Development of Automatic Process Planning System for Indexed 5-Axis Machining

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With the aim of reducing lead time in die and mold machining, we analyzed the work involved in die and mold machining process design and studied algorithms for automation. Regarding the studied algorithms, we selected tool diameters based on workpiece removal amount and calculated the tool position appropriate for the machining volume. Furthermore, we identified wasteful processes from the selected process candidates and eliminated these, thereby calculating recommended processes. We then confirmed that the recommended processes calculated from the studied algorithms were suitable for the indexed 5-axis machining of the workpiece forms.

Key Words: *indexed 5-axis machining, automatic system, process planning*

1. Introduction

In recent years, due to intensified global competitiveness in the die machining domain, a further reduction of lead time is being demanded. The 5-axis machining is receiving attention as a means to solving this issue. With this machining, by tilting tool orientation, it becomes possible to avoid interference with the workpiece, therefore making the use of highly rigid tooling with short tool protrusion length possible, holding promise regarding shorter machining time and higher accuracy.

Figure 1 shows the relationship between tool protrusion length/tool diameter (L/D) to tooling rigidity and cutting efficiency, when rough machining hardened steel with a ball end mill. Here, cutting efficiency is calculated from recommended conditions acquired from machining experimentations. This figure shows clearly that it is possible to significantly enhance tooling rigidity and cutting efficiency by shortening tool protrusion length. For example, if tool protrusion length could be shortened to L/D=3 in indexed 5-axis machining, compared with L/D=6 in 3-axis machining, it would be possible to improve tooling rigidity by four times and cutting efficiency by approximately 20 times.

However, since the tool orientation has an increased degree of freedom in indexed 5-axis machining, machining process design becomes extremely complicated. Therefore not only will designer be required higher skills than for 3-axis machining, the work itself becomes more time consuming. Considering the total lead time from machining process design to machining, even if the actual machining time was shortened through 5-axis machining, the time taken for machining process design would be extended, thereby not producing any overall benefit.

Accordingly, we have expanded upon the functions of the support systems[1), 2), 3)] for die machining process design developed previously for 3-axis machining, and developed a support system which makes the highly efficient process design of indexed 5-axis machining possible in a short time even without experts.

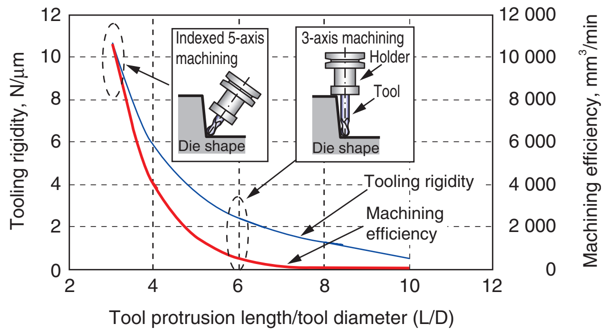


Fig. 1 Relationship between tool protrusion length/tool diameter (L/D) to tooling rigidity and cutting efficiency

2. Development Aims

In this development, for each machining process design task, we have contrived automated algorithms which rely not on experience and intuition, but instead on quantitative evaluation, and thereby developed a system where anyone can design highly efficient 5-axis machining processes easily and quickly. The aims of this system are to abolish the variation in machining quality that occurred up until now due to machining process design dependant on thinking tasks, and to shorten the total lead time taken for die fabrication.

Based on past machining experience, experts use specialized software such as CAM, and determine machining process design through a process of trial and error. In particular, the key point of indexed 5-axis machining process design is applying high rigidity tooling with short tool protrusion length over widest area possible, while switching tool orientation.

By investigating and analyzing machine process design work performed by people, we categorized 6 main tasks. The 1st task is to select multiple tools deemed to be necessary, after considering die shape, past results and so on.

The 2nd task is to search for tool orientations and tooling with the potential of machining efficiently throughout a wide range while 3-dimensionally evaluating interference issues from the tool with the largest diameter. Here, "tooling" refers to tools gripped in their holders with the predefined protrusion length. The 3rd task is to set the cutting conditions for the tooling decided upon. Here, "cutting conditions" refer to spindle rotation speed, feed rate, pickfeed, and cutting depth, and the common way of setting these is to use the past results or refer to the recommended values shown in tool manufacturers' catalogs. From the above three tasks, one process consisting of "tool orientation", "tooling" and "cutting conditions" is determined. From this point, the 4th task is to enter the determined process into CAM, calculate cutter path and confirm whether good or bad. Here, if the cutter path is not as was intended, the worker returns to the 2nd task, reviews process content, and revises cutter path. The 5th task is to check for any rest material using NC simulation, etc., and if found, a process with a different tool orientation is added to remove this, therefore the 2nd to 4th tasks must be repeated. Then, once a process has been designed that can machine the intended shape with the current tool diameter, the 6th task is carried out which repeats the 2nd to 5th tasks using a smaller diameter tool, in order to machine the edges of the workpiece. Ultimately, once tasks have been repeated for all tools up to that with the smallest tool diameter, the design of a process which can machine a workpiece from base material into a die shape is complete.

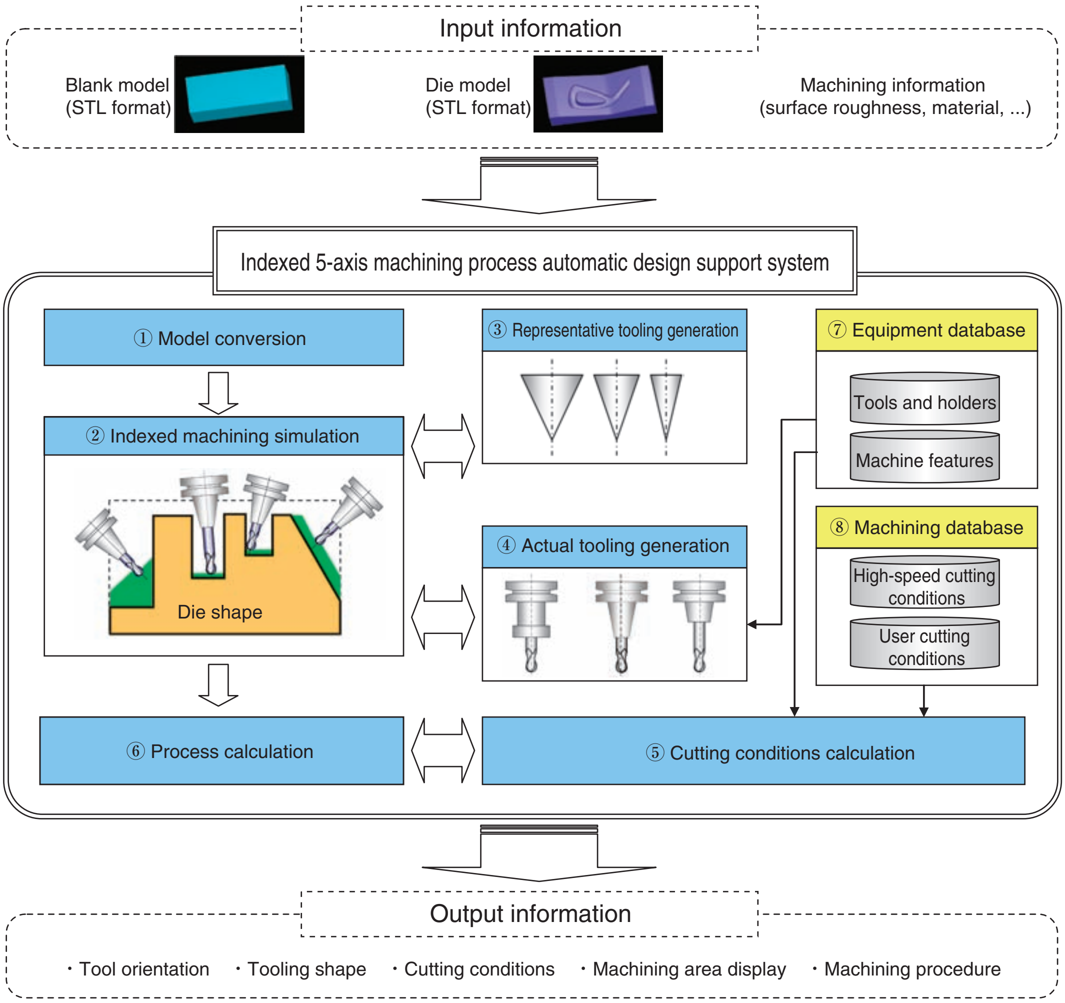


Fig. 2 Configuration of indexed 5-axis machining process automatic design support system

In this way, machining process design work is extremely cumbersome, involving the repetition of high-level thinking work which requires experience, knowledge and skill. Consequently, there is a tendency for longer work time to be required for the fabrication of good quality dies. Further still, depending on individual competence, machining processes may differ greatly, which significantly effects both final machining time and machining accuracy.

3. Overview of System Configuration

Figure 2 shows the overall configuration of the developed indexed 5-axis machining process automatic design support system.

The system contains the six modules and two databases shown below, such as machining simulation technology and structural analysis technology.

①Model conversion section which converts entered STL format die profile data into original data format
②Indexed machining simulation section which simulates indexed 5-axis machining using boolean operation
③A representative tooling generation section which automatically generates tapered tooling
④An actual tooling generation section which automatically generates tooling from tool and holder geometrical data
⑤A cutting condition calculation section which automatically calculates cutting conditions for each automatically generated tooling
⑥A process calculation section which selects the tool orientation, tooling and machining procedures which will give the shortest overall machining time including non-cutting time
⑦An equipment database section which registers information such as tools, holders and machine features
⑧Machining database section which registers cutting conditions data

4. Algorithm Overview

4. 1 Overall Process Flow

Figure 3 shows the flow of process and the positioning of individual modules for the machining process calculations used in this system. Processing steps are explained below.

Step 1: Automatic selection of working tool types

All registered tool types (tool diameter, cutter shape) are extracted from the equipment database, and the removable volume is evaluated for each tool under conditions of no interference. Then, tools which are evaluated to have a volume less than the predefined value are excluded. Through this process, tools with clearly low work capacity are removed from the list of candidates.

Step 2: Calculation of optimal tool orientation

Tool orientation which gives the greatest removal volume is calculated using representative tapered tooling generated from a preset value, in order to select the tool orientation candidates thought to be effective.

Step 3: Generation of non-interfering, high efficiency tooling

From tool and holder data, the optimal tooling with the highest rigidity and no workpiece interference is selected for the selected tool orientation.

Step 4: Calculation of high-speed cutting conditions

Referring to machine features contained in the equipment database and high-speed cutting conditions within the machining database, safe and highly efficient cutting conditions using the selected tooling are determined.

Step 5: Automatic judgment of stock

Indexed 5-axis machining simulation is performed with the selected tooling and judgment is made as to whether stock is left or not. In the case that there is, the process will be repeated from Step 2, calculating tool orientation, using stock as the blank model.

Step 6: Automatic judgment of smallest tool diameter

Judges if processing has been completed up to the smallest diameter tool and if it has not, processing will be repeated from Step 2 with the next tool diameter.

Step 7: Calculation of the optimal machining process

Unnecessary processes are removed from the selected process candidates, and the recommended process to achieve the shortest overall machining time is calculated.

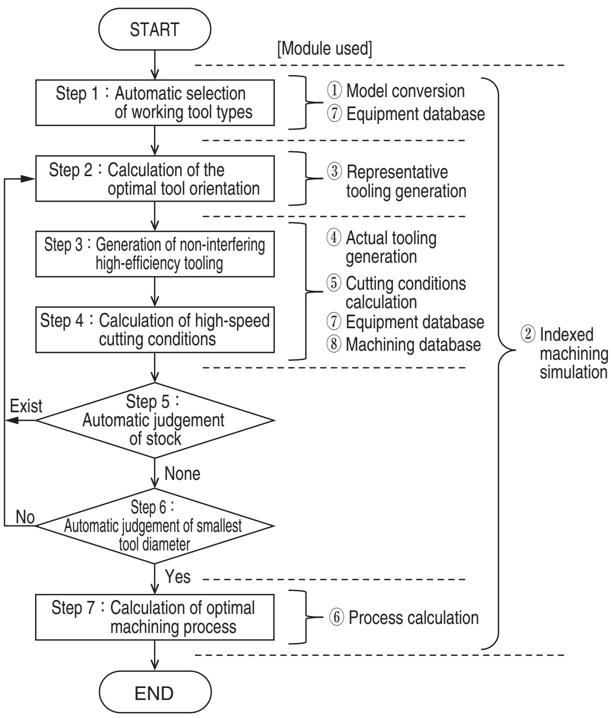


Fig. 3 Positioning of system process flow and each module

The below section will give a detailed description of important processing steps.

4. 2 Selection of Optimum Tool Orientation

The calculation processing procedures for optimal tool orientation (Step 2) are as follows:

Focusing on the removal volume of each tool orientation as an evaluation indicator, "removal volume mapping processing" is adopted[4)] which makes the orientation offering the largest removal volume effective.

Tool orientation is expressed with the two angles (θ, ϕ) shown in **Fig. 4**, and after simulating machining to obtain the removable volume at each orientation angle using tapered representative tooling without interference, this data is mapped, and the orientation which will give the largest removal volume is extracted[5)].

In Step 3 discussed in the next section, the optimum actual tooling is generated. In Step 4, cutting conditions are determined, and machining is simulated using the calculated tooling orientation, tooling, and cutting conditions, and, if any stock remains which can be removed in the remaining cut, the same processing is repeated, with the stock being the new material profile, and process candidate groups that can machine the entire

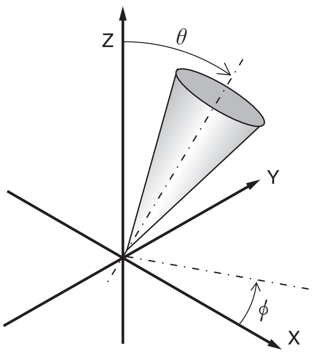


Fig. 4 Definition of tool orientation angle (θ, ϕ)

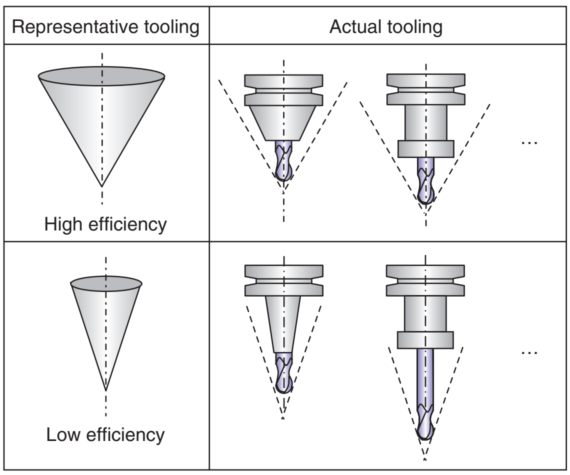


Fig. 5 Representative tooling and actual tooling

region with the pre-selected tools are calculated.

Here, because it would dramatically increase calculation time, it is not practically possible to calculate the optimal tool orientation for all the possible combinations of tools and holders registered in the database. Accordingly, this system separates machining efficiency into levels, gathers the representative tooling shapes to match the applicable efficiencies, and confirms the removal volume with that tooling. Representative tooling is expressed as a reverse triangular shape such as that shown in **Fig. 5**, and, for example, by setting a wide apex angle, it is possible to include highly efficient tooling with short protrusion length.

Figure 7 shows the results (removal volume map) when removal volume is acquired supposing machining against the two models shown in **Fig. 6** with tool orientation ranges $0° \leqq \theta \leqq 45°$ and $0° \leqq \phi \leqq 360°$ from solid block material.

This removal volume map is shown with θ as the horizontal axis and ϕ as the vertical axis. Red indicates an area with high removal volume while blue indicates area with low removal volume.

This removal volume map shows the relationship between tool orientation (θ, ϕ) and removal volume. With Model A, in the calculations when the 1st machining from the blank material is simulated, the optimal tool orientation which will have the greatest removal volume is (θ, ϕ) = (0, 0). Next, calculations are made for the 2nd machining to remove the stock which could not be removed with the 1st machining tool orientation due to interference, and optimal tool orientation is sought in four directions (θ, ϕ) = (30, 45), (30, 135), (30, 225) and (30, 315). Then, because the entire range can be machined with the 2nd orientation, no stock is left for any orientation in the 3rd machining. Through cross-checking with actual machining, we confirmed these calculations to be correct.

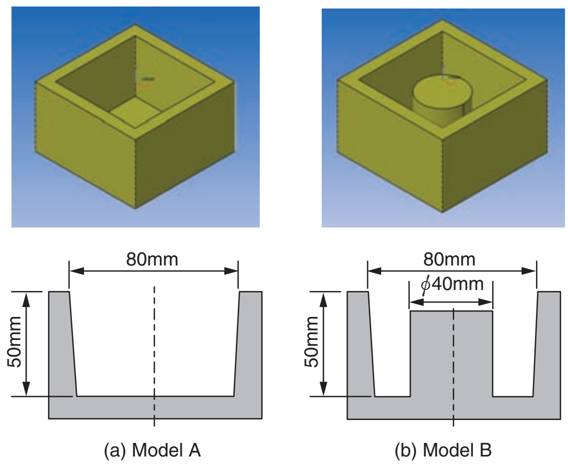


Fig. 6 Test model

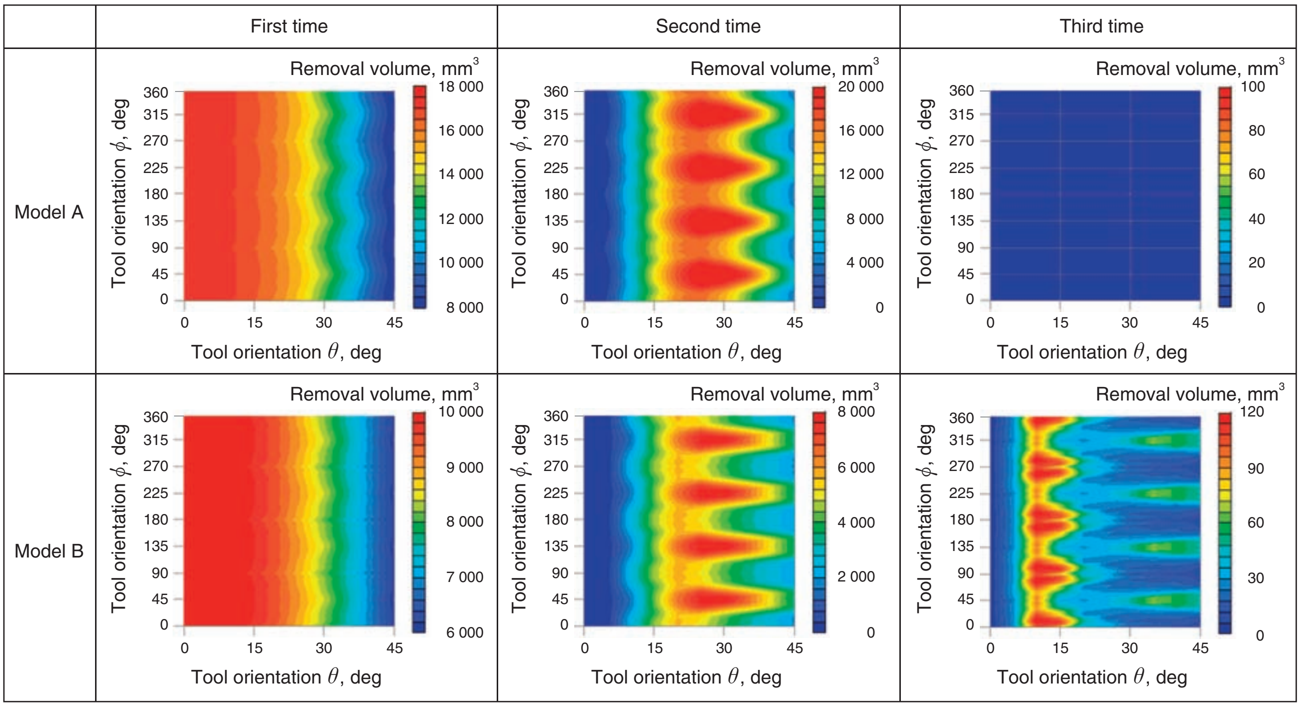


Fig. 7 Removal volume map

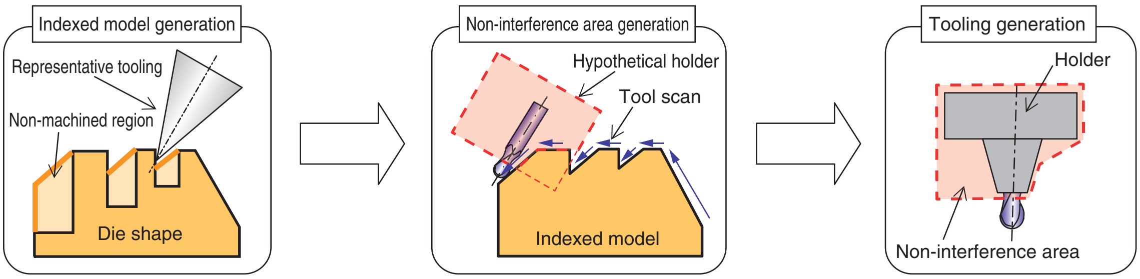


Fig. 8 Virtual holder processing

In contrast to this, in the case of Model B, the tendency of the removal volume is similar to Model A as far as the 1st and 2nd calculations are concerned, giving the same results for optimal tool orientation. However, due to the fact that a cylindrical shape exists in the center, the overall removal volume is less. In the 3rd calculation, the result differs to that of Model A, and the rest material is machined from the 2nd calculation, therefore an effective tool orientation for machining in all four directions can be obtained (θ, ϕ) = (12, 0), (12, 90), (12, 180) and (12, 270). In this way, in response to the shape of the die, tool orientation advantageous for the specific machining is automatically selected using a sequence.

If a person performs this type of quantitative judgment for multiple tool types, it would be extremely complex, therefore having the support of computer calculations is ideal.

4. 3 Generation of Non-Interfering High-Efficiency Tooling

Next, in Step 3, the most rigid tooling shape is generated which will not interfere when a die is machined using the acquired tool orientation. This processing adopts the "hypothetical holder processing" indicated in **Fig. 8**.

The procedures of hypothetical holder processing are shown below. First, the non-machined area that cannot be machined with the representative tooling in the relevant tool orientation is extracted. Then this area is added to the die shape to make indexed model. Next, the cylindrical shaped hypothetical holder is placed in the tool, and a scan of all the faces of the indexed model is done with the tool tip making contact. Then, if the hypothetical holder interferes with the indexed model during scanning, the section of the hypothetical holder which interfered is excluded. As this processing ultimately removes all of the interfering sections from the hypothetical holder after all faces have been scanned, a non-interference area is acquired which does not interfere with the indexed model. Next, from the combinations of tools and holders registered in the database, tooling is sorted with adjusted protrusion lengths that can be contained inside the hypothetical holder created in the above processing, and high-speed cutting conditions are calculated. From all the tooling combinations that can be contained, the tooling with the highest machining efficiency is selected, and a non-interfering and high efficiency tooling shape is generated.

In the calculation of high-speed cutting conditions during tooling generation, based on our original high-speed cutting conditions database, rigidity and resonance point of both tooling and the spindle are taken into consideration, and cutting conditions applicable to the actual machining are automatically calculated[6].

4. 4 Calculation of Optimum Machining Process with Total Machining Time as Index

Step 2 to Step 6 processing is carried out for all the tool types selected in Step 1, and in the last step optimal machining process is calculated (Step 7). Here, unnecessary processes are excluded from the process candidates, and the optimal, shortest, machining time is calculated. Processes referred to as "unnecessary" here are those where the machining area overlaps, and which can be replaced with one or more other processes.

Processing procedures are shown in **Fig. 9**. First, for all the candidate process combinations, overall machining volume is acquired, and combinations which have left over stock are excluded. Then, the machining efficiency of each tooling used for the selected process is calculated, overall machining times are compared based on the respective removal volumes, and the process which will take the shortest time is chosen as the optimal machining process.

Here, overall machining time is obtained by adding

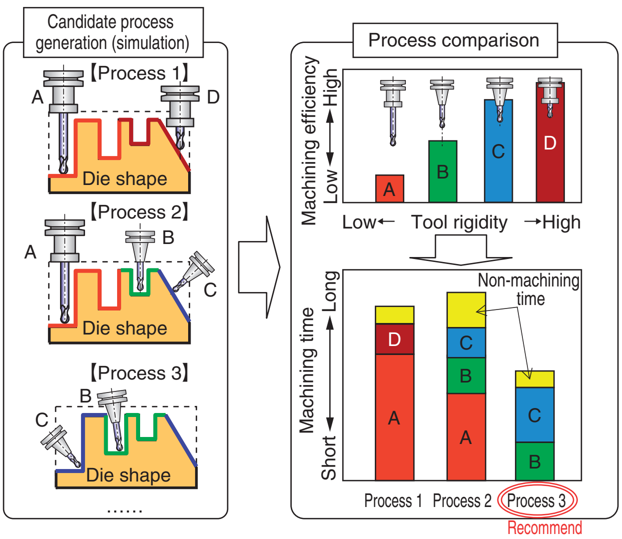


Fig. 9 Selection of recommended process

machining time and non-machining time calculated from actual machining simulation. Machining time is obtained from the removal amount and machining efficiency of the predefined tooling, while non-machining time refers to time unrelated to machining itself such as tool change and table indexed, and is adjusted to suit machine features by inputting parameters.

The above processing makes it possible to automatically calculate the machining process design with the shortest overall machining time.

5. Confirmation Based on Verification Results

Based on the following two verification results, we have confirmed that the indexed 5-axis machining processes can be calculated in accordance with workpiece profiles.

5. 1 Model A

In the equipment database of the system, 130 types of tool and 28 types of holder are registered in advance. Model A, shown in **Fig. 6**, was evaluated using tools which ranged in diameter from $\phi 2$ to $\phi 10$. As shown in **Fig. 10** (b), in the case of 3-axis machining, when the minimum tool diameter of $\phi 2$ is used, deep cutting (L/D=25) is necessary.

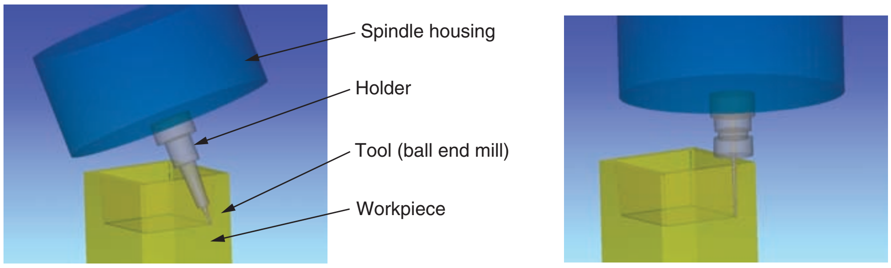
In the case of Model A, due to its relatively simple shape, it is possible to intuitively visualize that a tool orientation with the tool tip pointed towards the four corners at the base of the square pocket would be effective. However, to actually search for the correct tool orientation and safe tooling shape taking interference into consideration, time and effort are required.

When this system was applied to this case, calculations were completed in 7.5 minutes, and four each of roughing and finishing processes were acquired. **Table 1** shows the rough machining process list resulting from calculations. The 1st process uses 10mm diameter ball end mill oriented to the four corners (θ, ϕ) = (30, 45), (30, 135), (30, 225), (30, 315). The following process takes off the stock left in the corner using 5mm, 3mm and 2mm diameter tools in sequence. **Figure 10** (a) shows 2mm diameter tool orientation and tooling for the indexed 5-axis machining acquired through calculations, while **Fig. 10** (b) shows the tooling required for the same process in 3-axis machining for reference. From the tooling diagram, (a), one can see that a shrink fit holder and step ball end mill were automatically selected, and, compared with the tooling for 3-axis machining (b), is a far more advantageous tooling, offering highly rigid and non-interfering machining. Also, this system takes interference between spindle housing and workpiece into consideration.

Based on this process, the cutter path was generated in CAM, and actual machining time was predicted. The

Table 1 Roughing process list of Model A

Process No.	Tool diameter (mm)	Protrusion (mm)	Tool orientation (θ, ϕ) (deg)	Spindle speed (min^{-1})	Feed rate (mm/min)
1	ϕ10	19	(30, 45) (30, 135) (30, 225) (30, 315)	12 423	3 000
2	ϕ5	19	(30, 45) (30, 135) (30, 225) (30, 315)	19 300	2 500
3	ϕ3	16	(20, 45) (20, 135) (20, 225) (20, 315)	38 300	3 500
4	ϕ2	19	(20, 45) (20, 135) (20, 225) (20, 315)	33 000	1 600

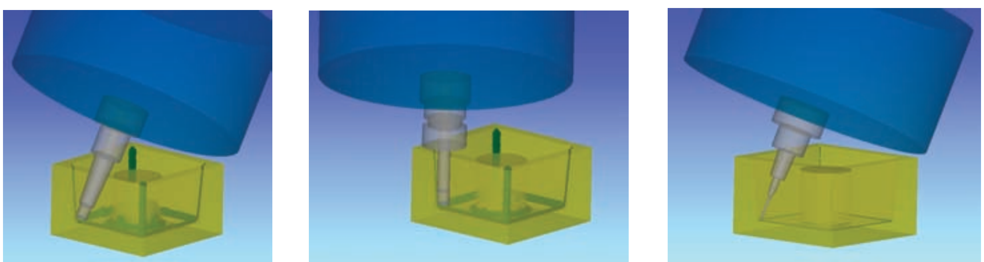


(a) ϕ2 tool for 5-axis machining process
(b) ϕ2 tool for 3-axis machining process

Fig. 10 Display of tool orientation and tooling shape for Model A

Table 2 Roughing process list of Model B

Process No.	Tool diameter (mm)	Protrusion (mm)	Tool orientation (θ, ϕ) (deg)	Spindle speed (min^{-1})	Feed rate (mm/min)
1	ϕ10	16	(20, 45) (20, 135) (20, 225) (20, 315) (10, 0) (10, 90) (10, 180) (10, 270)	13 800	3 300
2	ϕ10	52	(0, 0)	8 100	1 800
3	ϕ5	16	(20, 45) (20, 135) (20, 225) (20, 315)	20 700	2 900
4	ϕ5	40	(10, 0) (10, 90) (10, 180) (10, 270)	8 500	572
5	ϕ3	43	(20, 45) (20, 135) (20, 225) (20, 315) (10. 0) (10, 90) (10, 180) (10, 270)	10 985	421
6	ϕ2	34	(20, 45) (20, 135) (20, 225) (20, 315) (10, 0) (10, 90) (10, 180) (10, 270)	21 000	559



(a) 1st process (ϕ10 tooling)
(b) 2nd process (ϕ10 tooling)
(c) 6th process (ϕ2 tooling)

Fig. 11 Display of tool orientation and tooling shape for Model B result verified that this was a highly efficient process with a machining time 51% shorter than that of 3-axis machining designed by a person. Further still, with the conventional 3-axis machining, it was necessary to change the tool protrusion length for each depth however, in the indexed 5-axis process calculated by this system, it is possible to machine to the bottom face using one type of tooling with short protrusion length, reducing the working tool number from 12 to 8.

5. 2 Model B

Next, Model B, shown in **Fig. 6**, was evaluated through a calculation using the same conditions as Model A. Compared with Model A, Model B has more interfering objects in its center therefore deciding tool orientation and tooling becomes even more difficult.

In this system, calculations were completed in 13 minutes, and six roughing, four finishing processes were acquired. **Table 2** shows a list of these rough machining processes, while **Fig. 11** shows tool orientation and tooling.

The 1st process uses 10mm diameter ball end mill oriented to the four corners, (θ, ϕ) = (20, 45), (20, 135), (20, 225), (20, 315). In order to machine the stock, a further four orientations, (10, 0), (10, 90), (10, 180), (10, 270), were acquired. In the 2nd process, the 10mm diameter tool orientation was made vertical and the protrusion amount set to 52mm, then stock was machined. Then, with the 5mm, 3mm and 2mm diameter tools, the corner portions are machined one by one. The 6th process was the final machining using 2mm diameter ball end mill, machining from eight directions. This is a favorable machining process with no stock left.

6. Conclusion

From newly contrived algorithms, a support system for indexed 5-axis machining process design has been developed, and the following results obtained.

(1) Machining process design tasks performed by people were investigated and analyzed, and algorithms able to automatically perform each thinking steps through analytical means were devised.

(2) A system which automatically calculates highly efficient indexed 5-axis machining processes has been developed, where anyone can operate by simply entering the initial parameters.

(3) From verifying the system against two types of test models, it was confirmed that stock remaining-free, efficient indexed 5-axis machining process design could be automatically calculated.

From here on, we will continue research into even higher speed calculation method, aiming for a system that can perform calculations in a short time for large dies with an escalated data processing volume.

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