Analysis of Distortion Mechanism of Rolling Bearing Rings in Normal Quenching and Carburized Quenching

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This report introduces an application example of a heat treatment simulation technology in analyzing phenomena of the heat treatment process which are complicated and difficult to verify through experiments. Defining heat transfer coefficients conforming to actual temperature measurements has made it possible to perform heat treatment simulations that correspond closely to actual distortions. We have utilized this simulation technology to verify the heat distortion mechanism in normal quenching and carburized quenching, and as a result, predict that regarding heat treatment distortion produced in the oil quenching process, normal quenching, which causes martensitic transformation first on surfaces, is more sensitive than carburized quenching. From this, we have established that in the case of normal quenching, uniform cooling in the oil quenching process is effective for reducing heat treatment distortion, whereas for carburized quenching, it is important to implement measures in other processes.

Key Words: *heat treatment simulation, oil quenching, heat transfer coefficient, distortion, transformation plasticity*

1. Introduction

Portions of rings and rolling elements of rolling bearing rings must be able to withstand several GPa of contact stress and must therefore be heat treated either with high-carbon chromium bearing steel (e.g. JIS-SUJ variety) or carburized steel (e.g. JIS-SCr variety).

While improving strength, heat treatment induces the problem of heat treatment distortion. This distortion is corrected by grinding or other downstream processes but it is often the chief cause of increased manufacturing costs. Consequently, there is a strong demand to reduce the amount of heat treatment distortion. However, the various phenomena of the heat treatment process (temperature, phase transformation, stress, strain changes, etc.) are extremely complex, and the visualization of the various processes such as carburization at a high temperature or soaking, rapid cooling at quenching, etc., is difficult. These are considered to be the reasons why the approach to reducing heat treatment distortion has never advanced beyond the *qualitative indicator of making a simpler part shape and heating/cooling uniformly.* Indeed, there are still many unknowns regarding the impact each of the carburized quenching processes of heating, carburization, soaking, quenching (cooling) has on heat treatment distortion. For this reason, the reduction of heat treatment distortion is generally a process of trial and error reliant on the know-how of highly-experienced technicians.

Heat treatment simulation is a technology where the physical phenomena of the heat treatment process is calculated using finite element analysis. This technology has been implemented in a number of general-purpose software[1)] and makes it possible to verify the history of heat treatment process phenomena, which had been difficult with conventional testing. It is thought to be an effective means to consider the consequences of the conditions and results that create heat treatment distortion. However, the issue of analysis accuracy for the current heat treatment simulation technology needs addressing, as it is suggested that accuracy of the various input data required for such analysis (material property data and heat transfer coefficients, etc.) needs improving [2), 3)].

This report will introduce experiments and simulations on JTEKT's anchor product, the rolling bearing ring, to verify the differences between heat treatment distortion mechanisms in the cooling processes of normal quenching and carburized quenching. Identically-shaped rolling bearing rings will be used for these verifications and findings will be considered for use in the improvement of heat treatment simulation analysis accuracy, and the reduction of heat treatment distortion.

2. Action to Increase Accuracy of Heat Treatment Simulation

2. 1 Configuration of Heat Treatment Simulation

The framework for simulating the various phenomena which occur in the heat treatment processes of heating and cooling such as temperature, phase transformation, stress, strain, etc., was established in the 1980s[4). **Figure 1** shows the system for heat treatment simulation. Numerical analysis (Ⅰ) is the portion where elements necessary for heat treatment, (i.e. heat transfer, phase transformation, elasto-plastic and carbon diffusion) are calculated using a basic equation in accordance with the finite element method. How each of these elements effect the other (coupling) is also considered in this calculation. Next, material properties (Ⅱ) indicate the material property data necessary for calculations. Data dependent on temperature and carbon concentration such as the thermophysical properties, mechanical properties, linear expansion coefficient and phase transformation properties (time-temperature-transformation, transformation plasticity, etc.) of the steel grade is necessary. Finally, boundary conditions (Ⅲ) are the dynamic constraints necessary for elasto-plastic analysis and heat transfer coefficient necessary to calculate temperature change during quenching (cooling). JTEKT uses a heat treatment simulation software called DEFORM™-HT[5), which has systemized this framework to allow prediction of distortion, residual stress distribution, microstructure phase distribution, hardness distribution, carbon diffusion and so on of the rolling bearing ring.

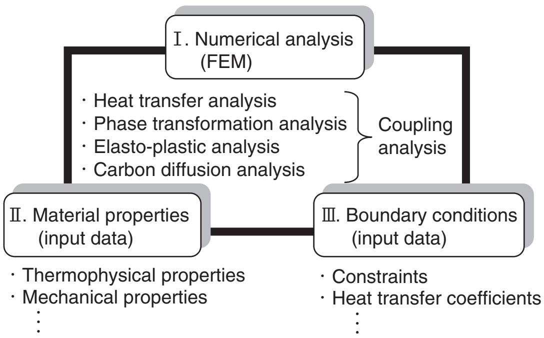

Fig. 1 Heat treatment simulation system

2. 2 Example of Heat Transfer Coefficient Calculation in Rolling Bearing Rings

All three parts of the system shown in **Fig. 1** of numerical analysis, material properties and boundary conditions, are required to accurately simulate heat treatment phenomena. The boundary conditions of the heat transfer coefficient change significantly depending on factors such as size, shape, applied temperature, quenching/cooling agent (coolant) and cooling agent (coolant) mixing method. Changes in the heat transfer coefficient greatly effect analysis results[3). These factors are generally determined by the technology and conditions peculiar to individual companies which use heat treatment (simulation software users). In other words, users need to accumulate know-how on the heat transfer coefficients to support their company's products and heat treatment conditions. This report introduces an example of calculating the heat transfer coefficient of oil quenched rolling bearing rings.

2. 2. 1 Various Heat Treatment Coefficient Calculation Methods

Typical calculation methods used for heat transfer coefficients in the rapid cooling process during quenching are the temperature gradient measurement method, steady state method, concentrated heat capacity method and inverse analysis. Of these, the most commonly used are the concentrated heat capacity method and inverse analysis[6). This report introduces a way of calculating the surface heat transfer coefficient from the measured cooling curve at an arbitrary position of the material subjected to heat treatment using inverse analysis, a method appropriate for steel parts with a relatively small heat transfer ratio.

2. 2. 2 Heat Transfer Coefficient Calculation

1) Cooling Curve Measurement

JTEKT uses an oil tank vacuum purging type horizontal batch furnace to continuously measure temperatures during heating, soaking and cooling processes, thus obtaining the cooling curve for actual quenching. By using a thermocouple transfer arm that follows the movement of the basket from the heating chamber to the oil tank (**Fig. 2**(a)), it is possible to measure the temperature changes in these processes at an arbitrary position within the basket (**Fig. 2**(b)) for the rolling bearing ring's cross-section and circumferential position.

Figure 3 shows the cooling curve when a rolling bearing ring with an outer diameter of ϕ72 mm, an inner diameter of ϕ62 mm, and a width of 17 mm is placed in the basket and from a holding temperature of 830℃

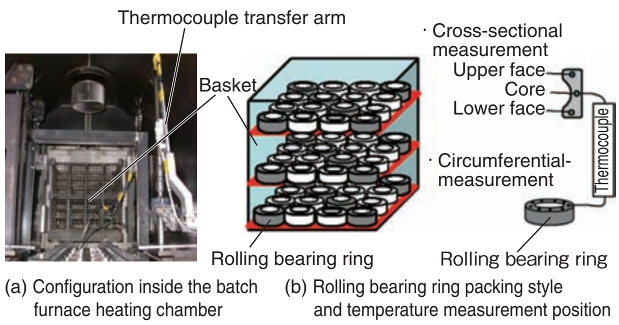

Fig. 2 Measurement method for cooling curves

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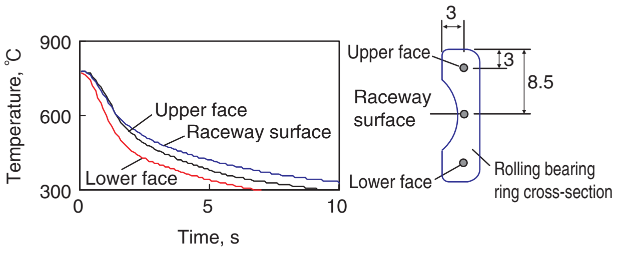

Fig. 3 Cooling curves of rolling bearing ring

is quenched with cold oil (oil temp. 80℃, no mixing). Temperature is measured using a grounded type sheath thermocoupleof ϕ1 mm. The figure shows that a difference arises in the cooling rate of the trajectory surface, upper face and lower face, with the order from fastest to slowest being lower face, upper face, then trajectory surface.

2) Inverse Analysis Application and Heat Transfer Coefficient Calculation

In inverse analysis, by setting the measured values shown in **Fig. 3** as input data, and using the inverse analysis templates of DEFORM^{TM}-HT, "Inverse Heat Transfer Templates", a heat transfer coefficient with a cooling curve of measured value ≒ calculated value, can be obtained. Here it must be pointed out that the solution is not necessary unique and inverse analysis has a flaw whereby multiple heat transfer coefficient solutions for which the measured value ≒ calculated value, could exist. In other words, depending on how the initial heat transfer coefficient required for inverse-analysis input data is applied, a different heat transfer coefficient solution will be obtained. As such, inverse analysis requires an appropriate initial value to be established in accordance with a physical principal.

At JTEKT, we have established the precondition of categorization into the individual stages of steam film, boiling and convection, which are characteristic to liquid cooling coolant such as oil. These are shown in **Fig. 4**. In addition, we have referred to heat transfer coefficients reported in the past with similar forms[7] (in the case of rolling bearing rings this is equivalent to ring test pieces) and adopted a method of defining heat transfer coefficient

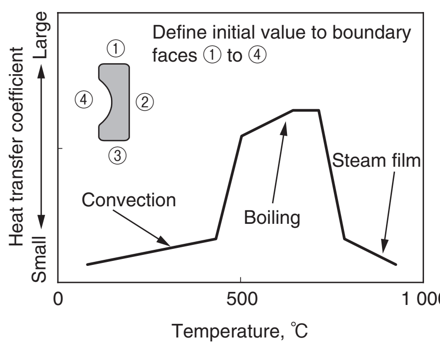

Fig. 4 Precondition for the initial heat transfer coefficient

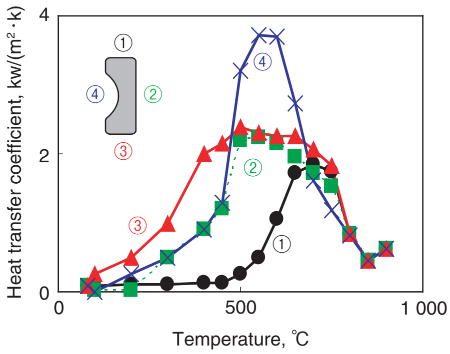

Fig. 5 Calculated heat transfer coefficient

initial values when performing inverse analysis. By using this method, for example in the case of oil quenching of a rolling bearing ring as shown in **Fig. 3**, it is possible to determine a heat transfer coefficient which considers the temperature dependency of the steam film, boiling and convection of all the boundary surfaces shown in **Fig. 5** of ① to ④ and thereby simulate quenching corresponding with actual non-uniform cooling.

3. Verification of the Heat Treatment Distortion Mechanisms of Normal Quenching and Carburized Quenching

3. 1 Focal Points of Mechanism Verification

Figure 6 is an example of the lead-up to heat treatment distortion occurrence in rolling bearing rings subjected to normal quenching and carburized quenching. As the figure shows, carburized quenching differs from normal quenching as the material is carbon steel and the upstream processes of forging and turning, as well as carburization and soaking processes are added. However, as heat treatment distortion is often evaluated after heat treatment (oil quenching) there are not many reports on how, for example, the added processes of carburization and soaking ultimately effect heat treatment distortion in products that have undergone carburized quenching and how this effect differs to normal quenching, which only involves the soaking process. That is to say, the reduction of heat treatment distortion of rolling bearing rings subject to normal quenching and carburized quenching should focus on the respective processes, but this is obviously not the case currently. As the first step in clarifying the contribution of each process to heat treatment distortion,

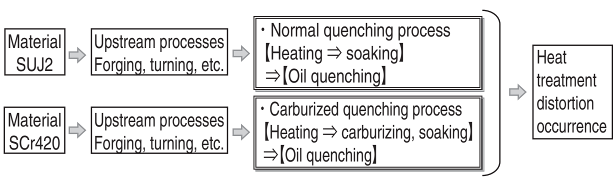

Fig. 6 Process of normal quenching and carburized quenching for rolling bearing ring

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we introduce an example which verifies only the impact of the oil quenching process of normal and carburized quenching on heat treatment distortion. In concrete terms, verification was made through quenching of a rolling bearing ring excluding the impact of upstream processes such as residual stress, heating, soaking and carburization and a simulated heat treatment with heat transfer coefficients equivalent to oil quenching.

3. 2 Experiment and Simulation Conditions

3. 2. 1 Test Pieces for Quenching Experiments

Two rolling bearing ring test pieces (ODϕ72, IDϕ62, W17) were fabricated, one from SUJ2, and the other from SCr420. The SUJ2 rolling bearing ring was spheroidized, turned, and then annealed to relieve stress. The SCr420 rolling bearing ring was turned, vacuum carburized, stood to cool, a predetermined carbon concentration diffusion obtained and finally annealed to relieve stress. **Figures 7** and **8** show the heat treatment qualities (hardness and microstructure) near the raceway surface for each test piece. The SUJ2 rolling bearing ring shown in **Fig. 7** is a uniform spheriodized structure with a hardness of approximately 200 HV. Meanwhile, the SCr420 rolling bearing ring of **Fig. 8** comprises of pearlite and cementite with 0.8% carbon content on the surface, ferrite and pearlite with 0.2% carbon content at the core, and a surface hardness of approximately 300 HV and core hardness of approximately 150 HV.

3. 2. 2 Quenching Experiment Conditions

In order to verify the impact of oil quenching in isolation, the quenching experiment used high-frequency induction heating which achieves uniform heating and soaking in a short time. After induction heating the SUJ2

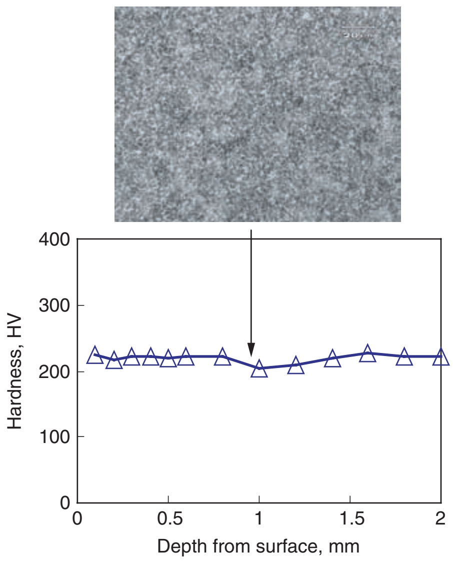


Fig. 7 Pre-quenching hardness and microstructure of SUJ2 rolling bearing ring

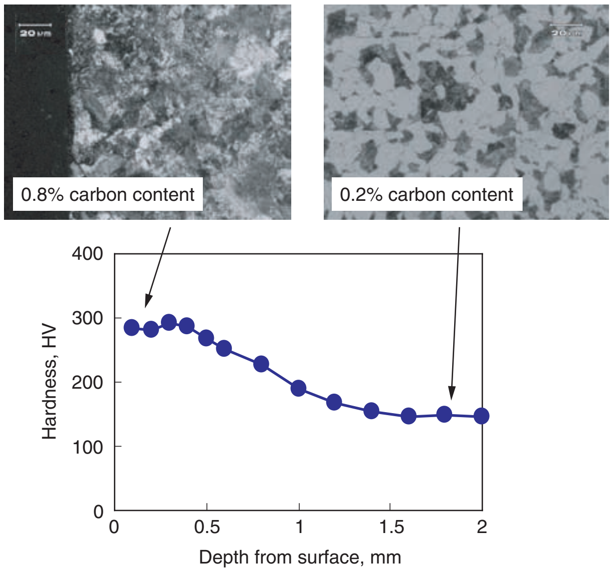


Fig. 8 Pre-quenching hardness and microstructure of SCr420 rolling bearing ring

and SCr420 rolling bearing rings shown in **Figs. 7** and **8** at a frequency of 1 kHz, output of 100 kW in less than a minute, they were quenched with cold oil (oil temp. 80℃, no mixing) so that the heat treatment distortion of the oil quenching alone could be evaluated, excluding the effects of residual stress and prolonged carburization from the upstream processes. Furthermore, the hardness of the SUJ2 test piece was approximately 820 HV across the total cross-section, whereas for the SCr420 test piece, surface hardness was approximately 820 HV, while core hardness was approximately 480 HV.

3. 2. 3 Quenching Simulation Conditions

The 3D finite element model shown in **Fig. 9** was used as analysis models for the SUJ2 and SCr420 test pieces. Half models were made with the YZ face symmetrical. There were 19 188 elements and 22 089 nodes. The material property data used thermophysical properties, mechanical properties, coefficient of linear expansion and phase transformation properties (isothermal transformation, transformation plasticity, etc.) with the temperature and carbon concentration dependency equivalent to JTEKT's SUJ2 and SCr420 taken into consideration. The heating

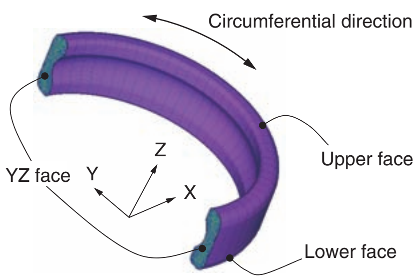


Fig. 9 Finite element model

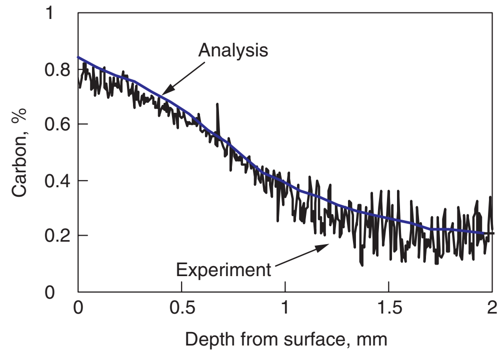


Fig. 10 Experimental and simulated carbon profiles of SCr420 rolling bearing ring

and soaking processes used a uniform temperature across all nodal nodes to correspond with the experiment and non-uniform cooling was only simulated for the oil quenching, using the heat transfer coefficients of the cold oil (80℃, no mixing) in **Fig. 5**. Carbon diffusion analysis was carried out on the SCr420 test piece prior to quenching analysis, and after simulating the carbon diffusion shown in **Fig. 10**, which is consistent with the heat treatment quality of **Fig. 8** obtained through vacuum carburization, oil quenching analysis was carried out.

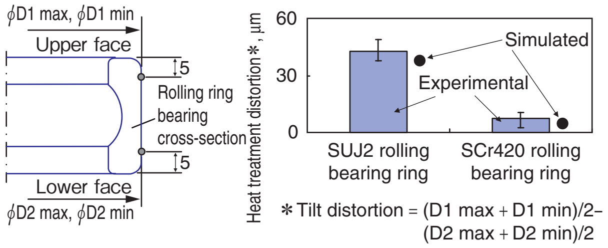


Fig. 11 Simulated and experimental distortion after oil quenching

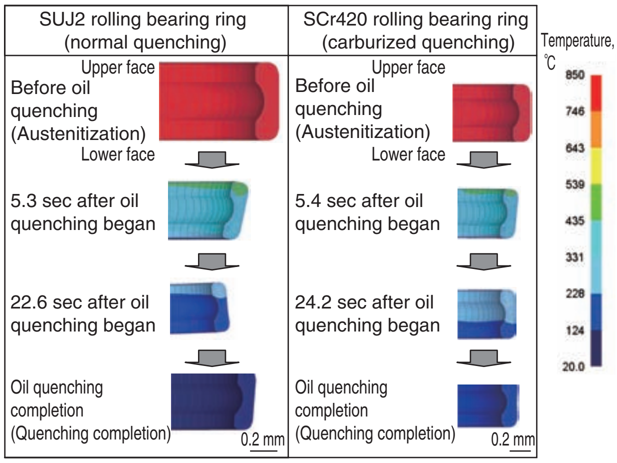


Fig. 12 Simulated temperature and distortion change through oil quenching of SUJ2 and SCr420 rolling bearing rings

3. 3 Results and Observations

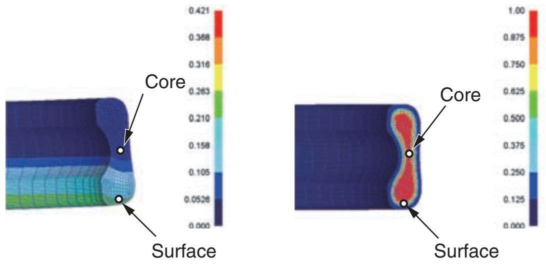
3. 3. 1 Distortion after Oil Quenching and Distortion History of the Oil Quenching Process

Figure 11 gives experimental and simulated results for heat treatment distortion following oil quenching. The heat treatment distortion mentioned hereinafter refers to the amount that the inner and outer circumferences of the rolling bearing ring lean in relation to the axial direction (tilt distortion). The figure confirms that the experimental and simulated results correspond well, and that the SUJ2 rolling bearing ring subjected to normal quenching had a bigger positive leaning distortion than the SCr420 rolling bearing ring subjected to carburized quenching.

Figure 12 gives the temperature and tilt distortion history of the oil quenching process found through simulation for the SUJ2 and SCr420 rolling bearing rings. In the case of the SUJ2 rolling bearing ring, 5.3 seconds after oil quenching began, a disparity in thermal shrinkage arose due to non-uniform cooling of the upper and lower faces, causing a positive leaning distortion to appear on the radial dimensions of the upper face larger than that of the lower face. Next, 22.6 seconds into the oil quenching process, due to the radial dimension of the upper and lower faces reversing, a negative tilt distortion occurred that was opposite to the abovementioned distortion which occurred after 5.3 seconds. When oil quenching was complete, the same positive tilt distortion appeared as that which appeared 5.3 seconds into the process. Meanwhile, oil quenching was commenced on the SCr420 rolling bearing ring in the same way (however, thermal expansion differs to the SUJ2 rolling bearing ring due the differing carbon contents) and 5.4 seconds later a positive tilt distortion appeared due the disparity in thermal shrinkage caused by non-uniform cooling. However, 24.2 seconds after oil quenching began, reversal of the relationship of the upper and lower face radial dimensions such as that seen in the SUJ2 rolling bearing ring was practically non-existent, with the same distortion as 24.2 seconds into the process being retained after oil quenching completion, demonstrating that the tilt distortion that occurs on the SUJ2 rolling bearing ring does not occur in the case of the SCr420 rolling bearing ring. From the above, we can predict that there is a high possibility the respective distortion histories upon oil quenching of the SUJ2 and SCr420 rolling bearing oil quenching differs.

3. 3. 2 Comparison of Normal Quenching and Carburized Quenching Distortion Mechanisms

The previous section proved through experiment and simulation that the tilt distortion history and amounts differed after oil quenching in normal quenching and carburized quenching. The reason for this was verified from the oil quenching process of martensitic



(a) SUJ2 rolling bearing ring (normal quenching) 22.6 sec later

(b) SCr420 rolling bearing ring (carburized quenching) 24.2 sec later

Fig. 13 Simulated results of volume fraction of martensite during oil quenching

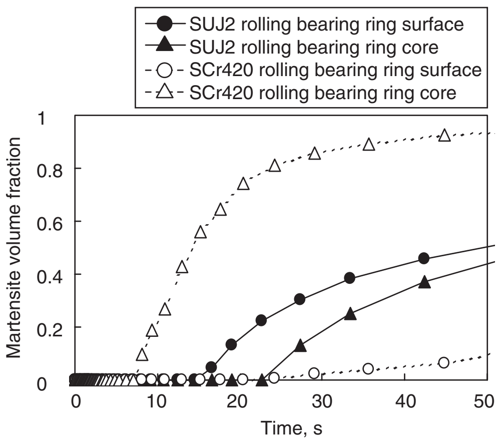


Fig. 14 Change of volume fraction of martensite during oil quenching

transformation and strain change. **Figure 13** shows martensite volume fractions of the SUJ2 and SCr420 rolling bearing rings 22.6 seconds and 24.2 seconds respectively into oil quenching. The behavior of these two test pieces differs in regards to tilt distortion. Also, **Fig. 14** shows the change in martensite volume fractions throughout the oil quenching process for the surfaces and core of the test pieces shown in **Fig. 13**. From **Figs. 13** and **14**, we can see that the martensitic transformation for the normally quenched SUJ2 rolling bearing ring progresses from the lower face surface which cools faster, to the core. In contrast, for the SCr420 rolling bearing ring subject to carburized quenching, martensitic transformation progresses from the core, irrelevant of cooling speed. This behavior in carburized quenching of martensitic transformation progressing from the core, the Ms point (martensitic transformation commencement temperature) depends on carbon content, and will lead to a reduction if the content of carbon increases[8].

Next, in order to further investigate how the differing martensitic transformation progression patterns of normal quenching and carburized quenching effect tilt distortion, we have looked at the circumferential strain related to that distortion. The individual circumferential strains were extracted along the upper face (AB) and lower face (CD) of the rolling bearing rings. **Figures 15** and **16** show the total circumferential strain and transformation plasticity strain during oil quenching (22.6 sec after commencement on SUJ2, 24.2 sec after commencement on SCr420) and after oil quenching is complete. Here, "total strain" is the sum of elasticity, heat, transformation, plasticity and transformation plasticity. These directly correspond with the tilt distortion of rolling bearing rings. Furthermore, transformation plasticity strain is a plasticity strain unique to heat treatment that occurs even under low stress such as the elasticity range of material in the process of martensitic transformation. It is calculated by a relation formula where the product of stress excluding hydrostatic pressure (stress deviation) and martensitic transformation speed is proportional to transformation plasticity strain speed[8].

For the SUJ2 rolling bearing ring shown in **Fig. 15**, the "During oil quenching" of (a) shows compressed transformation plasticity strain occurring due to transformation expansion on the lower face only where martensitic transformation has progressed. Meanwhile, the martensite on the upper face has not transformed, hence transformation plasticity strain has not occurred. Furthermore, total strain for the upper face is relatively smaller than that of the lower face, with the value reflecting a negative tilt distortion. The relationship of these upper and lower face transformation plasticity strains, in the "At oil quenching completion" of (b), is practically unchanged even after martensitic transformation has finished for the total cross-section, and this is reflected in the relationship of the upper and lower face total strains. In other words, we can predict that a positive tilt distortion occurs in normal quenching due to the difference in transformation plasticity strains of the upper and lower faces.

Meanwhile, in the case of the SCr420 rolling bearing ring shown in **Fig. 16**, in the "During oil cooling" of (a), martensitic transformation progresses from the core, with the austenite on the surface constraining the core. As a result, compressed transformation plasticity strain occurs at the core and, in the same way as the SUJ2 rolling bearing ring, due to the non-uniform cooling of the lower face with a faster cooling rate, is bigger on the lower face than the upper face. However, unlike the SUJ2 roller bearing ring, martensitic transformation has not occurred in the surface vicinity therefore transformation plasticity strain has not occurred and is zero for both the upper and lower faces. After this, in the "At oil quenching completion" of (b), because the martensitic transformation that was incomplete at (a) is now complete, compressed transformation plasticity strain has occurred in the surface vicinity. A point that should be noted here is that, compared with the SUJ2 rolling bearing ring, the

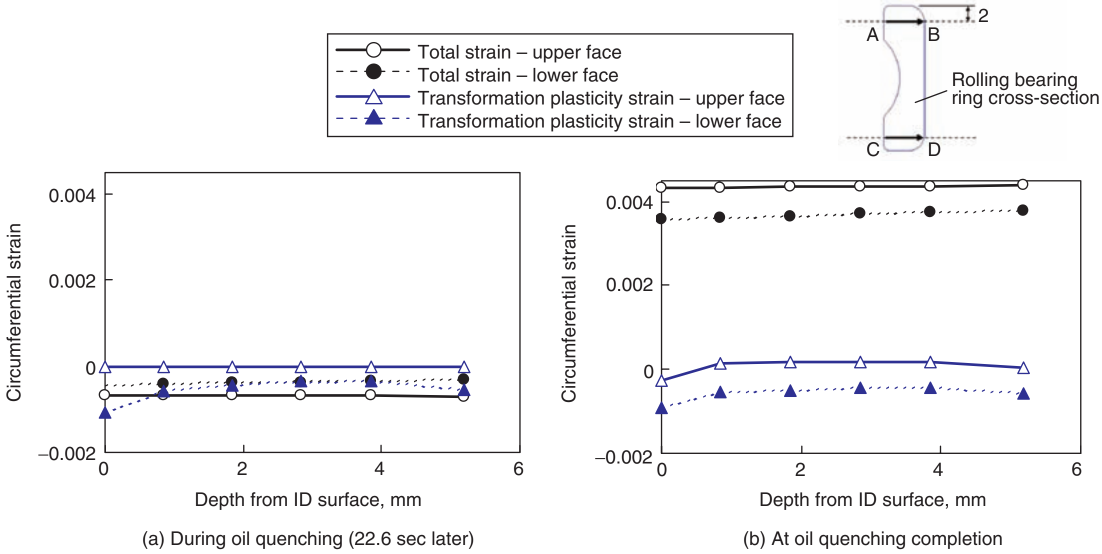


Fig. 15 Simulation results of tangential total strain and transformation plasticity strain during quenching of SUJ2 rolling bearing ring

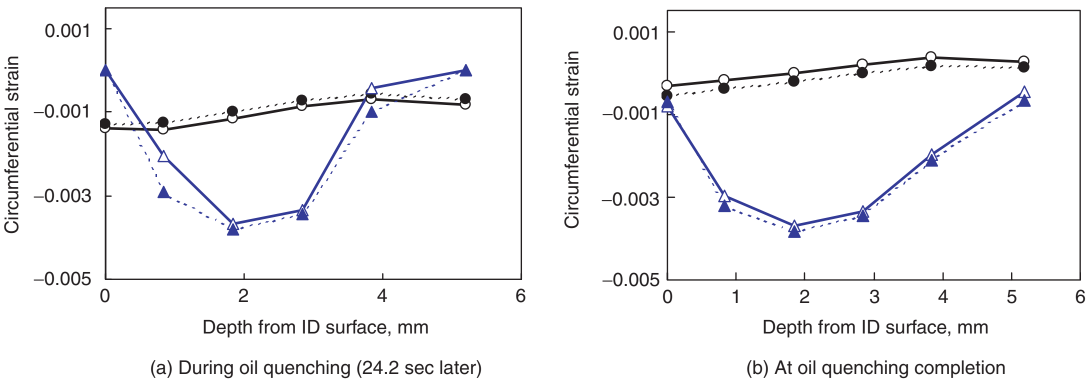


Fig. 16 Simulation results of tangential total strain and transformation plasticity strain during quenching of SCr420 rolling bearing ring

difference between the upper and lower transformation plasticity strains for the SCr420 rolling bearing ring is much smaller at oil quenching completion (b). This could be the reason why the tilt distortion of the SCr420 rolling bearing ring, which has undergone carburized quenching, is smaller than the tilt distortion of the SUJ2 rolling bearing ring, which has undergone normal quenching.

From the above, we can assume that the amount of tilt distortion differs between normal quenching and carburized quenching due to the significant difference in rolling bearing ring upper/lower face transformation plasticity strain behaviors in non-uniform cooling for the case where martensitic transformation occurs from the surface first (normal quenching) and the case where it occurs from the core first (carburized quenching). These results, insofar as a countermeasure for the reduction of heat treatment distortion, are an example that it would be effective to equalize the oil quenching process of normal quenching, whereas for carburized quenching it is important to develop countermeasures in other processes also.

4. Conclusion

This report has suggested a means of improving the analysis accuracy of heat treatment simulation and introduced heat treatment distortion mechanisms for normal quenching and carburized quenching using heat treatment simulation technology. Defining the heat transfer coefficient based on the actual cooling curve has made it possible to simulate heat treatment that corresponds well to actual distortion. From verifying the mechanism, we were able to predict that heat treatment distortion in the oil quenching process is more sensitive for normal quenching, where martensitic transformation occurs from the surface first, as opposed to carburized quenching. That is to say, this report suggests that equalizing cooling for normal quenching in the oil quenching process would be effective as a measure to reduce heat treatment distortion, and in the case of carburized quenching, countermeasures in other processes are also important.

By proactively utilizing the heat treatment simulation technology introduced in this report that clarifies complicated phenomena of the heat treatment process difficult to verify in experiments, JTEKT aims to promote the development of new-age material and heat treatment technology that contribute to the reduction of distortion and create higher performance.

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