Technical Paper

Manufacturing of High-precision Bevel Gears with Five-axis Machining

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For bevel gears which are used for an axle of dump trucks etc. as a gear for perpendicular-axis transmission, Komatsu made a change in a part of the gear cutting process, from exclusive units to the simultaneous five-axis control machining center (5MC), and has realized the productivity superior to the conventional exclusive units. Also, for the precision of the tooth surface, we introduced the characteristics of the five-axis machining to the heat correction that preliminarily incorporates expected distortion amount in the gear cutting as an inverse distortion shape to realize the heat correction to detailed distortion which is impossible with the exclusive units. This achieved high precision of bevel gears without the finishing process of tooth surface after heat treatment.

Key Words: *Five-axis machining, Bevel gear*

1. Introduction

Bevel gears are mostly used for transmission of power of a perpendicular axis. Komatsu uses them in a wide range of application including an axle in dump trucks and wheel loaders (**Fig. 1**). As the tooth surface of a bevel gear has complicated curves, bevel gears are mostly manufactured by using exclusive gear cutting machines. The general manufacturing process with exclusive gear cutting machines for bevel gears is called the spread blade fixed setting method (hereinafter called "5-cut"). Its cutting has three processes for a pinion and two processes for a gear (**Fig. 2** (a)). On the other hand, the simultaneous five-axis control machining center (5MC) that has recently been in practical use is now capable of accurate machining for complicated curved surfaces. We see many manufacturing results of bevel gears using it. With the five-axis machining, a pinion and a gear can be cut in one process respectively by using a general end mill and processes such as chamfering can be concentrated (**Fig. 2** (b)), which reduces the workpiece handling man-hour and products in process. However, the five-axis machining is generally considered to require very long time for machining and be inferior to the exclusive units in productivity. Komatsu has tackled with this challenge and has adopted the five-axis machining for some large machine models by substantially reducing the cycle time. In this paper, we would like to introduce the process of the adoption of the five-axis machining for bevel gears and the approach for the precision improvement utilizing the characteristics of the five-axis machining in Komatsu.

2. Transition to five-axis machining of bevel gears

As mentioned earlier, the gear cutting process using exclusive units has two processes for a gear and three processes for a pinion. The machines in Komatsu are old and have problems in efficiency and precision due to wear of their axes. Investments were considered for the future, however, large equipment made by manufacturers of exclusive units such as Greeson and Klingelnberg is very expensive. Therefore, we considered the five-axis machining whose equipment cost is about a half of that of the equipment above in an equivalent size.

The initial concerns for the transition to the five-axis machining of bevel gears were (1) durability of the tooth surface processed with an end mill and (2) productivity such as cost and production volume. We needed sufficient verification for them beforehand. The outline of the verification result is as below.

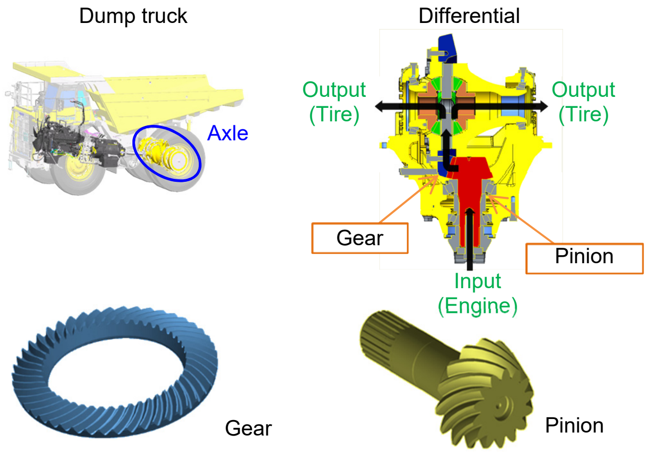


Fig. 1 Usage examples of bevel gears in Komatsu

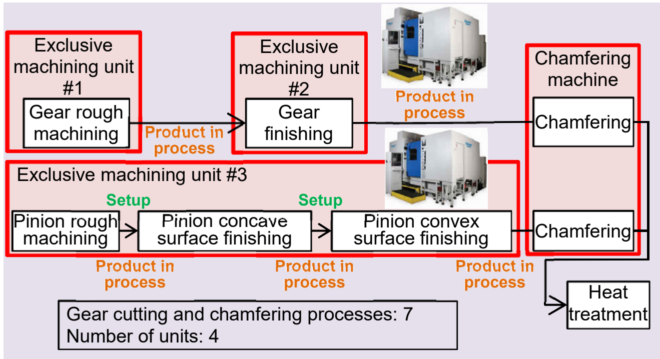
(1) Durability of tooth surface

As shown in **Fig. 3**, when processing gears by the five-axis machining, most of the time the side of the end mill makes swarf processing with a processing path connecting curved surfaces of a tooth. This feature, in comparison with the exclusive units, makes approximation errors called polygon errors on the curved surface and waviness due to the feed amount for one cutting of the end mill on the tooth surface, as shown in **Fig. 4**. They are unevenness of some micrometers and can be improved by shot peening or lapping, but such an additional process should be kept to the minimum necessary in terms of cost. Therefore, we carried out a verification test to see if the polygon errors and the waviness lower the durability. **Figure 5** shows an example of the tooth surface which went through the endurance test under the condition with an operation load of an actual machine up to the target time. The tooth surface had only a few micro pits in the test and its durability was confirmed to have no problem.

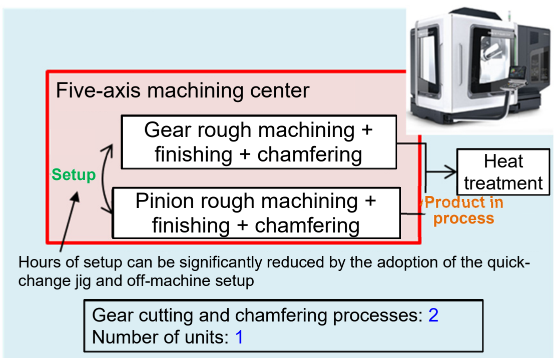
(2) Productivity of five-axis machining

At the beginning of the trial manufacture with the five-axis machining, we used the machining condition of the end mill mostly as recommended in the tool manufacturer's catalog. That machining condition was very poor in productivity. However, our Manufacturing Engineering Development Center has technologies such as analysis of vibration and analysis of cutting edge temperature for optimizing the machining condition and it was applied to the improvement of the machining condition. Together with it, the improvement such as a reduction of air cut by reviewing the processing path and the concentration of the chamfering process which was manual work with the exclusive units has been made, realizing a substantial reduction of cycle time compared to the exclusive units. **Figure 6** shows the result of the comparison to the cycle time with the exclusive units. Although the time of gear cutting was slightly increased, the cycle time was reduced by approx. 49% by the process concentration and a reduction of chamfering time.

We have solved the initial concerns we had as above and now proceed with the adoption of the five-axis machining mainly for large bevel gears.



(a) Manufacturing process with exclusive machining units



(b) Manufacturing process with 5MC

Fig. 2 Process concentration with 5MC

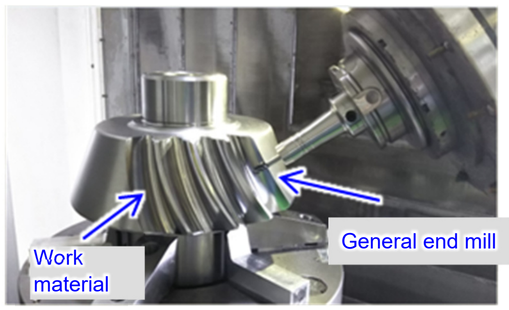
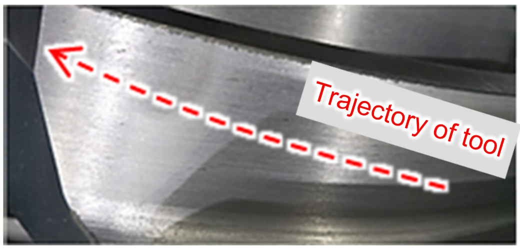
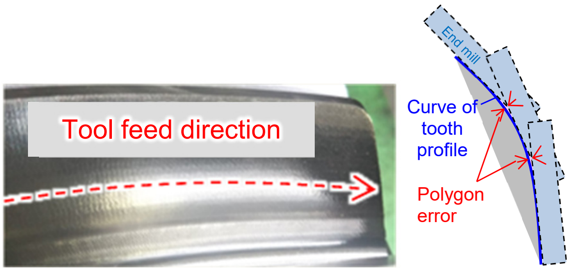


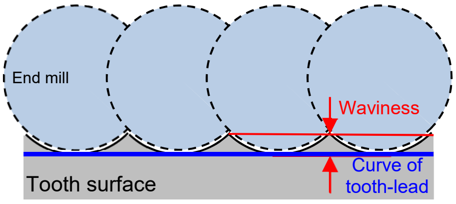
Fig. 3 Five-axis machining of pinions using a general end mill



(a) Tooth surface processed with exclusive units



Schematic diagram of cross section in tooth profile direction



Schematic diagram of cross section in tooth-lead direction

(b) Tooth surface processed with five-axis machining

Fig. 4 Appearance and characteristics of tooth surface processed with exclusive units and 5MC machining

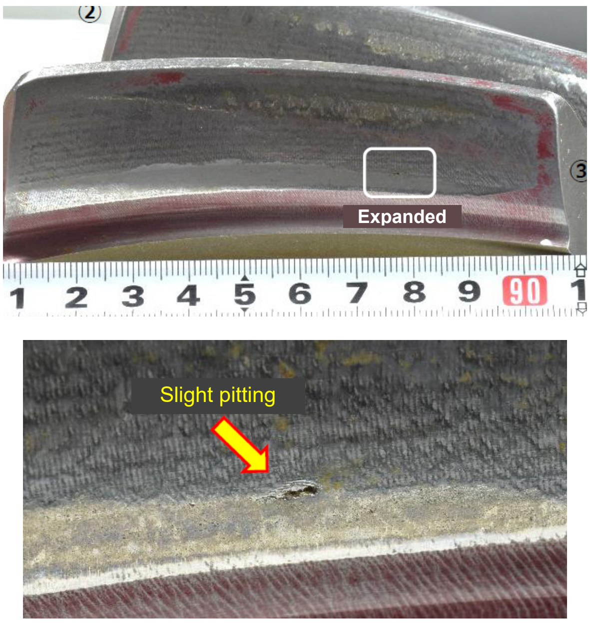


Fig. 5 Tooth surface after durability test operation

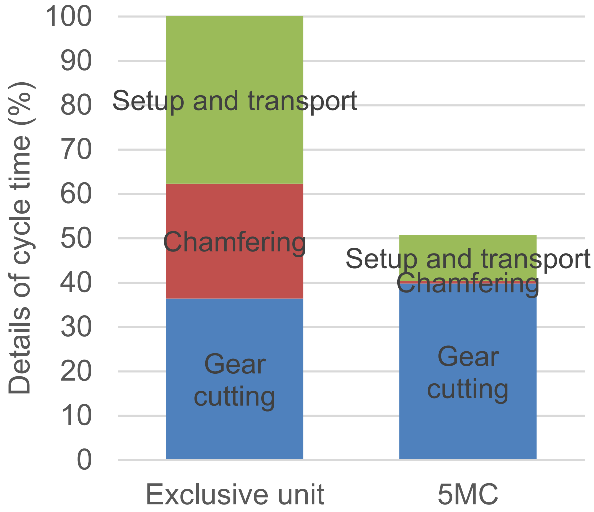


Fig. 6 Comparison of cycle time with exclusive units and five-axis machining

3. Manufacturing of high-precision tooth surface with five-axis machining

3.1 Heat treatment distortion and heat correction

After the gear cutting, a bevel gear goes through the processes of carburizing quenching, tempering, processing of the assembly reference surface and tooth surface lapping. Finishing process of the tooth surface is not performed after the heat treatment. In general, to improve the precision of the tooth surface, the finishing process of the tooth surface can be added after the heat treatment. However, we made efforts for the precision improvement in the gear cutting process before heat treatment to contain a cost increase.

When a bevel gear differs in shape from the desired tooth surface due to the heat treatment distortion, heat correction in which the expected distortion amount is preliminarily incorporated in the gear cutting to be made as an inverse distortion shape is generally applied.

In the 5-cut method with exclusive units, the concave and the convex surfaces of a pinion tooth are finished in different processes respectively, so that heat correction is applied only to the finishing process of the pinion as shown in the upper row of **Table 1** and the tooth surface of the gear that is distorted due to the heat treatment is mostly left as it is. At present, heat correction is applied to the pinion to get a desired tooth contact with the distorted tooth surface of the gear. To ensure the performance close to the design performance, it is desirable to apply heat correction to both the gear and pinion. However, as the exclusive units cut both of the concave and convex surfaces of a gear tooth simultaneously, it is difficult to get high precision of the both tooth surfaces simultaneously by heat correction. This, together with an additional cost required, have prevented actual adoption of this method. Also, as shown in **Table 2**, the effects of the heat treatment distortion to the tooth profile and the tooth-lead are not only comparatively simple changes such as a pressure angle error, a helix angle error and a crowning, but also complicated distortion with waviness which is impossible to accurately be corrected by heat correction using the exclusive units. On the other hand, with the five-axis machining, as a general end mill is used as a tool and the machining is made based on the coordinates of a tooth surface, high-precision heat correction is possible for a complicated heat treatment distortion only by modifying the NC program with a low cost in principle. Taking advantage of this, we considered concrete methods of high-precision heat correction technology based on the coordinates of a tooth surface.

Table 1 Comparison of heat correction between exclusive units and 5MC

Legend ○: Possible △: Partially possible except for waviness

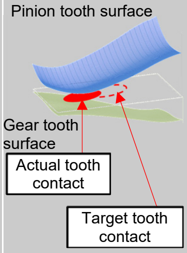
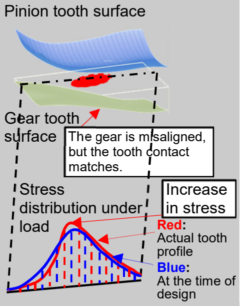
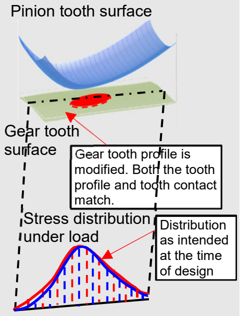
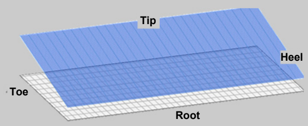
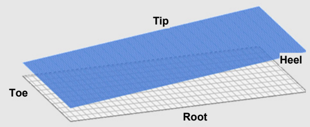
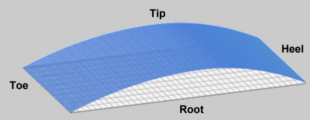
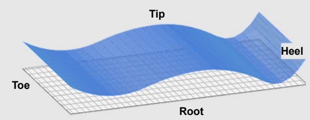
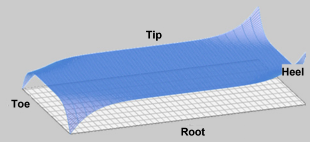
Gear to which heat correction is applied	Before heat correction	After heat correction	Exclusive unit	5MC
Pinion			○	○
Pinion & gear	Same as above		△	○

Table 2 Error types and correction possibility with exclusive machining units and 5MC

Legend ○: Possible ×: Not possible

Error type	Error image	Exclusive unit	5MC
Pressure angle error		○	○
Helix angle error		○	○
Crowning		○	○
Waviness		×	○
Local drooped shape		×	○

3.2 Measurement and correction method of errors of tooth surface

Tooth surface was measured using the HyB-85 manufactured by Osaka Seimitsu Kikai Co., Ltd. (**Fig. 7**). The amount of the error in the normal direction was measured with reference to the nominal tooth surface calculated on the basis of the gear specifications and the design summary (shape of the tool and information of the machining program of the exclusive unit). For the errors in the normal direction on the tooth surface, 29 points in the tooth-lead direction × 113 points in the tooth profile direction were measured for one tooth surface (**Fig. 8**). **Figure 9** shows the procedure to create a surface for heat correction based on the obtained error amount. The value calculated by multiplying minus to the error amount obtained through the measurement is the target amount of heat correction. The three-dimensional coordinates including this target amount should be calculated. As the information such as the shape of the tooth bottom is insufficient, these coordinates are taken in hypoid-facemill (ANSOL) and then have polynomial approximation as five to seven dimension curved surface and smoothing to output points of the target tooth surface for gear cutting including the tooth bottom. The output coordinates of the target tooth surface are connected on the 3DCAD to create the surface for CAM, from which the tool path is created and the processing program is output.

Fig. 7 Appearance of the HyB-85

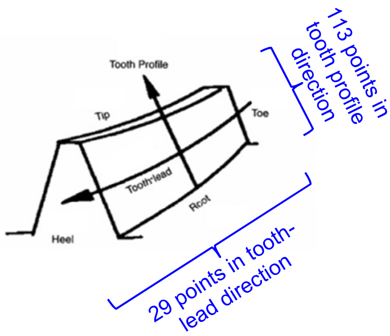


Fig. 8 Number of points measured with the HyB-85

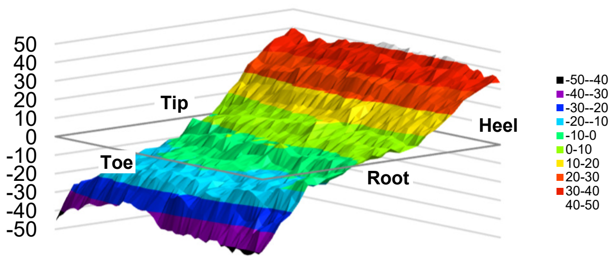


Fig. 10 Target amount (µm)

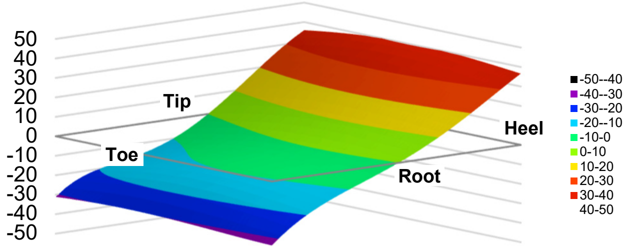


Fig. 11 Target amount with polynomial approximation (µm)

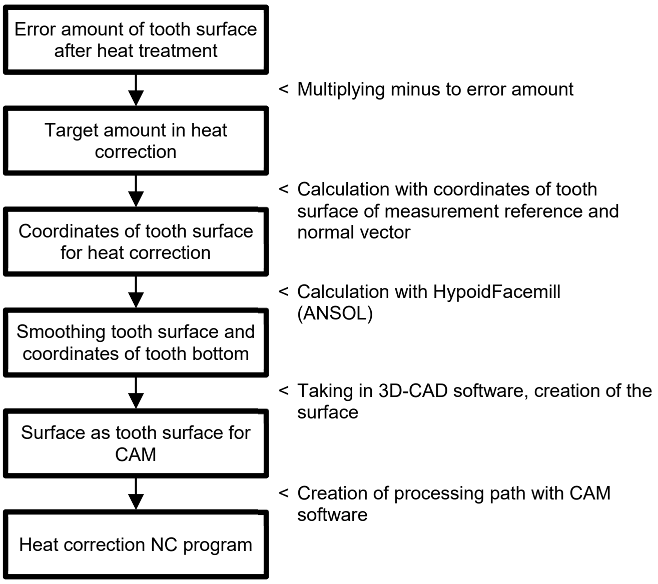


Fig. 9 Procedure of creation of surface for heat correction

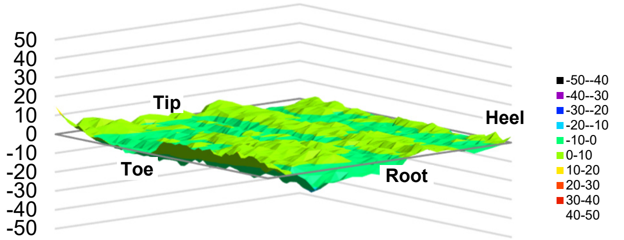


Fig. 12 Error amount with approximation (µm)

The target amount above (the negative value of the measured error amount) to the gear used in the test is shown in the graph in **Fig. 10**. The maximum error before the heat correction was 48 µm. The actual target amount with polynomial approximation of this value is shown in **Fig. 11**. The error amount with the approximation is shown in **Fig. 12**. As the result, the error by approximation is 15 µm at the maximum.

3.3 Precision of tooth surface after heat correction

We created an NC program based on the heat correction surface created for gears and carried out the processing. The appearance of the tooth surface after the processing is shown in **Fig. 13**. The obtained tooth surface was sufficiently smooth. Heat treatment is performed on the gear. **Figure 14** is the graph plotting the errors from the target shape in the evaluation area with the measurement result of the tooth surface with the heat treatment distortion. As the result, the maximum error was improved from 48 µm to 26 µm by the heat correction. **Figure 15** shows an example of errors from the target shape after the heat correction using the exclusive unit for reference. The pressure angle errors and the helix angle errors are corrected but large waviness in the tooth-lead direction caused by the heat treatment distortion remains. The maximum error amount is 37 µm. As the result, we can see that this method can realize high-precision heat correction.

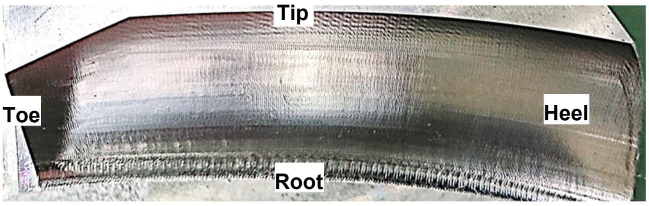


Fig. 13 Appearance of processed tooth surface after heat correction

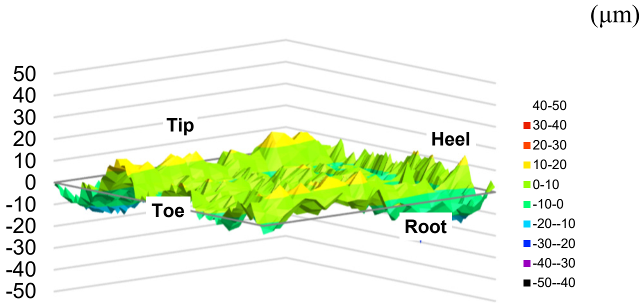


Fig. 14 Errors from target shape after heat correction

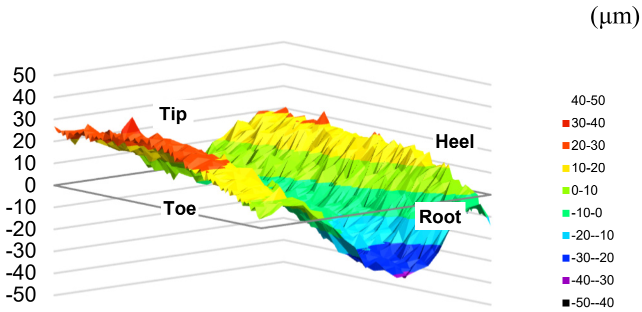


Fig. 15 Errors from OB target shape after heat correction using exclusive unit

4. Prospect for the future

In this paper, we have introduced the precision improvement by heat correction in the gear cutting process before the heat treatment. We expect that even higher precision will be demanded in the future. For meeting such demands, the finishing process for a tooth surface after the heat treatment is necessary. However, as we have mentioned, a cost increase is a concern for this method. We would like to proceed with the development of manufacturing technology for the tooth surface finish after the heat treatment that can contain a cost increase. Recently, the study of tooth profile with high productivity based on 5MC is in progress. Including the measures of tooth profile design combining design strength and productivity with this point of view, the possibility for further improvement in productivity and precision can be expected.

5. Conclusion

While many examples of process concentration with the 5MC have been introduced in the industry, we have introduced an example of the application to the target machining on curved surfaces and precision improvement with the five-axis machining unit in this paper. We think that this kind of manufacturing technology can be applied to items other than bevel gears. In particular, in large workpieces manufacturing, the cost should be significantly increased if the finishing process is added after the heat treatment; the method we introduced in this paper can contribute to the cost control. We will aim at further productivity improvement by making most of the characteristics of the five-axis machining together with the process concentration we mentioned at the beginning.

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[A comment from the authors]

The 5MC is the technology that can significantly contribute to automation including the process concentration we mentioned in the paper. It also has enabled part shapes taking advantage of its characteristics and free design combined with additive manufacturing. We would like to contribute to the future product appeal by utilizing these technologies.