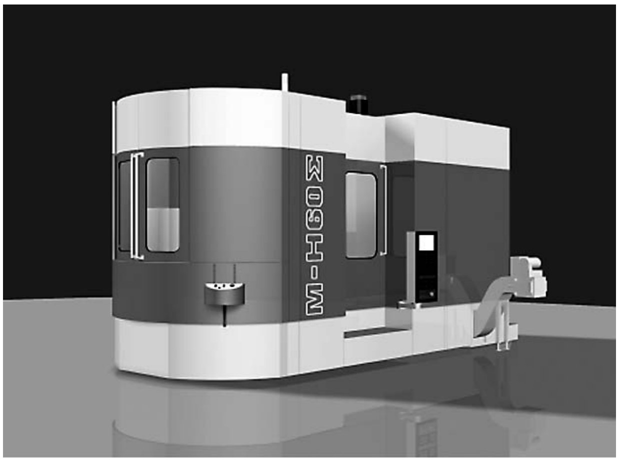


The Starting Point for "CREATION"
–"MACHINING CENTERS" Otherwise Known as "MOTHER MACHINES" Yesterday, Today, and Tomorrow–

HEKI KASUGAI
AKIHIKO FUJIWARA
HIROAKI SASAI
MASARU KAJIYAMA

1. Introduction

A machining center is known as a "machine that manufactures machines" or a "mother machine." Such machining centers have contributed to the development of industry as an essential machine that facilitates the manufacture of industrial products. As a machine that manufactures machines, there are many diverse types of machining centers in the world, including NC lathes.

The history of machining centers began in 1958 when Kearney & Trecker Corp of the U.S. developed the "Milwaukee-Matic Model II," the first practically applicable machining center. The name "machining center" was given at that time.

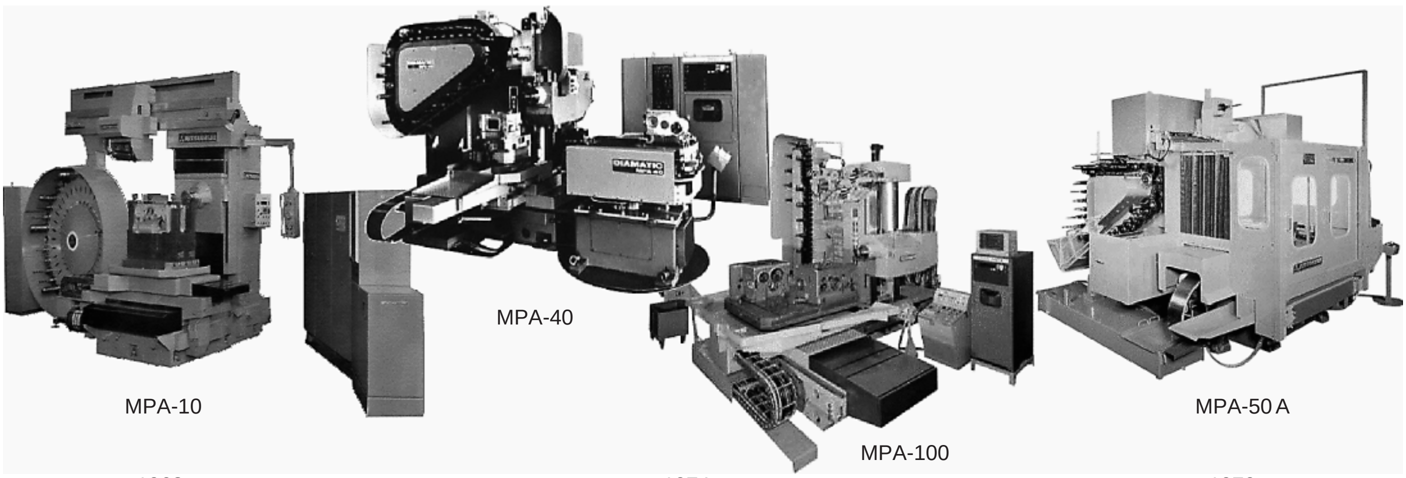
2. Machining centers - Yesterday

Mitsubishi Heavy Industries, Ltd. (MHI) began to study the introduction of NCs into the machining center around 1958. Responding to increasing industrial needs for rationalization during and after 1965, MHI developed two types of horizontal machining centers, the "MPA-10" and "MPA-15," in 1968, and introduced them to the market at that time (**Fig. 1**).

The Japanese economy entered a low growth period triggered by the "dollar shock" in 1971 and the "oil shock" in 1973. During this sluggish period, MHI developed the "MPA-50," "MPA-70," "MPA-40," and "MPA-100" machining centers in 1974 as forerunners to automated machining centers.

After that, MHI developed the "MPA-50A," "MPA-50B," "MPA-60A," and "MPA-80A" type machining centers in 1979, which mounted Automatic Pallet Changer (APC) and which allowed unmanned operation in response to FMS (Flexible Manufacturing System). Four times as many machining centers in the series were shipped than the preceding MPAs.

In 1983, MHI entered the market of vertical machining centers, which was occupied into the die and mold industry. The "MPA-V45," "MPA-V55," and "MPA-V65" machining centers introduced at this time, were having a function to compensate thermal displacement automatically for the first time in this industrial world, and to have dedicated automatic programming system. The MPA series was well received in the market.



1968 1974 1979

Fig. 1 History of machining centers Progress in horizontal type machining centers during the initial stage of development

With the availability of unmanned operation of machining centers, the commercial product lineup of Flexible Manufacturing Cell (FMC) and FMS systems became fulfilled, and their systematized products were further developed. MHI developed the "Free Flow Manufacturing System (F-FMS)" in 1985. Systems that require no complex controller gained a high reputation among domestic and overseas users, resulting in the delivery of a large number of F-FMS lines (**Fig. 2**).

Since then, MHI continued to introduce further model changes in machining centers based on the core concept of increasing productivity in response to demand for higher speed and higher accuracy, centering on improvements in feed rate and in main spindle speed. The increased main spindle speed and improved main spindle rotating accuracy are absolutely essential to a built-in motor. To this point, the horizontal machining center "M-HE Series" and the vertical machining center "M-VE Series", which were introduced to the market during the period from 1995 to 1996, fully adopted built-in motors to drive the main spindle. Along with the increases in the speed of the main spindle, MHI also enhanced the speed of the feed system and improved motion of the system. One example of such improvements is the introduction of a horizontal machining center by MHI with a pallet size of 800x800 mm (31.5x31.5") class that achieves a feed rate of 40 m/min (1 575 in/min).

3. Machining centers - Today

During the recent period of shifting of global manufacturing sites to Asia led by China, MHI introduced the Σ Series vertical machining centers "M-V50" and "M-V50-FM" in 2001 as high value-added machining centers. After the vertical Σ Series, MHI introduced the horizontal Σ Series machining centers "M-H60" and "M-H80" in 2002, further adding the "M-V70" and "M-V70-FM" to the Σ vertical machining centers as table size products (one grade larger than the preceding series).

Depending on the characteristics of the workpiece, the applications of the Σ Series were developed considering four core fields: die and mold, power generation equipment, aerospace, and automobiles (including other general use parts).

(1) Die and mold

The machining centers cover a range of molds in this field from aluminum molds to hard metal molds. The machining centers can be used to machine free curved shapes at high speed, high accuracy, and high quality.

(2) Power generation equipment

The machining centers in the field of power generation equipment include high rigidity machines that can be used to machine materials that are difficult to cut, and high performance machines such as five-axis machining center that machines turbine blades.

Fig. 2 F-FMS (free flow manufacturing system) line

(3) Aerospace

High speed and high performance machining centers (such as five-axis machining center) in this field include machining centers that can be used to machine aluminum materials into three-dimensional shapes at high speed, as well as high rigidity machining centers for machining materials that are difficult to cut similar to those in the power generation equipment field.

(4) Automobiles

Machining centers in this field include high speed machining and feeding machining centers that can be used to machine aluminum die casts, etc.; high rigidity and high speed machining centers for use in machine casting and steel, and the like.

3.1 Technologies supporting the die and mold field

The Σ Series of vertical machining centers is a grade that has been developed with the specific aim of being applied to the die and mold field. The development of the Σ Series began from understanding the jobsite in which the die and mold production process takes place in order to actualize high quality die and mold machining. In case of machining die and mold, the improvement in accuracy in the shapes and quality of the machining surface is important because a ball end milling is used to machine a shape through repeated cutter passes. For this reason, it was necessary to process the data of the commands to move the point groups on each three-dimensional shape at high speed, and to accurately correct delays in tracking the movement of the feed axis.

Studies of the main spindle rotating at high speed while inducing less vibration were conducted in order to improve the high quality of the machining surface. The criteria of rigidity evaluation with respect to a shape being machined in which frequent repetition of high acceleration and deceleration of feed occurs was reviewed with the aim of minimizing variations in machine attitudes during high acceleration and deceleration. Furthermore, MHI developed an FM control function to control high speed processing of the data of commands to move point groups and a function to correct delays in

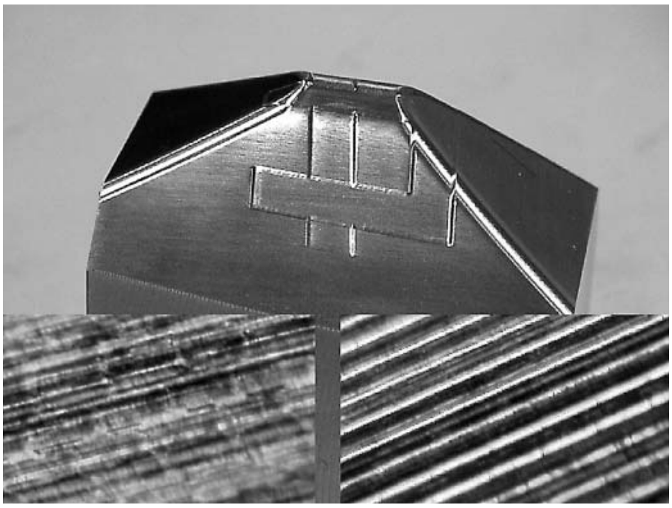


Fig. 3 Enlarged view of surface machined by ball end milling
Comparison of the grade of machined surfaces between a conventional machine and a M-V50-FM (giving superior grade)

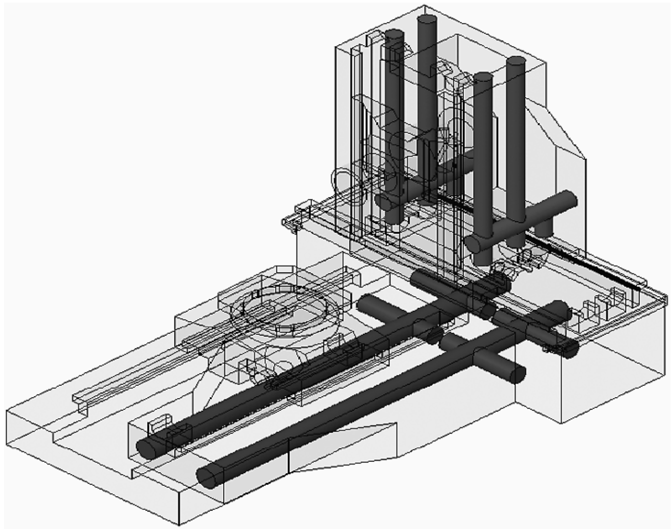


Fig. 4 Model of the ventilation of air into the machine body
Air is ventilated into the machining center body to make the body temperature equalization.

tracking the movement of feed axis with the aim of contributing to the high quality of any machining (**Fig. 3**).

The former function estimates the acceleration and deceleration of points during the working of a parts shape in the data of the infinitesimal point group beforehand, thereby generating commands of the optimal value for acceleration and deceleration that are appropriate to the rigidity of the machine.

In its efforts to reduce vibration of the main spindle, MHI developed a main spindle that rotates at a speed of 30 000 min^{-1} after extensive design and analysis of methods of suppressing vibration over the entire rotational speed range.

Owing to this development, MHI has developed a technology to evaluate and analyze the whole machine (the rotating body of main spindle and further including the machine base parts supporting the main spindle) to reflect the technology onto the overall machine. This is the first time that vibration evaluation (vibrational analysis) over the entire rotational range has been successfully carried out in the industry.

Moreover, MHI has successfully developed a pre-load switching mechanism for the main spindle bearings at both the low speed and high speed ranges to increase the rigidity of the main spindle in the low speed range, thereby achieving stable heavy machining at the low speed range and machining at the high speed range. These technologies are the result of the MHI exclusive analysis technology on rotational bodies for power generation equipment parts etc.

In order to assure the accuracy and stability of the machine, a three-point support bed has been adopted. Several measures have been adopted to suppress thermal displacement. First, the temperature of the machine body has been made equalization through the ventilation of air into the body (**Fig. 4**). An insulation cover has been installed to prevent heat from any machining from affecting the machine body, and multi-point temperature measurement and compensation function have been adopted in order to reduce any thermal displacement within ±0.005 mm (±0.0002”). In addition, a thermal analysis program based on the three-dimensional CAD plays a significant role in the effectiveness of these thermal analysis technologies.

3.2 Technologies supporting the power generation equipment field

Parts such as blades in the power generation equipment field used under high temperature environment are represented by heat-resistant alloys (titanium, Inconel, etc.) and stainless steels. These materials are difficult to cut and have complex three-dimensional machining shapes. Moreover, they must have high profile accuracy. The machines for these difficult to cut parts not only need to have high static rigidity but also high dynamic rigidity. In addition, they must maintain stable accuracy over a long period of time, thus making it essential that the machine have highly stable accuracy, including minimum thermal displacement.

In order to meet such requirements, the fundamental technologies briefly outlined below have been adopted in the horizontal machine centers of the Σ Series "M-H60" and "M-H80".

(1) Development of high torque and highly rigid main spindle

In order to realize a high torque and highly rigid main spindle, the main spindle motor torque was increased, and a high pre-load was adopted for the main spindle bearings. A mechanism to cool the bearing from the inside of the main spindle was applied as a technology to prevent temperature increases in the bearing under the increased pre-load of the main spindle bearing.

(2) Feed mechanism having both a dynamically rigid sliding guide and a motion performance of the rolling guide

MHI has developed all feed axes hydraulic static pressure sliding mechanism in which static load supports have been adopted on both the loading side and the counter-loading side in order to assure the high dynamic rigidity of the feed system.

The mechanism has eliminated variations in machine attitude, which are observed in conventional feed mechanisms that use resin sliding face material. The MHI mechanism is suitable for the machining of workpieces which require strict shape accuracy. A feed speed of 50 m/min (1968 in/min) was realized because the coefficient of friction is small.

3.3 Technologies supporting the aerospace field

The aerospace field also uses parts that are difficult to cut, as represented by heat-resistant alloys and stainless steels. Thus, the improvement of machining performance is also an issue of common concern with the power generation equipment field. To this point, the M-H Σ Series, which adopts a hydraulic static pressure sliding mechanism, assures high productivity in this field, as well.

In aerospace, machined parts manufactured from lightweight form materials of aluminum and magnesium comprise a large share of the main component parts. Notable features of these parts are the increased variety of accuracy of the final products and the increased variety of shapes that cannot be machined by linear three-axis machines. From the standpoint of machining parts by making a shape using point group data, these parts also share a common feature with die and molds.

A notable difference from die and mold machining, however, is that the die and mold is machined by die sinking and has rigidity of the workpieces. Many aerospace parts, on the other hand, have numerous ribs with thin thicknesses in shape [around 2 mm (0.078”)], and the rigidity of the workpiece is weaker than that of the cutting tool so that vibration is likely to occur during machining. In addition, importance is placed on fast machining to achieve specified shape.

3.4 Technologies supporting the automotive field

Advances in technologies that support the automotive field in recent years include the adoption of aluminum die casts as major parts and the adoption of resin parts enhanced by reductions in weight and the number of parts. For die cast parts, which have smaller machining margins, the minimization of non-cutting time is further pursued through the adoption of a main spindle with a high rotational speed and high rates of acceleration and deceleration together with the adoption of a high speed feed mechanism. In this field, more machining needs to be done to develop element technologies that respond effectively to the increases in speed, such as linear motors.

MHI has shifted to machining cells (machining centers for mass production lines) developed from exclusive-use machining lines as part of its efforts to introduce machines that respond effectively to these mass production fields. MHI introduced the "M-CM4A" (main spindle rotational speed of 12 000 min^{-1} with an acceleration of 1 G) to the market in 2002 in order to contribute to high efficiency production.

3.5 Technologies that support the operation of a user's machines

Technologies that assure high operating rates are essential to customers who have adopted machining centers as a means of competing in fierce cost battles. Such technologies add to the functionality and performance of the machining center itself.

From the beginning of its development, the Σ Series was subjected to Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) evaluations in order to assure that the machines would have hard-to-fail characteristics and be durable under a variety of working conditions. In addition, designs emphasized Total Productive Maintenance (TPM) in order to gather equipment requiring regular maintenance to a single location, so as to improve the ability to carry out visual inspections and maintenance more effectively. Furthermore, the machining centers of the Σ Series emphasize energy savings as a part of measures to realize ever greater environmental conservation.

A remote diagnostic system utilizing the most advanced communication infrastructures has also been brought into practical application. The system connects a machining center at a user site with the Service Section of the MHI Machine Tool Division via the Internet or Personal Handyphone System (PHS) to provide direct diagnosis of any failures that occur at the machining center at a distant location. This kind of IT-utilizing function is expected to be further developed and distributed in the future.

In the event that a failure does occur, the CS Center of MHI provides support to the user. The CS Center manages the Service Section and the Technology Section of MHI, and controls the integrated process down to problem solving from the viewpoint of the customer.

4. Machining centers - Tomorrow

The trend of shifting the production bases of machining centers to locations outside Japan is expected to increase further, if not accelerate. Nevertheless, parts for testing during the research and development stage and high added value parts that support the most advanced technologies will continue to be manufactured domestically in Japan as an exclusive industry.

Fig. 5 Head-tilting five-axis machining center

Given this background, MHI continues to develop high value added machining centers in the four fields described above on the basis of the Σ Series with the aim of shortening the lead time in production of these high value added parts.

4.1 Die and mold field - Tomorrow

In order to shorten the lead-time of the mold machining of hard materials and stainless steels, MHI has begun the research into fundamental technologies on high rigidity linear motors. In addition, MHI is promoting studies into increasing the more high speed and reducing the vibration of the main spindle with the aim of eliminating hand-finishing processes.

Furthermore, in order to improve the efficiency of the total process of die and mold production, MHI is examining ways of improving efficiency over the entire process, not only with respect to improving the efficiency of the working process of the machining center but also with respect to the automated preparation of optimum cutting programs using CAD/CAM and automated inspection processes, in short covering activity from the design stage to the inspection stage.

4.2 Power generation equipment and aerospace fields - Tomorrow

MHI has systematically identified the relation between tool wear and the dynamic rigidity of the machine in high speed machining of materials that are difficult to cut such as heat resisting materials. Based on these results, MHI has begun a range of studies into the selection of optimum tools and methods to be reflected in the design process.

On the machine side, MHI has selected a criteria of evaluation of machine rigidity applicable to high speed machining of materials that are difficult to cut, and has begun studies into fundamental technologies for improving machine rigidity.

The shortening of lead-times for machining aluminum alloys into complex shapes is an issue of critical concern. Consequently, the application of five-axis machining technology (combined machining technology) is absolutely necessary to minimize initial setup and preparatory work before machining and to ensure highly accurate machining. To this point, MHI plans to introduce a five-axis machining center that is optimum for working to the market (**Fig. 5**).

4.3 Automobile field - Tomorrow

MHI has extensive experience in production lines that are exclusive to automobile parts. To this field, MHI will provide machining cells that have flexible line structures and that run at super high speed thereby providing high productivity to accommodate medium to large volumes of parts production. In addition to parts produced in exclusive production lines, MHI will also develop small scale and highly accurate versatile machining centers for producing various types of medium to small lots of parts.

4.4 Technologies utilizing machining center - Tomorrow

In order to support the future of customers who utilize machining centers, it is very important not only to provide high functional machining centers but also to support the overall production activities of customers.

(1) Support for production technology

With the increase in high speed machining, optimal machining conditions become more difficult to grasp. On this point, MHI continues to accumulate the machining technology know-how (production methods, tool application engineering, conditions for machining, and measuring and evaluation technology) that maximizes the performance of MHI machining centers. MHI is planning to establish a system to provide the accumulated know-how to customers from the Manufacturing Technology Center (MTC) of MHI Machine Tool Division.

(2) Action to improve operating ratio

Intelligent machines are a keyword to improving the technology of machining center utilization in the future. Measures in this field include easy maintenance adopting the TPM concept, reduction of non-productive operating time of peripheral devices and equipment, full application of self-diagnostic functions with strengthened sensing functions, and full application of remote diagnosis utilizing network infrastructures. MHI Machine Tool Division is promoting the development of these basic technologies jointly with MHI Technical Headquarters.

(3) Production control systems including production at overseas locations

A system currently known as Manufacturing Execution System (MES), which is widely adopted in other production fields, will be introduced to the machine working sector in the near future. In response to the trend towards ever greater globalization, production data at individual production bases will used jointly throughout the world. Based on these expectations, MHI is in the process of establishing a production control system that includes existing FMC and FMS together with further high-level systems.

5. Conclusion

Near future, the manufacturing industry in Japan is expected to concentrate upon the high-level products and industries toward pursuing higher added value, high accuracy machining and high-level machining methods. Accordingly, identification and creation of fundamental technologies necessary to satisfy these high-level machining are required.

MHI produces products in the power generation equipment, aircraft, and aerospace facility fields that pursue further high accuracy and high durability. By taking part in the production technology development from the initial stage of these products, for solving prompt problem, MHI can achieve identification and abstraction of basic technologies promptly.

Furthermore, in order to satisfy these requirements, MHI Machine Tool Division promotes studies in basic technologies in close cooperation with the MHI Technical Headquarters. The effects of these investigations into basic technologies are reflected in the machining centers produced by MHI. Through continued technological development, MHI is confident of its ability of being able to provide machining centers that will be welcomed and highly regarded by customers wherever they may be.

MACHINE TOOL DIVISION

General Manager,
Machine Tool Division

Heki Kasugai

Akihiko Fujiwara

Hiroaki Sasai

Masaru Kajiyama