Optimization of cutting parameters with a sustainable consideration of electrical energy and embodied energy of materials

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Multi-objective optimization of CNC milling parameters considering both electrical energy and embodied energy of materials

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Abstract: In a CNC milling process, proper selection of cutting parameters can significantly reduce the electrical energy consumption. Many scholars have conducted cutting parameter optimization of the CNC milling operation for electrical energy saving during the past several years. However, in the CNC milling process, a large amount of auxiliary materials such as cutting tools and cutting fluid are consumed. The production process of these materials is energy-intensive and a lot of energy are consumed. Optimizing cutting parameters considering both the electrical energy consumption and embodied energy consumption of auxiliary materials can further reduce the environmental impact of the milling process. In this paper, an approach of cutting parameter optimization is proposed to maximize energy efficiency and machining efficiency for CNC milling operation. Firstly, the electrical energy consumption and embodied energy consumption of auxiliary materials during the CNC milling process are analyzed. The energy model of CNC milling is then proposed. Then a multi-objective optimization model for maximizing energy efficiency and machining efficiency is established. To verify the proposed multi-objective model, a case study is conducted and the results show that: i) the optimum cutting parameters of CNC milling process varies with the energy boundary whether including the embodied energy of the auxiliary materials or not; ii) cutting parameter optimization for maximum machining efficiency does not necessarily satisfy the maximum energy efficiency criterion; iii) the proposed multi-objective optimization model strikes a balance between maximum energy efficiency and maximum machining efficiency.

1 Introduction

In recent years, the increasing pressure from global energy crisis and climate changes has forced industry sector to reduce energy consumption and improve energy efficiency. In China, statistical data shows that industry sector is extremely energy-intensive and accounts for nearly 70% of the total energy consumption. Among the energy consumed by industry sector, machining industry accounts for almost a quarter of the total. However, although machining industry consumes a large amount of energy, its energy efficiency is quite low. As reported by Gutowski et al. (2006), only 14.8% of total energy is used for actual machining. Hence, improving energy efficiency and reducing energy consumption of machining process is important and imperative.

Many researchers have performed parameter optimization for reducing electrical energy consumption through experimental design. Negrete (2013) optimized the cutting parameters (cutting speed, cutting depth and feed rate) for minimizing electrical energy consumption in turning of AISI 6061 T6 by the Taguchi method. The results showed that feed rate is the most significant factor for minimizing electrical energy consumption. Higher feed rate provides minimum electrical energy consumption. The same method was utilized by Bilga et al. (2016) to conduct cutting parameter optimization in turning of EN 353 alloy steel for reducing machining tool electrical energy consumption. Their results also indicated that cutting depth is the most dominant input process parameter for electrical energy consumption. Similar work can be found in Zhang et al. (2015) and Negrete et al. (2016) with various focuses. For instance, Zhang et al. (2015) investigated the optimizing principles of cutting parameters for environmentally friendly machining austenitic stainless steel with high efficiency and little electrical energy consumption. Negrete et al. (2016) carried out a study of cutting parameter optimization to minimize electrical energy consumption during turning of AISI 1018 steel at constant material removal rate using robust design.

Apart from the above research, efforts began to move towards establishing models of cutting parameters and electrical energy consumption for parameter optimization. The first line of work focused on parameter optimization based on experimental data fitting models of electrical energy consumption. In the work presented by Bhushan (2013), an optimization work of turning cutting parameters for minimizing electrical energy consumption and maximizing tool life was presented. The response surface methodology (RSM) was applied to establish the electrical energy consumption and tool life models with respect to cutting parameters. Results of the research work showed that electrical energy consumption can be reduced by 13.55% and tool life can be increased by 22.12% with the optimized cutting parameters. Similar to the work presented by Bhushan (2013), optimization studies of the cutting parameters for electrical energy consumption reduction using the RSM only or combined with other techniques can be found in Campatelli et al. (2014), Yan and Li (2013) and Li et al. (2016a). For example, Campatelli et al. (2014) conducted an experimental approach by using the RSM to evaluate and optimize the cutting parameters to minimize the electrical energy consumption in a milling process. Yan and Li (2013) presented a multi-objective optimization method based on RSM and weighted grey relational analysis to deal with the trade-off between electrical energy, production rate and cutting quality. Optimization results indicated that low spindle speed cutting is more energy efficient and the electrical energy consumption could be reduced by 18.1% with high production rate and cutting quality. Li et al. (2016) proposed a method for optimization of cutting parameters with the objectives of electrical energy efficiency and processing time, which integrates Taguchi method, response surface method (RSM) and multi-objective particle swarm optimization algorithm.

Similar to the first one, the second line of work conducted parameter optimization based on empirical parametric models of electrical energy consumption. Velchev et al. (2014) presented an approach for optimization of cutting parameters for minimizing electrical energy consumption during turning. The model was used for the formulation of a model of electrical energy consumption expressed by the cutting parameters. An equation for the optimal cutting speed is devised by applying the minimum energy criterion. The study conducted by Altıntaş et al. (2016) presented a new model for evaluating the electrical energy consumed by a machine tool for processing a prismatic workpiece. A multivariable energy optimization was carried out with the variables of cutting speed, feed rate and cutting depth. In line with the work in Velchev et al. (2014) and Altıntaş et al. 2016, our prior work established single-pass and multi-pass parameter optimization models for electrical energy efficiency improvement (Li et al., 2016b; Li et al., 2017).

During the CNC machining process, a lot of auxiliary materials such as cutting tools and cutting fluid are used. The production process of these materials is energy-intensive and a large amount of energy are consumed (Dahmus and Gutowski, 2004). For instance, as reported by Ullah et al. (2011), the energy consumption to fabricate 1 cm^3 of tungsten carbide material, which is the main component of cutting tool insert, is 8590–9723.6 kJ. Hence, the embodied energy consumption of the auxiliary materials used in the machining process should be taken into account in modelling the energy consumption and parameter optimization. In the work presented by Rejemi et al. 2010, they extended the energy consumption boundary and modelled the total energy consumption by taking into account the electrical energy consumption of machine tool and the embodied energy of cutting tools. The optimum cutting speed for minimizing the total energy consumption of a single-pass turning operation was obtained. Based on the model proposed by Rejemi et al. 2010, Arif et al. (2013) optimized the cutting parameters of multi-pass turning operation for the minimum energy consumption consideration. Wang et al. (2014) further extended the model of Rejemi et al. (2010) by adding the embodied energy of cutting fluid into the total energy consumption model. Then they conducted cutting parameter optimization of single-pass turning operation with the objectives of energy consumption, production cost and machining quality. More recently, based on the model proposed by Wang et al. (2014), Lu et al. (2016) optimized the cutting parameters of multi-pass turning operation with the objectives of energy consumption and machining quality.

A perusal of current literatures concludes that the existing researches about parameter optimization of CNC machining are more concentrated on reduction of electrical energy consumption. While several researchers have taken into account the embodied energy of the cutting tools and cutting fluid, they only looked into turning process. No efforts have been made towards cutting parameter optimization of milling process to simultaneously reduce the electrical consumption and embodied energy consumption of auxiliary materials. In fact, milling is also a widely used processing method that removes metal by a rotating multiple tooth cutter. The milling process consumes large amount of cutting tools and cutting fluid. Cutting parameter optimization of the milling process considering both the electrical consumption and embodied energy consumption of auxiliary materials needed to be studied. Moreover, reducing energy consumption should avoid decreasing machining quality, increasing production cost or production time. In the past years, several multi-objective studies have been conducted to obtain optimum cutting parameters to minimize electrical consumption and embodied energy consumption of auxiliary materials as well as maximize machining quality and minimize production cost. However, no effort has been devoted to optimize cutting parameters with the aim to simultaneously reduce electrical consumption and embodied energy consumption of auxiliary materials as well as production time.

Motivated by these remarks, this paper fills this gap and studies multi-objective parameter optimization of CNC milling, with the aim to minimize electrical consumption and embodied energy consumption of auxiliary materials as well as production time. The rest of the paper is organized as follows. Section 2 analyzes the electrical energy consumption and embodied energy consumption of auxiliary materials of the CNC milling process. Section 3 proposes a multi-objective parameter optimization model considering the relationship of cutting parameters to energy efficiency and machining efficiency. Section 4 presents the experimental details of nonlinear regression for the proposed model. Section 5 shows the application case studies, including necessity validation of multi-objective optimization, comparison study and parametric influence on energy efficiency and machining efficiency. In Section 6, conclusions are presented and future work are discussed.

2. Energy consumption of CNC milling

As pointed out by Dahmus and Gutowski (2004), any system analysis should start with the definition of the boundaries of the system. In the case of energy consumption analysis of the CNC milling system, an extended boundary is defined to take into account both the direct energy and indirect energy. The direct energy is the electrical energy consumed by the machine tool during the milling process. It is used to power the machine tool components such as the spindle and feed motors. The indirect energy refers to the embodied energy of cutting tools and cutting fluid. The total energy consumption E_{total} of can be modelled as shown in Eq.(1).

$$E_{total} = E_{direct} + E_{indirect}$$

where E_{direct} and $E_{indirect}$ are the direct and indirect energy consumption. The detailed analysis is given below.

2.1 Direct energy consumption of CNC milling

The direct energy consumption during the CNC milling process is very complex. Generally, the CNC milling process can be divided into multiple states from the power consumption point of view, i.e. machine tool startup state, standby state, spindle acceleration/deceleration state, air cutting state, cutting state and tool changing state. Note that the machine tool startup state, standby state and spindle acceleration/deceleration state are independent on the cutting parameters. This paper mainly focuses on the electrical energy consumption during the air cutting state, cutting state and tool changing state and modeled them as shown in Eq.(2).

$$E_{direct} = E_{air} + E_{machining} + E_{tool\text{-}change} \tag{2}$$

where E_{air}, $E_{cutting}$ and $E_{tool\text{-}change}$ represent the air cutting energy, cutting energy and tool changing energy, respectively.

2.1.1 Air cutting energy

Air cutting operation is necessary for safety and machining quality consideration. During the air cutting state, the machine tool spindle moves along with the tool path defined by the numerical control program without removing material. The electrical energy consumption during this state can be calculated as shown in Equation (3).

$$E_{air} = \int_0^{t_{air}} \left(P_{basic} + P_{auxiliary} + P_{unload}\right) dt \tag{3}$$

where P_{basic} is the basic power consumption of the machine tool. $P_{auxiliary}$ is the auxiliary power consumption of the machine tool components activated along with the spindle rotating, such as the cutting fluid pump. The value of P_{basic} and $P_{auxiliary}$ are usually constants and can be measured by experiments. P_{unload} is the unload power consumed to keep the spindle rotating. t_{air} is the air cutting time.

According to the work presented by Li et al.(2016b), the unload power P_{unload} is a quadratic function of the spindle speed n, which can be represented as shown in Eq.(4).

$$P_{unload} = a_0 + a_1 n + a_2 n^2 \tag{4}$$

where a_0, a_1 and a_2 are unload power coefficients.

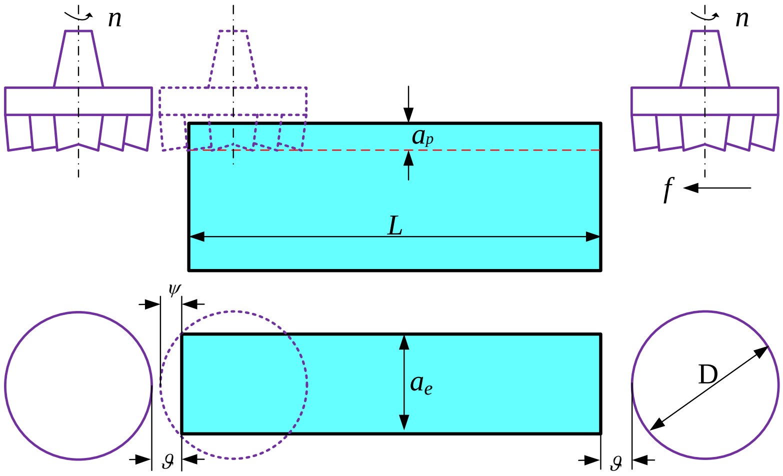

Fig.1. CNC milling operation

In the CNC milling process, as show in Fig.1, the air cutting time t_{air} is related to the length of the tool path and cutting parameters, which can be modeled as shown in Equation (5).

$$t_{air} = \frac{2\vartheta + D - \psi}{nf_z z} \tag{5}$$

where D is the cutting tool diameter. f_z is the feed rate per tooth. z is the number of inserts in the cutting tool. ϑ is the distance to protect the cutting tool and workpiece from potential accidents and damages. It is usually taken to be 5 mm. ψ is the approach distance, which can be calculated as shown in Eq. (6).

$$\psi = D/2 - \sqrt{(D/2)^2 - (a_e/2)^2} \tag{6}$$

where a_e is the cutting width.

2.1.2 Machining energy

The machining energy is the energy consumed during the material removal process. The energy consumption during the machining process can be calculated as shown in Equation (7).

$$E_{machining} = \int_0^{t_{machining}} \left(P_{basic} + P_{unload} + P_{auxiliary} + P_{cutting} + P_{additional}\right)dt \tag{7}$$

where $P_{cutting}$ and $P_{additional}$ are the cutting power and additional load loss power. $t_{machining}$ is the machining time, which can be calculated as shown in Equation (8).

$$t_{machining} = \frac{L}{nf_z z} \tag{8}$$

In the CNC milling process, the cutting power $P_{cutting}$ is the power consumed at the tool tip to remove the workpiece material. According to the work presented by Lu and Sun (2006), the cutting power $P_{cutting}$ can be calculated as shown in Eq.(9).

$$P_{cutting} = k_m v_c^{x_m} f^{y_m} a_p^{z_m} a_e^{w_m} \tag{9}$$

where k_m, x_m, y_m, z_m, w_m are cutting power coefficients related to machine tools, workpiece materials and cutting tools, which can be determined by experiments. v_c is the cutting velocity, $v_c=\pi Dn/1000$, a_p is the cutting depth.

The additional load loss power $P_{additional}$ is the electrical and mechanical loss in motor and transmission system generated by cutting load. The value of $P_{additional}$ is related to cutting power and hence the cutting parameters. During the CNC milling process, the cutting power $P_{cutting}$ and additional load loss power $P_{additional}$ can be modelled through experimental data fitting.

2.1.3 Tool changing energy

In the CNC milling process, the cutting tool will be worn due to the friction between cutting edge and the workpiece. When the wear of the cutting edge reaches the preset criterion, it will be replaced by a sharp one. The tool change energy $E_{tool\text{-}change}$ is evaluated from the basic power consumption of the machine tool P_{basic} and the corresponding tool change time $t_{tool\text{-}change}$, which can be expressed as shown in Eqs.(11)-(13).

$$E_{tool\text{-}change} = \int_0^{t_{tool\text{-}change}} P_{basic} dt \tag{11}$$

$$t_{tool\text{-}chenge} = t_{mt} \frac{t_{machining}}{T_{tool}} z \tag{12}$$

$$T_{tool} = \frac{C_T}{v_c^{x_T} f_z^{y_T} a_p^{z_T} a_e^{w_T}} \tag{13}$$

where t_{mt} is the time for changing one worn tool insert. T_{tool} is the tool life. C_T, x_T, y_T, z_T, w_T are the tool life coefficients.

2.2 Indirect energy consumption of CNC milling

During the CNC milling process, a lot of cutting tools and cutting fluid are needed to generate the final product. As mentioned in Section 1, the production process of these materials consumes a large amount of energy. The energy will be embodied in these materials and consumed till the end of life. In modelling the indirect energy consumption of the CNC milling process, the energy embodied in the cutting tools and cutting fluid is included, which can be seen in Eq.(14).

$$E_{indirect} = E_{tool} + E_{fluid} \tag{14}$$

2.2.1 Embodied energy of cutting tools

As stated in Section 2.1.3, when the tool wear reaches the preset criterion, it will be replaced by a sharp one. Accordingly, the embodied energy of the cutting tool will be consumed up. Generally, a cutting tool can be used for machining several parts before it reaching the preset wear criterion. The total embodied energy of cutting tool E_{tool} needed in a machining process is calculated based on the unit embodied energy of cutting tool $U_{embodied}$, tool life T_{tool} and machining time $t_{machining}$, which can be seen in Eq.(15).

$$E_{tool} = \frac{t_{machining}}{T_{tool}} U_{embodied} \tag{15}$$

where the unit embodied energy of cutting tool $U_{embodied}$ is related to the energy to fabricate the cutting insert material $E_{material}$, the volume of one insert V_{insert}, the number of cutting inserts z and the number of cutting edges of each insert N, which is calculated as shown in Eq.(16).

$$U_{embodied} = \frac{E_{material} V_{insert} z}{N} \tag{16}$$

2.2.2 Embodied energy of cutting fluid

In the CNC milling process, the cutting fluid is used for increasing tool life, improving surface finish and flushing away chips. The cutting fluid mainly includes two categories, i.e. the water-based cutting fluid and the oil-based cutting fluid. The water-based cutting fluid that mixed soluble oil with water together is usually used in the CNC milling process. Similar to the embodied energy of cutting tools, the total embodied energy of cutting fluid E_{fluid} consumed in the CNC milling process is calculated based on the unit embodied energy of cutting fluid U_{fluid}, replacement cycle of cutting fluid $T_{coollant}$ and machining time $t_{machining}$.

$$E_{fluid} = \frac{t_{machining}}{T_{coolant}} U_{fluid} \tag{17}$$

where the unit embodied energy of cutting fluid U_{fluid} is calculated as shown in Eq.(18).

$$U_{fluid} = \left(V_{in} + V_{ad}\right)\eta\rho E_{oil} \tag{18}$$

where V_{in} and V_{ad} are the initial and additional volume of the soluble oil. ρ is the density of the soluble oil. η is the concentration of the cutting fluid. E_{oil} is the energy to fabricate soluble oil.

Based on the analysis above, the total energy consumption E_{total} of the CNC milling process can be expressed in Eq.(19).

$$\begin{aligned} E_{total} &= E_{direct} + E_{indirect} \\ &= E_{air} + E_{machining} + E_{tool\text{-}change} + E_{tool} + E_{fluid} \end{aligned} \tag{19}$$

3. Multi-objective parameter optimization model

3.1 Variables

In a CNC milling process, cutting velocity v_c, feed rate per tooth f_z, cutting depth a_p and cutting width a_e have an impact on the energy efficiency and machining efficiency (Yan and Li, 2013). Given that the cutting width a_e is usually determined by the cutter diameter or the width of the workpiece, it is usually treated as a constant in the optimization process. Hence, the optimization variables considered in this paper are cutting velocity v_c feed rate per tooth f_z and cutting depth a_p.

3.2 Objective functions

3.2.1 Energy efficiency

Generally, the specific energy consumption (SEC), which refers to the energy consumed to remove 1 mm^3 of material, is a comprehensive representation method to measure the energy efficiency of the CNC machining system (Campatelli et al., 2014). In this paper, the total SEC of the CNC milling process considering the direct and indirect energy consumption is calculated as shown in Eq.(20).

$$SEC_{total} = \frac{E_{direct} + E_{indirect}}{MRV} \tag{20}$$

where SEC_{total} is the total specific energy consumption. MRV is the material removal volume, which can be calculated as shown in Eq.(21).

$$MRV = L \times a_e \times a_p \tag{21}$$

3.2.1 Machining efficiency

Similar to the specific energy consumption, the specific processing time (SPT) is the time required to remove 1 mm^3 of material (Albertelli et al., 2016). It is related to the total production time of the CNC milling process and the material removal volume, which is modelled as shown in Eq.(22).

$$SPT_{total} = \frac{t_{total}}{MRV} \tag{22}$$

where SPT_{total} is the total specific processing time. t_{total} is the total production time. As shown in Eq.(23), t_{total} is the summation of air cutting time t_{air}, cutting time $t_{cutting}$ and tool-change time $t_{tool\text{-}change}$.

$$t_{total} = t_{air} + t_{cutting} + t_{tool\text{-}change} \tag{23}$$

3.3 Optimization Model

With the variables and objectives defined above, the multi-objective parameter optimization model for energy efficiency and machining efficiency improvement is then formulated as follows:

$$minF(v_c, f_z, a_p) = (minSEC_{total}, SPT_{total}) \tag{24}$$

Subject to:

$$v_c^{min} \leq v_c \leq v_c^{max} \tag{25}$$

$$f_z^{min} \leq f_z \leq f_z^{max} \tag{26}$$

$$a_p^{min} \leq a_p \leq a_p^{max} \tag{27}$$

$$P_{unload} + P_{material} + P_{additional} \leq \eta P_m \tag{28}$$

$$T_{tool} \geq T_e \tag{29}$$

$$R_a = 318 \frac{f_z^2}{tg(L_a) + ctg(C_a)} \leq R_a^{max} \tag{30}$$

In the CNC milling process, many constraints are set to satisfy the processing requirements. Constraints (25)-(27) control the cutting velocity, feed rate per tooth and cutting depth to be within the acceptable range to avoid quick tool wear and machine tool damage, where v_c^{max}/v_c^{min}, f_z^{max}/f_z^{min} and a_p^{max}/a_p^{min} are the permitted maximum/minimum cutting velocity, feed rate per tooth and cutting depth. Constraint (28) ensures the power required for the milling operation will not exceed the maximum output power of the spindle motor, where P_m is the rated power of the spindle motor, and η is the overall efficiency of the machine spindle. Similarly, constraint (29) controls the cutting tool life will not be shorter than one T_e preset by users. In order to obtain good surface quality, it is imperative that the final surface roughness should be smaller than the permitted one R_a^{max} as shown in constraint (30), where L_a and C_a denote the lead angle and clearance angle of the tool tip, respectively.

4. Parameters identification of the energy model

As shown in Section 2, the developed energy model includes several parameters, such as coefficients of unload power a_0, a_1, and a_2, coefficients of cutting power k_m, x_m, y_m, z_m and w_m, and coefficients of tool life C_T, x_T, y_T, z_T and w_T. In order to identify these parameters of the energy model, a series of CNC milling experiments are conducted.

4.1 Experiment details

The CNC milling experiments were performed on a DAHE TH5656 CNC milling machine tool as shown in Fig.2. The workpiece machined had a length of 300 mm, width of 50 mm and height of 60 mm. The workpiece material was S45C carbon steel. Cutting tool with the diameter of 60 mm was used. The cutting tests were undertaken in wet machining with water-based cutting fluid. In Table 1, the parameters of the machine tool, cutting tool and workpiece are given.

During each test, power consumption of the machine tool and its spindle system was measured by a HC33C3 power sensor. The power sensor measured the power consumption by clamping current gauges and voltage meters onto the electricity supply wires. The Machine Tool Energy Efficiency Monitoring System (MTEEMS) developed by our group was used to present the real-time power profile.

Fig.2. Experiment setup

Table 1 Parameters of machine tool, cutting tool and workpiece

Item	Unit	Numerical data
Machine tool		
Motor power	P_{max}(W)	7500
Efficiency	η	0.85
Auxiliary component power	$P_{auxiliary}$(W)	525
Basic power	P_{basic}(W)	1210
Standby time	t_s(s)	300
Tool-changing time	t_{ct}(s)	480
Spindle speed	$[n^{min}, n^{max}]$(rpm)	[20,5000]
Feed velocity	$[v_f^{min}, v_f^{max}]$(mm/min)	[1,5000]
Cutting depth	$[a_p^{min}, a_p^{max}]$(mm)	[0.1,3]
Cutting tool		
Cutting insert material	Tungsten carbide	
Diameter	D(mm)	60
Lead angle	L_a (°)	10
Clearance angle	C_a(°)	8
Number of inserts	z	4
Energy to fabricate cutting tool insert material	$E_{material}$ (kJ/cm^3)	9156
Volume	V_{insert}(cm^3/insert)	0.4
Number of cutting edges of each insert	N	2
Workpiece		
Material	S45C carbon steel	
Length	L(mm)	300

Width	W(mm)	50
Cutting fluid		
Material	Soluble oil	
Initial volume	V_{in}(cm^3)	8.5×10^3
Additional volume	V_{ad}(cm^3)	4.5×10^3
Concentration	η	5%
Density	ρ(g/cm^3)	0.92
Energy to fabricate the cutting fluid material	E_{oil}(KJ/kg)	42287

4.2 Parameters identification of unload power P_{unload}

In this experiment, the spindle of the CNC milling machine tool rotated at different spindle speed with no load. The selected spindle speed covered the usually used values in practical machining process from 200rpm to 2000rpm with the increase of every 200 rpm. Each set was tested three times and the average unload power was recorded as shown in Table 2.

Table 2 Spindle speed and corresponding unload power

No.	1	2	3	4	5	6	7	8	9	10
n(rpm)	200	400	600	800	1000	1200	1400	1600	1800	2000
P_{unload} (W)	345	422	720	853	946	1128	1156	1324	1415	1503

With the experimental results above, the parameters of the unload power model can be identified through nonlinear regression, which can be seen in Eq.(31).

$$P_{unload} = 131.3 + 0.9854n - 1.52 \times 10^{-4} n^2 \quad \text{(R-Sq=98.9\%)} \tag{31}$$

4.3 Parameters identification of cutting power $P_{cutting}$ and additional load loss power $P_{additional}$

As mentioned in Section 2.1.2, the additional load loss power $P_{additional}$ is generated by the cutting load, the value of the additional load loss power $P_{additional}$ is related to the cutting power $P_{cutting}$ and the cutting parameters. Hence, in this experiment, the summation of the additional load loss power $P_{additional}$ and cutting power $P_{cutting}$ is modelled.

In order to make the experimental results reliable, the Taguchi's L_{25} orthogonal array was used to design the experimental plan. The cutting parameters and levels are shown in Table 3. The obtained experimental plan is listed in Table 4. For each test, a workpiece with the length of 300 mm was firstly machined to obtain the machining power $P_{machining}$. Then, the machine tool moved along with the toolpath without removing workpiece to obtain the air cutting power P_{air}. By this way, the summation of the additional load loss power $P_{additional}$ and cutting power $P_{cutting}$ was obtained as the difference between machining power consumption $P_{machining}$ and air cutting power consumption P_{air}. The measure was performed three times for each test. The average value of machining power consumption $P_{machining}$ and air cutting power consumption P_{air} are listed in Table 4.

Table 3 Cutting parameters and levels

Level	v_c（m/min）	f_z (mm/ tooth)	a_p(mm)	a_e(mm)
1	50	0.1	0.2	20
2	100	0.2	0.8	30
3	150	0.3	1.4	40
4	200	0.4	2.0	50
5	250	0.5	2.6	60

Table 4 Experimental results

No.	v_c (m/min)	f_z (mm/tooth)	a_p (mm)	a_e (mm)	$P_{machining}$ (W)	P_{air} (W)	$P_{cutting}$+ $P_{additional}$ (W)	T_{tool} (min)
1	60	0.1	0.2	20	1936	1755	181	117.4
2	60	0.2	0.8	30	2127	1764	363	66.9
3	60	0.3	1.4	40	2704	1750	954	46.2
4	60	0.4	2.0	50	3569	1764	1805	35.8
5	60	0.5	2.6	60	4793	1766	3027	29.4
6	90	0.1	0.8	40	2561	1921	640	22.7
7	90	0.2	1.4	50	3425	1906	1519	13.7
8	90	0.3	2.0	60	5012	1923	3089	9.8
9	90	0.4	2.6	20	3775	1894	1881	9.2
10	90	0.5	0.2	30	2247	1910	337	20.7
11	120	0.1	1.4	60	3668	1975	1693	10.5
12	120	0.2	2.0	20	3380	1983	1397	9.0
13	120	0.3	2.6	30	4169	1972	2197	5.5
14	120	0.4	0.2	40	2580	1963	617	13.2
15	120	0.5	0.8	50	4194	1985	2209	6.6
16	150	0.1	2.0	30	3291	2071	1220	5.0
17	150	0.2	2.6	40	5952	2092	3860	2.8
18	150	0.3	0.2	50	2901	2084	817	7.4
19	150	0.4	0.8	60	4932	2077	2855	3.2
20	150	0.5	1.4	20	4115	2098	2017	2.6
21	180	0.1	2.6	50	6108	2188	3920	1.8
22	180	0.2	0.2	60	3056	2183	873	4.8
23	180	0.3	0.8	20	3388	2174	1214	4.5
24	180	0.4	1.4	30	4351	2195	2156	3.3
25	180	0.5	2.0	40	8337	2168	6169	2.6

With the data acquired by the experiments, the summation of the cutting power $P_{cutting}$ and additional load loss power $P_{additional}$ was obtained (Table 4). The following Eq.(32) can be obtained through nonlinear regression.

$$P_{cutting} + P_{additional} = 92.33(v_c/60)^{0.942} f_z^{0.414} a_p^{0.679} a_e^{0.733} (R^2=95.0\%) \quad (32)$$

4.4 Parameters identification of the tool life T_{tool}

As shown in Equation (13), tool life is highly dependent on the cutting parameters. Similarly, in order to obtain reliable experimental results, the experimental plan in Table 5 was adopted. During the test, the flank wear of the cutting inserts was measured by a VHX-1000 microscope every one minute until the 0.3 mm tool rejection criterion was reached in any of the inserts. Each set was tested three times. The average tool life was recorded in the last row in Table 4. With the experimental results, the tool life can be modeled as follows.

$$T_{tool} = \frac{3.89 \times 10^6}{v_c^{2.65} f_z^{0.263} a_p^{0.350} a_e^{0.197}} (R^2=97.1\%) \quad (33)$$

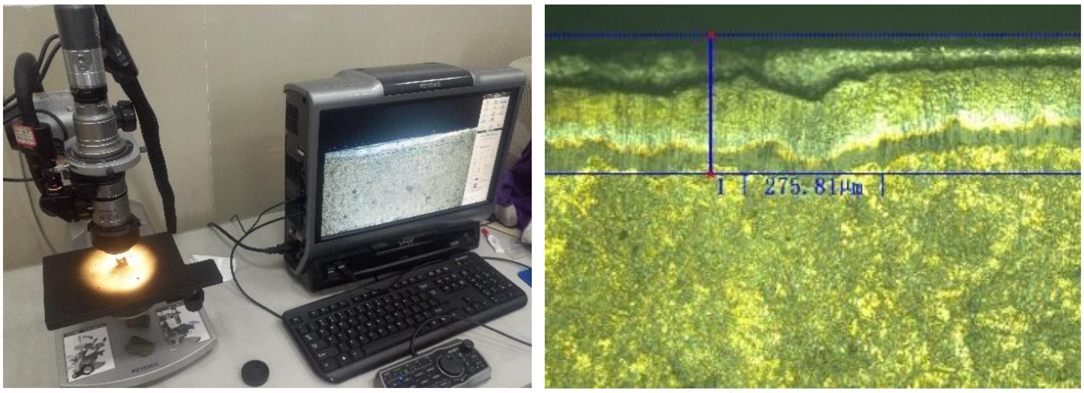

Fig.3. VHX-1000 microscope and cutting insert flank wear

5. Case study

5.1 Necessity of multi-objective optimization

In the CNC milling process, material removal rate (MRR) is usually represented as a function of cutting velocity, feed rate per tooth, cutting width and cutting depth. To demonstrate the necessity of multi-objective optimization, as shown in Table 5, different cutting parameter combinations are used to investigate the relationship of SEC and SPT with respect to MRR. The changes of machining and air cutting SEC, tool-changing SEC, embodied SEC of cutting tool, embodied SEC of cutting fluid and total SEC with respect to MRR are plotted in Fig.4. Similarly, the changes total SPT, tool-changing SPT, machining SPT and air cutting SPT with respect to MRR are plotted in Fig.5.

Table 5 Cutting parameter combination and the corresponding *MRR*

No.	n (rpm)	v_c (m/min)	f_z (mm/tooth)	a_p (mm)	a_e (mm)	MRR (mm^3/s)
1	300	56.52	0.1	0.3	45	1215
2	400	75.36	0.11	0.4	45	2376
3	500	94.20	0.12	0.5	45	4050
4	600	113.04	0.13	0.6	45	6318
5	700	131.88	0.14	0.7	45	9261
6	800	150.72	0.15	0.8	45	12960
7	900	169.56	0.16	0.9	45	17496
8	1000	188.40	0.17	1	45	22950
9	1100	207.24	0.18	1.1	45	29403
10	1200	226.08	0.19	1.2	45	36936
11	1300	244.92	0.2	1.3	45	45630
12	1400	263.76	0.21	1.4	45	55566
13	1500	282.60	0.22	1.5	45	66825
14	1600	301.44	0.23	1.6	45	79488
15	1700	320.28	0.24	1.7	45	93636
16	1800	339.12	0.25	1.8	45	109350
17	1900	357.96	0.26	1.9	45	126711
18	2000	376.80	0.27	2	45	145800
19	2100	395.64	0.28	2.1	45	166698
20	2200	414.48	0.29	2.2	45	189486
21	2300	433.32	0.3	2.3	45	214245
22	2400	452.16	0.31	2.4	45	241056
23	2500	471.00	0.32	2.5	45	270000

$MRR = n \times f_z \times z \times a_p \times a_e$

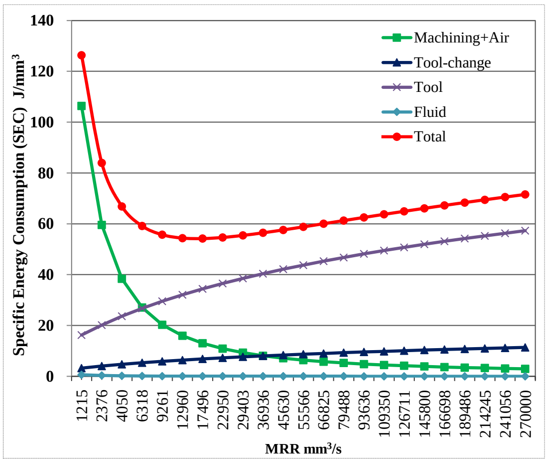

Fig.4. SEC changes with respect to MRR

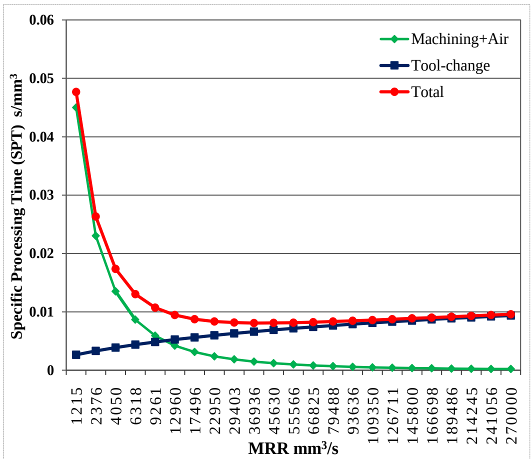

Fig.5. SPT with respect to MRR

As shown in Fig.4, with the raise of MRR, the machining and air cutting SEC decrease while the tool-changing SEC and embodied SEC of cutting tool increasing, resulting in the total SEC firstly decreasing and then increasing. The same situation can be found in Fig.5, The machining and air cutting SPT decrease but the tool-change SPT increase with the raise of MRR, resulting in a precedent of decreasing then increasing on the total SPT. However, reviewing Fig.4 and Fig.5, it can be found that the inflection points of the total SEC and total SPT are different. This indicates that there is trade-off between the total SEC and total SPT when optimizing the cutting parameters. Multi-objective optimization may be an effective method in achieving a balance between minimum SEC and minimum SPT.

5.2 Comparison study

To fully understand the influence of cutting parameters on the SEC and SPT, in this section, five optimization models are applied to the same machining process to show a comparison study. The optimization of the aforementioned models were solved by the multi-objective particle swarm optimization algorithm (MOPSO) as presented in our prior work (Li et al., 2016a). The optimization models and the corresponding optimization results are shown in Table 6. Model 1, Model 2 and Model 3 are the mono-objective optimization model with the objectives of minimum direct specific energy consumption SEC_{direct}, minimum total specific energy consumption SEC_{total} and minimum specific processing time SPT_{total}, respectively. Model 4 is the multi-objective optimization model with the objectives of minimum SEC_{direct} & SPT_{total}. Model 5 is the multi-objective optimization model with the objectives of minimum SEC_{total} & SPT_{total}.

Table 6 Optimization results

Optimization objective	v_c (m/min)	f_z (mm/z)	a_p (mm)	MRR (mm^3/ s)	SEC_{total} (J/mm^3)	SEC_{direct} (J/mm^3)	$SEC_{indirect}$ (J/mm^3)	SPT_{total} (s/mm^3)
Minimum SEC_{direct} (Model 1)	135.95	0.30	3.00	87710	12.08	5.21	6.87	1.748×10^{-3}
Minimum SEC_{total} (Model 2)	59.02	0.30	2.92	37062	7.72	5.94	1.78	1.764×10^{-3}
Minimum SPT_{total} (Model 3)	87.30	0.29	2.82	51179	9.12	5.58	3.54	1.646×10^{-3}
Minimum SEC_{direct} & SPT_{total} (Model 4)	118.11	0.29	2.88	70714	11.13	5.39	5.74	1.712×10^{-3}
Minimum SEC_{total} & SPT_{total} (Model 5)	78.26	0.27	2.92	44230	8.95	5.89	3.06	1.734×10^{-3}

From the optimization results in Table 6, it can be found that when the optimization objective is to minimize direct specific energy consumption SEC_{direct} (i.e. Model 1), the model seeks higher MRR in the permitted parameter range. This is because that although a higher MRR will increase the machining and air cutting power, the machining and air cutting SEC will decrease with the increase of removed workpiece material per unit time. However, the increasing MRR will aggravate the tool wear, resulting in the increase of tool-changing SEC. Hence, the optimum MRR should not increase indefinitely. Furthermore, with the MRR increasing, the serious tool wear will lead to a sharply increase of the embodied energy of cutting tool, resulting the increase of the indirect SEC and hence the total SEC. Therefore, when the optimization objective is to minimize total specific energy consumption SEC_{total} (i.e. Model 2), the model strikes a balance between the direct and indirect SEC and obtains the optimum MRR for the minimum SEC_{total}. Compared to Model 1, Model 2 decreases the indirect SEC by 74.09% and increases of the direct SEC by 14.01%, resulting in a decrease of the total SEC by 56.48%.

As shown in Fig.5, with the increase of MRR, the air cutting time and machining time will decrease but the tool-change time will increase due to the serious tool wear. Hence, when the optimization objective is to minimize specific processing time SPT_{total} (i.e. Model 3), the model seeks an optimum MRR to balance the air cutting time, machining time and the tool-change time. However, during the optimization process, Model 3 does not take the direct SEC or the total SEC into consideration. Compared to Model 1 and Model 2, it increases the direct SEC and total SEC by 7.10% and 24.50%, respectively.

When the optimization objective is to minimize SEC_{direct} & SPT_{total} (i.e. Model 4), the value of MRR of Model 4 is chosen between that of Model 1 and Model 3 to obtain a trade-off for minimizing direct SEC and SPT. Similarly, when the optimization objective is to minimize SEC_{toal} & SPT_{total} (i.e. Model 5), the value of MRR of Model 5 is also chosen between that of Model 2 and Model 3 to achieve a balance between minimum total SEC and SPT. Particularly, compared to Model 4, Model 5 decreases the total SEC by 19.59% with a slight increase of the SPT by 1.29%. This indicates that the proposed model (i.e. Model 5) has significant efficiency in minimizing total SEC and SPT.

5.3 Parametric influence on SEC_{direct}, SEC_{toal} and SPT_{total}

In this section, the effect of each parameter (i.e. cutting velocity, feed rate per tooth and cutting depth) on SEC_{toal} and SPT_{total} are analyzed.

5.3.1 Parametric influence on SEC_{direct} and SEC_{toal}

As depicted in Fig.6, the SEC_{direct} decreases with the increase of feed rate per tooth. However, the SEC_{direct} does not always increase or decrease with the increase of cutting velocity. Instead, there is an inflection point, before which it decreases and after which it increases. The same situation can be seen in Fig.8, where the SEC_{direct} is not always decreased with the increase of cutting velocity but with cutting depth. In Fig.10, it can be seen that the SEC_{direct} decreases with the increase of feed rate per tooth and cutting depth.

In the CNC milling process, when the value of cutting velocity, feed rate per tooth and cutting depth is low, the tool wear is very slight. The tool-change energy is small. With the increase of cutting velocity, feed rate per tooth and cutting depth, the air cutting power, machining power and the MRR will increase, resulting in the increase of the air cutting energy consumption, machining energy consumption and the MRV per unit time. When the increment of the MRV exceeds that of the air cutting energy consumption and machining energy consumption per unit time, the SEC_{derect} will decrease. However, as shown in Eq.(33), compared with the feed rate per tooth f_z and cutting depth a_p, the cutting velocity v_c is a dominant influence factor of the tool life. Higher cutting velocity v_c leads to a quicker tool wear and a shorter tool life, resulting in the increase of the tool-changing energy consumption. Hence, the SEC_{derect} decreases with the increase of feed rate per tooth f_z and cutting depth a_p, but it does not always decrease with the increase of cutting velocity v_c.

Compared to the SEC_{direct}, as shown in Figs.7 and 9, the 3D tendency surface of the SEC_{toal} is quite similar to that of Figs.6 and 8, except for different inflection points of the SEC with respect to the cutting velocity. Furthermore, in Fig.11, it also can be found that the SEC_{toal} decreases with the increase of feed rate per tooth and cutting depth.

The main reason for this phenomenon is explained as follows. The SEC_{toal} is a simulation of SEC_{direct}, embodied SEC of cutting tool and embodied SEC of cutting fluid. As shown in Fig.4, the influence of cutting parameters on embodied SEC of cutting fluid is negligible. With the increase of cutting velocity, the serious tool wear not only increase the tool-changing energy consumption, but also increase the embodied SEC of cutting tool. Hence, the inflection points of the SEC with respect to the cutting velocity of the SEC_{toal} is smaller than that of the $SEC_{direct.}$

From the analysis above and the optimization results in Table 6, it can be concluded that the optimum cutting parameters will vary with the energy boundaries. In the past, the studies of parameter optimization for CNC milling are more concerned about the direct electrical energy consumption. However, the neglected indirect embodied energy of cutting tools and cutting fluid should be paid much attention to as it is a dominant factor determining the optimum cutting parameters.

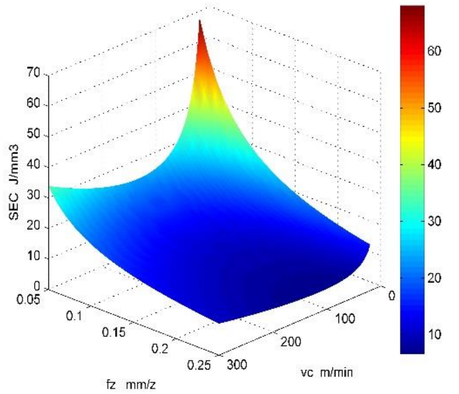

Fig.6. SEC_{direct} changes with respect to cutting velocity and feed rate per tooth (a_p=2.5mm)

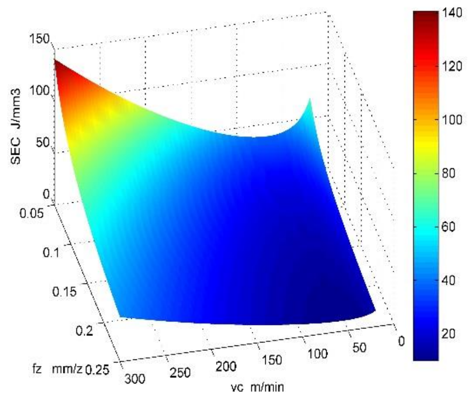

Fig.7. SEC_{toal} changes with respect to cutting velocity and feed rate per tooth (a_p=2.5mm)

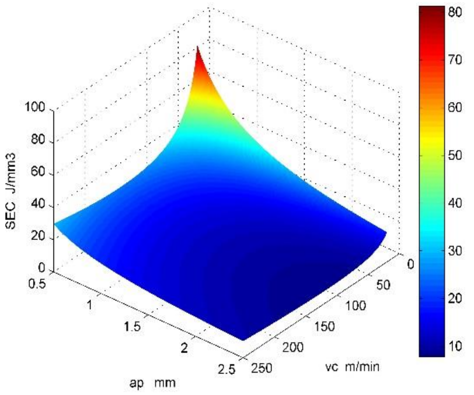

Fig.8. SEC_{direct} changes with respect to cutting velocity and cutting depth (f_z=0.2mm/z)

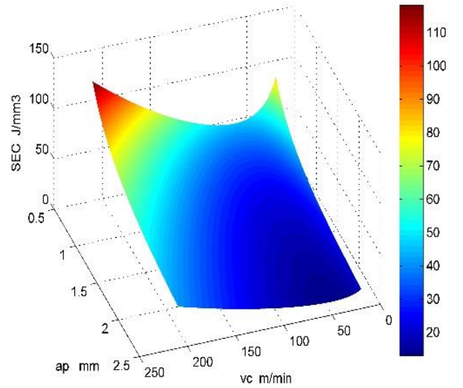

Fig.9. SEC_{toal} changes with respect to cutting velocity and cutting depth (f_z=0.2mm/z)

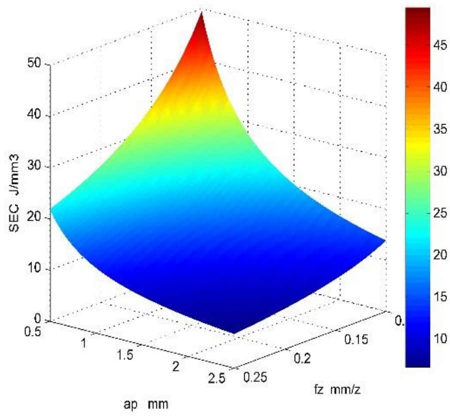

Fig.10. SEC_{direct} changes with respect to feed rate per tooth and cutting depth (v_c=100m/min)

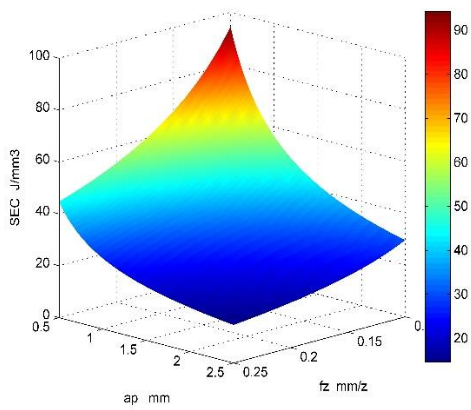

Fig.11. SEC_{toal} changes with respect to feed rate per tooth and cutting depth (v_c=100m/min)

5.3.2 Parametric influence on SPT_{total}

As shown in Fig.12, it can be seen that the SPT_{total} first decreases with the increase of cutting velocity, and then increases. However, it always decreases with the increase of feed rate per tooth. The similar situation can be found in Fig.13, where the SPT_{total} decreases with the increase of the cutting depth but does not always decrease with the increase of the cutting velocity. In Fig.14, it shows that the SPT_{total} decreases with the increase of feed rate per tooth and cutting depth.

In the CNC milling process, with the increase of cutting velocity, feed rate per tooth and cutting depth, the air cutting time and machining time to remove a specific volume of workpiece will be shortened. Hence, when the value of cutting velocity, feed rate per tooth and cutting depth is low, the SPT_{total} decreases with the increase of cutting velocity, feed rate per tooth and cutting depth. However, as the cutting velocity is a dominant influence factor of the tool life, higher cutting velocity leads to serious tool wear and an increase of the tool-changing time. Thus, with the continue increase of cutting velocity, the SPT_{total} will increase.

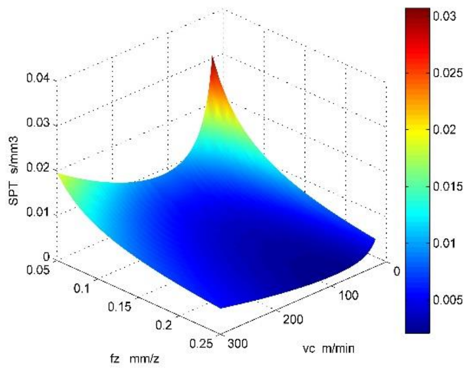

Fig.12. SPT_{total} changes with respect to cutting velocity and feed rate per tooth (a_p=2.5mm)

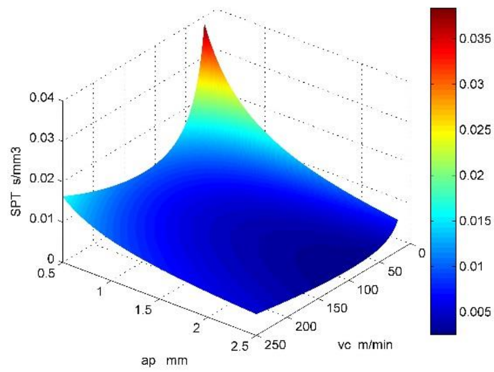

Fig.13. SPT_{total} changes with respect to cutting velocity and cutting depth (f_z=0.2mm/z)

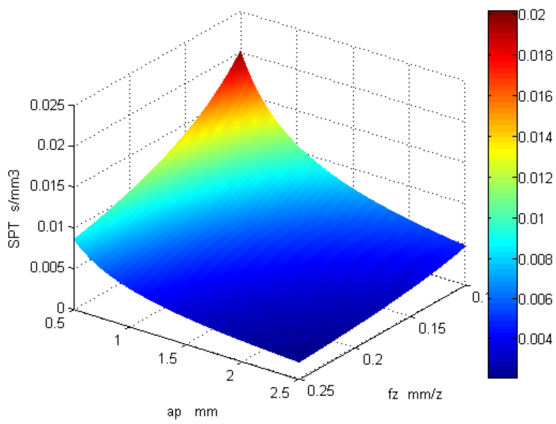

Fig.14. SPT_{total} changes with respect to feed rate per tooth and cutting depth (v_c=100m/min)

6. Conclusion

Cutting parameter optimization of CNC milling operations has been undertaken for several years based electrical energy decrement consideration. The current and urgent need to optimize cutting parameter for energy and carbon footprints reducing in CNC milling requires an extension of the energy boundary to take into account the embodied energy all the auxiliary materials. In this paper, a comprehensive energy model of CNC milling operation considering both the electrical energy and embodied energy of the cutting tools and cutting fluid is established and quantified through nonlinear regression fitting. Based on this model, a multi-objective cutting parameter optimization model is proposed to minimize the specific energy consumption and specific processing time. A case study is conducted to analyze the necessity of multi-objective optimization and parametric influence on specific energy consumption and specific processing time.

From the results of the case study, it is concluded that the optimum cutting parameters will vary with the energy boundary whether including the embodied energy of the auxiliary materials or not. Among the cutting parameters (i.e. cutting velocity, feed rate per tooth and cutting depth) of the CNC milling operation, cutting velocity is the most influential parameters for the specific energy consumption. The more comprehensive the energy requirements of the CNC milling process are accounted for, the lower cutting velocity should be chosen. Additionally, it also can be found that the optimum cutting parameters for maximum machining efficiency does not necessarily satisfy the maximum energy efficiency criterion. Multi-objective optimization is an effective method in achieving a balance between maximum energy efficiency and maximum machining efficiency.

This research can be extended in several directions. For instance, milling using multiple cutting tools is very attractive with machining efficiency and cost considerations. Tool sequence and cutting parameters optimization considering the embodied energy of the cutting tools and cutting fluid deserves a further study. More factory data is also needed to test the proposed model in the future.

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