can be concluded from the obtained P values. It was shown that the combination of depth of cut and feed per tooth has the high impact on the total power consumption value also. There are calculated the Sum of squared deviations (SSD), and Mean square deviation (MSD) also.

Table 2. ANOVA results for P (kW)

Source	SSD	DoF	MSD	F value	P value
Model	0.3080	4	0.0770	349.5844	< 0.0001
a_p	0.1196	1	0.1196	542.9272	< 0.0001
f_z	0.0711	1	0.0711	322.7243	< 0.0001
a_e	0.1169	1	0.1169	530.9688	< 0.0001
a_p i f_z	0.0505	1	0.0505	229.4249	0.0001
Residue	0.0009	4	0.0002		
Total	0.3089	8			

The statistical calculation gave a mean total power consumption value of $\overline{x}$ = 1.81, with a standard deviation of *SD* = 0.015. The signal-to-noise ratio is *S/N* = 61.17, which is desirable because it is greater than 4. The regression coefficient is R^2 = 0.99, which shows a great agreement between the experimental measured and modelled calculated data. Based on the mentioned statistical indicators, it can be concluded that the proposed model is adequate. The proposed the linear mathematical model with parameter interaction, for total power consumption on various cutting parameters is concluded in form:

$$P = 1.528 - 0.072 \cdot a_p - 2.925 \cdot f_z + 0.355 \cdot a_e + 1.185 \cdot a_p \cdot f_z \qquad (1)$$

Fig. 4 shows the response surfaces, obtained by surface response method (RSM) for total power consumption, obtained on the basis of various cutting parameters from the its domain, and the previous presented formulation. From the diagram, it can be concluded that total power consumption increases with the increase of the value of the cutting parameters, which is expected. As the values of cutting parameters increase, the total power consumption value increases more intensively. Basically, the analysis of experimental and calculated data show that the influence of linear combinations of technological parameters is very significant on total power consumption model responses.

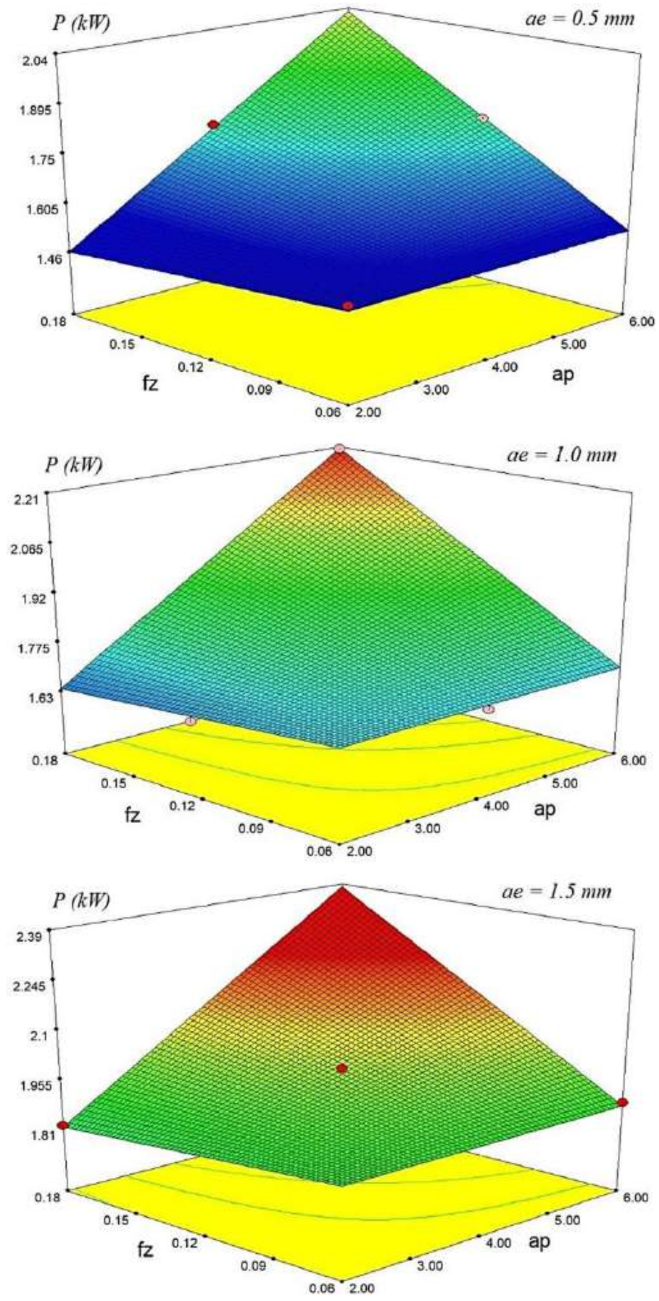

Fig. 5. Total power consumption model response

As process performance indicator, which evaluates the economic productivity the material removal rate *MRR* (mm³/min), was analysed. It is the amount of removed workpiece material in the unit of time. The relationships between the values of material removed ratio and cutting parameters are shown in the diagram in Fig. 6. The highest productivity value of *MRR* = 10313.2 mm³/min is obtained when using cutting parameters a_p = 6.0 mm, f_z = 0.18 mm/tooth and a_e = 1.0 mm. The lowest value is *MRR* = 573.0 mm³/min is obtained during machining with cutting parameters a_p = 2.0 mm, f_z = 0.06 mm/tooth and a_e = 0.5 mm. Greater productivity, i.e. material removal rate is achieved with an increase in cutting parameters.

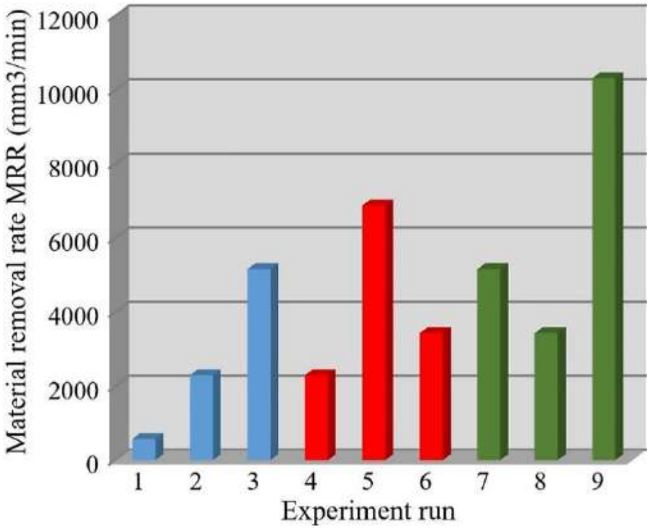

Fig. 6. Material removal rate values

In end milling operations, material removal rate can be calculated as the product of processing depth, milling width, and auxiliary movement speed (feed rate v_f) [2]. Feed rate v_f (mm/min) is product of feed per tooth f_z (mm/tooth), number of cutting tool teeth z_n, and spindle revolutions n (rev/min). However, material removal rate MRR (mm³/min) can be calculated as:

$$MRR = a_p \cdot a_p \cdot v_f = a_p \cdot a_p \cdot n \cdot f_z \cdot z_n \qquad (2)$$

After the formation of the material removal rate model, a variance analysis was conducted. Because material removal rate model is analytical, it is clear that the statistical analysis showed that the model is significant, and that the values of the varied cutting parameters and are equally significant. The mean value

$\bar{x}$= 4392 was obtained, and the standard deviation SD = 0.000. The signal-to-noise ratio is $S/N = 27$, and the regression coefficient is $R^2 = 1$. However, based on the mentioned values, it is concluded that the model is adequate. Using the surface response method, diagraph of material removal rate in dependence on cutting parameters, is obtained (Fig. 7).

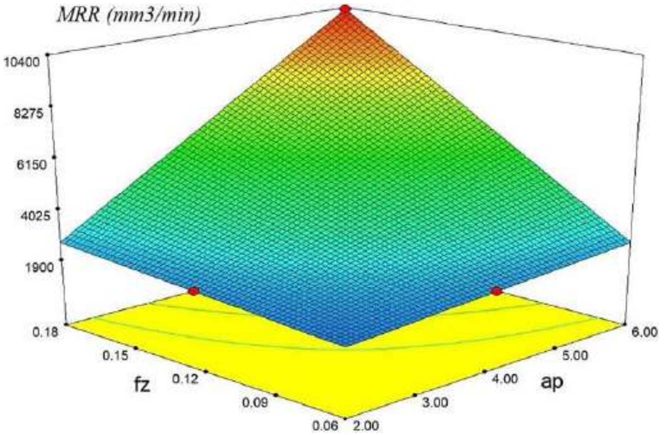

Fig. 7. Material removal rate model response

From the previous model response diagram, it can be concluded that productivity increases with increasing of cutting parameters values. As in the previous case, a more intense change of material removal rate occurs with input factor combinations with higher cutting parameter values.

3.1. Process optimization

In case of sustainable and high efficient machining, and rough machining especially, parameters related to power consumption and productivity are usually chosen as optimization functions. Rough machining of a cylindrical thin-walled workpieces, which is the subject of this research, it is necessary to mathematically describe the optimization procedure. According to previous, the objective functions are achive the maximum of process productivity, and the minimum of total power consumption. In table 3 is shown the mathematical framework of the optimization procedure. All outputs are assigned with the same importance. Also, the same importance is assigned to the domain boundaries of input and output input and output parameters.

Table 3. Optimisation framework

Param.	Target	Lower limit	Upper limit	Low weight	Up weight	Importance
a_p	In range	2	6	1	1	3
f_z	In range	0.06	0.18	1	1	3
a_e	In range	0.5	1.5	1	1	3
P	Min.	1.54	2.20	1	1	3
MRR	Max.	573	10313	1	1	3

The optimization procedure offered 198 possible solutions. As optimal cutting parameters were obtained: $a_p = 2.6$ mm, $f_z = 0.18$ mm/tooth, and $a_e = 1.37$ mm. This combination of this cutting parameters gives $MRR = 5087$ mm^3/min and $P = 1.86$ kW. There is concluded that desirability of the objective is relatively low and amounts 53%. The reason for this is the large number of opposite responses that are included in the optimization. The diagram of the change in the desirability of the optimisation solutions, depending on the depth of cut and feed per tooth, is given in Fig. 8. According to theory, when planning rough machining, higher values of cutting parameters should be used, which is exactly what the mentioned diagram shows. Furthermore, it can be concluded that only the combination of higher values of both cutting parameters leads to better results.

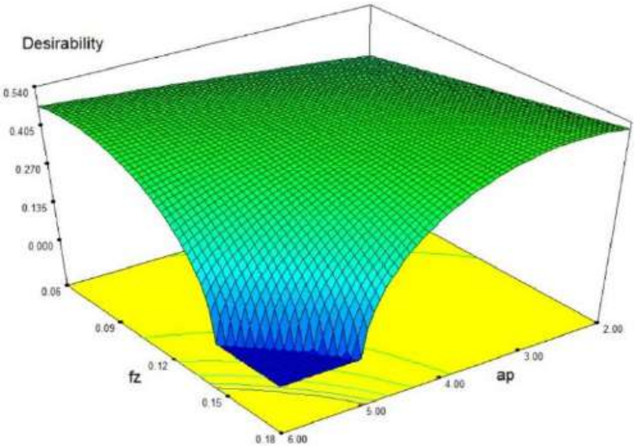

Fig. 8. Desirability of cutting parameters

4 CONCLUSIONS

In accordance with the requirements of modern sustainable and high-efficient machining, an experimental analysis of the milling process was carried out. Milling was performed on thin-walled parts made of carbon steel, according to Taguchi's experiment plan. Statistical analysis was performed on the obtained experimental data of total power consumption and process productivity. Based on the data, adequate mathematical models were developed. The analysis showed that increasing of total power consumption and material removal rate depending on the cutting parameters increasing. On the basis of adequate models, which can be incorporated into process control systems, process optimization was carried out. Total power consumption minimization and material removal rate maximization were set as optimization goals.

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