Modern Technology that Achieves Minute Cuts for Carbide and Brittle Materials

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In cutting processing, recent years have seen the need to process workpieces of various materials including carbide, brittle materials and other difficult-to-machine materials, as well as easy-to-machine ones including copper and graphite, with high accuracy and high efficiency. Mitsubishi Heavy Industries, Ltd. (MHI) has satisfied such needs with the µV1 micro milling machine, our independently-developed optical image type tool measuring system, as well as by enhancing machining technology, enabling different existing processing machines used for different workpiece materials and/or different processes to be integrated into a single unit.

1. Introduction

In an attempt at differentiation from the products produced in emerging countries, mainly in continuously growing Southeast Asia, domestic manufacturers are pressing for the production of higher-precision and higher value-added products for quick delivery at low cost. With these situations, where domestic manufacturers are placed in the background, it is notable at present that durable high-precision dies are in growing demand for the long-term stable production of high-precision and high-quality products and, as a material for dies, cemented carbide, which is excellent in heat and wear resistance, is being employed.

Since cemented carbide is characteristically very hard but brittle, electrical discharge machining or grinding rather than cutting has been used for machining it thus far. Recently, however, the development of cutting tools has advanced, and direct machining of cemented carbide dies by cutting is coming to a practical level in terms of quality, quickness of delivery and cost. On the other hand, in electrical discharge machining as well, electrode materials and the machining methods used were further developed, gradually bringing low-cost, but high-efficiency machining into reality.

It is necessary in machining to process with high accuracy, high efficiency difficult-to-machine materials such as cemented carbide, as well as easy-to-machine materials such as for electrodes used in electrical discharge machining. To meet the needs of covering both material extremes, MHI has thus far exerted efforts for high-accuracy, high-efficiency machining of various materials, using the "µV1" micro milling machine (the main specifications of which are shown in **Table 1**) and this paper introduces actual examples of such efforts and the technologies to materialize them.

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Table 1 Main specifications of μV1 micro milling machine

Travel	X/Y/Z axis	450 x 350 x 300 mm
	Spindle end to table top	150 to 450 mm
Table	Working surface	500 x 400 mm
	Maximum workpiece size	500 x 500 x 200 mm
	Maximum loading capacity (equal distribution)	125 kg
	Table top shape	T groove width 14 x 3 grooves, 100 mm-pitch
	Floor to table top	850 mm
Spindle	Rotation speed	400 to 40000 min^{-1}
	Spindle taper hole	HSK-E32
Feed rate	Rapid traverse rate	15000 mm/min
	Cutting feed rate	1 to 15000 mm/min
Automatic tool changer	Number of tools stored	18pieces, 30 pieces (option)
	Maximum tool diameter	Φ40 mm
	Maximum tool length	130 mm
Machine dimensions	Height	2260 mm
	Width x depth	1920 x 2065 mm
	Weight	5500 kg

2. Carbide/brittle material machining

2.1 Problem with carbide/brittle material machining

Some tools for cutting cemented carbide mainly use a diamond coat or sintered diamond, but the cuts of any tool are on a level of several μm to submicron-level, particularly in terms of finishing. Such ultra-minute-cut machining raises the problem that, if error factors such as machinery positioning inaccuracy, thermal displacement inaccuracy and vibration are significant, the tool cannot cut into the material or that the tool cuts in too deeply causing breakage.

At the same time, since cutting conditions are intensified in rough processing for higher efficiency of machining, cutting loads increase to cause chatter marks and tool damage if the machine or spindle is less rigid. The process machine used for rough processing must therefore be different from that for finishing, causing a heavier burden of processes and equipment.

Moreover, unless the position of the machining point at the tool end, as well as thermal displacement, vibration and other behaviors can be grasped correctly, machining becomes difficult, which also makes on-machine measurement technology important. A typical on-machine tool measuring device is of a contact type, which lets the tool directly contact the sensor for detection, or a laser type, in which the tool interrupts laser light for detection.

If the timing of measurement is inappropriate in laser type measurement, a machining error may sometimes occur, which is also naturally seen in contact type measurement where the tool is brought to a halt for measurement. This is because in the case of laser type measurement, which allows for instantaneous measurement while the tool turns, it is impossible to determine whether the thermal displacement in the spindle or the tool has converged, and unless the timing of measurement is right, thermal displacement can take place after measurement.

2.2 The μV1 and optical image type tool measuring system-based solution

The μV1 uses ball bearings in its spindle and makes high rigidity compatible with low fast vibration characteristics by means of its own special oil lubrication and spindle internal cooling, thereby realizing low thermal displacement, long-term stability and repetitive reproducibility. In addition, a sideway is employed on the machine body to provide high rigidity and high attenuation characteristics, resulting in highly rigid equipment that is a high-precision process machine but capable of rough processing.

Regarding on-machine measuring technology, MHI developed its own “optical image type tool measuring system” using a CCD camera, enabling the thermal displacement of the spindle and tool to be measured in real time while allowing the tool to turn at the speed of rotation with which the tool is machined.(1)

2.3 Example case of machining

(1) Carbide drilling and profiling

Superfine cemented carbide was subjected to drilling and profiling. **Table 2** shows the cutting conditions and **Figure 1** is a workpiece photo. The achieved efficiency of machining was as high as 4 minutes for per hole for drilling and 24 minutes per shape for profiling.

Table 2 Cutting conditions for carbide drilling and profiling

Process	Tool	Spindle rotation speed (min^{-1})	Feed rate (mm/min)	Pick feed pitch (mm)	
				XY	Z
Drilling	Φ1.0 drill	20000	8	−	0.0004
Profiling	Φ1R0.5 ball end mill	30000	300	0.25	0.05

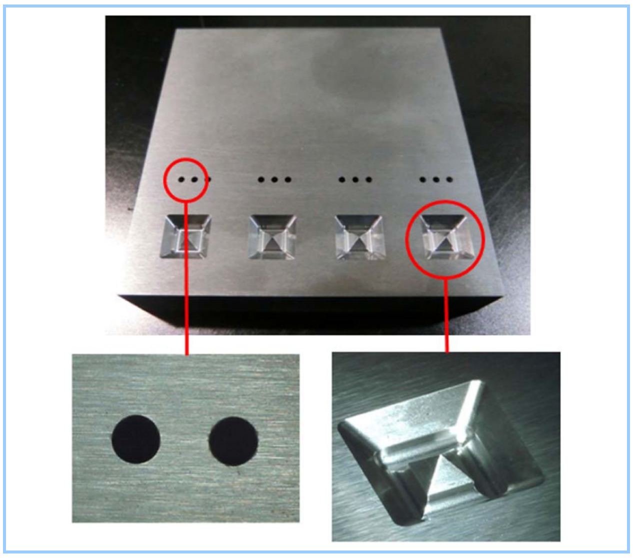

Figure 1 Carbide drilled and profiled workpiece

(2) Carbide punch and die machining

Superfine cemented carbide was machined into punch and die shapes. **Table 3** shows the cutting conditions and **Figure 2** is a workpiece photo. In total, punch profiling took 4 hours and 40 minutes, while die shaping required 6 hours and 30 minutes. Nevertheless, good fitting accuracy could be obtained without tool wear.

Table 3 Cutting conditions for carbide punch and die machining

Process	Tool	Spindle rotation speed (min^{-1})	Feed rate (mm/min)	Pick feed pitch (mm)	
				XY	XY
Very rough processing	Φ6R3 ball end mill	10000	200	0.4	0.1
Rough processing	Φ1R0.5 ball end mill	30000	200	0.2	0.05
Rough processing	Φ0.6R0.3 ball end mill	30000	150	0.1	0.02
Semi-finishing	Φ0.3R0.15 ball end mill	30000	100	0.03	0.01
Semi-finishing	Φ0.2R0.1 ball end mill	30000	100	0.01	0.01
Finishing	Φ3R1.5 ball end mill	27500	200	0.08	0.005
Finishing	Φ1R0.05 radius end mill	30000	200	0.1	0.01
Finishing	Φ0.2R0.2 ball end mill	30000	200	0.01	0.01
Finishing	Φ0.8R0.4 ball end mill	30000	200	0.01	0.01

Figure 2 Carbide punch- and die workpieces

(3) SiC ceramic grooving

SiC ceramic, which is the third hardest material after diamond and boron carbide, was cut. **Table 4** shows the cutting conditions and **Figure 3** is a workpiece photo. Although Z-axial cuts were as ultra-minute as 0.001 or 0.002 mm, the resulting machining was favorably free from any damage in shape.

Table 4 Cutting conditions for SiC ceramic grooving

Process	Tool	Spindle rotation speed (min^{-1})	Feed rate (mm/min)	Pick feed pitch (mm)	
				XY	Z
Outer ring rough processing	Φ1 flat end mill	40000	100	0.5	0.002
Outer ring finishing	Φ1 flat end mill	40000	100	–	0.002
Center hole rough processing	Φ4 flat end mill	40000	100	–	0.001
Center hole finishing	Φ1 flat end mill	40000	100	0.03	0.002
Blade shape rough processing	Φ1 flat end mill	40000	100	0.03	0.002
Blade shape finishing	Φ1 flat end mill	40000	100	0.03	0.002

Figure 3 Grooved SiC ceramic workpiece

3. Copper/graphite machining

3.1 Problem with copper/graphite machining

Copper or graphite is mainly used as material for electrodes in electrical discharge machining. Generally, copper and graphite are better in terms of machinability than steel material, and accordingly the cutting conditions can be intensified.

With today's need for smaller/higher-functioning products, the die and the electrode shape has also been further miniaturized and its complication has been increased.

When such a miniaturized/complicated shape is machined at a high speed, the shape being machined often collapses if the machine itself or the feed system has poor rigidity or if the machine is improperly controlled. To prevent this, the cutting conditions can be relaxed for slow machining, but when a complicated shape is machined three-dimensionally, the production process suffers from issues such as increased machining time, since machining is carried out by making fine cuts while the position of the workpiece is changed.

3.2 μV1-based solution

The μV1 has, as noted above, a high-rigidity structure in its spindle and in the machine body. In addition, the employment of large-diameter narrow-pitch ball screws and a strong support system in the feed axes results in a high-rigidity, high-response feed axes system. Furthermore, based on the high-speed, high-accuracy NC control function, the use of MHI's proprietary control-tuned “HGP2 Control” has realized a mechanical behavior of the shape being machined never collapsing even during high-speed fine/complicated profiling.

Although more machines have adopted a linear motor to drive the feed axes rather than ball screws, linear motors are good at running for long distances at high speed, but weak in stopping on a dime or remaining halted, and this indicates that the movements for detailed/complicated shapes while machining take time in contrast to their image. This is well exemplified with cases where a heavy load is lifted by hand or, using a jack. It is found quicker to simply lift it by hand, but it is much easier to use a jack for a quick accurate vertical motion.

3.3 Example case of machining

(1) Connector copper electrode machining

An electrode (small fin-shaped) used for a connector die was machined. **Table 5** shows the cutting conditions and **Figure 4** is a workpiece photo. Its profile is square by nature, but machining with HGP2 control turned off has rounded the corners to collapse the shape as shown in Figure 4(a). In contrast, the HGP2 control-on state has brought about high-speed, high-accuracy machining even without shape collapse (Figure 4(b)).

Table 5 Cutting conditions for connector copper electrode machining

Process	Tool	Spindle rotation speed (min^{-1})	Feed rate (mm/min)	Pick feed pitch (mm)	
				XY	Z
Rough processing	Φ6 flat end mill	8000	1000	3.0	0.5
Fin rough processing	Φ0.8 flat end mill	30000	1000	–	0.1
Semi-finishing	Φ0.4R0.2 ball end mill	40000	1200	0.05	0.05
Finishing	Φ0.4R0.2 ball end mill	40000	1500	0.01	0.05

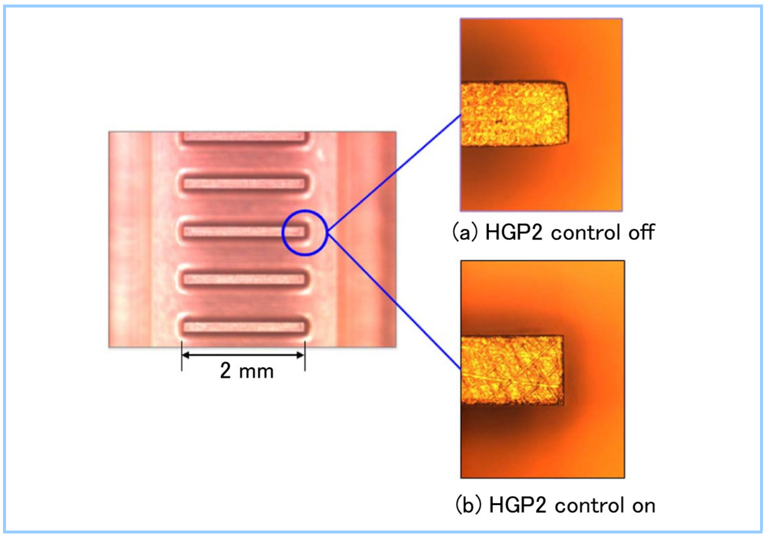

Figure 4 Workpiece machined into connecter copper electrode

(2) Bevel gear die-purpose graphite electrode machining

As a rule, graphite electrodes, unlike copper ones, have advantages such as high machinability and no burrs, and they allow the flow of large amounts of current for electrical discharge machining, while at the same time there are also risks including the occurrence of abnormal friction and surfaces that are too rough. Recently, “copper graphite” or graphite-impregnated copper has attracted attention, the risks and costs of which were mitigated while taking advantage of graphite’s advantages

Bevel gear die-purpose electrodes were machined using copper graphite. **Table 6** shows the cutting conditions. Then actually prepared electrodes were used to practice electrical discharge machining of cemented carbide dies and after that, the μV1 was used to finish the work. In **Figure 6**, a machined copper graphite electrode appears at the top, cemented carbide subjected to electrical discharge machining with a copper graphite electrode is shown at the lower right, and the same workpiece further subjected to finish cutting with the μV1 is at the lower left. The number of man-hours required could be reduced by about 13% from the level of existing cases where electrical discharge machining was followed by polishing.

Table 6 Cutting conditions for bevel gear die-purpose graphite electrode machining

Process	Tool	Spindle rotation speed (min^{-1})	Feed rate (mm/min)	Pick feed pitch (mm)	
				XY	Z
Rough processing	Φ6R1 radius end mill	8000	2500	2.0	0.5
Semi-finishing	Φ3R0.5 radius end mill	30000	2000	1.0	0.1
Finishing	Φ1.5R0.5 radius end mill	31000	1000	0.5	0.03

Figure 5 Copper graphite electrode workpiece (above) and bevel gear die (lower left: finished, lower right: unfinished)

4. Conclusion

Example cases of high-accuracy, high-efficiency machining of cemented carbide, brittle materials, copper, and graphite with the μV1 micro milling machine were introduced. In terms of the recently notable machining of cemented carbide in particular, the μV1's concept of maintaining high accuracy stably for a long time and the technology of its optical image type tool measuring system to accurately measure tool end match such machining needs well. Moreover, rough processing through to finishing can be undertaken by one μV1 unit for workpieces made of a wide range of materials, from those referred to as difficult-to-machine materials to easy-to-machine ones. MHI considers that those customers having thus far used different machines for different workpiece materials, as well as for different processes, can advantageously curtail equipment and costs.

In the future, MHI will endeavor to further upgrade the machine tool, its options and machining technology in an effort to meet market needs, thereby contributing to the manufacturing industry, even in some small way.

Reference

1. Sato, Y. et al., Precision Machining by Optical Image Type Tool Measurement System, Mitsubishi Heavy Industries Technical Review Vol. 50 No. 1 (2012) pp. 10-15