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Optimization of Cutting Parameters in High-Speed Milling of Hardened Alloy Steels SKD11 to Minimize Energy Consumption Based on PSO Algorithm

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***Abstract* – This paper focuses on evaluating the influence of cutting parameters on the energy consumption of CNC machines when high-speed rough milling (HSRM) of alloy steel SKD11 after heat treatment (55HRC). At the same time, the problem is to find the optimal cutting parameters to ensure the minimum energy consumption through the particle swarm algorithm (PSO). The conditional optimization problem is bound to limit the values for the variables and limit the objective function. The experiments are carried out based on the level 2 orthogonal experimental method. The regression equation describing the relationship between the cutting parameters and the energy consumption of the CNC machine is built based on the experimental results. The research results show the reliability of the regression equation and serve as the basis for the calculation of cost reduction when high-speed milling of alloy steel after heat treatment.**

***Keywords* – High Speed Milling, Alloy Steel, Energy Consumption, Optimization.**

I. INTRODUCTION

High-speed machining (HSM) is a metal cutting method with a cutting speed of 5 to 10 times that of conventional machining, the temperature at the cutting area will be reduced because it is transferred to the chip [1]. Compared with traditional machining, HSM has outstanding advantages. High-speed machining can reduce machining times by up to 50% and reduce machining costs by 30-50%, depending on the specific case [2].

In metalworking and cutting, processing hard materials in general and hard alloy steel, in particular, is always a difficult problem, complicated by physical phenomena of the cutting process as well as different processing requirements. Distinguished from HSM of aluminum, low and medium hardness alloys (below 30HRC), or traditional machining. The problem of HSM of hard alloys has been interested in research in the world for many years. Studies on cutting force can be considered in [3], [4], cutting temperature in [5], [6], vibration in [7], [8], cutting tool wear in [9], [10], roughness in [2], [11], [12].

The energy consumption in the machining process in general and high-speed machining in particular accounts for a significant part of the production cost, so it is necessary to be taken into account in evaluating the economy and improving the efficiency of the whole process. According to the 2014 the CO2 emissions report of the US energy agency [13], 90% of energy consumption is in industrial production. Therefore, industries in general and the field of mechanical manufacturing in particular need to be responsible for minimizing energy consumption. Many studies have shown that if the technological process can be optimized in the production stages, it is possible to reduce energy consumption from 6% to 40% compared to the present [14]. In fact, the wasted energy is mainly in the roughing step, the balance between machining productivity and energy consumption needs to be considered. In the finishing machining step, product quality is the core issue. Some studies on energy consumption in the machining process are mentioned below [15], [16], [17], [17], [19], [20], [21], [22], [23]. These works have not mentioned the problem of high-speed machining. Experimentally statistics the energy consumption of machining machines is performed in [15] and [22]. Statistical models are valuable for evaluating the efficiency of the machining process. The relationship between technological parameters, cutting environment and wasted energy when machining AISI P20 steel alloy is described in [16]. The influence of technological parameters on surface roughness and energy consumption is evaluated in [17] when machining AISI 1045 alloy steel based on Taguchi and ANOVA techniques. The energy consumption between different materials is mentioned in [18]. The technological parameters are studied in [19] for minimizing wasted energy and increasing tool life when machining Al and SiC alloys. The energy consumption when milling low-hardness alloys, taking into account the influence of the feed strategy is conducted in [20], [21], [24]. A parametric model of energy consumption when machining micro-drills is analyzed in [22]. Basically, the researches on energy consumption in the cutting process mentioned above have the processing objects of low hardness materials with conventional turning, milling and drilling methods. The field of the HSM for high-hardness materials has not been mentioned much.

There have been many studies on the problem of optimizing energy consumption on CNC machines as in [25-32]. However, these works only deal with low-hardness materials, not considering the HSM and hard alloys.

This paper focuses on research on optimizing the energy consumption when high-speed rough milling of alloy steel SKD11 after heat treatment with hardness above 55HRC. The relationship between shear parameters and energy consumption is shown through the construction of regression equations. Level 2 orthogonal empirical method is applied to build this mathematical equation. The swarm algorithm (PSO) is applied to find the optimal set of cutting parameters that minimize energy consumption.

II. Materials and Methods

A. *Experimental Design*

The experimental objective of HSFM of alloy steel SKD11 after heat treatment (55HRC) is to determine the relationship between cutting parameters (depth of cutting, feed rate, and spindle speed) in HSFM with energy consumption of CNC machine through the regression equation. This equation is built based on the level 2 orthogonal empirical method. The workpiece material is SKD11 (Japanese Standard JIS G4404) with the composition described in Table 1.

Table 1. Chemical composition of SKD11 alloy steel workpiece.

Ingredient	C (%)	Si (%)	Mn (%)	Cr (%)	Mo (%)	V (%)	P (%)
SKD11	1.4-1.6	≤0.6	≤0.6	11-13	0.7-1.2	≤1.1	≤0.03

SKD11 workpiece was heat-treated in the Turbo-IPSEN furnace and hardness measured on an FR-1E/Hard machine (Fig. 1). Hardness measurement results with the average value of SKD11 alloy steel workpiece after heat treatment reached 55 HRC.

Regarding machining machines, experiments were carried out on HSM machines DMC1450V manufactured in 2018. The maximum tool speed according to X, Y, Z reaches 42.000 mm/min, the spindle speed reaches the maximum of 20.000 rpm, the spindle power reaches 35 kW, the maximum load force on the X, Y, Z axes reached 6.5 KN. The maximum position accuracy reaches 6μm (According to VDI/DGQ 3441).

The cutting tool used for the experiment is a specialized high-speed carbide Endmill tool YG SGN09080H. The cutting tool code is NX5070 SGNF09080H, cutting diameter is 8mm, shank diameter is 8mm, cutting length is 20mm, total tool length is 65mm with 4 cutting teeth (Fig. 2).

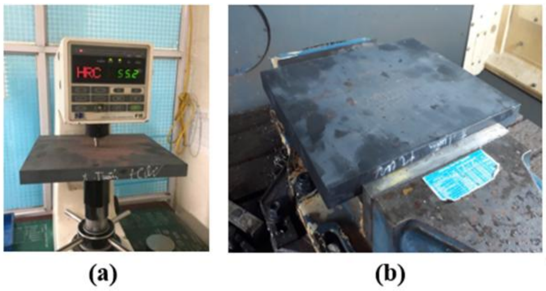

Fig. 1. FR-1E/Hard hardness tester and SKD11 55HRC work piece.

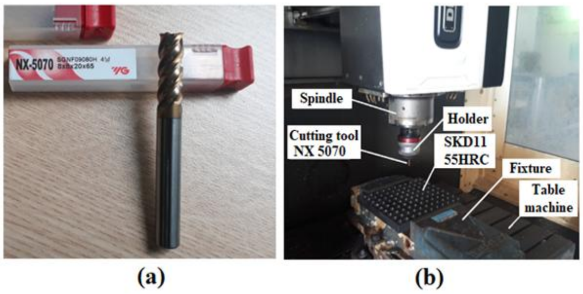

Fig. 2. Carbide Endmill tool YG SGN09080H and experimental model.

The energy consumed by the CNC machine during the machining process is determined indirectly through the power consumption of CNC machine respect to time. The power of the machine is determined based on measuring the effective voltage value and effective amperage of the CNC machine. Therefore, the energy measuring device used is the MAVOWATT 230 measurement system [33], the KAISE voltage measurement devices, and the EXTECH effective amperage [34] (Fig. 3). The diameter of the circular pocket before finishing is 21.8 mm. The required pocket diameter is 22mm. Pocket depth reaches 11mm.

Fig. 3. Energy measuring devices.

The level 2 orthogonal experimental method is a nonlinear planning method, the structure has a center [35]. The number of influencing factors is 3 factors (cutting depth, feed rate, and spindle speed or cutting speed), the stepover parameter is fixed. The total number of experiments to be performed is 15. The α quantity is the distance from the center of the experimental structure to the position of points on the coordinate axis of the structure. Conventional influencing factors according to the variables are as follows, cutting depth t(mm) is x_1, the feed rate F(mm/min) is x_2, spindle speed n(rev/min) is x_3. Note that the spindle speed can be related to the cutting speed ($V_c\,(m/min)$) through the calculation given below.

$$V_c = \frac{\pi D n}{1000} \tag{1}$$

where, D is the tool diameter, $n(rev/min)$ is the spindle speed.

B. *Perform Experiments*

Based on the study of previous publications on the HSM for different materials, different hardness, assessment of the machining ability of SKD11 with HRC55, the machining ability of CNC machines, the domain of cutting parameters recommended by the cutting tool manufacturer, and test machining results, the range of experimental cutting parameters value are specifically selected as shown in Table 2. The experimental matrix table is described in Fig. 4. Experiments from 16 to 19 were performed at the center of the experimental structure to evaluate the reliability of the regression equation and verify the calculated results.

C. *Collect Experimental Results*

The value of energy consumed is measured in the roughing machining. The energy consumption measurement results are presented in detail in Table 3.

Table 2. Limiting domain of cutting parameters value.

Cutting Parameter	t	F	V_c	n
Variables	x_1	x_2	x_3	x_3
Lower limit ($-\alpha$)	0.57	378.5	55	2188
Low (-1)	1	400	60.3	2400
Basic (0)	3	500	80.4	3200
High (+1)	5	600	100.5	4000
Upper limit (α)	5.43	621.5	105	4181

Table 3. Experimental results.

No	**I (A)**	**U (V)**	**Time (s)**	**E (KWh)**
1	4.06	410	142	0.0657
2	3.98	410	693	0.3140
3	4.34	410	212	0.1049
4	4.10	410	1037	0.4846
5	4.48	410	142	0.0725
6	3.81	410	693	0.3009
7	4.10	410	212	0.0990
8	4.30	410	1041	0.5096
9	3.41	410	170	0.0660
10	4.00	410	1491	0.6796
11	3.63	410	274	0.1131
12	4.01	410	447	0.2043
13	4.30	410	340	0.1663
14	4.09	410	340	0.1584

No	I (A)	U (V)	Time (s)	E (KWh)
15	3.81	410	340	0.1475
16	3.92	410	340	0.1519
17	3.80	410	340	0.1473
18	3.77	410	340	0.1458
19	3.78	410	340	0.1464
20	3.68	410	340	0.1424

No	X1	X2	X3
1	+	+	+
2	-	+	+
3	+	-	+
4	-	-	+
5	+	+	-
6	-	+	-
7	+	-	-
8	-	-	-
9	+alpha	0	0
10	-alpha	0	0
11	0	+alpha	0
12	0	-alpha	0
13	0	0	+alpha
14	0	0	-alpha
15	0	0	0

(a)

No	t (mm)	F(mm/min)	n (rev/min)
1	5	600	4000
2	1	600	4000
3	5	400	4000
4	1	400	4000
5	5	600	2400
6	1	600	2400
7	5	400	2400
8	1	400	2400
9	5.43	500	3200
10	0.57	500	3200
11	3	621.5	3200
12	3	378.5	3200
13	3	500	4181
14	3	500	2188
15	3	500	3200
16	3	500	3200
17	3	500	3200
18	3	500	3200
19	3	500	3200

(b)

Fig. 4. Experimental matrix table.

Based on the theory of orthogonal experimental planning at level 2 [35] and the experimental results in Table 3, the basic parameters for the construction of the regression equation are determined. The number of experiments in the center is $m = 4$ (values of experiments in the center are shown from hole 16 to hole 19). The number of degrees of freedom corresponding to the number of experiments in the center is $f = m - 1 = 3$. The confidence probability is 95%. The STUDENT [36] distribution criterion is $t(0.05,3) = 3.182446$. From calculating the coefficients of the regression equation, the standard deviations of these coefficients and comparing them with the STUDENT criterion, a mathematical equation that describes the relationship between cutting parameters and energy consumption in HSRM for alloy steel SKD11 after heat treatment is calculated and described as follows

$$E = 0.18743 - 0.18375x_1 - 0.050742x_2 + 0.0392x_1x_2 + 0.1162x_1^2 - 0.02873x_2^2 - 0.02626x_3^2 \quad (2)$$

To evaluate the reliability of the regression equation, calculate the compatible variance value of $S_{tt}^2 = 0.0029$, the recurrence variance value is $S_{th}^2 = 0.00008$, the calculated FISHER criterion is $F = 1.0467$, this value is much smaller than the value. The standard value corresponding to the 95% confidence level is $F_{0.05}(8;3) = 17.007$. Therefore, the regression equation ensures reliability. The regression equation reconstructed on the ANOVA module of DESIGN EXPERT 12 software also gives similar results (Fig. 5).

Change the variable back to the cutting parameters

$$x_1 = \frac{t - t_0}{\Delta t}; x_2 = \frac{F - F_0}{\Delta F}; x_3 = \frac{n - n_0}{\Delta n} \quad (3)$$

Where, t_0, F_0 and n_0 are the cutting parameters at the basic level. $\Delta t, \Delta F$ and Δn are the range of the cutting parameter variation. The regression equation is rewritten according to the cutting parameters as follows

$$E = 0.18743 - 0.18375\frac{(t-t_0)}{\Delta t} - 0.050742\frac{(F-F_0)}{\Delta F} + 0.0392\frac{(t-t_0)}{\Delta t}\frac{(F-F_0)}{\Delta F} + \\ +0.1162\left(\frac{(t-t_0)}{\Delta t}\right)^2 - 0.02873\left(\frac{(F-F_0)}{\Delta F}\right)^2 - 0.02626\left(\frac{(n-n_0)}{\Delta n}\right)^2 \quad (4)$$

where, $t_0 = 3; \Delta t = 2; F_0 = 500; \Delta F = 100; n_0 = 3200; \Delta n = 800$ and limited values: $0.57 \le t \le 5.43; 378.5 \le F \le 621.5; 2188 \le n \le 4181$.

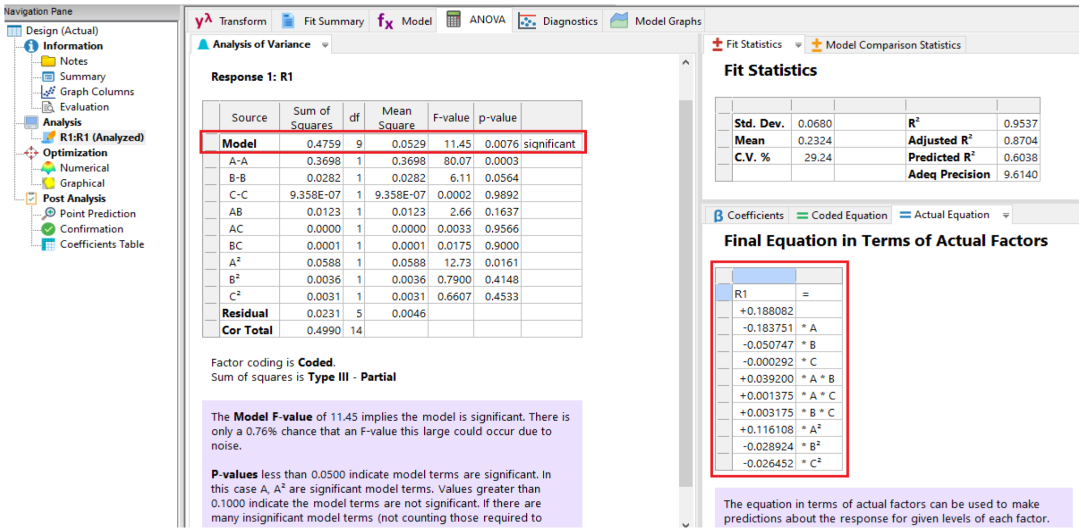

Fig. 5. Verification results on ANOVA/DESIGN EXPERT software.

D. *Optimization of Cutting Parameters*

Objective is necessary to find the optimal cutting parameters to ensure the minimum the energy consumption in the machining process with the allowable limit conditions corresponding to the machining capabilities of CNC machines and cutting tools. Boundary conditions are the limit values of variables. The algorithm is built on the basis of the following conditions $-1.215 \le x_1,\ x_2,\ x_3 \le 1.215;\ E > 0,$ respectively limit the technological parameters are given as $55 \le V_c \le 105\ (m/min)$, $2188 \le n \le 4181(rev/min)$; $375.5 \le F \le 621.5(mm/min)$ and $0.57 \le t \le 5.43(mm)$. The PSO algorithm [37], [38] is used and its parameters are described in Table 4.

Table 4. PSO parameters.

No	Parameters	Symbols	Value
1	Number of search loops	*MaxIt*	100
2	Initial particle swarm size	*npop*	100
3	The inertia coefficient	w	1
4	Acceleration coefficient for each individual	c_1	2
	Acceleration coefficient of the particle swarm	c_2	2

Optimal Results

The optimal calculation program is built on MATLAB software. The optimal value is found after the 7th iteration and the minimum energy value that can be achieved after is $Y_{NImin} = 0.005(KWh)$ at $x_1 = 0.5857$, $x_2 = 1.215$, $x_3 = -1.215$. These optimal values correspond to the cutting parameters are $t = 4.17(mm)$, $F = 621.5(mm/ph)$, $n = 2213(vg/ph)$ and $V_c = 55.6(m/ph)$.

E. *Results and Discussion*

Evaluation of the effect of depth of cut (*t*) and feed speed (*F*) (Fig. 6)

Corresponding to the optimal value is $x_3 = -1.215$, the energy consumption regression equation reflecting the influence of depth of cut and feed rate has the form as follows

$$E = 0.148753 - 0.18375x_1 - 0.050742x_2 + 0.0392x_1x_2 + 0.1162x_1^2 - 0.02873x_2^2 \quad (5)$$

Evaluation of the Effect of Depth of Cut (t) and Cutting Speed (V_c) (Fig. 7)

For the optimal value of $x_2 = 1.215$, the energy consumption equation reflecting the influence of cutting depth and cutting speed has the form as follows

$$E = 0.083367 - 0.1361x_1 + 0.1162x_1^2 - 0.02626x_3^2 \quad (6)$$

Evaluation of the Effect of Feed Speed (F) and Cutting Speed (V_c) (Fig. 8)

According to the optimal value $x_1 = 0.5857$, the energy consumption equation reflecting the influence of cutting depth and cutting speed has the form as follows

$$E = 0.11967 - 0.02774x_2 - 0.02873x_2^2 - 0.02626x_3^2 \quad (7)$$

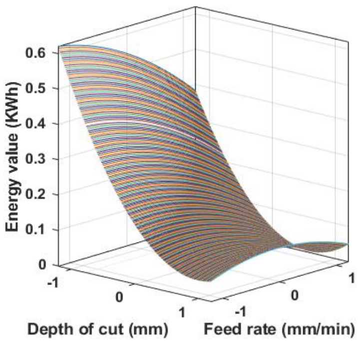

Fig. 6. Effect of depth of cut and feed rate.

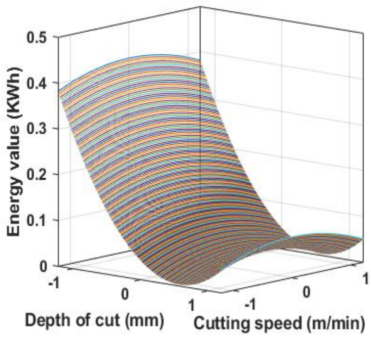

Fig. 7. Effect of depth of cut and cutting speed.

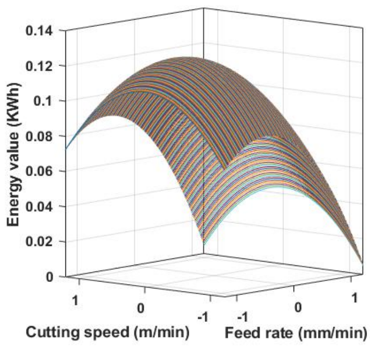

Fig. 8. Effect of feed rate and cutting speed.

From Fig. 6 it can be seen that the energy consumption is greater when the cutting depth and feed speed are smaller. In contrast, the larger the depth of cut and the feed rate, the smaller the energy consumption. At the highest feed rate, but the cutting depth is small, the energy consumption is still high. This shows that the depth of cut greatly affects the energy consumed in the machining process.

It is easy to see the similarity between Fig. 6 and Fig. 7, the value of depth of cut greatly affects the energy consumption, cutting speed has an influence but not significant. Increasing the cutting speed does not consume much power. Not only that, the energy consumption shows signs of decreasing as the cutting speed continues to increase.

Fig. 8 shows that the energy consumption will be minimum when the feed rate is maximum and the cutting speed is maximum. The minimum cutting speed also allows the energy to be reduced. Clearly, increasing or decreasing the cutting speed does not affect energy consumption as much as increasing or decreasing the feed rate. If the feed rate and cutting speed are at an average level (zero level in the experiment), the energy consumption will be huge. For high-speed machining, the spindle speed is often very large, so the trend in machining programming to reduce energy consumption will be to try to increase the value of the feed rate.

III. Conclusions

In general, the influence of cutting parameters on energy consumption of the CNC machine when high-speed roughing milling of alloy steel SKD11 after heat treatment has been considered. The optimal cutting parameters are also found according to the constraint condition of the variables and the objective function.

The research results can make some clear judgments as depth of cut has the greatest influence on energy consumption. The larger the depth of cut, the lower the energy consumption and the higher the machining productivity due to the reduction in time costs. However, it should be noted that increasing the depth of cut in hard alloy high-speed roughing will greatly affect the workability of the cutting tool (abrasion of the cutting tool, reduced tool life), cutting force and vibration may increase. Although the cutting speed does not affect the energy consumption as much as the feed rate but the cutting parameters clearly influence each other. Therefore, the selection of the optimal cutting mode needs to carefully consider the goals of the problem such as energy consumption, cutting force, vibration, cutting heat, and tool wear. Anyway, the results of this study also contribute to building a basis for evaluating the influence of cutting parameters and serving the multi-objective optimization problem when high-speed rough milling of hard alloy steels.

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