Gear Cutting and Grinding Machines and Precision Cutting Tools Developed for Gear Manufacturing for Automobile Transmissions

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It is a never-ending theme for motorcycle and automobile manufacturers, for whom the Machine Tool Division of Mitsubishi Heavy Industries, Ltd. (MHI) manufactures and delivers gear cutting machines, gear grinding machines and precision cutting tools, to strive for high precision, low cost transmission gears. This paper reports the recent trends in the automobile industry while describing how MHI has been dealing with their needs as a manufacturer of the machines and cutting tools for gear production.

1. Gear production process

Figure 1 shows a cut-away example of an automobile transmission. **Figure 2** is a schematic of the conventional, general production processes for transmission gears. The diagram does not show processes such as machining keyways and oil holes and press-fitting bushes that are not directly relevant to gear processing. Normally, a gear hobbing machine is responsible for the process before heat treatment. A gear shaping machine, however, processes workpieces such as stepped gears and internal gears that a gear hobbing machine is unable to process. Since they employ a generating process by a specific number of cutting edges, several tens of microns of tool marks remain on the gear flanks, which in turn causes vibration and noise. To cope with this issue, a gear shaving process improves the gear flank roughness and finishes the gear tooth profile to a precision of microns while anticipating how the heat treatment will strain the tooth profile and tooth trace. After heat treatment, it was usual only to finish the portion of the gear that accommodates a bearing.

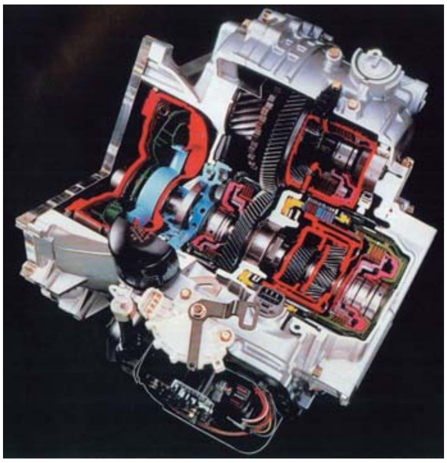

Fig. 1 An automobile transmission

2. Recent trends in gear production[1]

As described above, gear tooth finishing based on the predicted distortion due to heat treatment takes place conventionally before the heat treatment process. The recent stringent requirements for higher precision, however, prompts processes such as gear grinding and honing to finish the gears to take place more frequently after heat treatment. Since sophisticated processing techniques such as gear shaving have not readily taken root overseas, gear grinding is more often the choice.

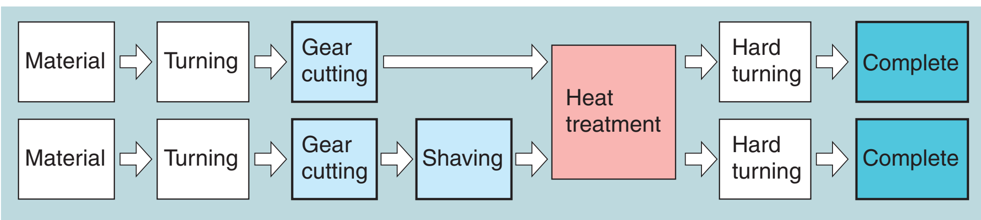

Fig. 2 Conventional production processes for transmission gears.
Normally up to the gear hobbing process. Gears requiring high-precision call for the shaving process.

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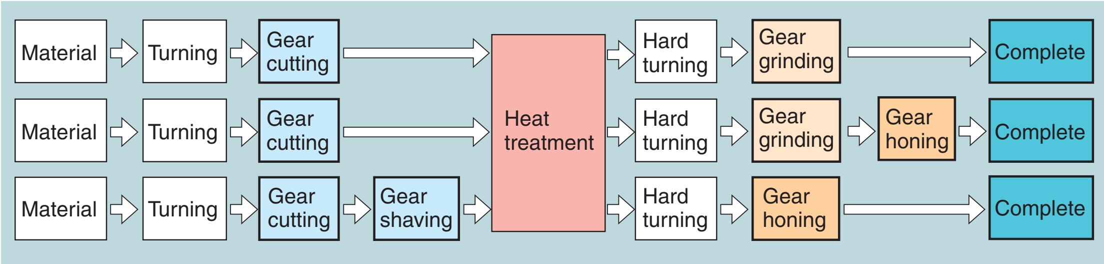

Fig. 3 Recent production processes for transmission gears
Gears requiring high-precision call for finishing processes after heat treatment. Gears of conventional accuracy end at the shaving process.

Figure 3 shows recent gear production processes. The honing process improves gear flank roughness and creates a three-dimensional tooth profile. However, since finishing after heat treatment pushes up production costs, attempts to reduce the total cost are in progress. Since each gear in a transmission is separately responsible for vibration and noise, each calls for its own optimal finishing method regarding precision and cost. For example, a gear undergoing the grinding process calls for improved hobbing precision instead of eliminating the shaving process. Another example is that the honing process calls for shaving before heat treatment to save tool costs while stabilizing the pre-process precision and reducing the machining allowance. Plastic processes such as die forging are also recent choices that increasingly employ a monoblock forging method to produce clutch teeth among others. The following summarizes the recent trends in transmission gear production.

(1) Employing dry cutting
- To improve productivity of gear cutting by high speed cutting.
- To reduce tool costs by making tool life longer.
- To reduce cutting oil costs by employing dry cutting.

(2) Skipping shaving process
- To skip the shaving process if tooth grinding comes after heat treatment.

(3) Employing a monoblock forging process for clutch teeth
- To use plastic processes (eliminating machine cutting processes).
- To make gears compact.

(4) Developing gear production overseas and operators being less skilled
- To call for machine tools with ease of operation and maintenance.
- To enhance and improve operator support software and pre-services.

(5) Employing optimal processes for workpieces
- To provide various machine tools to satisfy each method of processing.

3. Precision cutting tools

(1) Coating for dry cutting

Getting rid of coolant from workshops is not only environmentally friendly but also reduces costs. To this end, MHI has developed the world's first dry gear cutting system.[2] More specifically, the development of cutters protected by Super Dry Coating as well as gear hobbing machines suitable for dry cutting has realized dry gear hobbing. MHI's gear shaper also employs the dry cutting method.

During hob cutting, the tip of the hob cutter reaches a high temperature which makes it wear quickly. Hob cutters protected with Super Dry Coating have improved thermal strength. Since this enables the cutting speed to be increased from the conventional 100 to 120 m·min^{-1} to as high as 200 m·min^{-1} while suppressing tool tip wear to double the tool life, productivity has improved considerably.

Figure 4 compares the changes in the coat compositions between Super Dry Coating and the conventional TiN coating. When exposed to high temperatures, the TiN coating has its Ti oxidized and is transformed into a brittle structure. Super Dry Coating, on the other hand, is considered to have its aluminum selectively oxidized to form a strong, hard layer.

Recently, MHI has developed the Super Dry II Coating with its high temperature oxidization characteristics enhanced even further to realize a cutting speed as high as 250 m·min^{-1}. The Super Dry II Coating also demonstrates high anti-oxidization characteristics at the high temperature of 1,200°C.

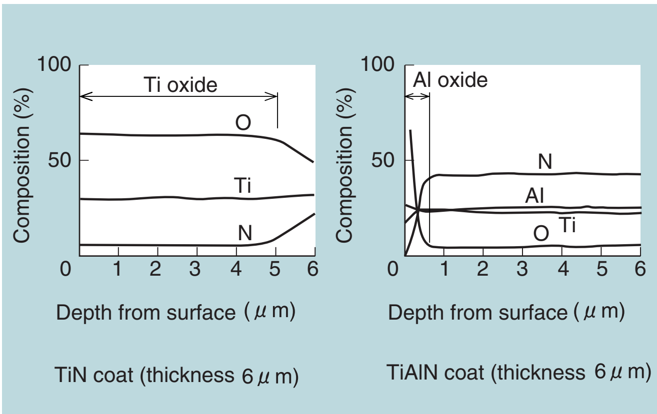

Fig. 4 Comparison of coat compositions
800 °C, in atmosphere, maintained for 5 hours

(2) Carbide hob cutters for finishing after heat treatment

Finishing by a carbide hob cutters is gaining acceptance for small diameter gears such as steering pinions because they are difficult to process on a gear grinding machine after heat treatment due to the interference of the grinding wheel. MHI offers carbide hob cutters for finishing that are a combination of ultra-fine particles, carbide alloy and a coating.

(3) Surface-treated shaving cutters

The shaving process accounts for the most of the gear finishing process. Surface treatment raises the surface hardness of the shaving cutter to extend the tool life which in turn reduces the tool cost. Combined with the high rigidity design that takes the elastic deformation of teeth into account, the tool life actually improves 1.2 to 2 times (**Fig. 5**).

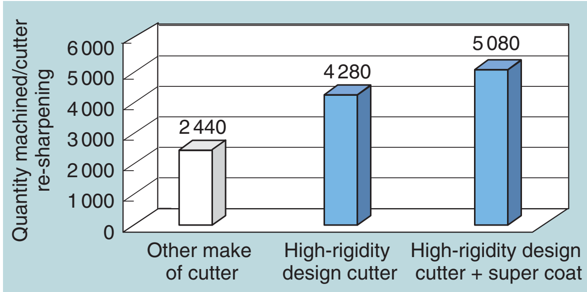

Fig. 5 Improving life of shaving cutters

4. E series gear cutting and grinding machines

To answer the needs of the automobile industry as described in Section 2 of this paper, MHI has integrated the gear cutting and grinding machines such as gear hobbing, gear shaping and gear shaving machines into the E series along with the development of cutting tools. The newly developed ZE series of gear grinding machines for the generating process are also available. The letter "E" of the E series stands for being ecological, economic and excellent. The following concepts are the basis of the developments.

(1) Global standard

Clearly defining the standard specifications compatible with development of production overseas.

(2) Thorough measures for energy saving and the environment

Standardization of energy-saving circuits and measures against noise.

(3) Improving ease of operation and maintenance

Improvement in operator support systems and measures against operators being less skilled.

(4) Unification of line concept

Establishing a unified, total concept from hobbing machines, gear shapers, shaving machines, gear grinding machines to cylindrical grinding machines.

(5) Compatible with flexible production

Organizing major units into packages and modules to make line configuration and re-configuration easy.

These developments have involved striving for customer satisfaction and implementation of CFT activities comprising the marketing, design, assembly and service functions. The standard specifications incorporate past complaints and defects, customers' requirements and specifications in an organized manner.

The development design thoroughly mobilized the 3D-CAD system while a full design review for ease of operation and better workability took place in addition to FEM analysis. MHI also strives to develop servo technology that has resulted in the NC guide gear shaper ST series, synchronous shaving machines and synchronous honing machines. **Figure 6** lists MHI's lineup of gear

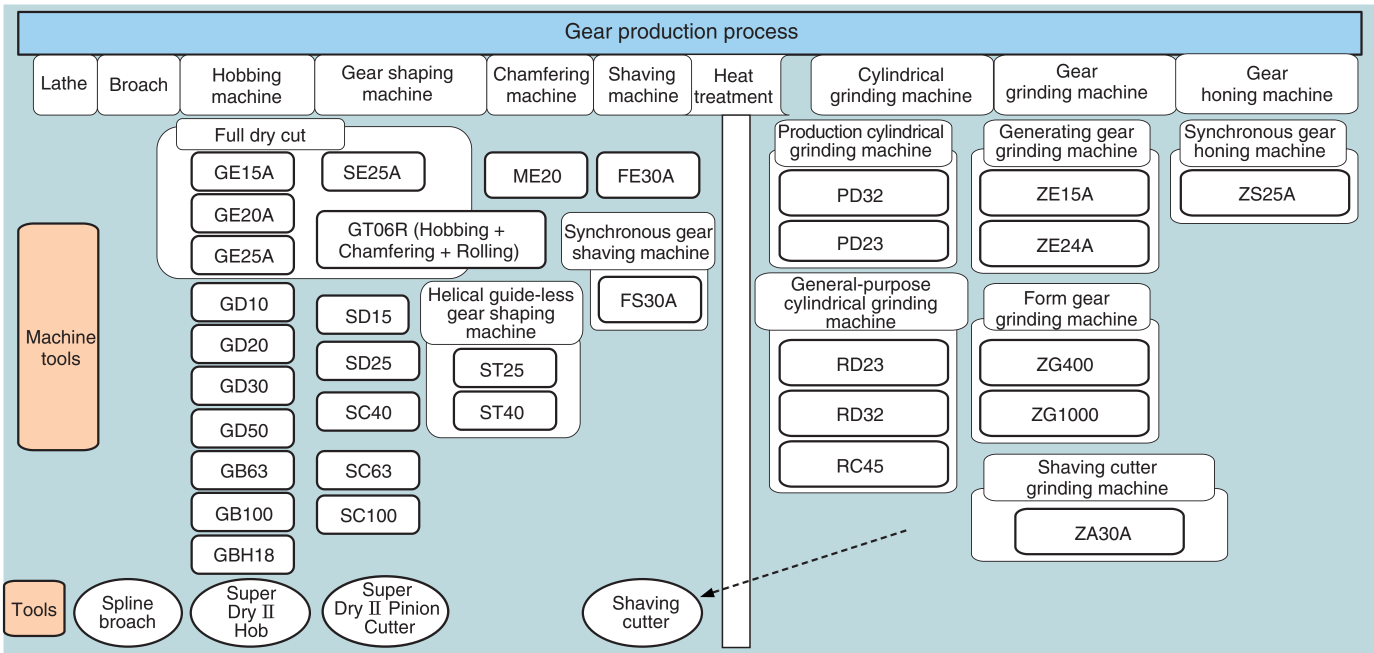

Fig. 6 Lineup of MHI's gear processing machines and gear cutters

processing machines. By manufacturing and marketing gear processing machines such as gear hobbing, shaping and shaving machines, various gear grinding machines, cylindrical grinding machines and cutting tools and even commercially producing actual gears in quantity, MHI is a total gear processing system manufacturer unparalleled in the world.

4.1 GE series gear hobbing machines compatible with dry cutting

To be compatible with dry cutting, the E series gear hobbing machines incorporate the following features.

(1) Discharging chips: A cover provided in the machine prevents chips from scattering. A steeply sloped cover made of stainless steel smoothly discharges chips out of the machine.

(2) High-speed operation: Adopting a spindle and table spindle structure compatible with a cutting speed of 250 m·min^{-1}.

(3) Heavy cutting: Improving the machine rigidity and employing large-capacity spindle motors.

The GE15A is available for choice in either the standard type with a conventional layout or the line-integration type shown in **Fig. 7** that can later hook up with the modular-designed gantry loader with a narrowed width.

This machine is capable of machining a workpiece as shown in **Fig. 8** at a cutting speed of 250 m·min^{-1} for a cycle time of 14.3 seconds, reducing the cost by approximately 45%. **Figure 9** shows the benefits of introducing this machine. If equipped with a coolant unit, the machine becomes capable of conventional wet cutting.

4.2 Dry cutting gear shaper SE25A

Figure 10 shows the newly developed E series gear shaper model SE25A. With the structure around the spindle redesigned for high-speed dry cutting, the machine improves the maximum spindle stroke speed from 1,500 min^{-1} to 1,800 min^{-1} and the cutting speed from 90 m·min^{-1} to 130 m·min^{-1}. To suppress vibration during high-speed cutting, which is an issue with the gear shaper because of the reciprocating motion of the cutter, the SE25A has a new model balancer shaft. The arrangement successfully suppresses the vibration during high-speed cutting to 1/6 or less of conventional models.

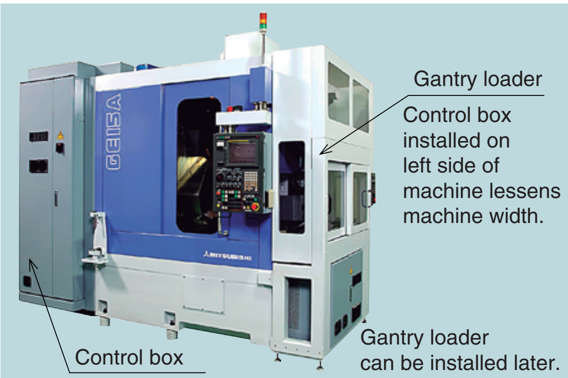

Fig. 7 General view of GE15A (compatible for line integration)

Workpiece specifications	
Module	1.4
Number of teeth	34
Face width	25 mm
Pressure angle	17.5°
Helix angle	22.5°RH
Tool specifications	
Type	Solid hob
Outside diameter	φ58 mm
Starts	4
Flute	16
Coating	Super Dry II
Machining parameters	
Machining method	Climb cut
Hob rotational speed	1 370 min^{-1}
Cutting speed	250 m/min
Axial feed rate	2.0 mm/rev
Cycle time	14.3 s

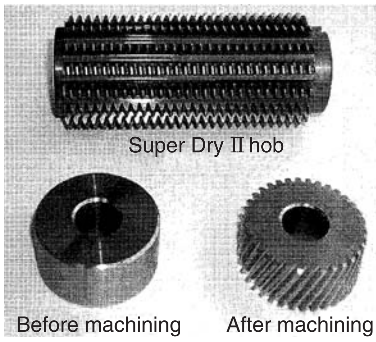

Fig. 8 Actual processing data

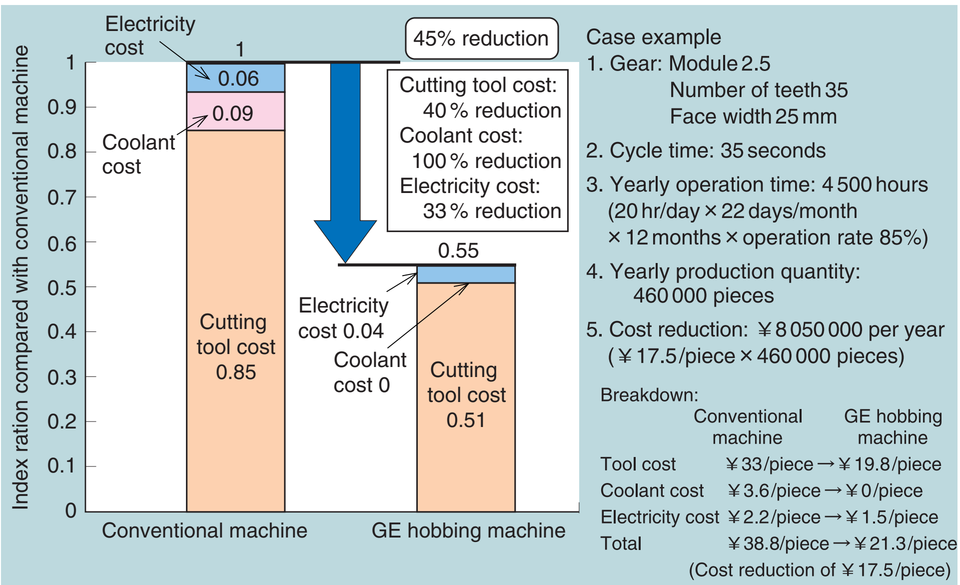

Fig. 9 Case example: Benefits of introducing dry cutting

Fig. 10 General view of gear shaper model SE25

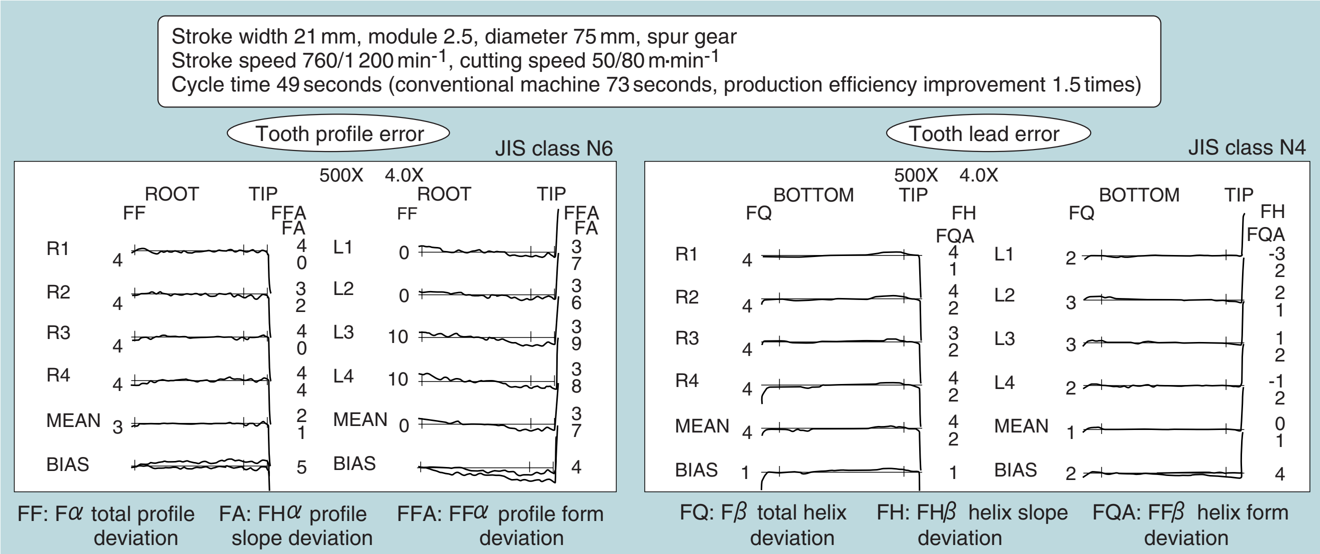

Fig. 11 Example of machining by SE25A

Workpiece specifications		Machining parameters	
Module	2.5	Stroke speed (min-1)	600/1 000
Number of teeth	2.8	Cutting speed (m·min-1)	40/66
Diameter (mm)	75	Circumferential feed (mm/str)	2.618/1.1122
Face width (mm)	15	Radial feed (mm/str)	0.009/0.01
Helix angle	Spur gear	Cycle time	90s

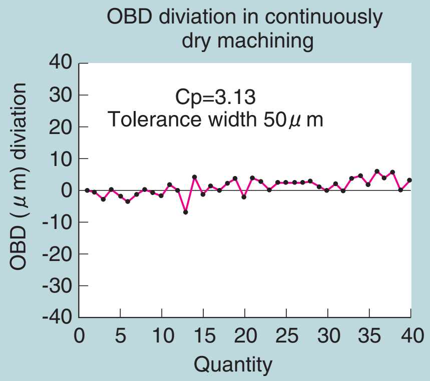

Fig. 12 OBD variation at continuously cutting

Figures 11 and **12** show case examples of machining by SE25A. Restricting vibration results in stable, favorable machining accuracy. The thermal deformation that could be a problem with dry cutting remains low while the over ball diameter during continuous machining is also stable. As with the GE15A, the SE25A is also capable of both dry and wet cutting.

4.3 Gear shaving machine FE30A

Figure 13 shows the newly developed model FE30A. Reviewing the column and saddle structures using FEM analysis improved their rigidity. The operation panel has a large color graphics display to ensure easier operation and maintenance. The feature for monitoring the spindle load currents helps to establish the machining parameters. In addition, data entry on the NC screens alone allows tapers and the crowning amount to be corrected. **Figures 14** and **15** illustrate the principle and actual data samples, respectively.

4.4 Gear grinding machines

Grinding gears after heat treatment to reduce vibration and noise from transmission gears and improve final accuracy is drawing attention. As the E series gear grinding machines, MHI has developed models ZE15A/24A[3] to meet these needs. These machines have the following features.

Fig. 13 General view of FE30A

(1) Use of threaded, general grinding wheels and the shift grinding method realizes stable, high precision grinding and reduces the tool cost.
(2) Use of built-in motors on the grinding and table spindles realizes high-speed, high-precision grinding.
(3) With the dresser mounted on the ring loader, dressing while being clamped by the Hirth coupling realizes high precision dressing on the machine.
(4) Use of the standard 8-axis NC system and various machining support software offers ease of operation and maintenance.

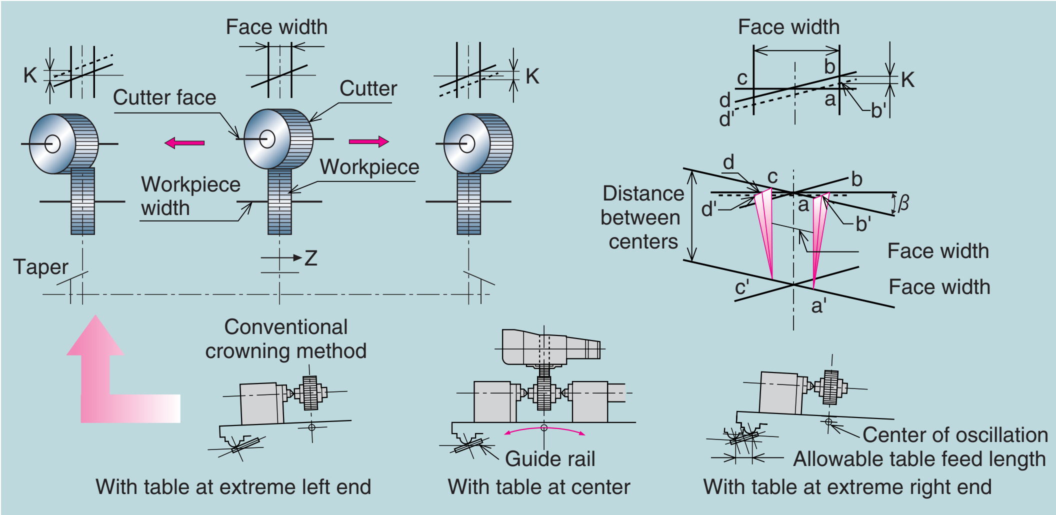

Fig. 14 Taper/crowning principle

Machining example

A simple data entry on the operation display can revise crowning and taper/crowning.

		Zero setting	Tooth trace correction	Crowning	Taper/crowning
Data entry (mm)	Amount of crowning	0.0	0.0	0.03	0.03
	Axis A compensation	0.0	0.02	0.0	0.0
	Amount of taper	0.0	0.0	0.0	0.02
Tooth trace accuracy Workpiece mn: 3 ϕ 144 β 0 z 30 Cutter: ϕ 220.3 β : 12 RH Diagonal machining					

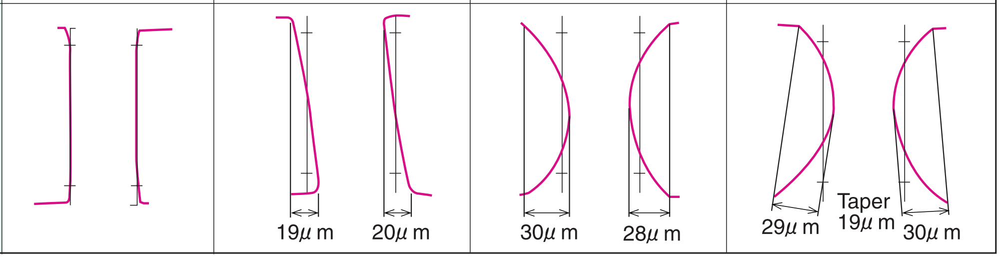

Fig. 15 Revised of taper and crowning

Fig. 16 Gear grinding machine model ZE15A

While an operator conventionally has to fine tune the dresser to correct the pressure angle of a gear tooth, these machines, as shown in **Fig. 18**, only require data entry on the NC screens to easily correct the gear tooth pressure angle, which in turn contributes to a considerable improvement in workability and stable gear quality. **Figures 16** and **17** show the general machine view and an example of grinding parameters, respectively.

4.5 High-speed, high-precision synchronization

Placing emphasis on developing a high-speed, high-precision synchronous system, MHI has been the world leader in developing the NC guide gear shapers and synchronous shaving machines.

(1) NC guide gear shaper

When machining a helical gear, a gear shaper uses a device called a guide to make the cutter have a spiral motion along the tooth trace. Since a dedicated guide that matches the lead of each cutter is necessary, a skilled operator has to change the guides when using cutters with different leads. MHI's ST series gear shapers numerically control the spiral motion.

Figure 19 illustrates the guide structure.

These machines are capable of machining a two-step gear with different helix angles by a single chucking as shown in **Fig. 20**.

(2) Synchronous gear shaving machine

In general, a gear shaving machine drives the cutter while the workpiece trails it. With no control exercised over the workpiece in its direction of rotation, conventional shaving machines are unable to

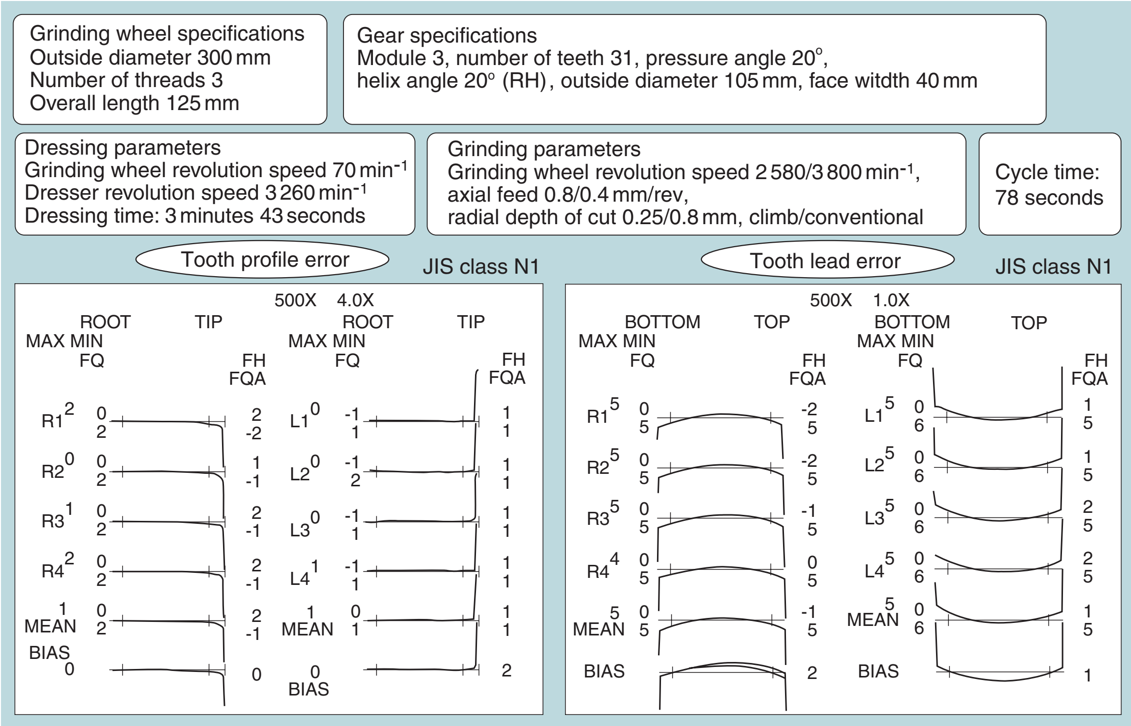

Fig. 17 Example of gear grinding by ZE15A

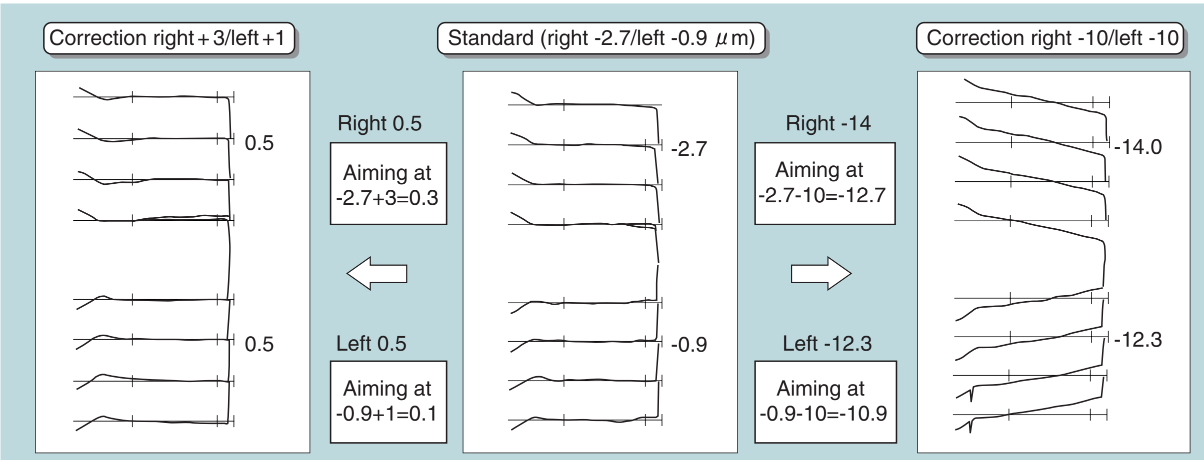

Fig. 18 Pressure angle correction

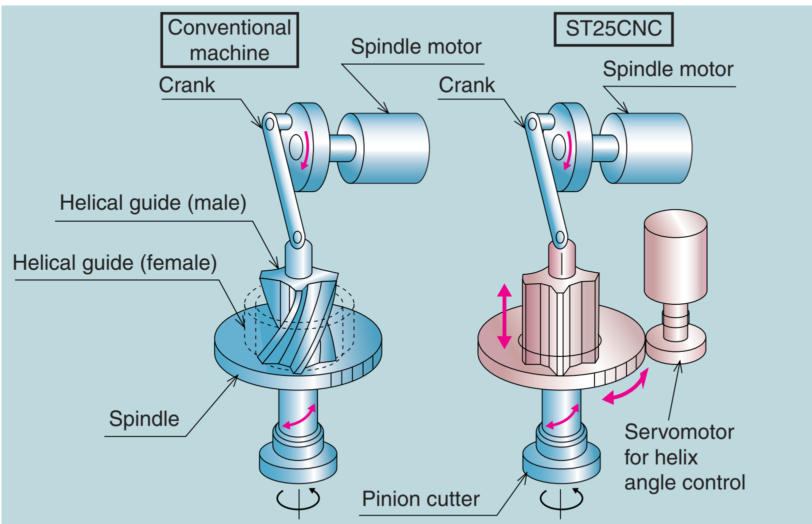

Fig. 19 Illustrated explanation of guide structure

Fig.20 Machining two-step gears

improve the pitch accuracy. This has moved MHI to develop the synchronous gear shaving machine model FS30A.[4] **Figure 21** shows how much this machine improves the pitch accuracy. While the synchronous shaving finishes the teeth with the workpiece rotating in one direction only, the conventional machines have to change the cutter rotation between the forward and reverse directions. Eliminating the switching between the two directions contributes to reducing the cycle time. In addition, since the synchronous control maintains the correct positional relationships between the cutter and the workpiece, the cutter can copy its tooth profile correctly on the workpiece. It has been reported that this makes the tool life control easy and has a favorable effect on extending the tool life.

5. Conclusions

As a comprehensive manufacturer of gear processing systems producing both machine tools and cutting tools, MHI has developed the dry cutting system, E series machine gear grinding machines, among others, while anticipating the future trends of the automobile industry. While continuing to develop product systems that anticipate the need of customers, MHI is also willing to offer the comprehensive services including remote monitoring of production lines, implementation of pre-services and enhancing production support systems.

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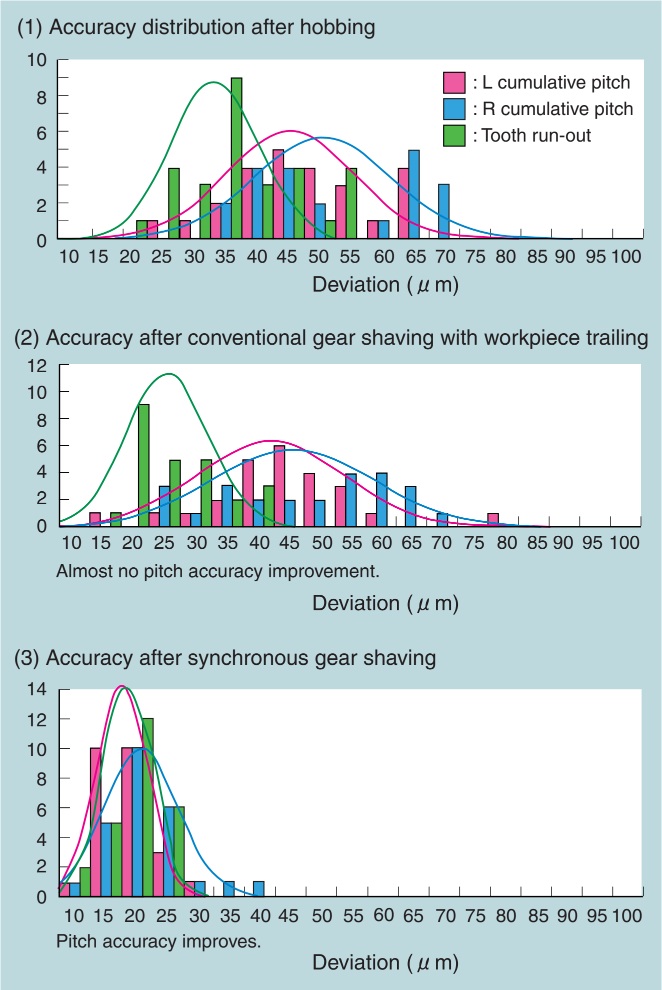

Fig. 21 Improvement in pitch accuracy by synchronous gear shaving machine


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