Invited paper

Development of an Autonomous Machine Tool without the Need to Prepare an NC Program

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Abstract – An autonomous machine tool has been developed to solve fundamental issues with the current command method using NC programs, and some key technologies for its realization have been devised. In the process planning system, various process plans are prepared, and the appropriate process plan can be selected to achieve flexible machining operations. Digital Copy Milling, digitizing the principle of copy milling, has opened up new possibilities for machine tool control. The NC machine tool can be directly controlled with the 3D CAD data of the product shape. Direct machining without the need to prepare an NC program, adaptive control which changes the cutting conditions in accordance with the cutting load, and fault detection can be performed. Machining shape simulator and cutting force simulator are integrated to achieve simultaneous prediction with milling operation for providing the possibility of milling process control and fault detection.

Key Words: autonomous machine tool, computer aided process planning, real-time tool path generation, milling process simulator

1. Introduction

As opposed to traditional NC machine tools, which machine according to pre-set programs, intelligent machine tools do based on their own decision making. The evolution in machine tools is summarized as shown in Fig. 1 [1]. Despite the evolution of machine tools themselves such as the handle of multiple axes and various tasks, the NC programs which use letters and numbers in machine tools' operating commands are being used.

To generate NC programs, the machining sequence, tool paths, and cutting conditions all need to be determined in advance. That means that once its automatic operation has begun, no changes can be made to the tool path or cutting conditions, or depth of cut in particular, during milling operation. Moreover, even if cutting overload or chatter vibration is detected during milling operation, the milling process control according to the situation is not possible. On the other hand, it requires a great deal of time and effort to prepare safe and secure NC programs.

An autonomous machine tool has been developed to solve these fundamental issues with the current command systems using NC programs. Also, some key technologies devised for its realization are introduced in this paper.

2. Proposed Autonomous Machine Tool

Existing NC machine tools perform machining operation by faithfully following the NC program in a passive manner. However, autonomous machine tools do their operations in an active manner, based on their own decision making according to the 3D CAD data of the product shape without the need to prepare NC programs.

A proposed autonomous machine tool is comprised four function modules: 1. Management, 2. Strategy, 3. Prediction, and 4. Observation. The Management module contains a process planning function (CAPP: Computer Aided Process Planning) and determines, in accordance with the 3D CAD data for the product shape, the milling sequence as well as the cutting tools and conditions to be used. The Strategy module contains a Digital Copy Milling (DCM) function which generates the tool path during machining operation in real time, and it controls the machining process by providing feedback on the machining conditions predicted by the Prediction module or measured by the Observation module. The Prediction module has a function for predicting any changes to the machining shape during machining operation, and for estimating the cutting force. Hereinafter, the details of the process planning, the copy milling and the machining process simulation which are the distinctive functions are explained. They do not work independently but rather by complementing each other to realize an autonomous machine tool.

Its main feature is DCM, which controls the NC machine tool by generating the tool path during milling operation. There have been numerous studies done on intelligent machine tools and adaptive control [2], but the concept of an autonomous machine tool which actively performs machining operation without the need for a NC program is not found elsewhere.

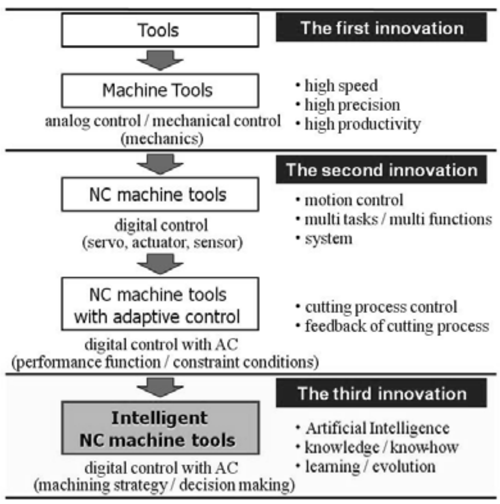


Fig. 1 Evolution of machine tools toward intelligent machine tools [1]

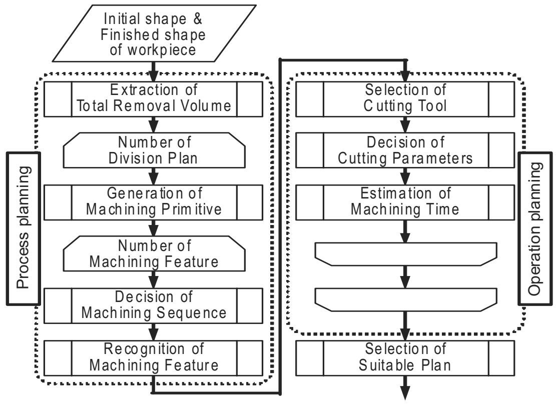


Fig. 2 Flowchart of flexible process planning system [3]

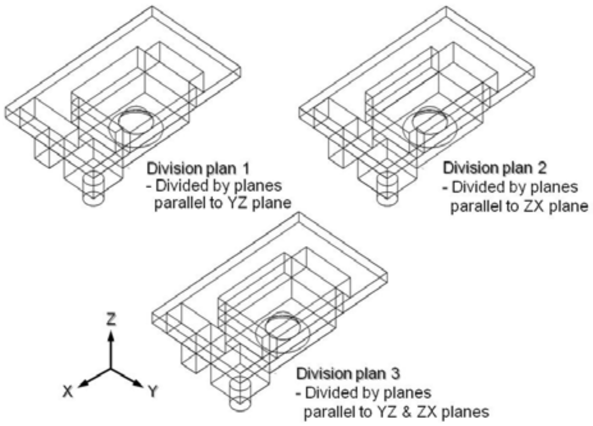


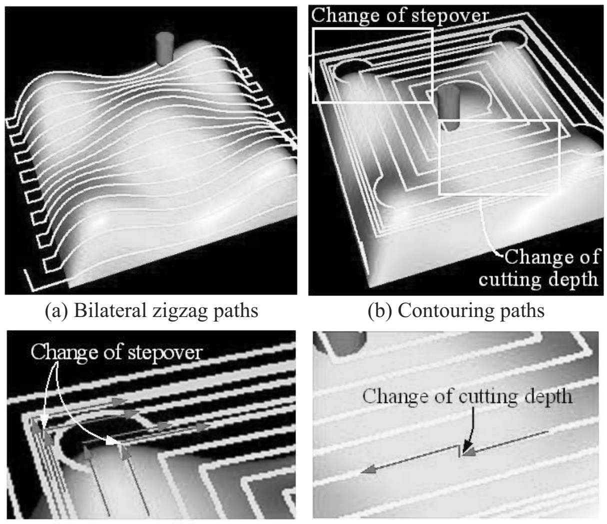
Fig. 3 Machining primitives generated from TRV

3. Flexible Process Planning

Studies using the concept of machining features for the automation of process planning are wide-ranging. However, there are many restrictions on machining features and product shapes, and the selective extraction of machining features is not taken into consideration. In this study, the total removal volume (TRV) from the material shape and the 3D CAD model of the product shape is extracted. By taking the shape during milling operation as the material shape, the TRV can be similarly extracted, even when process re-planning is required due to a machining problem, for instance.

Figure 2 shows the flowchart of flexible process planning system developed here [3]. Considering the milling height in the z-axis direction, the TRV is first divided by planes parallel to the XY plane, and then divided by planes parallel to either the YZ plane or the ZX plane. Depending on the division sequence, various division options can be prepared. Machining primitives are the smallest unit in machining, and are obtained by dividing the extracted TRV. Examples of machining primitives generated according to the 3 division options are shown in Fig. 3.

The milling sequence is determined considering to the spatial relationship between the generated machining primitives. When the milling sequence of the machining primitives has been decided, the machining features can be recognized from the number of open faces and the connections of the edges. The "open face" mentioned in the rules indicates a surface which is in contact with the air. While milling operation proceeds, new open faces appear, but these are also taken into consideration and used to recognize machining features.



(a) Bilateral zigzag paths (b) Contouring paths

(c) Change of stepover (d) Change of cutting depth

Fig. 4 Advantages of real-time tool path generation

The cutting tool types used for milling are determined beforehand for each recognized machining feature. When determining the cutting tool types to be used, the cutting tool diameter suitable for milling the machining feature is determined on the basis of the relation between machining feature dimensions and the cutting tool diameter held by the machine tool. The cutting tool information held by the machine tool has been prepared in advance.

The cutting conditions are determined using Case Based Reasoning (CBR), referring to past machining cases stored in a database. With regard to the required milling details (workpiece, cutting tool type, finishing conditions), cases with similar details are extracted from the database. Differences from the cutting conditions in the extracted machining cases are reflected, and the cutting conditions are determined based on those average values. The database contains 1182 machining cases focusing on end milling.

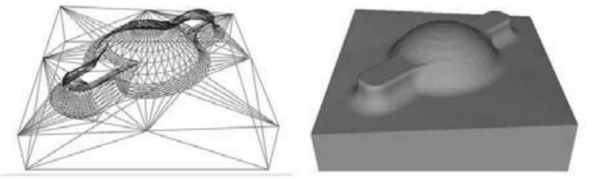
The advantage of computer aided process planning is the possibility of evaluating the machining time and costs of several process plans. In the process planning system introduced here, various process plans can be prepared depending on the division options. The total machining time and the count of cutting tool change are predicted, and the appropriate process plan can be selected to achieve flexible machining operations.

4. Digital Copy Milling

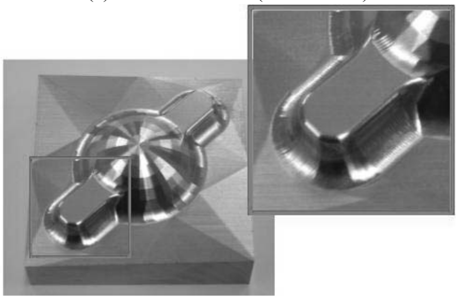
For the realization of flexibility and autonomy in machining, tool paths need to be generated in real time, and NC machine tools need to be directly controlled. Therefore, the Digital Copy Milling (DCM) function, digitizing the copy milling principle, has been developed.

In copy milling, a mock-up is prepared, and when the operator manually copies this model operating a probe, a tool of the same shape as the probe moves simultaneously and a product of the same shape as the model is produced. In DCM, a tool path is generated in real time while the virtual probe, modeled on the computer, automatically copies the virtual model which is a 3D CAD model of the product shape. As a result, the NC machine tool can be directly controlled with the 3D CAD data.

Figure 4 shows an example of an automatically generated tool path.



(a) 3D CAD model (STL format)



(b) Finished surface

Fig. 5 Direct machining using Digital Copy Milling (DCM)

The feature that distinguishes it most clearly from the current command method using NC program is the fact that stepover or the axial depth of cut can be changed during milling operation. As illustrated in Figs. 4(b), (c), (d), even when cutting conditions are changed, a new tool path is autonomously generated from that point up to the end of the milling operation. Studies have so far verified the effectiveness of DCM as follows [4]:

1） As the NC machine tool is controlled with the 3D CAD data on the product shape, no NC program needs to be prepared.

2） Autonomous machining becomes possible based on 3D CAD data of the product shape, through integration of the process planning and the operation planning functions.

3） As tool paths are generated during milling, adaptive control is realized for cutting conditions under cutting load feedback, and tool breakage is avoided.

When using the DCM, and after preparing 3D CAD data for the product shape and the material shape, machining can start immediately without generating an NC program in CAM (hereinafter called direct machining). Direct machining requires process planning where milling sequences, cutting tools used and cutting conditions are automatically determined. Therefore, a commercial process planning software package called Mill-Plan, developed by Toyota Central R&D Labs. Inc., has been integrated with the DCM. By performing direct machining, its effectiveness is verified.

In this case, process information (e.g. milling operation sequence, milling area for each operation, cutting tools used, and cutting conditions) is automatically decided by Mill-Plan from 3D CAD data of the product and material shapes. In DCM, the tool path is generated in real time based on this process information, and machining operation can start immediately by sending NC commands generated by the DCM to the machine tool. For that reason, process planning or NC programming in CAM performed by the operator are unnecessary, and time and effort spent at the machining preparatory stage is significantly reduced.

The machining results are shown in Fig. 5. CAM operation time was 0 min., total machining time came to 113 min. and 25 sec., and there were no particular issues during milling operation. As a comparison test with direct machining, the current method for which an NC program is required was performed. Where the same shape was machined with exactly the same machining equipment, the operator required approximately one hour for preparing an NC program with CAM, and the total machining time came to 98 min. and 12 sec. The total machining time for direct machining was longer than for the current method, but for single item machining, such as prototyping or mold machining, comprehensive lead time including milling preparation time can be reduced in direct machining.

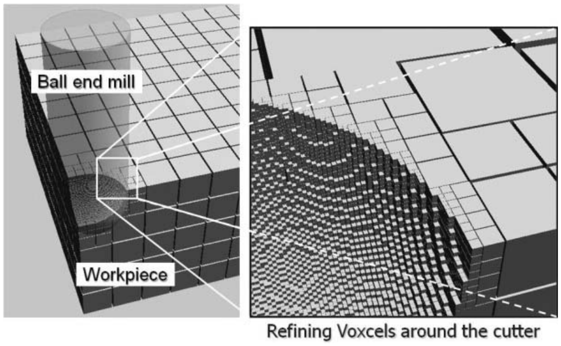


Fig. 6 Cutter-workpiece engagement

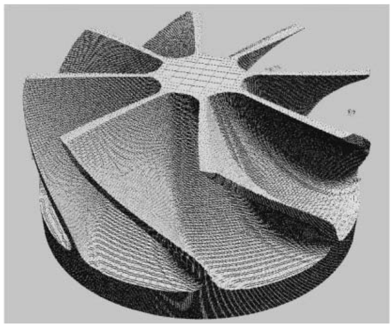


Fig. 7 Example of overhung milling shape simulation

5. Machining Process Simulation

An example of milling shape simulation using a voxel, a model built up from minute 3D cubes, can be seen in Fig. 6. Though shape representation and shape processing are simple, the cubes needed to represent detailed shapes must be small, and a vast amount of memory is needed for the representation of shapes. Therefore, a milling shape simulator that requires only small amount of memory since represents shapes in hierarchically structured cubes, representing only the detailed parts of the shape in small cubes has been developed. Voxel models can also express shapes with an overhang, such as the impeller shown in Fig. 7, and can be applied to milling shape simulations for 5-axis machining.

To predict cutting force in this study, an instantaneous cutting force model with which realistic simulation results can be obtained relatively easily was used. With the instantaneous cutting force model, changes in cutting force during one tool revolution can be calculated from the actual cutting thickness obtained from the geometrical relation between the tool and the workpiece as well as from the cutting coefficients obtained experimentally. If cutting conditions are obtained, such as the radial and axial depths of cut required for the milling shape simulator’s detection, then the cutting force can be predicted in real time.

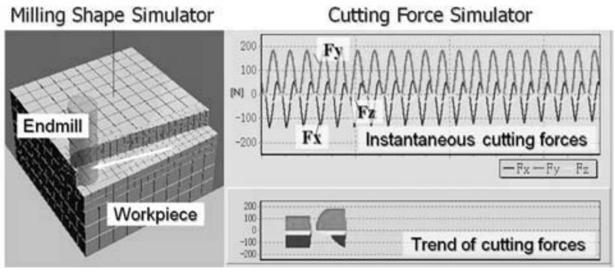
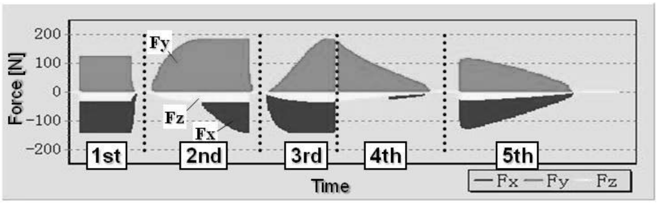
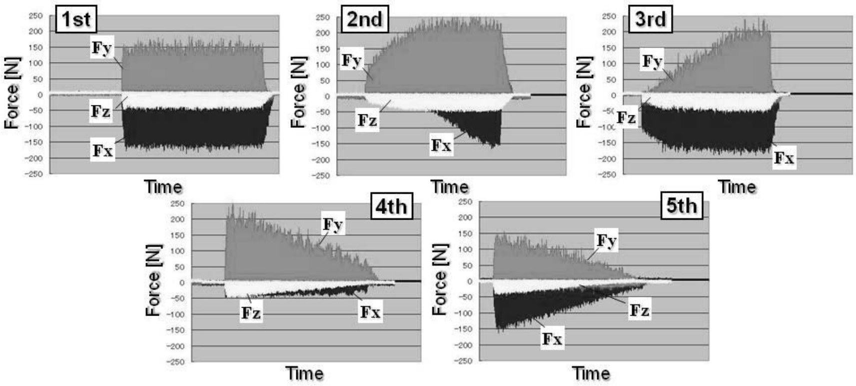


Fig. 8 Simulated milling shape and cutting forces



(a) Simulated cutting forces



(b) Measured cutting forces

Fig. 9 Comparison between simulated and measured cutting forces in cutting test

Figure 8 shows an example of a milling process simulator with integrated milling shape and cutting force simulators [5]. The image on the left shows the change in the milling shape, while the instantly calculated cutting force waveforms of that instant are displayed on the right hand side. The milling shape simulator detects the interference of the tool and the workpiece, calculates the radial and axial depths of cut, and makes it clear that the cutting force during one tool revolution has been predicted by the cutting force simulator.

Figure 9 shows the comparisons and verifications of the cutting forces predicted by the milling process simulator and the actually measured cutting forces. Omitting the details of the cutting conditions, the end mill machining was performed in the following sequence (*Rd*: radial depth of cut, *Ad*: axial depth of cut):

1. *Rd*: 5 mm fixed, *Ad*: 6 mm fixed, up cutting
2. *Rd*: 0 → 10 mm gradual change, *Ad*: 6 mm fixed, down cutting
3. *Rd*: 0 → 10 mm gradual change, *Ad*: 6 mm fixed, up cutting
4. *Rd*: 5 mm fixed, *Ad*: 6 → 0 mm gradual change, down cutting
5. *Rd*: 5 mm fixed, *Ad*: 6 →0 mm gradual change, up cutting

The cutting tool diameter was 10 mm, and the workpiece was FC250 cast iron. The predicted cutting force and the measured one are consistent for both the difference of cutting direction and the changes in depth of cut. [6]

Simultaneous cutting force prediction with milling operation provides the possibility of milling process control and fault detection by comparing the measured cutting force with the predicted one. Both of the milling process control and fault detection are effective functions to realize an autonomous and intelligent machine tool.

6. Conclusion

In this paper, an autonomous machine tool have been developed to solve fundamental issues with the current command method using NC programs, and some key technologies for its realization have been introduced. DCM in particular, digitizing the principle of copy milling, has opened up new possibilities for machine tool control. The machining process simulator with integrated machining shape simulator and cutting force simulator, moreover, provides new functions, including machining process control reflecting prediction results and fault detection in the machining operation.

Specifically, through DCM which allows for sequential control of NC machine tools while generating tool paths during milling operation based on 3D CAD data of the product shape, the following functions which are not possible with the current command method using NC programs have been performed: 1. direct machining without the need to prepare an NC program before milling operation, 2. adaptive control which changes the cutting conditions in accordance with the cutting load during milling operation, 3. fault detection in the cutting load and avoiding tool breakages, and 4. flexible process planning for the determination of milling sequence and cutting tools used in accordance with changes in production planning or the production situation.

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