Technologies of High-Precision 5-Axis Machine µV1-5X and Machining Examples

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In the field of high-precision machining in Japan, a required machining accuracy of ±1 µm has become more common for 3-axis machines. Amid this, customers are also beginning to request equivalent accuracy for 5-axis machines. However, achieving such high-precision machining on a 5-axis machine is difficult because it not only has more components but also involves multiple factors that can degrade precision. To address this demand, we developed the high-precision 5-axis machine µV1-5X using our unique technologies, which realizes high-precision machining equivalent to that using a 3-axis machine. The µV1-5X can be applied to high-precision machining conventionally performed using a 3-axis machine, in addition to machining complex three-dimensional shapes accomplished only using a 5-axis machine.

1. Introduction

Recently in Japan, in the field of high-precision processing including die machining, customers have been actively considering the introduction of 5-axis machines to improve machining accuracy. Specifically, they are shifting to 5-axis machines that can machine five faces without reclamping the workpiece to minimize machining errors due to setup changes and, in precision die machining that frequently uses ball endmills, they use such techniques as always cutting with the tool tilted relative to the workpiece, instead of cutting by the tip of the tools where the peripheral velocity is zero, to improve machined surface quality. To address these demands, manufacturers are rapidly offering a variety of peripherals including application software. To facilitate the introduction of 5-axis machines, it was a must to market a high-precision 5-axis machine that provides machining accuracy equivalent to that of 3-axis machines, so we have developed the high-precision 5-axis machine µV1-5X. The following are the technologies used in the µV1-5X and the evaluation of its machining performance.

2. Features of µV1-5X

The µV1-5X is a high-precision 5-axis machine developed based on the high-precision 3-axis machine µV1, which has already gained popularity in the market. The external appearance and the main specifications of the µV1-5X are shown in **Fig. 1** and **Table 1**, respectively. As to structural

Fig. 1 External appearance of µV1-5X

Table 1 Specifications of µV1-5X

Axis travel	X-, Y-, and Z-axes (Linear axes)	450 × 350 × 300 mm
	B-axis (Tilt axis)	130° (–10° to +120°)
	C-axis (Rotation axis)	360° (Continuous)
Table	Working surface	ϕ100 mm
	Max. workpiece size (Outer diameter)	ϕ160 mm (Shape limited)
	Max. loading capacity	20 kg
Spindle	Rotational speed	400 to 40000 min^{-1}
	Taper size	HSK–E32
Feedrate	X-, Y-, and Z-axes (Linear axes)	15000 mm/min
	B-axis (Tilt axis)	75 min^{-1}
	C-axis (Rotation axis)	100 min^{-1}
Automatic Tool Changer (ATC)	Tool storage capacity	18 tools (Optional : 30 tools)
	Max. tool diameter	ϕ40 mm
	Max. tool length	130 mm
Machine size & weight	Height	2370 mm
	Floor area (Width x Depth)	1920 × 2054 mm
	Weight	5500 kg

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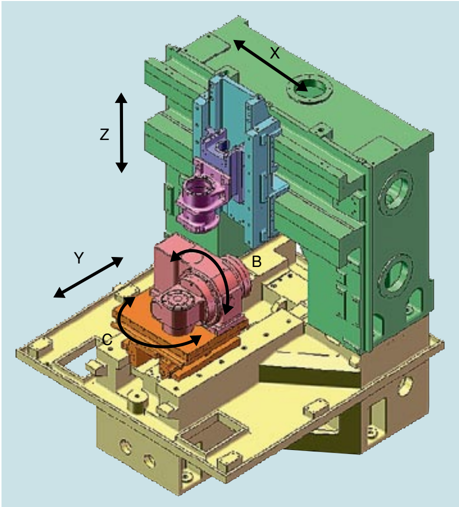

Fig. 2 Drawing of µV1-5X

form, the µV1-5X is a table-swivel type machine with a tilt axis (B-axis) and a rotation axis (C-axis) on its table. **Figure 2** is a drawing of the µV1-5X. It is designed to prevent machining accuracy from being affected by inertial forces generated by acceleration or deceleration of axis travel on both the B- and C-axes during machining on the workpiece side and on the spindle side, by laying out the tilt axis (B-axis) in parallel with the Y-axis and using mainly the X-axis on the spindle side to feed the workpiece in a longitudinal direction. This structural form also has advantages in removing the chips produced during machining because they are ejected to the front and right/left sides of the tilting rotary table and enabling the positions of the workpiece and the tool during machining to be viewed easily in front of the operator.

3. Accuracy improvements in µV1-5X

On a 5-axis machine, geometric deviations on the tilt and rotation axes must be considered in addition to those inherent to a 3-axis machine. Improving machining accuracy of a 5-axis machine depends on how the accumulation of these additional deviations can be reduced. Therefore, in developing the 5-axis machine µV1-5X that provides machining accuracy equivalent to that of 3-axis machines, we conducted a simulation analysis on how the geometric deviation and positioning accuracy of each machine element affects the machining accuracy and yields the optimum values.

Using the schematics we extracted 13 deviation items with respect to the geometric deviations that arise on both

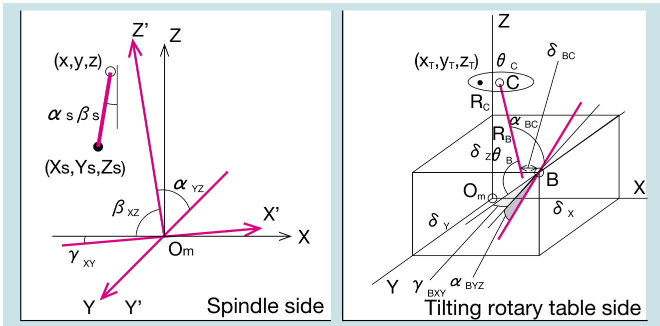

Fig. 3 Geometric deviations on spindle and tilting rotary table

Table 2 Geometric deviations and positioning accuracy

	Geometric deviation or axis positioning accuracy	Optimum value	Actual value
Machining accuracy	Circularity (Target accuracy)	2.1 µm/ϕ80 mm	1.95 µm/ϕ80 mm
αYZ	Squareness of Y-axis to Z-axis in YZ plane	2 µm/200 mm	2 µm/200 mm
αZS	Parallelism of Z-axis to spindle in YZ plane	1 µm/100 mm	1 µm/100 mm
βXZ	Squareness of X-axis to Z-axis in XZ plane	2 µm/200 mm	1 µm/200 mm
βZS	Parallelism of Z-axis to spindle in XZ plane	3 µm/300 mm	3 µm/300 mm
γXY	Squareness of X-axis to Y-axis in XY plane	3 µm/300 mm	2 µm/300 mm
⊿X	X-axis positioning accuracy	±1 µm	±0.25 µm
⊿Y	Y-axis positioning accuracy	±1 µm	±0.35 µm
⊿Z	Z-axis positioning accuracy	±1 µm	±1.0 µm
BRX	X-axis backlash	1 µm	0.2 µm
BRY	Y-axis backlash	1 µm	0.1 µm
BRZ	Z-axis backlash	1 µm	0.4 µm
αBC	Squareness of B-axis to C-axis in YZ plane	3 µm/300 mm	3.8 µm/300 mm
αBYZ	Parallelism of B-axis to Y-axis in YZ plane	3 µm/300 mm	1.4 µm/300 mm
βBXZ	B-axis (tilt angle) origin	1 µm/100 mm	4 µm/100 mm
γBXY	Parallelism of B-axis to Y-axis in XY plane	3 µm/300 mm	3 µm/300 mm
δBC	Coaxiality of B-axis to C-axis in XZ plane	3 µm	8 µm
δX	Position of B-axis (tilt angle) center coordinate (in X-axis direction)	1 µm	–
δY	Position of B-axis (tilt angle) center coordinate (in Y-axis direction)	1 µm	–
δZ	Position of B-axis (tilt angle) center coordinate (in Z-axis direction)	1 µm	–
⊿B	B-axis indexing accuracy	±2 sec	±1.9 sec
⊿C	C-axis indexing accuracy	±2 sec	±1.4 sec
BRB	B-axis backlash	2 sec	2 sec
BRC	C-axis backlash	2 sec	2 sec

the spindle side and the tilting rotary table side. **Figure 3** outlines these geometric deviations. We then added 10 items that represent the positioning accuracy of each axis and, for a total of 23 items, determined the optimum values so that the circularity is maintained at 2 μm or less in simultaneous 5-axis machining of a ϕ80 cone frustum. Then, we adjusted the machine based on these optimum values and obtained the results shown in **Table 2**. Although there are three items in which the actual value is worse than the optimum value, adjustments were made to improve the accuracy for other items. The resulting machining accuracy of the μV1-5X will be provided in the next "Examples of machining with μV1-5X" section.

4. Examples of machining with μV1-5X

4.1 Simultaneous 5-axis machining of a cone frustum

Although the JIS standard for the evaluation of 5-axis machines is currently being proposed, in general, the cone frustum finishing method provided in NAS979 is a well-known standard. Therefore, we conducted simultaneous 5-axis machining of a cone frustum (80 mm outer diameter) based on this standard, which is described here. First, it should be noted that "simultaneous 5-axis machining of a cone frustum" is a method for evaluating the circularity of the cross-section when finishing the side surface of a cone-frustum shaped workpiece by simultaneously controlling each of the three linear axes (X-, Y-, and Z-axes) and the two rotation axes (B- and C-axes). **Figure 4** shows how the machine was set up for the cone frustum machining and **Fig. 5** shows the resulting circularity data. The circularity results show that the μV1-5X, after the abovementioned adjustments for accuracy improvements, could attain a circularity of 1.95 μm/ϕ80 mm, the same level of the target machining accuracy, in the simultaneous 5-axis machining taking error factors for all of the five axes into account. For reference, the circularity obtained in 2-axis machining (X- and Y-axes) using the same machine was 1.5 μm/ϕ40 mm, which means that, although the machining diameter differed, the machine provides a machining accuracy equivalent to that of 2 linear-axis machining.

4.2 Groove machining before finishing

Next, as a machining example to show that the μV1-5X is not only a high-precision 5-axis finisher but also a versatile machine applicable to rough machining, we would like to introduce groove roughing using a ϕ8 endmill. For this groove roughing example, the infeed amount was set to 1 mm, which is the machining limitation of the HSK-E32 with a ϕ8 endmill. HSK-E32 is the tool holding mechanism adopted in high-speed and high-accuracy spindles such as one used for the μV1-5X. **Figure 6** shows the machine setup for the

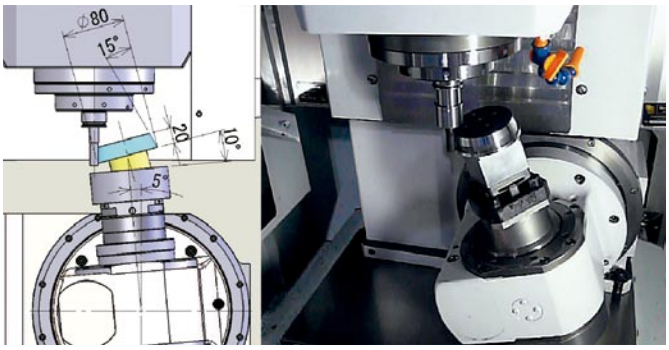

Fig. 4 Simultaneous 5-axis machining of a cone frustum

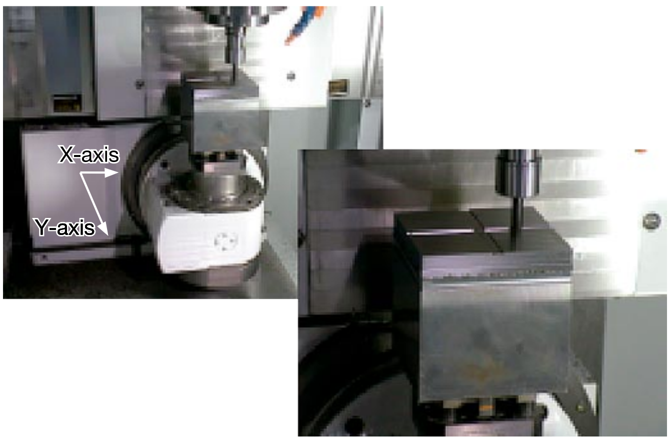

Fig. 6 Groove machining before finishing

THP TR300 U05.00/J 00.09 DEMONSTRATION

Resulting LS circularity		Datum	Spindle
Feature name	A	Filter type	Gaussian
Measurement No.	02	Filter	1-15 upr
O	1.95 μm	Shape	100.0 %
E	0.30 μm	Measurement mode	Outer circumference
∠	289.5 deg	Measurement date	12-06-2008
→	2.30 μm	Measurement time	11 : 18 : 33
Scale	5.00 μm		
Z height	86.5 mm		
Radius	91.3930 mm		

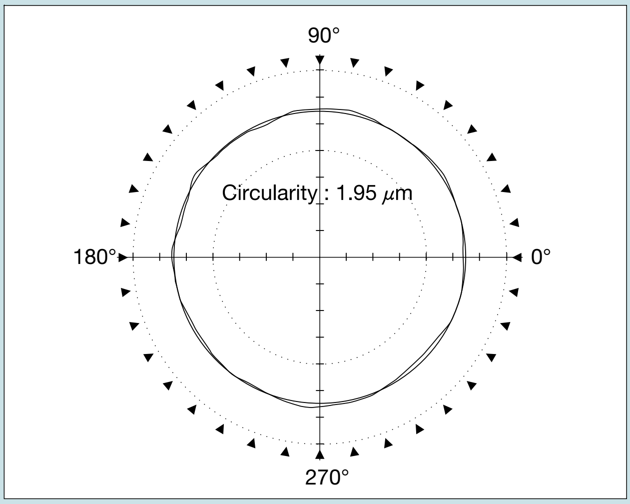

Fig. 5 Resulting circularity from simultaneous 5-axis machining of a cone frustum

Table 3 Cutting conditions for groove machining before finishing

Spindle rotational speed (min^{-1})	6000
Feedrate (mm/min)	960
Infeed amount (mm)	1
Tool	Solid carbide 4-blade endmill $\phi 8$
Amount of tool overhang (mm)	25
Workpiece material	NAX55
External lubrication	Dry

Table 4 Resulting straightness from groove machining before finishing

X-axis direction	Y-axis direction
2.7 μm	2.0 μm

groove machining before finishing and **Tables 3** and **4** show the cutting conditions and the resulting straightness data, respectively. According to the results in Table 4, the straightness is around 2 μm (including surface roughness) in both the X-axis and Y-axis directions, which means that no chatter occurred during machining and hence the μV1-5X is a robust machine that withstands roughing. Besides these advantages, the μV1-5X offers capabilities to complete all machining jobs from roughing to finishing on a single machine; for example, in addition to the attachment of workpiece jigs, it is capable of machining M6 screw holes for automatic chuck jig plates that are widely used for this class of machines.

5. Conclusion

The μV1-5X, developed by optimizing each machine element, enables high-precision machining not feasible with conventional 5-axis machines. Our future efforts will be on improving the working efficiency through peripherals such as machining support equipment. Finally, we will continue to pursue and propose ideal machines that help customers in the machining industry in high-speed, high value-added, and high-efficiency machining.


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