Recent Attempts to Control Heat Treatment Distortion Using Simulation in Japan

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The demand for precision in heat-treated parts is becoming stricter year by year, which promptly requires more sophisticated control of heat-treatment distortion. In order to focus on the application of heat treatment simulation, which is effective in predicting distortion, nitriding, induction hardening, and combination treatment of carburizing or nitriding and induction hardening were selected as heat treatments that have less uncertainty in terms of distortion variation. The heat treatment constructed by applying heat treatment simulation and strain control support software to the above-selected heat treatments was named "logical heat treatment." The plan based on this idea, "Development of a Simulation-Assisted Distortion Control System for Logical Heat Treatment," was adopted by the Go-Tech Project (the project to support research and development of growth-oriented small and medium enterprises) to be implemented from FY2022 to FY2024. The development of the distortion control system is underway using COMSOL Multiphysics®. A practical process that is similar in concept to the combination treatment of carburizing and induction hardening in the logical heat treatment is also described in this review.

Keywords: *heat treatment simulation, simulated strains-based approach, COMSOL multiphysics*

1. Introduction

The increasingly stringent requirements for precision in heat-treated parts have been solved by reducing heat-treatment distortion through long-term trial and error. Furthermore, significant economic losses are incurred due to shaping and grinding for distortions that are not corrected. The report[1] in the 2000s states that 850 million euros are spent annually in Germany in the field of power transmission equipment alone.

In recent years, the effectiveness of heat treatment simulation in predicting distortion has been recognized. This technology is expected to be more effective when applied to heat treatments with less variation in distortion: nitriding, induction hardening, and combination treatment with carburizing/nitriding and induction hardening. Furthermore, a more powerful distortion control system can be realized by adding sub-software for optimizing the geometry and explaining the distortion mechanism. The heat treatment supported by the control system is called "logical heat treatment" by those involved, including the author.

The project based on the above idea has been adopted as "Development of a Simulation-Assisted Distortion Control System for Logical Heat Treatment" in the Go-Tech Project (Research and Development Support Program for Growing Small and Medium Enterprises) for fiscal years 2022 to 2024. The Project is a Japanese program by the Ministry of Economy, Trade and Industry (METI) to support researches and developments for the advancement of basic manufacturing technologies and services, which are conducted in collaboration with research institutions such as universities and public research institutes, in cooperation with small and medium-sized enterprises.

On the other hand, in Japan, there have already been successful examples of distortion-controlled heat treatment using heat treatment simulation, such as induction hardening alone and combination treatment of vacuum carburizing and induction hardening. The latter, named "mild carburizing process," is applied to gears, bearing races, etc., and its relationship with the logical heat treatment is discussed in this paper.

2. Logical heat treatment to prevent distortion

2.1 Concept

A new concept solution is being attempted to solve the problem of heat treatment-induced distortion. The approach is to avoid the use of heat treatments that include a group rapid cooling process, which results in a large variation in distortion. When the variation is small, prediction by heat treatment simulation is effective in solving the problem.

Nitriding has long been recognized as a heat treatment method that minimizes distortion and its variation. In this process, parts are held by a group at a set temperature to precipitate nitrides beneath their surfaces, followed by slow cooling. On the other hand, induction hardening also has a small variation in distortion, which is because the parts are individually induction heated and then spray hardened. Furthermore, the combination treatment of nitriding and induction hardening or carburizing and induction hardening is a process to avoid variation in distortion.

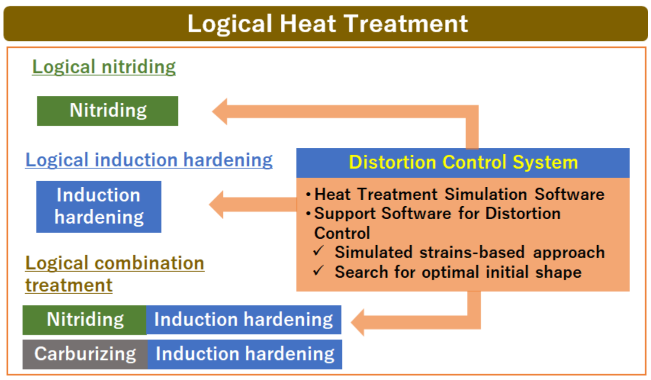


Figure 1 Diagram of logical heat treatment

Figure 1 depicts a situation in which heat treatments without group rapid cooling are supported by the distortion control system. This system includes heat treatment simulation software and two types of support software for distortion control which are based on the simulated strains-based approach[2] and the search for optimal initial shape. As shown in Figure 1, the heat treatments that do not include the process of group rapid cooling, and are supported by the distortion control system, which is called "logical heat treatment" as already mentioned.

Currently, simulation software for induction hardening and combination treatment of carburizing and induction hardening is used by some companies that manufacture and use such treatment facilities. On the other hand, there is no commercial software for nitriding simulation. Therefore, commercial simulation software is not available for the combination treatment of nitriding and induction hardening. Logical heat treatment emphasizes the control of distortion, but also considers the control of residual stress.

2.2 Development of distortion control system

The heat treatment simulation software included in the distortion control system consists of the finite element method (FEM) functions corresponding to each analysis, plus microstructure change prediction and mixture law functions, as shown in Figure 2. The development of this software is supported by COMSOL Multiphysics®[3], a simulation platform that provides fully coupled multiphysics modeling capabilities.

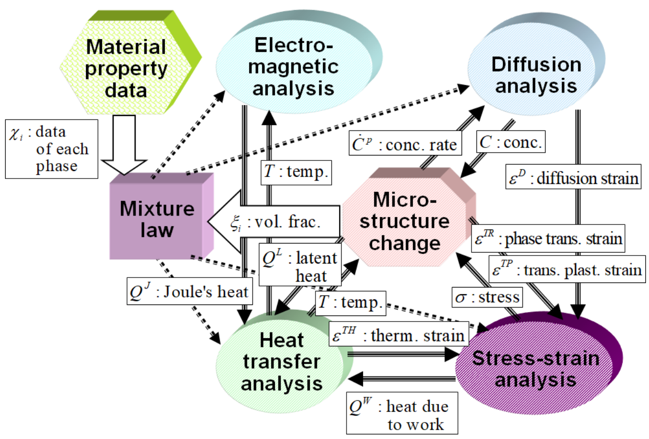


Figure 2 Configuration of heat treatment simulation

The heat treatment simulation software includes computational solid mechanics capabilities. The V&V methodology for the development of these capabilities is described in the guide[4] published by ASME. In this software development, V&V for other functions will be performed according to this guide. Examples of validation in the development of heat treatment simulation have already been reported[5].

Heat treatment distortion and residual stresses can be better controlled by understanding the mechanisms of their occurrence. These mechanisms can be clarified by analyzing simulation results, especially the behavior of various strains. This analysis method is called the simulated strains-based approach[2] and has been made possible by the fact that various strains can be easily obtained by simulation.

As an example of the simulated strains-based approach, Figure 3 schematically illustrates its application to elucidate the mechanism of curving generation[6] in a Japanese sword specimen. The distributions of axial expansion strain (thermal + transformation strains), elastic strain, plastic strain, transformation plastic strain, and total strain are depicted, which are obtained from the simulation at the end of cooling, along the center line of the specimen cross-section indicated by the single-dashed line.

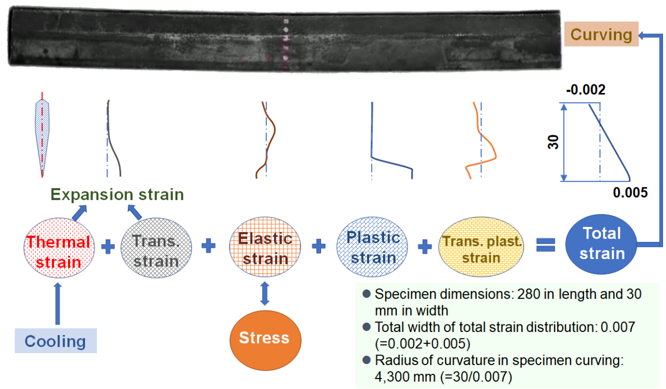
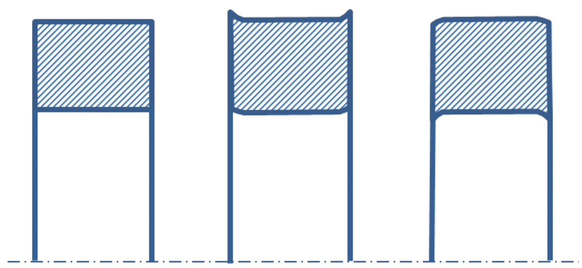


Figure 3 Application of the simulated strains-based approach to curving generation in Japanese sword specimen

The total strain is distributed in a linear form with 0.005 on the cutting-edge side and -0.002 on the opposite side. This distribution is caused mainly by the positive region on the edge side in the expansion and plastic strains. Since thermal strain disappears in the final cooling state, the expansion strain distribution is caused by martensitic transformation strain generated in the cutting edge.

On the other hand, the positive region of plastic strain at the cutting edge is caused by the rapid cooling of this area for about 1.5s from the start of cooling due to the effect of the clay coated here. At the same time, a negative thermal strain and a countervailing positive elastic strain are produced in this region. Therefore, this area is in a state of tensile stress, and positive plastic strain accumulates when this stress value exceeds the elastic range. The transformation plastic strain contributes to a decrease in curving at the cutting edge and an increase in curving in a slightly inner range. The procedure for determining the radius of curvature of the Japanese sword specimen curve from the full width of the total strain distribution is shown in the lower right of Figure 3.

To simplify the use of the simulated strains-based approach, a function of the support software for distortion control will be developed. This is to extract various strain data from heat treatment simulation results along appropriately specified lines in the model and draw them as distribution diagrams.



(a) Before nitriding (Normal processing) (b) After nitriding (Normal processing) (c) Optimum pre-nitriding shape

Figure 4 Optimum pre-shape in nitrided ring

Another function of the support software for distortion control is to search for the optimal shape for a nitrided part before processing. Figure 4 schematically illustrates the idea of this search, which was included in the paper[7)] on nitriding distortion in the 1940s. That is, a ring with the cross-sectional shape shown in Figure 4(a) before nitriding is distorted at its edge after nitriding, as shown in Figure 4(b). Based on this distortion, if the cross-sectional shape before nitriding is set as shown in Figure 4(c), the cross-sectional shape after nitriding will be close to the ideal shape shown in Figure 4(a). Based on this idea, a function for optimizing the pre-nitriding geometry will be developed in the support software for the distortion control.

3. A practical combination process

3.1 Concept

It has already been mentioned that the logical heat treatment includes a combination process of carburizing and induction hardening. As described by Obayashi[8,9)], this idea has been realized at Aisin Corporation in the mass production of actual parts and named "mild carburizing process." Its realization required not only the introduction and combination of conventional equipment, but also the discovery of optimal conditions for their operation. Note that vacuum carburizing is selected for carburizing used in mild carburizing process. Currently, this process is applied to parts such as gears and bearing races.

Mild carburizing process can be regarded also as a method designed to optimize the distribution of hardness and residual stress in gear teeth, which is difficult to achieve with induction hardening alone[8,9)]. Earlier, it was noted that the fatigue strength of induction hardened gear parts was lower than that of carburized and quenched ones.

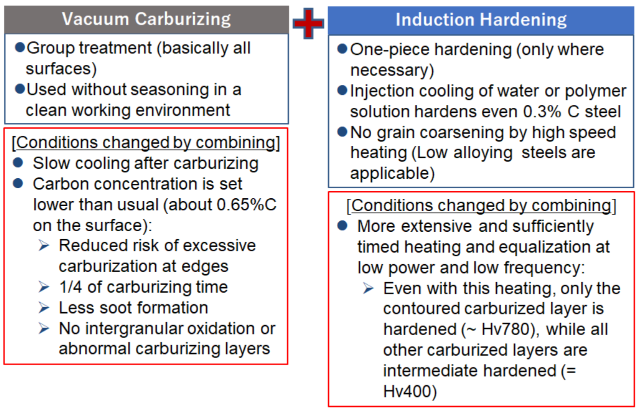


Figure 5 Characteristics of mild carburizing process

3.2 Conditions changed by combining

Figure 5 shows a summary of the features of mild carburizing process. The benefits of replacing gas carburizing with vacuum carburizing are an improved working environment, an elimination of seasoning, and a reduction in installation space by half. On the other hand, the combination treatment reduces the surface carbon concentration from 0.8 %C to 0.65 %C. This is because spray cooling with water or a polymer solution after induction heating enables the hardening of even 0.3 %C steel.

A setting of 0.8% C causes problems such as cementite precipitation, soot formation, intergranular oxidation, and abnormal carburizing layers, and also requires chamfering to prevent excessive carburizing at the edges and delicate adjustment of carburizing concentration. Mild carburizing process not only eliminates these problems, but also provides performance equivalent to conventional gas carburizing and quenching, and reduces the carburizing processing time from four hours to about one hour.

In the induction hardening of gears with a carbon concentration distribution by vacuum carburizing, the high-carbon portions are hardened regardless of the size of the heating range. Furthermore, it is possible to achieve a near-ideal shape after quenching by controlling the heating at different locations and the direction and distribution of the water spray. However, heat treatment simulation is used for the above-mentioned control[10)].

4. Conclusion

The demand to reduce distortion caused by heat treatment of components is becoming stronger with the recent development of new products. Here, an example of a Japanese attempt to address this requirement, the logical heat treatment, is presented. This heat treatment appears to truncate some of the past efforts to address distortion variation. However, the concept of selecting the best of established techniques and reinforcing them is highly feasible. The development of the simulation-assisted distortion control system for the logical heat treatment is supported by the Ministry of Economy, Trade and Industry of Japan as its JPJ005698 program to support research and development by small and medium-sized enterprises.

On the other hand, the mild carburizing process is a method already used in mass-production processing. From the perspective of the logical heat treatment, it appears that the simulated strains-based approach is not fully applied there. However, heat treatment simulation has been used effectively, so the process is described here as a method related to the logical heat treatment.

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