# Latest Technical Trends of Machine Tools

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*Since the machine tool is "a machine for making machines," it is often called the mother machine. It can be classified into the three processing material groups "ferrous," "non-ferrous," and "hard and brittle," or into the four usage-purpose industrial groups "automotive," "semiconductor and electric machine," "aerospace," and "die/mold." Here, the latest technical trends of grinding machines are described.*

***Key Words***: *machine tool, high accuracy, high efficiency, high productivity, ultra-precision, environment*

## 1. Introduction

Lately the hollowing out of Japanese manufacturing industries has been occurring as a result of the transfer of production to overseas sites. In order for the machine tool industry of Japan as a supply base to the world market to maintain a superior position, it is working to develop machines with competitive cost and maintained function, focusing on environmental aspects and energy saving materials to create top-class machines with multiple functions and ultra-precision and ultra-high speed capability. This paper describes trends regarding machine tools in the world's leading countries and their technology outlines and technical trends regarding grinding machines using fixed abrasive grains.

## 2. Trends regarding Machine Tools and Their Technology in Leading Countries

Production of machine tools has been fluctuated in conjunction with business cycles. Japan, Germany and U.S.A. are the top producers as shown in **Fig. 1**. The world market share of Japan and Germany in 2001 was about 47 percent.

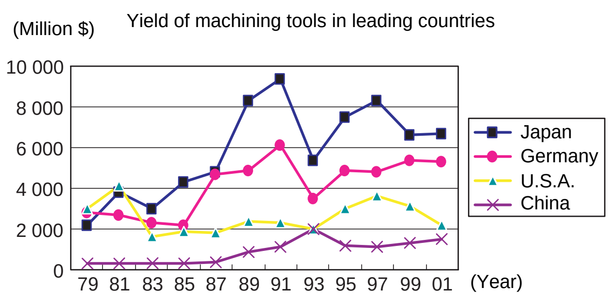



**Fig. 1** Yield of machining tools in leading countries[2)]

Japan overtook America and became the top machine tool manufacturer in 1982, and it has kept this position for the last 20 years or so. It was possible for Japan to secure this top position because it was the first country to adopt NC for general machinery and strove to accommodate the requirements of high accuracy and capacity from Japan's rapidly expanding home electric appliance and automobile manufacturers. However, European countries are rapidly catching up in adopting NC, and Germany in particular is expected to overtake Japan to move into the top position. Considering this background, we have studied the latest technical trends to determine element technology and machining methods required of next-generation machines based on a review of patent applications.

1) High-accuracy, high-efficiency machine tools
- High-speed main spindle····Bearing technology that enables high-speed rotation over 10 000 $min^{-1}$ for long hours
- Parallel mechanism····Technology that allows the direct movement to the target position at high speed
- Linear motor drive····High-accuracy positioning technology at high thrust force and high acceleration
- Multiple-machining······Technology that allows machining of multiple processes at one chuck, e.g. a grinding center

2) Machine tools that provides ultra-precision machining
- Semiconductor wafers···Flattening technique of nano level
- Die machining···Machining technique of nano level for aspherical lens and so on.
- Machining of arduous materials·····High-precision machining technique for crystal, ceramics, sapphire, etc.

3) Environmentally friendly machine tools
- Mineral-oil free·····Dry machining (metal chips, waste oil and waste fluids, and mist dispersion)
- Energy saving, noise prevention technique

## 3. Position of Grinding Machines

The percentage of grinding machines among the total production of machine tools in Japan is about 10 percent as shown in **Table 1**. In production lines with lathes, milling machines, machining centers, etc, grinding machines are positioned as the anchorman. The grinding process is placed between cutting and polishing (free abrasive grains). Although recent progress in hard turning and net shape machining is tending to make the grinding process unnecessary, there is much possibility of expanded use of grinding in the future because of the significant advance of cBN, diamond and other super-abrasive grinding wheels that enable high-efficiency machining that can compete with lapping and lathing. The following are the superior features of grinding[3].

- High-efficiency grinding is possible.
- Forming and reforming of tools (grinding wheels) can be done easily.
- Rigidity of tools (grinding wheels) is high and accurate motion transcription is possible.
- Cutting edge has high hardness and superior wear resistance. Suitable for hard and brittle materials.
- Tool (grinding wheel) rigidity and grinding rigidity can be changed with relative ease.

**Table 1** Yield of machining tools in Japan[1]

100 million yen

| | Total in Japan | Grinding machines | Ratio | Remarks |
|---|---|---|---|---|
| 1990 | 13 034 | 1 562 | 11.9% | Max. yield |
| 1994 | 5 540 | 680 | 12.3% | Min. yield |
| 2000 | 8 146 | 785 | 9.6% | |
| 2001 | 7 764 | 830 | 10.7% | |
| 2002 | 5 851 | 562 | 10.6% | |

## 4. Technical Trends of Next Generation Grinding Machines

The main issues for the next generation grinding machines (fixed abrasive grains) are:

- High-precision, high-efficiency and high-productivity technology……Secure cost competitiveness in automobile manufacturing industry
- Ultra-precision machining technology……Applicable for information, communication and semi-conductor industries
- Environmentally friendly technology……Protection of global environment

In particular, the development of machines focused on compact/high-precision parts is needed.

### 4. 1 High-Speed Grinding

The production system for automobile components is going through changes from few-kind to variable-kind, variable-volume mass-production. Consequently, from a production technology point of view, machining technology that permits flexibility in production and high productivity with minimum cost is required.

### 4. 1. 1 Grinding Theory of High-Speed Grinding

High-speed grinding (more than 100 m/s grinding stone peripheral velocity) for the purpose of attaining higher efficiency is discussed here from the theoretical point of view.

$$Z' = Vw \times \Delta \quad (1)$$

$$Ft = Cp\left(\frac{Vw \times \Delta \times b}{Vs}\right) + \mu \mathrm{Fn} \quad (2)$$

$$Fn = Cp\left(\frac{\pi \times Vw \times \Delta \times b}{2 \times Vs}\right) \tan\alpha \quad (3)$$

$Z'$ : Removal volume per unit time and unit grinding stone width
Ft : Tangential force of grinding resistance
Vw : Workpiece speed
$\Delta$ : Depth of cut of grinding stone radius
Cp : Grinding energy ratio
b : Grinding width
Fn : Normal component force of grinding resistance
Vs : Peripheral velocity of grinding stone
$\alpha$ : Half vertical angle of grain
$\mu$ : Friction coefficient between grinding stone and work piece

From the above formulae (2) and (3), the following was found.

- Grinding efficiency Z' (formula (1)) can be improved without increasing grinding resistance Ft, Fn by increasing Vs and Vw simultaneously at the same ratio. Moreover, grinding resistance can be made smaller by increasing only Vs (peripheral velocity of grinding stone) without changing grinding efficiency Z'. **Figure 2** shows the effect of high-speed grinding by increasing the peripheral velocity of the grinding stone. Surface roughness Ra also shows improvement.

By improving the grinding efficiency Z' (formula (1)), Cp (grinding energy ratio) is reduced and energy-saving efficient grinding can be achieved.

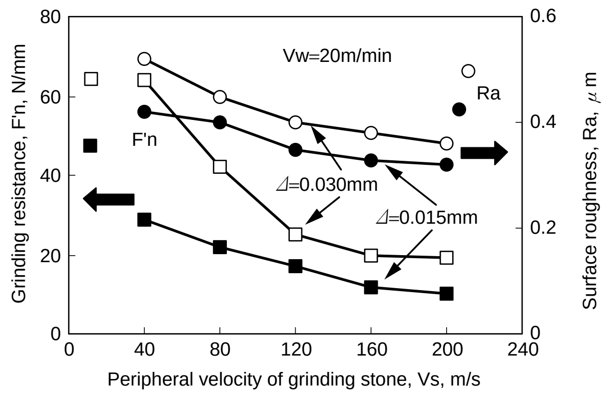



**Fig. 2** Effect of high-speed grinding by increase in peripheral velocity of grinding stone[5]

### 4. 1. 2 Advantages of High-Speed Grinding

· Improvement in production efficiency and cost reduction
  Increase in grinding material removal rate
  Extension of dressing interval (longer life)
· Improvement in quality
  Improvement in surface roughness
· Capable of grinding non-heat-treated steel
  (Impossible to grind at normal velocity due to build-up edge)

### 4. 1. 3 Element Technology of High-Speed Grinding

· Truing/ dressing by super-abrasive grinding wheel
· High-speed, high-precision wheel spindle
· Safety, noise, and dynamic balance, etc.

The truing and dressing technology of super-abrasive grinding wheels influences grinding performance the most. When a prismatic diamond rotary dresser is used, the velocity ratio with grinding wheels is important, and the following processes are taken.

· Implement up-truing of the wheel at the dressing velocity ratio 1.0 in order to secure the accuracy of the wheel surface
· Implement down-truing of the wheel at the dressing velocity ratio 0.9 in order to form the cutting edge by generating fine rupture

In case of high-speed grinding, however, the wheel velocity is as high as 100 m/s to 200 m/s. In order to rotate the diamond rotary dresser at the same velocity, it is necessary to increase the outside diameter of the truer as large as that of the wheel diameter or to increase the rotational speed of the dresser. For example, when the wheel diameter is $\phi$ 455 (100 m/s of wheel velocity) and the truer diameter is $\phi$ 100, a spindle of about 20 000 $min^{-1}$ rotational speed is needed. The problems here are:

· Difficulty in securing the spindle rigidity in the limited space
· Increase in truer diameter or adoption of high-frequency motor causes increased cost

A simple method of solving these problems is to grind at high rotational speed (100 m/s of wheel velocity) after implementing truing at lower wheel velocity. The difference in the conditions, however, causes the following problem.

· Decrease in grinding accuracy due to the increase in deflection from the centrifugal expansion of cBN wheels

As a result, truing must be executed in the same conditions as those for grinding in all cases. One of the most effective solutions is the electric discharge truing, but the details are not described here.

**Table 2** Experimental data

(Grinding wheel: cBN80 0 150VN1E)

| Rotational speed of grinding wheel, $min^{-1}$ | Radius expansion, $\mu$m | Deflection, $\mu$m |
|---|---|---|
| 500→2 500 | 5 | No change |
| 500→5 000 | 23 | 7 |

### 4. 1. 4 Compound Technology ······ High-Speed Grinding and Electrical Discharge Truing

The advantages of electrical discharge truing are:

· Dresser spindle rigidity need not be considered due to non-contact truing method.
· Free from restriction of wheel velocity
· Truing of metal bond wheel is possible.

Concerning the high-speed grinding described above, it is to be noted that the cost of a cBN wheel is expensive i.e. several million yen. However, if a small wheel (e.g. $\phi$ 305mm) at high-speed grinding can achieve the same grinding efficiency as a larger wheel, this will lead to the compactness of the machine and not increase the total cost. We are confident that high-efficiency machining by high-speed grinding will contribute to the competitiveness of the automobile industry, etc. in the future.

### 4. 2 Ultra-Precision Grinding Technology

Ultra-precision grinding technology for electronic and optical parts has been improved mainly because of advancement in grinding technology using free abrasive grains. Despite that, there is a growing tendency to change to fixed grains nowadays.

The main reasons are
· Requirements for improvement in environmental problems
· Improvement in productivity
· Easy control of grinding volume

Demand for grinding hard and brittle materials such as silicon wafers and sapphire substrates for LED is expected to expand more and more in the future. LED in particular is expected to be widely applied to signals and vehicles and further to general lighting fittings in the year 2010. As shown in **Fig. 3**, the production volume of LED wafers is predicted to be 2 million pieces/yr in the year 2010.

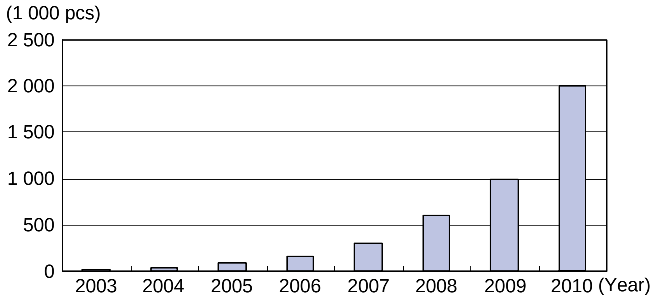



**Fig. 3** Yield prediction of LED wafers (in terms of 2 inches)

### 4. 2. 1 Ductile Mode Grinding

There are pressure transcription and motion transcription in the surface formation theory for the material removal grinding.

Pressure transcription······Lapping by free abrasive grains, polishing and honing using fixed wheels, super-finish grinding.

Motion transcription······Ductile mode grinding using fixed abrasive grains.

(With grinding using normal fixed grains, there exists spark out grinding due to the residual stock removal ratio by brittle mode grinding. Here two spheres of motion transcription and pressure transcription are mingled.)

The problem with the grinding of hard and brittle materials is the deterioration of quality due to the damaged layer or fractures. The surface energy that causes the damage is proportional to the square of the grain depth of cut, dg. Grinding of hard and brittle materials to a smooth surface without fractures is termed the ductile mode grinding. The individual grain depth of cut, dg is the fundamental of the cutting operation. The conditions for the ductile mode grinding are:

① dg ≦ dc    dg: grains depth of cut (**Fig. 4**)
dc: transition point of ductility and brittleness (less than 0.1 $\mu$ m, which varies depending on the kind of materials.)
When dg>dc, grinding is done by brittle rupture, such as cracks, in the brittle mode

② A grinding wheel consisted of a plenty of uniformed grains

③ A machine with little thermal displacement satisfying ultra-precision, high-rigidity motion

④ Truing of a grinding wheel in the ductile rupture mode

⑤ Grinding conditions in which the wear mode of the grinding wheel is ductile mode

The problems are:

· Low productivity
· Maintaining the ductile mode grinding in the production line is impossible.
· High elemental technology to realize motion transcription is required.

Hence there are many problems to be solved.

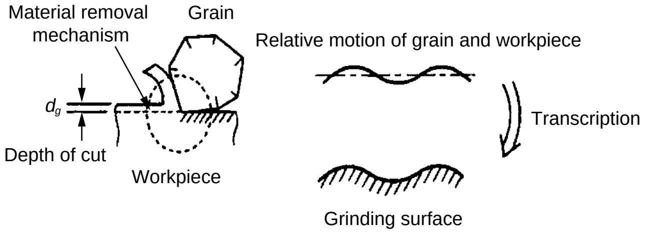



**Fig. 4** Motion transcription by ductile mode[4)]

### 4. 2. 2 Constant-Pressure Feed Grinding

Ductile mode grinding is ultra-precision grinding based on new grinding theory, and the ELID grinding method is one means of achieving the grinding conditions described in **4. 2. 1**. But there remain many technical problems to be overcome. The constant-pressure feed grinding described hereafter is considered to be one grinding technique based on a new concept that enables the grinding of hard and brittle materials without fractures. As shown in **Fig. 5**, the constant-pressure mechanism is placed in the direction of grinding, and the constant-positioning mechanism is placed in the direction of the machined surface. The mechanism controls the motion of the machine depending on the material characteristics to be ground with the constant feed thrust force (max. 200g) and executes grinding according to the cutting performance of the grinding wheel. Ideally, the grinding normal-direction force should be zero.

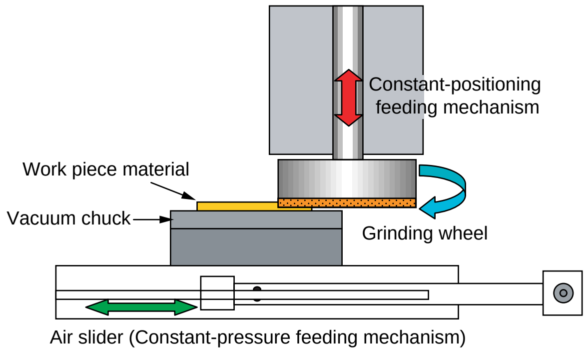



**Fig. 5** Constant-pressure feeding mechanism[6)]

The following remain as technical issues:

· How to control the constant-pressure feed mechanism force (air or motor driven mechanism with no irregular feed thrust force)
· How to develop a new type of high-efficiency grinding wheel

However, this constant-pressure feed grinding can be considered a promising grinding technique for the future.

### 4. 2. 3 Other Techniques

Other main techniques for the future are (details not described):

· Grinding of wide-angle aspherical lens for dies
· Fixed grain lapping process for glass disks

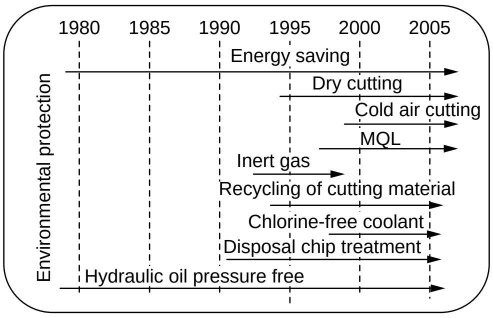
### 4. 3 Environmentally Friendly Machine Tools

Machine tools are considered to be environmentally friendly products with little environmental burden at the time of production and disposal, and their recycling ratio is high with no harmful materials. However, the environmental burden during use is said to be more than 95 percent, as machine tools are a typical production goods type with long-life. Since this effect on the whole industry is large, it is necessary to solve the problems more than ever.

### 4. 3. 1 Trends of Environment Related Patent Application

As shown in **Table 3**, the technology coping with environmental protection can be classified largely in two groups.

**Table 3** Technology coping with environment protection[2)]




· Mineral-oil free
· Energy saving

Regarding trends in patent applications, while only a few patent applications related to energy-saving technology were made starting in 1992, a remarkable increase in the number of such patent applications began again 1997. Among other applications, patent applications on mineral-oil-free technology, particularly dry, MQL, and cold air machining have increased remarkably. Furthermore, an attempt to integrate hydraulic fluid, lubricant and cutting fluid has just started, although it is a significantly difficult approach.

### 4. 3. 2 Energy Saving

Power consumption of a machining tool is generally as shown in **Table 4**. On the other hand, standby energy consumed besides operating hour consumption is said to amount to as much as 40 to 50 percent. Standby energy is the energy consumed when the machines are not in operation and includes fixed portion of idle running of main shafts (**Fig. 6**). Since it is impossible to eliminate this standby time of the main shafts, it is important to develop the technology to reduce the standby energy. There are many technical problems to be solved such as the thermal displacement at ON/OFF of the main shafts. Items for reducing the standby energy are summarized in **Table 5**. On the other hand, the shortening of actual operating time and the reduction in processing energy while the machines are in operation (in process) must be considered. They are summarized in **Table 6**.

It is difficult for grinding machines to eliminate or reduce drastically the amount of coolant compared with that for the cutting machines. The technological development in this area is still immature, which is one of the issues for future study.

**Table 4** Power consumption of machining tool

| | |
|---|---|
| Machining position of main shaft etc. | 40% |
| Coolant supply device | 20% |
| Workpiece transfer mechanism | 20% |

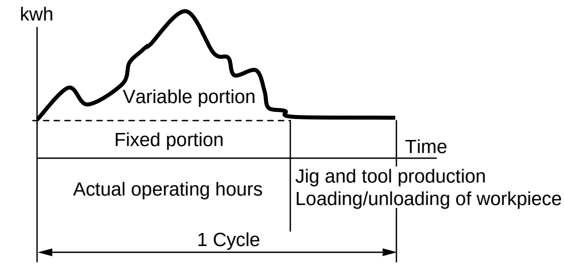



**Fig. 6** Energy consumption of machining tool[7)]

**Table 5** Items for reducing standby energy

· Supply of cutting fluid, air, etc. only when necessary
· Stop conveyers at no load
· Balancer without power consumption
· Automatic power cut when not needed (interception of power)
· Cooling mechanism of the control panel (cooling fins, optimized shape)
· Stop main shafts, etc.

**Table 6** Reduction of energy when grinding

· Wheel spindle of low power consumption, low heat generation
· Weight reduction of moving body
· Reduction of coolant by a trace of cooling water + a trace of lubricant
· Techniques to reduce sliding friction loss······hydrostatic pressure etc.
· Improvement in driving efficiency······direct drive
· Adoption of high efficiency devices······motor etc.

## 5. Summary on Next Generation Grinding Machine

It is important to develop the grinding technology to keep pace with the cutting machines in high-efficiency processing, to excel the lapping processing field in the ultra-precision processing and to realize the digitalization of grinding comparable with the cutting tools through the innovation in grinding wheels (grinding wheel of our dream).

## 6. Conclusion

Japanese machine tools have made remarkable progress through development of NC devices and reinforcement of tools. However, the recent diversification of market needs encourages the industry to seek the future direction. Japanese manufacturers are seeking machine tools of high productivity in order to win against Chinese competitors. Besides, there is a strong movement to compete with China through ultra-precision machining technology. Looking back on these points, the importance of IT technology is also to be considered. That is to say, these are flexible systems to accommodate the fluctuation of market demands and the intelligence technology to cover the shortage of technicians. Nevertheless, it is necessary to develop technologies based on the concept of selection and concentration while keeping a close eye on the activities of automotive, electronic and semiconductor industries.

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