Controlling Gear Distortion and Residual Stresses During Induction Hardening

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Management Summary

Induction hardening is widely used in both the automotive and aerospace gear industries to minimize heat treat distortion and obtain favorable compressive residual stresses for improved fatigue performance. The heating process during induction hardening has a significant effect on the quality of the heat-treated parts. However, the quenching process often receives less attention even though it is equally important. Deformation Control Technology's (DCT's) past experiences have shown that the cooling rate, the fixture design and the cooling duration can significantly affect the quality of the hardened parts in terms of distortion, residual stresses and the possibility of cracking. *DANTE*, commercial, FEA-based software developed for modeling heat treatment processes of steel parts, was used to study an induction hardening process for a helical ring gear made of AISI 5130 steel. Prior to induction hardening, the helical gear was gas-carburized and cooled at a controlled cooling rate. The distortion generated in this step was found to be insignificant and consistent; therefore, the modeling investigation in this paper focused on the spray quench of the induction hardening process. Two induction frequencies in a sequential order were used to heat the gear teeth. After induction heating, the gear was spray quenched using a polymer/water solution. By designing the spray nozzle configuration to quench the gear surfaces with different cooling rates, the distortion and residual stresses of the gear can be controlled. Tooth crown and unwind were predicted and compared for different quenching process conditions. The study demonstrates the importance of the spray duration on the distortion and residual stresses of the quenched gear.

Introduction

High-frequency induction hardening is more environmentally friendly than traditional quench hardening processes such as gas furnace heating followed by immersion quenching in oil. It also provides flexibility in control on the case depth, residual stress state, and part distortion. Due to these advantages, the induction hardening process is widely used in the gear industry for case hardening. During induction heating, the energy to heat the part is generated internally by eddy currents in response to the imposed alternating magnetic field. The energy density distribution in the near-surface layer is directly related to the distance between the inductor and the part, as well as the frequency of the inductor. Lower frequency heats the part deeper over a longer time period because the eddy current gradient in the part surface is lower, meaning the Joule heating extends deeper into the part interior. In contrast, higher induction frequency heats a shallower layer over a shorter time. The temperature distribution in the part is a combined result of induction heating, thermal conduction and phase transformations.

In many induction hardening processes, both medium and high frequencies are used to reach the desired temperature field and hardened case depth. The heating may be a two step process, i.e., a different frequency for each step, or a single step with dual frequency application. Simultaneous dual frequency (SDF) induction heating applies both medium and high frequencies in the part simultaneously to generate a more uniform temperature distribution in curved surfaces such as gear tooth profile (Ref. 1). The energy percentage of medium and high frequencies during SDF induction heating can be adjusted, which provides greater flexibility in controlling temperature distribution in complicated part shapes. The other common induction hardening process for gear components is to apply two sequential induction frequencies. Lower frequency is normally used first to heat the gear root, followed by higher frequency to heat the gear tip. A time delay can also be applied between the two frequencies to more flexibly control the temperature distribution in the component.

Induction hardening is a transient thermal process. During induction hardening of steel components, both the thermal gradient and the extent of phase transformation simultaneously contribute to the evolution of internal stresses and distortion. Recent developments in heat treatment modeling technologies make it possible to understand the material's response during heat treatment processes, such as how the internal stresses and distortion are generated. *DANTE* is a commercial FEA-based software developed for heat treatment modeling of steel components, including furnace heating with liquid or gas quenching, or induction hardening processes with spray quenching (Ref. 2). *DANTE* was not developed to model the electromagnetic physics of induction heating. A temperature distribution predicted from an induction heating model or from experimental measurements can be imported to drive the model. *DANTE* can also be effectively used to simulate the temperature field produced during induction heating by using Joule heating, i.e., i^2r heating, based on the depth of the hardened case in the part (Ref. 3). In this paper, a carburized helical gear was induction heated using two

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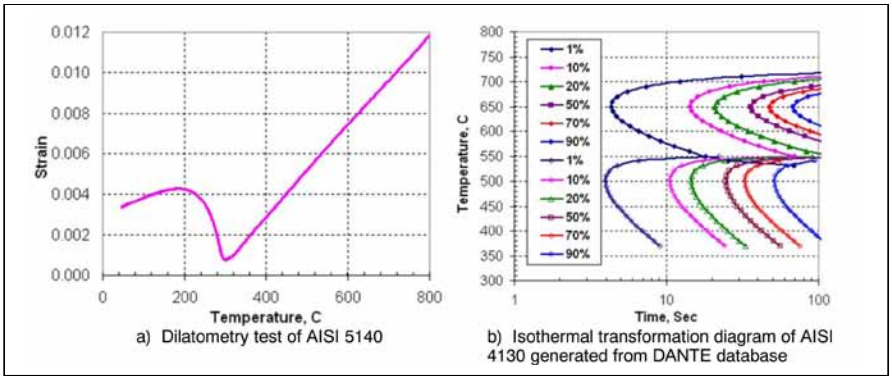


Figure 1—Phase transformation kinetics.

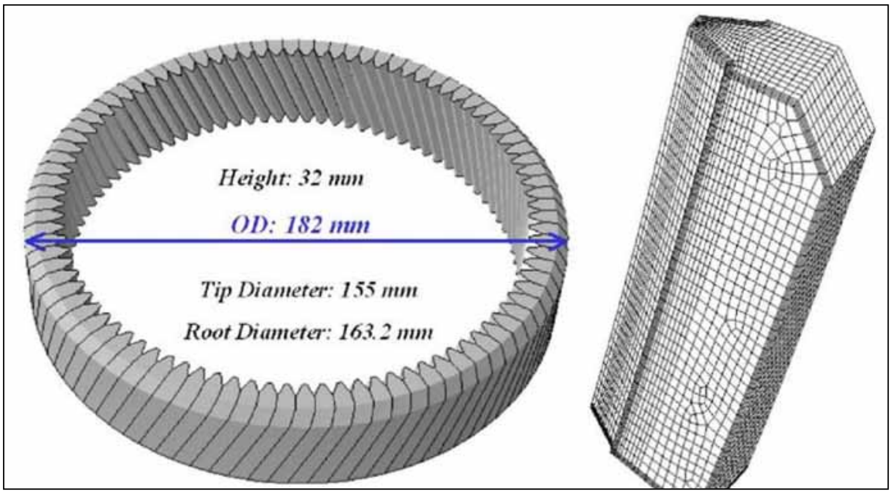


Figure 2—(a) CAD model of transmission gear and (b) single-tooth finite element model.

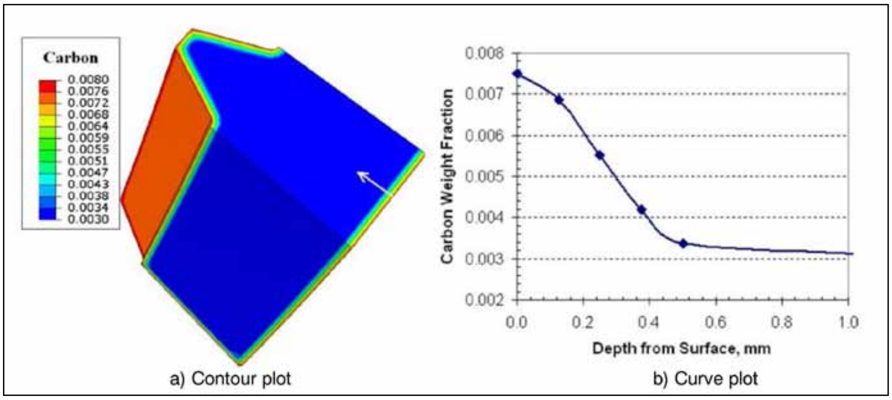


Figure 3—Carbon distribution.

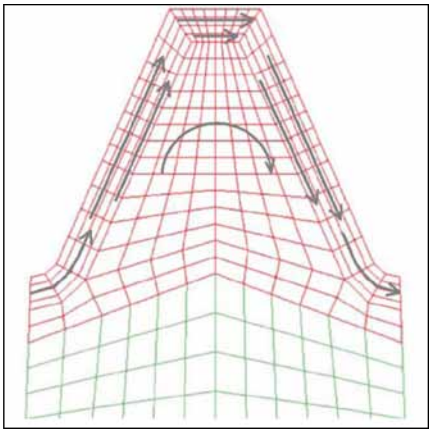


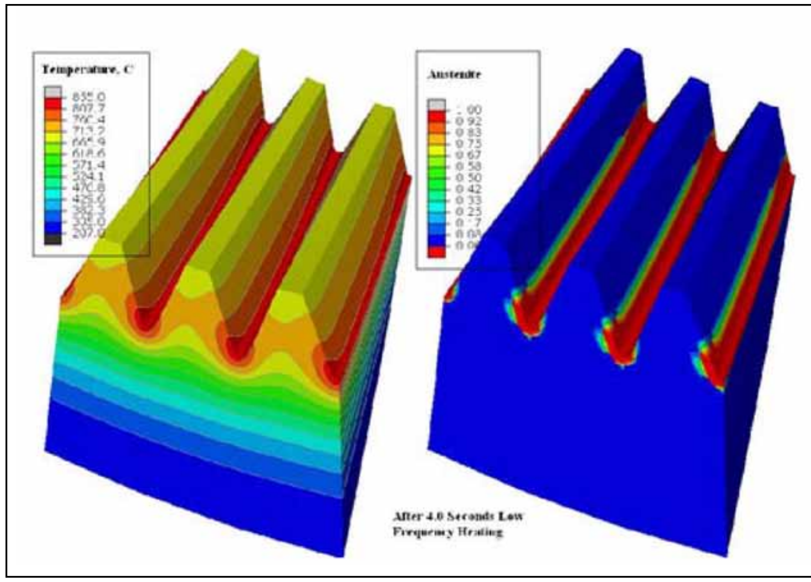
Figure 4—Schematic plot of eddy currents in the part during induction heating.

sequential induction frequencies, followed by spray quenching. The effect of spray quenching on the distortion was studied using the modeling results.

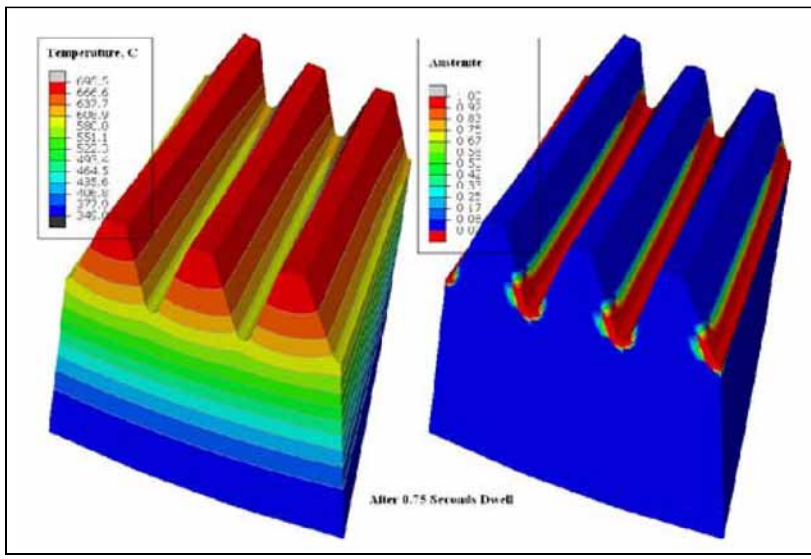
Material Characterization for Heat Treatment Modeling

The ring gear studied in this paper was made of AISI 5130 with a chemical composition of 0.83% Mn, 0.22% Si, 0.15% Ni, 0.80% Cr, 0.04% Mo and 0.30% C in weight percentage. The gear was gas-carburized prior to induction hardening to improve the strength of the surface layer. To model the induction hardening process, the phase transformation data of base carbon and high carbon steels of this grade are needed. Dilatometry experiments were done previously for this steel grade with series of carbon levels (Ref. 4). Figure 1a shows the dilatometry experimental data for continuous cooling of AISI 5140. The phase transformation kinetics for both martensitic and diffusive phase transformations were fitted from this type of dilatometry data, with different carbon levels and testing conditions. Isothermal transformation diagrams (TTT diagrams) can be generated from a *DANTE* database (Fig. 1b) for AISI 5130. The isothermal and continuous-cooling diagrams can be generated to evaluate the hardenability of a given steel grade and carbon level.

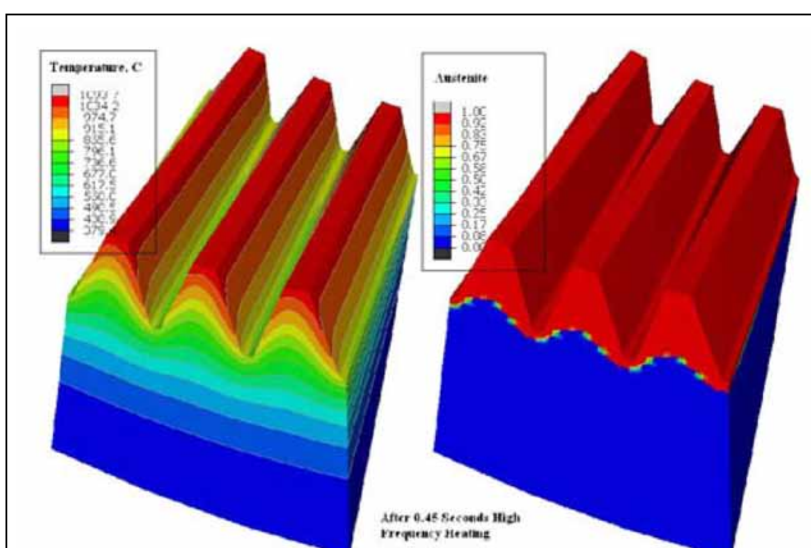
The mechanical properties are also required to model the distortion and residual stresses from the heat treatment of steel parts. The mechanical properties—yield, hardening and recovery—change with the composi-



a) After 4.0 seconds low frequency heating



b) After 0.75 seconds dwell



c) After 0.45 seconds high frequency heating

Figure 5—Temperature and transformed austenite during heating.

tion of different phases, carbon content and temperature. In *DANTE*, the mechanical properties of individual phases are defined based on experiments. A mixture law is used to describe the global response of the material linking with the phase transformation kinetics.

Finite Element Modeling (FEM)

A CAD model of the ring gear is shown in Figure 2a. The internal helical gear has 92 teeth. The tip diameter is 155 mm, the outer diameter is 182 mm and the height is 32 mm. A single-tooth finite element model was created and is shown (Fig. 2b). The finite element model has 23,372 nodes and 20,784 hexahedral elements. Fine elements are used in the shallow surface of the gear to more accurately catch the carbon and thermal gradients during heat treatment. Cyclic symmetric boundary conditions are applied so that the single-tooth model represents the whole gear, with an assumption that all the teeth behave the same during the heat treatment process.

Pre-Induction Hardening Process

Prior to induction hardening, the gear was gas carburized, followed by a controlled, slow cooling. The carburization process was used to increase the hardness and strength of the surface layer. The carburization temperature was 875 °C and the carbon potential of the furnace was 0.80%. The total carburization time was 2.0 hours. Figure 3a shows a cut view of carbon distribution at the end of the carburization process. The sharp corner of the gear tip has a slightly higher carbon than the other surfaces due to the geometry effect. The carbon distribution in terms of depth from the outer surface is shown (Fig. 3b). The approximate carbon case depth, defined by 0.45% carbon, is 0.35 mm. After carburization the gear was cooled to room temperature in a controlled atmosphere. The obtained microstructure in the core of the gear is mainly pearlite; the carburized case has a combination of martensite and bainite. The distortion from the controlled cooling process is consistent, which can be compensated for in the

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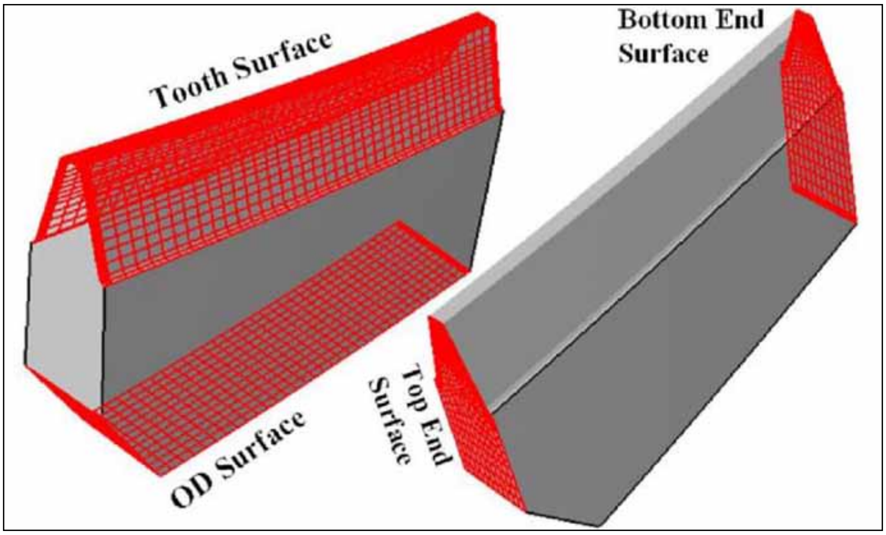

Figure 6—Part surfaces defined for setting up spray quenching model.

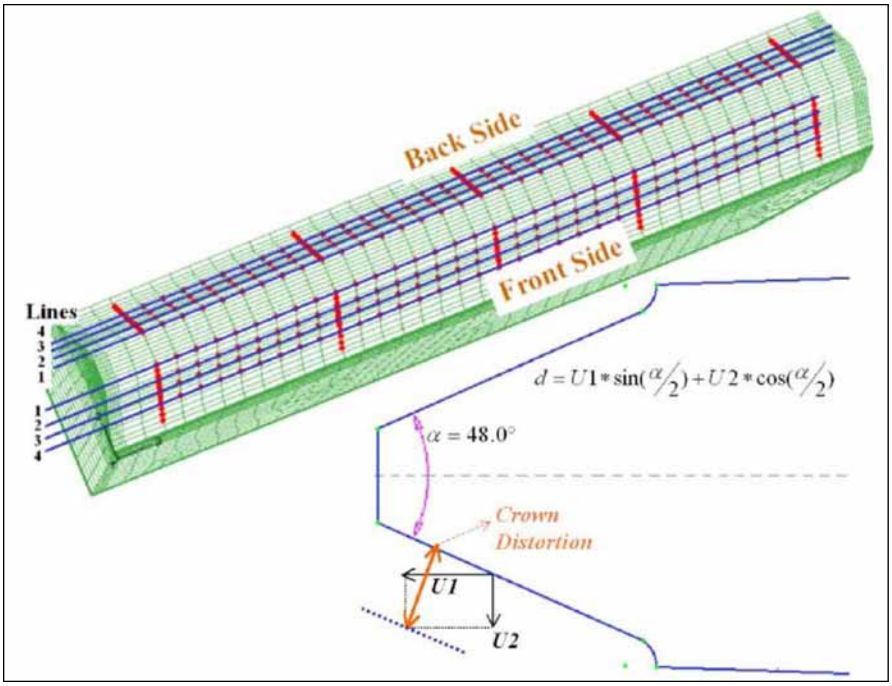

Figure 7—Tooth surface crown distortion calculation using *DANTE* modeling results.

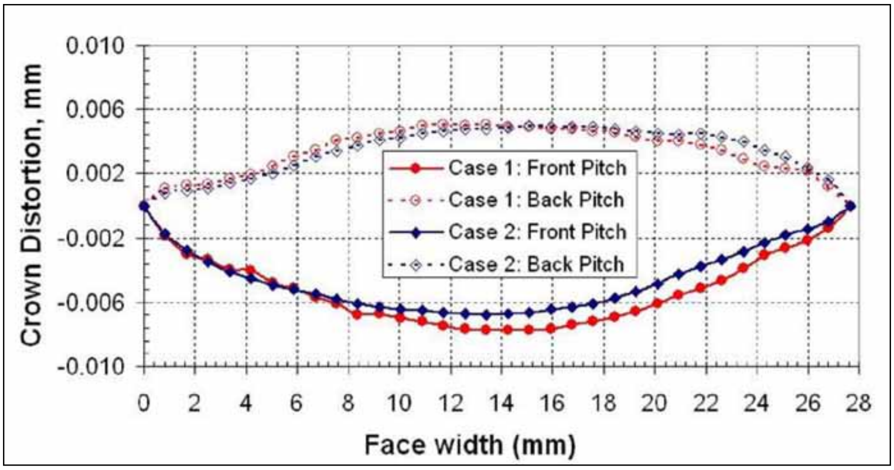

Figure 8—Comparison of crown distortion for the two quenching processes.

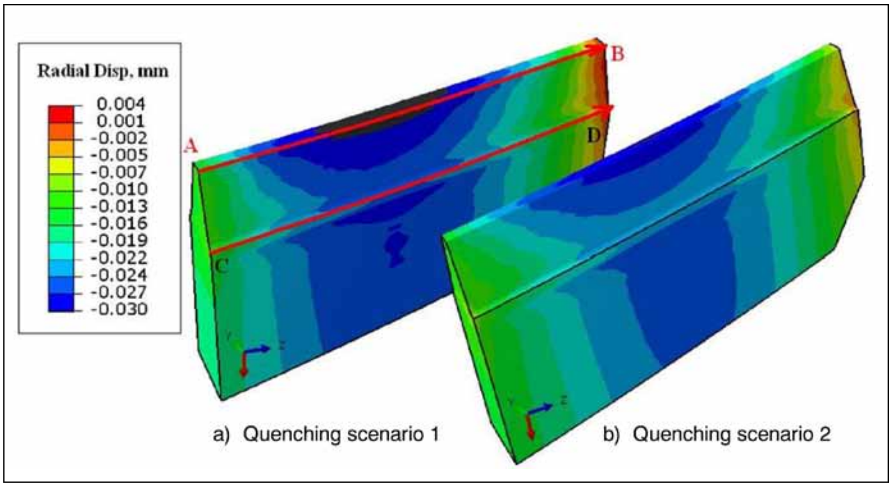

Figure 9—Contour plots of radial displacements after induction hardening.

gear design by adjusting the green shape dimensions. Therefore, this study focused on the induction effect of the induction hardening process.

Induction Hardening Process

Two sequential induction frequencies were used to heat the inner gear teeth; there was a short delay between the two heating stages. A brief schedule of the induction hardening is listed below:

- Medium frequency heating for 4.0 seconds
- Dwell for 0.75 seconds
- High-frequency heating for 0.45 seconds
- Spray quench

Instead of modeling the physics of the electromagnetic field generated by the inductor, the *DANTE* model directly applies the heat power by the eddy current in the part following the Joule rule, as shown (Fig. 4). Uniform heat energy distribution in the gear axial direction was assumed. Medium-frequency heating generates more heat in the gear root, while high-frequency heating generates more heat in the tip of the tooth. The dwell time between the two heating stages is important, as this allows time for thermal diffusion. The heat energy applied in the model can be adjusted to improve model accuracy using data from experiments with thermocouples and metallography of the hardened case profile; the latter method is used in this paper. Alternatively, the power distribution predicted by induction software such as *ELTA* could also be used to drive the *DANTE* model (Ref. 5). In this paper, results for one induction heating and two spray quenching scenarios are presented. Spray quenching is assumed to start immediately after the heating step—without delay. Residual stress states and distortion were predicted by *DANTE* and the effects of the process variables on distortion are discussed.

The temperature and austenite distribution after each heating stage are shown (Fig. 5). After 4.0 seconds of heating at a medium frequency, the surface temperature of the gear root is about 815 °C, the tooth tip is about 700 °C and the OD surface temperature is about 280 °C. The gear root area is predicted to have formed austenite, but the tooth tip has not. During the 0.75-second dwell, the heat diffuses from the inner to the outer surface by thermal conduction. A small amount of heat is lost to the environment by radiation and air convection, which are also included in model. At the end of the 0.75-second dwell period the gear tip temperature has had a small drop; but the temperature at the gear root has dropped significantly—from 815 °C to 595 °C. The temperature at the outer diameter surface has increased—from 280 °C to 350 °C. No phase transformation occurs during the dwell time. The third stage is a high-frequency heating for 0.45 seconds. At the end of the third-stage heating the temperature at the tooth tip has increased to 1,050 °C, the root temperature has increased to 850 °C and the OD surface temperature has increased to 380 °C. The austenite distribution profile is shown (Fig. 5c).

After induction heating the gear is spray quenched to room temperature without delay. As shown (Fig. 6), the gear surface is defined as four regions to model the quenching process: i.e., 1) tooth surface; 2) OD surface; 3) top-end surface; and 4) bottom-end surface. Quench fixture and spray nozzle configurations were designed to flexibly quench each individual surface at a controlled rate. In this paper a water/polymer solution was used as the quenching media. The average heat transfer coefficient was assumed to be 5.0 (kW/m^{2}K) during the spray quench. Two spray scenarios were modeled to investigate the quenching effect on distortion. Scenario 1 sprayed all the exposed surfaces; scenario 2 sprayed the tooth surface only.

Distortion Analysis Using Finite Element Models (FEMs)

The gear modeled in this paper has a thin wall thickness and the cooling rate of the water/polymer spray is sufficiently fast to miss the nose of the diffusive phase transformations (Fig. 1b). The martensitic phase distribution in the actual hardened ring gear closely matches the predicted austenite distribution (Fig. 5c). The crown distortion and unwind of the teeth are the two main distortion modes for this gear. *DANTE* models predicted the nodal displacements after the heat treatment process and these nodal displacements were used to calculate the crown distortion and unwind angle. The crown distortion in this paper is defined as the bowing amount of the tooth face at the pitch diameter line, as shown by Line 3 in Figure 7 for both sides of the tooth. A simplified equation is used to convert the predicted nodal displacements to the values of bowing.

$$d = U1 \sin\left(\frac{\alpha}{2}\right) + U2 \cos\left(\frac{\alpha}{2}\right)$$

where:

- d is bowing value, representing how far the surface point moving away from its original position
- $U1$ is radial displacements from the model results
- $U2$ is circumferential displacements from the model results
- α is tooth angle (Fig. 7)

The crown distortion is defined as the maximum bowing value from the original position.

The crown distortions of the pitch lines on both sides of the tooth are shown (Fig. 8). The *X*-axis represents the axial position from the bottom end surface to the top end surface, with $X=0$ located at a point 2 mm from the end. The displacements are calculated with around 2 mm from each end to avoid the significant distortion on the edge. Without any distortion all the lines will align perfectly with $Y=0$. For the front tooth surface a negative

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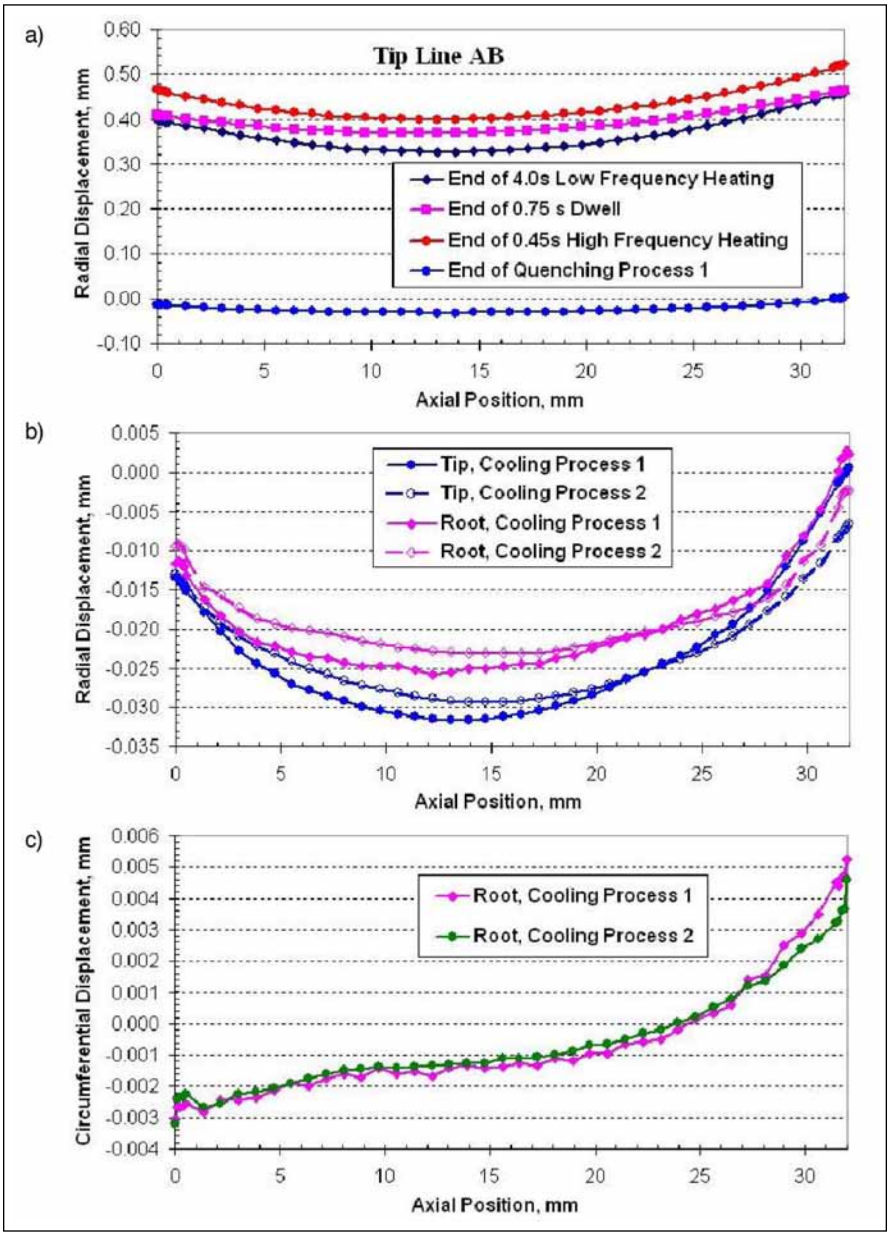

Figure 10—(a) Radial displacement of the gear tip line AB at different stages of heat treating processes; (b) radial distortion at the end of quench; (c) gear tooth unwinding distortion.

crown distortion value means bow outward. For the back-tooth surface a positive crown distortion means bow outward. For quenching scenario 1, the crown distortion of the front pitch is 7.8 µm and that of the back pitch 5.8 µm. The crown distortion of the front pitch is reduced by about 1.0 µm for the second quenching scenario. However, the crown of the back pitch has no significant difference between the two quenching scenarios.

Both the thermal gradient and phase transformations contribute to the gear distortion. Computer modeling makes it possible to determine the intermediate gear shapes during heating and quenching processes, and to understand how the distortion is generated. With this knowledge the process can be improved to reduce the distortion without heavy reliance on trial-and-error experiments; these can be accomplished on a computer. Two straight lines—AB and CD (Fig. 9)—are selected to investigate the intermediate gear geometry during the induction hardening process. Line AB is located along the tip edge of the gear and line CD is along the middle of the gear root.

During induction heating the gear expands in both the radial and axial directions. The displacements at the end of each heat treatment stages are plotted in Figure 10. The *X*-axis (Fig. 10) represents the axial position, starting from the bottom end surface. Both points A and C have *X* values of 0.0 mm. A global Cartesian coordinate system as shown (Fig. 9) is used to plot the displacements; a positive radial displacement represents expansion and a negative radial displacement represents shrinkage.

Using scenario 1 as an example, the radial displacements of gear tip (line AB) are plotted at the end of each stage (Fig. 10a). At the end of the 4.0-second, medium-frequency heating, the radial displacement at point A is 0.4 mm, compared to the 0.45 mm at point B located at the opposite gear end. The lowest radial expansion along the line AB is 0.32 mm—located mid-height of the gear. The gear tip surface has an inward bow, due to the thermal expansion of the inner teeth. The top end has a large chamfer on the OD surface and its wall is thinner, leading to a higher temperature at point B than that at point *A* during heating; as a result, point B has higher radial expansion. After the 0.75-second dwell, the heat transfers from the inner teeth to the outer surface and the thermal gradient in the radial direction decreases. Without any significant change of the radial displacements at point A and B, the radial displacement at mid-height increases, thus reducing the inward bow of the tooth.

After the 0.45-second, high-frequency heating period the temperature of the inner teeth has increased to 1,050 °C. The temperature gradient between the inner teeth and the OD surface has increased during this stage. Figure 10a shows that radial expansion has increased—as has the amount of the inward bow.

The thermal stress and stress induced by phase transformation can cause plastic deformation during both heating and quenching. After quenching the gear to room temperature the thermal expansion of the gear is gone; any plastic deformation generated during the process will end up as distortion. Note that the volume change due to phase transformation will cause some level of size change, which should be uniform. Figure 10b shows the radial distortion at the end of the quenching process. The gear tooth shows an average radial

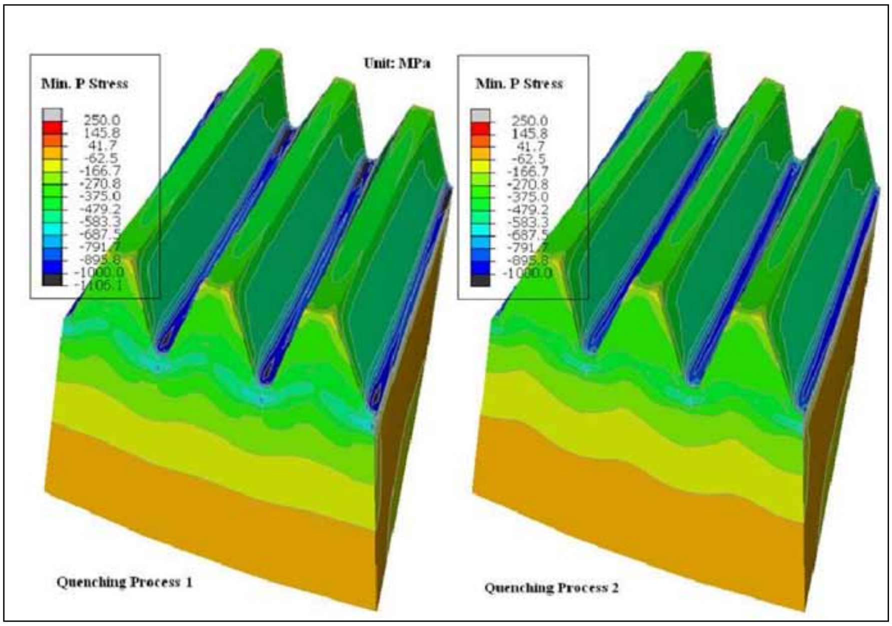

Figure 11—Residual stress state after hardening, showing minimum principal stress.

shrinkage of 0.02 mm and the inward bow is reduced in comparison to that at the end of the heating stages. About a 3 μm difference in axial bow distortion is shown between the two quenching scenarios. The gear tip has less radial shrinkage compared to that of the gear root, meaning that the gear tooth thickness has increased after hardening.

Another important distortion mode is the gear tooth helical angle change after the hardening process. The circumferential displacements (along the root line CD in Figure 9) are plotted for both quenching scenarios (Fig. 10c). The circumferential displacements are used to calculate the helical angle change due to the induction hardening process. The average unwind angle of the teeth is about 0.025° and there is no significant difference between the two quenching scenarios. The axial height of the gear after induction hardening increased slightly.

Residual stresses after heat treatment are important to the fatigue performance of the gear. As shown (Fig. 11), the gear root is predicted to have a compressive residual stress of 1,000 MPa in compression after induction hardening. The two cooling scenarios do not have a significant difference on residual stress distribution in the root area, so the gear resistance to bending fatigue should be similar.

Summary

Using computer simulation, two induction hardening scenarios have been examined for a carburized ring gear made of 5130 steel. Induction hardening using a two-step heating method, followed by spray quenching, was shown to produce the desired residual compressive stress in the gear root area, but also to cause a small amount of unwind and radial shrinkage. The tooth shape moved radially inward a small amount and also hour-glassed slightly as the carburized layer was transformed to martensite. Knowing this in advance, the green tooth form can be altered so that it moves to the proper, final shape during induction hardening.

References

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