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Multi-objective tool sequence optimization in 2.5D pocket CNC milling for minimizing energy consumption and machining cost

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Abstract

Tool sequence selection is an important task for 2.5D pocket milling and has a significant influence on both the energy consumption and machining cost of the final product. In this paper, the influence of tool sequence on energy consumption is firstly analyzed. Then a multi-objective tool sequence optimization model is proposed with the objective of minimizing energy consumption and machining cost and solved by the graph algorithm. Finally, a case study is carried out to validate the proposed model and search for the trade-off solutions between energy consumption and machining cost.

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*Keywords:*Tool sequence optimization;Energy consumption;CNC milling;2.5D pocket

1. Introduction

In 2013, the energy consumption of industrial sector accounts for 30% of the total energy used in the United States [1]. In the case of China, it makes a large contribution to overall energy consumption of over 60% of the total [2]. Thus, reducing energy consumption of industrial sector is identified as a priority area due to the global increasing imbalance between energy supply and demand. In fact, CNC machining is a widely used subtractive process in the industrial sector, which is responsible for a substantial portion of the total industry consumed energy. Reducing the energy consumption of CNC machining processes can account for significant decrement of the environmental impact.

In recent years, many researchers have studied the issue to characterize energy consumption of machine tools. Gutowski et al. differentiated the energy requirements for a wide range of machining processes into a constant and a variable portion. The fixed power comes from the basic equipment required to support the accomplishment of the machining tasks; while the variable portion is dependent on the rate of material processing [3]. Based on the work of Gutowski et al., Li et al. explored the breakdown of fixed energy consumption of machine tools into auxiliary, cooling hydraulic, lubrication, and other power units. Six machine tools covering different machining processes are selected for this investigation in order to evaluate the future energy savings [4]. In the work presented by Balogun and Mativenga, the direct energy requirements of general mechanical machining processes were also studied [5]. A comprehensive overview of such models can be found in [6].

Based on the above researches, efforts related to the energy reduction of machining processes have been made in the perspectives of cutting parameters optimization and process planning optimization. For instance, Velchev et al. proposed a model to minimize energy consumption with respect to insert grade, feed rate and cutting depth [7]. Rajemi et al. modelled and optimized the energy of a turning process in order to derive an economic tool-life and cutting parameters that satisfied the minimum energy footprint requirement [8]. Similarly, Valera and Bhavsar explored the effect of cutting parameters on surface roughness and power consumption in turning operation. The experiments found that increase in spindle speed improves surface finish at the cost of power consumption, while increase in feed rate or depth of cut multiplies both roughness and power consumption [9]. Apart from the researches related to the parameter optimization for energy consumption reduction, many studies focused on the

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optimization of the machining process planning. Newman et al. pointed out that energy consumption of interchangeable machining processes can differ significantly, by at least 6% of the total in low loads and is likely to up to 40% at higher loads [10]. The work presented by Zhang et al. shows that the machining features of the workpiece are used to automatically or semi-automatically generate feasible process plans with energy consumption consideration [11]. Other relevant works can be found in [12].

CNC milling is a widely used processing method that removes metal by a rotating multiple tooth cutter. Milling using a set of cutting tools has become very attractive with machining efficiency and cost considerations. Thus, the cutting tool sequence selection is an important activity in process-planning for milling. In recent years, many researchers have studied the challenges associated with tool sequence selection. D'Souza et al. described a valid method based on the Directed graph to find an optimal tool sequence for the lowest machining cost in 2.5D and 3D pockets rough machining [13-14]. Chen et al. presented a toolpath generation approach based on the medial axis transform and proposed an optimization model of selecting multiple tools with the aim of minimizing production time in 2.5D pocket rough milling [15]. Geng et al. developed a toolpath length estimation approach to determine an optimal tool sequence in sculptured surfaces milling for maximizing the machining efficiency [16]. Yao et al. have formulated a multipart milling problem using the geometric algorithms to select an optimal tool sequence for reducing the machining time in several distinct 2.5D pockets milling [17]. Other relevant work on optimization of tool sequence can be found in [18-19].

A perusal of current literature concludes that existing research about tool sequence optimization in 2.5D pocket milling is only concentrated on reduction of machining time and cost. While significant efforts have been devoted to analyse energy consumption of machine tools, little of them looked into tool sequence optimization. However, the energy consumption of the milling process is highly dependent on the tool diameter as the machining power and time vary with it [20]. Thus, optimizing tool sequence can effectively reduce the energy consumption in CNC milling process.

Given the lack of work in optimizing the tool sequence considering energy consumption reduction, this paper fills this gap and studies multi-objective tool sequence optimization with the aim of minimizing energy consumption and machining cost for 2.5 D pocket CNC milling. The rest of the paper is organized as follows. Section 2 is the statement of the optimization problem. Section 3 analyses the influence of tool sequence on energy consumption. In Section 4, a multi-objective tool sequence optimization model is proposed for minimizing energy consumption and machining cost. The solution through the graph algorithm is presented in Section 5. The validity of this approach is demonstrated through a case study Section 6, followed by the conclusion and future research in Section 7.

2. Problem Statement

With the development of automatic tool changers in modern CNC milling center, it is practical to use multiple cutting tools to quickly finish the product, as large tools can rapidly generate the rough shape and a smaller clearing tool can generate the net-shape. For a given2.5D pocket, the accessible area of each feasible tool is restricted by its internal geometry. Smaller tools have larger accessible areas inside the pocket as compared to larger ones.

The problem of optimal tool sequence selection in 2.5D pocket machining is defined as follows. Given a 2.5D pocket and there are a set of cutting feasible tools $T_f=\{T_1,T_2,\ldots,T_n\}$ with diameter $D(T_1)> D(T_2)>\ldots>D(T_n)$. The critical tool T_{cri} (i.e. T_n) is the only one feasible tool which is small enough to machine the pocket completely without gouging, hence each tool sequence contains the cutter T_{cri}. The problem is to find an optimal tool sequence $T_f^*=\{T_1^*,T_2^*,\ldots,T_m^*,T_n\}$ of $T_f=\{T_1,T_2,\ldots,T_n\}$ to produce the 2.5D pocket with the goal of incurring the minimum combined energy consumption and cost, and the cutters will be used in descending order of sizes.

3. Tool sequence influence on energy consumption of the 2.5D pocket CNC milling

3.1. Composition of energy consumption in CNC milling

The energy consumption of a milling operation can be calculated as shown in Eq.(1):

$$E = E_0 + E_u + E_c + E_a \tag{1}$$

Where E_0 is the fixed energy consumed by the machine modules, E_u is the unload energy to keep the spindle rotating, E_c is the cutting energy to remove the workpiece material and E_a is the additional load loss energy generated by cutting load [21].

According to the work presented in [21], the energy consumption of the machine tool can be calculated as:

$$\begin{aligned} E &= E_0 + E_u + E_c + E_a \\ &= P_0.(t_{air} + t_c) + P_u.(t_{air} + t_c) + P_c.t_c + P_a.t_c \end{aligned} \tag{2}$$

Where P_0 is the fixed power consumed by the activated machine components that ensure the operational readiness of the machine tool, such as lighting and coolant pump. P_u is the unload power when spindle runs steadily without material removal. P_c is the cutting power consumed at the tool tip for removing workpiece material. P_a is the additional load loss power generated by cutting force, which is a linear function in terms of the cutting power P_c, i.e. $P_a=b_mP_c$, where b_m is the correlation coefficient. t_{air} is the air cutting time without removing material, t_c is the cutting time to remove the workpiece material.

When machining the 2.5D pocket, there may be many feasible milling strategies with different tool sequences. The accessible area of each feasible tool varies with the pocket internal geometry and the tool sequence. From Eq. (2), it can be found that the energy consumption for each feasible tool sequence varies with the unload power P_u, cutting power P_c, air cutting time t_{air} and cutting time t_c. The detailed analysis is given below.

3.2. The influence of tool diameter on unload power and cutting power

In the milling process, the cutting parameters $p(n,f_v,a_p,a_e)$

differs with the cutting tool diameter $D(T)$. As the unload power P_u and the cutting power P_c are related to the cutting parameters $p(n,f_v,a_p,a_e)$, the unload power P_u and the cutting power P_c will differ with the cutting tool diameter $D(T)$.

$$\begin{cases} P_u = f[D(T)] \\ P_c = f[p(n, f_v, a_p, a_e), D(T)] \\ p(n, f_v, a_p, a_e) = f[D(T)] \end{cases} \tag{3}$$

Where n, f_v, a_p and a_e are the spindle speed, feed rate, width of cut and depth of cut, respectively.

3.2.1. The influence of tool diameter on unload power

The unload power P_u is mainly consists of the power demand by motors, inverters and transmission, which is a quadratic function in terms of the spindle speed n [21]:

$$\begin{aligned} P_u &= P_{u0} + a_1 n + a_2 n^2 \\ &= P_{u0} + a_1\left(\frac{1000 v_c}{\pi D(T)}\right) + a_2\left(\frac{1000 v_c}{\pi D(T)}\right)^2 \end{aligned} \tag{4}$$

Where P_{u0}, a_1 and a_2 are unload power coefficients, v_c is cutting velocity. From Eq.(4), it can be found that the unload power P_u is dependent on the tool diameter $D(T)$.

3.2.2. The influence of tool diameter on cutting power

The cutting power P_c is related to cutting force F_c and cutting velocity v_c. The simplified relationship is given below [8]

$$P_c = F_c \times v_c \tag{5}$$

$$F_c = k_{F_c} \frac{C_F a_p^{X_F} f_z^{y_F} a_e^{u_F}}{D(T)^{q_F} n^{w_F}} \tag{6}$$

$$v_c = \frac{\pi D(T) n}{1000} \tag{7}$$

Where k_{Fc}, C_F, x_F, y_F, u_F, q_F, w_F are the corresponding exponents related to the cutter and workpiece material. From Eq.(5)-(7), it can be found that the cutting power P_c will change with the tool diameter $D(T)$.

3.2. The influence of the accessible area on air cutting time and cutting time

Air cutting time t_{air} and cutting time t_c are dependent on the air cutting length l_{air} and cutting length l_c respectively. When machining the 2.5D pocket, the accessible area A_f of each cutting tool differs with its internal profile. Besides, the accessible area A_f of a specific cutting tool will also change with different tool sequence. Hence, the air cutting length l_{air} and cutting length l_c will be changed due to different tool sequence. For that reason, the air cutting time t_{air} and cutting time t_c will be changed. The influence of accessible area A_f on air cutting time t_u and cutting time t_c can be expressed as follows

$$\begin{cases} t_{air} = f(l_{air}) \\ t_c = f(l_c) \\ (l_{air}, l_c) = f(A_f) \end{cases} \tag{8}$$

3.3.1. The accessible area with different tool sequence for a specific cutting tool

Given an feasible tool set $T_f = \{T_1, T_2, \ldots, T_n\}$ with diameter $D(T_1) > D(T_2) > \ldots > D(T_n)$, and for any two feasible tool T_i、T_j($i<j$ and i，$j \in n$)which has the accessible area $A_f^{\,i}$、$A_f^{\,j}$ respectively, then $A_f^i \subset A_f^j$. In other words, smaller tools have larger accessible areas inside the pocket as compared to larger tools. Furthermore, no matter which larger tool is used before T_j, as long as the T_i has done its own areas machining then the shape of the pocket is always same [18]. Consider a tool sequence with m feasible tools which are selected from the feasible tool set T_f, let $A_f^{\,k}$ (k=1,2,…,m) and ΔA_f^k represent the theoretical accessible area and the actual accessible area of the k^{th} feasible tool respectively. Then the actual accessible area of the feasible tools can be expressed as follows

$$\Delta A_f^k = \begin{cases} A_f^k, k = 1 \\ A_f^k - A_f^{k-1}, 1 < k \le m \end{cases} \tag{9}$$

3.3.2. The influence of the accessible area on air cutting time

The air cutting time t_{air} is related to the air cutting length l_{air} and the air cutting feed rate f_v^{air}

$$t_{air} = \frac{l_{air}}{f_v^{air}} = \frac{l_{air-q}}{f_v^{air-q}} + \frac{l_{air-s}}{f_v^{air-s}} \tag{10}$$

Where $l_{air\text{-}q}$, $l_{air\text{-}s}$ are the air cutting length of the rapid-feed movement and slowly-approach motion without material removal respectively, and $f_v^{air\text{-}q}$, $f_v^{air\text{-}s}$ are the related air cutting feed rate. In the pocket machining process, the actual accessible area of a specific cutting tool is determined by the previous one in a feasible tool sequence. Hence, for a specific cutting tool, its actual accessible area ΔA_f^k varies with different tool sequence. The air cutting length $l_{air\text{-}q}$ and $l_{air\text{-}s}$ will be changed due to the changed actual accessible area ΔA_f^k.

3.3.3. The influence of the accessible area on cutting time

Similar to the air cutting time, the cutting time t_c is also related with the cutting length l_c and the cutting feed rate f_v^c. In the milling process, the Contour-Parallel strategy is usually used to generate the toolpath. Thus, the cutting time t_c can be calculated approximately as follows.

$$t_c = \frac{l_c}{f_v^c} = \sum_{i=1}^{N} \frac{l_c^i}{f_v^c} = \sum_{i=1}^{N} \frac{\Delta A_f^i}{a_e f_v^c} = \sum_{i=1}^{N} \frac{\Delta A_f^i}{\xi D(T) f_v^c} \tag{11}$$

Where N is the number of machining passes, $l_c^{\,i}$ is the tool path length of the i^{th} pass, ξ is the interval factor of toolpath.

As shown in Eq.(11), the cutting time t_c is related to the tool path length l_c which is determined by the tool diameter $D(T)$ and its actual accessible area ΔA_f.

4. Multi-objective tool sequence optimization model

4.1. Variable

As discussed above, the energy consumption of 2.5D pocket CNC milling varies with different tool sequences, thus the tool sequence is the optimization variable in this paper.

4.2. Objective functions

For the tool sequence optimization, many researchers have studied the optimization objectives of machining time or cost. In this paper, the objectives of energy consumption and machining cost are synthetically considered.

4.2.1. Energy consumption

From the analysis of section 3.3.1, suppose S_k represents the pocket's shape after the k^{th} (k=1,2…m) tool has machined its accessible area. Thus, the energy demand $\Delta E_k(S_k, S_{k-1})$ of the k^{th} tool T_k in machining process can be obtained by

$$\begin{aligned}\Delta E_k(S_k,S_{k-1}) &= P_0(t_{air}+t_c)+P_u(t_{air}+t_c)+P_c t_c+P_a t_c \\ &=(P_0+P_u)\left(\frac{l_{air-q}}{f_v^{air-q}}+\frac{l_{air-s}}{f_v^{air-s}}+\sum_{i=1}^{N}\frac{\Delta A_f^i}{\xi D(T) f_v^c}\right)+(1+b_m)\sum_{i=1}^{N}\left(P_c^i\cdot\frac{\Delta A_f^i}{\xi D(T) f_v^c}\right)\end{aligned} \tag{12}$$

Thus, the total energy consumption can be expressed as

$$E_{total}=\sum_{k=1}^{m}\Delta E_k(S_k,S_{k-1}) \tag{13}$$

4.2.2. Machining Cost

The machining cost is the sum of overhead cost C_O, cutting tool cost C_T, and energy cost C_E. Thus, the machining cost $\Delta C_k(S_k,S_{k-1})$ of the k^{th} tool T_k can be generally described as

$$\Delta C_k(S_k,S_{k-1})=(C_O+C_T+C_E)_k \tag{14}$$

Thus, the total energy consumption can be expressed as

$$C_{total}=\sum_{k=1}^{m}\Delta C_k(S_k,S_{k-1}) \tag{15}$$

4.2.2.1. Overhead cost C_O. Overhead cost is modelled as the production of the overhead cost per unit time R and the total machining time

$$C_M = R\times(t_{air}+t_c) \tag{16}$$

4.2.2.2. Cutting tool cost C_T. Cutting tool cost $C_T$is associated with cutting time and the tool life as shown in Eq.(17)

$$C_T=\lambda_t t_c / T_l \tag{17}$$

Where λ_t and T_l represent the unit price and life of cutting tool respectively, the tool life can be calculated by Taylor equation [23] as shown in Eq.(18)

$$T_l=\left(\frac{C_v k_v d^{q_v}}{V_c a_p^{x_v} f_z^{y_v} a_e^{u_v} z^{p_v}}\right)^{\frac{1}{m}} \tag{18}$$

Where k_v, C_v, q_v, x_v, y_v, u_v, p_v, m are the corresponding coefficient.

4.2.2.3. Energy cost C_E. Energy cost C_E is evaluated from the product of the energy consumption ΔE multiplied by its unit cost λ_e, which can be expressed as

$$C_E=\lambda_e\cdot\Delta E \tag{19}$$

4.3. Multi-objective optimization model

There are two methods to solve the problem of multi-objective optimization. The first one uses an aggregation of the objectives to remain in the single-objective context. The other one is the so-called Pareto multi-objective optimization. Due to the features of simple concept, computational efficiency, and easy implementation, the first technique is adopted in this paper. The optimization objective weighted sum of energy consumption and machining cost can be expressed as

$$\Delta V_k\left(S_k,S_{k-1}\right)=w_1\Delta E_k\left(S_k,S_{k-1}\right)+w_2\Delta C_k\left(S_k,S_{k-1}\right) \tag{20}$$

where ΔV_k is the optimization objective weighted sum of energy consumption and machining cost of the feasible cutting tool T_k, w_1 and w_2 are the weight coefficients, $w_1+w_2=1$.

With the variable and objectives defined above, the multi-objective tool sequence optimization model for minimizing energy consumption and machining cost of 2.5D pocket CNC milling is then formulated as follows

$$\min F(T_f^*)=(\min E_{total},\min C_{total})=\min\sum_{k=1}^{m}\Delta V_k(S_k,S_{k-1}) \tag{21}$$

$$s.t.\begin{cases}T_f^*=\left\{T_1^*,T_2^*,\ldots,T_m^*,T_n\right\}\subseteq T_f=\{T_1,T_2,\ldots,T_n\},0\le m\le n-1\\ \Delta V_k\left(S_k,S_{k-1}\right)=w_1\Delta E_k\left(S_k,S_{k-1}\right)+w_2\Delta C_k\left(S_k,S_{k-1}\right)\\ S_k\in S=\{S_1,S_2,\ldots,S_n\},1\le k\le n\end{cases}$$

5. Optimization solution

5.1. Determination of the feasible tool set

Based on the internal geometry of the pocket, the smallest tool size $D(T_s)$ for pocket machining equals to the minimum distance between a convex vertex and another one. The largest tool size $D(T_l)$ can be obtained from the maximum offset distance without gouging. The critical tool T_{cri} and the efficient tool T_{eff} are the smallest feasible tool and the largest feasible tool respectively.

Generally, the diameter of the critical tool $D(T_{cri})$ and the efficient tool $D(T_{eff})$ are equals to $D(T_s)$ and $D(T_l)$ respectively. But in fact, there are not always the tools whose diameters are same as $D(T_s)$ and $D(T_l)$. Hence, a method to select the critical tool T_{cri} and efficient tool T_{eff} is proposed in this paper.

Given X cutting tools(1,2,…,X) with the diameter in descending order, the critical tool T_{cri} and efficient tool T_{eff} are then selected by the following Eq.(22) and Eq.(23)

$$T_{cri} = \begin{cases} T_i, & \exists D(T_i) = D(T_s), i = 1,2..., X \\ T_{i+1}, & \exists D(T_{i+1}) < D(T_s) < D(T_i), i = 1,2..., X-1 \end{cases} \tag{22}$$

$$T_{eff} = \begin{cases} T_i, & \exists D(T_i) = D(T_l), i = 1,2..., X \\ T_{i+1}, & \exists D(T_{i+1}) < D(T_l) < D(T_i), i = 1,2..., X-1 \end{cases} \tag{23}$$

Thus the feasible tool set can be expressed as

$$T_f = \{D(T_f) | D(T_{cri}) \le D(T_f) \le D(T_{eff})\} \tag{24}$$

5.2. Identification of the accessible area

In the 2.5D pocket milling process, it is imperative to identify the accessible area of each feasible tool. In this paper, the Contour offset approach [13] proposed by D'Souza et al. is adopted.

5.3. Graph algorithm

As shown in Fig.1, an example of the graph that represents all feasible tool sequences with 5 tools is given. In which the *node* represents the shape of the pocket after t_i is done machining. Fig.1, 16 feasible tool sequences can be obtained by the 15 node pairs. The *edge* is the energy consumption and machining cost. For instance, *edge (3,4)* is the energy consumption and machining cost for t_4 after t_3 is done. The optimal tool sequence is the minimum energy consumption and machining cost from the start node to the final node which can be obtained using Dijkstra algorithm [14]

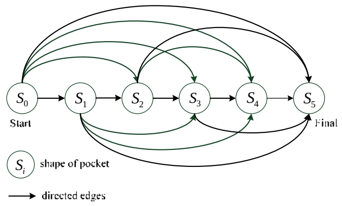

Fig.1 Directed graph representation of tool sequences

6. Case study

To validate the proposed model and optimization approach, a case study on machining a 2.5D pocket, as shown in Fig.2, is conducted. The machining experiments are performed on a PL700 vertical machining centre. During the experiment, 15 cutting tools are available in the workshop with the diameters {2,4,5,6,8,10,14,16,18,20,28,32,36,40,45}. The critical tool $D(T_{cri})$=6mm and the efficient tool $D(T_{eff})$=20mm are identified according to Eq.(22) and Eq.(23). After that, the feasible tool set T_f ={20,18,16,14,10,8,6}is obtained through Eq.(24).The total stock of roughing and finishing are 6.00mm and 0.12mm respectively. Meanwhile, in order to ensure the machining accuracy and surface quality of the production, the critical tool T_{cri} is only one feasible cutter who is adopted in finishing operation. Before the machining, as shown in Table1, the number of machining passes and cutting parameters of each feasible cutting tool are obtained according the work in [22]. In Table2 and Table3, the machining cost and the coefficients in the relevant equations are listed.

Table 1. Cutting parameters of each feasible cutting tool

Cutting tool	T_1	T_2	T_3	T_4	T_5	T_6	T_7	
							R_{ough}	F_{inish}
$D(T)$(mm)	20	18	16	14	10	8	6	6
A_f(mm^2)	4410	4749	4994	5213	5645	6062	6185	6185
n(r/min)	788	876	1005	1190	1452	1755	2021	2736
f_v^c(mm/min)	153	181	207	231	276	306	329	265
a_p(mm)	3.0	3.0	2.0	2.0	1.5	1.5	1.2	0.12
a_e(mm)	17.1	15.4	13.6	12.0	8.5	6.9	5.2	4.3
N	2	2	3	3	4	4	5	1

Table 2.The related cost of machining

R	λ_e	λ_t (RMB)						
($RMB/hour$)	(RMB/kwh)	T_1	T_2	T_3	T_4	T_5	T_6	T_7
55	0.83	405	360	320	275	205	175	150

Table 3.The coefficients in relevant equations

No.	The coefficients
Eq.(4)	P_{u0}=7.15, a_1=16.49×10^{-2}, a_2=-2.6×10^{-5}
Eq.(6)	k_{Fc}=1,C_F=119,x_F=1.0,y_F=0.7,u_F=0.85, w_F=0.13,q=0.73
Eq.(12)	P_0=1450, f_v^{air-q}=5000, f_v^{air-s}=100, b_m=0.2
Eq.(18)	C_v=145,k_v=0.8,q_v=0.44,x_v=0.1,y_v=0.26,u_v=0.24,p_v=0.13,m=0.5
Eq.(20)	w_1=0.45,w_2=0.55

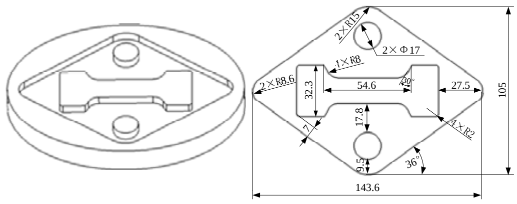

Fig.2. A 2.5D pocket with complex islands

6.1. Optimization results

As shown in Table 4, the optimization results of Minimum energy E_{total}, Minimum cost C_{total} and Minimum E_{total}&C_{total} are obtained respectively. The calculated machining time T_p is also listed in Table 4. Moreover, the energy consumption for 6 tool sequences with only the critical tool and a larger feasible tool are shown in Table 5.

Table 4. Optimization results

Optimization objective	Tool sequence	T_p/s	E_{total} /kwh	C_{total} /RMB	$\sum_{k=1}^{m}\Delta V_k$ /%
Minimum E_{total}	T_3,T_7	749.9	0.424	52.35	9.13
Minimum C_{total}	T_2,T_6,T_7	856.2	0.489	46.28	8.99
Minimum E_{total}&C_{total}	T_2,T_3,T_7	853.4	0.473	46.95	8.94
Empirical strategy	T_5,T_7	991.0	0.533	53.49	10.13
One tool strategy	T_7	1303.3	0.682	60.84	12.13

Table 5. Energy consumption for 6 tool sequences with only the critical tool and a larger feasible tool

The schemes of two tools	T_1,T_7	T_2,T_7	T_3,T_7	T_4,T_7	T_5,T_7	T_6,T_7
Energy E_{total}/kwh	0.557	0.529	0.424	0.432	0.533	0.536

6.2. Results analysis and discussion

From the optimization results in Table 4, it can be concluded that milling using a tool sequence with multi-tools shows significant advantages in reducing energy consumption and machining cost compared to single-tool sequence with the only critical tool. For instance, compared to single-tool sequence (T_7), the milling strategy with the tool sequence (T_2,T_3,T_7) reduces the energy consumption and machining cost by 30.6% and 22.8% respectively.

When the optimization is to minimize energy consumption and machining cost, the milling strategy with the tool sequence (T_2,T_3,T_7) strikes a balance between the energy consumption and machining cost. Compared to the milling strategy to minimize energy consumption, it increases energy consumption by 11.5% but decreases machining cost by 10.3%. Similarly, compared to the milling strategy to minimize machining cost, it increases the machining cost by 1.4% but decreases the energy consumption by 3.3%. In addition, when compared to the empirical milling strategy, the energy consumption and machining can be reduced by 11.3% and 12.2% respectively.

The cutting tools in optimal tool sequence should not be too much. The reason is that every tool change incurs a machining time and energy consumption penalty due to the rapid-feed movement and slowly-approach motion without material removal of cutters.

The tool sequence which has shorter machining time also shows a decreasing trend in energy consumption. This is because in such kind of machine tools whose fixed power P_0 accounts for a large proportion of the total input power P_{total}, reducing the machining time means saving energy.

As shown in Table 5, energy consumption for 6 tool sequences with only the critical tool and a larger feasible tool are given. The energy consumption firstly decreases with the increase of the larger feasible tool diameter, and then increases. This is because that a larger feasible tool can quickly remove the workpiece material and reduce the machining time. Hence the total energy consumption can be reduced as the fixed energy is time dependent and takes a big part of the total energy consumption. However, with the larger feasible tool diameter increase, its accessible area decrease, the workpiece material need to be removed by the critical tool increases. This may increase the machining time due to the lower material removal rate of the smaller critical tool. For this reason, the total energy consumption increases. So the advantage of larger cutters' high machining efficiency cannot be considered blindly when choose cutting tools.

7. Conclusion

In this paper, the influence of tool sequence on energy consumption of 2.5D pocket CNC milling is firstly analyzed. And a multi-objective tool sequence optimization model for minimizing energy consumption and machining cost is proposed and solved by the graph algorithm. Finally, a case study is conducted to validate the proposed model and approach and find the trade-off solutions between energy consumption and machining cost. Based on the work presented in this paper, manufacturers can easily select the optimal tool sequence to reduce energy and save cost in 2.5D pocket CNC milling process. Further study of tool sequence optimization for freeform surface milling considering energy consumption will be our future research.

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