

Development of High-Speed and High-Precision Production Technology for Mock-up Models

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ABSTRACT

Technologies for 5-axis machining and high-speed machining were developed with the objective of shortening development schedules and achieving higher-precision quality in the Numeric Control (NC) machining of mock-up models, compared to conventional NC machining which consists mainly of 3-axis machining. The conventional NC machining format was thoroughly reviewed in terms of infrastructure, hardware, software, and machining technology. By developing a new system that links CAD/CAM software with the NC machine, 5-axis NC machining and 3-axis high-speed machining technologies have become possible. At the same time, high quality NC data creation time was reduced. As a result of these new technologies, the NC process has become five times faster than the conventional methods.

1. Introduction

The development of mock-up modeling technology has seen considerable improvements in the areas of speed and quality of NC machining on a full-scale model. This was made possible through improvements in machining technology and the increasing experience of engineers.

It was possible to enhance the efficiency by simply upgrading the older tools to the latest available tools. However, performance could not readily be demonstrated if balance was not maintained among the latest tools, computer technologies, and those who handle them. It is important, therefore, to set ambitious goals, and implement them by carefully going over the plans. We have set the development goal for NC machining to be three times the speed and ten times the accuracy than before. As a result of thorough study of the issues to achieve the goal, we recognized the need for

high-speed and high-precision NC machines as well as improvement in NC data creation speeds.

In the past, the design surface was finished by hand after machining. For this reason, we were not able to verify the CAD data against mockup models. As a result, it was necessary to produce verification models frequently.

First, we began the development by trying high speed and accuracy in order to improve the processing speed of mock up models. And then, we transitioned to 5-axis machining from 3-axis machining with 5-axis machining technology, as shown in Fig. 1. Thereafter, we were able to achieve our goal, along with the multiplier effect of improved NC machine performance. As a result, we were able to guarantee verification of mockups through CAD data with no need to produce verification models. This paper discusses these results and related technologies.

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Fig. 1 View of 5-axis machining

2. Development Targets

We focused mainly on the following development areas to achieve the goal of enhancing NC machining speed by three times.

- Develop a high-speed, high-precision 5-axis NC machine
- Develop software for 5-axis NC data

The development goal of the high-speed, high-precision 5-axis NC machine was as follows:

1. Shorten rough machining time by 1/3
2. Shorten finish machining time by 1/3

The development focus of 5-axis NC data software was as follows:

1. Develop 5-axis machining software and its implementation
2. Shorten NC data creation time by 1/2

The main issue was to achieve these requirements.

3. Development of a High-speed, High-precision 5-axis NC Machine

3.1. Specifications

The NC machine has a long Z axis, and is large enough to accommodate one full-scale mock-up, as shown in Fig. 2. When compared with horizontal-type and small machines, it was unfavorable in terms of accuracy and machining conditions. However, we have come up with a structure to



Fig. 2 5-axis NC machine

maintain the required accuracy. One of the most important units of this machine was the 5-axis head, which was newly designed to improve machining accuracy, rigidity, and machining speed over the previous design. The NC controller was developed with the basis of controlling the Rotating Tool Control Point (RTCP). The cast-iron structure was adopted in order to maintain the stability and strength to withstand the stresses of high-speed machining as well as the resonance during machining.

Hollow Shaft Kegel (HSK) taper was adopted in a built-in spindle in order to handle high-speed rotation.

The machining speed was based on the linear axis 20 m/min (the rotating axis was synchronized), with durability equivalent to existing machines, and full consideration was given to the maintenance of the NC machine. On the hardware side, zero backlashes for each rotating axis was an essential requirement. Although positioning accuracy of each rotating axis was guaranteed through scale feedback, the precise position of the tool tip could not be guaranteed, and errors were not completely eliminated. One issue was eliminating errors of several μ m when the coordinates of the axis were reversed.

3.2. RTCP and 5-axis NC Machine Actions

As shown in Fig. 3, it is very important to note that NC actions changed completely, depending on whether the RTCP function was ON or OFF. Previously, this function was not available and so was set as RTCP OFF as shown in the diagrams. In creating NC data, head simulation and actions of the NC machine differed. This is why it requires certain expertise in creating data. Although initially there were numerous problems with the NC controller software, immediately after RTCP was implemented those problems were resolved and automated actions are now possible. During NC data creation, the head simulation display matched the real actions of the NC machine, which made it possible to check the data before machining with that data. In operating the NC machine, head actions became faster than the speed of the F command value, thereby necessitating a more balanced speed control.

3.3. 5-axis Machining Test

As the 5-axis machine consists of numerous moving

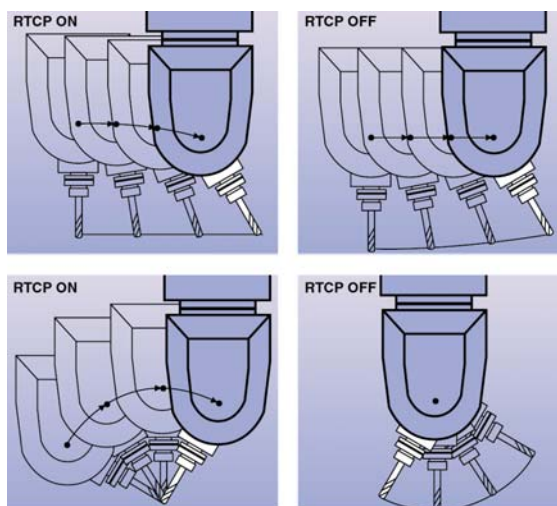


Fig. 3 Movement of RTCP on/off

parts, the static accuracy guaranteed by NC machine manufacturers is not sufficient. It is important, therefore, to guarantee dynamic accuracy at the time of trials. There is no standardized dynamic testing method by the NC machine manufacturers; thereby tests consist of machining spherical surfaces, tapered cones, and machining actual products.

When 5-axis machining was not common in the past, testing through trial and error was repeated. A pair of samples, shown in Fig. 4, confirm different results when RTCP is ON and OFF. These samples specify flat surface machining to simplify measurements. This was aimed at confirming overall precision of the way the NC machine is assembled and basic dynamic actions of the 5-axis control as well as verifying the relationships between 5-axis head and each axis.

Machining produced a washboard appearance when RTCP was OFF, as shown in Fig. 4. This test piece was machined with a ball end mill, which B-axis (C-axis) was rotated +45 degrees to -45 degrees in longitudinal direction.

The machining conditions were as follows:

- Tolerance :0.005 mm
- Machining step :0.4 mm
- Tool : ϕ 20 ball end mill
- Spindle speed :10000 rpm
- Feed rate :1500 mm/min

It is unique for NC data to produce different results depending on whether the NC machine is turned ON or OFF, even though exactly the same NC data is used. Needless to say, RTCP ON is the basic state. However, some pieces could be machined with RTCP OFF, depending on the shapes being machined and the quality of the NC data. The results of machining were measured, and static positioning accuracy of the X, Y, Z, B, and C axes were checked and determined whether any errors in the shape of the workpiece was being made. Static movements were also confirmed by making synchronous adjustments of the NC controller at the same time.

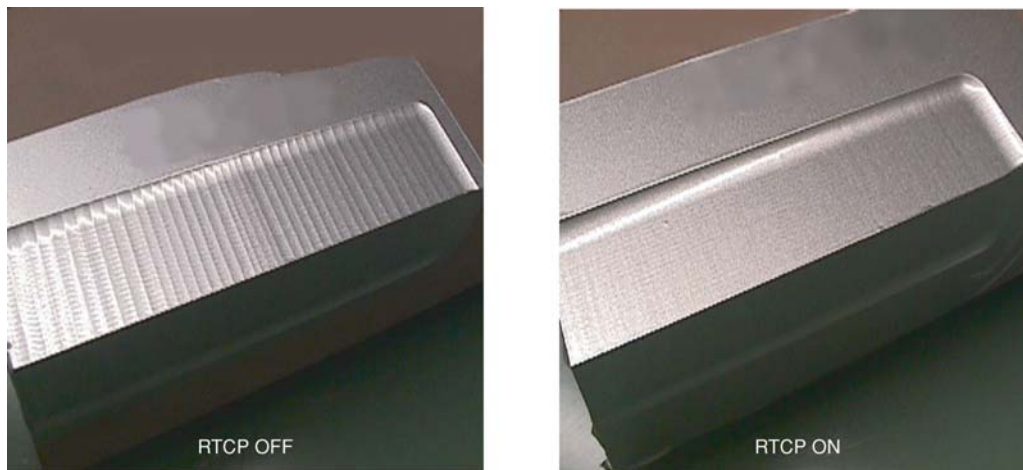


Fig. 4 Result of RTCP on/off

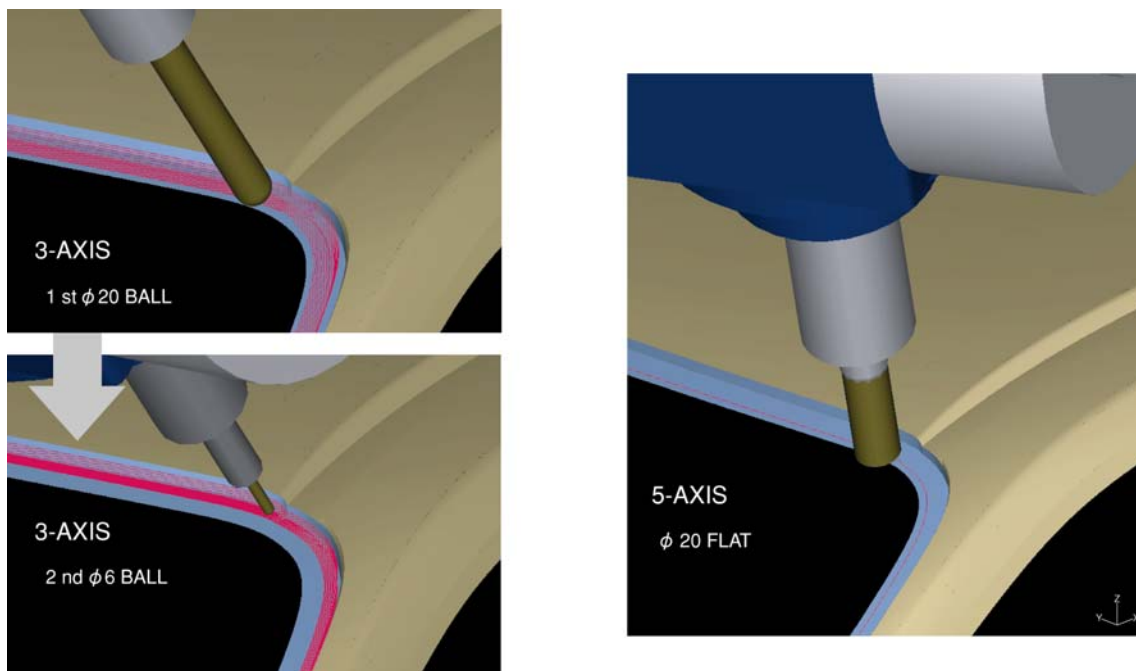


Fig. 5 Difference between 3-axis machining and 5-axis machining

When problems arose through this inspection, we had to explore whether there were problems with the way the NC machine was assembled while re-verifying how the 5-axis head was retrofitted to solve these problems. Next, we verified accuracy and movements of each part through machining.

It was necessary, therefore, to exert effort in making adjustments to guarantee accuracy of the 5-axis NC machine besides the time spent on the basic 3-axis, at the time of its' implementation.

4. Development of 5-axis NC Data Software

4.1. 5-axis NC Data Software

While most of the personal computer CAM software currently available on the market offers sufficient capabilities for 2-axis and 3-axis machining, they are generally not very user-friendly for fixed 5-axis machining, and some do not even support it at all. Furthermore, functions of creating NC data for 5-axis machining are limited, and there are few that are suitable for machining mock-up models. Therefore, we developed software that was suitable for model machining.

4.2. NC Data Creation for 5-axis Contour Machining

In the past, contours of mock-up models were machined with a ball end mill using 3-axis NC data, as shown in Fig. 5. This process was the most common practice with conventional NC machining. Also, this function is essential for mock-up model machining. This section compares machining methods of the NC machining process for window areas as shown in Fig. 5.

The 3-axis machining process was as follows:

Process 1 ϕ 20 ball Rough machining Multiple paths
 Process 2 ϕ 20 ball Finish machining Multiple paths
 Process 3 ϕ 6 ball Rough machining Multiple paths
 Process 4 ϕ 6 ball Finish machining Multiple paths

The machining in processes 1 through 4 takes longer time due to multiple paths and thus, some un-machined areas remain.

The 5-axis machining process was as follows:

Process 1 ϕ 20 flat Rough machining one path

Process 2 ϕ 20 flat Finish machining one path

As a result, the number of processes was cut in half and the machining time was reduced to 1/3. In addition, the quality of machining was improved without un-machined areas.

The 5-axis machining enabled the use of a flat-end mill, and it offered an innovative method of reducing machining processes.

The 5-axis machining features were as follows:

- Reduced machining time
- Improved machining quality
- Reduced tool cost
- Shortened NC data creation time (fewer processes)
- Reduced time to create CAD models of contoured shapes

Recently, we have seen much progress made in machining by high speed and high precision of NC machines. However, these results indicate that in some instances, it is more effective to implement 5-axis machining instead of trying to make the NC machines faster.

4.3. NC Data Creation for 5-axis Surface Machining

The surface machining is one of the most important functions in the 5-axis machining. It performs machining of design surfaces (multiple surfaces) with a flat or corner radius end mill along surfaces.

Normally, 3-axis machining is more accurate and stable than 5-axis machining. However, for a mock-up model, it is more effective to process on a large surface through 5-axis machining with a corner radius end mill rather than faster and finer machining with a ball end mill. In the past, there was a problem of remaining grind marks with the 5-axis machining software. Because of the poor quality on fillet shaped parts, the only alternative was machining faster and finer with 3-axis machining as shown in Fig. 6. The grind marks were caused by the direction of machining in the NC data. However, the primary cause was the increased head movement and the quality deterioration of the 5-axis data at the shape change point. 5-axis surface machining became possible for fillet-shaped parts by minimizing the 5-axis head movement.

The machining conditions for the pieces shown in Fig. 6

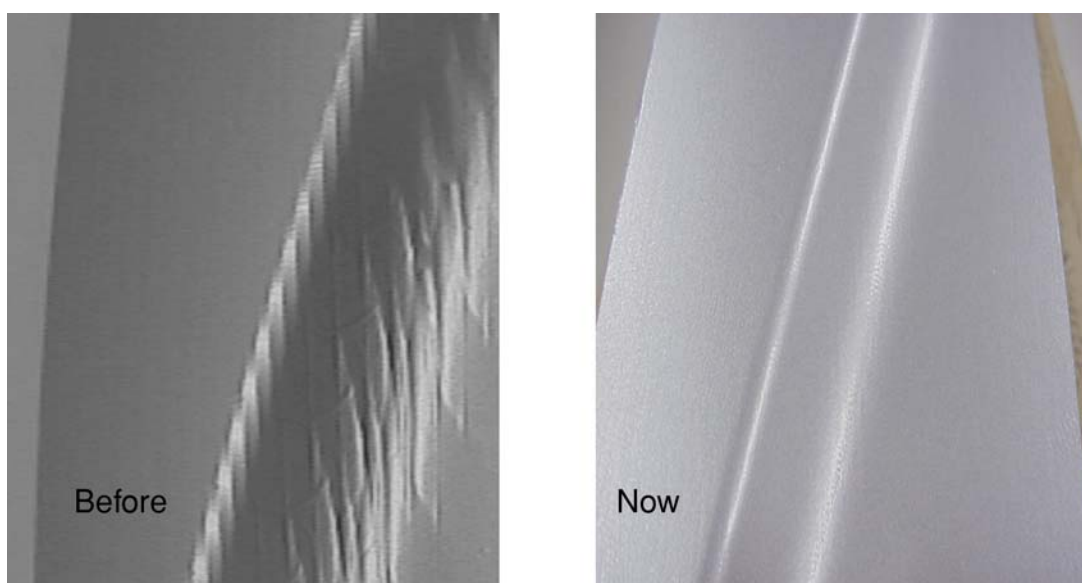


Fig. 6 Result of fillet on part using 5-axis machining

were as follows:

- Tolerance :0.005 mm
- Machining step :Basic setting, 2 mm
- Tool : $\phi 20$ R3 corner radius end mill
- Machining direction :Before – Axial direction + fixed stepping
Now – Direction along surface + variable stepping

It shows the resulting quality affected by the variable stepping.

4.4. New Functions Successfully Implemented Through Joint Development

5-axis NC data with constant machining step left grinding marks where the shape changes, as shown in Fig. 7. It was necessary to have variable step machining to eliminate this problem, as shown in Fig. 8. This was a very important function particularly when using a flat end mill with the 5-axis machining. This function, called “constant scallop height,” is essential for high-quality machining of design surfaces. This function was developed in conjunction with the 5-axis attitude change control.

The 3-axis machining with a ball end mill produced a fairly high-quality surface by making the machining step narrower and setting the grinding mark amount to scallop height 0.005 mm or less, as shown in Fig. 9. This principle was applied in developing the 5-axis machining.

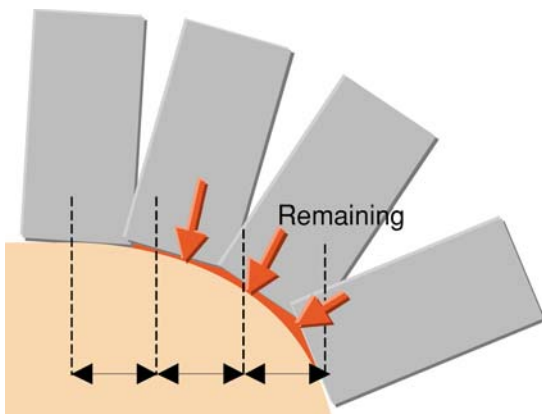


Fig. 7 Constant step over 5 mm

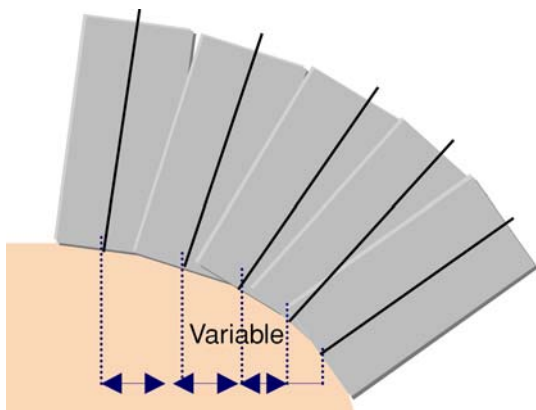


Fig. 8 Variable step over 3-7 mm

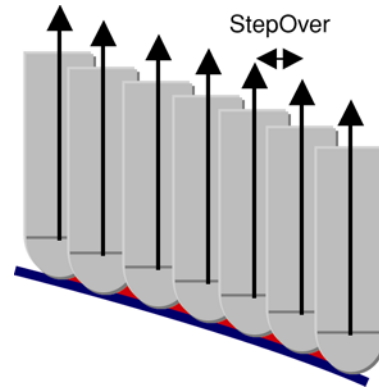


Fig. 9 3-axis milling with step over 0.77 mm

As an example, Fig. 10 shows a simulation using the 5-axis machining on a roof. It was made easy to create the optimal NC data by simulating the 5-axis head and the rotating axis. There was no interference of the 5-axis head in this simple example. However, it becomes extremely useful in complex shapes.

The machining conditions for this simulation were as follows:

- Tolerance :0.005 mm
- Machining step :Specified by scallop height of 0.005 mm
- Tool : $\phi 40$ flat end mill
- Machining direction :Direction along surface + variable stepping
- Feed rate :20 m/min.

A smooth design surface and large machining area, such as a roof, was an optimal shape for 5-axis machining. The machining time was reduced to 1/10 in 5-axis machining with the use of a large flat end mill, compared to 3-axis machining. Furthermore, the quality of the machined results with 5-axis machining was quite different from that obtained with 3-axis machining, as shown in Fig. 11. However, it was very difficult to reduce the amount of time needed for creating data. Even though the NC path calculation is quick, it takes longer to verify the NC data in simulation for 5-axis machining than for 3-axis machining because of a need to check the head movement.

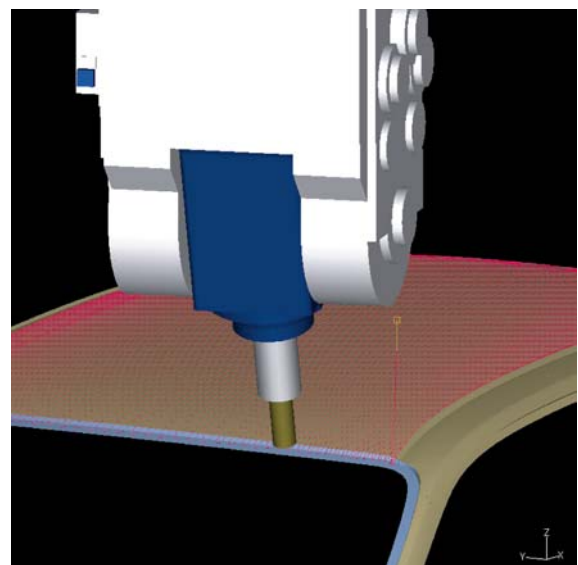


Fig. 10 Simulation by 5-axis machining with flat endmill

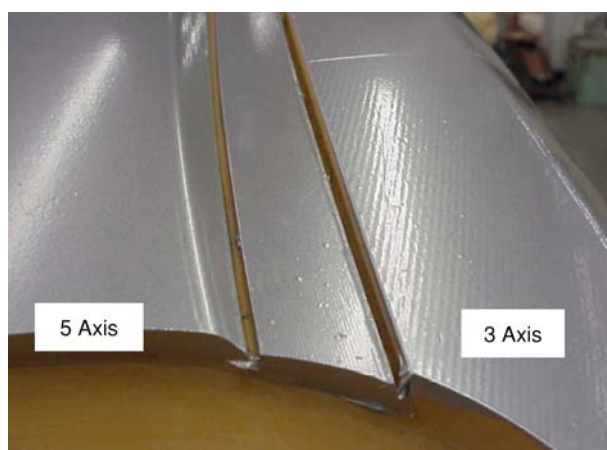


Fig. 11 Difference between 5-axis machining and 3-axis machining

The machining conditions for the ball end mill were as follows:

- Tolerance :0.005 mm
- Machining step :0.65 mm
- Tool : ϕ 30 ball end mill
- Machining direction :Direction of X axis
(machining axis: 45 degree tilt)
- Feed rate :30 m/min.

The entire roof surface after 5-axis machining is shown in Fig. 12.

The 5-axis machined surface reflects the fluorescent lights more clearly than the 3-axis machined surface, which indicates the higher quality.

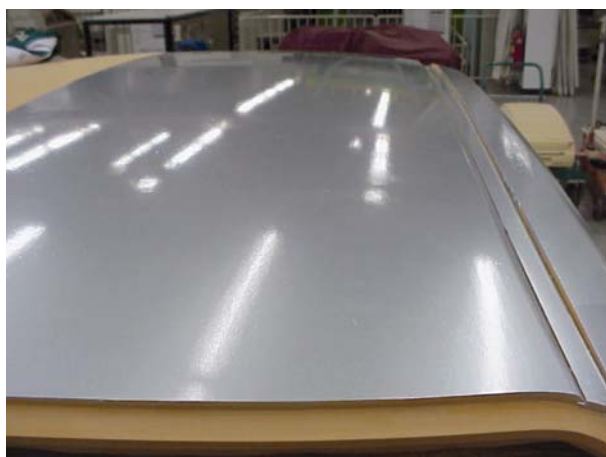


Fig. 12 Result of 5-axis machining

5. Results of Development

The objective of shorter mockup model development time was achieved by shortening rough machining time, NC data creation time, and finish machining time. The software for 5-axis machining was also developed and implemented. Furthermore, the development of 5-axis machining technology demonstrated the capability of reducing machining times not only by increasing machining speeds, but also by optimizing the machining methods. Also, it confirmed improvement in machining quality.

As a result, the machining speed was increased by five times, which far exceeded the original objective.

6. Conclusions

5-axis machining technology had been developed as a core technology for mock-up model NC machining, as opposed to the conventional 3-axis machining. The proprietary technology was developed, because there were few general-purpose hardware and software machining technologies available in this field.

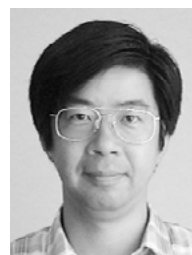
As a result, the capability of practical 5-axis NC machining technology was demonstrated, and machining times were greatly reduced by the multiplier effect from the increased 3-axis machining speed. Furthermore, the system was developed to supply high quality NC data, confirmed by simulation, in a timely manner. This resulted in increasing the NC machining speed by five times.

The authors wish to extend their appreciation to those who cooperated in perfecting this new technology.

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