Technical Paper

Construction of Heat Treatment Database and Enhancement of Simulation Technique

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A heat treatment database was developed to optimize the development of heat treatment parts and manufacturing conditions. Data related to carburized and induction hardened gears was input to construct the database. The analysis speed of computer simulation of heat treatment quality has been dramatically increased, allowing analysis of large scale models such as entire shapes of gears using a personal computer. Benchmark simulation currently undertaken as an industry-academia joint project was carried out and the accuracy of simulation analysis was evaluated. The fluctuation range of hardness of carburized gears of construction equipment manufactured in full-scale production was estimated using the database and simulation.

Key Words: *Heat Treatment Database, Heat Treatment Simulation, Heat Treatment, Carburizing, Hardness, Residual Stress, Distortion, Gear*

1. Introduction

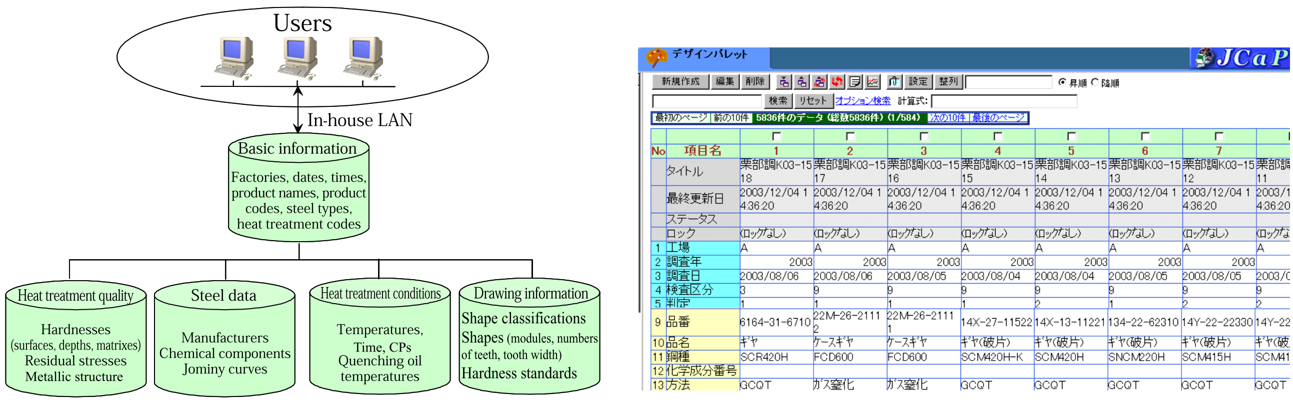
The construction of a database on actual heat treatment and the development of computer simulation to virtually reproduce heat treatment processes are underway as important tools to develop parts that are heat treated and to optimize manufacturing conditions. This database and this computer simulation are expected to efficiently enable more accurate studies by using them in combination by fully exploiting their characteristics rather than using them independently. This will assure optimization of the development and manufacturing conditions as a result.

Sizeable activities are being undertaken at present also internationally on a joint industry-government-academia basis to enhance analysis accuracy and to expand applications for heat treatment simulation. In Japan, the Society of Materials Science, Japan, (Material Database Research Subcommittee) and The Japan Society for Heat Treatment (Quenching and Simulation Research Committee) are constructing databases for data for steel properties[1] and benchmarking of heat treatment simulation[2]. The virtual heat treatment tool for monitoring and optimizing the HT Process (VHT) Project for intelligent manufacturing systems (IMS) of Manufacturing Science and Technology Center Data was undertaken to develop technology for optimization through simulation, databases, artificial intelligence (AI) and other tools[3]. Komatsu jointed this project and further enhanced its technology.

In this research, a heat treatment database was first developed on gears, which are typical heat-treated parts, and data was input. Next, as heat treatment simulation technology, benchmark simulation was conducted to refine analysis technology and to evaluate the accuracy of the simulation analysis. Lastly, a study of fluctuations in heat treatment quality during manufacture was conducted using this database and parts and simulation. These development and study cases are summarized.

2. Construction of Heat Treatment Database

The database system JCaP [4] sold on the market was used as a heat treatment database of heat-treated parts because JCaP met the necessary requirements. In the project, a database whose configuration is shown in **Fig. 1** was developed, and more than 6,300 data groups of various plants on carburized and induction hardened gears were input to it. This database is accessed by the related departments of Komatsu through an in-house LAN and is used in forecasting heat treatment quality, studies of drawing standards, selection of steels, setting heat treatment conditions, and evaluation of quality fluctuations in heat treatment in high-volume production.



(a) Configuration of heat treatment database (b) Example of input sheet for the database

Fig. 1 Newly developed heat treatment database

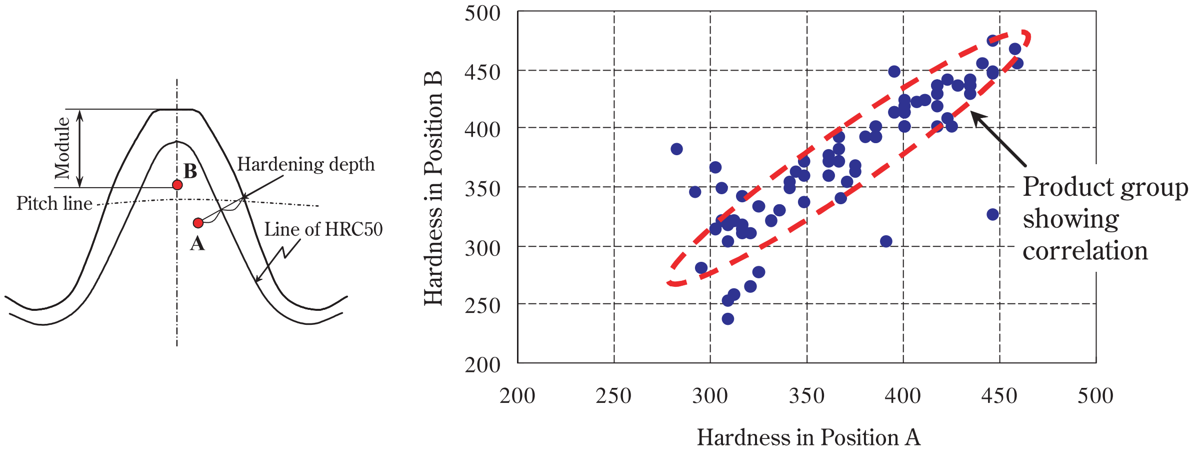


Fig. 2 Relationship of hardness of matrix in different positions of carburized gears

As an example of utilization of this database, evaluation of hardness in two positions (Positions A and B) of the matrixes (uncarburized parts) of gears with different modules is shown in **Fig. 2**. Positions A and B show a strong correlation in hardness. However, some parts deviate from this correlation, and these cases can be checked. As in this case, the quality of parts that are manufactured in high volume can be evaluated easily using the database.

3. Enhanced Heat Treatment Simulation Technique

3.1 Enhanced analysis functions

Heat treatment simulation currently requires the analysis of partial models of parts in more detail and analysis of overall models to evaluate heat treatment strains. For example, in the case of carburized gears, the profile of one tooth has to be split into a fine mesh to evaluate the gear accuracy, requiring analysis using cyclic symmetry boundary condition. Models of entire parts have to be fabricated to analyze deformation of entire parts such as bending and distortion so that the models become large.

An analysis function cyclic symmetry boundary condtion was developed adding the function to the heat treatment simulation that has been developed in the past (GRANTAS)[5), 6)]. As for elasto-plastic analysis, an analysis speed about 90 times faster compared with the conventional method was attained using the static implicit method and a high-speed matrix solver such as the ICCG method in order to dramatically increase the analysis speed. This enables the analysis of large-scale models such as those with about 40,000 nodes, which has not been possible in the past in one day using a personal computer. Top-class analysis speed in heat treatment simulation has been accomplished.

3.2 Benchmark simulation

In benchmark simulation to evaluate the analysis accuracy of simulation, the collection of data on steel properties, identification of heat transfer coefficient during quenching in experiments and measurement of heat treatment quality were conducted as joint work to best avoid uncertain factors and to precisely evaluate the analysis results. The analysis results and measured values were compared and studied.

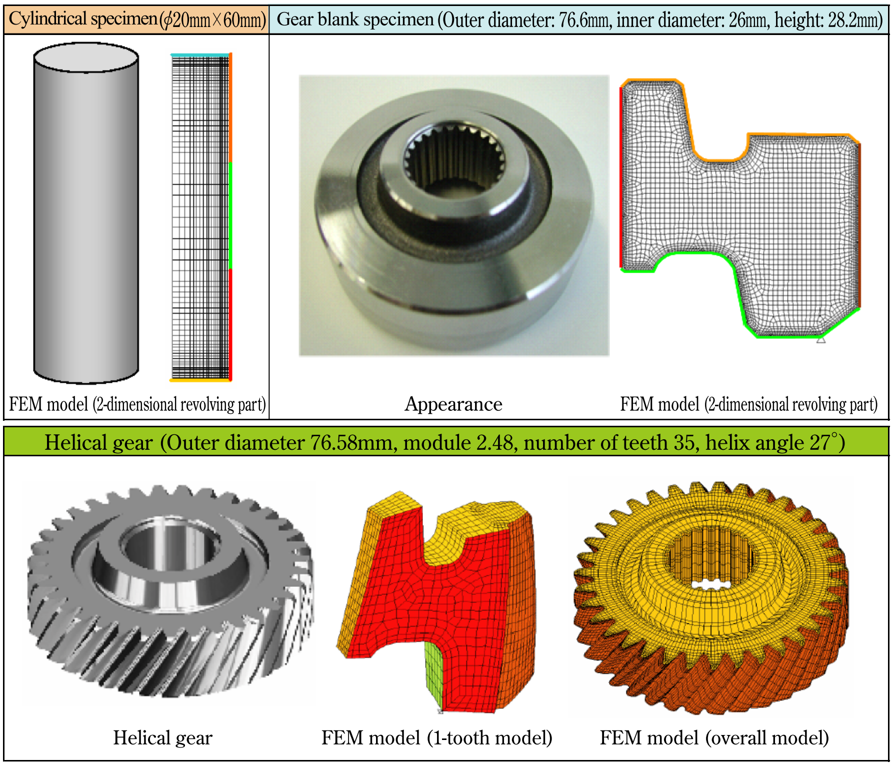


Fig. 3 Test piece and analysis model

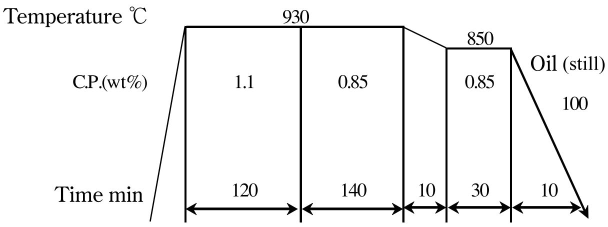


Fig. 4 Conditions for gas carburizing and quenching

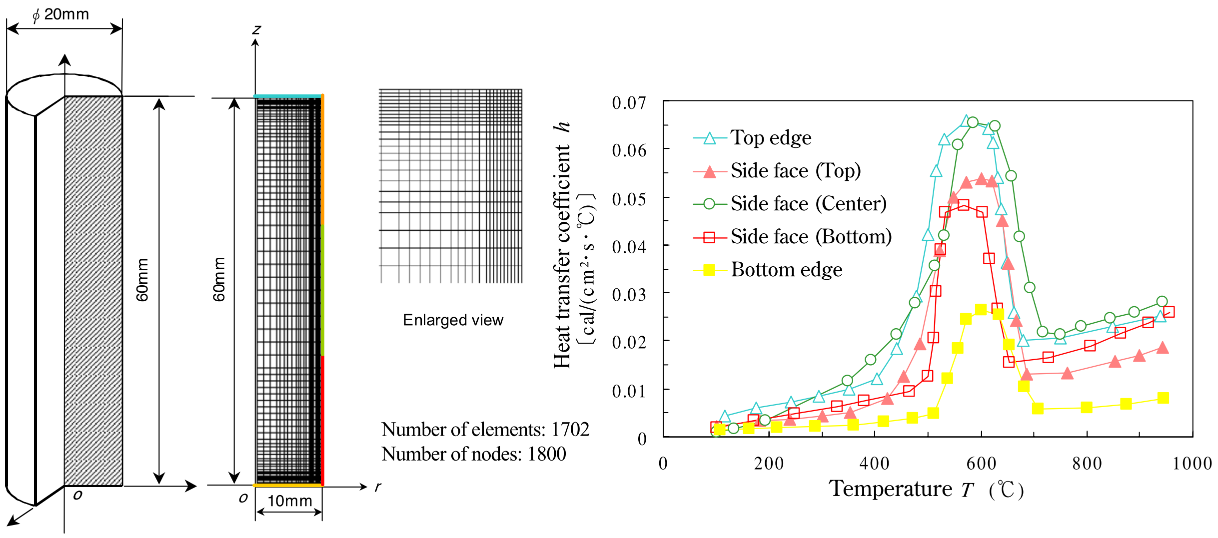
3.2.1 Experiment and analysis method

Cylindrical specimen, gear blank specimens that were not cut to fabricate gears and helical gears were tested in this research to evaluate the impact of shape by heat treatment experiment and simulation using the analysis models shown in Fig. 3. The measured values and the calculated values were studied by comparing them. As the heat treatment experiment, low-alloy steel (JIS SCr420) generally used in automobile gears was used as the steel and was gas curburized under the conditions shown in Fig. 4. The low-alloy steel was quenched in still oil. The cylindrical test piece was placed vertically during quenching, while the gear blank specimen and helical gear were placed horizontally. The heat transfer coefficient of the cylindrical test piece and gear blank specimen in the analysis of the quenching process that were set for each region of the parts based on the measured cooling curves were used. The same heat transfer coefficient as that for the blank specimen was used in analyzing the test helical gear.

3.2.2 Results of experiments and analysis

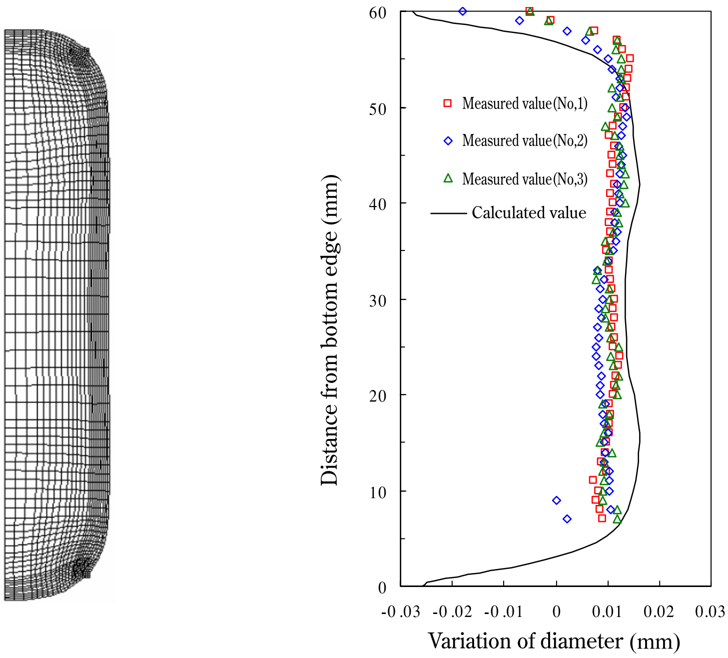
(1) Cylindrical specimen

Identification of the heat transfer coefficient on the surface in analysis of heat transfer during quenching was obtained by calculating an approximate value of the heat transfer coefficient from the cooling curve of a silver cylindrical test piece using the lumped heat capacity method and the quenching process of the SCr420 steel cylinder was conducted using the value as an initial surface boundary condition. A value that was obtained by repeating corrections of the heat transfer coefficient so as to approximate the calculated value of the cooling curve to the measured value was used[7]. The analysis model and the heat transfer coefficient that were calculated are shown in Fig. 5. The shape after deformation following carburizing and quenching obtained in the analysis that used this heat transfer coefficient (deformation indicated in the diagram at a magnification of 100) and the amount of deformation in the radial direction are shown in Fig. 6. Good results could be obtained with the calculated values in that the amount of deformation and overall shape were almost identical to the measured values.



(a) Analysis model (b) Heat transfer coefficient

Fig. 5 Analysis model and heat transfer coefficient of cylindrical specimen



(a) Calculation results (b) Measured and calculated values

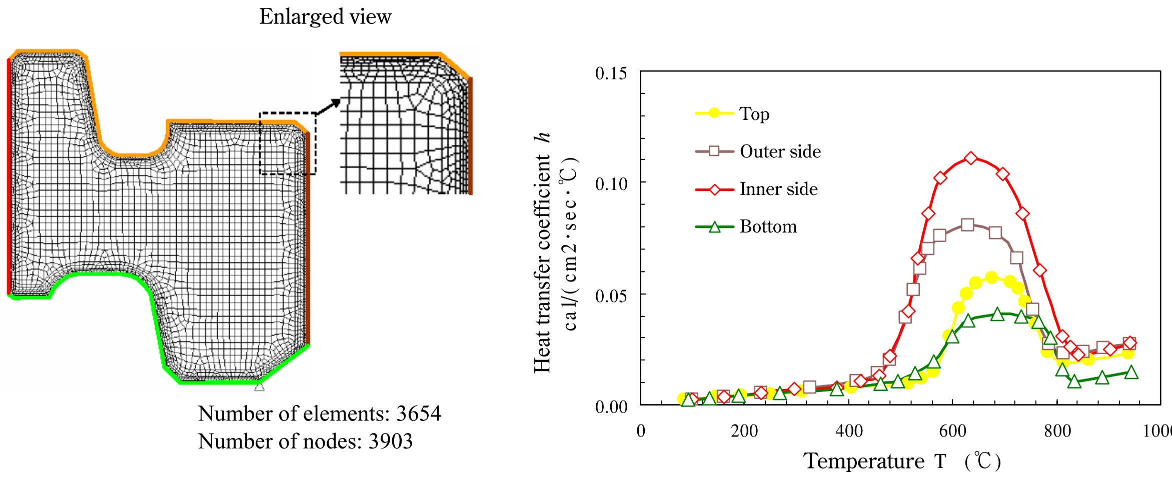
(Displacement indicated at magnification of 100)

Fig. 6 Deformation of cylindrical specimen after carburizing and quenching

(2) The helical gear blank specimen

The helical gear blank specimen was analyzed using entirely the same data as those for the cylindrical test piece except for the heat transfer coefficient during quenching. Identification of the coefficient of thermal conductivity on the surface used in the analysis of heat transfer during quenching was performed using the same method as that used for the cylindrical test piece. **Fig. 7** shows the analysis model of the gear blank specimen and the heat transfer coefficient that was obtained. The hardness distribution of the gear blank specimen after carburizing and quenching is plotted in **Fig. 8**.

The calculated values show a hardness distribution almost identical to the measured values, indicating that differences in hardness due to position are also evaluated. However, the calculated values are somewhat higher than the measured values for hardness near the surface. The amount of retained austenite in the high-carbon-concentration region increases due to stabilization of the residual austenite during quenching when the oil temperature is especially high as in this experiment. Lowering of hardness due to this needs be taken into consideration in simulation.



(a) Analysis model (b) Heat transfer coefficient

Fig. 7 Analysis model and heat transfer coefficient of gear blank specimen

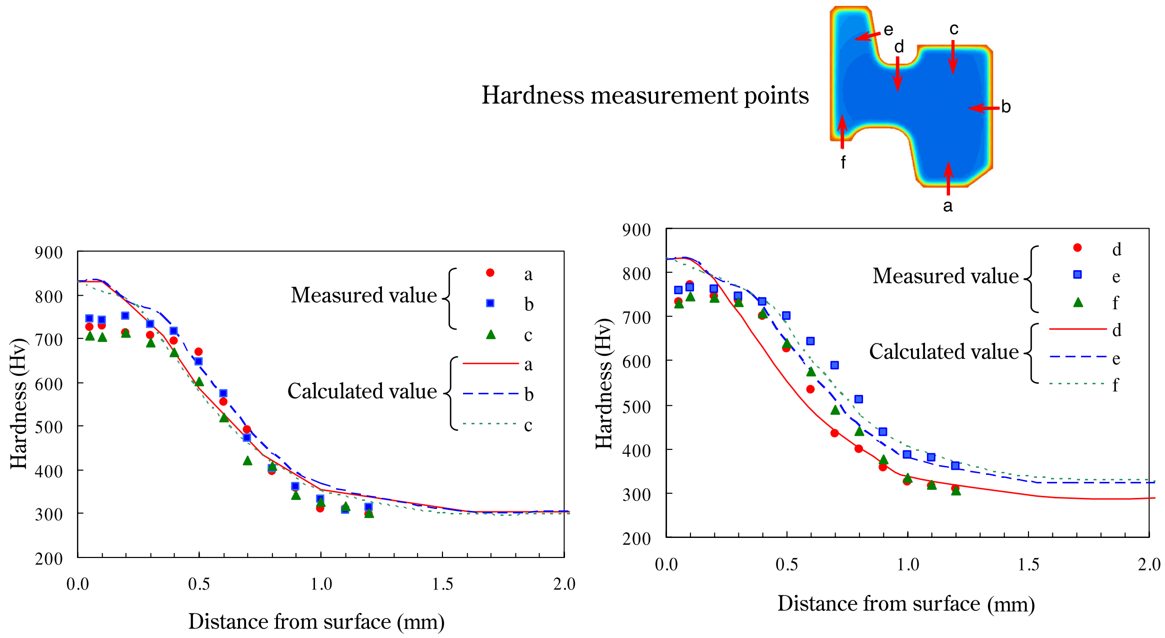


Fig. 8 Hardness distribution of gear blank specimen after carburizing and quenching

Fig. 9 illustrates the shapes before and after carburizing and quenching. In the diagram, the shape after deformation is shown by increasing the amount of deformation 100 times to more clearly show deformation trends. The diagram shows that the outer diameter is shrunk in radial deformation in the measured values and that most of the shrinkage occurs on the bottom. The calculated values also show similar shrinkage and the shape also produces similar results. Compared with the measured values, the calculated values are about 1/2 that of the measured values in the amount of deformation. This may be explained by differences in the timing of phase transformation, which are easily due to the balance in the cooling properties, the quenching properties of the steel and other factors when a part whose mass is different in inner and outer diameters is quenched. Discrepancy is liable to occur between the actual situation and the simulation in these circumstances. The amount of deformation for the top in the height direction when the bottom is used as the standard was almost identical between the measured and the calculated values. Furthermore, whereas the measured values are almost flat on the face of the external periphery on the top, the calculated values incline toward the outer diameter side, and the shape after deformation does not match. Nevertheless, the shapes of the other faces after the deformation show a trend that is relatively similar between the measured and the calculated values. It is safe to conclude that the overall deformation is reproduced by the simulation.

Variations in outer and inner diameter before and after carburizing and quenching are plotted in **Fig. 10**. The measured values show deformation where the outer diameter swells and the inner diameter shrinks. Compared with this, both the outer diameter and inner diameter of the calculated values show shrinkage, indicating differences in variations in outer diameter.

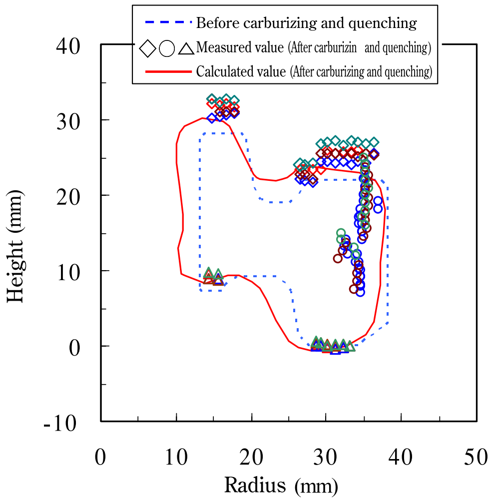


Fig. 9 Deformation of gear blank specimen after carburizing and quenching
(Displacement indicated at magnification of 100)

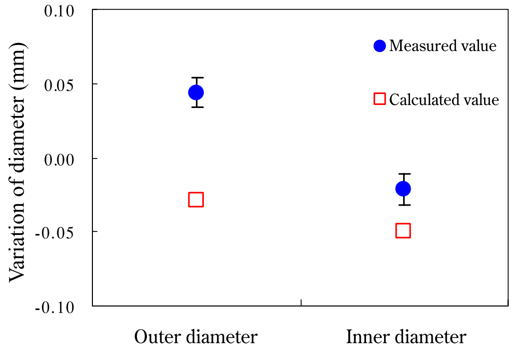


Fig. 10 Diameter variation of gear blank specimen after carburizing and quenching

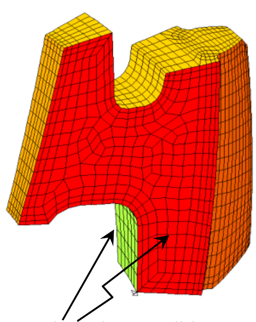
(3) Helical gear

The analysis of helical gears required an overall model to evaluate deformation of the entire gear. However, due to the processing ability of the computer (personal computer), fine-mesh division (large-scale model) was limited. The analysis was therefore conducted by fabricating a one-tooth model with a fine-mesh division and an overall model with a slightly rough-mesh division as shown in **Fig. 11**. The same heat transfer coefficient as that used with the gear blank specimen was used in analyzing the helical gears.

Fig. 12 compares the measured values in the hardness distribution of the teeth after carburizing and quenching and the calculated values of the one-tooth model. The analysis accuracy was good. **Fig. 13** shows the calculation results of the deformation of the one-tooth model and the overall model after carburizing and quenching by enlarging 50 times. The front view of tooth trace deformation tends to show deformation whereby the tooth traces at both ends of the teeth become prominent; that is, the helical angles tend to decrease. The tooth deformation with the one-tooth model and the overall model shows almost identical trends.

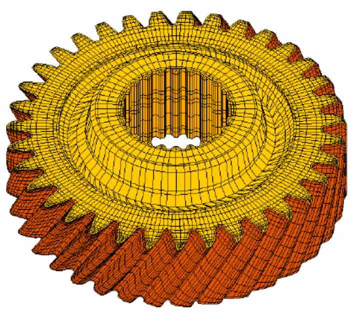
Variations in the inner diameter of the blank specimen and the helical gear before and after carburizing and quenching are plotted in **Fig. 14**. The differences between the one-tooth model and the overall model are not very large, indicating that deformation can be evaluated with the overall sample that had a slightly rough mesh. Compared with the blank specimen, the inner-diameter spline of the helical gear greatly shrank in the measured values. Compared with this, the shrinkage of the inner-diameter spline of the helical gear was somewhat smaller than the shrinkage of the blank specimen, showing a reverse trend compared with the measured values. The amount of deformation also greatly differed from the measured values. This can be attributed mainly to the impact of the heat transfer coefficient. It will be necessary to set a heat transfer coefficient that can reproduce cooling curves of helical gears in the future to study diameter variations caused by the impact of cooling on the inner and outer diameters.

The calculation results of the bear blank specimens to the one-tooth model and the overall model after carburizing and quenching are shown in **Fig. 15**. Large gear blank specimens by compression were applied to the roots of the one-tooth model and the overall model as axial stresses. The gear blank specimens are almost equal in the one-tooth model and the overall model.



Number of elements: 4518
Number of nodes: 5641

(a) One-tooth model



Number of elements: 35726
Number of nodes: 42980

(b) Overall model

Fig. 11 Analysis model of helical gear

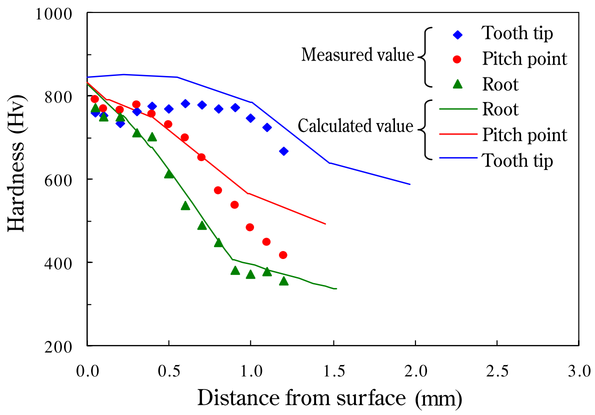


Fig. 12 Hardness distribution of helical gear after carburizing and quenching

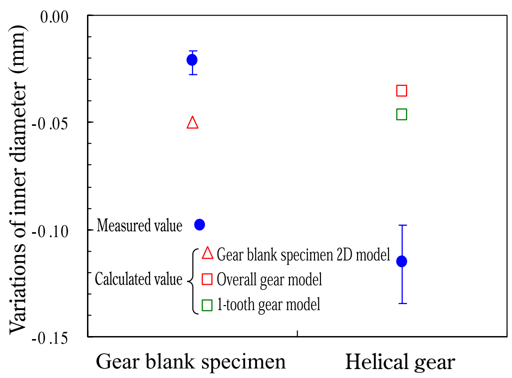


Fig. 14 Variations of inner-diameter spline diameters of gear blank specimen and helical gear

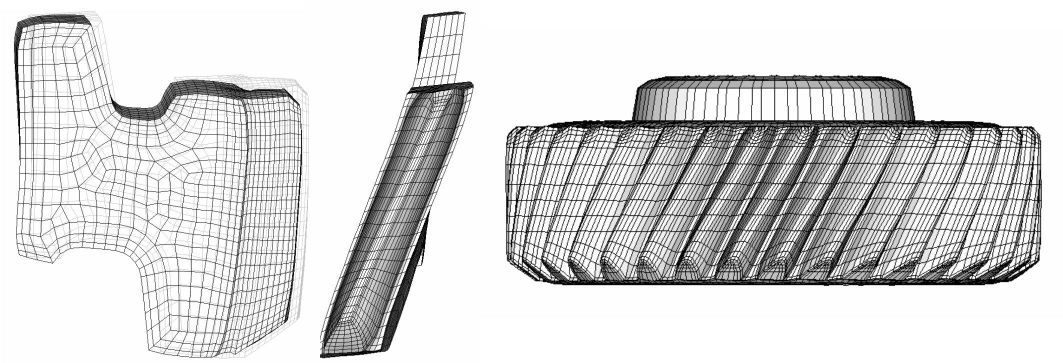


Fig. 13 Calculated distortion of helical gear after carburizing and quenching (Displacement indicated at magnification of 50)

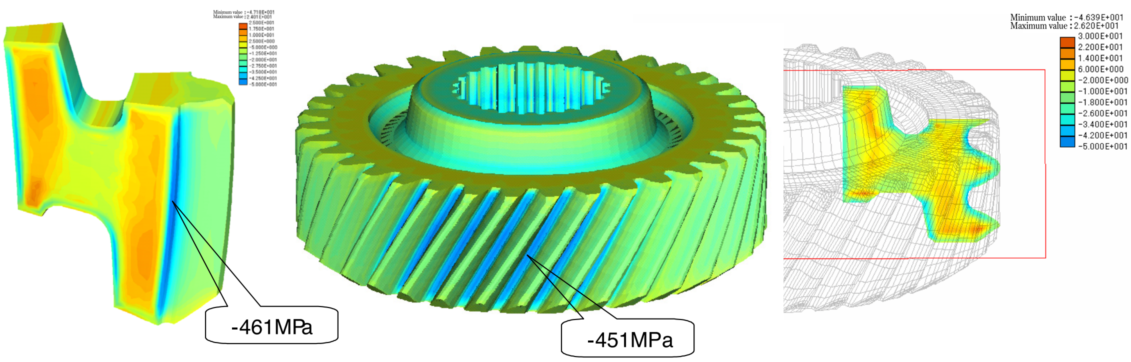


Fig. 15 Calculated residual stress of helical gear after carburizing and quenching

4. Application Examples of Database and Simulation

Hardness distribution is an important quality of heat-treated parts and the fluctuation range of hardness during high-volume production of gears is an important control item to ensure the fatigue strength. Forecasts of fluctuation ranges of hardness during high-volume production are necessary for parts that are to be developed anew. To quantitatively evaluate the hardness fluctuation range, factors that affect the hardness were evaluated by combining the database and simulation. In the following example, the hardening depth and matrix hardness of the teeth of carburized gears that were produced in large quantities were evaluated.

The spur gears of Module 3.25 were evaluated using SCM418H by carburizing and quenching them. As factors that affect gear hardness, fluctuations in the quenching proper-

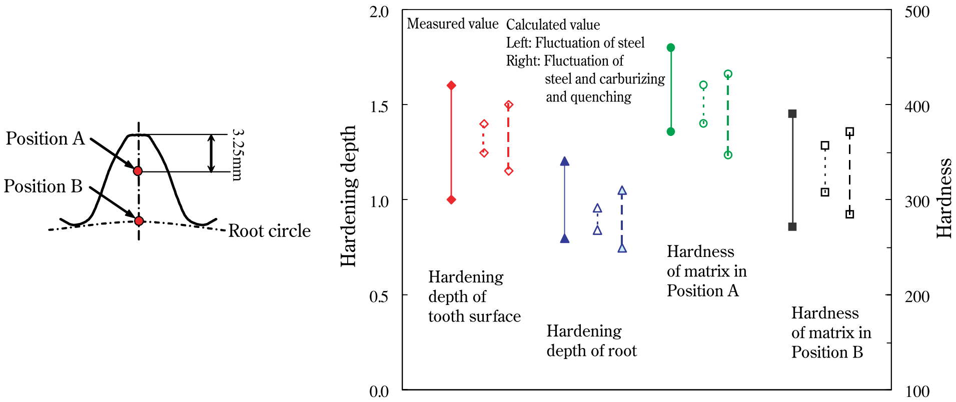


Fig. 16 Hardness fluctuations of gear taking change in steel and fluctuations of heat treatment conditions into consideration (Measured and calculated values)

ties of steel and heat treatment conditions were evaluated. Using performance data input to the database, the measured hardness values of 31 gears, the chemical components of 32 steel charges and their quenching properties (Jominy curves) were extracted. First, the high and low limits of the Jominy curves and their chemical compositions were used in the simulation as actual values of steel to evaluate the impact of fluctuations in the chemical compositions of steel. The other conditions were made constant.

Next, as fluctuations in the carburizing and quenching process, simulation was performed taking into consideration the carburizing conditions (carburizing temperature and carbon potential) and fluctuations in the coefficient of thermal conductivity during quenching. The fluctuation range of the carburizing conditions were set based on results of actual operating conditions, and a value that could reproduce the fluctuation range of the matrix hardness was used as the heat transfer coefficient during quenching. The actual hardness data and simulation results are plotted in Fig. 16. The calculated values on the left-hand side of the diagram are the fluctuation range of hardness by the chemical composition of steel, and the calculated values on the right-hand side are the fluctuation range of hardness by fluctuations in heat treatment conditions. The plotting shows that more than 84% of the gears are within the range of the hardening depth forecasted by the simulation, and that more than 84% of the gears are within the forecasted range of the matrix hardness when the fluctuation range of the heat transfer coefficient is estimated to be about 30%. The results confirm that simulation can almost evaluate the actual fluctuation range of hardness.

5. Conclusion

A heat treatment database on gears was developed, and the performance data of carburized and induction hardened gears during high-volume production was input. To enhance the simulation technology, analysis functions that used cyclic symmetry boundary condition were developed, and a significant improvement was made to increase the analysis speed. Using these results, benchmark simulation was performed. The following was achieved as conclusions of this research.

(1) A database comprising basic information, heat treatment quality, steel data, heat treatment conditions and drawing information was developed as a heat treatment database on gears, containing more than 6,300 data groups.

(2) The database thus constructed has been opened to related in-house departments through an in-house LAN and is now being used.

(3) Analysis functions cyclic symmetry boundary condtion were developed to enhance the simulation technology. As for elasto-plastic analysis, an analysis speed about 90 times faster compared with the conventional method was attained, achieving a top-class analysis speed using the static implicit method and a high-speed matrix solver such as the ICCG method.

(4) As benchmark simulation, a cylinder test using SCr420 steel and simulation of the carburizing and quenching process of gear blank specimens and helical gears were conducted. The results showed a relatively good match with the measured values in the hardness and overall deformation trends of the shapes. Nevertheless, differences were observed in the amount of strain such as fluctuations in the inside diameters of the helical gears, and a continuous study is needed in the future.

(5) A forecast of hardness fluctuations in carburized gears during high-volume production was performed using the heat treatment database and simulation. The forecast results show that actual fluctuation ranges can be evaluated by simulation.

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Introduction of the writer

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[A few words from the writer]

Handing down organization-developed technologies has become more difficult than before, and this situation has become an imminent problem for us. Parts in construction equipment in particular are diverse in shape and material. Furthermore, they are large. For this reason, the transmission of organization-developed technologies is very difficult in heat treatment that is strongly influenced by shape, steel and mass effects. Nurturing human resources alone will not solve all problems, and technology that will make possible theoretical studies using simulation and other techniques will become indispensable in the future, in addition to the accumulation and effective utilization of technical information in the past such as databases. Our plans for the future include the expansion of our technology to materials, evolving to the simulation of fatigue strength.