Optimizing Cutting Conditions in Single Pass Face Milling for Minimum Cutting Energy, Time, Cost, and Surface Roughness

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Abstract. Technology evolution and the demand of modern life have led to more using for machine tools which are the basic energy consumption devices in manufacturing. Subsequently, CO_2 emissions in the atmosphere will increase, causing several climate changes such as the greenhouse effect. As the resources and energy in the earth are limited and getting fewer and fewer, sustainable manufacturing is gaining more and more attention to produce the same product with less negative environmental impacts. In this paper, a mono-objective optimization for sustainable manufacturing is presented. Such approach needs a balance between economic and ecological aspects. Thus, the objective of this work is machining product with less environmental impacts by minimizing consumed energy with respect to technological and economic constraints. The consumed energy is modelled based on the dynamic behavior of the cutting forces. A case study of single pass of face milling operation is carried out using the particle swarm optimization tool. The surface quality is adopted as an objective in this work. Three decision variables are taken into account during the resolution such as rotational speed, axial depth of cut and feed per tooth. Results show that the proposed optimization model has a great efficiency to find a trade-off between the four objective functions in order to minimizing them.

Keywords: Sustainable manufacturing · Optimization · Particle swarm · Consumed energy

1 Introduction

In manufacturing, the machining process is the main electrical energy consumer [7]. In fact, the CNC machining has an important effect on environment due to the high level of electrical energy consumption [3] and global warming [10]. Thus, the reduction of the consumed energy by the machining process is important [6]. For this reason several works aim to study the relationship between the electrical energy demanded and cutting

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parameters during machining. For example, Luan et al. [9] utilized the response surface method (RSM) to study the effect of cutting parameters (cutting speed, axial depth of cut, radial depth of cut and feed per tooth) on the consumed energy during a face milling operation. The obtained results minimize the consumed energy and ameliorate the surface roughness. Wang et al. [12] used genetic algorithm to find optimum values of cutting parameters in case of high speed milling process in order to achieve maximum machining efficiency. Jang et al. [5] adopted particle swarm algorithm to obtain optimum cutting parameters that reduce energy consumption in milling operation case and minimal lubrication case. Li et al. [8] presented a resolution of a multi objective problem of energy efficiency and cutting time in case of milling process based on Tabu Search algorithm (TS). Results show that the radial and axial depths of cut are the significant parameters on the consumed energy while the spindle rotational speed is the most significant on the cutting time. Alberteli et al. [1] presented an optimization of both consumed energy and treatment time of a face milling operation. Firstly, mono variable optimization considering only the cutting speed is performed. Secondly multi variable optimization, using a multi-dimensional exhaustive enumeration method considering the axial depth of cut, feed per tooth and cutting speed, to minimize both the energy consumption and the production time, is performed. Tapoglou et al. [11] have elaborated a novel approach in order to ameliorate the energy efficiency of machine tools based on online cutting conditions optimization.

The common point between the backgrounds of developed works described above that they all strived to minimize the consumed energy by the milling machine tool. However, the time variation of the milling forces during the removing material process as well as the incorporation of the surface roughness as an objective during the optimization of the consumed energy is neglected. Thus, the aim of this work is to develop a new model of face milling machining energy optimization by considering cutting time, surface roughness and cutting cost factors.

2 Objective Functions

The objective function can be modeled as the sum of four objective functions describing cutting time; cutting consumes energy, machining cost and surface quality as described in the above sections.

2.1 Cutting Time

The required time to remove material is calculated using the following equation:

$$f_1 = t_{machining} = \frac{L + d_a}{\Omega f_z N} \tag{1}$$

where L is the workpiece length, Ω is the spindle rotational speed, f_z is the feed per tooth, N is the tool teeth number and d_a is the approach distance calculated as following:

$$d_a = D/2 - \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{a_e}{2}\right)^2} \tag{2}$$

where a_e is the radial depth of cut and D is the tool diameter.

2.2 Machining Energy

The mathematical model of cutting energy is presented in the next equation:

$$E_{machining} = \int_0^{t_{machinning}} P_{machinning}(t)dt \tag{3}$$

where $P_{machining}(t)$ is the variable power consumed by the machining system (spindle and axis feed) at the tool tip to remove material which can be estimated by the next model shown in equation:

$$f_2 = E_{machining} = \int_0^{t_{machining}} P_{machinning}(t)dt = \int_0^{t_{machining}} \left(F_t(t)\ V_c + F_f(t)\ V_f\right) dt \tag{4}$$

where V_c and V_f are respectively the cutting speed and the feed rate, $F_t(t)$ and $F_f(t)$ are respectively the tangential and the feed components of the cutting force. These two forces are variable and their values change with time due the non-linearity of the milling operation. They are calculated in two steps: firstly we calculate the differential tangential $dF_{t,i}$ radial $dF_{r,i}$ and axial $dF_{r,i}$ components for the ith tooth which are expressed as a nonlinear function of varying chip load $h(\Phi_i)$ expressed as following [2]:

$$\begin{cases} dF_{t,i}(\Phi_i(t)) = g(\Phi_i(t))k_t a_p h(\Phi_i(t)) \\ dF_{r,i}(\Phi_i(t)) = k_r g(\Phi_i(t))k_t a_p h(\Phi_i(t)) \\ dF_{a,i}(\Phi_i(t)) = k_a g(\Phi_i(t))k_t a_p h(\Phi_i(t)) \end{cases} \tag{5}$$

where k_t, k_r and k_a are the specific pressure of the cutting force considered as constants, a_p and f_z are respectively the axial depth of cut and the feed per tooth and $g(\Phi_i(t))$ is a function describing whether the ith tooth is active or not. It is expressed as following:

$$g(\Phi_i(t)) = \begin{cases} 1, & \Phi_{st} \le \Phi_i(t) \le \Phi_{ex} \\ 0, & else \end{cases} \tag{6}$$

with Φ_{st} and Φ_{ext} are respectively the cutter entry and exit angles.

The variable chip generated during the machining phase is composed of two components: static h_s and dynamic h_d caused by the instantaneous angular position of the ith tooth $\Phi_i(t)$.

$$h(\Phi_i(t)) = \underbrace{f_z \sin(\Phi_i(t))}_{h_s} + \underbrace{(u_x(t) - u_x(t-\tau))\sin(\Phi_i(t)) + \left(u_y(t) - u_y(t-\tau)\right)\cos(\Phi_i(t))}_{h_d} \tag{7}$$

where $\Phi_i(t)$ is modelled as following:

$$\Phi_i(t) = \Omega\, t + (i-1)\,\Phi_p \tag{8}$$

where Φ_p is the tooth spacing angle.

For a face milling process, the cutting forces components acting on the workpiece on feed direction X, on normal direction Y and on axial direction Z are obtained from the next equilibrium relation:

$$\begin{Bmatrix} dF_{x,i}(\phi_i(t)) \\ dF_{y,i}(\phi_i(t)) \\ dF_{z,i}(\phi_i(t)) \end{Bmatrix} = \begin{bmatrix} -\cos(\phi_i(t)) & -\sin(\phi_i(t)) & 0 \\ \sin(\phi_i(t)) & \cos(\phi_i(t)) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} dF_{t,i}(\phi_i(t)) \\ dF_{r,i}(\phi_i(t)) \\ dF_{a,i}(\phi_i(t)) \end{Bmatrix} \tag{9}$$

The total cutting force components in the X, Y and Z directions are computed by summing the elementary cutting force components exerted by all tooth. It can be expressed:

$$F_c(t) = \begin{Bmatrix} F_x(t) \\ F_y(t) \\ F_z(t) \end{Bmatrix} = \begin{Bmatrix} \sum_{i=1}^{N} d\,F_{x,i}(\phi_i(t)) \\ \sum_{i=1}^{N} d\,F_{y,i}(\phi_i(t)) \\ \sum_{i=1}^{N} d\,F_{z,i}(\phi_i(t)) \end{Bmatrix} \tag{10}$$

To estimate these forces components, a resolution of the differential equation of motion of a spindle flexible structure using the finite element method [4], as shown in Eq. (11), is elaborated.

$$[M_b]\{\ddot{q}\} + 2\Omega[G_b]\{\dot{q}\} + \left(\left[K_b - \Omega^2[C_b]\right]\right)\{q\} = \{F_c(t,q)\} \tag{11}$$

where $[M_b]$, $[G_b]$, $[K_b]$ and $[C_b]$ are respectively the mass, the gyroscopic, the stiffness and the centrifugal matrices. The vector $\{q\}$ denotes the degrees of freedom vector caused by elastic movements and associated to different nodes. The second member constitutes the total cutting force.

2.3 Surface Quality

The quality of the surface is described by the roughness which is adopted as a function to minimize in our work and it is modeled as following:

$$f_3 = kV_c^{x_1} f_z^{x2} a_p^{x3} \tag{12}$$

where x_1, x_2, x_3 and k are constants depending on workpiece and tool material.

2.4 Machining Cost

The machining cost is calculated as a sum of machine cost, tool cost and energy cost as expressed:

$$f_4 = C_{total} = k_0 t_{machining} + k_e E_{machning} + k_t \frac{t_{machining}}{T} \tag{13}$$

where k_0 is the machine cost during the cutting phase, k_e is the cutting energy cost, k_t is the tool cost and T is the tool life modelled by [13]:

$$T = \left(\frac{C_T D^{b_v}}{V_c f_z^{u_v} a_p^{e_v} a_e^{r_v} z^{n_v}} \right)^{1/x_v} \tag{14}$$

where b_v, u_v, e_v, r_v, n_v, C_T and x_v are constants.

During the optimization of the objective functions, some constraints must be satisfied. In the next section, we describe those constraints.

3 Constraints

3.1 Cutting Power

The cutting parameters values should verify the condition on the available power. In fact, the machining consumed power must be lower than the maximum power available on the spindle machine P_{max} as shown:

$$g_1 = \frac{k_s a_p f_z N V_c}{60{,}000 \Pi D} \leq P_{max} \tag{15}$$

where k_s is a specific pressure of the cutting force.

3.2 Cutting Force

The cutting force applied by the cutter tool on the workpiece must be lower than the maximal one that can be supported by the cutter tool. So, a constraint on the cutting force should be taken into account as following:

$$g_2 = \frac{k_s a_p f_z N}{\Pi D} \le F_{max} \tag{16}$$

3.3 Constraint with the Tool

The rupture resistance condition of a milling cutter constraint is written as following:

$$g_3 = \frac{8 k_s a_p f_z z V_c}{\Pi^2 D^3} \le \tau_{max} \tag{17}$$

4 Mathematical Formulation

In this paper, the objective is to find the optimum cutting parameters in a single pass of face milling operation (rotational speed Ω, feed per tooth f_z and axial depth of cut a_p) to minimize the cutting time f_1, the cutting energy f_2, the surface roughness f_3 and the machining cost f_4 at the same time. In order to normalize the total objective function, an optimization of each function is elaborated to obtain f_1^* the minimum cutting time, f_2^* the minimum cutting energy, f_3^* the minimum surface roughness and f_4^* the minimum cutting cost. Our optimization problem is described as following:

$$\begin{cases} min(F) = \dfrac{f_1}{f_1^*} + \dfrac{f_2}{f_2^*} + \dfrac{f_3}{f_3^*} + \dfrac{f_4}{f_4^*} \\ s.c: \begin{cases} g_1 \le f_{max} \\ g_2 \le P_{max} \\ g_3 \le \tau_{max} \end{cases} \end{cases} \tag{18}$$

The limit of the machine tool must be also considered as following:

$$\begin{cases} \Omega_{min} \le \Omega \le \Omega_{max} \\ f_{zmin} \le f_z \le f_{zmax} \\ a_{pmin} \le a_p \le a_{pmax} \end{cases} \tag{19}$$

5 Results and Discussions

To resolve the optimization problem, particle swarm algorithm (PSO) is used firstly to find f_1^*, f_2^*, f_3^* and f_4^* and secondly to find the minimum global objective function F. Indeed, PSO can solve a variety of difficult optimization problems and it is characterized with a few parameters to adjust, which makes it particularly easy to implement. Furthermore, research show that PSO algorithm has a better performance compared with other algorithms. In our study, each resolution is repeated 10 times to decrease the random effect of PSO algorithm. The tool and the workpiece materials are respectively carbide and steel. The parameters used during the simulation are summarized in Table 1.

The mono objective optimizations performed for the same milling process of only one objective function results are recapitulate in Table 2. For each optimization we calculate the value of the others function based on the optimum cutting conditions.

Table 1 Simulation parameters

Parameters	Value
Workpiece length (mm)	100
Tool diameter (mm)	40
Radial depth of cut (mm)	20
Axial depth of cut range of variation $[a_p^{min}\ a_p^{max}]$ (mm)	[1, 4]
Feed per tooth range of variation $[f_z^{min}\ f_z^{max}]$ (mm/tooth)	[0.1; 0.6]
Rotational speed range of variation $[\Omega^{min}\ \Omega^{max}]$ (rpm)	[397,8; 2387]
Roughness parameters	$k = 1.001$, $x_1 = 0.0088$, $x_2 = 0.3232$, $x_3 = 0.3144$
Machine cost ($/min)	$k_0 = 0.3$
Tool cost ($)	$k_t = 6.87$
Energy cost ($/KWh)	$k_e = 0.13$
Specific pressure (N/mm^2)	$K_s = 2000$

The cutting parameters obtained by minimizing the cutting time are different from ones obtained by minimizing surface roughness, cutting energy and cutting cost. Similar results are obtained for the cutting energy, the surface roughness and cutting cost. For this reason a global optimization of these four functions is elaborated as described in Eq. (18) in the next step. The results of the best solution obtained from the 10 resolution performed are summarized in Table 3.

Table 2 Optimization results of only one objective function

Model 1			Model 2			Model 3			Model 4		
$f_1^* = 1.075$ (s)			$f_2^* = 3.19 \times 10^2$ (J)			$f_3^* = 0.6$ (mm)			$f_4^* = 6.92$ ($)		
f_2 (J)	f_3 (mm)	f_4 ($)	f_1 (s)	f_3 (mm)	f_4 ($)	f_1 (s)	f_2 (J)	f_4 ($)	f_1 (s)	f_2 (J)	f_3 (mm)
1.063×10^3	1.3	22.96	6.43	1.63	6.92	10.2	4.46×10^3	9.64	6.28	3.19×10^2	1.63

Table 3 Optimization results of the global objective function

Minimization model 5	f_1 (s)	f_2 (J)	f_3 (mm)	f_4 ($)	$Min(F)$
Best solution	3.055	$5.11\ 10^2$	1.3	11.06	6.22

We conclude that the proposed optimization model (model 5 given by Eq. 18) ensure a balance between the minimum machining time, minimum machining energy, minimum machining cost and minimum of surface roughness. Indeed, compared to model 1, model 5 increases the machining time by 64.81% but decreases the cutting energy by 52%, the surface roughness are similar and the cutting cost is decreased by 52%. In comparison to model 2, it decreases the cutting time by 53%, the surface roughness by 20.24% but increases both the cutting energy and the cutting cost by 37%. When model 5 is compared to model 3, it decreases the cutting time by 70.04%, the cutting energy by 88% but increases the surface roughness by 54% and the cutting cost by 12%. Finally, compared to model 4, model 5 decreases the cutting time by 51.35% and the surface roughness by 18.75% but it increases the cutting energy and the cutting cost both by 37%. Those results prove that the proposed model 5 has a great efficiency to find a trade-off between the four objective functions in order to minimizing them.

6 Conclusion

In this paper, a mono objective optimization of a global model for minimizing cutting time, cutting cost, cutting energy and surface roughness is proposed and solved through PSO algorithm. A case study of single pass of face milling operation is conducted and search for the trade off solutions of minimizing cutting time, cutting cost, cutting energy and surface roughness. Three decision variables are taken into account such as rotational speed, axial depth of cut and feed per tooth. This work ameliorates the background described above by considering the surface roughness as an objective function and by considering the dynamic behavior of the cutting force during cutting energy modeling. As perspective, we propose to validate the obtained results from PSO algorithm by other results obtained from another algorithm such as Genetic Algorithm. We can also optimize a multi-pass face milling operation.

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