High-speed & High-accuracy Precision Die Milling Machine: MVR-FM Developed for Die & Mold Manufacturing as Base of Mass-production

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Die milling machines, with higher performance (speed, precision, etc.) and reasonable cost, are required for reduction of milling time and polishing process. Mitsubishi Heavy Industries, Ltd. (MHI) has developed a die milling machine MVR-FM equipped with FM control system (MHI's proprietary high-speed, high-accuracy contouring control system). The new milling machine is also equipped with high-precision feed system using X-axis twin-ball screw and Z-axis direct drive, and 12 000 min^{-1} high-speed spindle with low vibration. The new machine is designed based on portal table moving type machining center MVR. Hopefully, the newly developed machine will contribute to the development of die mold milling, the base of industry.

1. Introduction

There are increasingly strong demands for reduction of die manufacturing cost and delivery term. In order to satisfy to such demands and to win in the competition with the rival manufacturers, reducing the milling time and the polishing process are indispensable. For realization of reduced the milling time (= high-speed milling) and the polishing process (high-precision milling) MHI has developed a new die milling machine MVR-FM with a high cost value based on MHI's portal table moving type machining center, MVR.

This paper introduces MVR-FM, giving description mainly of the technologies used in the machine for realization of high-speed, high-accuracy milling.

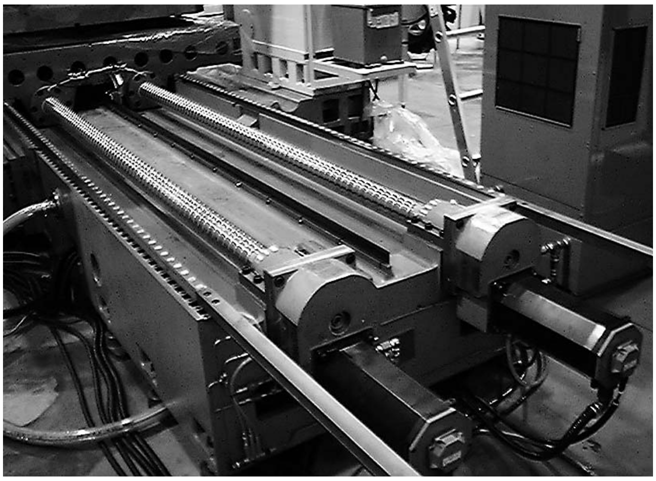

Fig. 1 X-axis twin ball screw
Indicates two pieces of ball screw installed at the rear end of the bed.

2. Technologies for realization of high-speed, high-accuracy milling

2.1 Machine configuration

As shown in the photograph above, the table travels back and forth (along X-axis) on a longitudinally arranged bed. Further, the crossrail installed on the front guide of the column bridge composed of two pieces of column and bridge travels up and down (along W-axis). A saddle travels at the front of the crossrail left and right (along Y-axis), and the ram that passes through the saddle travels up and down (along Z-axis). Each axis is subjected to precision drive by means of ball screw and linear scale. The main spindle is located at ram end to cut the work piece mounted on the table.

2.2 X-axis twin-ball screw drive

The heavy work mounted on the table is driven by ball screw in the portal table moving type machining center. However, deflection or torsion occurs in the ball screw system at the time of acceleration/deceleration because of the inertia of the work table. The deflection or torsion causes error against positional command at acceleration/deceleration, leading to tiny damage of the die milling surface. Further, the driving force induces vibration of the ball screw system, causing disordered milling pick on the die milling surface. Since a strong rigidity is required for the X-axis drive system in die milling machine MVR-FM, the table is driven by using two pieces of ball screw and drive motor as shown in **Fig. 1**. This leads to the rigidity of the drive system to grow two times stronger. Moreover, compared with the case where the rigidity is improved by increasing the ball screw diameter, the new method restrains the increase of drive system inertia, ensuring high controllability and reducing the error.

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2.3 High-precision ram direct drive

In die mold milling of automobile outer panels such as bonnet, door, etc., a periodic fluctuation such as mesh of gear in the Z-axis drive system causes pattern on the die mold surface. Hence, the drive motor and the ball screw are directly connected in the MVR-FM, and the oil pressure balancer is installed to compensate the ram weight, realizing a high-precision drive.

2.4 High-speed and low-vibration spindle ensuring high productivity

The MVR-FM is equipped by standard with a 12 000 min^{-1} high-speed spindle. Connected directly to the built-in motor, the spindle has low vibration and less torque fluctuation, contributing to the reduction of die mold finishing time and improving the quality of the die mold milling surface.

2.5 High-speed and high accuracy control (FM control)

In order to carry out high-accuracy precision die milling it is necessary to correct the errors caused by control system lag in addition to minimize the errors of the machine system. The MVR-FM is equipped with original high speed and high accuracy machining control (FM control) system.

The NC controlled machine tools such as NC milling machine, etc. are generally considered to move correctly depending on programmed command. In actual practice, however, some shape error exists caused by the lag of the feed axis servo system. The error amount is becoming larger for larger curvature of shape and higher machining speed. This makes no problem for positioning and linear machining such as milling, drilling. But in die milling (free curved machining), the shape gets deformed when the machining speed becomes high and the speed has to be slowed down to get precision-machining in terms of shape. Thus, one has to face the dilemma.

There is a method called feed forward control that reduces the shape error to try to solve the aforesaid problem. In the case of the MVR-FM, however, the design concept is based on making the shape error amount zero rather than simply reducing it. The machine causes no shape error in machining even when the machining speed is increased.

Fig. 2 shows a block diagram of the feed forward system that improves the shape error reducing the lag of servo characteristic with speed feed forward and acceleration feed forward. The inward shape error exists in free curved machining. The inward shape error (ΔR) is directly proportional to the square of machining speed, and indirectly proportional to the virtual radius (R) as expressed in the equation;

$$\Delta \mathrm{R} = \frac{(T_1{}^2 + T_2{}^2)\,V^2}{2R}$$

The constants are;

T_1: acceleration/deceleration time constant

T_2: determined positional loop gain and feed forward factor

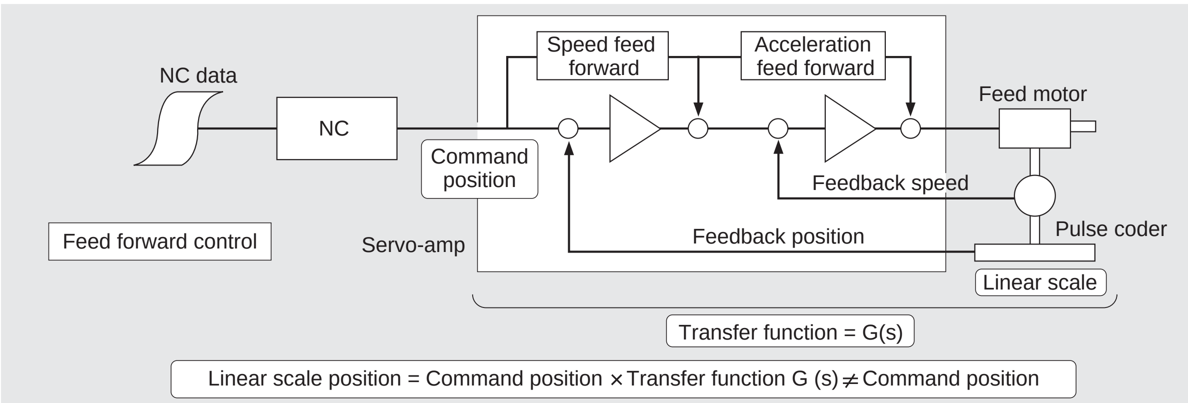


Fig. 2 Block diagram of feed forward control

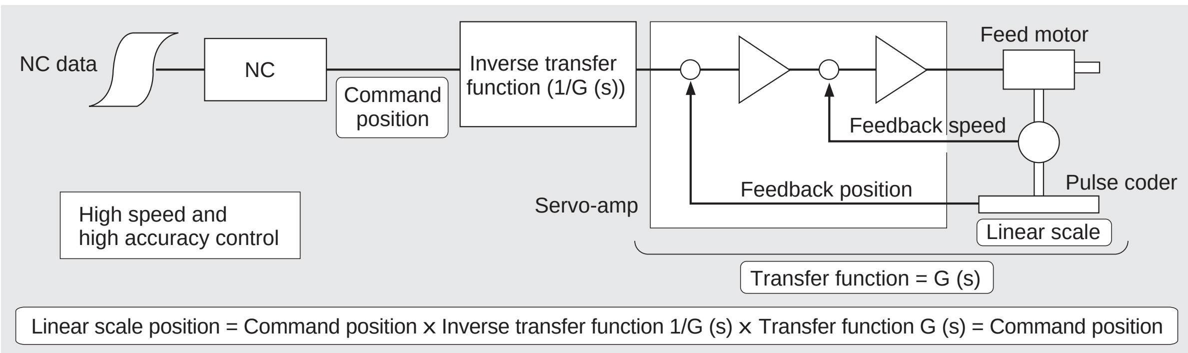


Fig. 3 Block diagram of high speed and high accuracy control (FM control)

Hence, the machining speed had to be slowed down more when the virtual radius was smaller (i.e. the curvature was larger).

Fig. 3 shows a block diagram of the high speed and high accuracy control using inverse transfer function that cancels the servo system delay and reduces the shape error to zero. With the transfer function of the servo system supposed to be G(s), when the command position applied with the inverse transfer function 1/G(s) is transmitted to the servo, the result obtained by further applying the servo transfer function G(s) becomes the machine position (= linear scale position).

After that,

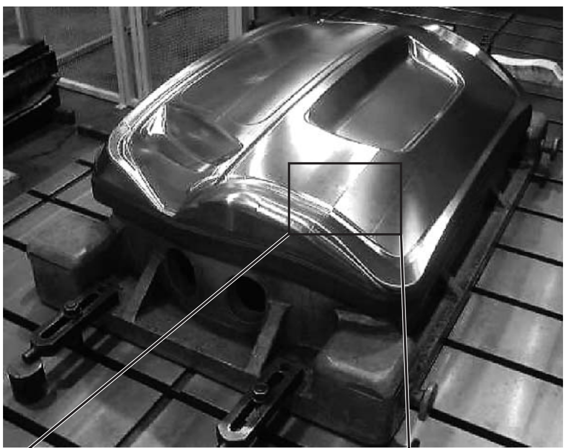
machine position = command position x 1/G(s) x G(s)
 = command position

It is possible to get free shaped machining with zero shape error being independent of the shape curvature or machining speed.

The basic theory is as mentioned above, but for practical use, following functions have been added to the machine.

(1) Multi-block acceleration/deceleration function

In die milling using a fine segment program (a data obtained by approximating the free curved surface with short segments), the speed gets slowed down before attaining the target level in case the number of processing blocks is limited. Hence, acceleration/deceleration has to be carried out over enough multiple blocks in order to constantly obtain the data equivalent to the travel distance required for acceleration.



Spindle: 12 000 min^{-1}
Cutting feed: 8 m/min
ϕ 30 ball end mill
Pick: 0.5 mm

Fig. 4 Example of the die for automobile outer panel
Indicates an example of the die for automobile outer panel showing high-quality milling surface with ordered milling pick.

(2) Automatic shape follow-up speed control function

When the acceleration in a corner or in a shape with extremely large curvature (i.e. with extremely small virtual radius) exceeds the permissible level, it causes vibration and deteriorates the machined surface precision. NC program is pre-read and the machining shape is identified in FM-control. The optimum feed rate is automatically determined according to machining shape by detecting the corner of machining shape and calculating the curvature based on the allowable acceleration calculated from the rigidity of the machine.

(3) Smoothing function

When the NC program sampling is rough, the kinked points of the blocks may appear on the cut surface. This function can achieve high-quality machined (smooth cut) surface and high speed machining by interpolating the fine segment program.

3. Example of die mold milling

The portal table moving type die milling machine like MVR-FM is often used for press dies mainly for automobiles, and especially the die of automobile outer panels requires high-quality machined surface and high-speed machining.

Fig. 4 shows the die for rear trunk of a hatchback car (milling at spindle speed 12 000 min^{-1} and feed speed 8 m/min), indicating the milling surface with ordered milling pick. The reciprocating milling pick depth difference (reciprocating level difference) as index of milling surface quality has been improved by 50% as compared with conventional MHI machines and the milling time has been improved by more than 30%.

Fig. 5 shows the die for automobile inner panels, which does not need the milling surface quality and the milling speed as high as that of the automobile outer panels. However, the die for automobile inner panels consists of the complicated shapes. Various attachments (MVR-FM universal head etc.) and precision positioning of cross rails to an arbitrary place is possible, ensuring machining freedom for realization of high productivity.

Spindle: 3 200 min^{-1}
Cutting feed:1.6 m/min
ϕ 20 carbide
ball end mill
Pick: 0.4 mm

Fig. 5 Example of the die for automobile inner panel
Indicates an example of the die for automobile outer panel showing complicated shapes.

Table 1 List of main specifications

	MVR 25−FM	MVR 30−FM	MVR 35−FM
Table working range; width (mm)	1 500	2 000	2 500
length (mm)	3 000 – 5 000	3 000 – 5 000	4 000 – 5 000
Distance between columns (mm)	2 050	2 550	3 250
Each axis travel; X: Table, longitudinal	Table length + 200		
Y: Saddle, crosswise	2 500	3 000	3 500
Z: Ram, vertical (mm)	700	←	700
W: Crossrail, vertical	800	←	1 100
Each axis rapid traverse rates; X: Table, longitudinal	30	←	22
Y: Saddle, crosswise	30	←	22
Z: Ram, vertical (mm)	10	←	10
W: Crossrail	3	←	3
Maximum cutting feed rate (m/min)	XY-axes 15, Z-axis 10		
Permissible mean feed rate (m/min)	6		
ATC Number of tools (piece)	50		
Maximum tool length (mm)	Standard: 400 (Optional: 500)		
Maximum tool weight (kg)	25		
Tool change time	5 sec (6 sec)		
ATT Mountable ATT	Standard: Dummy plate 30 kW/12 000 min^{-1} RH 30 kW/6 000 min^{-1} OP: Extension 22 kW/6 000 min^{-1} OP: Universal head 15 kW/5 000 min^{-1} Every 5 deg. Automatic indexing, OP: Every 1 deg		
AAC rack	For 2 ATT + Additional rack		
NC device	FANUC 18 i		

4. Specifications

Thanks to the original FM control technology, etc., the MVR-FM can be used for milling of diverse die molds including the die for automobile panels. Machines with table size ranging from width: 1.5 - 2.5 m and length: 3 - 5 m and various optional functions are available to meet the customers' needs. Main specifications are given in **Table 1**.

5. Conclusions

High accuracy for NC data was realized by adopting MHI's own FM-control technology and high-accuracy, high-rigidity feed system. The quality of milling surface (reciprocating level difference) is improved by 50% compared to the conventional MHI machines, and the die polishing process can be reduced. The milling time for outer panels is reduced by 30% after the above-mentioned feed system and the 12 000min^{-1} high-speed spindle are adopted. High productivity for die manufacturing is realized.

Hopefully, the high-speed, high-accuracy precision die milling machine MVR-FM with excellent cost performance will contribute to the development of die and mold manufacturing as the base of industry.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