Technical Paper

Development of optimal tooth flank in spiral bevel gears by contact analysis and measurement

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Bevel gears have complicated tooth flank form and, as they mesh perpendicularly, the meshing is in a very complicated condition. On the other hand, as tooth flank form design and production control have been exclusively entrusted to the empirical method provided by cutting machine manufactures so far, detailed study was difficult. In recent years, the development of the simulation technology is being made to measure the tooth flank form of bevel gears and to grasp their meshing conditions led by universities and automotive manufacturers. Given this situation, Komatsu has got rid of the empirical method implemented so far, and developed evaluation technologies ranging from tooth flank form measurement applicable to large bevel gears to tooth contact analysis that calculates meshing condition, and applied these technologies to the development of heavy-duty dump trucks.

1. Introduction

Bevel gears are gears that transmit rotation and power between two intersecting shafts and are used for an axle of construction machinery such as a dump truck. Of these gears, as spiral bevel gears have very complicated tooth flank form and mesh perpendicularly, it was very difficult to grasp a meshing condition. In the history of bevel gears, aspects from design to production control have been exclusively entrusted to the empirical method provided by cutting machine manufacturers (Gleason Corporation and Klingenberg GmbH) and are supported by intuition and experience of skilled engineers and operators. Komatsu is no exception.

To grow out of such a situation, Japanese automotive manufacturers started the development of measuring technology of the tooth flank form from around 1975 and measuring machines were released to the market recently[1].

In addition, the development of simulation technique to grasp a meshing condition of bevel gears has advanced[2] and this technology has begun to be applied to the development of automobiles[3].

To grow out of the empirical method implemented so far and to develop bevel gears that can secure high durability and reliability, Komatsu has developed the technology ranging from tooth flank form measurement of large bevel gears to tooth contact analysis that calculates a meshing condition, and have applied this technology to the development of heavy-duty dump trucks, as reported hereunder.

2. Features and problems of bevel gears

Spiral bevel gears, a subject in this report, are gears used for an axle of a dump truck as shown in **Fig. 1** and rotating shafts are intersecting at right angles to transmit power

outputted from the engine to wheels. The tooth flank form of the spiral bevel gear is twisted in a curved line in the lengthwise direction as shown in **Fig. 2** and different length at both ends in the profile direction is an external characteristic. Displacement of the meshing position called deflection occurs in the bevel gear and pinion because the entire differential is deformed during power transmission due to the tooth flank form of the bevel gear set and structural characteristic of the differential. **Fig. 3** shows an appearance of deformation of the gear under load based on the FEM analysis of the differential. In what condition the differential is as a result of deformation is not known, and as this changes depend on gear specifications (spiral angle and pressure angle) and supporting structure, gears and structure have been designed empirically.

Bevel gears were developed more than 70 years ago and are important gears that are still produced all over the world as hypoid gears in automobiles. However, since gear design and production control have been exclusively entrusted to the empirical method provided by cutting machine manufactures, the improvement of performance and quality of bevel gears has stagnated. An inability to grasp the tooth flank form geometrically can be mentioned as a cause for the above. Many of general cylindrical gears use an involute helicoid curve as a tooth flank form and accuracy management is performed by directly measuring the tooth flank using a tooth flank form measuring machine. On the other hand, since the tooth flank of bevel gears could not be measured, the tooth flank form of bevel gear has been judged by so-called "tooth contact" (area where paint applied to the tooth flank peeled off during   meshing). **Fig. 4** shows the manufacturing process of bevel gears. Gears undergo a gear cutting process and carburizing and quenching process, and finally, the tooth flank form is adjusted by lapping in which the tooth flank is shaved by engaging the pinion and gear together with abrasive grains. Finally, tooth contact inspection is performed for a set of the pinion and gear of this combination and this set of the combination is assembled into an axle.
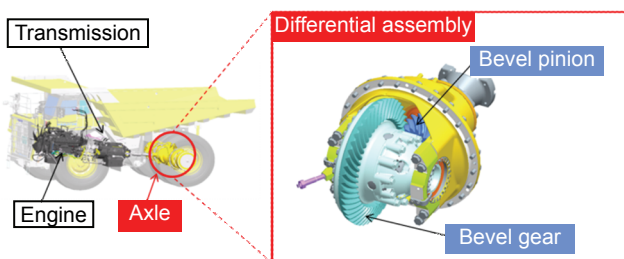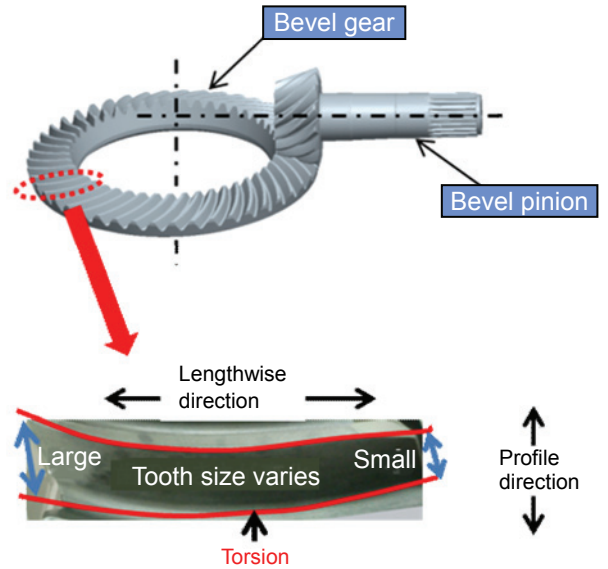

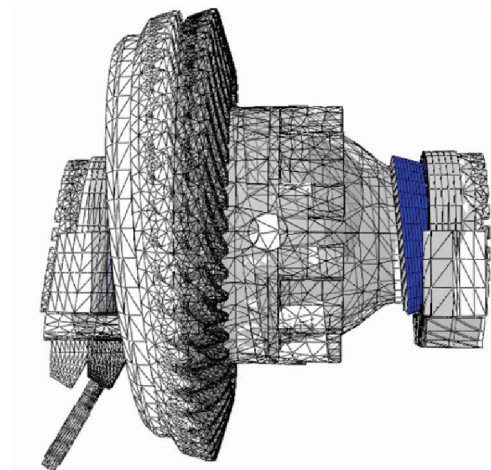**Fig. 2**　Tooth flank form of bevel gear

Fig. 3　Appearance of deformation of differential during power transmission revealed by analysis

In tooth contact inspection, only comparatively high range on the tooth flank is detected under no load, and only a part of the tooth flank can be evaluated. Besides, the detailed tooth flank cannot be identified. When bevel gears actually transmit power, the entire tooth flank is used for meshing in a condition in which deflection occurs, but this condition cannot be inferred from tooth contact inspection. As tooth contact is judged by person's sensory evaluation, the judgment varies greatly depending on individual persons, which is a problem. Such technical issues do not allow for design and manufacture based on a tooth flank form, which is performed for general cylindrical gears, for bevel gears, making it difficult to improve quality and to secure reliability. On the other hand, as durability of bevel gears used for large construction machinery is largely affected by their tooth flank

Fig. 1　Area where bevel gear is used

form, a tooth flank form measuring machine commercially available for hypoid gears of automobiles has been modified to suit large bevel gears in order to evaluate a tooth flank form that can obtain a good meshing condition, and at the same time, technology to simulate a gear meshing condition has been developed for large bevel gears.

3. Development of evaluation technology based on tooth flank form

3.1 Proposal of tooth flank form design method

The conventional development method of bevel gears is, as shown in **Fig. 5 (a)**, to prototype tooth flank form by trial and error and to evaluate it based on a tooth contact test under no load. Consequently, tooth flank forms could not be studied in detail and the repetition until the tooth flank form was decided often took much time. Furthermore, tooth contact under load could be evaluated only on a bench test. To solve this situation, as shown in **Fig. 5 (b)**, the aimed tooth flank form based on deflection assumed in advance is set and "tooth contact analysis" to simulate a meshing condition is performed. After sufficiently performing the desk study based on this, trial manufacture of gears starts. The tooth flank form of prototyped gears is measured by a gear accuracy measuring machine specifically designed for large bevel gears (joint development with Osaka Seimitsu Kikai Co., Ltd.). Next, tooth contact analysis is performed using the actual measured tooth flank form. If the aimed meshing condition is not achieved, gear cutting conditions are studied again. This enables the development of a tooth flank form fully studied and confirmed before a bench test is conducted. Besides, tooth contact analysis is also performed after the bench test so that appropriateness of assumed deflection can be evaluated. Thus, a tooth flank form in consideration of supporting rigidity can be designed before a durability bench test is conducted. Thus the efficient development of a tooth flank form superior in durability is realized.
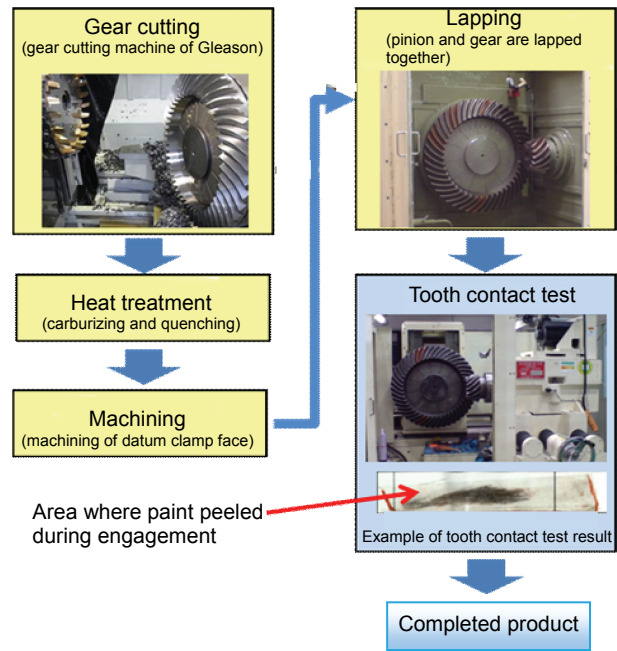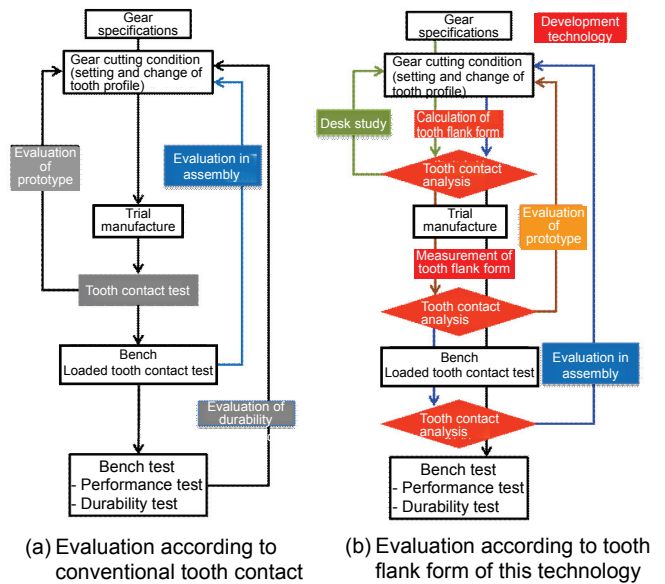

Fig. 4 Manufacturing process of bevel gear

(a) Evaluation according to conventional tooth contact

(b) Evaluation according to tooth flank form of this technology

Fig. 5 Development method of bevel gear

3.2 Tooth flank form measurement by measuring machine for large bevel gears

The measuring machine specifically designed for large bevel gears used this time has been developed for large bevel gears based on a commercially available tooth flank form measuring machine for hypoid gears of automobiles. **Fig. 6** shows a scene where a large bevel gear is being measured, and the tooth flank form can be measured in details. The measurement is made for 29 lines in the profile direction and 9 lines in the lengthwise direction, and 113 points per line can

be measured. While a conventional three-coordinate measuring machine measures 45 points per tooth flank, this measuring machine, which measures 3,277 points, has the capability of measuring the entire tooth flank form in overwhelming detail as its feature. For measurement, deviation from the reference flank is outputted with the theoretical machined tooth flank calculated from the machining settings at the time of gear cutting. **Fig. 7** expresses the measurement result in a contour diagram format, and the gear shows deviation from the theoretical machined tooth flank reference, and the pinion shows deviation from the conjugate flank (flank that meshes with the gear theoretical machined tooth flank without deviation) of the gear theoretical machined tooth flank. Evaluation can be made on the entire tooth flank. As can be understood from the measurement example shown in **Fig. 7**, in a tooth flank that actually presents a complicated curved surface, the gear has flat shape and pinion has crowning-like shape in general if the theoretical machined tooth flank is used as the point of reference.
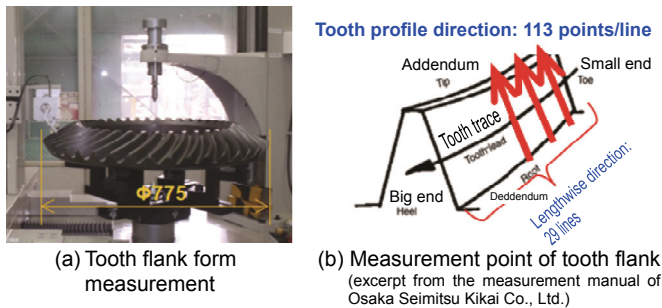
then to define a set of points where the pinion and gear are closest as a contact line by changing the rotational angle in succession. Next, when load sharing at each meshing position is received on the contact line, contact width is calculated for each area using the two-dimensional Herzian contact formula. A result close to the actual tooth contact can be reproduced by combining measured tooth flanks having mutual deviation for analysis[4]. In unloaded tooth contact analysis, the result is calculated, assuming a region where the pinion and gear surfaces move closer to each other within a certain distance as unloaded tooth contact. **Fig. 9** compares the result between an actual tooth contact test under no load and the analysis of an actual tooth flank form, from which good agreement between the two can be observed. Since tooth contact under no load can be measured comparatively easily in an actual component, a correlation between simulation and the actual component can be evaluated.

(a) Tooth flank form measurement

(b) Measurement point of tooth flank
(excerpt from the measurement manual of Osaka Seimitsu Kikai Co., Ltd.)

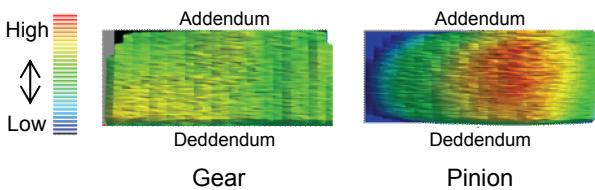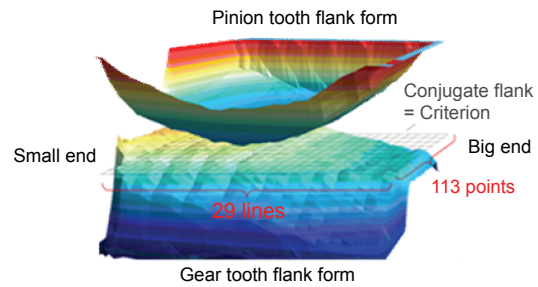**Fig. 6** Measuring machine for tooth flank form of large bevel gear

Fig. 7 Contour diagram of tooth flank form measurement result

3.3 Tooth contact (meshing) analysis

The tooth contact analysis method has been jointly developed by Komatsu and Kyoto University based on the software developed by Kyoto University for hypoid gears so that Komatsu's large bevel gears can be analyzed. **Fig. 8** shows the tooth contact of the measured tooth flank forms of the pinion and gear schematically. A method used in the tooth contact analysis is first to obtain the gear rotational angle, and

Fig. 8 Analysis of tooth contact between measured tooth flank forms

(a) Result from tooth contact test

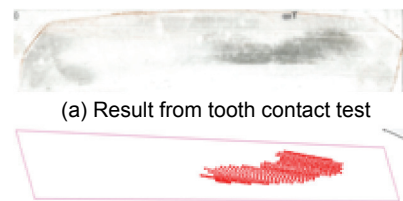(b) Analysis result according to measured tooth flank form (no load)

Fig. 9 Comparison between tooth contact test under no load and analysis result

In analysis, the advantage is the capability of calculating contact pressure, sliding velocity, flash temperature, transmission error, etc. during meshing in addition to tooth contact under load, and if assumed or actually measured deflection is inputted, tooth contact close to actual state under load can be reproduced. **Fig. 10** shows examples of the analysis output, and items necessary for studying strength and noise, such as contact pressure, flash temperature, transmission error, etc., can be evaluated.
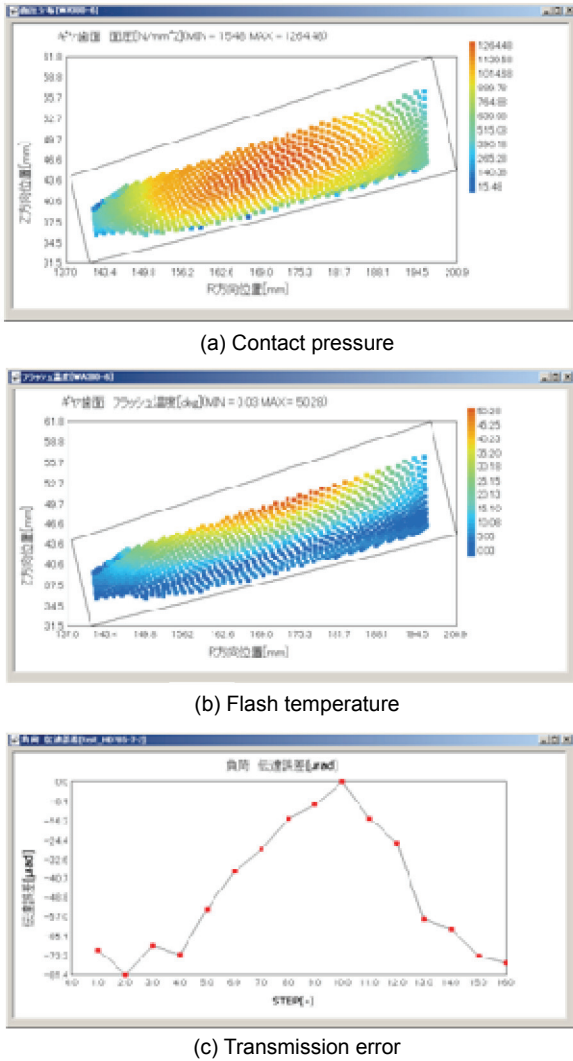
(a) Contact pressure

(b) Flash temperature

(c) Transmission error

Fig. 10　Example of outputs by analysis

4.　Evaluation of meshing condition

In bevel gears, for adjustment during assembly and movement amount of tooth contact, the axial direction and offset direction of the pinion and gear are defined as shown in **Fig. 11**, and measurement and evaluation are made based on the relative difference in each axis.

Deflection that affects meshing differs depending on the supporting structure of the bevel gear, and one method to obtain the value is to assume it from a loaded tooth contact test in an actual gear box. An actual deformation amount when a load is applied is considered to be complicated as shown in **Fig 3**. Here, however, displacement of the relative position of the pinion and gear caused by such deformation is only considered to be defined as being displaced in each direction of VHG shown in **Fig. 11**. The method of a loaded tooth contact test is, as shown in **Table 1**, to conduct a tooth contact test at the normal tooth contact initial position by dividing a load into two to three stages and to record actual tooth contact under each load. Analysis is conducted in the same condition and the difference between the tooth contact position obtained by analysis and tooth contact in a test in the actual component is considered to be equivalent to deflection. Deflection under each load is converted to a movement amount of VHG for making an assumption by adjusting and aligning VHG so that the tooth contact position obtained by analysis matches the actual tooth contact position. To improve the accuracy of the estimation, a similar test and analysis are conducted by displacing the initial position in the H direction in two to three ways. Thus, the deflection as shown in **Fig. 12** can be estimated.

Table 1　Assumption of deflection based on loaded tooth contact test

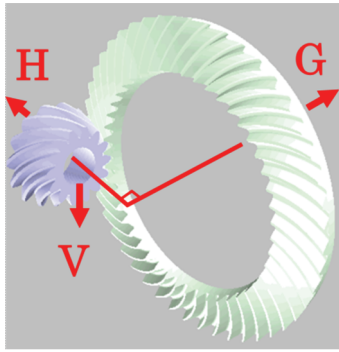| Load torque		Assembly reference position	H -0.2	H +0.2	H +0.2
4% (Full torque rate)	Test				
	Analysis		Tooth contact shifts to deddendum side		Shifts to addendum side
25%	Test				
	Analysis				
50%	Test				
	Analysis				

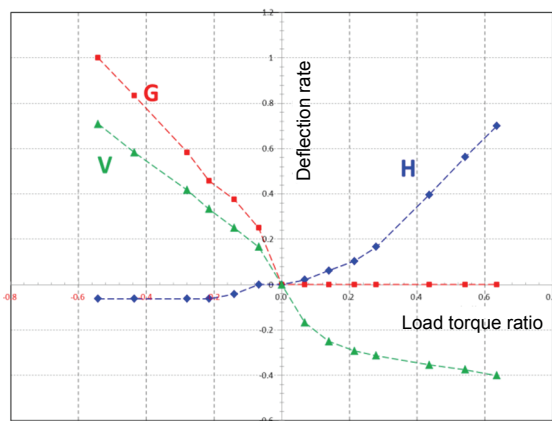**Fig. 11** Definition of each axis of bevel gear

Fig. 12 Obtained deflection

5. Development of bevel gear for new dump truck

The tooth flank form of bevel gears in a newly developed model of a large dump truck has been designed using a new design method of bevel gears shown in **Fig. 5**. As deflection cannot be actually measured at the design stage in the case of new design, deflection of the development model is set with reference to the measured result of an existing differential whose supporting structure is similar and whose vehicle size is close, and the tooth flank form has been set so that the target durability can be obtained.

In actual trial manufacture, gear cutting conditions have been changed in consideration of heat treatment distortion obtained from tooth flank form measurement so that the tooth flank form set in a completed product can be obtained. Next, a loaded tooth contact test was conducted using a manufactured bevel gear. In prior study, tooth contact as shown in **Fig. 13 (a)** was aimed, but actually a result different from the assumption was obtained as shown in **Fig. 13 (b)**, and it was judged that the target durability could not be obtained in this meshing condition. As the difference between tooth contact analysis and tooth contact of the actual test is considered to be

the very difference of deflection, deflection that reproduces tooth contact in **Fig. 13 (c)** is assumed. As a result, it was found out that deflection was smaller than the assumption. Therefore, the tooth flank form suitable to determined deflection was redesigned and a similar test was conducted again. The test result agreed with the analysis result as shown in **Fig. 14**.

In a series of developments, bevel gear design and evaluation of durability based on a tooth flank form could be performed, and furthermore, the calculation of deflection by FEM is being made because the necessity of the desk study of deflection has become clear.
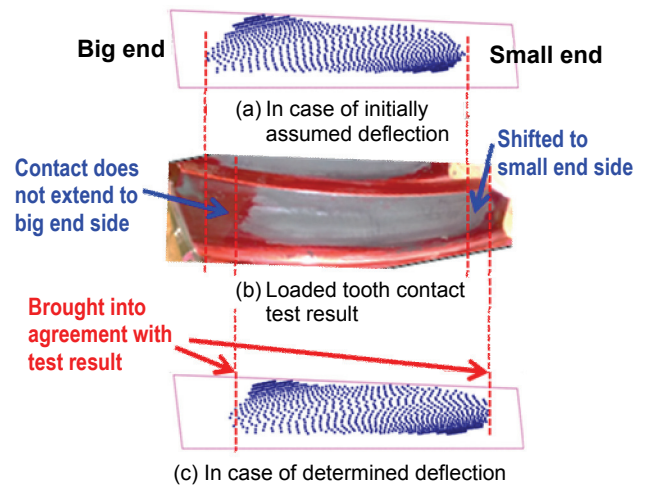

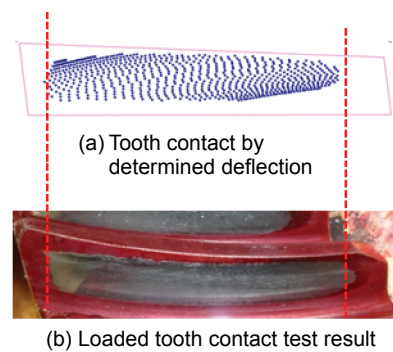**Fig. 13** Tooth contact of newly developed bevel gear

Fig. 14 Tooth contact test result after improvement of tooth flank form

6. Conclusion

1. Tooth flank form measurement of hypoid gears and tooth contact technology promoted mainly by automotive manufacturers have been applied to large bevel gears and a gear design method based on the tooth flank form standard instead of the conventional tooth contact

standard has been developed.

2. Bevel gears for a new model have been designed using the developed method and an appropriate tooth flank form has been designed and prototyped using the developed method.

Acknowledgments

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(3) Keiichiro Tobisawa, Masaki Kano, Kohei Saiki, Tsuyoshi Hanakawa, Takeshi Yokoyama, "Real Tooth Contact Analysis of Hypoid Gear without Using Mathematical Reference Tooth Surfaces", Transactions of Society of Automotive Engineers of Japan, Vol.37, No.1 (2006), pp.119-124.

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Introduction of the writers

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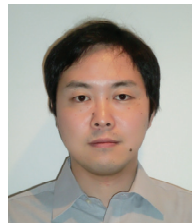Joined Komatsu Ltd. in 2002
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[A few words from writers]

This development was an academic-industrial alliance with Kyoto University. The technology development and application this time has allowed for the measurement and analysis, which are similar to those for general cylindrical gears, for bevel gears. Considering that we relied on intuition and experience in design and manufacture of large bevel gears so far, we think "visualization" has greatly advanced. In the future, we would like to establish this development technology in-house and to utilize this technology not only for tooth flank form design but also for quality improvement and highly accurate strength evaluation. We would like to express our sincere gratitude to Powertrain Development Center of Development Division and Osaka Plant who have been jointly proceeding with the development in implementing this project.