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A Study on the Thermal Deformation Simulation of Spur Gear According to the Heat Zones in Heat Treatment Process

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열처리 공정에서 가열 영역에 따른 평기어의 열변형 해석에 관한 연구

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ABSTRACT

In order to improve fatigue life of transmission gear carburizing is normally used. Carburizing is a very good process to achieve low cost and high performance. The machined gears are heated up to carburizing temperature and then cooled rapidly in an oil bath to produce high surface hardness. The gears may undergo excessive thermal distortion during heating and rapid cooling. In order to predict the distortion during heating and rapid cooling, a coupled thermo-mechanical simulation is needed. In the current research, the simulation of heating and cooling was performed. The results show that the thermal distortion and the residual stresses are well predicted by the coupled simulation. In addition, induction heating and rapid cooling simulation is carried out to predict the thermal distortion. The amount of distortion is compared. It is shown that induction heating is very effective to reduce thermal distortion.

Keywords : Spur Gear(평기어), Heat Treatment(열처리), Thermal Deformation(열변형), Heating Zone(가열영역), Rapid Cooling(급냉)

1. Introduction

Case hardening refers to the technique of hardening parts with complex shapes, such as gears for automotive transmissions, to uniform thicknesses. Case hardening methods include the carburizing method, the nitriding method, and induction hardening. Among these, the carburizing and induction hardening methods are used mostly with gear components requiring high durability and high wear resistance; this is because these two hardening methods have the ability to form a high-hardness hardening layer on the surface.

In the carburizing method, the overall gear is heated into the austenite region and then carbon is evenly penetrated into the surface at high temperatures. The gear is then hardened using a

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cooling method. In induction hardening, the teeth of the gear are hardened after heating them locally through induction heating. Induction heating methods are divided into those using a single frequency and those using a dual frequency.

Due to the differences in the area where the gear is heated, the carburizing and induction hardening methods tend to produce thermal deformation showing different aspects during heat treatment. In addition, even if the same induction heating method is used, differences also occur in the heating area depending on single or dual frequencies are used; thus, thermal deformation varies accordingly. Thermal deformation is important in the process of heat treatment for gear components, leading to the need for in-depth studies on thermal deformation using the Finite Element Method (FEM).

Some studies have been conducted to predict thermal deformation in the heat treatment process through Finite Element Analysis (FEA) taking into account heat transfer, thermal expansion, and phase deformation[1-5]. Studies are also being carried out to identify materials' physical properties, which are difficult to obtain from experiments, by calculating their thermodynamics and applying them to Finite Element Analysis (FEA)[6,7]. These studies have been conducted on parts with simple shapes; thus far, no thermal deformation studies have been done on more complex parts such as gears.

Therefore, this study focuses on identifying thermal deformation behavior for flat gear, which is the study's target. This behavior was analyzed during heat treatment with the carburizing method which is a cooling method applied after the overall gear is heated and the induction hardening method which is a cooling method applied after the gear's partial components are heated. The occurrence of thermal deformation based on the heating area featured in the overall heating method and in the partial heating method was quantitatively predicted.

2. Finite Element Analysis and Experiments

2.1 Analytical Models and Conditions

The flat gear used in this study had the following specifications: 80 mm external diameter, 52.5 mm internal diameter, 5.6 mm teeth height, and module 2.5.

The finite element model used in the heat treatment analysis is represented in Fig. 1 to observe cooling deformation after the gear teeth were heated. Additionally, a 1/2 axially symmetric teeth model was used to shorten the analysis time. The material used in this study was SCM440, and the values of thermal-physical property required for heat treatment analysis were calculated utilizing JmatPro, a thermodynamics-based materiality calculation program. A number of values of thermal-physical properties that are difficult to obtain via experiments were derived, as Fig. 2 shows. Materials' convective heat transfer coefficients that have a major effect on heat transfer during cooling were analyzed by applying the results of existing experiments[5]. The analytical program used in this study was DEFORM-2D, and Elasto-Plastic Analysis was performed considering heat transfer and phase deformation.

In order to review the thermal deformation effects of the heat treatment process based on heating area,

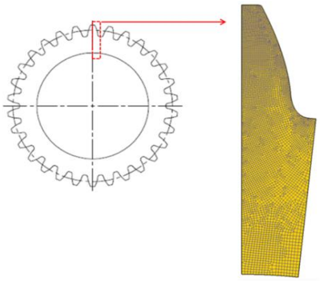
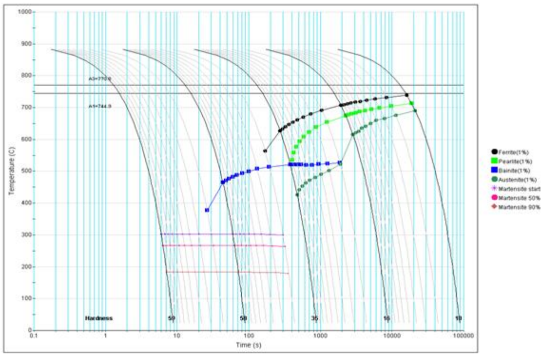
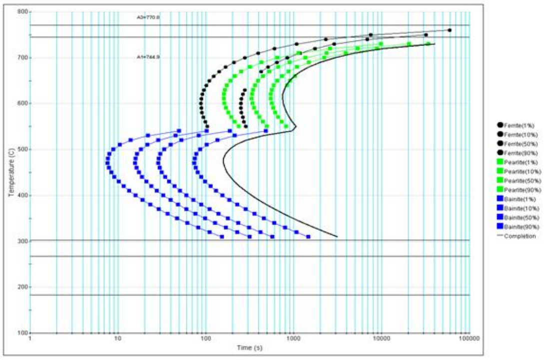


Fig. 1 Finite elements model for simulation



(a)CCT



(b)TTT

Fig. 2 CCT/TTC Curve of SCM440

Table 1 Simulation conditions

No.	Heat treatment conditions
1	Carburizing
2	Single-frequency (Small heating zone)
3	Single-frequency (Medium heating zone)
4	Single-frequency (Large heating zone)
5	Dual-frequency

the heat treatment process was conducted under three heat-treatment conditions: carburizing, single-frequency induction heating, and dual-frequency induction heating. The heating time during single-frequency induction heating was set to three conditions in order to identify the heating area and thermal deformation according to the heating time. Table 1 presents the detailed analysis conditions.

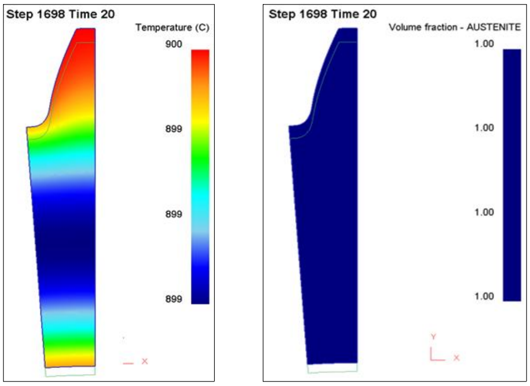
2.2 Experimental Method

To analytically verify the analysis results, deformation after heat treatment of the single-frequency induction-heated flat gear was measured. The analysis and experimental results were then compared. Deformation measurements were taken using a three-dimensional measuring instrument. The specifications for the high-frequency equipment used in this study were 200 kW and 50 kHz. Circular coils were manufactured and used. After induction heating, water was used for rapid cooling (i.e., quenching). Finally, the flat gear's external diameter and internal diameter were measured before and after heat treatment.

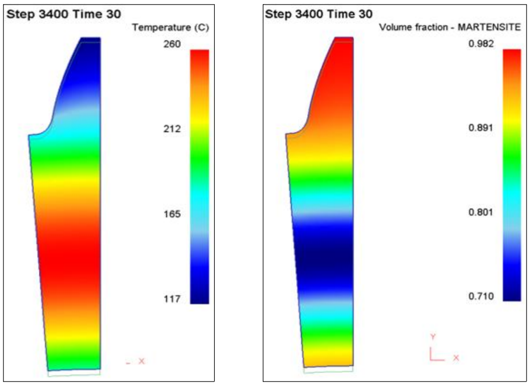
3. Results and Considerations

3.1 Analysis Results

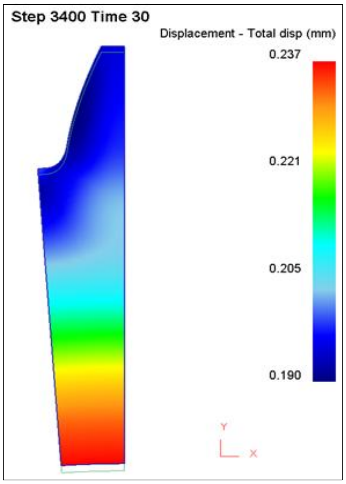
Fig. 3 represents the results of the thermal deformation analysis of the analysis condition No. 1, where the overall flat gear is heated. Analysis No. 1 refers to an analysis of the carburizing process, showing a temperature distribution where almost all of the area from the teeth to the core part of the gear during heating heats up to 900°C. Thermal deformation is caused by thermal expansion and phase deformation due to heating. Shrinkage occurs during the cooling process and, as the metamorphosis from austenite to martensite begins, expansion occurs and then retraction occurs again. During this time, the gear's core part has a slower cooling speed than the teeth of the surface; thus, the gear's core part does not undergo complete martensitic transformation. Once the cooling process is almost complete, the external diameter of the flat gear increases and the internal diameter increases as well. In this study, deformation occurred after cooling, and the external diameter was modified to 0.190 mm while the internal diameter was modified to 0.237 mm.



(a) Heating temperature (b) Austenite fraction

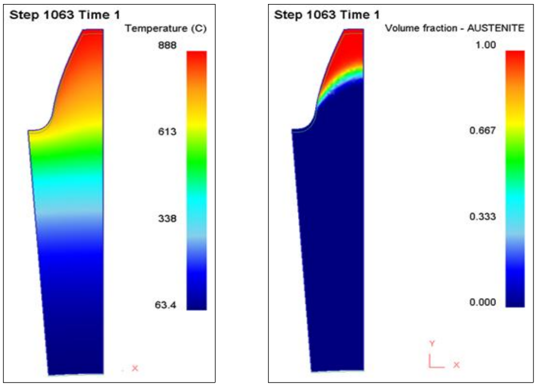


(c) Cooling temperature (d) Martensite fractioin

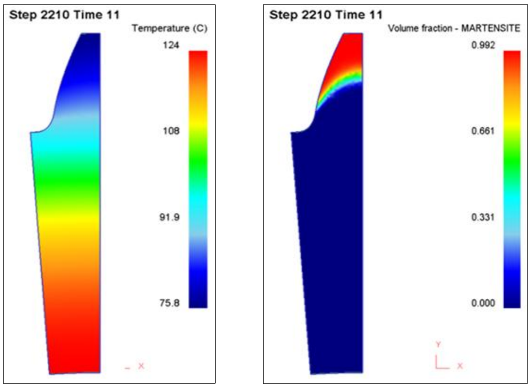


(e) Deformation

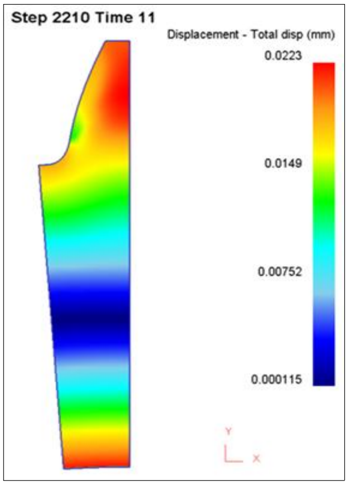
Fig. 3 Results of simulation No.1



(a) Heating temperature (b) Austenite fraction

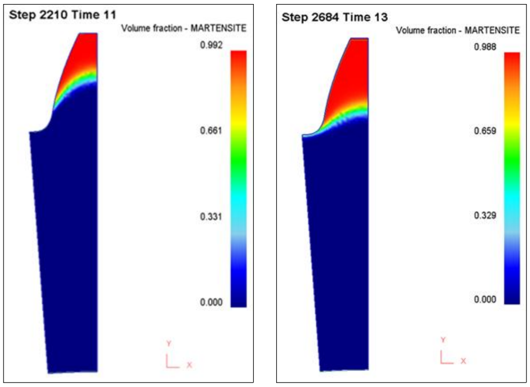


(b) Cooling temperature (d) Martensite fractioin

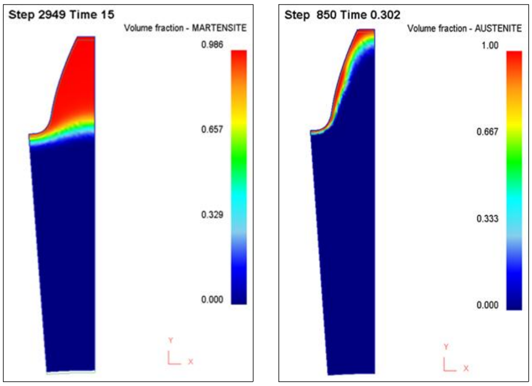


(e) Deformation

Fig. 4 Results of simulation No.2



(a) No.2 (b) No.3



(c) No.4 (d) No.5

Fig. 5 Results of martensite fraction

Fig. 4 shows the thermal deformation analysis results of analysis condition No. 2, where only the teeth of the flat gear are heated by single-frequency induction heating. After heating, only the tips of the teeth were intensively heated up to 888°C, leading to the appearance of austenite. Later, a rapid cooling process (i.e., quenching process) was initiated, and the austenite region transformed into martensite. In water cooling, the cooling speed is extremely fast; thus, we were able to observe that most of the austenite mutated into martensite. After cooling, the external diameter was modified to 0.0223mm while the internal diameter was found to have undergone little deformation. The results showed that partial heating produced approximately 10 times less deformation than overall heating.

Table 2 Thermal deformation results of simulation

No.	Defomation (mm)
1	0.190
2	0.022
3	0.085
4	0.151
5	0.031

Fig. 5 shows the fraction of martensite after cooling via induction heating conditions. For single-frequency heating, the martensite fraction tended to increase as the heating time increased. In the case of dual-frequency heating, we identified that the hardening layer depth was very thin along the surface of the teeth.

Table 2 presents the maximum deformation of the external diameter after cooling was completed. Deformation was shown to be the largest in the first condition where the entire flat gear was heated. In contrast, deformation was generally small with the induction heating condition where the components of the flat gear were heated partially. Overall and partial heating had a deformation difference of about 10 times. In the case of single-frequency induction heating, the deformation increased as the heated area increased. In dual-frequency induction heating, the area being heated was the smallest, which resulted in the smallest amount of deformation. In other words, the amount of thermal deformation that occurs is determined by the size of the area that is transformed into martensite.

3.2 Experimental Results

To verify the reliability of the finite element model, the single-frequency induction heating method was compared with the heat-treated prototype and deformation. Fig. 6 shows a macro-structure photograph of the flat gear that was heat-treated with

Fig. 6 Experimental results of single-frequency induction heating

Table 3 Thermal deformation results

heating process	simulation No. 4	Experiment	Error
Single-frequency induction heating	0.151	0.166	9 %

the single-frequency induction heating method. The comparison of martensite regions with the analysis data indicates that the structure distribution was most similar to No. 4, making it possible to confirm the accuracy of the induction heating analysis. The results of measuring the external diameter of a heat-treated flat gear via the single-frequency induction heating method were also compared with the analysis results, as Table 3 shows. The measurement revealed that the error was about 9%, confirming that thermal deformation can be predicted very accurately.

4. Conclusion

This study conducted an in-depth analysis and experiments on thermal deformation that occurs after the quenching process (i.e., rapid cooling process) based on different heating areas in the heat treatment process. The following conclusions were obtained.

1. Thermal deformation behavior in the quenching process after the heating of flat gear can be predicted accurately and analytically.
2. Based on heating area, thermal deformation showed a tendency to decrease in the following order: carburizing, single-frequency, and dual-frequency induction heating methods. Additionally, we were able to confirm that thermal deformation increases as the heating time increases during single-frequency induction heating.
3. This study has identified that the size of the martensite region generated after cooling has a significant effect on thermal deformation.
4. This study confirmed that when heat treatment is conducted using a single-frequency induction heating method, the amount of thermal deformation in the experimental and analytical results is very similar.

References

1. Kang, S. H., Im, Y. T., “Thermo-elasto-plastic Finite Element Analysis of Quenching Process of Carbon Steel”, Journal of Materials Processing Technology, Vol.192-193, pp.381~390, 2007.
2. Kang, S. H., Im, Y. T., “Three-dimensional Thermo-elastic-plastic Finite Element Modeling of Quenching Process of Plain-carbon Steel in Couple with Phase Transformation”, International journal of mechanical sciences, Vol. 49, No. 4, pp.423~439, 2007.
3. Carlone, P., Palazzo, G. S., Pasquino, R., “Finite Element Analysis of the Steel Quenching Process: Temperature Field and Solid-solid Phase Change”, Computers & mathematics with applications, Vol. 59, No. 1, pp.585~594, 2010.
4. Suh, C. H., Kwon, T. H., Kang, K. P., Choi, H. Y., Kim, Y. S., Kim, Y. S., "Thermo-mechanical Simulation of Boron Steel Cylinders during Heating and Rapid Cooling", Transactions of

Materials Processing, Vol. 23, No. 8, pp.475-481, 2014.

5. Suh, C. H., Kwon, T. H., Jeon, H. W., Oh, S. K., Park, C. D., Choi, H. Y., Moon, W. S., "Thermal Deformation Simulation of Boron Steel Square Sheet in Fluid Cooling Process", Transactions of Materials Processing, Vol. 26, No. 1, pp.5-10, 2017.
6. Lee, S. Y., Lee, K., Lim, Y. H., Jeong, W. C., “Study on Heat Transfer Characteristic in Hot Press Forming Process”, Transactions of Materials Processing, Vol. 22. No. 2, pp.101~107, 2003.
7. Kang, K. P., Lee, K. H., Kim, Y. S., Ji, M. W., Suh, Y. S., “Prediction of Phase Transformation of Boron Steel Sheet during Hot Press Forming using Material Properties Modeler and DEFORM-HT”, Transactions of Materials Processing, Vol. 17, No .4. pp.249~256, 2008.
8. Byun, J. H., Byun, S. D., Yi, C. H., “A Study on SCr420HB Helical Gear Deformative Simulation by Heat Treatment Quenching Method”, Journal of the Korean Society for Heat Treatment, Vol. 28, No. 1, pp.24-31, 2015.
9. Ahn, M. J., Ahn, I. H., Lyu, S. K., "A Study on the Carburizing Treatment of SCM415 Steel Spur Gear", Journal of the Korean Society of Manufacturing Process Engineers, Vol. 10 No. 1, pp.67-72, 2011.
10. Bae, k. Y., Yang, Y. S., Park, B. O., “Analysis of Deformation of Automotive Helical Gear in Heat Treatment of Carburized Quenching”. Journal of the Korean Society of Precision Engineering, Vol. 27, No. 11, pp.84-91, 2010.
11. Kim, H. J., Choi, S. C., Lee, D. J., Kim, H. Y., “Analysis of the Carburizing Heat Treatment Process for SNCM Alloy Steel Using the Finite Element Method“, Journal of Mechanical Science and Technology, Vol. 30, No. 10, pp.1248-1292, 2006.