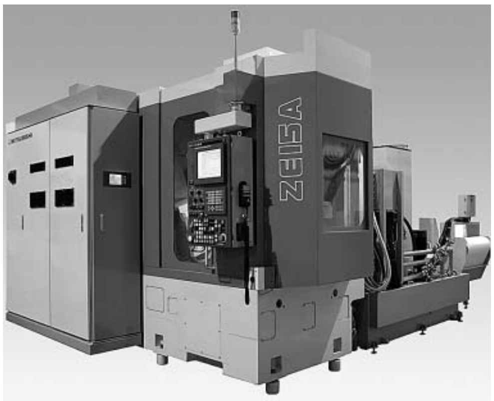

ZE15A Gear Grinding Machine for economical hard gear finishing of quiet, small gears

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In recent years the demands for precision machining of gears in automobile transmissions, for low noise and vibrations, has been ever increasing. Historically, conventional finish machining of gears was a pre-heat treatment operation typically by shaving. However, the requirement for higher precision forced a shift toward a post heat treatment operation using a generating process, which eliminates thermal distortion, thus enabling high quality and precision. The Mitsubishi ZE15A gear-grinding machine was duly developed for the high production line applications and launched into a domestic market typically dominated by European machines.

1. Introduction

Gear grinding can generally be divided into two types; Generating and Form grinding. Generating grinding uses similar principles to gear hobbing but utilizes a threaded worm grinding wheel to realize high precision and efficiency for the mass production user. Because the domestic market for generating gear-grinding machines has, in the most part, been monopolized by European suppliers, an urgent call for a competitive domestic gear-grinding machine has been recognized.

Mitsubishi Heavy Industries (MHI) has developed the ZE15A gear-grinding machine, adopting the generating process, in order to respond to the needs of a rapidly expanding market. The main specifications are given in **Table 1**.

(1) High precision grinding due, in part, to on-machine, automatic dressing of the vitrified grinding worm.
(2) High efficiency grinding using multiple threaded vitrified grinding worms.

Table 1 Main specifications of the ZE15A gear grinder

No	Item		Specification
1	Maximum diameter of work	(mm)	ϕ150
2	Machinable module		1–4
3	Number of (grindable) teeth		5–1 000
4	Worm dia. × length	(mm)	Outer diameter ϕ300 × length 125
5	Maximum worm rpm	(min^{-1})	4 500
6	Maximum number of threads		7 Max. pitch 32 mm
7	Maximum table rpm	(min^{-1})	1 500
8	Main spindle (continuous rated)	(kW)	17
9	NC system		Fanuc 160 iMB
10	Machine weight	(kg)	10 000

(3) Ease of use for the user achieved via interactive dialog functions and full CNC control of all axes.

This paper describes the principle of grinding and control for the ZE15A before presenting some machining examples.

2. Machining principle

2.1 The grinding principle

As shown in **Fig 1** (a) generating gear grinding uses a threaded worm type wheel. Similar to hobbing, the grinding worm is held in continuous synchronized mesh with the pre-cut gear (workpiece) as it moves in the feed direction, thus enabling involute generation. Compared to form grinding the generating process has a higher tooth-to-tooth pitch precision, and combined with easy automation a faster cycle time is achieved.

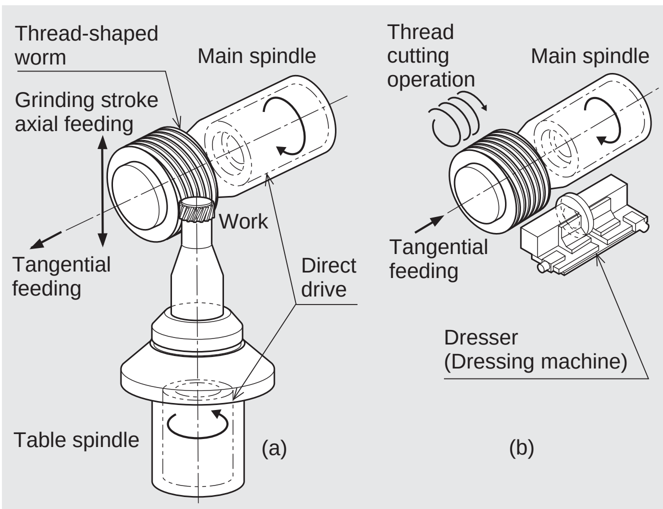

Fig. 1 Machining and dressing operation
Indicates the traveling direction and rotating direction at machining and dressing.

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2.2 High efficiency grinding using multiple threaded grinding worms

The high rotational speed of the table spindle, allows the use of multiple threaded worms thus ensuring high efficiency grinding. In the work example shown in section 5, grinding time is 150 seconds with a single thread worm. However, when a 3-start worm is used the table spindle RPM is increased 3 times resulting in a reduced cycle time of 50.5 seconds.

2.3 Integrated dressing of the grinding worm

As in the case for form gear grinding the threaded generating grinding worm also requires dressing to maintain its shape and sharpness. Setting the worms shift axis in tangential feed mode and synchronizing it with the worm's rotational spindle allows dressing of the grinding worm to commence.

Without removing the grinding worm from the machine the NC controlled dressing device is automatically introduced to the grinding worm and the diamond dressing discs passed tangentially along the worm's length for smooth continuous dressing. Owing to the fully automatic nature of the operation dressing times are kept to a minimum.

2.4 Diagonal grinding and wheel life

In order to ensure high-efficiency machining, diagonal grinding is adopted in the ZE15A. Combining synchronous feed motions of the axial and tangential axes as shown in Fig 1 (a) diagonal grinding is performed. With this method, heavy duty grinding is possible, because new cutting edges on the grinding worm are constantly introduced throughout the grinding operation.

Normally the diagonal method employs the entire length of the grinding worm before it is subjected to automatic dressing. Typically, for the example workpiece shown in **Table 2**, dressing frequency occurs between 30 and 40 parts.

Average wear per dress, of the worm's diameter is 0.4mm. Since the grinding worm has an outside diameter between 220mm and 300mm its life can be calculated up to 8000 workpieces.

With a grinding worm cost approximately 100,000 yen per piece the tool cost per piece is 12 to 13 yen, substantially satisfying customer demands.

3. Machine development

3.1 Main grinding/table spindle design and highly precise synchronized control

In order to realize a high efficiency gear grinder using multiple threaded grinding worms, synchronized control of the grinding and table spindles to the highest precision is required. Using conventional kinematics between the drive motor and the spindle was not an option owing to errors produced by non-linear elements such as backlash etc. thus making it impossible to achieve the desired synchronization accuracy. In addition a gear train in itself causes the workpiece to generate noise, which defeats the object of producing quiet gears.

The ZE15A therefore adopts an integrated direct drive design as shown in **Fig 2**.

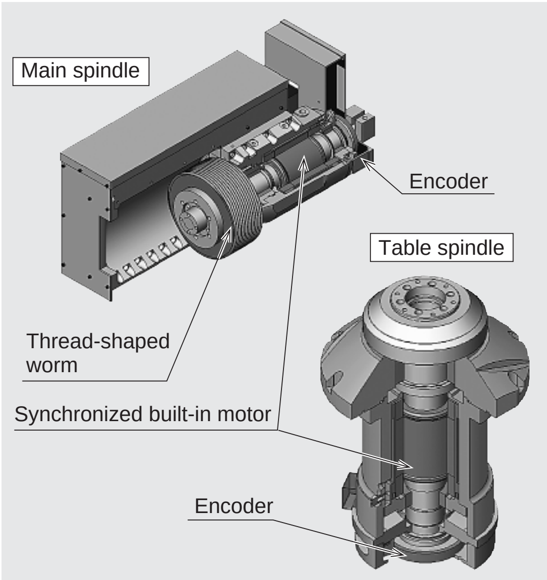


Fig. 2 Structural diagram of main spindle and table spindle
Indicates Direct-drive structure using built-in motor.

Table 2 General items of work and grinding conditions

General items of work for grinding	General items of worm	Grinding conditions		
Module 3	Outer diameter ϕ300 mm		Set	Finish
Gear 31	Worm width 125 mm	Worm rotating speed (min^{-1})	2 850	3 800
Pressure angle 20°	Number of threads 3	Grinding speed (rate) (m/sec)	45	60
Torsional angle (direction) 20° Right	Worm used: CXY120I8V104	Axial feeding (mm/rev)	0.8	0.4
Material SCM 415 Surface hardness HRC 60		Radial depth (mm)	0.25	0.08
Outer diameter ϕ105 mm		Feed direction	Climb (grinding)	Conveyor
Tooth width 40 mm		Coolant	Water insoluble	

The grinding and table spindles have a maximum speed of 4500 and 1500RPM respectively. The direct drive technology employed for both spindles ensures high control performance within the aforementioned RPM range. When grinding using threaded worm-grinding wheels, load fluctuations are experienced owing to the lower precision of the workpiece coming from rough machining and heat treatment operations. These errors are mainly due to cumulative pitch errors that cause fluctuation of the work rotation thereby having a large effect on the precision of the post machined gear.

In light of this special attention has been given to the constant periodic nature of the load fluctuation. A "feed forward control system"(1) (a system where control input amount is successively obtained from the periodical error amount for control) employed in MHI's gear shapers, has been applied to reduce the periodic error rate approximately 15%, drastically improving the precision requirement of the machine.

3.2 Mechanism of the dressing unit. (Patent pending)

In order to save space the dressing unit of the ZE15A is incorporated into the ringloader as shown in **Fig. 3**. Positioned in front of the grinding worm during dressing, the dressing unit is clamped with high precision using a Hirth coupling.

When viewed from the grinding worm the dressing unit is arranged at the workpiece side so that factors causing shape errors of the grinding worm, such as main spindle run out error etc. can be reduced. Further, since dressing utilizes the grinders NC axes no additional exclusive axes are required for the dresser.

During workpiece grinding the dressing unit is shifted to its park position as shown in Fig. 3. Loading and unloading of workpieces takes place via the ringloader simply by indexing over the dressers park position.

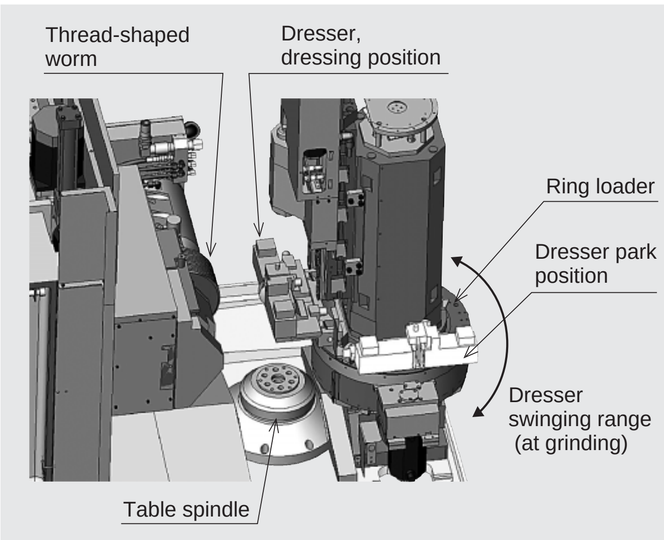


Fig. 3 Dressing unit
Dresser was installed on the ring loader.

3.3 High speed tooth meshing system.

For gear grinding it is necessary to detect the tooth space of the incoming workpiece in order to achieve meshing between the grinding worm and the workpiece teeth. A non-contact sensor is used which detects the teeth over the entire part circumference and sets meshing position. All this is controlled by a high speed processing circuit in approximately 1 second.

4. Supporting software for machining

4.1 Machining simulation

An important tool in gear grinding is the machining simulation for the post-machined tooth profile and lead. It is especially advantageous when complex tooth profiles and leads are required over simple tooth shapes. This is especially true when detailed modifications are required to produce gears with low noise and vibration under load.

As an example, the machining simulation for a crowned lead of a helical gear is described below.

Introducing a curvilinear continuous displacement of the machines radial axis as the grinding worm feeds axially through the workpiece is the normal way to carry out lead adjustment. The result of this process simulation is shown in **Fig. 4**.

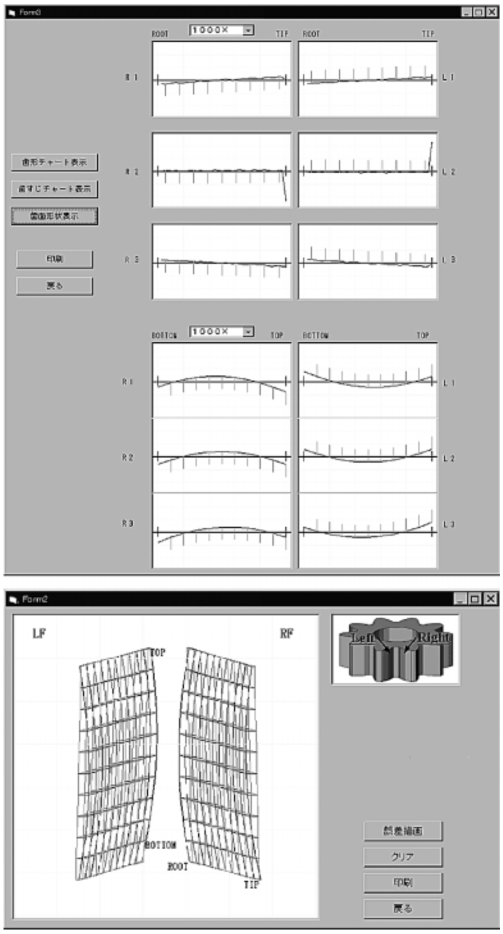


Fig. 4 Results of simulation
The machining simulation for a crowned lead of a helical gear.

The result shows that target crowning has been achieved by means of the corrective motion. It also shows that although the tooth profile at the center of the face width does not show any change, the profile angle at either ends of the tooth face width, where the grinding worm enters and exits the cut, does show change.

In addition the machining simulation allows comparison and analysis of the tooth shape difference if there is a synchronization error. This is an effective tool for pre-detection and troubleshooting.

4.2 Ease of use machining

The conventional method of pressure angle adjustment on a gear-grinding machine, when using a threaded worm, is shown in **Fig. 5**. With this method the skill of the operator was required in using a scale or gauge in order to set the rotating angle of the dresser to the desired pressure angle.

Thus special skills and time were needed to achieve the desired corrections.

For the ZE15A, a new method of automatic correction has been developed. The desired profile correction is simply achieved by entering the pressure angle correction amount into the machine control. MHI established the method of modifying each pressure angle for left and right flanks. The dressing and machining operation for modification of the pressure angle is analyzed without adjusting the setting angle of the dressing unit manually. The results of this modification method are shown in **Fig. 6**.

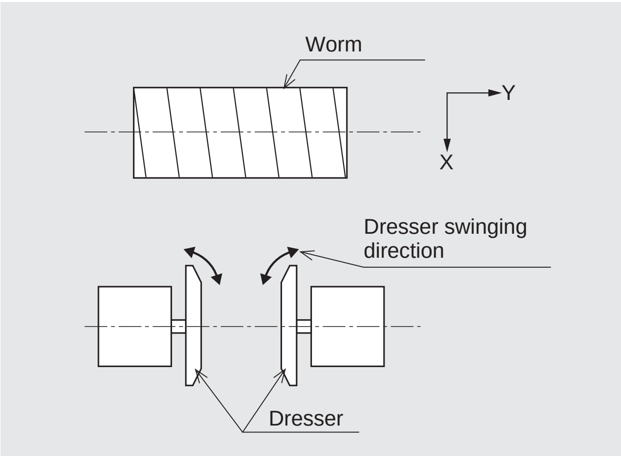


Fig. 5 Conventional pressure angle correction method
Dresser installation angle is manually adjusted.

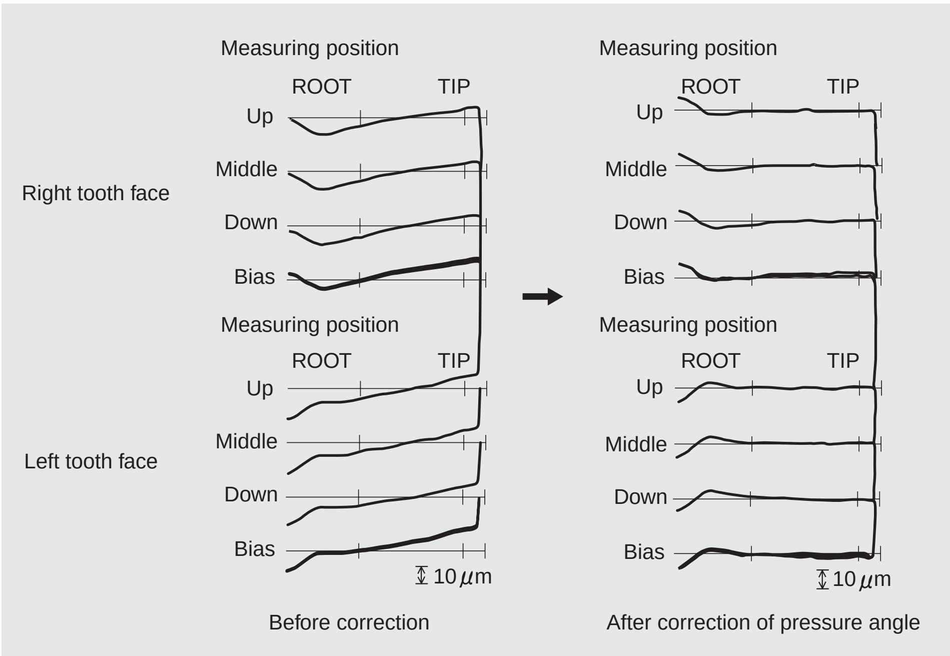
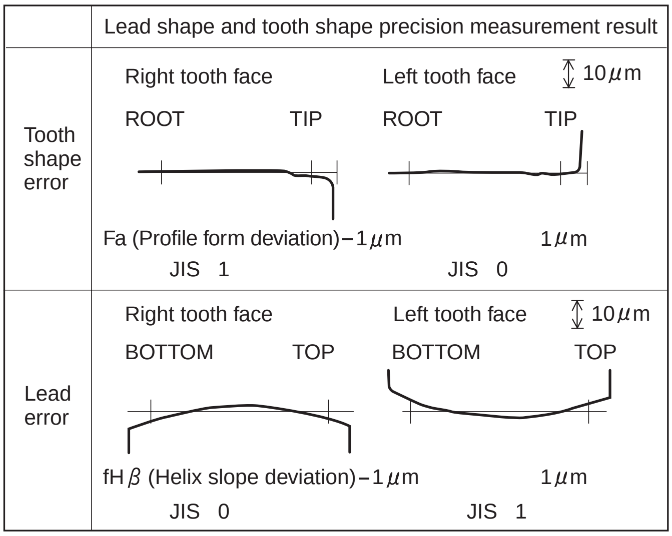


Fig. 6 Result of automatic correction of pressure angle
(Right flank: −10 μm / left flank + 10 μm)



Note: The lead error for corrected tooth shape indicates the value excluding the crowing rate.

Fig. 7 Lead shape and tooth shape precision
Indicates the lead shape and tooth shape precision of the work after grinding.

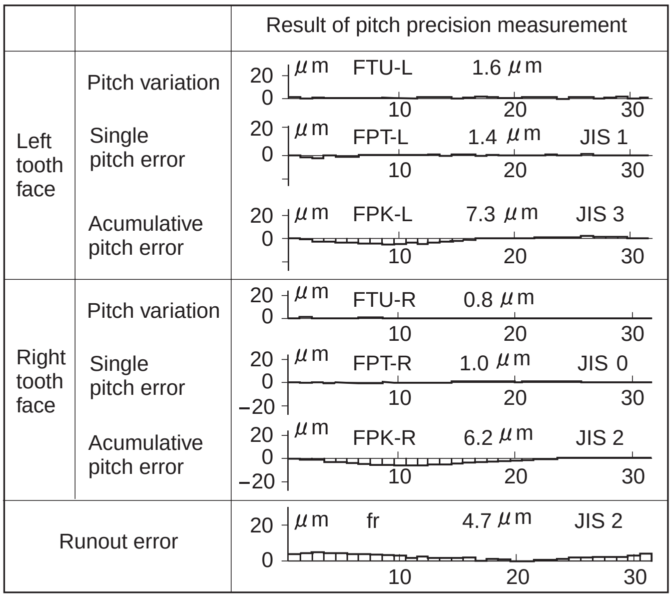


Fig. 8 Pitch precision
Indicates the pitch precision of the work after grinding.

5. Machining example

A machining example using the ZE15A is shown in **Table 2**, **Fig. 7** and **Fig. 8**, with a machining time of 50.5 seconds (excluding tooth meshing and part loading), and workpiece gear tooth quality to JIS class-3. This example, which is a typical automotive gear, is considered to satisfy the requirements of noise, durability and process cost.

6. Conclusion

A high precision, high efficiency gear-grinding machine has been developed in response to the needs of the mass production industry. The large expansion anticipated in this machine tool segment, will cater for the future realization of:

(1) On-machine dressing functions for multiple threaded grinding worms and
(2) Ease of use grinding through the adoption of full CNC and interactive input functions.

Reference

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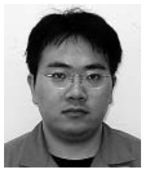
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