Development of 3D Tooth Surface Creation Processing Technology Using Gear Skiving

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With the promotion of electrification, the need for a mechatronic integrated unit such as E-Axle is increasing.

The gears used in E-Axle are required to have the optimum tooth profile and at the same time to be as compact and light weight as possible without generating vibration or noise.

This paper introduces technological advancements for machining of high-precision, compact gears with the optimum tooth profiles required for E-Axle, including a process for creating 3D tooth profile surfaces and a workpiece/cutting tool phase detection function. These advancements are based on original research and logic development.

Key Words*: gear skiving, BEV, E-Axle*

1. Introduction

We are now in a period of centennial change, and recent years have seen the increased promotion of electrification as a means of achieving carbon neutrality and the Sustainable Development Goals (SDGs). In the automobile industry in particular, Battery Electric Vehicles (BEVs) are becoming more and more popular as replacements for internal combustion engine vehicles.

E-Axle, an integrated mechanical and electrical unit, has attracted attention as an electric power train for BEV. E-Axle is expected to contribute to improved space efficiency through downsizing, and to extended cruising ranges by saving energy.

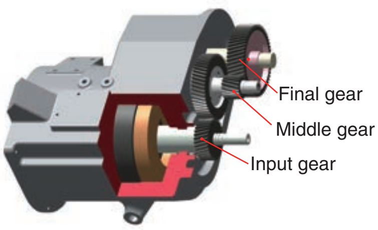

Fig. 1 E-Axle model

2. Requirements for Gears in BEV

2. 1 BEV and E-Axle

Table 1 shows the characteristics of internal combustion engine vehicles and BEVs. For internal combustion engine vehicles, the noise and vibration generated when the gears are engaged are not noticeable because of the engine noise. On the other hand, BEVs do not have engines, meaning that even small amounts of noise and vibration will be more noticeable, so E-Axle must run quieter. In addition, layout constraints are an issue as there are various mounting arrangements of E-Axles on front and back to support 4WD, as well as in-wheel arrangements. E-Axle needs to be compact, lightweight, quiet, and efficient.

Table 1 Comparison of internal combustion engine vehicles and BEVs

	Internal combustion engine vehicle	BEV
Power source	Engine	Motor
－Noise and vibration	High	Low
－Rotation speed	Low speed	High speed
－Layout	Front fixed	Optional
Cruising distance	Long	Short

2. 2 Requirements for Gears

Several types of gears, such as input gears, middle gears, and final gears, are used for E-Axle, and the size of the gears is directly linked to the unit size. Since the rotation of the motor is transmitted as driving force by the meshing of the gears, the meshing becomes a source of vibration and noise.

Furthermore, when a load is applied to the tooth surface when the gears are engaged, the gears and gear shafts are deformed and the meshing state deteriorates. Therefore,

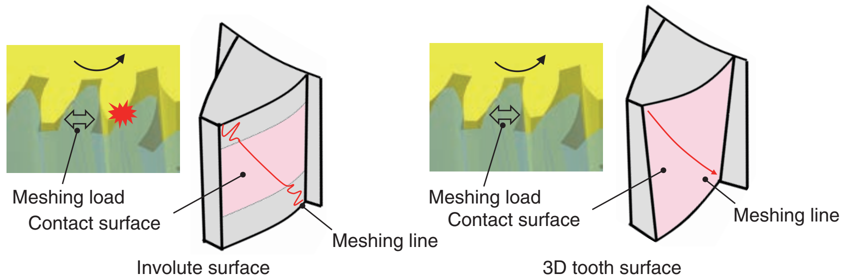

Fig. 2 Optimal tooth profile

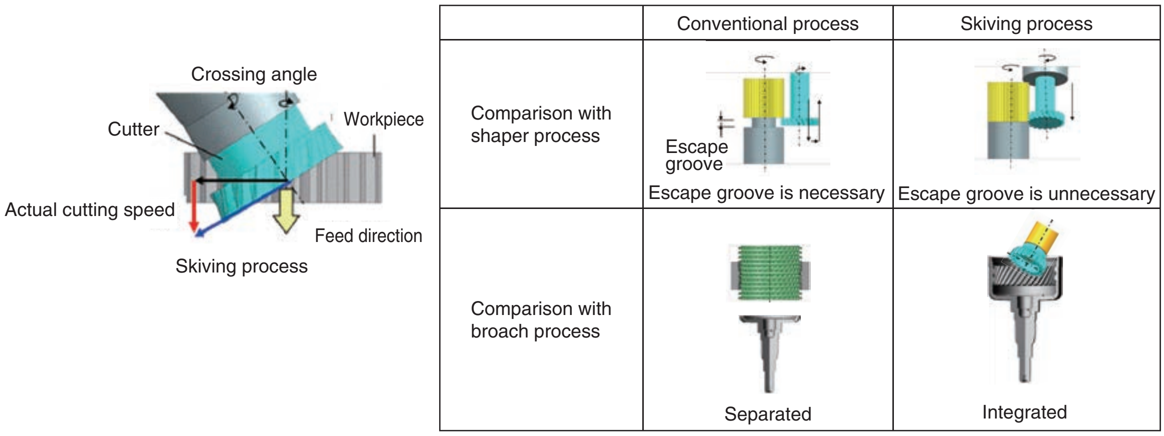

Fig. 3 Comparison of skiving method and other methods

the gears used for E-Axle must not only be compact and highly accurate, but also have an optimum tooth profile that provides ideal engagement under load (**Fig. 2**).

3. Development of 3D Tooth Surface Creation Processing Technology Using Gear Skiving

3. 1 Gear Skiving Process

Gear skiving is a creative gear cutting processes performed using a gear-shaped tool. As shown in **Fig. 3**, the principle involves using the relative speed generated by the tilting of the tool and the workpiece and rotating them synchronously.

The gear skiving process has many advantages over other gear manufacturing processes. Compared to the shaper process, the relief part is not required, and the incomplete tooth profile part can be shortened, which enables to reduce the size of the product[1]. In addition, compared to the broach process, it has the advantage that an internal gear can be integrated, and by controlling the tooth profile and machining trajectory of the tool, it is possible to easily adjust tooth profile correction factors such as crowning[1].

3. 2 Development of 3D Tooth Surface Creation Processing Technology

3D tooth surface creation processing technology is a technology that can create various free-form surfaces, and is made possible by combining tooth profile and lead (**Fig. 4**).

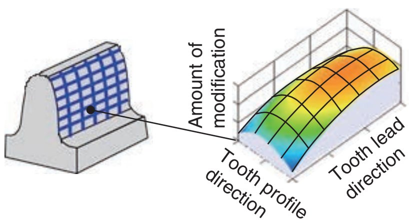

Fig. 4 3D gear face

The process is shown in **Fig. 5**. Conventionally, the tooth surface shape can be created only by moving the tool linearly along the axis of the workpiece, but creating a 3D tooth surface shape requires further changes in the angle of the workpiece.

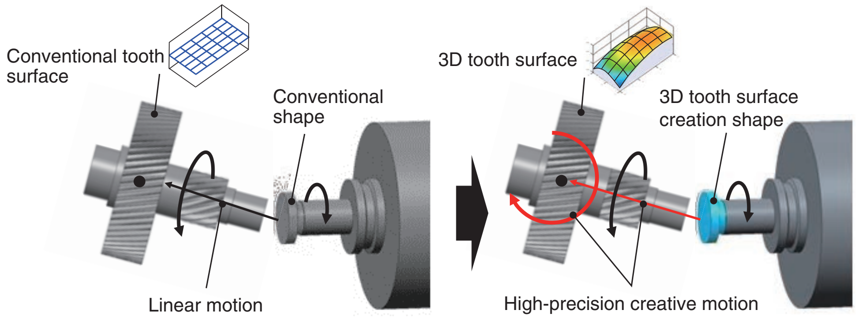

Fig. 5 3D tooth surface creation processing method

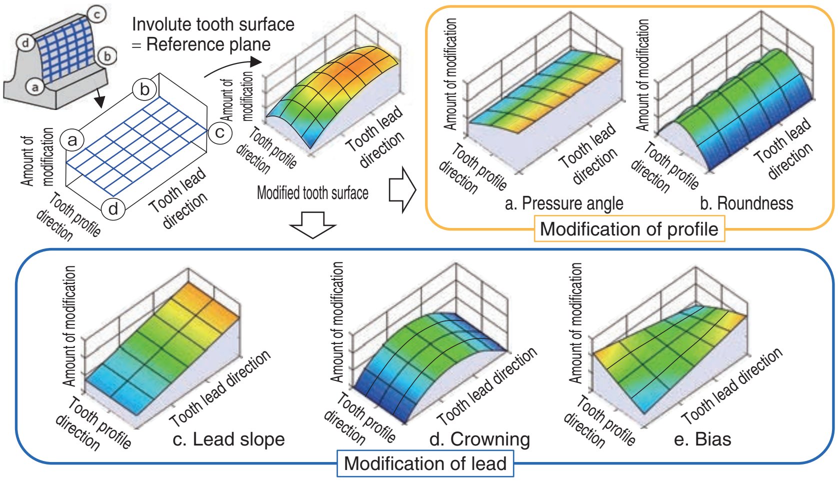

Fig. 6 Five factors that forms free curved surface

To obtain 3D tooth surfaces, as shown in **Fig. 6**, tooth shapes such as the pressure angle and tooth profile roundness are created by the tool shape, and tooth shapes such as tooth streak inclination, crowning, and bias are created by mechanical motion. 3D curved surfaces can be created by combining a tooth profile and tooth trace shape.

To actually perform such machining, the optimum shape tool must be used and machining must be carried out while smoothly changing the angle of the workpiece, so machine element technology and control technology are required (**Fig. 7**).

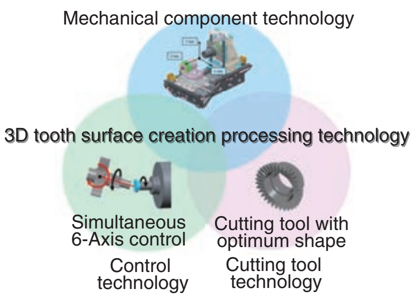

Fig. 7 3D tooth surface creation processing technology

4. Development of Processing Machine

4. 1 Gear Skiving Center GS200H5

We developed the gear skiving center GS200H5 in 2016. The GS200H5 is a machining center that can perform turning and gear cutting in addition to standard cutting operations by incorporating high-precision synchronous control, a high-speed high-rigidity workpiece spindle, skiving tool technology, and machining center technology.

The GS200H5 provides high productivity and high accuracy by consolidating gear manufacturing processes that previously required a dedicated machine for each process (**Fig. 8**).

Now, to provide an advanced 3D tooth surface creation process, we have developed a direct drive (DD) table and a control function that can perform high-precision operations with high followability. In addition, we have developed a high-precision machine equipped with a workpiece/tool phase detection function that allows for phase matching of compound gears and finishing after quenching (**Fig. 9**).

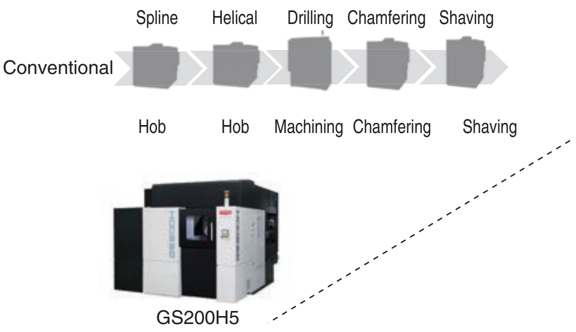

Fig. 8 Example of process consolidation

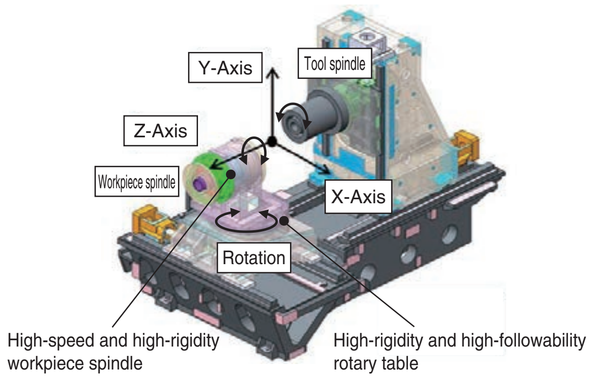

Fig. 9 High-precision machine

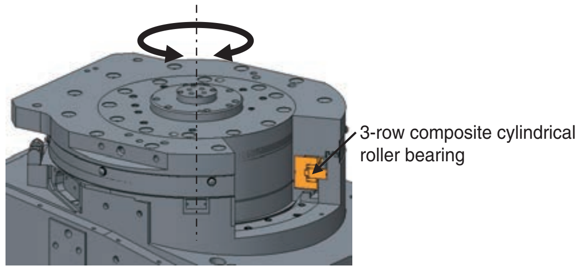

Fig. 10 Direct drive table

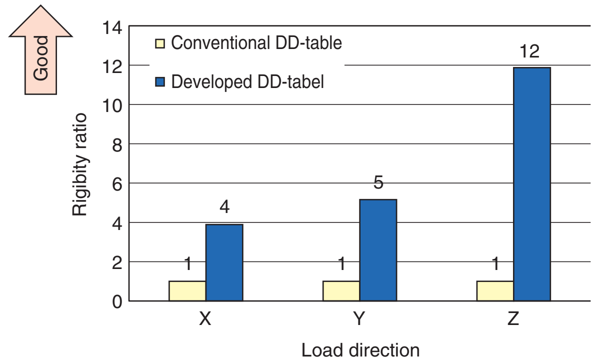

Fig. 11 Rigidity comparison

4. 2 Development of Components and Functions

1) Mechanical component

(1) High-rigidity and high-accuracy direct drive motor (DD) table

To perform highly-efficient gear skiving processes with a highly accurate 3D tooth surface creation process, the rotary table needs to have high followability as well as rigidity.

To achieve high followability, we adopted a direct drive motor system and an in-house manufactured 3-row composite cylindrical roller bearing with high rigidity and high accuracy (**Fig. 10**). By reviewing the internal structure, the amount of displacement due to the machining load was minimized, and the rigidity is extremely high compared to the conventional method (**Fig. 11**).

(2) Workpiece/Cutting tool phase detection function

In E-Axle, a two-stage gear is used, and if there is a phase error between the two gears, it causes vibration and noise, and the transmission efficiency also deteriorates.

For the highly accurate phase matching process, we devised a phase detection function consisting of a cutting tool phase detection device that detects the phase of the skiving cutter and a workpiece phase detection device that detects the phase of the gear (**Fig. 12**). By using our own logic, we can perform rapid high-precision phase measurement and control it to perform high-precision gear cutting (patent pending).

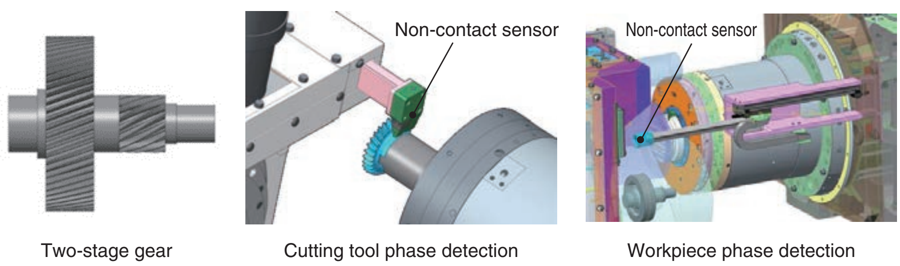

Fig. 12 Phase detection unit

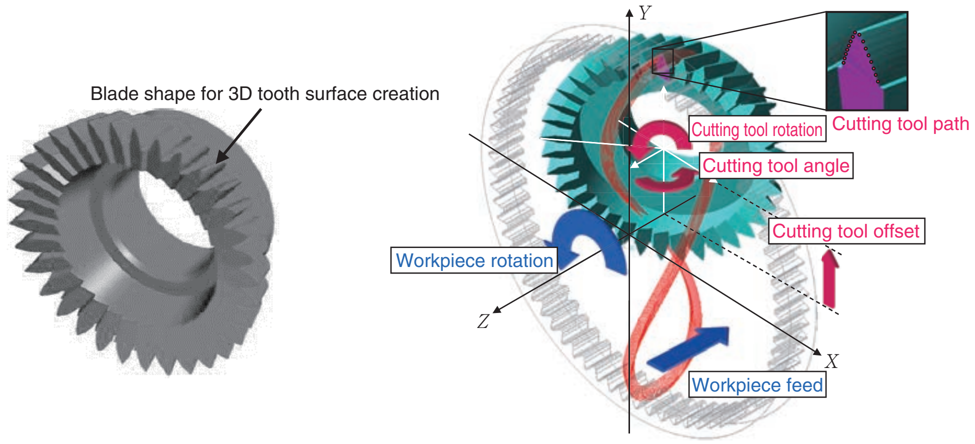

Fig. 13 Tool design

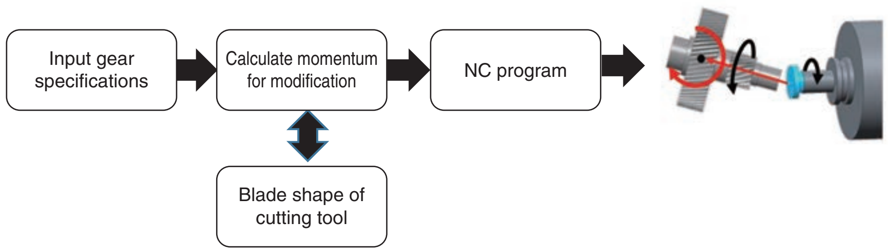

Fig. 14 Flow of 3D tooth surface creation process program

2) Cutting tool

Unlike the conventional skiving process, the 3D tooth surface creation process is performed by combining linear and rotational motion. Therefore, the blade of the tool needs to be the optimal shape which takes mechanical motion into consideration, not the conventional shape.

To achieve this, we developed our own simulation and designed the blade shape. Alongside this, we developed a tool for creating a 3D tooth surface by molding the tool (**Fig. 13**).

3) NC program creation function

Since the 3D tooth surface creation process uses simultaneous 6-axis processing, it is difficult to manually create processing programs that can create the optimal tooth surface shape. To ease creation of these programs, we have developed a new automatic program creation function.

Figure 14 shows the automatic program creation flow. By inputting simple gear specifications, it is possible to automatically perform calculations and easily create NC programs for 3D tooth surface creation processes.

5. Processing Example

5. 1 Finishing Process of Two-stage Pinion Gear

In the parallel axis gear type E-Axle, a two-stage gear is used, but it must be compact.

Conventionally, when finishing the small diameter gear part of a two-stage gear, gear grinding is performed using a thread-shaped grinding wheel. In the case of gear grinding, as shown in **Fig. 15**, the grinding wheel has a large diameter, so it is necessary to widen the gear spacing so that interference does not occur. This leads to the problems as the product becomes larger.

On the other hand, the skiving process has good tool accessibility and can narrow the distance between gears, making it possible to produce compact products. Furthermore, by using 3D tooth surface creation processing technology, highly accurate finishing of the tooth surface shape can be achieved.

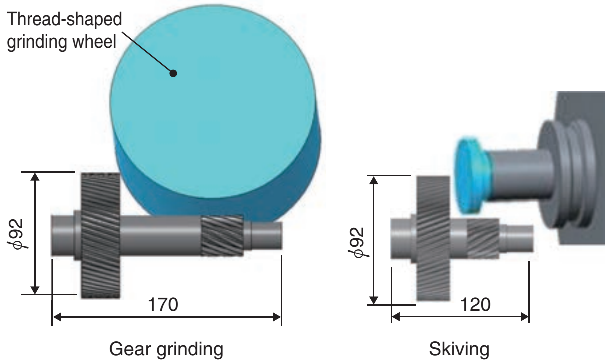

Fig. 15 Skiving process advantage

A process evaluation was performed on the two-stage gear, which is the workpiece shown in **Fig. 16**. In this process evaluation, a finishing process after heat treatment was performed using a skiving cutter made of a carbide material.

The results of the process evaluation are shown in **Fig. 17**. Using the 3D tooth surface creation process, the gear accuracy was equivalent to JIS 5 class, and the bias adjustment amount was ±1.5 µm. In addition, by using the phase detection function, we were able to obtain a result with a phase error of 0.023°.

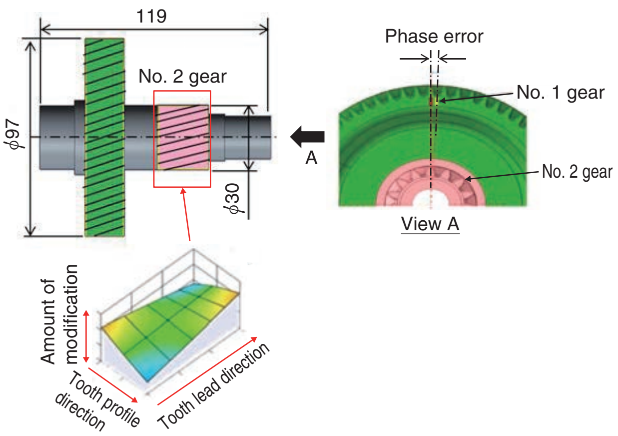

Fig. 16 Two-stage pinion gear

Using this technology, we were able to advance miniaturization and weight reduction, as well as improve the quietness and efficiency of our E-Axle (**Fig. 18**).

Fig. 18 Developed E-Axle

5. 2 3D Tooth Surface Creation Process of Thin Ring Gear

A thin ring gear (**Fig. 19**) is used in the planetary gear mechanism type E-Axle. When heat treatment is performed after gear cutting, thermal strain of the workpiece is generated and the gear accuracy deteriorates, so it is difficult to achieve the target accuracy.

Therefore, we considered that the required accuracy after heat treatment could be achieved by performing a process adjustment (**Fig. 20**) taking into consideration the anticipated thermal strain of the workpiece by using the 3D tooth surface creation processing technology and evaluating the process.

In this process evaluation, we performed a process adjustment taking into consideration the anticipated strain during heat treatment, and prior to heat treatment targeted to keep the pressure angle error of the final product accurate to within 6.0 µm after heat treatment.

The results of the process evaluation are shown in **Fig. 21**. In the conventional process, the pressure angle error before heat treatment was 2.0 µm, but it deteriorated after heat treatment to 11.0 µm, and the final accuracy was not reached. However, by performing the process adjustment using 3D tooth surface creation processing technology, the pressure angle error after heat treatment was 3.0 µm, and the required accuracy could be achieved.

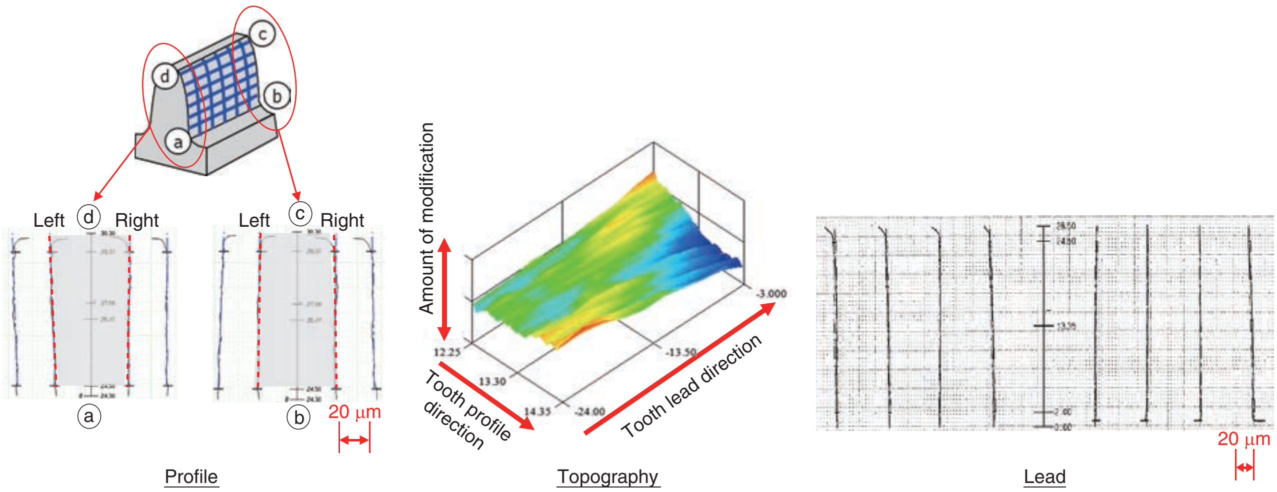

Fig. 17 Processing results

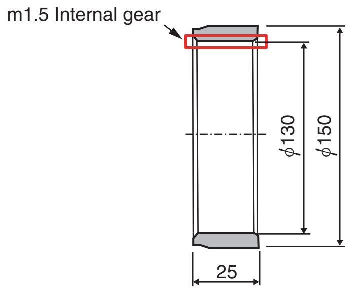

Fig. 19 Thin ring gear

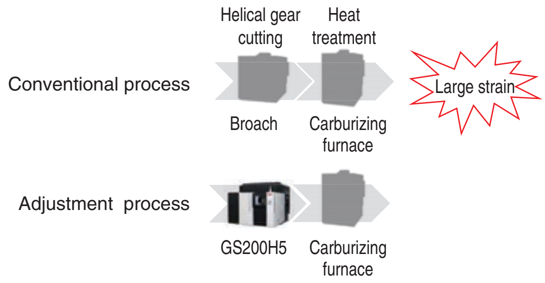

Fig. 20 Process

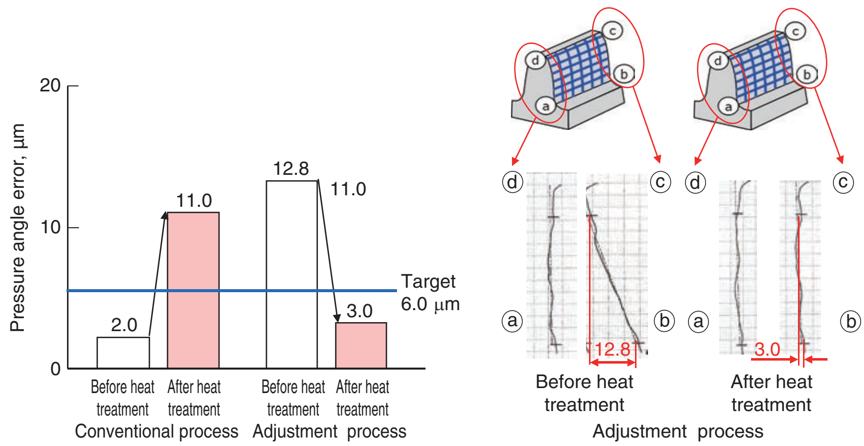

Fig. 21 Processing results

6. Conclusion

By using the newly developed 3D tooth surface creation processing technology and phase detection function, we have demonstrated that it is possible to efficiently process small highly-accurate gears with optimal tooth profiles required for E-Axle.

In addition, by combining the gear skiving center GS200H5 with other technologies we have developed, we have built a high-productivity, low-cost production line. We think that it will be possible to create compact gears required for BEV that produce less noise and vibration, and to dramatically improve the added value of various units including the E-Axle. We will continue to keep abreast of changes in the world, promote further technological development, and contribute to the technological innovation of gears.

* Gear skiving center is a registered trademark of JTEKT Corporation.

References

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