Gear Grinding Processing Developed for High-Precision Gear Manufacturing

YUKIHISA NISHIMURA*1
YUJI ASHIZAWA*1
TOSHIFUMI KATSUMA*1
YOSHIKOTO YANASE*1
KOICHI MASUO*1

In recent years, many industries have been trying to introduce gear grinding machines, backed by the increasing demands for low-noise gears in automotive transmissions and for high-precision large gears in construction machines, gearbox for wind turbine systems, and printing machines. To address these demands, Mitsubishi Heavy Industries, Ltd. (MHI) has developed and added to its product line-up two gear grinder products: the ZE series for mass production of small gears and the ZG series for medium and large sized gears. This document describes the features of these products from the technical standpoint and explores the future prospects of gear grinding because it is anticipated that more manufacturers will adopt this machining technique.

1. Introduction

In recent years, from mass-produced small gears to medium and large sized gears, gear finishing technologies are used after heat treatment to reduce vibrations and noise from automotive transmissions or to improve the efficiency and reduce the size of wind power generators. As for the techniques for finishing gears after heat treatment, gear grinding is commonly used in addition to carbide hobbing and honing.

To address the diversified gear-grinding needs of customers, MHI offers two lines of gear grinder products: the ZE series for mass production of small gears and the ZG series for medium and large sized gears. The following describes the features of these products.

2. Features of the ZE series gear grinding machine

2.1 Diagonal grinding

Gear grinders introduced into an automotive transmission gear manufacturing line must satisfy productivity and tool cost requirements in addition to machining accuracy. To attain this, in ZE series gear grinding machines, we adopted the continuous generating-grinding technique using a multi-thread grinding wheel. The use of diagonal grinding in conjunction with the synchronized high-speed and high-precision control of the wheel and work spindles realizes high-accuracy and high-efficiency grinding.

Figure 1 shows a schematic diagram of diagonal grinding. Diagonal grinding is a grinding technique in which the grinding wheel is fed into the workpiece in an axial direction while being shifted along the tangential feed axis. This grinding technique has advantages in preventing the wear of the grinding wheel and improving the grinding efficiency with stable precision, because the workpiece is constantly ground by new abrasives. ZE series grinders provide the functionality to automatically dress the multi-thread grinding wheel using the rotary dresser and perform diagonal grinding while sequentially shifting the portion of the grinding wheel that grinds the workpiece. **Figure 2** shows the transition of the tooth profile pressure angle when the grinding wheel ground 40 workpieces between dressing cycles. According to the graph, the variation on both the right and left flanks is 2 μm or less, which means that the machine provides stable grinding precision even in high-volume gear production. Moreover, ZE series grinders can finish approximately 8,000 gears per grinding wheel because

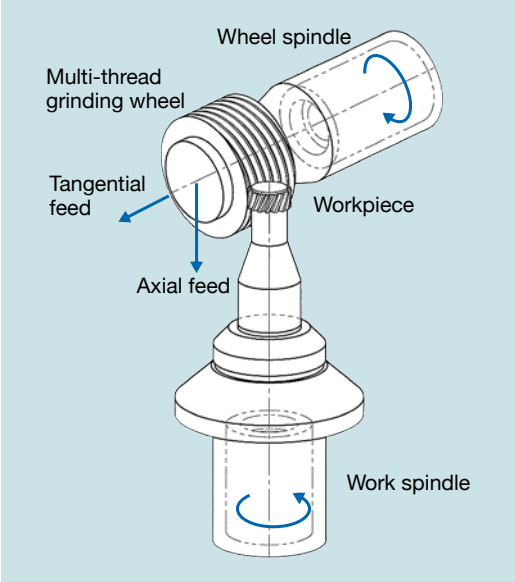


Fig. 1 Schematic diagram of diagonal grinding
Grinding wheel is fed axially into workpiece while being shifted in a tangential direction.

*1 Machine Tool Division

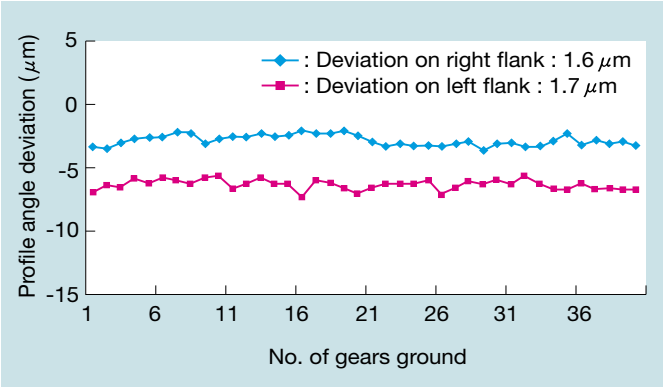


Fig. 2 Transition of profile angle deviation between dressing cycles
Transition of pressure angle when 40 workpieces were ground continuously between dressing cycles.

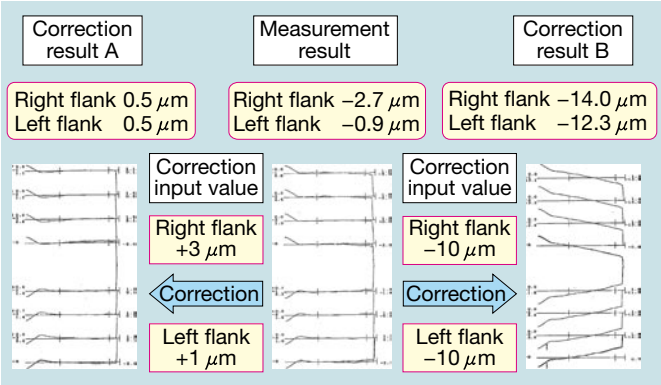


Fig. 4 Example of pressure angle correction
Correction amount is entered based on result of accuracy measurement.

it allows the dressing interval to be set to as many as 40 workpieces. This means that the cost of grinding can be reduced to as low as 12 to 13 yen per workpiece.

2.2 Modification of tooth profile pressure angle

In the ZE series, to obtain a high-accuracy tooth profile, the rotary dresser is set to almost the same position as that of the workpiece so that the grinding wheel is dressed on the machine in the same position and posture as when a workpiece is ground. Because the dresser is set and adjusted by an operator, there is a possibility of a setting error, which in turn causes a profile pressure angle deviation. Although, on competitors' machines, the correction of the pressure angle is accomplished manually by fine-adjusting the dresser position, to help inexperienced operators, we developed a functionality that completes this adjustment by simply entering NC data. The process of fine-adjusting the dresser position is to change the relative positional relationship with the grinding wheel and this is achieved by using the NC system to move each axis to correct the grinding wheel position with the dresser fixed. **Figure 3** is a schematic diagram that illustrates this function. Figures 3 (a) and 3 (b) show the relative positions of the wheel and dresser spindles before and after pressure angle correction, respectively. To develop this function, we analyzed the relative positional relationship between the two spindles when correcting the pressure angle.

Figure 4 shows an example of correcting the pressure angle by entering the required correction amounts for both tooth flanks into the NC system. It can be seen that the correction results almost reflect the input values. This function is becoming indispensable for customers in Japan where the number of experienced operators is decreasing and in overseas manufacturing plants without experts.

2.3 Machining simulation technologies

In developing the ZE series, we created a machining simulation program based on the theory of meshing between threaded grinding wheel and workpiece and the existing simulation technologies. A simulation example is shown in **Fig. 5**. The figure represents the shapes of both tooth flanks at three points along the face width when the leads are crowned. These are biased flank shapes in which the tooth profile pressure angle changes in the direction of the face width. The simulated data was very close to the actual machining data collected from the grinders, so we decided to use the program to simulate various machining applications.

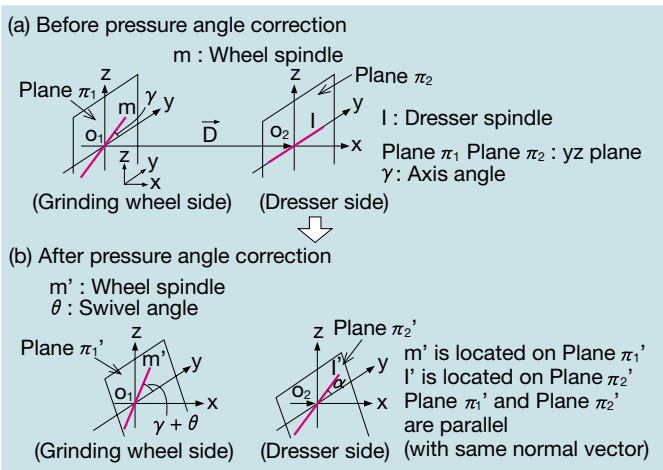


Fig. 3 Pressure angle correction

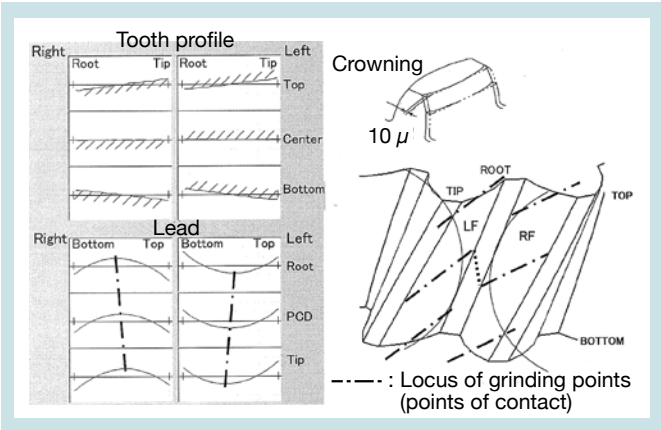


Fig. 5 Simulation of generating grinding

2.4 Machining example of automotive transmission gears (ZE24A)

Using the ZE24A grinder, we finished a final gear (module of 2.5, number of teeth 74, and face width 25 mm) with a cycle time of 1.5 minutes and the accuracy of the finished gear was JIS N1 grade for the tooth profile and lead and JIS N3 grade for the pitch, respectively. The machining result is shown in **Fig. 6**.

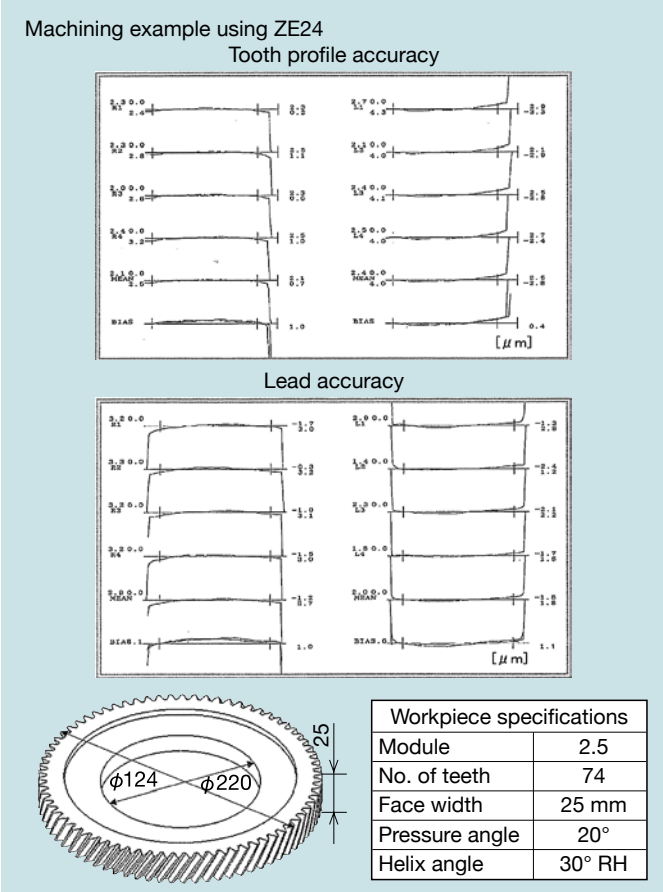


Fig. 6 Machining result
An automotive final gear was finished in 1.5 minutes to JIS N3-grade accuracy.

3. Features of ZG series gear grinding machines

3.1 Tooth profile and lead correction

ZG series grinding machines use vitrified grinding wheels, which can be dressed into any shape on the machine for complex tooth profile correction. Moreover, these grinders can correct the lead of gear teeth by controlling the amount of radial infeed of the grinding wheel. ZG series grinders provide the standard tooth profile and lead patterns shown in **Fig. 7** and allow the operator to specify the preferred tooth profile and lead in an easy, conversational manner.

3.2 On-machine measurement

For medium- and large-sized gear grinding machines on which the replacement and measurement of the workpiece is time-consuming, there is a strong demand for the on-machine measuring capability. In addition to the on-machine measurement function, ZG series grinders also provide the ability to calculate the correction amount automatically

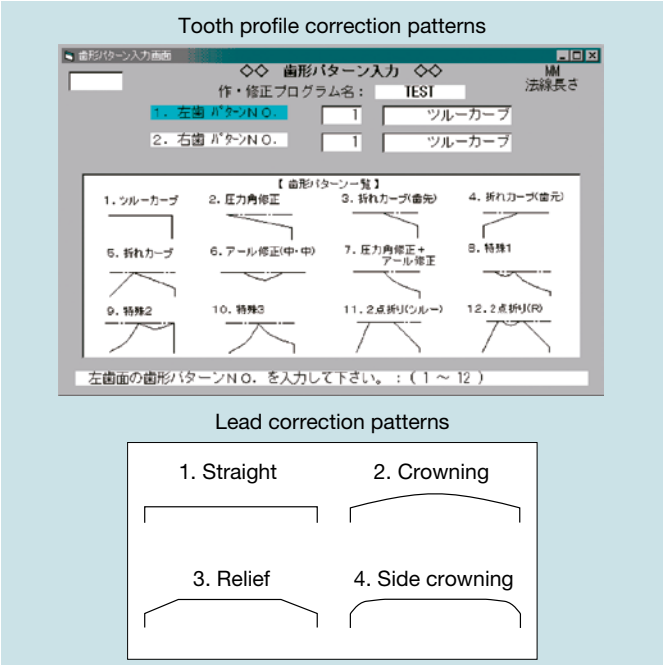


Fig. 7 Tooth profile and lead correction patterns
Tooth profile and lead can be entered and corrected in an easy, conversational manner.

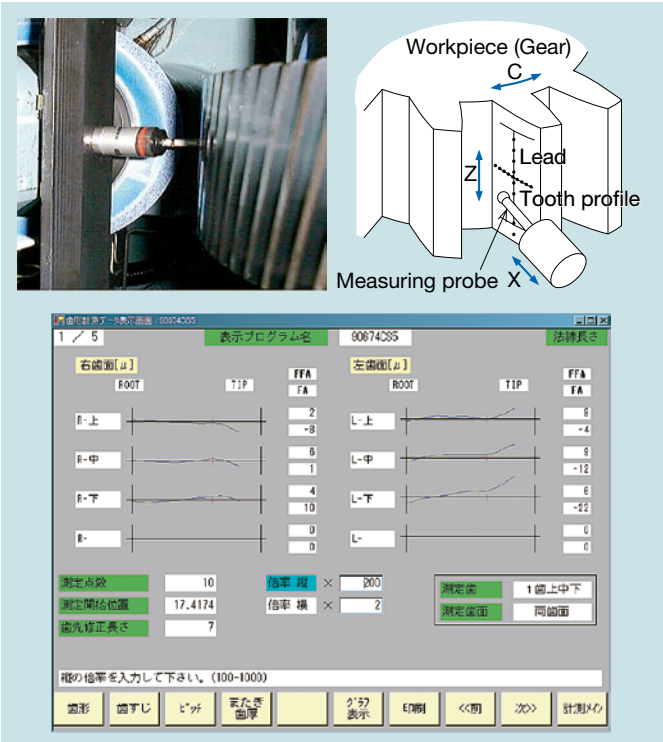


Fig 8 On-machine measuring system and measurement result
Tooth profile, lead, pitch can be measured.

from the measurement result in an effort to automate jobs that require operator experience. **Figure 8** shows the appearance of the measuring system and an example of a measurement result.

3.3 Bias modification

In profile grinding, the grinding wheel makes a line contact with the workpiece and its direction is different from the locus of the points of contact in generating grinding. This also appears as a difference in the flank shapes. Particularly, when you crown a helical gear, generating grinding and profile grinding produce opposite trends of biased flank shapes. Because many customers want to modify biased flank shapes as desired, in profile grinding, we provide the ability of flank shape modification that controls the contact lines and machine operations. On the ZG series, bias modification is accomplished by the motion of the additional tangential wheel feed axis during grinding. **Figure 9** shows an example of bias modification and its simulation result.

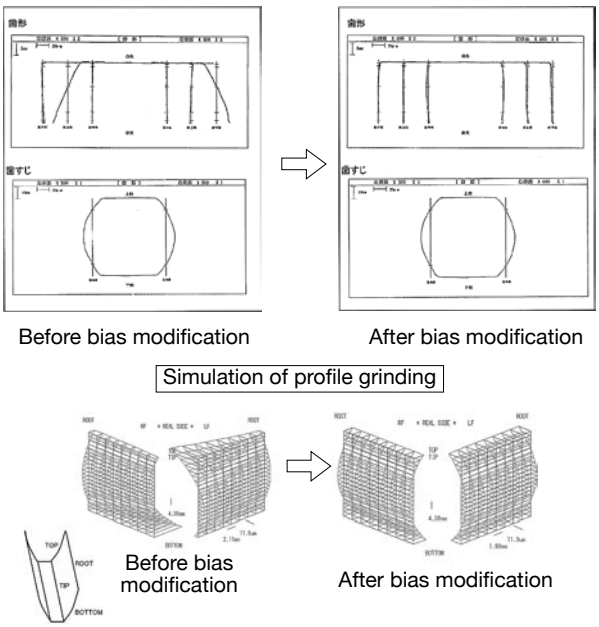


Fig. 9 Example of bias modification
Tooth profiles were made almost equal at top, middle, and bottom of face width.

3.4 Machining support software

In order to grind the tooth flanks of the workpiece with high accuracy, it is important to set grinding and dressing conditions. In particular, in profile grinding, the operator needs to specify the dressing interval appropriately because a grinding cycle may include several dressing cycles. Therefore, ZG series grinders provide the ability to automatically calculate grinding conditions in the formula as shown below as a means to assist unskilled operators.

Regarding the grinding conditions, the recommended conditions are calculated automatically based on the specific cutting rate Qw' and the grinding stock as follows:

Qw' (mm^2/s)=ΔX (mm) × F (mm/min)/60

Where,

ΔX (mm): Amount of radial infeed

F (mm/min): Axial feedrate

Using the above formula, optimal radial infeed amount and feedrate values are set for each cycle. Next, the cutting volume limit is set according to the grinding wheel in use, and then the dressing interval is calculated automatically from the cutting conditions as follows.

Dressing interval =

Cutting volume limit (mm^3/mm)/Amount of removed flank (mm^3/mm)

Using the above formula, an optimal dressing interval is set based on the specifications of the grinding wheel and workpiece. **Figure 10** shows an example of how the grinding conditions are set automatically.

(Set value)

	Q'w (mm^3/mms)	Cutting volume limit (mm^3/mm)
Rough grinding	5.0	600
Semi-finish grinding	2.0	300
Finish grinding	1.5	300

Total radial infeed 0.826 (mm)
(Amount of radial infeed)

(Grinding conditions)

	Amount of radial infeed (mm)	No. of grinding cycles (times)	Feedrate (mm/min)	Grinding pass	Dressing interval (No. of teeth)
Rough grinding	0.121	6	2479	Conventional/ Climb	15
Semi-finish grinding	0.06	1	2000	Conventional	30
Finish grinding	0.04	1	2250	Conventional	45

Fig. 10 Automatic calculation of grinding conditions

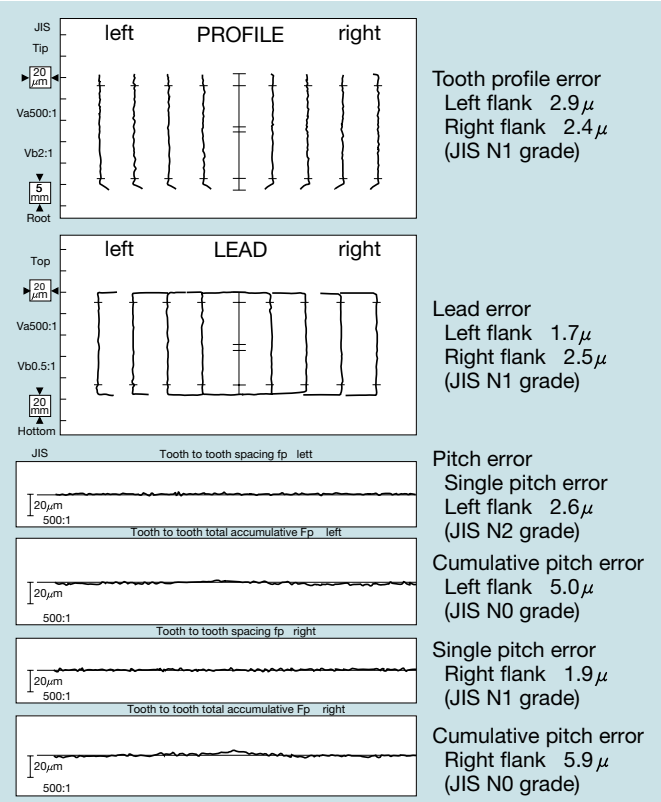
3.5 Machining example (1)

Figure 11 shows an example of grinding a large gear using the ZG1000 grinder.

We finished a large gear (module 5, number of teeth 162, face width 95 mm, grinding stock in tooth thickness 0.45 mm) with a cycle time of 3 hours 45 minutes, and the accuracy of the finished gear was JIS N2 grade (JIS N0 grade for the cumulative pitch).

3.6 Machining example (2)

In gear grinding, as with other types of grinding, the surface roughness is also an important factor in addition to the accuracy of the tooth profile and lead. Since, in gear lubrication, the oil film parameter λ (= film thickness/surface roughness) is closely related to the lubrication effects and damage to the flank surface, the improvement of the surface roughness has a large impact on the improvement in the



Workpiece specifications

Module	5	mm	Helix angle	15.4°	
No. of teeth	162		Outer diameter	850	mm
Pressure angle	20°		Face width	95	mm

Fig. 11 Machining example of a large gear (Machining result)
Finished gear was finished to a machining accuracy of JIS N2 grade.

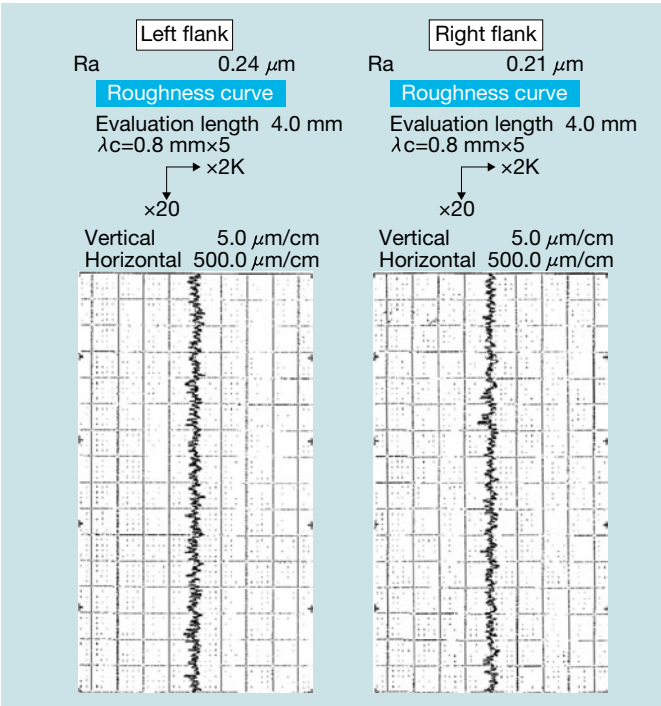


Fig. 12 Machining example of a large gear (surface roughness)

performance and life expectancy of a gear. On these points, the Mitsubishi ZG1000 gear grinder has achieved a surface roughness of Ra 0.3 μm in large gear grinding. **Figure 12** shows a machining example.

4. Development of future gear grinding technologies

4.1 ZE15/24A (Generating gear grinding machine)

(1) Bias grinding

As mentioned above, even in generating grinding, crowning a gear tooth causes the tooth profile to be biased. However, in response to today's customer needs, we find it necessary to develop technologies to control this bias.

(2) Improvement in grinding speed

To accomplish high productivity and cost reduction, there is a strong demand for high-speed grinding. Although the grinding speed V has been approximately 60 m/s^{-1} conventionally, it is now approximately 75 m/s^{-1} in practical use. In the future, it is anticipated that this will be increased to as high as 90 m/s^{-1}. The reduction of the non-cutting time in a grinding cycle is also a requirement.

4.2 ZG400/1000 (Profile gear grinding machine)

(1) Line-up of large gear machines

In the market of gearbox for wind turbine systems, there is an increasing need for gear machines that can handle a workpiece diameter of ϕ1,000 mm or larger to support the target workpiece diameter of approximately 1.5 to 2.5 m.

(2) On-machine measuring system with higher precision and higher speed

On a large gear grinding machine, unloading and then reloading a workpiece is time-consuming. Therefore, it is becoming more important to develop an on-machine measuring system improved in accuracy and speed.

(3) Adoption of a direct drive technology

It is considered necessary to adopt a direct drive technology because high-precision control is impossible if any clearance exists in each axis.

(4) Ease of workpiece centering

For large gears, facilitating the centering of the workpiece is an important technology because it is difficult and time-consuming.

(5) Development of production support systems

There is an increasing demand for production support systems that assist customers in simulating the tooth profile, estimating the grinding accuracy, automatically calculating the grinding conditions, and more.

5. Conclusion

For gears used in automobiles, construction machines, wind turbine systems, and general industrial machinery, there is an increasing need for high accuracy and customers

are seeking high-precision, easy-to-use, and low-cost gear grinding machines. To address this, for the grinding of relatively small gears (ϕ250 mm or less) used for automobiles, we developed gear grinders that feature high efficiency, high precision, and low running cost by adding diagonal grinding and other capabilities to conventional generating gear grinding techniques. As a result, more automobile gear manufacturers are introducing our machines into their manufacturing lines. On the other hand, for the grinding of ϕ500 mm or larger gears used in construction machines, wind turbine system, and so on, we offer a line-up of profile gear grinding machines with additional tooth profile/lead correction and on-machine measurement capabilities to improve operability and more customers are introducing them into their gear machining facilities. We will continue to offer gear grinding machines that feature higher efficiency, higher precision, lower running cost, and easier operation.

Yukihisa Nishimura

Yuji Ashizawa

Toshifumi Katsuma

Yoshikoto Yanase

Koichi Masuo