Machining Shape Analysis for Cylindrical Gear Grinding with Threaded Grinding Wheel

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It is very important to estimate tooth flank after grinding cylindrical gears. This report explains a newly developed software that can simulate tooth profiles after grinding using 3-D models of a threaded grinding wheel and tooth flank, and calculate their locations in the machine, motions in the grinding process, and amount of tooth flank removed by grinding. This software helps to reduce time spent using trial and error to determine machine settings and motions and also reduce wheel wear by understanding the contact area of the wheel more accurately.

***Key Words**: gear grinding, simulation, tooth flank, threaded grinding wheel, contact area*

1. Introduction

Automobile transmissions are used to efficiently transmit power from the engine, motor, or other sources. Demand for quietness and efficiency is continuing to grow for the gears which are an important mechanical element of a transmission, and tooth flank profile accuracy is required on a micrometer scale. Gear grinding is widely used as the finishing machining method to achieve this.

Because high efficiency machining is required with gears which are mass produced for automobiles or other products, generally a generating grinding method using a threaded grinding wheel is used. With a generating grinding method, a V-shaped dresser or other tool first forms the threads in the grinding wheel as shown in **Fig. 1** (a), and then the formed grinding wheel engages with the workpiece and rotates in synchronization with it, grinding the tooth profile as shown in **Fig. 1** (b). With this manufacturing method, the grinding wheel and workpiece are in contact with several teeth, and the contact point sequentially changes. Consequently, understanding the mechanism of the grinding process becomes more challenging. For this reason, actual machining and readjustment based on the results are performed repeatedly to produce the target tooth flank profile, a process which requires considerable time.

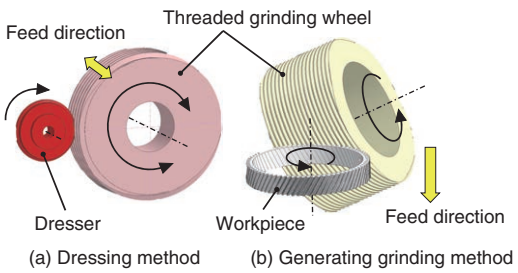


Fig. 1 Gear grinding process

Therefore, an analysis tool was developed to predict the tooth profile shape after gear grinding on a computer. This paper introduces the verification of the calculation accuracy of the developed tool and provides examples of its use.

2. Issues with Generating Grinding

When operating gears, misalignment of the gear shaft, tooth bending deflection, housing machining error, or other factors can adversely affect the meshing conditions of a pair of gears under load, causing vibration and noise. As a countermeasure, the involute tooth flank profile shape is ordinarily deliberately changed (hereafter referred to as “tooth flank profile modification”) to produce the ideal mesh under load[1]. The modified tooth flank profile can generally be divided into the five modification elements shown in **Fig. 2**. The size of each modification element (amount of modification) is expressed as the amount of error relative to the involute tooth profile in the desired evaluation area. To produce the desired tooth flank profile, it is necessary to machine each modification element to the desired amount of modification. Tooth flank profile modification is performed based on the combination of the grinding wheel shape and the relative motion of the grinding wheel and workpiece. For example, to modify tooth profile rounding, it is necessary to change the grinding wheel shape, which means changing the dresser shape. If the intended tooth profile shape was not obtained, it is necessary to remanufacture the dresser, requiring time

and cost before repeat machining can be performed. In particular, with complex tooth profile modifications, even when the tooth profile shape is feasible in terms of bench design, there are cases when it cannot be achieved due to restrictions of the machine, grinding wheel specifications, workpiece specifications, or other elements. In such cases, it is necessary to redo the tooth profile design through trial machining, increasing the development lead time.

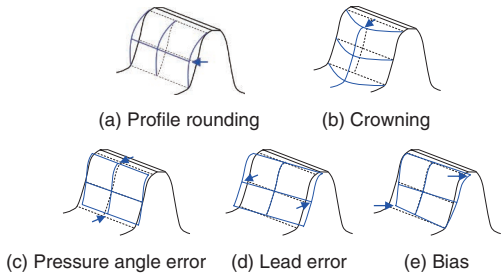


Fig. 2 Tooth surface indicators

Extending the life of the grinding wheel during mass production is also an important issue that leads to cost reductions. With generating grinding that uses a threaded grinding wheel, the operating surface of the wheel after machining the workpiece suffers shape disruptions due to wear, adversely affecting machining accuracy. Therefore, before machining the next workpiece, the grinding wheel is moved in the axial direction (grinding wheel shifting). This process is repeated, and when the grinding wheel has been completely used up from end to end, dressing is performed to reform the thread shape on the grinding wheel. The number of workpieces that can be machined with one dressing is called the dressing interval, and it affects the machining cost. Conventionally, there was no means of deciding the amount of grinding wheel shift, and the initial value was decided based on past results. Finding the appropriate value while performing actual machining requires a long time before the start of mass production.

To resolve the above issues, this analysis tool includes a function that visualizes the contact area of the grinding wheel and workpiece during machining and provides features that help set the shifting amount.

3. Development of the Grinding Analysis Tool

3. 1 Grinding Analysis Tool

The simulation flow of the developed grinding analysis tool is shown in **Fig. 3**. Grinding is divided into a process of forming the grinding wheel using the dresser and a process of machining the workpiece using the formed grinding wheel. Similarly, this analysis tool is divided into a dressing simulation part and a grinding simulation part, designed to accurately reproduce actual grinding. In the dressing simulation part, the dresser shape and the basic grinding wheel specifications are input, and the dresser analysis model and pre-dressing grinding wheel model are generated. At the same time, the motion path during dressing is calculated, and the dresser and grinding wheel models are placed in relative positions according to the dressing motion. The parts where interference between the dresser and the grinding wheel occurs are removed from the grinding wheel model to determine the grinding wheel shape after dressing.

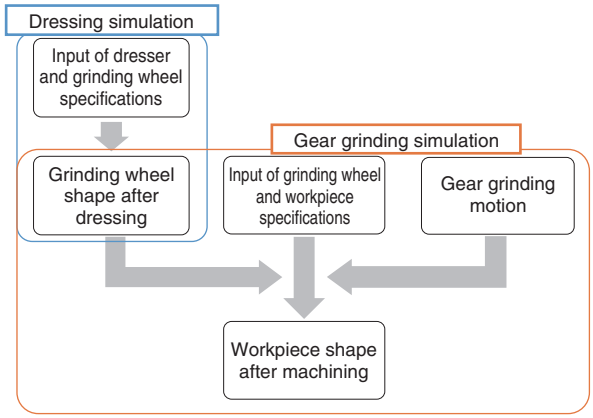


Fig. 3 Simulation flowchart

In the gear grinding simulation part, first the pre-machining workpiece model is generated based on the workpiece specifications, then the grinding motion path is calculated from the machining conditions. Next, the grinding wheel model and workpiece model that were created in advance are placed in relative positions according to the grinding motion. The locations of interference are removed by calculation from the workpiece model to determine the workpiece shape after machining.

Figures 5 and **Fig. 6** show the output results obtained from the cross-section shown in **Fig. 4**. An approximate line is found from the tooth profile and tooth trace shapes, and figures are calculated for the pressure angle error, profile rounding, bias, lead error, and crowning. These calculation results are indicated in a manner similar to the measurement results from a gear measuring machine, allowing for easy comparison. Based on the above, the developed analysis tool can be used to determine before machining whether or not the design target shape can be satisfied.

The tool also includes a topography display function that allows not just the specified cross-section described before, but the entire tooth flank to be understood, as shown in **Fig. 7**. As a result, it is possible to conclude that there are no abnormalities in the tool shape or tooling path.

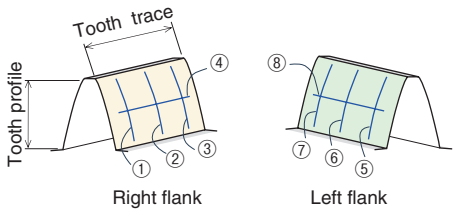


Fig. 4 Tooth evaluation positions

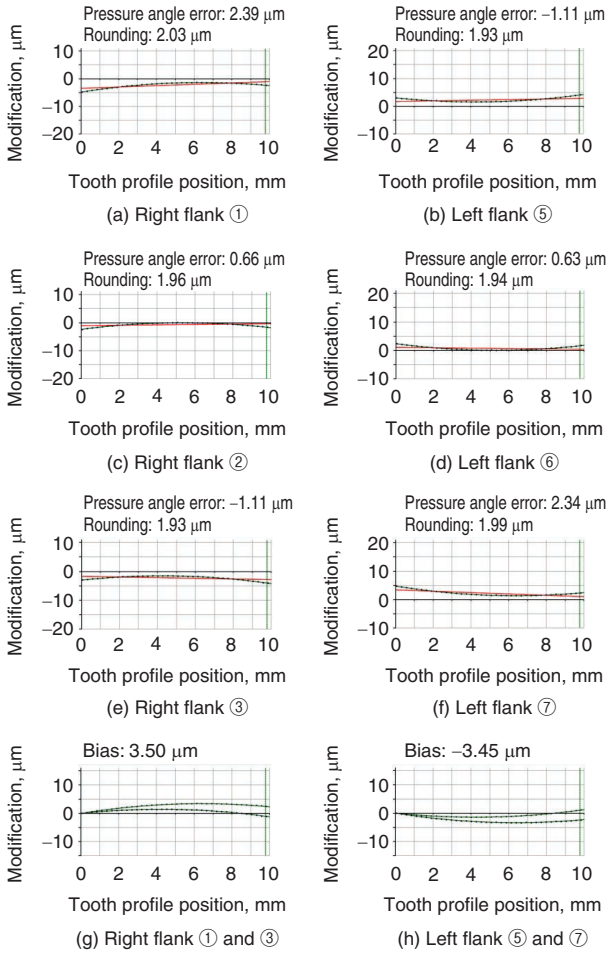


Fig. 5 Analytical software results screen

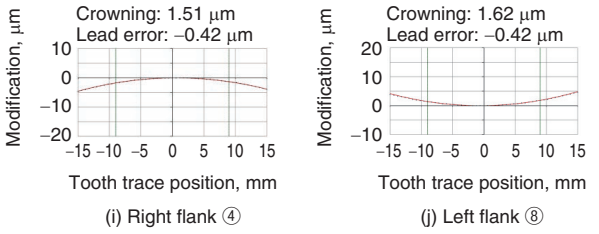


Fig. 6 Analytical software results screen

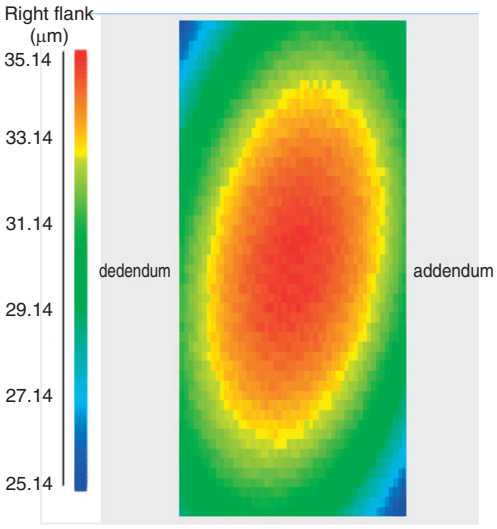


Fig. 7 Tooth flank topography

3. 2 Verification of Analysis Results

To verify the suitability of the simulation analysis, the calculated values from the analysis tool were compared with actual measured values of a gear that was machined under the same conditions as the simulation. **Figure 8** (a) shows the comparison results for the tooth profile shape, and **Fig. 8** (b) shows the comparison results for the tooth trace shape. The shapes of the calculated values and the actual measured values were nearly identical for the tooth profile and tooth trace shapes. As shown in **Table 1**, the difference for all modification elements was less than 1 μm, verifying the suitability of the analysis tool.

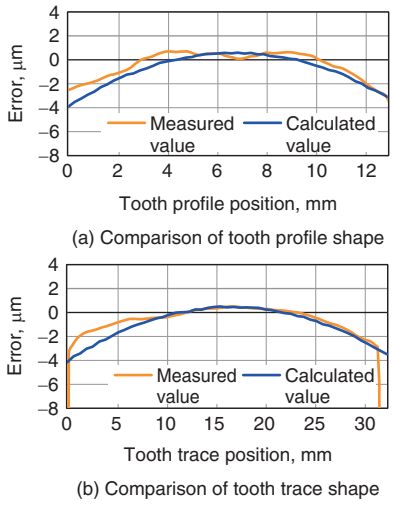


Fig. 8 Comparison of actual machining and simulation results

Table 1 Comparison of tooth indicators

Comparison item		Measured value	Calculated value
Tooth profile	Pressure angle error, μm	1.2	0.7
	Profile rounding, μm	1.6	2.0
	Bias, μm	3.2	3.5
Tooth trace	Lead error, μm	0.2	−0.4
	Crowning, μm	1.2	1.5

4. Calculation of Grinding Wheel Contact Area

4. 1 Generating Grinding Point on Worm Plane

One characteristic of generating grinding using a threaded grinding wheel is that only a portion of the meshing range between the grinding wheel and the gear is in contact. As shown in **Fig. 9** (a), a point on the gear tooth profile is machined by a specific point on the worm plane of the grinding wheel. For this reason, the point of contact follows a trajectory that moves at an angle on the worm plane of the grinding wheel as shown in **Fig. 9** (b).

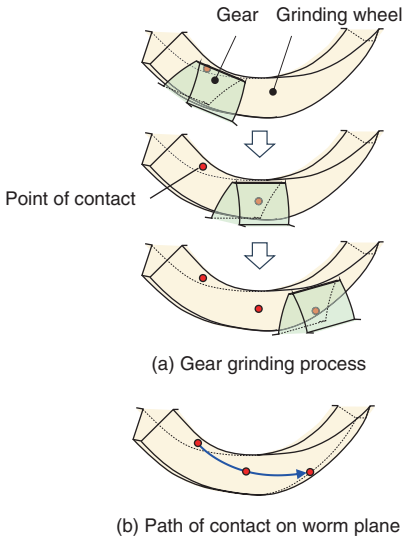


Fig. 9 Contact position in generating gear grinding

4. 2 Visualizing the Grinding Wheel Contact Area

This analysis tool sequentially stores the contact area while performing grinding analysis, and can output both the instantaneous contact area of the grinding wheel and workpiece, as well as the cumulative contact area. Using this function, it is now possible to display the contact area using the grinding wheel width position and the tooth depth position as shown in **Fig. 10**. By comparing the contact area at machining count N and count N+1, it is possible to easily check for any area overlap or wasted unused area.

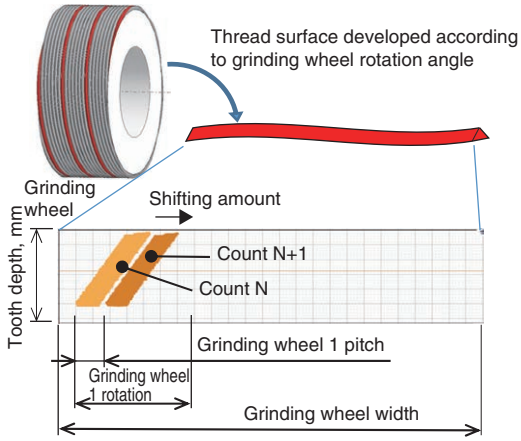


Fig. 10 Grinding wheel contact area

4. 3 Verification of the Grinding Wheel Contact Area

To verify the contact area analysis results, the grinding wheel shape after machining was measured in a spiral direction using a dial gauge. **Figure 11** shows the comparison results between the contact area predicted by analysis and the wear area that was actually measured. The contact area found by analysis matches the worn part of the grinding wheel, indicating the part that was actually used in grinding. The reason that the wear area is larger than the analysis width is thought to be due to variation in the machining allowance during actual machining, and to variation in the machining allowance between the left and right tooth flanks.

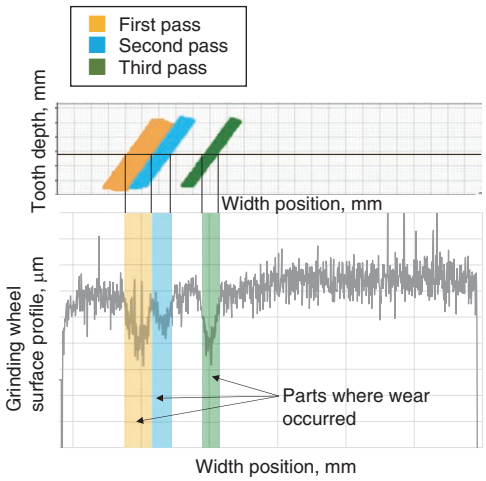


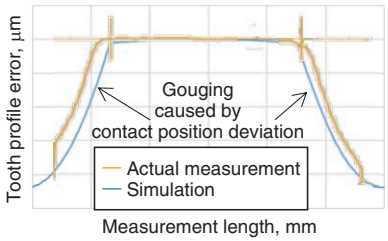
Fig. 11 Comparison of grinding wheel contact area

5. Example of Use of the Analysis Tool

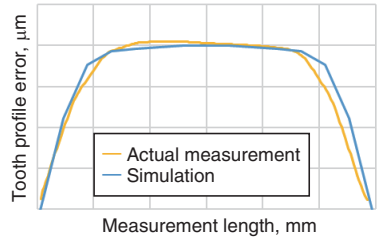
5. 1 Avoiding Interference During Machining of End Relief Shape

One method of tooth profile modification is end relief modification. When gear misalignment occurs in a transmission, the contact parts of the gear pair move toward the edge of the tooth end, and so-called edge contact increases the compressive stress in the local area, frequently demanding the tooth profile. An effective countermeasure to this is end relief, which creates a large relief only at the face width edge[2].

To achieve this machining, the grinding wheel must cut to a depth of several tens to a hundred μm when grinding the edge. It was found that if an unintended part of the grinding wheel was involved in machining, or if the contact position was displaced, the desired shape was not produced as shown in **Fig. 12** (a). Therefore, using the analysis tool, the machining motion was adjusted with consideration for contact position deviation to produce the target tooth profile. As a result, the intended tooth trace was obtained as shown in **Fig. 12** (b). When performing complex tooth flank modification, previously trial machining and evaluation were conducted repeatedly to improve the machining accuracy. In contrast, using the analysis tool makes a desktop study possible, and can reduce the man-hours and number of workpieces required for trial machining as shown in **Fig. 13**.

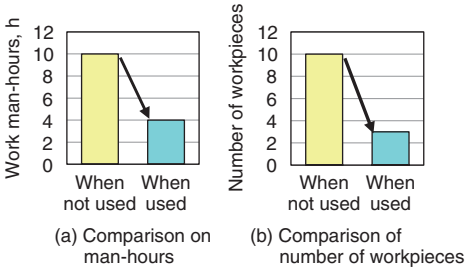


(a) No consideration for contact position deviation



(b) With consideration for contact position deviation

Fig. 12 Comparison of lead of end relief machining



(a) Comparison on man-hours (b) Comparison of number of workpieces

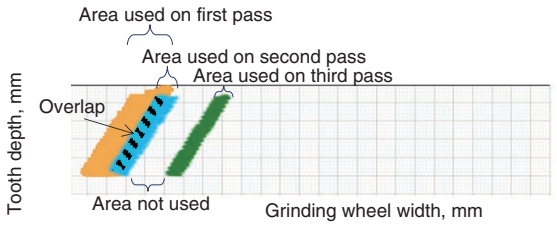
Fig. 13 Effect of reducing using analysis tools

5. 2 Adjusting the Amount of Grinding Wheel Shift

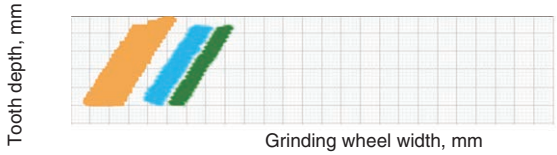
As described before, the grinding wheel is shifted in the axial direction after each machining. However, even for a single machining count, when multiple machining passes are made such as rough machining and finishing machining, the grinding wheel is shifted for each pass in nearly all cases.

Figure 14 shows an example of analysis using the analysis tool that changed the shifting amount of the contact area during three-pass machining. In this example, before the change, the area used at the first pass and second pass overlapped. At the same time, there was a large unused area between the second pass and the third pass. After the change, the overlap between the first pass and second pass was eliminated, and the unused area between the second pass and third pass was reduced.

By visualizing the grinding wheel position used, it was possible to optimize the shifting amount. This can be expected to reduce tool costs by improving the grinding wheel lifetime during mass production, and to improve tooth flank accuracy by avoiding overlap of the positions used.



(a) Before change



(b) After change

Fig. 14 Grinding wheel position used

6. Conclusion

In this paper, a machining shape analysis tool for cylindrical gear grinding using a threaded grinding wheel was developed. This tool made it possible to analyze gear grinding which was previously verified by trial machining, and to achieve precise tooth profile modification and optimization of the machining conditions. The results from verification of the analysis tool calculation accuracy and from the example of its use are as follows.

(1) A gear grinding analysis tool was developed that can perform analysis with a tooth profile error of 1 μm or less compared to the actual machined part.
(2) Desktop verification of complex tooth flank modification logic such as end relief has become possible. As a result, the man-hours and number of workpieces required for trial machining were reduced.
(3) Based on the analysis results of the grinding wheel position used, the shifting amount was optimized, reducing tool costs and improving tooth profile accuracy.

In the future, this analysis tool will be used to contribute to performance improvements and cost reductions to meet future gear needs.

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