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# INTELLIGENT CAM SYSTEM FOR MANUFACTURING OF DIE/MOLD

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## ABSTRACT

An intelligent CAM system for manufacturing of die/mold has been developed by DBM Research Consortium. This system allows even inexperienced operators to successfully apply the method of direct endmilling of hardened steel using (Al,Ti)N-coated micro-grain carbide cutters for pre-finish cutting processes of die/mold. This system supports process design for rough and intermediate-rough cutting, decision of cutting conditions, and tool life estimation. Fixed cycles such as spiral, trochoid and corner machining are fully utilized in the proposed CAM system along with a feed rate adaptation strategy for constant cutting forces. They are applied mainly for removing critical regions in the tool path pattern. Those regions are characterized by an excessive cutting engagement and excessive cutting force. The intelligent CAM system was verified experimentally for rough and intermediate-rough machining in the case of manufacturing a cavity-type mold. The system achieved good results with regard to productivity and costs.


## 1 Introduction

The worldwide market for die/mold has shown increasing demand for short manufacturing and delivery times as well as low price and high quality. In die/mold industry, the fundamental change of manufacturing die/mold has occurred with increasing general availability of (Al,Ti)N-coated micro-grain carbide endmills[1]. They are capable of machining hardened steel of the hardness up to about HRC53 and engender the so-called Hardened Steel Machining Method in manufacturing die/mold, which has the potential to significantly reduce the process lead time by either eliminating or reducing ineffective grinding and heat treatment processes. Knowledge of appropriate cutting conditions and tool life prediction must be established for such advanced tools to be useful for industrial practice because these tools react very sensitively to unsuitable cutting conditions. In other words, design of optimal cutting conditions and generation of appropriate CL data become the most difficult problem for machining of hardened steel.

Complex and free-formed shape of die/mold requires CAD/CAM software for NC-controlled milling. Many commercial CAD/CAM systems exist for die/mold; nevertheless, most of them can not meet the requirement mentioned above. Fundamentally, they can only generate tool path patterns using the profile offset method from product geometry. For that reason, experienced and skillful operators still have to decide cutting conditions that are suitable for the purpose. For example, there are quite often severe concave contour cuttings, which cause a remarkable increase of cutting engagement and cutting forces. For such cutting , feed rate control must be done by experienced and skillful operators for safety and efficiency. It is difficult for inexperienced operators to generate appropriate control programs including process design for die/mold production using conventional CAD/CAM systems.

This study constructs an intelligent endmilling system for manufacturing die/mold. It uses a relatively compact database to determine appropriate cutting conditions. It can be smoothly integrated into a CAD/CAM system. Moreover, its objective is to enable even an inexperienced operator to apply the method of direct endmilling of hardened steel with reasonable ease and favorable economic outcomes. Furthermore, a feed rate adaptation strategy for constant cutting forces based on our previous study is also applied along with appropriately designed fixed cycles for efficient removal of critical regions.

## 2 Construction of Intelligent CAM System

### 2.1 Objectives, Structures and Limitations

The main objective of the intelligent CAM system is automatic process design and NC program generation for rough and intermediate-rough cutting for small and middle-sized die/mold made of hardened steel (this study considers die steel JIS SKD6l, which is widely used in Japan's die/mold industry) using a radius endmill( (Al,Ti)N-coated micro-grain carbide). The system can determine the tool diameter and cutting conditions depending upon mathematically-expressed productivity and manufacturing cost criteria.

An overviewed flow of the system is shown in Fig. 1. First, from a 3D CAD model of die/mold, CL data are produced for a tool candidate by use of commercial CAD/CAM-software. Subsequently a tool path pattern analysis is performed and critical tool path regions are detected geometrically. Then, fixed cycles such as trochoid milling are applied for removing them. For the remaining tool paths, the feed rate is adjusted in curved contours to prevent chipping and tool breakage by keeping the cutting forces constant. This constant cutting force strategy is also applied for each fixed cycle. Next, NC programs are generated and the machining time and cost are estimated. The entire process design is carried out for different endmill candidates (cutter diameter). Finally, the endmill with the most effective result is chosen for use for the actual cutting process.

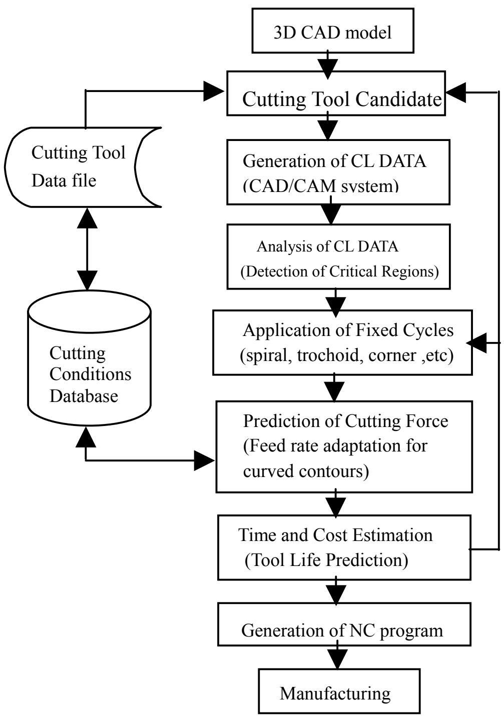



**Fig. 1 General flow of the intelligent CAM system**

The process contains various subsystems and algorithms to realize these functions.

(a) *Tool selection subsystem*

This algorithm is intended to select a suitable end mill from candidates based on the material removal ratio and so forth, which leads to the lowest time and costs for the desired machining operation.

(b) *Path pattern analysis subsystem*

This subsystem detects critical regions geometrically in given tool path patterns. There are regions where cutting engagement becomes too large in tool path patterns generated by the profile-offset method; such regions may engender high cutting temperature and excessive cutting forces.

(c) *Fixed cycle subsystem*

This subsystem inserts fixed cycles on regions where cutting conditions become critical throughout rough and intermediate-rough cutting processes. The fixed cycle is a subset of cutting operations that has a certain tool path pattern; it is used to remove a certain type of geometric feature, such as helical boring, spiral milling, trochoid milling, and corner milling.

(d) *Cutting force estimation subsystem*

This subsystem is intended to maintain the average cutting force during the cutting of curved contours by calculating an adjusted feed rate for each tool path to prevent chipping and tool breakage.

(e) *Tool life estimation subsystem*

This subsystem estimates the percentage of the tool life of the end mill has already been spent. This estimate is calculated based on a database constructed from results of standard cutting tests. Our recent study revealed that tool life becomes much shorter when the cutting engagement angle of an end mill is too large, even if the constant cutting force strategy is adopted. Tool life is estimated depending on cutting conditions with compensation of this effect.

(f) *Cutting time and cost estimation subsystem*

This subsystem mathematically estimates the machining time and costs throughout rough and intermediate-rough cutting processes. This algorithm determines the most effective process design with lower machining time and costs.

### 2.2 Cutting Process of Die/Mold by the system

#### 2.2.1 Rough Cutting

In most cases, a cavity is more difficult to machine than the core because of its shape. Cavity molds are usually rough-cut layer by layer in contour cutting using a radius endmill which has a higher material removal rate compared to a ball endmill of the same diameter. Rough cutting starts from an approach hole machined by helical boring and then milling towards the periphery. A core mold is also machined layer by layer, by starting at the periphery and then milling towards the core shape. After one layer is cut, the endmill is lowered by an axial depth of cut and the next layer is cut, similar to the rough cutting process of the cavity mold.

#### 2.2.2 Intermediate-Rough Cutting

The objective of the intermediate-rough cutting process is to reduce or eliminate of step-shaped leftover volume that remains after rough cutting. It also accelerates the following intermediate and finish cutting processes. In most cases, it is carried out by a radius endmill. Allowance for the following intermediate-finish cutting operation is usually about 1-0.5mm. Intermediate-rough cutting is characterized by an axial depth of cut that is much smaller than that of the rough cutting process. However, the intermediate-rough cutting process is important from the viewpoint of machining time and accuracy of the die/mold since it influences the time spent on subsequent intermediate-finish and finish cutting processes. Also in the intermediate-rough cutting process, the contour cutting is usually used.

### 2.2.3 Definition and Types of Fixed Cycles

Tool path patterns generated by CAD/CAM software using the profile offset method for rough and intermediate-rough cutting frequently give localized critical regions for cutting, especially for cavity molds. It is effective to apply standardized cutting approaches to address this problem. The fixed cycle pattern is useful for such a purpose. It is often used as pre-cutting for rough cutting. For example, a simple rectangular pocket can be machined by four prepared fixed cycles as shown in Fig. 2: helical boring, spiral milling, trochoid milling, and corner milling. Only helical boring used for machining an approach hole for rough cutting process, is performed by a ball endmill (Fig. 3(a)). In these fixed cycles, trochoid slot milling is suitable for removing localized critical regions in the given tool path patterns detected by the path pattern analysis subsystem(Fig. 3(b)). Another advantage of this classification is that the process in each fixed cycle can be studied individually. Thereby, the number of cutting parameters that must be designed simultaneously are reduced to a manageable scale.

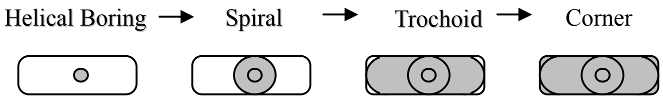
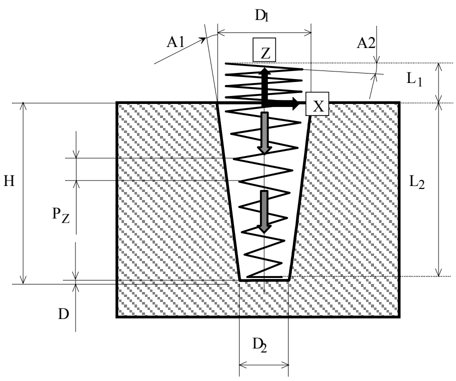
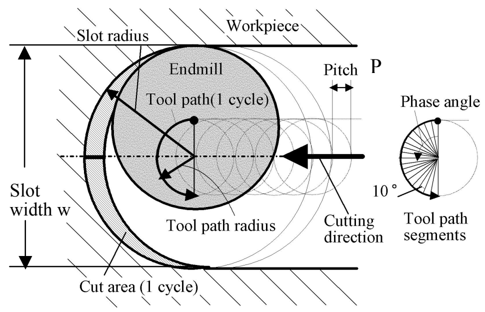



**Fig. 2 Typical fixed cycles for pocketing(Cavity)**

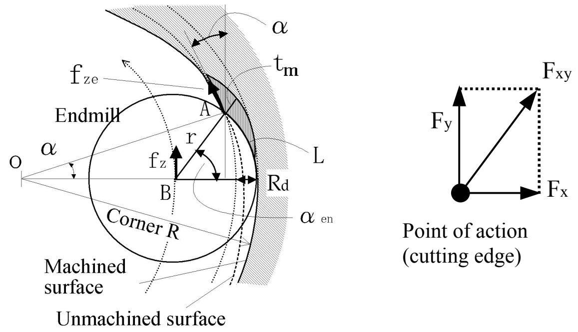



(a) Helical boring




(b) Trochoid milling

**Fig. 3 Schematics of fixed cycles with parameters**




(a) parameters (b) Cutting force components

**Fig. 4 Geometrical relationship for concave contour cutting**

### 2.3 Decision of the Cutting Feed Rate

Selection of a suitable feed rate is a crucial task for cutting of die/mold made of hardened steel. A critical problem with the cutting of concave contours is increased cutting force. Therefore, the goal must be to maintain cutting forces at the same level as that in straight cutting. This can be accomplished by optimizing the feed rate along the tool path.

The basic approach is to predict cutting force while machining and to adjust cutting parameters (e.g., the feed rate) so that the cutting force becomes constant. A second-order cutting force model, from our previous work [2], is expressed generally by the following equation:

$$F_{xy} = \beta_0 + \beta_1 t_m + \beta_2 L + \beta_{11} t_m^2 + \beta_{22} L^2 + \beta_{12} t_m L \qquad (1)$$

where $F_{xy}$ denotes the average cutting force value in XY-plane, and $t_m$ and L are the maximum undeformed chip thickness and cutting arc length respectively. The six coefficients ($\beta_0, \ldots, \beta_{12}$) are identified by conducting a set of straight cutting experiments using the least-squares method. Fig. 4 shows geometric relations associating $t_m$ and L for concave contour endmilling. For cutting force control, a target force $F_{xy}$ is preset first; then the feed rate is solved from the above force model. The target force is determined from the standard conditions for straight cutting or industrial recommendation. Fig. 4 shows that the feed rate must be decreased for smaller tool path contour radius to keep the cutting force constant.

### 2.4 Estimation of the Tool Life

Tool life estimation provides an important look-ahead capability for die/mold manufacturing when considering that tool cost comprises as much as 20% of the total cost of die/mode manufacturing. In practice, it is desired to machine die/mold in one single setup with one endmill. In this study, the total cutting length is used as a measure of tool life; and it can be simply assumed that the total cutting length is constant under the feed rate control described in the previous section, as the following.

$$L_f = \sum_i L_i = C \qquad (2)$$

Therein, $L_f$ is a measure of tool life as the sum of all the cutting arc lengths $L_i$. Nevertheless, the validity of this assumption is subject to various constraints. The tool life of an endmill becomes very short at the cutting of concave contour, in particular when radius ratio $K_r$(machined surface radius/endmill radius) becomes very small. Fig.5 shows experimental cutting length against radius ratio $K_r$. As can be seen from this figure, cutting length becomes constant for larger radius ratio $K_r$. Incidentally, when radius ratio $K_r$ equals to infinity, it is equivalent to straight cutting. In contrast to that, cutting length becomes much shorter when radius ratio $K_r$ is smaller than 2.0. This short tool life arises from temperature elevation on the endmill at concave contour cutting: the time with a cutter engaged in the cutting increases concomitant with the cutting engagement angle($\alpha_{en}$ in Fig. 4(a)). The increased time engenders large temperature elevation on the endmill cutter and, consequently, a high rate of tool wear. As an intermittent cutting process, the end milling process has a thermal mechanism that periodically repeats the cycle of heating under cutting and cooling under non-cutting. Our recent study shows that tool life becomes also much shorter with increasing cutting engagement angle even if a constant cutting force strategy is adopted. The tool wear rate appears to be greatly affected by the cutting engagement angle.

Considering this thermal effect on the tool wear rate for die/mold cutting, the tool life model (2) must be modified as the following.

$$L_t = \sum_i L_i \cdot \gamma \qquad (3)$$

In that equation, $\gamma$, the correction coefficient, is governed by the engagement angle $\alpha_{en}$. Another study by the authors has shown that the flank surface temperature of the worn cutting edge rose sharply at engagement angles larger than 40˚. This fact concurs with the sharp drop in tool life when radius ratio $K_r$ is smaller than 2.0, as seen in Fig.5. Therefore, the region subject to such a high cutting engagement angle must be avoided or be removed first by additional tool paths using fixed cycles. By integrating the total cutting length $L_t$ along the tool path, one can estimate the consumption of tool life at any given point using the ratio of $L_t$ to $L_f$.

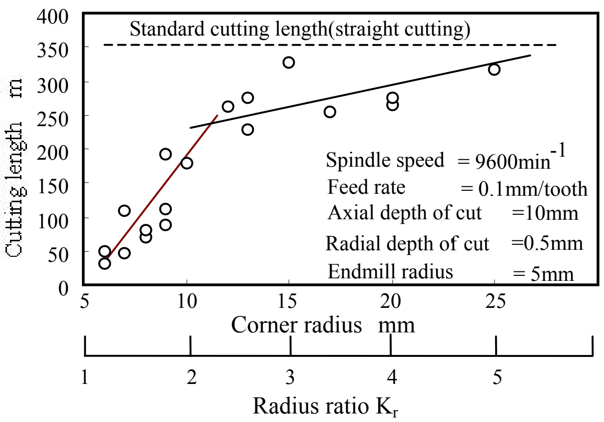
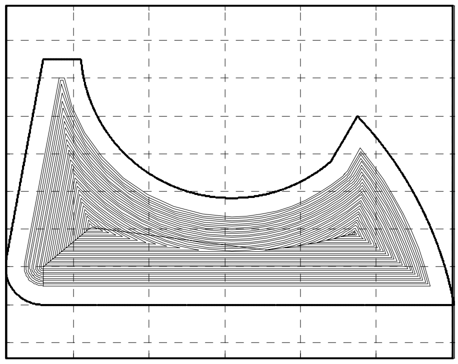



**Fig. 5 Relation between radius ratio $K_r$ and tool life in endmilling concave contour**

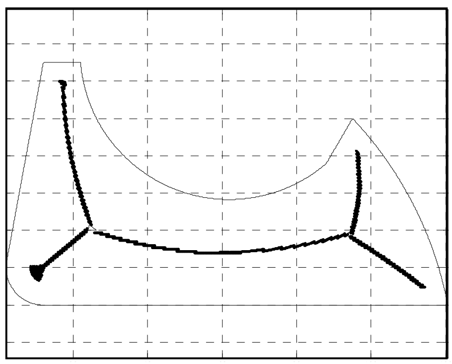
## 2.5 Detection of Critical Regions in the Tool Path Pattern

As described in the previous sections, trochoid milling is a fixed cycle, which is suitable for removing localized critical regions in the given tool path patterns. However, trochoid milling is still a tough cutting with severe conditions for tools and its productivity is lower than side endmilling because of the existence of air-cut time. Therefore, the removed area using trochoid milling must be as small as possible. In this system, critical regions with engagement angle over 40˚ are targeted for milling with this fixed cycle. The trochoid slot can be curved and its width can be changed depending on the geometry. For other tool paths, only feed rate adaptation strategy is applied. The diameter of endmill should be selected so as to cut the concave contour with the smallest radius.

Fig. 6(a) shows an example of tool paths for rough cutting calculated using CAD/CAM software. It is a typical example of tool path patterns by the profile offset method. A region with engagement angle over 40˚ can be calculated as shown in Fig. 6(b). After tool paths by trochoid milling are added for this critical region, all tool paths are recalculated and a new NC program is generated.



(a) Tool path pattern for rough-cutting



(b) Region with engagement angle over 40˚

**Fig. 6 Detection of the critical regions(example) (vertical pitch=10mm, horizontal pitch=20mm)**

### 2.6 Cutting Process Optimization by the System

The optimization of cutting process and NC generation by the intelligent CAM system for targeted die/mold is performed through selection of a suitable endmill and the decision of appropriate cutting conditions using various subsystems and algorithms.

At first, an appropriate tool diameter is selected from candidates using the objective function representing manufacturing time and costs. This study only addresses machining cost and tool costs, which are identified as major costs for die/mold machining processes. The total costs for rough and intermediate-rough cutting processes are given by the following equation.

$$C = c_m T_m + c_t \frac{L_t}{L_f} \qquad (4)$$

In this equation, $c_m$ and $c_t$ are the cost per unit machine time and the cost per a tool, respectively. The ratio of $L_t$ to $L_f$ indicates how much of the tool life has been consumed. Tool life $L_f$ is obtained from the experiment under standard cutting conditions.

As a next step, cutting conditions for the selected tool are decided so that the appropriate consumption ratio of one endmill becomes about 90% by the estimation subsystem. In practice, it is desirable that die/mold are machined in a single setup with one endmill. Fig. 7 shows the main flow of above process.

Assumptions and restrictions in the process design described above in the latest version of the intelligent CAM system are the following:

(a) It supports only two types of endmills: (Al,Ti)N-coated micro-grain carbide ball and radius endmills with the diameters of 6, 8, 10,12,13 and 16mm.

(b) The life prediction is limited to cutting of hardened die steel SKD61 (HRc53) by a radius endmill.

(c) Cutting conditions are chosen to permit the rough and intermediate-rough cutting processes of one die/mold by one ball and one radius endmill cutter.

(d) Only fixed cycles described in section 2.2.3 are used in the process design.

## 3 Case Study

We examined a case study to verify the feasibility of the intelligent CAM system developed in our research. Its major objectives are to:

(a) confirm that all intelligent CAM system modules perform the intended tasks smoothly;

(b) verify that intelligent CAM system prediction algorithms and the database can be applied to actual die/mold making process; and

(c) confirm that usage of the developed intelligent CAM system improves manufacturing time and costs, compared to those of an experienced operator using a conventional CAD/CAM system.

The NC programs used in this case study have been generated using the commercial CAD/CAM system TOOLS in conjunction with the developed intelligent CAM system. Tool selection, process design, decision of cut distributions and the selection of cutting conditions have also been done under support by the intelligent CAM system. The tool life of the endmills under the selected cutting conditions and the cutting time are predicted and ultimately compared to actual values. Machining was carried out on a vertical 3-axis machining center OKK VM-4.

### 3.1 Workpiece and Tools

The mold machined in this case study is shown in Fig. 8; it is a small, box shaped cavity with steep side walls. The workpiece material is hardened steel SKD61 with approximate hardness of HRC 53. The volume to be removed in the cutting process is approximately 220mm$^3$. Optimal diameter of 10mm for radius endmill was determined by the system. Cutting conditions for

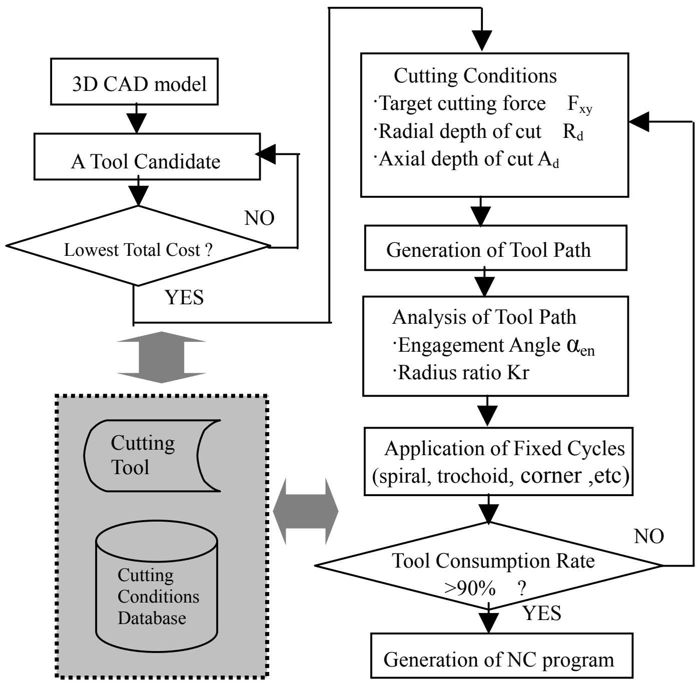



**Fig. 7 General flow of process design by the system**

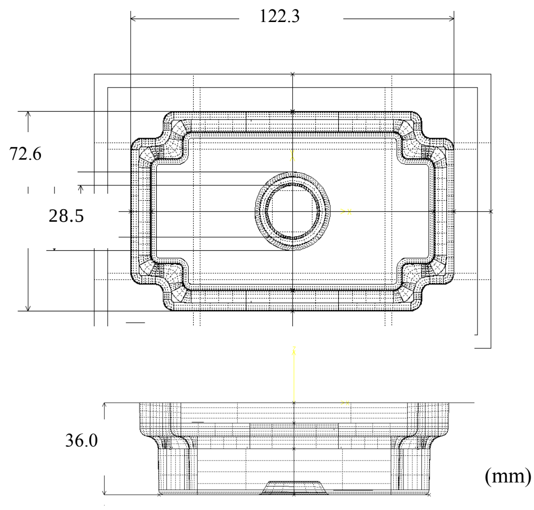



**Fig. 8 Shape and dimensions of the cavity mold**

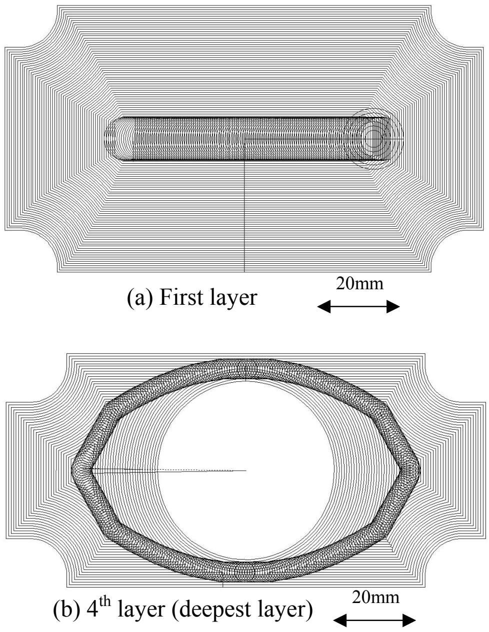



**Fig. 9 Tool paths for rough cutting (with trochoid tool path added for critical regions)**

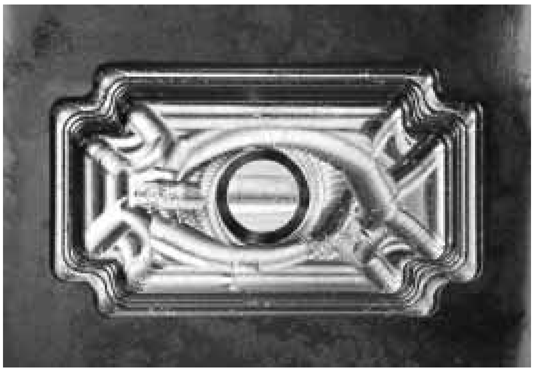


**Fig. 10 Machined workpiece after rough and intermediate-rough cutting**

**Table 1 Case study results**

| | Intelligent CAM System | Conventional CAD/CAM (TOOLS) |
|---|---|---|
| Cutting length (m) | 56.07 | 153.90 |
| Cutting time (min) (Predicted cutting time) | 33:51 (25:27) | 42:47 |
| Time required for (min) programming(approx.) | 60:00 | 30:00 |
| Removal ratio ( $mm^3$/min) | 6.63 | 5:21 |
| Tool wear | normal wear $V_B$=0.04mm | normal wear $V_B$=0.1mm chipping(small) |

rough cutting and other cutting processes with their tool path patterns are also decided. For example, standard cutting conditions for rough cutting are the following with tool path patterns shown in Fig.9: spindle speed=4800rpm: feed rate=0.1mm/cutter: radial depth of cut=0.5mm: axial depth of cut =10mm: and so force. This figure shows that the axial depth of cut for rough cutting was divided into four layers; the critical region detected in the deepest layer machined by trochoid milling differs greatly from that in the first layer.

For comparison, another cutting condition and tool paths using only a ball endmill were determined by an experienced operator using a conventional CAD/CAM system. It is conventionally a standard way; machining of small and middle-sized die/mold is usually done using a ball endmill. In this case, standard cutting conditions using a ball endmill with a 5 mm radius(2 flutes) for rough cutting are: spindle speed=4800rpm; feed rate=0.05mm /cutter; radial depth of cut=3.5mm; axial depth of cut =0.6mm, and so forth.

## 3.2 Machining Results

Table 1 shows the obtained results of rough and intermediate -rough machining processes. Machining of the cavity mold was carried out with just one ball endmill and one radius endmill. As shown in this table, cutting time was reduced by 20% and removal ratio was increased by 27% over the conventional method. The actual cutting time was longer by 35% compared to predicted time by the system, mostly because the commanded feed rate cannot be achieved at corners because of servo delay. The conventional scheme allowed longer cutting length because it requires machining of 58 layers with a small axial depth of cut. After rough and intermediate-rough machining by the intelligent CAM system, normal flank wear($V_B$=0.04mm) was observed at the cutting edge with no serious failure, which proved clearly the validity of the developed cutting condition database and the effectiveness of an integrated system including the fixed cycle of trochoid milling.

## 4 Conclusions

An intelligent CAM system for manufacturing die/mold was developed. A cutting condition database for endmilling hardened steel by (Al,Ti)N-coated micro-grain carbide cutters was also developed based on cutting experiment results. This integrated system allows an inexperienced operator to apply the method of direct endmilling of hardened steel successfully. It supports process design and decision of cutting conditions for rough and intermediate-rough cutting processes in conjunction with integrated subsystems such as feed rate adaptation, tool life estimation, and others. Results of the case study for machining a box-shaped cavity mold validated the productivity improvements of the developed system with the database over that of the conventional method.

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