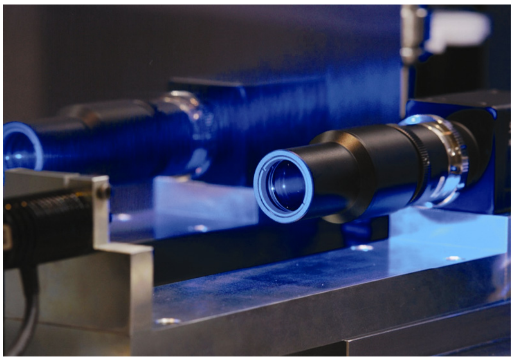
Precision Machining by Optical Image Type Tool Measurement System



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Due to the globalization of production bases and increasing demand for accuracy in recent years, machines and applications that can achieve stable accuracy independently from the operator's skill are necessary. Mitsubishi Heavy Industries, Ltd. (MHI) has been seeking technologies that can meet such needs. Our uniquely developed optical image type tool measurement system can automatically optimize and perform warm-up of the machine, tool measurement, machining and other processes that were conventionally dependent on the operator's experience and intuition. The stable accuracy of the machines and the user friendliness of the applications that MHI has attained can meet the latest needs in the manufacturing industry, such as the creation of high-added value, the shortening of delivery time and the stabilization of quality.

1. Introduction

In the manufacturing industry, which is undergoing globalization, there is growing demand for the creation of high-added value and the shortening of delivery time in the Japanese market, as well as quality stabilization and the improvement of productivity in the overseas market. In respect to processing equipment, not only are basic machine capabilities such as high speed, high accuracy, high stability and high reproducibility increasingly in demand, but so are peripheral applications such as on-machine measurement.

In responding to these requests, MHI has equipped the µV1 micro milling machine (exterior view shown in **Figure 1** and specifications in **Table 1**) with our uniquely developed optical image type tool measurement system to work on various high precision machining and measurement tasks.

This paper describes the features and examples of the system.

Figure 1　µV1 micro milling machine

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Table 1 Specifications of μV1 micro milling machine

Travels	X-axis x Y-axis x Z-axis		mm	450×350×300
	Spindle end to table surface		mm	150 to 450
Table	Working area		mm	500×400
	Maximum workpiece size		mm	500×500×200
	Maximum laden weight (distributed evenly)		kg	125
	Shape of upper surface	Width of T-grooves	mm	14
		Pitch	mm	100
	Floor to table surface		mm	850
Spindle	Rotation speed		min^{-1}	400 to 40000
	Tapered hole of spindle		-	HSK-E32
Feedrate	Rapid traverse		mm/min	15000
	Cutting feedrate		mm/min	1 to 15000
Automatic tool change device	Number of tools		-	18 or 30 (optional)
	Maximum tool diameter		mm	ϕ 40
	Maximum tool length		mm	130
Machine dimensions	Height		mm	2355
	Width x length		mm	1920×2054
	Weight		kg	5500

2. Features of μV1 micro milling machine

One of the inhibitory factors for high precision machining is the thermal displacement of the machine. In particular, the thermal displacement of the spindle, which is the greatest heat source, accounts for a large portion of such factor. The maximum rotation speed of the spindle of the μV1 is 40,000 min^{-1}, and this machine uses ball bearings, not noncontact bearings such as air bearings, in order to attain high rigidity. As a result, it is important to reduce and remove the high heat generated by friction and pressure during high speed rotation of the ball bearings.

Typical spindles have a coolant path only in the external jacket, which is the casing of the spindle. However, the μV1 has an additional coolant path inside the high-speed rotating spindle, in addition to our unique method for lubricating the bearing in order to forcibly and quickly remove the generated heat (**Figure 2**). In this way, the μV1 reduces thermal displacement to the minimum level, even at the maximum rotation speed of 40,000 min^{-1}, and attains stability after the saturation of displacement and high reproducibility in repeating starts/stops of spindle rotation (**Figure 3**).

Such stability and reproducibility establish a foundation for not only machining accuracy, but also the improvement of on-machine measurement accuracy and reliability.

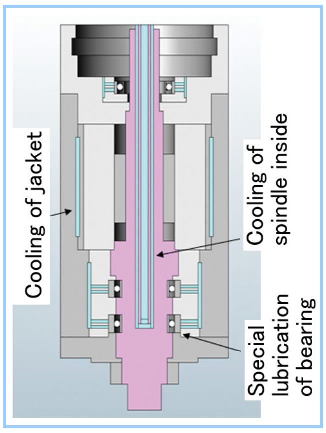

Figure 2 Spindle cooling system

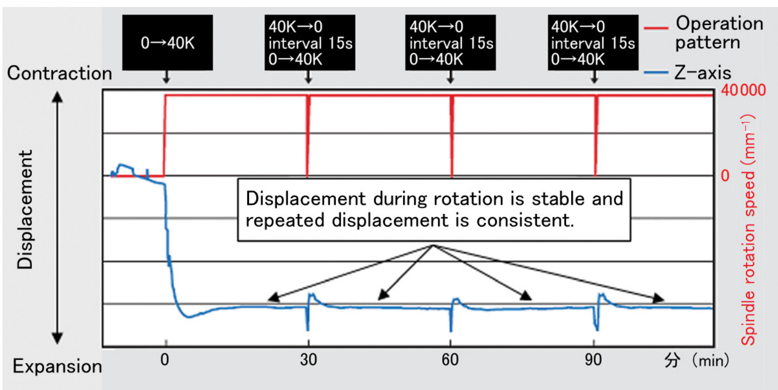

Figure 3 Spindle thermal displacement

3. Features of optical image type tool measurement system

For high precision machining, on-machine measurement including tool measurement and workpiece measurement is essential and one of the important factors equal to machine accuracy, because measurement errors directly result in machining error. In the past, however, machine tool manufacturers simply equipped their products with measuring instrument manufacturer's products, and left their operation to users.

Taking this into consideration, we decided to develop on-machine measurement applications that are more convenient from a user perspective. The newly developed optical image type tool measurement system resolves various problems with existing tool measurement devices. Existing tool measurement devices are classified into contact types where the tool makes contact with a sensor and laser types where the tool blocks the laser beam, and both have various features. However, they have the following problems:

(1) Contact type

- Tool breakage due to impact caused by contact may occur to tools with smaller diameters, particularly in the case of tools with a diameter of 1 mm or smaller.
- Measurement errors caused by wear of the measuring surface of the sensor may occur.
- Measurement is performed in a stopped state. Errors such as thermal displacement due to rotation after measurement may occur.

(2) Laser type (**Figure 4**)

- An error due to a possible difference between the actual end of the tool and the laser beam radiation point may occur.
- Because measurement uses the blocking rate of the laser beam, an error may occur depending on the shape of the tool end.
- A tool thinner than the laser beam cannot be measured because it cannot block the laser beam sufficiently.

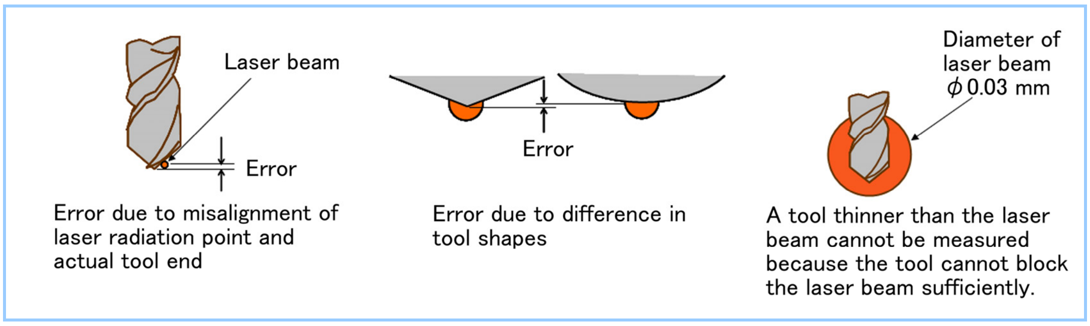

Figure 4 Existing laser type tool measurement system

These systems also have an operational problem where a measurement error may occur due to thermal displacement of the machine described in the previous section. Laser type methods can measure the tool during its rotation, but can only perform instantaneous measurement using the on/off signal of the laser beam. Therefore if measurement is performed during ongoing thermal displacement, for example, all of the subsequent thermal displacement will result in machining error.

To prevent such errors, typically tool measurement is performed after a "sufficient" warm-up operation. However, how long is "sufficient?" On the other hand, the contact type method needs to stop the spindle for the measurement of a tool. However, how necessary is it to take the instantaneous thermal displacement into consideration? Like the answers to these questions, the actual operation significantly depends on the operator's skill, experience and intuition.

The optical image type tool measurement system uses a high resolution CCD camera to perform tool measurement where no contact occurs and the tool is measured as an area, not a point. As a result, problems with existing tool measurement devices are resolved. **Figure 5** shows the configuration of the optical image type tool measurement system.

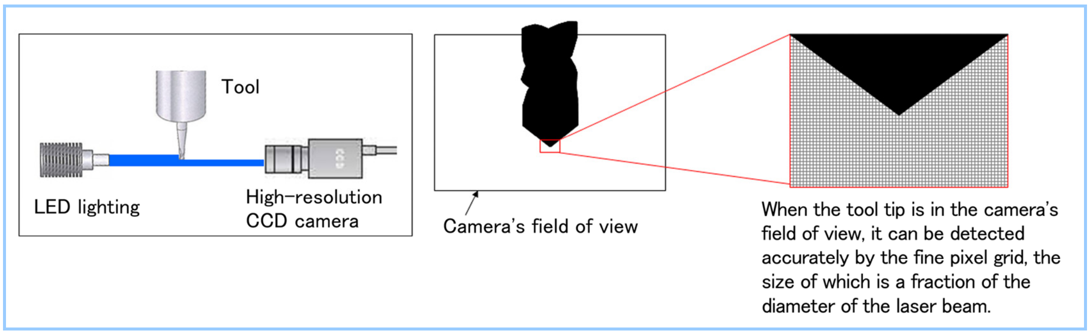

Figure 5　Configuration of the optical image type tool measurement system

A saturation determination function has also been added. This function uses continuous data collected by the camera to measure changes in the condition of the machine and the tool with a certain time interval, and then detects the saturation and stabilization of their thermal displacement. **Figure 6** shows a schematic view. This function enables the system to automatically optimize and perform warm-up, measurement and machining processes that were dependent on the operator's skill in the past.

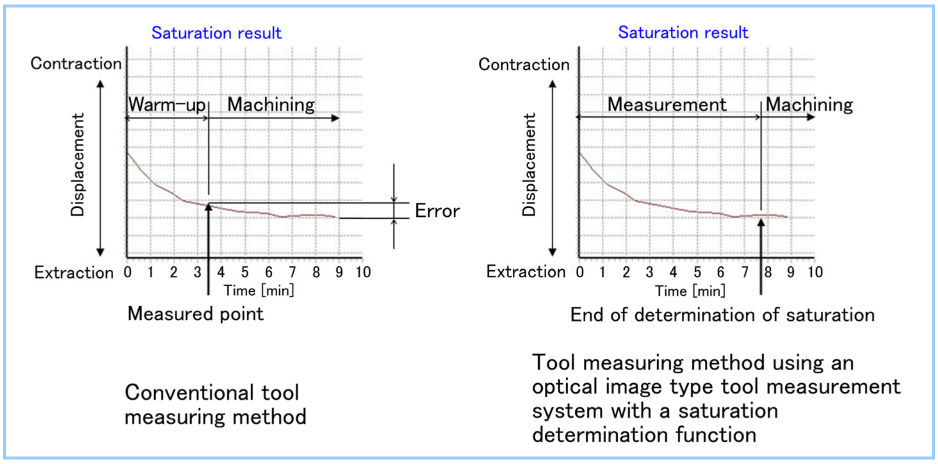

Figure 6　Comparison of existing system and optical image type system

4. Examples of high precision machining

One example where the problems with the existing tool measurement devices as described above appear on actual machining is mold machining, and direct machining in particular. In many cases, direct machining uses different tools with different diameters or shapes to cut a mold, and the machining conditions differ for each tool. In such cases, a difference in machined height between tools may occur as a result of measurement errors caused by differences in tool shapes, or differences in thermal displacement saturation time due to different spindle speeds. Hand finishing or polishing for correction can also take time, or even result in the workpiece being discarded and a new one created from scratch in the worst case scenario.

Because such machining often takes a long time, the wear of the tool and the thermal displacement of the machine, tool, workpiece, etc., due to the heat generation of the machine, as well as changes in peripheral temperature during machining, may cause machining accuracy errors.

We developed and implemented test machining to verify whether or not these problems can be resolved by an optical image type tool measurement system. **Table 2** shows the machining conditions. In this verification, six different tools with different diameters and shapes were used at different speeds to form tile shapes on a workpiece targeting a single height. For each tool, tool length measurement was performed before and during machining so that differences in length between tools, wear of the tool, and thermal displacement of the spindle were eliminated. In addition, the saturation determination function was used to automatically stabilize thermal displacement during machining. The height of the reference plane of the workpiece was measured several times in machining so that the thermal displacement of the workpiece could automatically be eliminated.

Table 2 Machining conditions

Tool number	Tool type	Spindle rotation speed (min^{-1})
1	R3 ball end mill	16,000
2	ϕ 2 flat end mill	20,000
3	R2 ball end mill	26,000
4	ϕ 1 flat end mill	32,000
5	R0.5 ball end mill	40,000
6	ϕ 0.3 flat end mill	40,000

The length of the probe used for workpiece height measurement was measured on-machine by the optical image type tool measurement system in each case. In the conventional measurement of workpieces and tools, the length of the probe, the height of the tool length measuring device, and the distance between the spindle and the table at the machine home position are considered as fixed values, and these values are used to calculate the height of the workpiece and the length of the tool. However, because these dimensions have natural thermal displacement caused by heat generation of the machine and changes in peripheral temperature, measurement errors occur. In order to eliminate these errors relatively, the length of the probe was measured by the tool measuring device as described above.

The optical image type tool measurement system enables accurate measurement of the probe length, which was difficult for existing tool measuring devices. **Figure 7** shows the probe length, the workpiece reference plane height, the tool length, and the machine peripheral temperature in actual workpiece machining. Although it took four days in total to finish machining, this was not continuous machining; the machine was turned off after eight to ten hours of machining each day, and then was turned on the next day before machining was resumed. The measured value of the probe length varied significantly (this value includes thermal displacement of not only the probe, but also the machine and the tool measuring device) because the change in the peripheral temperature of the machine was up to 5 degrees. If the conventional method, which considers this variation as a fixed value, were used, an error equivalent to this value would have occurred. Of course, this was a verification test where measurement errors from the conventional method increased because the machining was interrupted by being intentionally turned off, and the measurement of the workpiece reference height was performed in each case; therefore this differs from the actual machining of a workpiece. However, in the case of the machining of many workpieces, resetting a workpiece or re-machining, an error in workpiece measurement appears at each stage, and the ability to eliminate such errors is meaningful.

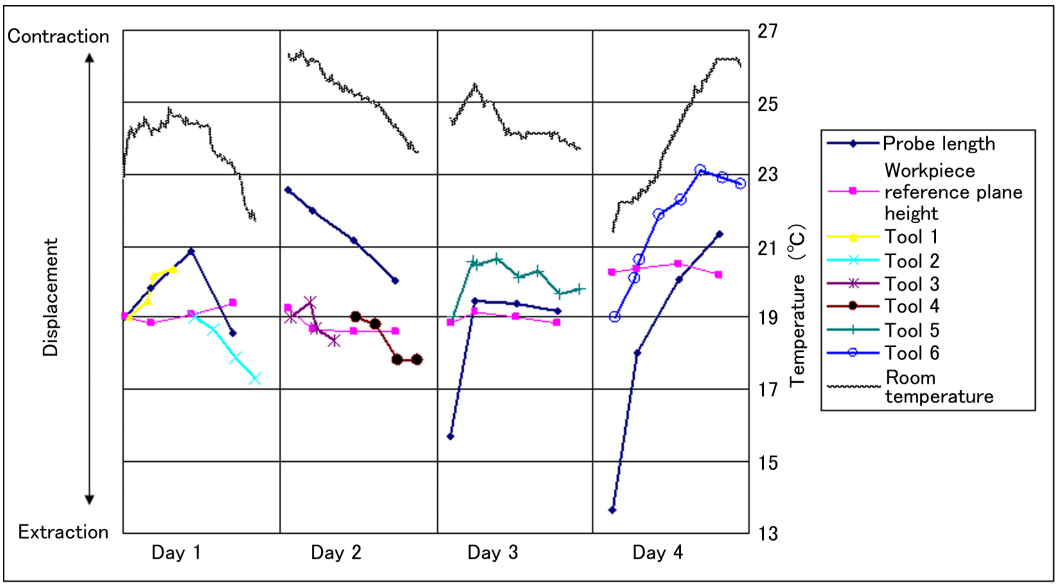

Figure 7 Measurement result in actual workpiece machining

Figure 8 shows the measured unevenness of the machined workpiece surface. The height difference for a straight line passing over all planes machined with the six types of tools is slight; this verifies the error suppression effect of the optical image type tool measurement system. In fact, at a user's site, a machine delivered with this system was well received after it attained a machining accuracy of 2 μm when measurement was performed with this method after automatic changes of workpieces.

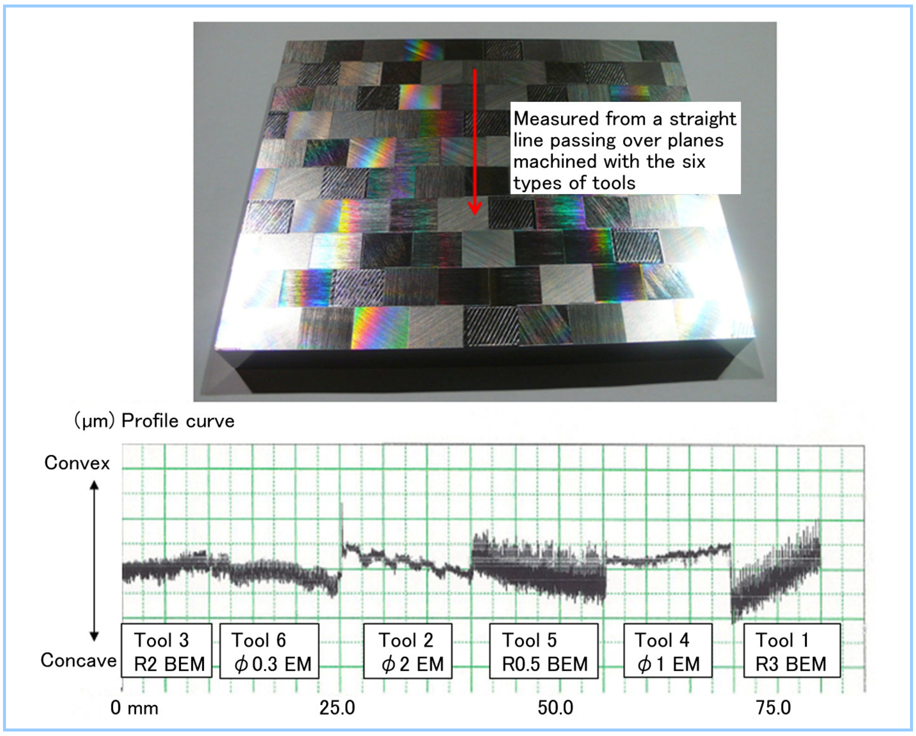

Figure 8　Measured unevenness of the machined workpiece surface

5. Conclusion

Examples of accurate machining using the μV1 micro milling machine equipped with the optical image type tool measurement system are described above. This system enables the machine to automatically optimize and perform warm-up, measurement, and machining processes that were dependent on the operator's skill in the past, and can attain accurate machining using multiple tools, which was conventionally a difficult task.

MHI will continuously seek the further improvement of machine technologies, as well as applications such as on-machine measurement, in order to meet market needs and make a contribution to the development of the manufacturing industry.