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SELECTION OF OPTIMUM CUTTING CONDITIONS USING A SIZE TOLERANCE PREDICTION MODEL FOR PERIPHERAL END MILLING

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ABSTRACT

This paper describes a strategy for selection of optimum cutting conditions for a single-pass peripheral end milling, when the size tolerances of component parts are specified. Most of the currently available optimization strategies are based on economic parameters such as production cost and machining time. In most cases, however, size tolerance is the first criterion for accepting the manufactured parts. Two variations of the strategy are proposed: one is based on technical parameter only, namely, specified part tolerance and the other is based on both technical and economical parameters, namely, specified part tolerance and economic cutting speed. The results indicate that the proposed two variations of the strategy can be implemented successfully for selection of optimum cutting conditions, which are based on either technical or both technical and economic parameters; thus providing a realistic solution to the cutting condition selection problem.

Keywords: Peripheral end milling; Size tolerance; Optimization

1. INTRODUCTION

Since early twentieth century, the optimization of machining operations through selection of cutting conditions has attracted the attention of many researchers. In 1907, Taylor [1] showed that the material removal rate of a single pass turning operation can be maximized through proper selection of cutting speed. However, the progress in developing a comprehensive optimization strategy has been rather slow due to lack of fundamental understanding of various machining processes. In recent years, it has gained renewed interest due to the availability of advanced computer-based tools. The CIRP working group on Modeling of Machining Operations is playing a vital role in advancing knowledge in this area. Current state-of-the-art in modeling and optimization of different machining operations may be found in [2, 3] but only those papers relevant to the present study are discussed here.

Wang [4] optimized the minimum production time and cost per component for end milling operations, subjected to a number of constraints such as feed force, spindle torque, machine tool power, machine tool speed, feed boundary, and surface roughness, by selection of cutting speed and feed rate. Cakir and Gurarda [5] optimized two machining conditions (namely, cutting speed and feed rate) for milling operations by applying a circular direction search method to minimize production cost. Their model included tool life, cutting power and surface roughness as *functional constraints* and spindle rpm and available maximum feed rate as *regional constraints*. Ghani, Choudhury and Hassan [6] applied statistical methods such as Taguchi method and Pareto ANOVA for optimizing surface roughness and the resultant force of end milling operation by selection of cutting speed, feed rate and depth of cut. Reddy and Rao [7] optimized surface roughness for end milling operation by selection tool geometry (namely, rake angle and noise radius) and cutting parameters (namely, cutting speed and feed rate) by using genetic algorithm. Recently, Jawahir and Wang [3] proposed a hybrid predictive model for optimum selection of cutting conditions and cutting tools; their objective functions for a milling operation included surface roughness, cutting force, tool life and metal removal rate.

It is worth noting that none of the above-discussed researchers has included size tolerance in their optimization strategy. To the best of our knowledge, none of the existing optimization strategies for various machining operations include size tolerance in their cutting conditions optimization strategy, although it is the first criterion for accepting the manufactured parts in most cases. It is probably difficult to predict the size tolerance of manufactured component parts due to the existence of several contributing factors for errors. Nonetheless, in our previous paper [8], we have demonstrated that it is possible to predict the size tolerance of a prismatic component machined through peripheral end milling under typical machining conditions. A logical extension of this work is to apply this model to solve inverse problems, which is the main objective of this study. For example, selection of cutting conditions based on specific size tolerance of component parts. Inclusion of size tolerance is beneficial from a technical point of view because it guarantees the function of the product. It can yield economic benefits as well by reducing scatter of size variations of machined parts, thus preventing rejects.

2. SCOPE

Size tolerance is the total amount of variation permitted in the actual size of a component part or a feature, which controls linear and angular dimensions. For the sake of simplicity, this study only deals with linear dimensions for a prismatic component that are normally defined by the distance between two parallel surfaces.

The cutting experiments were conducted using HSS flat-end type end mills manufactured by YG-1, South Korea with 16 mm diameter, four flutes, 30º helix angle, 10º rake angle and 55 mm tool overhang. The chosen workpiece material was Aluminum 2014-T6. The cutting tests were carried out on a vertical machining centre ACE-V30 manufactured by Daewoo Heavy Industries Ltd using *down milling* without the use of coolant. The axial depth of cut was 16 mm for cutting experiments. Here, it must be pointed out that machining operations are also greatly influenced by *cutting configurations* (that is, tool material, tool diameter, and tool geometry) which are not included in this study. Therefore, the results presented here many not necessarily be valid, when different cutting configurations are used.

A Kystler, type 9257B dynamometer was employed for measuring the three force components F_x, F_y and F_z of the instant cutting force. The machined components were measured with an On-Machine Measurement (OMM) system equipped with a MP700 Renishaw probe.

3. SIZE TOLERANCE PREDICTION MODEL

The size tolerance prediction model includes a cutting force model, a tool deflection model and a cutter diameter estimation model. The cutting force model tool and deflection model has been developed at the Intelligent Manufacturing Systems Lab, Pohang University of Science and Technology, South Korea as part of their ongoing research on *virtual manufacturing*. The cutter diameter estimation model is under development at the CAD/CAM Lab, Curtin University of Technology, Australia. The details of these models are available in [8-12]; only a brief description is given below.

3.1 Cutting Force Model

The cutting force model used is based on the mechanics of the cutting process and is, therefore, commonly known as the *mechanistic force model*. The underlying assumption behind such models is that the cutting forces are proportional to the uncut chip area. However, these models are not entirely analytical and their accuracy depends heavily on empirically determined *cutting force coefficients*, which are a function of cutting conditions and, as a result, cannot be applied readily to various cutting conditions. The adopted cutting force model has overcome this shortcoming by providing a method, details of which are available in [9], for determining *cutting-condition-independent cutting force coefficients*. For accurate prediction of the cutting force, the model also takes into account the movement of the position of the cutter due to tool deflection and tool runout as well as the ploughing effect resulting from the rounded cutting edge.

The schematic view of the end milling process and the adopted coordinate system for modeling are illustrated in Fig. 1, where *x* is the direction parallel to the feed in the plane perpendicular to tool axis, *y* is the direction perpendicular to *x* (in the same plane), and *z* is the direction of the tool axis that is perpendicular to both *x* and y. Each cutting force component is calculated in the following manner:

Firstly, the end milling cutter is divided into a finite number of coaxial disk elements and then the *x*, *y* and *z* components of force acting on a flute at a particular instant are obtained by summing up the force components acting on each individual disk element. Finally, the total force acting on the cutter is obtained by adding force components acting on all flutes.

The cross-section of the cutter, cutter rotation, feed direction and cutting edge location angles are illustrated in Fig. 2. In down milling, the cutter engages with the maximum uncut chip thickness. As the cutter rotates, the uncut chip thickness reduces, thus resulting in reduction in the force components. However, the actual profile of the force graph is greatly influenced by entry and exit angles, which are a function of radial and axial depth of cuts, cutter diameter and helix angle.

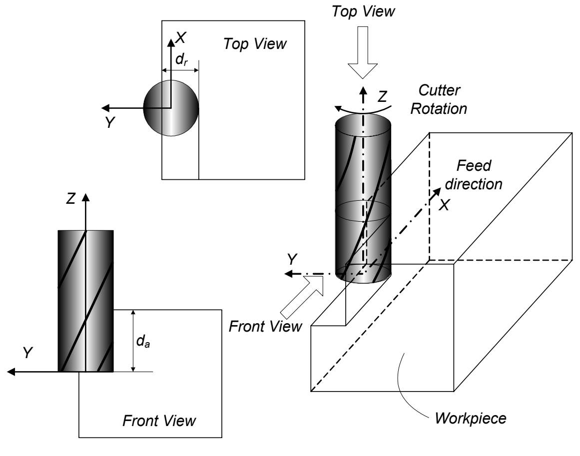

Fig 1: Schematic view of the end milling process geometry and coordinate system

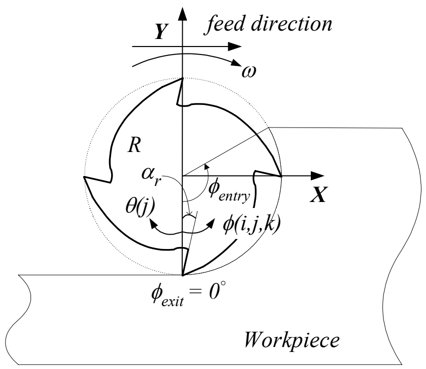

Fig 2: Cross-section of the cutter

3.2 Tool Deflection Model

The end mill is modeled as a cantilever beam, rigidly gripped by the tool holder, whereas the cutting force is applied near the non-supported end (Fig. 3). Due to the helical profile of the cutting edge, the point of application of the cutting force varies from the non-supported end to the axial depth of cut. The amount of tool deflection for each disk element in the *y* direction (direction of interest for generating surface error) can be calculated by summing defection of all disk elements.

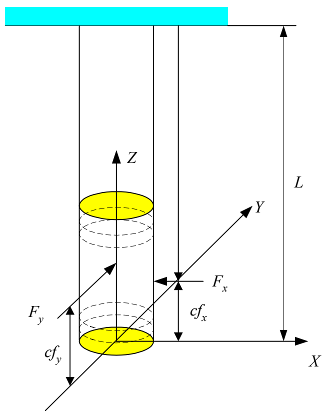

Fig 3: Tool deflection model

3.3 Cutter Diameter Estimation Procedure

The dimensional repetition and predictability of workpiece size tolerances is closely related to the correct tool diameter supplied to the CNC controller during machining operations. Traditionally, the nominal size of the cutter is provided to the controller, thus resulting in significance machining errors. This is because the cutter itself has a tolerance (for example, a ϕ*16.000* end mill used in the present machining experiments had a -0/+ 0.030 mm tool manufacturer's specified size tolerance). This problem is exacerbated by the fact that the cutter usually has run out errors. We also need to consider its rotating and effect tool ware. Hence, the actual cutter diameter during cutting is unknown. Experienced machinists are aware of this problem and adopt many approaches to rectify it. For example, they take a measurement prior to the final cut and compensate the error during the final cut.

At Curtin University, a research project has been undertaken to come up with a viable solution for this problem. Different options were under investigation including the use of a non-contact measuring system such as laser scan micrometer for on machine measurement of the cutter diameter. Until an acceptable solution was found, the problem was solved by determining the tool diameter during machining by cutting a soft material (paraffin block) to avoid tool deflection error. Initially, a slot was cut and was then enlarged on both sides by 1 mm. The feed directions were so chosen that both cuts were executed through down milling. Special measures were taken to keep the tool runout to its minimum of around 5 microns. More than 50 measurements of the slot width were taken and as a result, the revised cutter diameter supplied to the controller was *16.102* mm. Consequently, the differences between the measured and simulated averages were reduced to 7 microns, or the prediction error was about 19.4%.

4. SIMULATION RESULTS

The effect of cutting speed and feed rate on size tolerance is shown in Fig. 4. The figure shows that size tolerance is always directly proportional to feed rate and inversely proportional to cutting speed. The influence of cutting speed at low feed rate appears to be greater than the influence of cutting speed at higher feed rate.

Fig. 5 demonstrates that size tolerance is always proportional to the feed rate but not to the radial depth of cut. Therefore, there is a possibility of achieving a required size tolerance through proper selection of radial depth of cut. Minimum and maximum levels, respectively, are noted near the radial depth of cut equal to a quarter and a half of the cutter diameter. The minimum occurs due to a balanced loading and unloading of all flutes at a redial cut, fulfilling the following condition [8]:

$$\phi_{entry} = \phi_c \tag{1}$$

For a four flute cutter, like the one used in this study, the depth of cut is equal to half of the cutter diameter and this type of cutting is known as *half immersion cutting*. Therefore, for a four flute cutter, the best surface is produced by half immersion cutting; this has been observed in a few other studies [13,14].

On the other hand, the maximum size tolerance is produced due to most imbalanced loading and unloading of all flutes at a radial cut, fulfilling the following condition:

$$d_r = R\,[1 - \cos[(d_a/R)\tan\theta_h]] \tag{2}$$

$$d_a = (R/\tan\theta_h)\cos^{-1}(1 - d_r/R) \tag{3}$$

A detailed analysis of these conditions may be found in [8]. In the present example:

$$d_r = 8[1 - \cos[(16/8)\tan 30]] = 4.77\ mm \tag{4}$$

$$d_a = (8 / \tan 30) \cos^{-1} (1- 2/8) = 10.01 \text{ mm} \qquad (5)$$

The knowledge obtained through these simulation results will be applied to develop a cutting conditions optimization strategy.

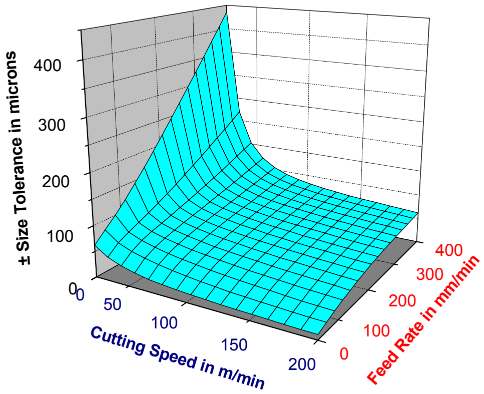

Fig 4: Effect of cutting speed and feed rate on size tolerance (radial depth of cut = 2 mm)

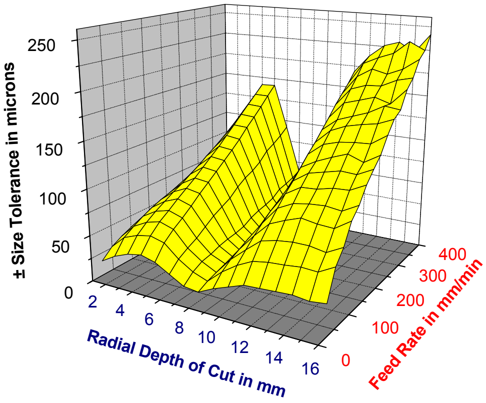

Fig 5: Effect of radial depth of cut and feed rate on size tolerance (cutting speed = 50 m/min)

5. SELECTION OF CUTTING CONDITIONS

Eq. (3) shows that size tolerance can also be optimized by varying axial depth of cut. However, in practice, this approach is seldom used because the axial depth of cut is usually selected on the basis of workpiece geometry and any additional pass for the sake of optimization may prove to be uneconomical. Nevertheless, in some special cases, this option may be worth pursuing.

Based on the acquired knowledge through simulation, an optimization strategy for a single pass peripheral end milling has been developed. The strategy has two variations, which are presented below:

5.1 Technical Optimization

According to this strategy, the cutting conditions are optimized on the basis of specified part tolerance, which is a technical parameter. A 3D search strategy has been adopted in which the search ranges for cutting speed and feed rate are nominated by the user and are usually based on machine tool specifications. The minimum depth of cut is selected on the basis of the accuracy of the workpiece prior to machining and the maximum is calculated applying Eq. (2). The step for each variable is chosen carefully. An example of the ranges and steps selected for the cutting parameters are given in Table 1.

Table 1: Ranges and steps for cutting parameters

Cutting Parameters	From	To	Step
Cutting Speed (m/min)	25	225	+5
Feed Rate (mm/min)	400	100	-20
Radial Depth of Cut	4.6	0.2	-0.2

The search starts from the minimum cutting speed, maximum feed rate and maximum depth of cut. In each step, eight combinations of the variables, which are represented by eight corners of a cube as illustrated in Fig. 6, are calculated and the values are compared. The next move is when the progress will be the greatest. The first three steps of a search example are listed in Table 2. Note that the expected tolerance value is reduced form 340.2 micron to 175.9 micron in three steps. The optimization results of this search, along with some others, are given in Table 4.

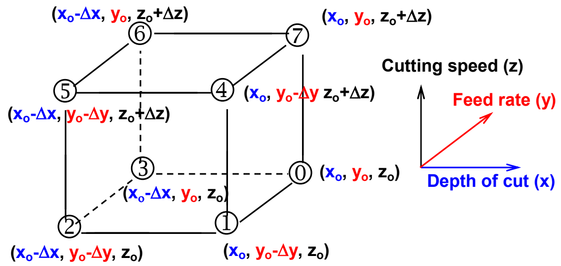

Fig 6: Geometric representation of the 3D search strategy

5.2 Technical and Economical Optimization

According to this strategy, the cutting conditions are optimized on the basis of both technical and economical parameters, namely, specified part tolerance and economic cutting speed. It is common knowledge that cutting speed has the greatest effect on machining time and cost [15] among the three cutting parameters considered. Formulae are available for calculation of economic cutting speed. For example, the economic cutting speed for the minimum cost may be calculated using the following formula [15]:

$$V_{c\,\min} = \frac{C_v}{\left[\left(\frac{1}{n}-1\right)\frac{C_w + C_d T_c}{C_d}\right]^n} \qquad (6)$$

The cutting speed that yields the maximum production rate may be calculated using the following formula [15]:

$$V_{p\max} = \frac{C_v}{\left[\left(\frac{1}{n}-1\right)\times T_c\right]^n} \tag{7}$$

The coefficients used in Eq. (6) and (7) such as C_w (tooling cost) and C_d (direct operation cost) are site dependent and C_v (cutting speed constant in Taylor's tool life equation), which is numerically equal to the cutting speed that gives a tool life of 1 minute, depends on all the input parameters for the cutting operation such as tool material and workpiece material. Therefore, we propose to select the economic cutting speed using Eq. (6) or (7) at shop floor level on case by case basis. Then a 2D search is carried out in feed rate and radial depth of cut domain. The first three steps of such a search are illustrated in Table 3. In this case, the economic cutting speed was calculated as 50 m/min. A comparison of results shown in Tables 2 and 4 reveals that the speed of optimization is faster in the case of technical optimization. This is because the cutting speed is kept constant throughout the optimization search in case of technical and economical optimization. Hence, its effect is not reflected in the results. However, the main drawback of the technical optimization strategy is that it does not guarantee economical cutting speed. The results of technical and economical optimization strategies are shown in Table 5.

Another variation of this approach may be to generate contour plots similar to the one shown in Fig. 7. The cutting speeds required for these contour plots are determined by using the economical cutting speed formulas expressed in Eq. (6) or (7). These plots can be very useful tools at shop floor level because they allow the machinist to select the suitable feed rate and depth of cut combinations based on the specified size tolerance without any calculation and the decision will be based on both technical and economical parameters. For example, it may be seen in Fig. 7 that a ± 52 microns size tolerance can be achieved with 120 mm/min feed rate and 2 mm depth of cut.

6. CONCLUDING REMARKS

In this paper, a strategy is presented for selection of optimum cutting conditions for a single-pass peripheral end milling, when the size tolerances of component parts are specified. Two variations of the strategy are proposed: one is based on the technical parameter only (that is, the specified part tolerance) and the other is based on both technical and economical parameters (namely, specified size tolerance and economic cutting speed). Several examples are presented to demonstrate the effectiveness of the strategy. Results indicate that the proposed optimization strategy can be implemented successfully for selection of optimum cutting conditions. The contour plot representing constant tolerance values can be a useful graphical tool at shop floor level for selection of cutting conditions that are based on both technical and economic parameters.

Table 2: First three steps of the optimization search: Technical optimization only

Step/ Point	d_r (mm)	f (mm/min)	v (m/mim)	T (µm)	ΔT (µm)
Step 1					
0	4.6	400	25.0	340.2	0
1	4.6	380	25.0	323.5	16.7
2	4.4	380	25.0	318.0	22.2
3	4.4	400	25.0	334.5	5.7
4	4.6	380	30.0	270.2	70.0
5	4.4	380	30.0	265.4	74.8
6	4.4	400	30.0	279.0	61.2
7	4.6	400	30.0	283.3	56.9
Step 2					
0	4.4	380	30.0	265.4	0
1	4.4	360	30.0	252.3	13.1
2	4.2	360	30.0	247.9	17.5
3	4.2	380	30.0	261.3	4.1
4	4.4	360	35.0	217.5	47.9
5	4.2	360	35.0	213.8	51.6
6	4.2	380	35.0	225.0	40.4
7	4.4	380	35.0	229.1	36.3
Step 3					
0	4.20	360	35.0	213.8	0
1	4.20	340	35.0	202.5	11.3
2	4.00	340	35.0	199.2	14.6
3	4.00	360	35.0	210.2	3.6
4	4.20	340	40.0	178.8	35.0
5	4.00	340	40.0	175.9	37.9
6	4.00	360	40.0	185.5	28.3
7	4.20	360	40.0	188.5	25.3

Table 3: First three steps of optimization search: Technical and economical optimization

Step/ Point	d_r (mm)	f (mm/min)	v (m/mim)	T (µm)	ΔT (µm)
Step 1					
0	4.6	400	50.0	173.7	0
1	4.6	380	50.0	165.8	7.9
2	4.4	380	50.0	164.3	9.4
3	4.4	400	50.0	172.2	1.5
Step 2					
0	4.4	380	50.0	164.3	0
1	4.4	360	50.0	156.3	8.0
2	4.2	360	50.0	154.0	10.3
3	4.2	380	50.0	161.4	2.9
Step 3					
0	4.20	360	50.0	154.0	0
1	4.20	340	50.0	146.0	8.0
2	4.00	340	50.0	144.7	9.3
3	4.00	360	50.0	152.1	1.9

Table 4: Optimization results for on-pass peripheral milling: Technical optimization only

Target Size Toleance T (± micron)	Optimized Cutting Parameters		
	v (m/mim)	f (mm/min)	d (mm)
56.0	90.0	140.0	3.0
37.0	105.0	80.0	2.4
70.0	150.0	340.0	4.0
44.0	60.0	300.0	0.8

Table 5: Optimization results for on-pass peripheral milling: Technical and economical optimization

Target Size Toleance T (± micron)	Optimized Cutting Parameters		
	v (m/mim)	f (mm/min)	d (mm)
56.0	50.0	100.0	2.6
145.0	50.0	340.0	4.0
50.0	50.0	80.0	2.2
84.0	50.0	160.0	4.0

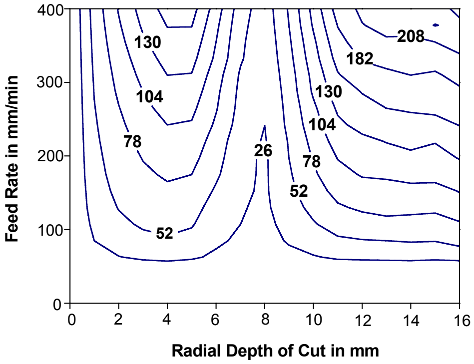

Fig 7: Contour plot showing constant tolerance values in ± microns

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8. NOMENCLATURE

Symbol	Meaning	Unit
R	Cutter radius	(mm)
V	Cutting speed	(m/min)
f	Feed rate	(mm/min)
d_r	Radial depth of cut	(mm)
d_a	Axial depth of cut	(mm)
T	Size tolerance	(µm)
θ_h	Cutter helix angle	(deg)
ϕ	Angular position of the cutter	(deg)
L	Tool overhang	(mm)
cf_x	Centre of cutting force (x)	
cf_y	Centre of cutting force (y)	
C_d	Direct operation cost	($/min)
C_w	Cost of tooling	($/tool change)
T_c	Tool change time	(min)
ϕ_{entry}	Cutter entry angle	(deg)
ϕ_{exit}	Cutter exit angle	(deg)
ϕ_c	Flute spacing angle	(deg)