Development of the Gear Processing Digital Twin

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In the automotive industry, electric units (eAxles) are becoming increasingly prominent, and the gears used in these units must be compact and highly precise. To meet the evolving needs of the industry, it is essential to reduce lead times for prototype evaluation. This paper discusses the development of simulations for gear prototype evaluation using DX (Digital Transformation) based on skiving machining, and how it can reduce lead times for prototype evaluation.

Key Words: *gear double digital twin, gear processing digital twin, gear skiving, eAxle, DX (digital transformation), simulation tool*

1. Introduction

As the global movement aiming at achieving carbon neutrality and SDGs picks up pace, the demand for electrification is growing rapidly, and in the automobile industry as well, the electric unit known as eAxle (electric axle) is gaining attention. An eAxle is composed of an inverter, motor, and gears, and the internal gears must be compact[1)] (**Fig. 1**). At the same time, because greater efficiency and quietness than ever before are required, the optimal tooth surfaces that achieve ideal meshing under load, in other words modified tooth surfaces, are necessary. In order to rapidly develop new gears to meet these gear requirements, it is necessary to rapidly complete prototype design and evaluation. However, because with conventional prototype evaluation processes, design and prototyping are performed repeatedly, there is the issue of the increase in man-hours required.

In order to resolve this issue, this report introduces an effort for the use of digital transformation (DX) to shorten prototype evaluation periods with skiving machining.

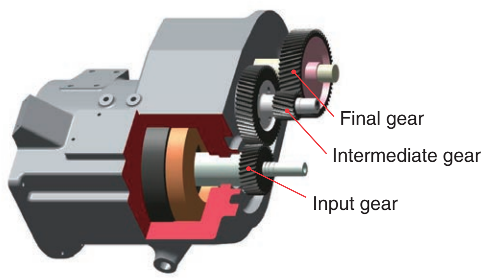

Fig. 1 eAxle model

2. Skiving Method

Skiving is one generating tooth cutting method that machines using a gear-shaped tool similar to a gear shaper. As shown in **Fig. 2**, with this manufacturing method, the tool and workpiece are inclined relative to each other, and the relative speed generated by synchronized rotation is used to perform gear machining. Compared to hobbing, the skiving method features better tool accessibility to the workpiece, can shorten the incomplete tooth profile part, and can reduce the size of the gears.

With skiving, when modifying the tooth profile direction, the tool blade shape is changed. When modifying the tooth trace direction, the machine movement is changed. It is possible to create any gear tooth profile by combining modifications in both directions, enabling creation of the optimal tooth profile with the high compactness and quietness required of an eAxle (**Fig. 3**).

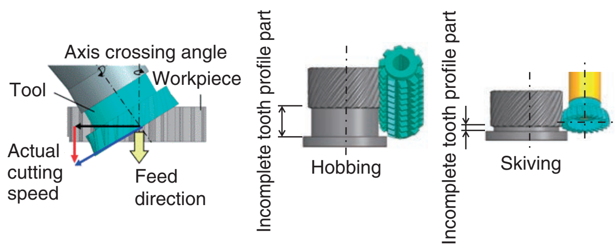

Fig. 2 Skiving method

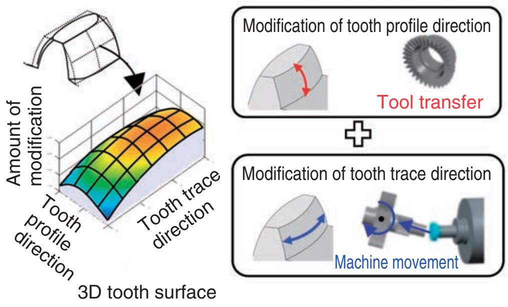

Fig. 3 Gear face modification processing method

3. Gear DX

3. 1 Gear Double Digital Twin

In order to improve the efficiency and quietness of automobile reduction gears, it is necessary not only to perform high precision manufacturing of the gear itself, but also to consider assembly error, shaft bearing rigidity, and other factors of component parts, and to optimize the entire reduction gear system. The JTEKT Group is constructing a simulation system known as the gear double digital twin[2] (**Fig. 4**).

With a gear performance digital twin, the gear specifications, component elements, and other factors can be optimized to create a reduction gear with high strength and low noise with consideration for gear transmission error, misalignment, and bearing strain. A gear processing digital twin automatically selects the tool design and machining conditions, predicts machining accuracy, and optimizes the various machining processes in order to manufacture the ideal gear. By linking a gear performance digital twin and a gear processing digital twin, it is also possible to optimize the tooth surface shape with reduction gear performance as the target function.

3. 2 Gear Processing Digital Twin

First, **Fig. 5** shows the series of processes from gear specification requirements to prototype completion. After the required specifications for the automobile component are decided, the component design, processing study, and prototype evaluation processes are performed. Conventionally, at each process of the processing study, the design study and the creation and transfer of various data are all manual work, and the long man-hours are a problem. In addition, when a quality problem occurs

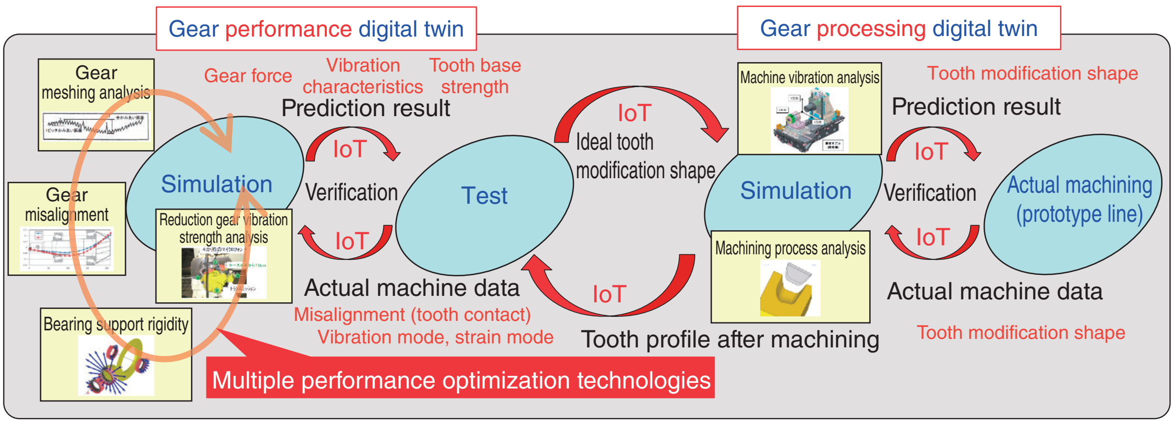

Fig. 4 Gear double digital twin concept

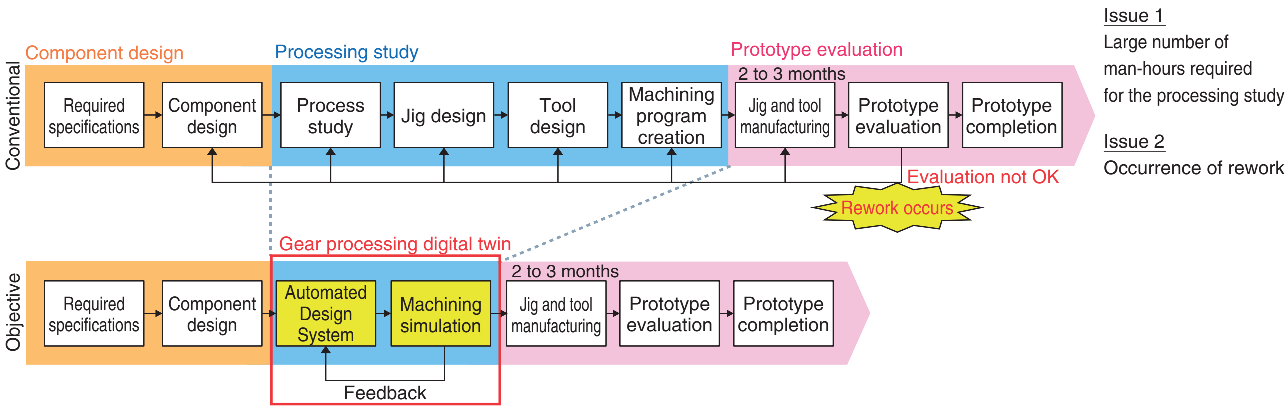

Fig. 5 Prototype evaluation process

during prototype evaluation, because 2 to 3 months are required in order to remanufacture the jigs and tools, overall several months of rework occur.

The developed gear processing digital twin is composed of an Automated Design System and machining simulation. The Automated Design System can automatically perform process design, jig design, tool design, and creation of the machining program at once, and can reduce the man-hours required for the processing study.

With the machining simulation, the tooth surface shape can be predicted before actual machining based on vibration characteristics information. In addition, feedback of the simulation results to the Automated Design System enables a detailed study of various designs at the processing study stage, and can reduce rework during prototype evaluation.

4. Developed Simulation System

4. 1 Automated Design System

4. 1. 1 System Overview

This section explains the system that automates the processing study for skiving, in other words the Automated Design System. As shown in **Fig. 6**, this system is composed of five functions: process estimation, jig design, tool design, interference check, and NC program creation. The information necessary for the processing study can be obtained by simply inputting the gear specifications and outside diameter dimension of a workpiece.

The main functions of the Automated Design System, namely the process estimation function and tool design function, will be explained in detail.

1) Process estimation function

This function automatically selects the machining conditions and calculates the cycle time based on the required workpiece specifications (**Fig. 7**).

The approximate tool shape is calculated from the workpiece specifications, and analysis of the undulations of the tooth surface and cutting conditions is used to automatically select the tool parameters which will minimize undulations after machining. Next, machining conditions suitable for those tool parameters are selected from a past database, and the machining cycle time is calculated. Because a cycle time estimate report is generated automatically, it is possible to perform process estimation quickly regardless of the operator’s level of experience.

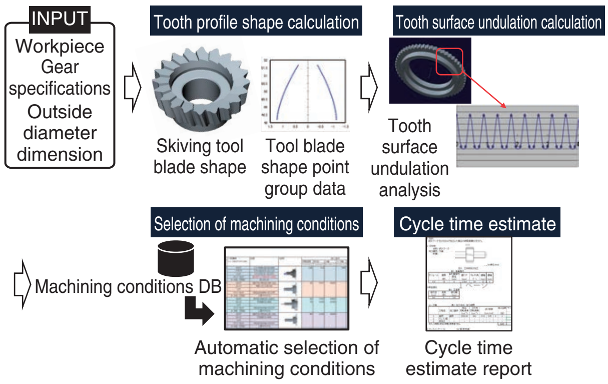

Fig. 7 Process estimation function

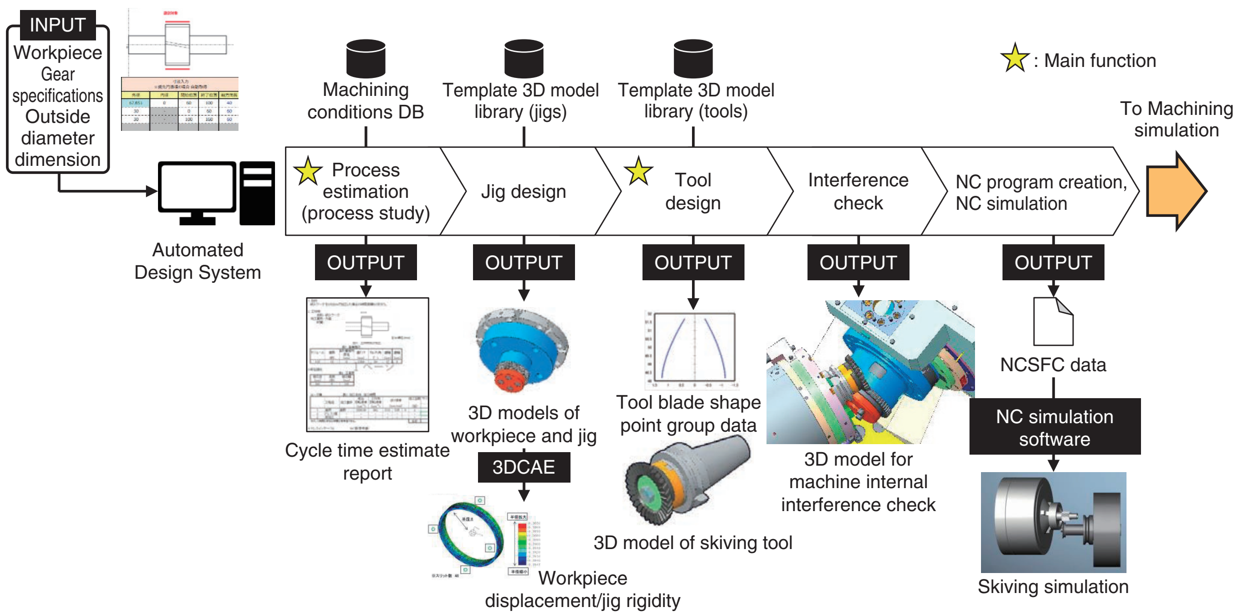

Fig. 6 Automated design system flow

2) Tool design function

This function automatically performs detailed design of the skiving tool blade shape and design of the grinding wheel for forming the tool (**Fig. 8**).

First, skiving tool blade shape data is generated from the workpiece specifications. Then grinding wheel shape data that can actually be manufactured is generated based on the generated tool blade shape data.

Next, tool blade shape data is generated from the grinding wheel shape data that was generated at the previous process, and finally the workpiece shape data and gear generating diagram are output from the tool blade shape data. The required workpiece shape is then compared with the shape after machining for the tool shape that is actually manufactured. This allows the consistency of both to be checked in advance, and can reduce rework during tool manufacturing.

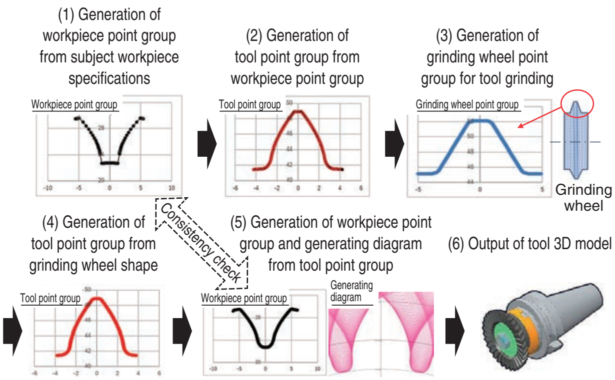

Fig. 8 Tool design function

4. 1. 2 Reduction in Man-Hours

The effects in terms of reduction in man-hours in the processing study using the developed Automated Design System are shown in **Fig. 9**. Conventionally, each process is performed by manual work, and the man-hours that took 14 days were reduced to 1 day after system introduction.

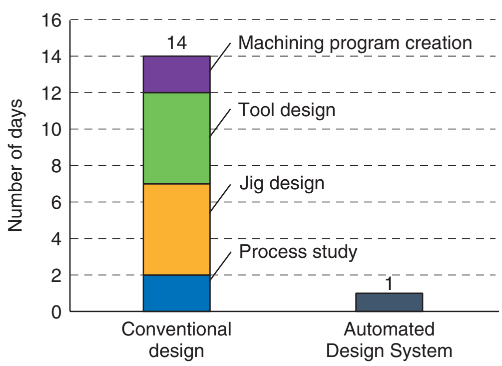

Fig. 9 Reduction effect

4. 2 Machining Simulation

This section explains the machining simulation in detail. This simulation can predict the tooth surface shape based on vibration characteristics information.

As shown in **Fig. 10**, a skiving simulation performs coupling analysis using the three calculation modules for shape calculation, cutting force calculation, and vibration calculation. At shape calculation, tool and workpiece interference calculations are performed for skiving based on gear generating theory, and the cutting depth and other information necessary for cutting is calculated. Next at cutting force calculation, the cutting force is found from the aforementioned cutting information and cutting constant. Then at vibration calculation, vibration is calculated from the found cutting force and the relative dynamic rigidity of the tool and workpiece, and feedback of this vibration is provided to shape calculation. By repeating the above and performing machining in the simulation, the gear accuracy is obtained from the difference between the workpiece shape after machining and the target workpiece shape.

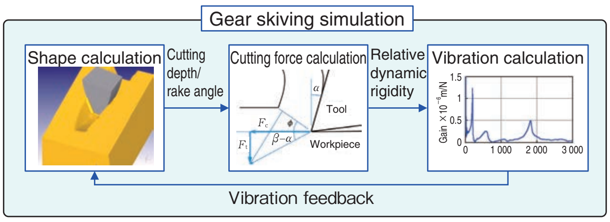

Fig. 10 Machining simulation for gear conceptual diagram skiving

Figure 11 shows an example of machining simulation results output. The gears used in an eAxle require accuracy of several μm or less for both tooth trace shape error and tooth profile shape error. This machining simulation can perform gear accuracy analysis that satisfies this requirement.

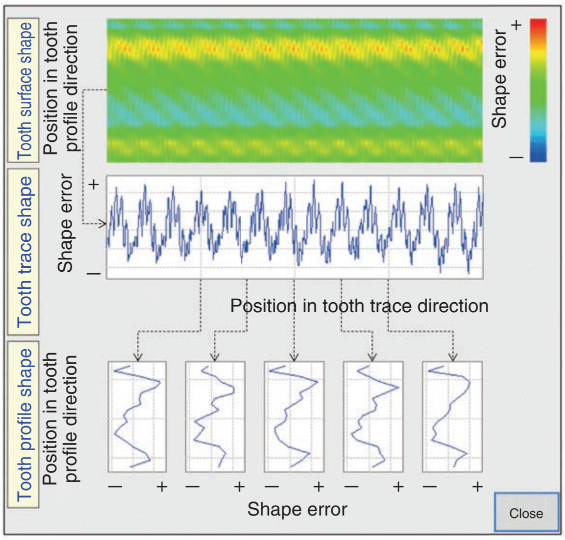

Fig. 11 Example of machining simulation results output

5. Conclusion

Development of the automated design simulation that is a component element of the gear processing digital twin was able to reduce man-hours involved in the processing study by approximately 90%. Because the tooth surface shape can be predicted with consideration for vibration characteristics, the machining simulation can reduce man-hours required for rework during actual machining. This enables rapid prototype evaluations of the gears that are requested by the customer.

In the future, we will provide the results from the gear processing digital twin simulation as feedback to the gear performance digital twin, and work to improve system functions in order to optimize all processes from gear concept design through machining.

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