Comparison of Cutting Strategies for High Productive End Milling

M. S. Uddin[1], A. Matsubara[2], S. Ibaraki[3] and T.Yasuda[4]

[1]Kyoto University, Japan, 6068501, ms_uddin@preceng.mbox.media.kyoto-u.ac.jp
[2]Kyoto University, Japan, 6068501, matsubara@prec.kyoto-u.ac.jp
[3]Kyoto University, Japan, 6068501, ibaraki@prec.kyoto-u.ac.jp
[4]Hitachi Construction Machinery Co.,Ltd, Japan, 300-00131, yasuda06@Hitachi-kenki.co.jp

Abstract. This paper presents the comparison of high-speed milling and heavy milling by using the visual chart approach. To search for more efficient cutting process for 2.5D parts, an interactive process planning and analyzing method is introduced. Geometries to be machined are decomposed into combinations of machining features. Then, cutting strategies are interpreted into constraints on cutting conditions and cutting performance. Several combinations of machining features are examined based on the evaluation of machining time in the charts.

1.1 Introduction

Owing to the development of high-speed machining centers and cutting tools, high-speed cutting has become one of the major trends in many manufacturing applications [1]. In the high-speed cutting, small depth of cut and large feed rate are typically selected in accordance with the spindle speed. In contrast, expert operators in job shops often employs a heavy cutting strategy, on which large depth of cut and small feed rate are selected. As end mills have versatility to cut various shapes, comparison of the cutting strategies is not easy.

Computer aided process planning systems (CAPP) [2,3,4] have been developed to support the decision making process of human operators. There are two approaches to develop CAPP. One approach is to translate experienced operators' experiences into intelligent software: production rules, fuzzy logics, and neural networks. These tools are useful, as they can emulate the decision making process of experts, but expert's strategies are often implicit and difficult to translate into software. Another approach is to introduce an optimization method to decide process parameters. Although this approach has potential to give highly optimized solutions, its performance and reliability completely depend on the quality of models and calculation algorithms used in the optimization. Moreover, reasons of selecting the conditions may not be understood intuitively. Wang proposed an economic method to define optimization strategies for single pass end milling operations[5]. In Wang's work, various possible constraints are shown in feed-speed diagrams, which give a deeper understanding of the characteristics of the problem. However, to apply this method to machining of actual parts, the axial depth of cut and the radial depth have to be also considered.

This paper presents the comparison of high-speed milling and heavy milling by using a simple process planning method. Higher productive cutting conditions of 2.5 dimensional machine parts are searched. First, we introduce a process model to predict cutting forces, which is closely related to performance indices. Then, we present a methodology to compare different cutting strategies with respect to mainly the machining efficiency. In this methodology, cutting strategies are interpreted into constraints on cutting conditions and cutting performance. Several combinations of machining features are examined based on evaluation of the machining times. Finally, these results are shown in the charts, by which we can find high productive cutting plan and conditions visually.

1.2 Cutting Force Model

There have been many researches on cutting force models [6]. Among them, a mechanistic model is suitable for CAD/CAM operations, as it is given from the tool geometry, cutting conditions, and cutting coefficients obtained from the experiments. We use the simple model [7] for easy implementation of the algorism.

Figure 1 shows the view of workpiece and end mill. Parameters of a end mill are D: diameter (mm), θ_h: helix angle (rad), N: number of teeth. Cutting conditions are R_d: radial depth of cut (mm), A_d: axial depth of cut (mm), f_t: feed per tooth (mm/tooth), V: cutting speed (m/min), S: spindle speed (min^{-1}). α is the rotation angle of the tooth (rad), α_{st} is the entry angle, and α_{fin} is the exit angle of immersion. Figure 2 presents cutting force coefficients, K_t, K_r, and K_t, which are applied on the cutting point in the tangential, radial, and axis directions, respectively. By these coefficients, feed, normal, and axial components of the cutting forces are described as follows:

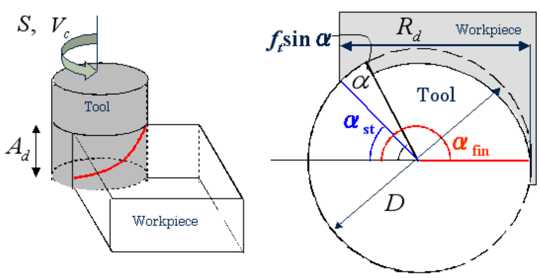


Figure 1. Tool and workpiece interference

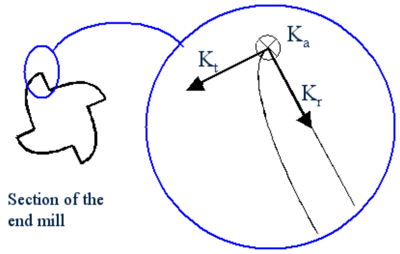


Figure 2. Cutting coefficients

$$f_m(\alpha)=\begin{cases}(-K_t\cdot\cos\alpha-K_r\cdot\sin\alpha)\cdot f_t\cdot\sin\alpha & \alpha_{st}\le\alpha\le\alpha_{fin}\ , \\ 0 & otherwise\end{cases} \quad (1)$$

$$f_s(\alpha)=\begin{cases}(-K_t\cdot\cos\alpha+K_r\cdot\sin\alpha)\cdot f_t\cdot\sin\alpha & \alpha_{st}\le\alpha\le\alpha_{fin}\ , \\ 0 & otherwise\end{cases} \quad (2)$$

$$f_a(\alpha)=\begin{cases}-K_a\cdot f_t\cdot\sin\alpha & \alpha_{st}\le\alpha\le\alpha_{fin}\ . \\ 0 & otherwise\end{cases} \quad (3)$$

Cutting forces of one teeth in feed, normal, and axial directions are obtained as

$$F_{m1}(\theta)=\int_0^{A_d} f_m(\alpha)\,dz \quad , \quad F_{s1}(\theta)=\int_0^{A_d} f_s(\alpha)\,dz \quad ,$$
$$F_{a1}(\theta)=\int_0^{A_d} f_a(\alpha)\,dz \quad (4)$$

where, θ is the rotaion angle of the end mill. Superposing the cutting forces of all the flutes gives cutting forces applied on the end mill:

$$F_m(\theta)=\sum_{i=1}^{N}F_{mi}\left(\theta-\frac{2\cdot\pi}{N}\cdot(i-1)\right) , \ F_s(\theta)=\sum_{i=1}^{N}F_{si}\left(\theta-\frac{2\cdot\pi}{N}\cdot(i-1)\right)$$
$$F_a(\theta)=\sum_{i=1}^{N}F_{ai}\left(\theta-\frac{2\cdot\pi}{N}\cdot(i-1)\right) \quad (5)$$

where *i* is the teeth index.

1.3 Machining Fueatures and Process Planing

1.3.1 Machinng Features

Process planning involves various operations: recognition of machining features, selection of cutting tools and path patterns, decision of cutting conditions. In this paper, we utilize a feature-based process planning. Figure 3 shows examples of machining features and tool paths. As the volume to be cut is decomposed into machining features, tool paths can be parameterized by cutting conditions. There are several combinations of machining features that removes the same volume, which are to be selected based on the process evaluation.

1.3.2 Evaluation of Cutting Performance

Cutting performance is usually evaluated on the following indices: machining time; machining accuracy (geometrical accuracy, dimensional accuracy, surface roughness), tool life. To compare the performance of different cutting strategies, our system handles those indices as follows.

(1) Machining time

The machining time is calculated for each combination of machining features by taking possible cutting conditions into account.

(2) Machining accuracy

Machining processes are roughly divided into roughing and finishing processes. Finishing processes use limited cutting conditions to assure surface quality. Since the productivity is the main focus of our system, we focus on roughing process, and thus accuracy indices are less prioritised. However, in order not to influence finishing surface, machining errors on surface are examined based on the tool defection model as shown in Figure. 4. In this figure, a tool is regarded as a simple cantilever, and its deflection is calculated from a predicted cutting force, where y_c is the displacement of tool center, θ_c is the deflection angle of tool tip, w is the distributed cutting force (normal cutting forces divided by A_d). Machining errors are evaluated by horizontal and vertical displacements:

$$\delta l_s = y_c + (D/2)(1-\cos\theta_c)\ , \quad (6)$$
$$\delta l_a = (D/2)\sin\theta_c\ . \quad (7)$$

(3) Tool life

In order to consider tool life as cutting performance, database is necessary for the combination of tool, material, and cutting conditions. Since it is difficult to prepare the prefect database for real applications, we introduce cutting forces as an index to predict the tool life, including the occurrence of tool breakage.

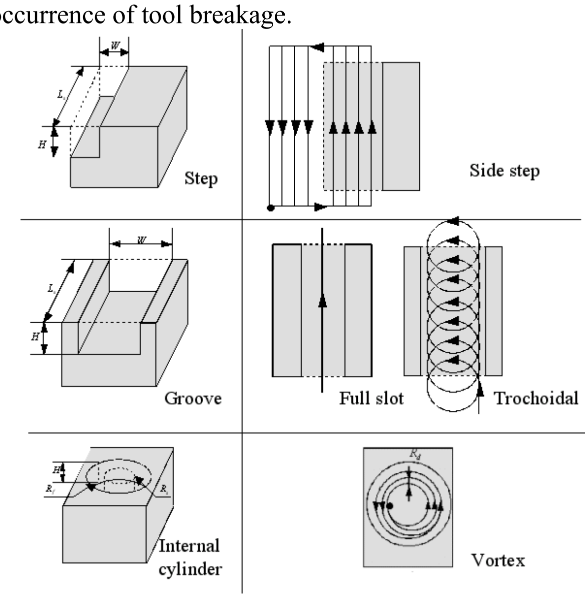


Figure 3. Examples of machining features and tool path cycles

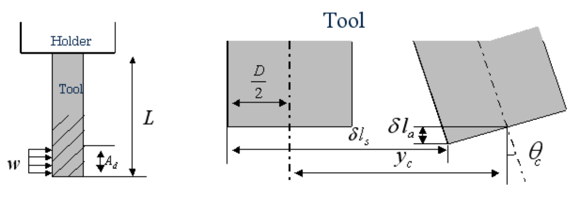


Figure 4. Tool deflection model and machining errors

1.2.3 Interpretation of Cutting Strategies

In the proposed system, each cutting strategy is interpreted as constraints on cutting conditions or cutting performances. For example, two basic cutting strategies, namely, 1) high speed cutting with smaller depth of cut and higher feed rate, and 2) heavy cutting with larger depth of cut and lower feed rate, are interpreted as constraints as follows:

Constraint 1 (Heavy cutting): In heavy cutting, constraints must be imposed to avoid the tool breakage. For example, the cutting force is constrained to be under some allowable maximum value.

Constraint 2 (High-speed cutting with constraints on machining errors): cutting strategies that make machining errors under a specified value are searched. In such a case, a constraint on machining error of side surface is set.

Constraint 3 (High speed cutting): In high-speed machining cases, typically upper limits of depths of cut and cutting forces are constrained.

1.2.4 Process Planing Procedure

The procedure to decide cutting conditions is summarized as follows:

(1) Cutting strategy is interpreted into a set of constraints on cutting conditions and performance indices.
(2) Actual constrains on cutting conditions are given.
(3) Constraints on cutting forces are calculated or given directly.
(4) The machining patterns are prepared by combining defined machining features.
(5) The machining time for each combination of the cutting conditions is calculated and shown in the charts.

As an example of (5), Figure. 5 shows how to decide cutting conditions for machining features. This case is for side step milling. Suppose that the constraint is set as, F_{xy} < 2000N, where F_{xy} is the resultant cutting force in the feeding and normal directions. Possible A_d and R_d are calculated by $A_d = H/m$, $R_d = L/n$, where, m, n are numbers of cutting paths, and H and W are the height and the width of the step, respectively. Then, candidates of cutting conditions that satisfy the constraints are shown as circles. The combination of cutting conditions that minimize the machining time is selected.

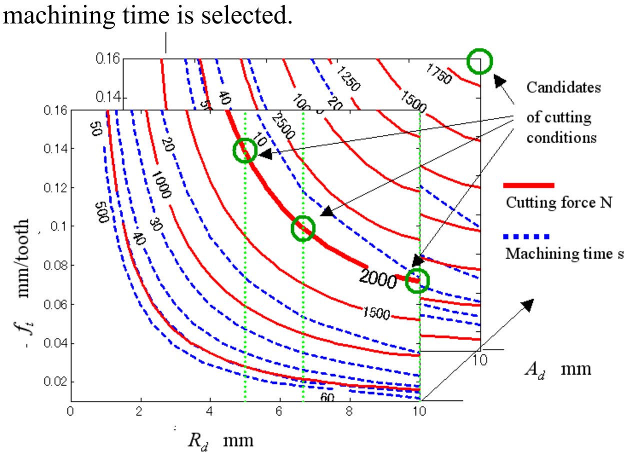


Figure 5. Candidates of cutting conditions

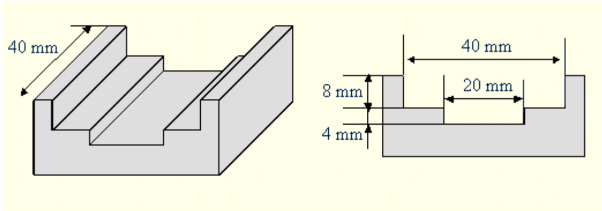


Figure 6. Workpiece geometry

Table 1. The specifications of the end mill

Material	Sintered carbide
Diameter D	10 mm
Number of teeth N	4
Helix angle θ_h	$2\pi/9$ rad
Young modulus E	534.4×10^9 Pa

Table 2. The cutting conditions (fixed values and constraints)

Projection length L	35 mm
Cutting feed rate	≦ 10000 mm/min
Feed rate at air cut	10000 mm/min
Cutting velocity V_c	88.0 m/min
Spindle speed S	2800 min^{-1}
Feed per tooth f_t	0.019～0.16 mm/tooth
Axial depth of cut A_d	≦ 22 mm
Radial depth of cut R_d	≦ 10mm

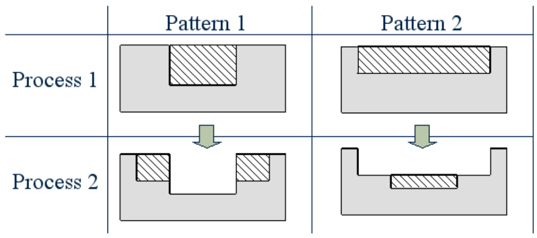


Figure 7. Cutting patterns and processes

1.3 Case Study

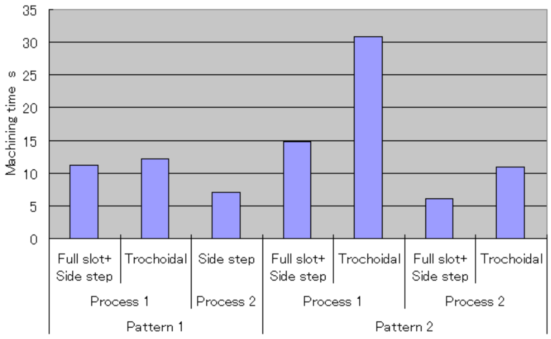
This section shows a case study to illustrate the comparison of cutting strategies by using the present system. Figure 6 shows a workpiece used in the case study. The workpiece material is carbon steel. The specifications of the end mill used in the case study are shown in Table 1. Table 2 shows cutting conditions and their constraints, which are obtained by considering the machine tool's specifications catalog data of the cutting tool. Possible operation patterns are shown in Figure. 7.

Three cutting strategies, as shown in Section 1.2.3, are considered. The combination of cutting conditions that minimizes the machining time is searched. Specifically, constraints are set as follows in each strategy:

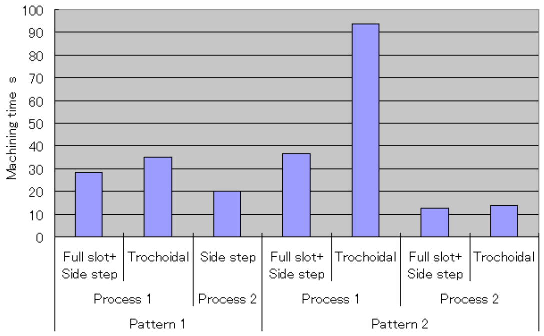
Constraint 1 (Heavy cutting): the constraint on cutting force is given as F_{xy} < 2000 N.

Constraint 2 (High-speed cutting with constraints on machining errors): the machining error of side surface is constrained as $\delta l_s \leq 40\ \mu m$.

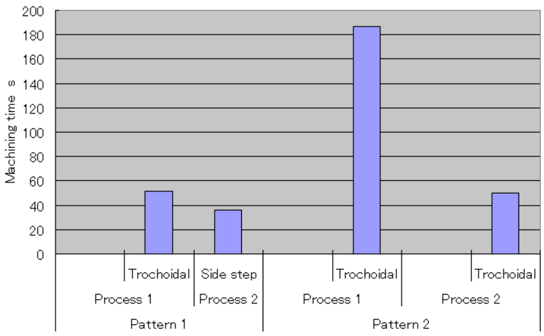
Constraint 3 (High speed cutting): the radial depth of cut and the cutting force are constrained respectively as R_d < 1 mm and F_{xy} < 1000 N.



(a) Constraint 1



(b) Constraint 2



(c) Constraint 3

Figure 8. Comparison of machinng time

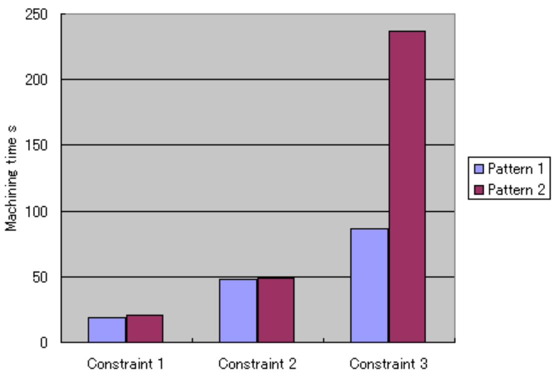


Figure 9. Comparison of machinng time

Figures 8 and 9 show the machining time of each feature and summarized results, respectively. As can be seen in these figures, the machining time gets shorter in the order of constraints 3-2-1. In constraint 3, the machining time in pattern 2 is much larger than that in pattern 1. This is because trochoidal cutting of a slot with a large width takes time. Table 3 shows obtained cutting conditions and calculated cutting forces in each machining pattern 1. In

Table 3. Cutting conditions and caluculated cutting forces in pattern 1

Constraint -Process - Feature		f_t mm /tooth	A_d mm	R_d mm	F_{xy} N
1-1-	Full slot	0.14	6	10	2000
	Side step	0.11	12	5	2000
1-2-	Side step	0.09	8	10	2000
2-1-	Full slot	0.02	12	10	766
	Side step	0.16	12	1.67	908
2-2-	Side step	0.13	8	2.5	791
3-1-	Trochoidal	0.16	12	1	1000
3-2-	Side step	0.16	8	1	365

the constraint 2, cutting forces are less than 1000 N, but the machining time is shorter than that in the constraint 3. One reason is that the trochoidal cutting has longer machining time than full slot + side step cutting. The other reason is that all the cutting conditions are upper bounded by the constraints. One solution to solve this problem is introducing high-speed tools. In die and mold machining, high-speed tools with smaller depth of cut are often employed for the safety reason. However, since such tools are expensive for machining of medium carbon steel, it is better to use the heavy cut strategy.

1.4 Conclusion

This paper presents a scheme to compare several machining starategies in end milling process by using visual charts. In this methodology, cutting strategies are interpreted into constraints on cutting conditions and cutting performance. The results show that the constarin on the axial depth of cut and the radial depth are quite imortant to obtain high productive process.

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