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PROPOSAL OF THE EXTENDED SYSTEM FRAMEWORK OF INTELLIGENT MACHINE TOOL

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ABSTRACT

In this paper, the extended framework of the intelligent machine tool for 2.5 dimensional part machining is proposed. This system consists of three layers and simple interfaces using the machining features and "motion & process control package". In a case study, it is shown that productivity can be improved without increasing the cutting force by the simulation.

INTRODUCTION

Authors have been developing the intelligent machine tool for drilling, tapping and end milling[1-3]. In these studies, the basic concept of intelligent machine tool that optimizes the machining process by the 3-level feedback controls and the machining data base was shown. This basic concept is simple and works well in such simple operations as drilling and tapping. However , for the complex machining like contouring by end milling, the above basic concept is not sufficient because process planning and operation planning for intelligent machine tool are still under development. In order to achieve the high productivity and reliability for complex machining, not only the control but also the process planning and operation planning should be appropriate in the viewpoint of the cutting technology.

Seethaler proposed the process planning system in 2.5 dimensional milling[4]. In his study, the basic ideas are described; process control that uses the process planning information of each machining feature, dynamic process planning using the feed-backed information of the machining process and sharing the data base between process control and process planning. Furthermore, in order to achieve these ideas, extended G-code interface based on the open architecture CNC system is proposed.

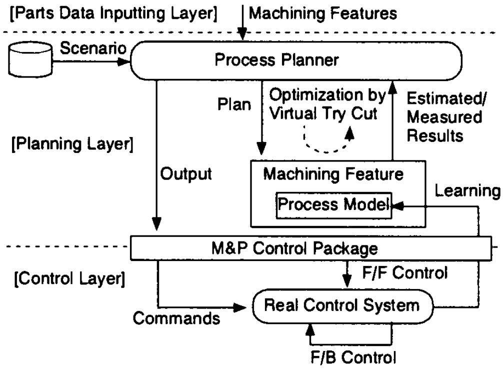

Figure 1. THE GENERAL STRUCTURE OF MACHINING FEATURE-BASED CONTROL SYSTEM

Some other researchers had studied the system architecture for intelligent machine tool. Yamazaki proposed CNC architecture (TRUE-CNC) that integrates the process planning, analysis, control and measurement including the method to extract the machining know-how[5]. Narita studied the process planning method that modifies the NC program based on the estimated result of the end milling by virtual machining simulator [6]. Shirase studied the real time process planning method that modifies the depth of cut by virtual copy milling system[7].

Although each of these researches is interesting, in order to realize the total process optimization which authors aim at, the system should satisfy the following requirement.

(1) Not only feed back(FB) control but also feed forward(FF) control should be conducted using the information at the time of the process planning by closely integrating the process planning that process control.

(2) Machining process model should not only be shared from the process planning and process control but also be associated to the machining feature clearly, because in the 2.5 dimensional part machining that we are concerned in this paper, machining process phenomenon is different for every machining feature (accordingly the process model is also different).

(3) Commanded data or monitored data between process planning and control should be clearly associated to the machining feature so that the system can always judge what kind of machining is conducted now or which data base should be updated from the monitored data.

(4) The system should make use of the characteristic of the part machining that it often contains the repetition of the same kind of operation or machining feature to get higher productivity and reliability.

Then, authors propose the extended system framework for intelligent machine tool shown in Figure 1. It consists of three layers of part data inputting layer, planning layer and control layer. The core module is process planner and the core tool is the motion and process (M&P) control package. Process planner is a kind of auto-programming system, which utilizes M&P control package as programming tool.

The process planner designs the process and the operation of each machining feature. Here each machining feature has the models which represent its machining process, and is used to estimate the machining results. This enables to optimize the plan by virtual try cut. Then optimized plan is translated to the data of the M&P control package. M&P control package is a collection of conventional and advanced canned cycles. While the conventional canned cycles generate only motion commands, the advanced ones give control method, parameter and reference of process, motion and servo control.

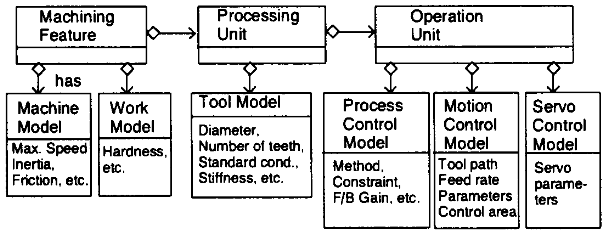

Figure 2. STATIC MODEL STRUCTURE

At the control layer, the M&P control package sends commands or parameters which are already optimized in the planning layer to the real control system to conduct FF control which covers up the weak points of the FB control.

Furthermore the system updates the model in the machining feature from the monitored data. Thus, learning control is naturally achieved by repeatedly using the machining feature which includes this updated model when the part contains multiple similar machining.

SYSTEM FRAMEWORK

Figure 2 shows the static structure of the model represented in UML language[8]. A machining feature is divided into processing units, and each processing unit is further divided into operation units. Machine model and work model are held in the machining feature, supposing machine and workpiece do not change while machining a workpiece. On the other hand, since the tool may be changed in general in each process, tool model is

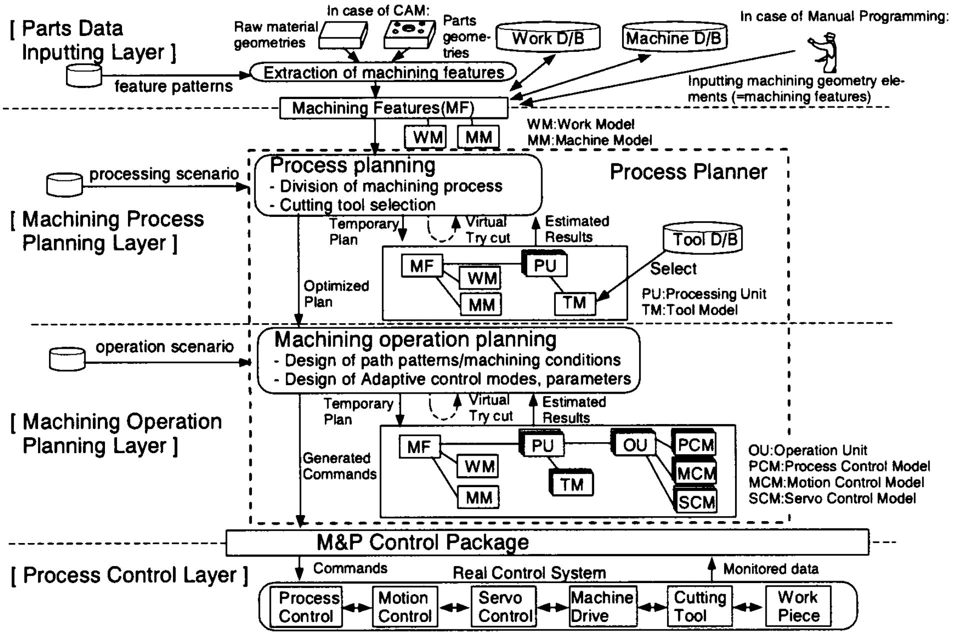

Figure 3. WHOLE SYSTEM STRUCTURE OF THE PROPOSED SYSTEM

held in the processing unit. Furthermore, since the control technique may be changed for every operation unit, the models of the process/motion/servo control are held in each operation unit.

The whole system structure is shown in Figure 3. The lowest layer is the process control layer, and it corresponds to the basic INC system proposed formerly[1].

On the parts data inputting layer, the machining features are extracted from the raw material geometries and the finished parts geometries or inputted through human machine interface.

The planning layer is further composed of the machining process planning layer and the machining operation planning layer. On the machining process planning layer, division of machining process, determination of processing order and cutting tool selection are made based on the processing scenario. Here, cutting forces, machining time etc. are estimated based on the model held in each machining feature (virtual trial machining), and the most excellent processing scenario is selected, and then the process planning is performed according to the selected scenario. On the machining operation planning layer, the path pattern, machining conditions, the adaptive control mode and its parameter are decided to each machining process unit based on the operation scenario. The model is used even here to estimate the result of each process, and the best scenario is chosen, then finally the machining conditions are optimized.

On the lowest layer, the M&P control package send optimum commands suited for each operation to the each controller. The commands here indicate, for example, the tool path, machining conditions and the control parameters. The monitored data are used to update the model as is explained later.

In this system structure, information which is necessary for the machining is instructed basically from the higher layer down to the lower layer, and FB control by adaptive control is used together in the process control layer, and, in addition, the models in the machining feature also play the role as the data base which is updated by learning and reused again in the higher layer.

Thus, this system has the clear structure of three layers and the interface between the layers, so the model-based optimal planning and control can be achieved easily.

THE GENERAL METHOD OF PLANNING

In general, the optimization problem in the machining process planning or operation planning needs huge amount of calculation because its design variables are too many. In this point of view, it is not practical to solve this problem directly. Moreover, it is not appropriate to use the same machining model for the whole variable space, because the models and its parameters are seldom general for the wide range of machining.

So, in this paper, the candidates of machining plan are selected beforehand based on operator's know-how in advance, then after that, semi-optimization is done by using the local model around the candidates. The local model can be acquired comparatively easily by learning as described later.

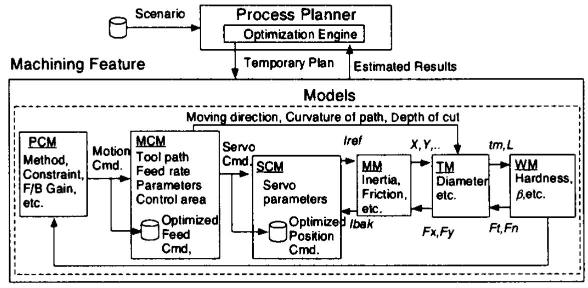

Figure 4. PLANNING PHASE

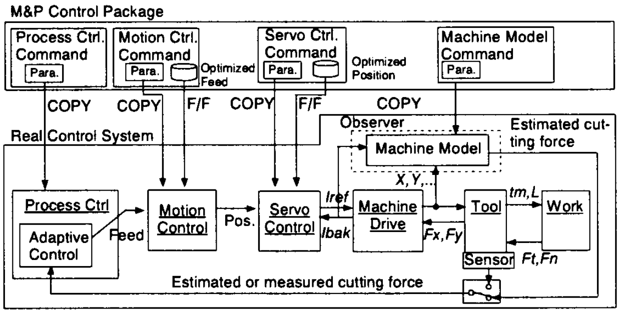

Figure 5. CONTROL PHASE

As shown in Figure 4, the process planner makes a temporary plan according to the typical design patterns of skillful operator(scenario), and inputs the solution to the models of the corresponding machining features. The model simulates the process behavior, and the estimated results are returned to the process planner. After performing local optimization near each candidate based on the estimated results, the process planner compares each candidate's result and chooses the best one.

Thus, semi-optimal plan is obtained easily by using both the operator's know-how and the local model. This optimization is done respectively in each of the machining process planning layer and the machining operation planning layer.

THE GENERAL METHOD OF CONTROL

The control which uses the model of the machining feature is done at the control phase. The structure or the parameter of each control model of the machining process, motion and servo which is already optimized in the planning layer are copied onto actual control unit before the machining. The optimum feed speed pattern etc. calculated through the process of optimizing in the planning layer are memorized in the commands, and they are used as the feed forward references to the real control system. As a result, even when an enough response is not obtained due to some delay in the control loop, the better performance can be achieved easily by the combination of FF control and FB control without consuming much computation power while control.

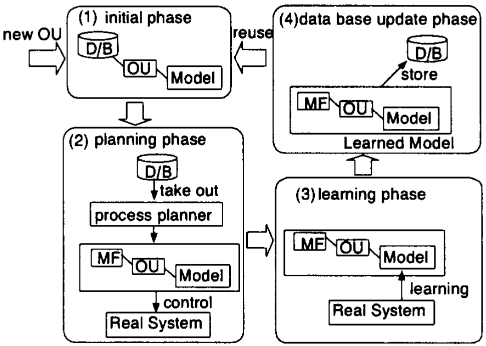

Figure6. LEARNING BY REUSE OF THE MODEL

THE GENERAL METHOD OF LEARNING

Each model of the machine, the tool, and workpiece is identified from measurements from the controlled system and the commands to the control system. For example, as a work model in end milling, the cutting force F_n is assumed to obey the following equation(2nd order response surface):

$$F_n=\beta_0+\beta_1 t_m+\beta_2 L+\beta_3 t_m^2+\beta_4 L^2+\beta_5 t_m L \quad (1)$$

where t_m is the undeformed maximum chip thickness, L is the undeformed chip length and β_j (j=0,1,...,5) are the coefficients.

As t_m and L are easily calculated from the feed, the depth of cut, moving direction vector and curvature of the tool path, coefficients β_j can be identified from this t_m ,L and observed F_n using the least squares method. The identified model is stored in machining feature and is again returned to each data base(Figure 6). When the same kind of machining is appeared, the same machining feature and the model are used again.

CASE STUDY

In this chapter, a sample part which has a slot and four holes with threads(shown in Figure 7) is taken as an example, and processing flow and simulation results are shown.

The specifications of the machining features, raw material and available tools are shown in Tables 1,2,3 respectively.

Process Planning

The processes of each machining feature are decided first in the process planning phase.

MF1: Slot machining feature. Suppose that the following two scenarios 1 and 2 exist. The first one uses the slotting in the center in Y-axis direction, then widen the slot by side milling. The second one uses X-axis directional side milling from the front face toward the back face in zigzags, then finishes the both sides by side milling in Y-axis direction. Cutting conditions in each scenario are shown in the Table 4.

Two cutting tools($\Phi 10$,$\Phi 16$) are available in each scenario, so totally 4 plans are generated. Figure 8 shows the divided area of one of the generated plans with the first scenario and the tool of 10mm diameter. Table 5 shows the cutting conditions, cutting forces, machining time(t) and other variables. Here, w is the ratio of cutting force to its allowable value.

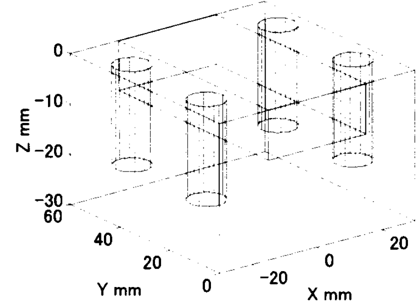

Figure 7. GEOMETRIES OF THE SAMPLE PART

Table 1. MACHINING FEATURES OF THE PART

MF	Type	Size(mm)	number	Note
MF1	slot	30*60*1(X,Y,Z)	1	Side acuracy <0.01mm
MF2	hole with thread	M10*20	4	blind hole

Table 2. DATA OF THE RAW MATERIAL

Kind	Size (mm)
carbon steel(JIS S45C)	hexahedron(60*60* 30)(X,Y,Z)

Table 3. AVAILABLE CUTTING TOOL

Tool No.	Type	size (mm)	V (m/min)	fz	Constraint ($Fmax$)	note
T1	Square End Mill	Φ10	90	0.09 mm/teeth	300N (side cutting) / 600N (slotting) (*1)	(*3)
T2	Square End Mill	Φ16	90	0.09 mm/teeth	600N (side cutting) / 1200N (slotting) (*1)	(*3)
T3	Drill	Φ8.5	100	0.25 mm/rev	2500N (*2)	-
T4	Tap	M10*1.5	30	-	-	-

(*1)radial force (*2) thrust force (*3)4 teeth

Table 4. SCENARIOS FOR SLOT

scenario No.	Type	Kind	direction	A_d (mm)	R_d	V	fz
1	Rough	Slotting	Y	10	1D	V_0	f_0
	Semi-Fin.	Side cut	Y	10	0.1D	V_0	f_0
	Finish	Side cut	Y	10	0.2mm	V_0	$f_0/2$
2	Rough	Side cut	X	10	0.1D	V_0	f_0
	Semi-Fin.	Side cut	Y	10	1mm	V_0	f_0
	Finish	Side cut	Y	10	0.2mm	V_0	$f_0/2$

(V_0,f_0 are standard values of V,f_z respectively)

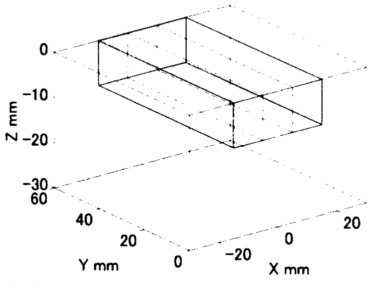

Figure 8. A GENERATED PLAN (SCENARIO 1,Φ10 TOOL)

Table 5. GENERATED PLANS IN THE PROCESS PLANNING PHASE FOR SLOT

No	Scenario No.	Φ	Processing Unit	R_d (mm)	f_z (mm)	n	F_n (N)	w	t (s)	Σt (s)	Σwt (s)
#1	1	10	slot	10	0.09	1	823	1.37	4.3	108.0	143.0
			side(semi)(L)	1	0.09	10	299	1.00	43.2		
			side(semi)(R)	1	0.09	10	299	1.00	43.2		
			side(fin)(L)	0.2	0.04	1	53	2.95	8.6		
			side(fin)(R)	0.2	0.04	1	53	2.95	8.6		
#2	1	16	slot	16	0.09	1	1331	0.67	7.2	108.0	52.6
			side(semi)(L)	1.6	0.09	5	483	0.48	36.0		
			side(semi)(R)	1.6	0.09	5	483	0.48	36.0		
			side(fin)(L)	0.2	0.05	1	54	0.45	14.4		
			side(fin)(R)	0.2	0.05	1	54	0.45	14.4		
#3	2	10	side(rough)	1	0.09	60	896	2.99	63.4	89.3	248.9
			side(semi)(L)	1	0.09	1	299	1.00	4.3		
			side(semi)(R)	1	0.09	1	299	1.00	4.3		
			side(fin)(L)	0.2	0.04	1	53	2.95	8.6		
			side(fin)(R)	0.2	0.04	1	53	2.95	8.6		
#4	2	16	side(rough)	1.6	0.09	38	1448	1.45	40.7	83.9	76.6
			side(semi)(L)	1	0.09	1	316	0.32	7.2		
			side(semi)(R)	1	0.09	1	316	0.32	7.2		
			side(fin)(L)	0.2	0.05	1	54	0.45	14.4		
			side(fin)(R)	0.2	0.05	1	54	0.45	14.4		

As you see in this Table, since the weighed total time Σwt is the smallest in the case of plan #2, plan #2(scenario 1, Φ16) is selected as the best plan in the process planning phase.

MF2: hole with thread feature. Suppose that the following one scenario exists. In this scenario, a hole is drilled first, then thread is machined by the tap. Cutting conditions are shown in the Table 6. The cutting conditions, cutting forces, machining time(t) and other variables are calculated similarly. The scenario 1 which is the only one candidate is simply selected here.

Table 6. SCENARIOS FOR SLOT

scenario No.	Type	Kind	direction	V	f_z
1	Rough	Drilling	Z	V_0	f_0
	Finish	Tapping	Z	V_0	f_0

Operation Planning

Based on the determined plan in the process planning phase, the operations of each process are planned in the operation planning phase. In this phase, tool path for each operation is generated, and cutting conditions (radial depth of cut R_d or feed f_z) are tuned so that the cutting force may be regulated to the given constraint in each operation.

MF1: Slot Machining feature. Scenario 1 tunes R_d, and scenario 2 tunes f_z in the rough or semi-finish process as shown in Table 7. Note cutting conditions are not changed in the finish process not to affect the quality of the machined surface.

Figure 9 shows the paths of the generated plans with the first operation scenario(1). In Figure 10, relation between time t and cutting force ratio(w) are shown. The "×" marks show the four solutions obtained in the process planning phase, and the circles show the two solutions obtained in the operation planning phase. Each curve is a hyperbola that passes t and w shown in Table 5. According to this Figure, plan #2(scenario 1, Φ16) is selected in the process planning phase, then at the operation planning phase, the scenario (1) is selected as the best plan.

Table 7. OPERATION SCENARIOS FOR SLOT

scenario No.	Type	R_d	f_z
(1)	Rough/Semi-finish	tuned	-
	Finish	-	-
(2)	Rough/Semi-finish	-	tuned
	Finish	-	-

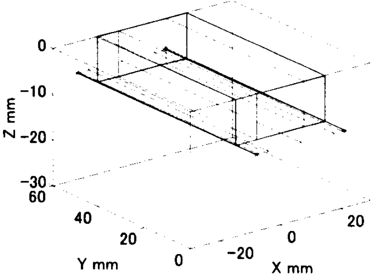

Figure 9 A GENERATED PLAN (SCENARIO (1))

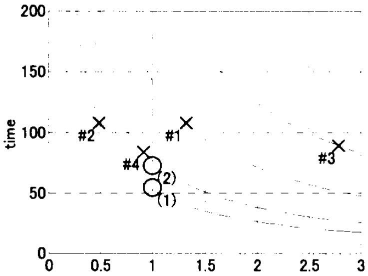

Figure 10. TIME VS CUTTING FORCE FOR SLOT

MF2: Hole with thread feature. Suppose that only one scenario exists. In this scenario, feed f_z in drilling is tuned so that the cutting force may be regulated to the given constraint in each operation. Note cutting conditions are not changed in the tapping process. The only scenario is simply selected here.

Process Control

Drilling operation is taken as an example to show the effect of feeding forward the optimized feed speed. The target thrust force is set to 2500N except at the entrance of the hole where the target thrust force is 1250N to avoid the hole location error. The hardness of the workpiece is assumed to be 20% harder than expected. In Figure 11, the feed rate F and thrust force F_z of FB controller, FF controller and the proposed controller that combines both FF and FB control are compared. Horizontal axis shows the Z-axis moving length of tool from the reference point.

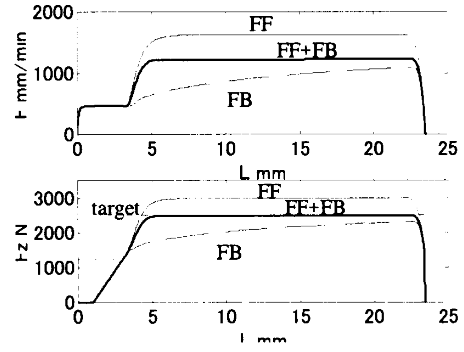

Figure 11. THE FEEDRATE(UPPER FIGURE) AND CUTTING FORCE(LOWER FIGURE) IN EACH CONTROL

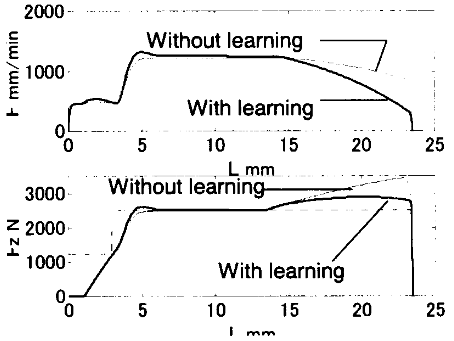

Figure 12 THE FEEDRATE(UPPER FIG.) AND CUTTING FORCE(LOWER FIG.) IN EACH CONTROL (THIN LINE=FF+FB, THICK LINE=FF+FB+LEARNING)

In the case of FB control, the control delay is too large that the cutting force does not reach the target thrust force quickly. In the case of FF control, cutting force goes over the target thrust force because the hardness of the workpiece was harder than expected. On the other hand, in the case of FF+FB control, the quick response and cutting force regulation can be both achieved.

Learning Control

Figure 12 shows the effect of learning control in the drilling. In this example, disturbance force that emulates the chip clogging is also added(The amount of disturbance increases as the tool move toward the bottom of the hole). With learning, the cutting force reaches the target thrust force more quickly, and is less affected by disturbance. This is because accurate modeling makes it possible to raise both the FF and the FB gain.

Figure 13 shows the total machining time and the average cutting force error(dF) in all the processes of the sample workpiece shown in Figure 7. The hardness of the workpiece varies from 80% to 120% of the nominal value, and the time and the cutting force error are averaged. By using the combination of the FF, FB and learning control, both the machining time and the cutting force could be controlled successfully.

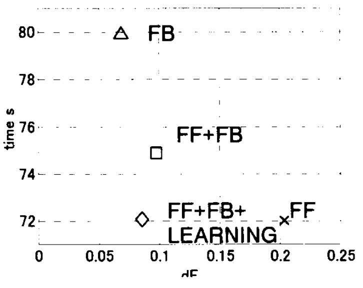

Figure 13 THE CUTTING FORCE ERROR(dF) AND MACHINING TIME IN EACH CONTROL

CONCLUSIONS

In this study, the framework of the intelligent machine tool system including the process planning and operation planning which is available for the complicated machining like end milling was proposed. Using this framework, FF control and learning control can be realized easily, and it is especially effective when similar repeated operations are contained like most of the machining of parts. As a case study, part with slot and holes is taken as an example, and it was shown that productivity can be improved while cutting force is kept under the allowable level by simulation.

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