Innovative Induction Hardening Process with Pre-heating for Improved Fatigue Performance of Gear Component

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Contact fatigue and bending fatigue are two main failure modes of steel gears, while surface pitting and spalling are two common contact fatigue failures—caused by alternating subsurface shear stresses from the contact load between two gear mates. And when a gear is in service under cyclic load, concentrated bending stresses exist at the root fillet—the main driver of bending fatigue failures. Induction hardening is becoming an increasingly popular response to these problems, due to its process consistency, reduced energy consumption, clean environment and improved product quality—but not without issues of its own (irregular residual stresses and bending fatigue). Thus a new approach is proposed here that flexibly controls the magnitude of residual stress in the regions of root fillet and tooth flank by pre-heating prior to induction hardening. Using an external spur gear made of AISI 4340 as an example, this new concept/process is demonstrated using finite element modeling and *DANTE* commercial software.

Introduction

Residual stresses embedded inside a hardened gear are critical to its fatigue performance. There are two main failure modes for gear components: contact fatigue and bending fatigue. In service, one pair of gears transfer torque load through the contact of two teeth. High shear stresses co-exist with high hydrostatic pressure under the contact surface. Depending on the load magnitude and the gear size, the depth of the highest shear stress point varies. To improve the contact fatigue life, the hardened case depth needs to be deeper than the highest shear stress point. Compressive residual stresses located inside the hardened case benefit the contact fatigue performance (Ref. 1). The bending fatigue failures are commonly found at root fillet location where tooth flank and root meet. Under the contact load between two gears, the root fillet experiences cyclic stresses, which is the driver of bending fatigue failure. Compressive residual stresses from heat treatment or other surface processing can significantly improve the bending fatigue performance (Ref. 2).

Induction hardening is more environmentally friendly than conventional furnace heating and liquid quenching. It also provides flexibility in control of case depth, residual stresses, and part distortion. Due to these advantages, the induction hardening process is becoming more popular to harden steel gears.

During induction heating, the energy to heat the part is generated inside the part by eddy currents in response to the imposed alternating magnetic field. The energy distribution in the part is directly related to the distance between the inductor and the part, the frequency and power of the inductor. Lower frequency and lower power heat the part deeper over longer time period. Higher frequency and higher power heat a shallower layer over shorter time period. The temperature distribution in the part is a combined result of induction heating and thermal conduction. During induction hardening of steel components, both thermal gradient and phase transformations simultaneously contribute to the evolution of internal stresses and shape change. Recent developments in heat treatment modeling technologies make it possible to understand the material's responses during heat treatment processes, such as how the internal stresses and distortion are generated. *DANTE* is a commercial heat treatment software based on the finite element method (Refs. 3-5) that was designed to model the responses of steel parts during heat treatment processes. The material's responses include phase transformations, deformation, residual stresses, hardness, etc. Typical heat treatment process steps include austenitization, carburization, quench hardening, and tempering. Phase transformation kinetics and mechanical properties are required for modeling the heat treatment processes (Refs. 6, 7). *DANTE* has a validated database for most common low- and medium-alloy carbon steel grades that have been used successfully in the past to model induction hardening processes (Refs. 8, 9). With the help of computer modeling engineers with *DANTE* software have discovered that residual compression at the root fillet of a gear can be enhanced by applying pre-heating prior to induction hardening. The pre-heating process can be implemented either by furnace or induction heating. In this paper, this process is demonstrated by computer modeling, using an AISI 4340 spur gear example.

Phase Transformation Kinetics

Phase transformations are involved in most heat treatment processes of steel components. During heating, initial phases transform to austenite, and carbides dissolve while being held at the austenitization temperature. During cooling or quenching steps, austenite transforms to ferrite, pearlite, bainite, or martensite, depending on the cooling rate and hardenability of the steel grade. At different heat treatment stages, or at different regions in a part, the material can be composed of different phases and the volume fractions of individual phases are functions of chemical composition and thermal history. To model the heat treatment process of steel components, accurate descriptions of material properties and process information are required. The basic material property data includes phase transformation kinetics, and thermal and mechanical properties of individual phases.

Phase transformations during quenching are classified as diffusive and martensitic transformations. The diffusive transformation is time- and temperature-driven, and the martensitic transformation is mainly temperature-driven. The two types of phase transformation models used in *DANTE* are described in Equations 1 and 2.

$$\frac{d\phi_d}{dt} = v_d(T)\,\phi_d^{\alpha 1}(1-\phi_d)^{\beta 1}\,\phi_a \tag{1}$$

$$\frac{d\phi_m}{dT} = v_m(1-\phi_m)^{\alpha 2}(\phi_m+\varphi\phi_d)^{\beta 2}\,\phi_a \tag{2}$$

where

ϕ_d is the volume fractions of individual diffusive phase and martensite transformed from austenite

v_d is a transformation mobility and is a function of temperature

$\alpha 1, \beta 1$ (superscripts) are constants of diffusive transformation

ϕ_a is the volume fraction of austenite

ϕ_m is the volume fractions of individual diffusive phase and martensite transformed from austenite

v_m is a transformation mobility and is a constant

$\alpha 2, \beta 2$ (superscripts) are constants of martensitic transformation

φ is a constant of martensitic transformation

For each individual phase formation, one set of transformation kinetics parameters is required.

Different experiments can be used to characterize phase transformations, such as a dilatometry test, Jominy end-quench test, metallographic characterization, etc. Among these experiments, the dilatometry test is preferred due to its accuracy and economic advantage, as well for yielding more useful data (Ref. 7). Figure 1a is a strain curve of a martensitic phase transformation dilatometry test for AISI 4340. The X-axis is temperature in Celsius, and the Y-axis is strain from the combined effects of thermal shrinkage and phase transformations. During this specific cooling test the cooling rate of the sample is fast enough to avoid diffusive phase formations. During cooling, the dilatometry sample shrinks with the temperature dropping. When the sample reaches the martensitic transformation starting temperature (Ms), martensitic formation starts with volume expansion. The strain change during transformation is a combination of thermal strain and phase transformation volume change. The data obtained from this specific dilatometry test include coefficient of thermal expansion (CTE) for austenite and martensite, martensitic transformation starting and finishing temperature (Ms, Mf), transformation strain, and phase transformation kinetics (transformation rate) — from austenite to martensite. These data are critical to the accuracy of modeling the internal stresses and deformation during quenching.

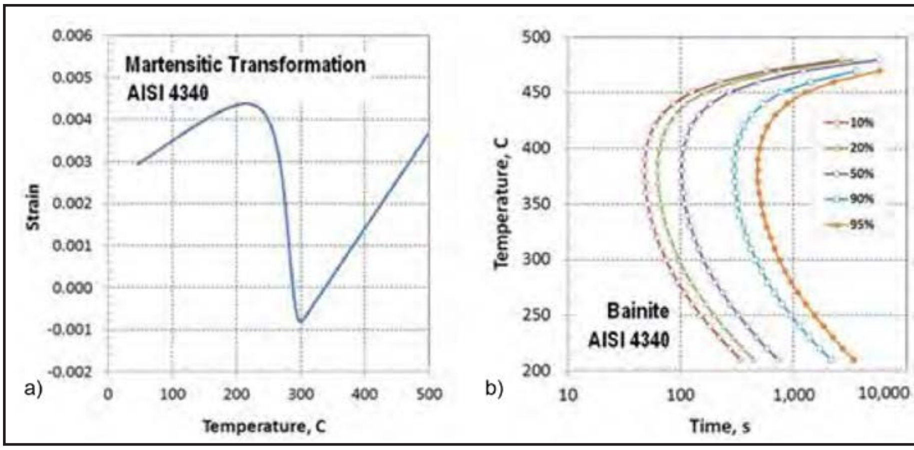

Figure 1 Dilatometry strain curve during continuous cooling (a); bainitic TTT diagram of AISI 4340 generated from DANTE database (b).

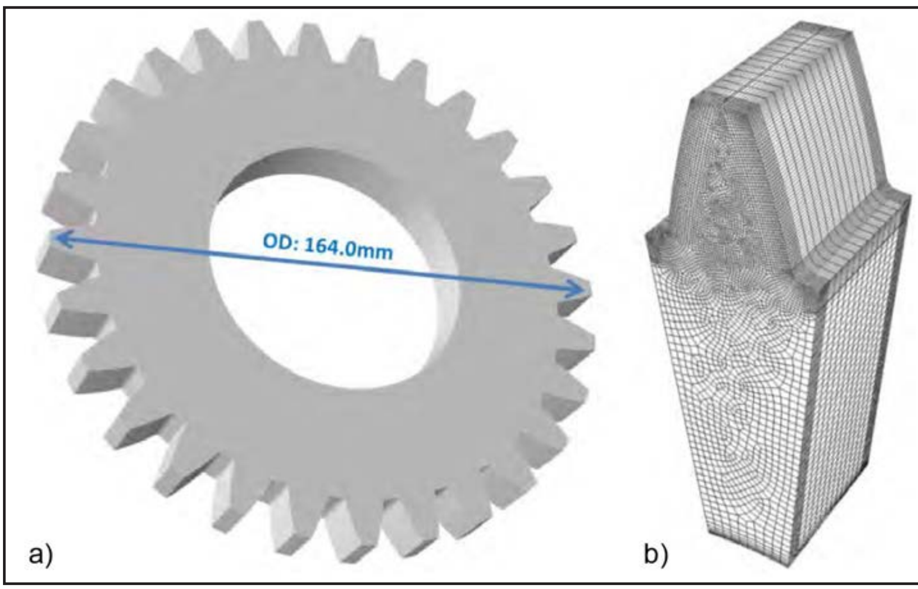

Figure 2 CAD model of the spur gear (a); single-tooth FEA model (b).

Diffusive transformations can also be characterized by dilatometry tests. In general, a series of dilatometry tests with different cooling rates are required to fit a full set of model parameters for diffusive and martensitic phase transformations. Once the phase transformation kinetics parameters are fit from dilatometry tests, TTT/CCT diagrams can be generated for users to review. TTT/CCT diagrams are not directly used by *DANTE* models of phase transformation kinetics, but they are often useful because they directly represent the hardenability. Figure 1b is the bainitic, isothermal transformation diagram (TTT) created from the *DANTE* database. The incubation times for ferritic and pearlitic transformations are much longer than that of the bainitic transformation for this steel, and therefore will not be discussed in this paper.

Descriptions of Gear Model and Heat Treatment Process

A spur gear (Fig. 2a) is selected to study the effect of pre-heating temperature on residual stresses. The outer diameter of this gear is 164.0 mm; the inner diameter 75.7 mm; and the thickness 15 mm. This gear has a total of 28 teeth. With the assumption that all teeth behave the same during the whole heat treatment process, a single-tooth model with cyclic boundary condition is used to represent the entire gear. The finite element meshing of the single-tooth model is shown in Figure 2b, with 106,850 nodes and 98,784 linear hexagonal elements. Fine elements are used in the part surface to catch the thermal and stress gradients.

Instead of modeling the electromagnetic field, the power distribution generated by inductor is applied directly to drive the heat treatment model. The power distribution can either be predicted by electromagnetic modeling software, or be estimated based on the relations of inductor power, frequency, and part geometry; both methods have been successfully used in the past (Refs. 8, 9). In this study the induction hardening process is simplified as two steps: 1) induction heating the gear teeth for 3.5 seconds, and 2) spray quench the gear to room temperature using a 6% polymer solution. There is no dwell-time between heating and spray quenching. The induction hardening process is also compared with traditional oil quench. Two oil quench processes are modeled: 1) furnace heating and oil quench of an AISI 4340 gear, and 2) furnace heating, carburization, and oil quench of an AISI 4320 gear. The carburization temperature is 900°C, held in 0.8% carbon potential atmosphere for 6 hours.

Six induction hardening processes are modeled. The first model has no pre-heating, and the other five models assume uniform pre-heating temperatures of 200°C, 250°C, 300°C, 350°C, and 400°C, individually. With pre-heating, the time duration and frequency of induction heating are kept the same, but the power of the inductor is reduced to avoid overheating the teeth. The powers of inductor are 80%,

75%, 70%, 65% and 60%, for pre-heating temperatures of 200°C, 250°C, 300°C, 350°C, and 400°C — relative to the inductor power without pre-heating. The temperature distributions at the end of the 3.5 s heating are shown in Figure 3 for all the six scenarios. The lower bounds of the legends in Figure 3 vary with pre-heating temperatures, and the upper bounds are the highest temperatures at the root. The temperature at root for the process without pre-heating is about 1,100°C, comparing to 1,050°C for all cases with pre-heating.

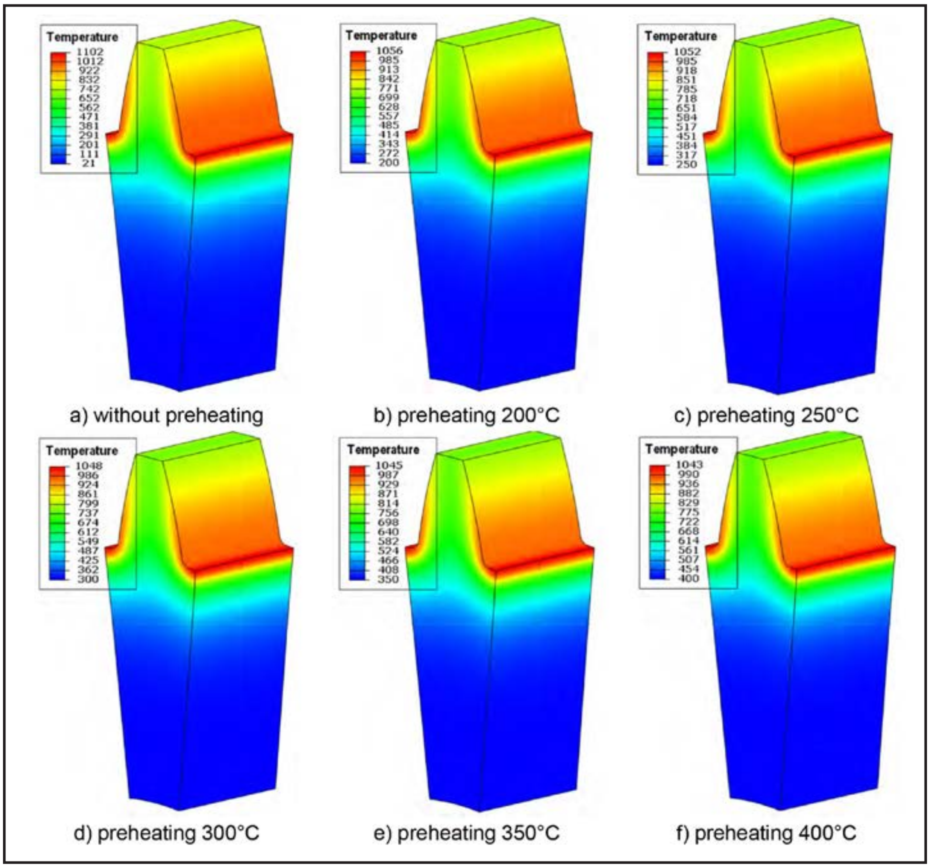

Figure 3 **Contours of temperature distribution at the end of induction heating.**

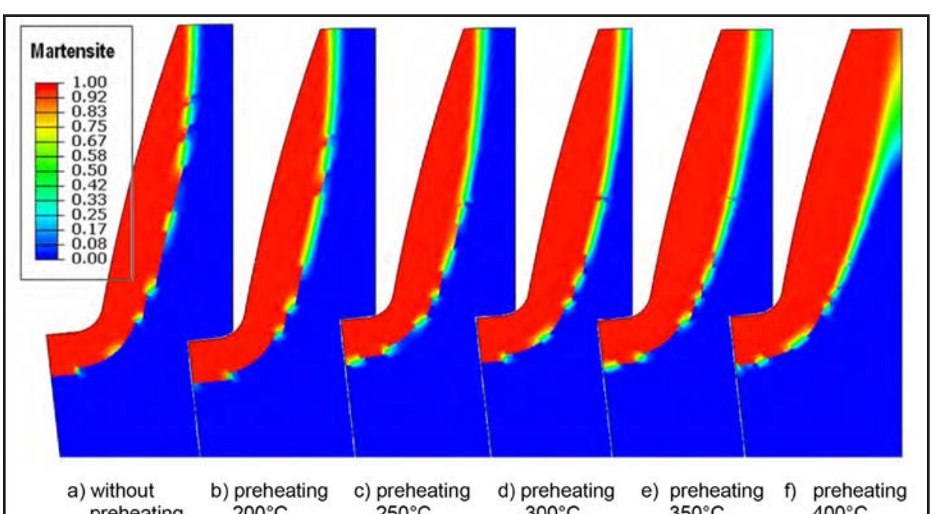

Figure 4 **Contours of martensite distribution from various induction hardening scenarios.**

For all six induction hardening scenarios, the depths of hardened layer at the root are kept closely to 1.5 mm. However, the obtained martensite distributions at the tooth tip have a significant difference due to the pre-heating effect. With higher pre-heating temperature, more martensite is formed at the tooth tip. In general, a partially hardened tooth tip is preferred to reduce the possibility of brittle crack at the tooth tip edges (Fig. 4).

Results and Discussions

In this study a global Cartesian coordinate system was used to calculate the stresses for all the heat treatment models. The origin of the global Cartesian coordinate system is located on the axis of the gear. Once the models are completed, two local cylindrical coordinate systems are created to post-process the tangential stresses at the tooth flank and root fillet regions (Fig. 5a). The tangential stresses at the root fillet are plotted using the first local cylindrical coordinate system, and the tangential stresses at the tooth flank are plotted using the second local cylindrical coordinate system. Figure 5b shows two highlighted lines representing the root fillet (CD) and pitch (AB), individually. Using the local cylindrical coordinate systems, stresses away from the root fillet or tooth flank are no longer tangential to the surface. Tangential, residual stresses predicted at the root fillet are used to evaluate the bending fatigue performance of the gear.

The tangential residual stresses at the root fillet are compared between induction hardening and traditional oil quench hardening processes. Oil quench of AISI 4340 creates a residual tension around 200 MPa at the root fillet (Fig. 6a). A combination of carburization and oil quench creates a residual compression around 580 MPa at the root fillet (Fig. 6b). The magnitude of the residual compression at the edge is to 350 MPa — or 230 MPa less than that at the middle width location. The effect of carburization on residual stresses has been reported in previous publications (Refs. 10, 11). The induction hardening process without pre-heating creates a residual compression about 500 MPa at the root fillet (Figure 6c). The case depth of induction hardening is deeper than that of carburization and oil quench. After induction hardening, the magnitude of tensile stress under the case is higher in order to balance the compression in the hardened case.

Residual stresses in the tangential direction at the tooth flank are shown (Fig. 7) for the same three hardening scenarios described in Figure 6. Slight tension is predicted for the oil quench of the AISI 4340 gear. A thin layer of compression is predicted for carburization and oil quench of the AISI 4320 gear. For the induction hardening process without pre-heating, the layer of compression is deeper and a higher magnitude of tensile stress is predicted under the case,

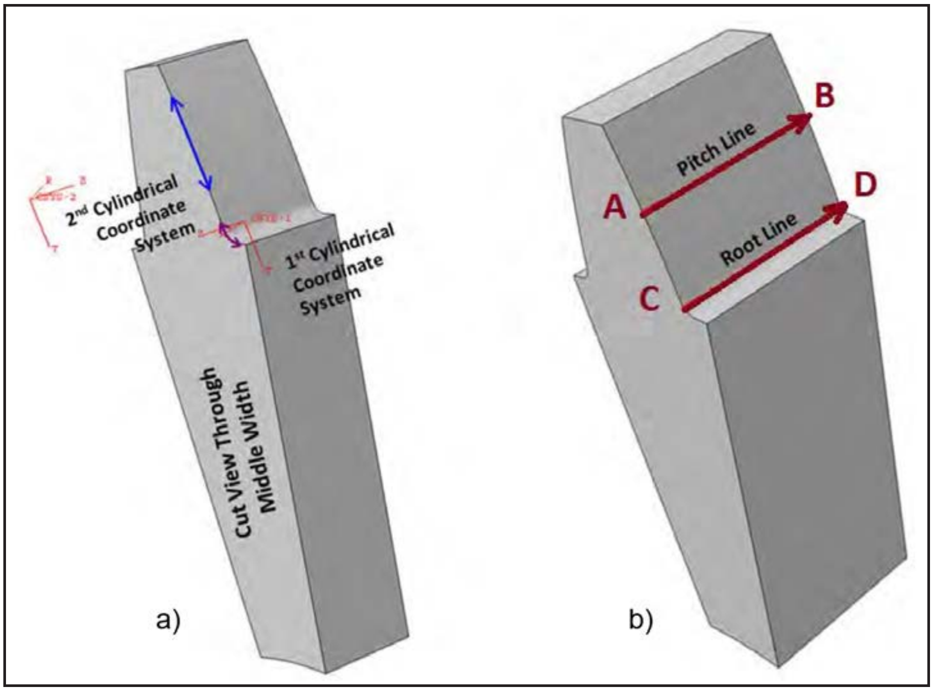

Figure 5 Definitions of two local, cylindrical coordinate systems (a); pitch and root fillet lines selected for post-processing tangential residual stresses (b).

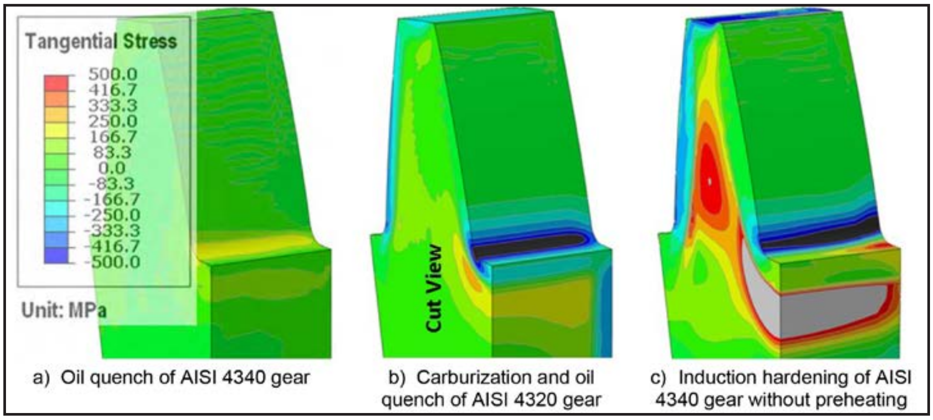

Figure 6 Contours of tangential residual stress at root fillet using the first local, cylindrical coordinate system.

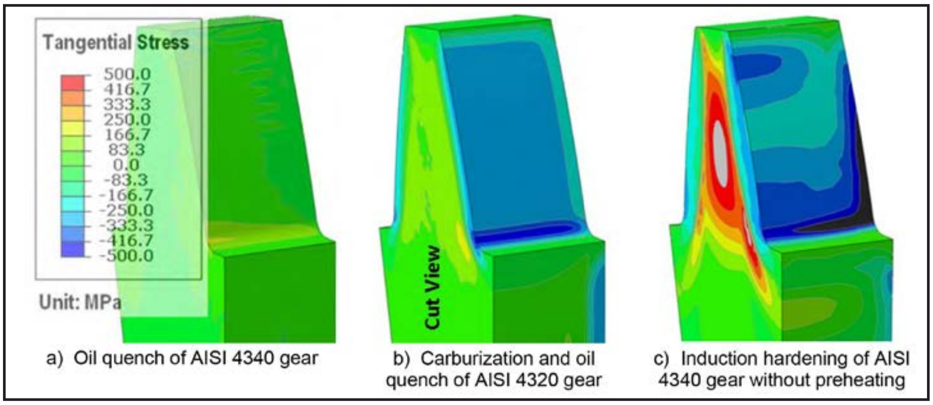

Figure 7 Contours of tangential, residual stress at tooth flank.

comparing to the carburization and oil quench process.

The effect of the pre-heating temperature on tangential residual stresses at the root fillet is shown in Figure 8 by the three pre-heating temperatures of 200°C, 300°C, and 400°C. The magnitude of residual compression at the root fillet are 750 MPa, 900 MPa, and 1,000 MPa, respectively, for the three scenarios. Pre-heating prior to induction hardening can effectively enhance the residual stresses at the root fillet. Relative to the traditional induction hardening without pre-heating, the increase of compression at the root fillet from a 200°C pre-heating temperature is 250 MPa, which is significant to the bending fatigue performance. With a higher pre-heating temperature, the effect can be more significant. However, care must be taken with the consideration of residual stresses at other regions beyond just the root fillet.

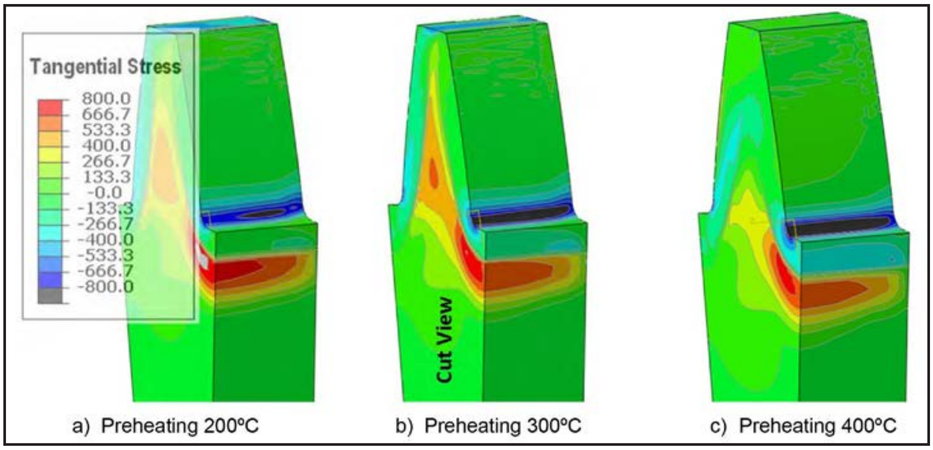

Figure 8 Contours of tangential, residual stress at root fillet.

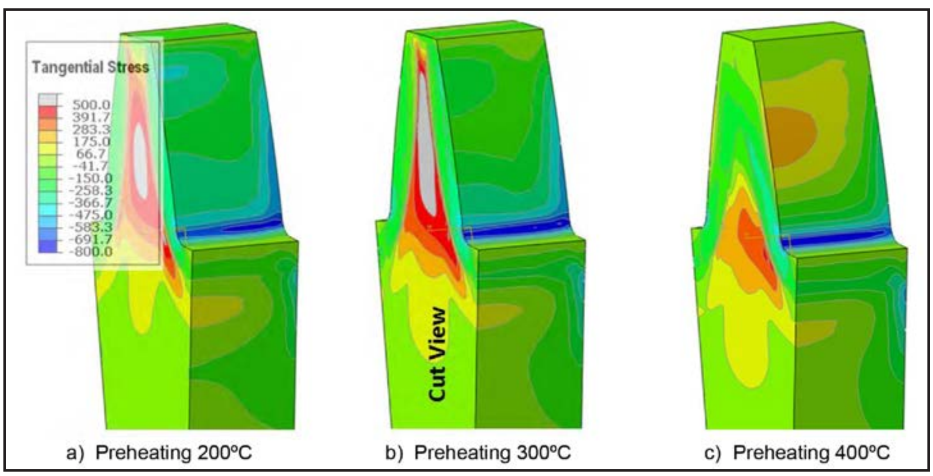

Figure 9 Contours of tangential, residual stress at tooth flank.

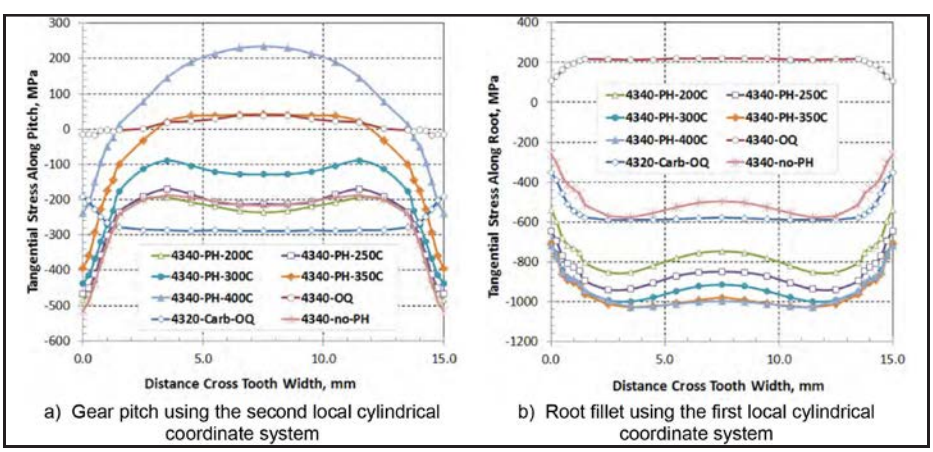

Figure 10 Comparison of tangential, residual stress from various heat treatment scenarios.

The pre-heating temperature affects the residual stresses not only at the root fillet, but also at the tooth flank. The residual stresses in the tangential direction at the tooth flank are calculated using the second local cylindrical coordinate system, and the contours of residual stresses are shown in Figure 9 for the three pre-heating temperatures of 200°C, 300°C, and 400°C. By increasing the pre-heating temperature from 200°C to 400°C, the magnitude of surface compression decreases. Surface tension is predicted with a 400°C pre-heating temperature. With higher pre-heating temperature, less power is required to austenitize the gear tooth during heating. The thermal gradient from the surface to the core is lower during both heating and quenching processes, which is the main reason for less compression obtained at the tooth flank.

The residual stresses in the tangential direction along the pitch line AB and the root fillet line CD in Figure 5b are plotted in Figures 10a and 10b for all the hardening processes. The X-axis is the distance from one face of the gear (point A or C) in the axial direction. The Y-axis is the tangential stresses along the two lines calculated using the two local cylindrical coordinate systems. By increasing the pre-heating temperature, the residual compression at the root fillet is enhanced, but the residual compression at the tooth flank is damaged when the pre-heating temperature is over 300°C. Depending on the load condition and failure mode in service, the pre-heating temperature can be optimized to balance the residual compression at both root fillet or tooth flank for improved fatigue performance.

Quench hardening is a high material's nonlinear process due to phase transformations. Distortion is inevitable, but accurate prediction of distortion using modeling helps the process optimization to minimize distortion. The predicted radial distortions for all eight hardening scenarios are shown in Figure 11. The contours shown are the radial distortion relative to the dimension prior to heat treatment. Also, Figures 11a–f represent the distortions caused by induction hardening, and Figures 11g and h are from oil quench. Pre-heating prior to induction hardening can have a significant effect on the distortion — especially when the whole tooth or a large region of the tooth is hardened rather than merely a shallow surface layer — which is shown in Figure 11f with a 400°C pre-heating temperature scenario. The same legend is used to plot the contours of radial distortion caused by the induction hardening processes, so the color of the contour represents the magnitude of distortion from Figures 11a–11f. A higher pre-heating temperature tends to generate higher distortion, which is mainly due to the more regional phase transformation in the tooth. Significant radial shrinkages are predicted for both oil quench scenarios. Different legends are used for the two oil quench scenarios. In this study the oil quench processes create larger distortion relative to the induction hardening processes.

During quenching, time and temperature are the two main drivers of phase transformations. Both thermal gradient and volume change caused by phase transformations contribute to the evolution of stresses. As shown in Figure 12a, one straight line MN is selected to demonstrate the relationship among temperature, phase transformation and stresses. The line MN is located at the middle width of the gear, with point M right on the surface and point N at a depth of 3 mm. The line MN is normal to the tangent of the root fillet. The induction hardening process with 250°C pre-heating temperature is used for this demonstration. The time is reset to zero at the beginning of the spray quench. The X-axis in Figures 12 b–d is the distance from the root fillet surface, with X = 0.0 mm representing the surface point M. The Y-axes are the volume fraction of austenite, temperature, and tangential stress, respectively. At time 0.0 s (the beginning of spray quench), small compressive stresses along the line MN are predicted, which is mainly caused by the thermal expansion of the tooth from induction heating.

During spray quenching, the cooling rate is fast enough to avoid the formation of diffusive phases, and martensite is the only phase transformed from austenite. The martensitic transformation starting temperature (Ms) is about 305°C for AISI 4340. At 1.219 s during quench, the

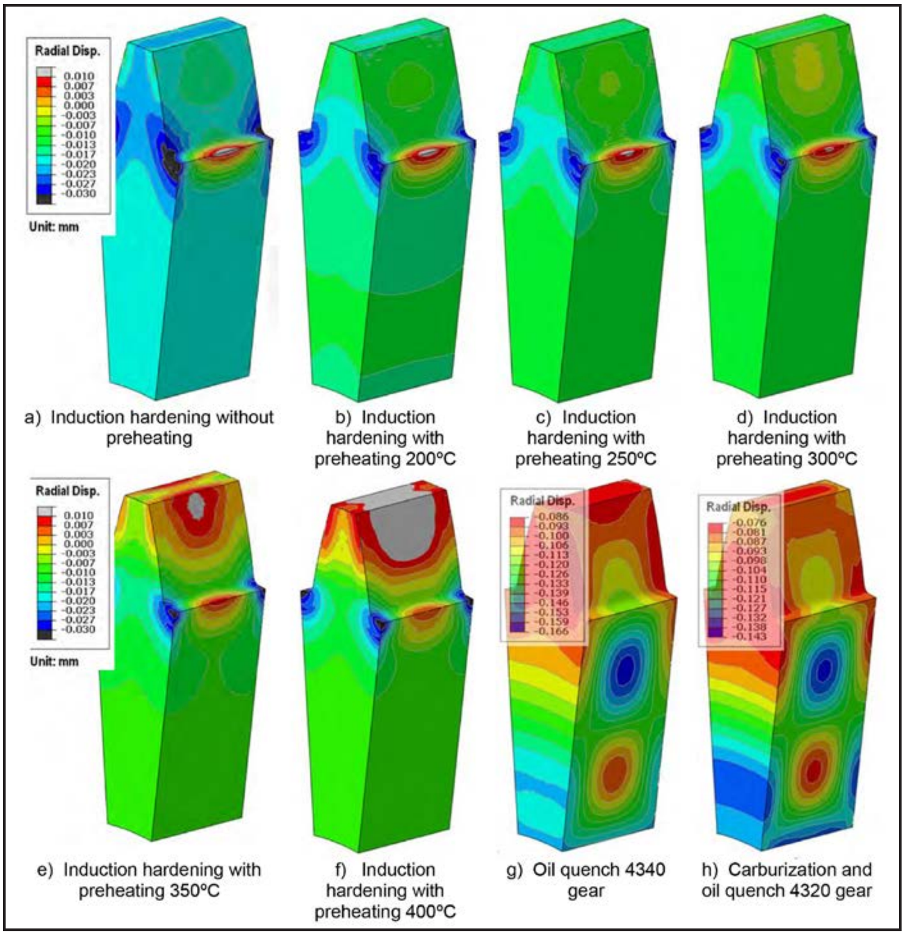

Figure 11 Comparison of radial distortion from various heat treatment scenarios.

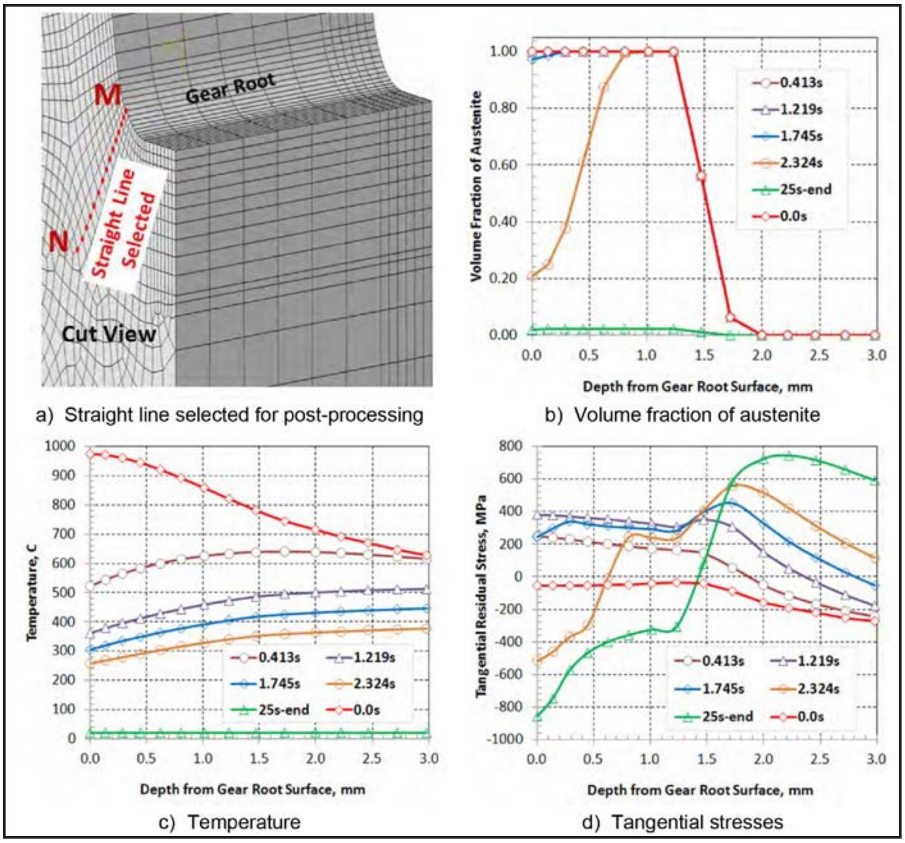

Figure 12 Evolution of temperature, phase, and stress during spray quenching (induction hardening with 250° C pre-heating).

temperature at the surface point is about 360°C (Fig. 12c). Martensite is not yet formed on the surface because the temperature is above Ms. Thermal shrinkage at the gear surface creates tensile stresses along line MN (Fig. 12d). At 1.745 s during quench, a small amount of martensite is formed on the surface and the volume expansion due to martensitic transformation reduces the magnitude of tensile stress in the transformation region. At 2.324 s during quenching, about 80% martensite is formed on the surface. The volume expansion from martensitic transformation shifts the surface stress from tension to a compression around 500 MPa. As shown in Figure 12c, the thermal gradient along line MN is relatively low, and the phase transformation plays a critical role to the stress evolution. The gear reaches room temperature at 25 s in quench. The residual stress at the surface point M is about 850 MPa in compression. With pre-heating prior to induction hardening, the bore continues to cool after the transformation of the austenite layer is completed. The further non-uniform thermal contraction contributes to residual compression at the gear root fillet.

Summary

An innovative approach of pre-heating prior to the induction hardening process is proved to be effective in enhancing the residual compressive stresses at the root fillet of gear components, which benefits the bending fatigue performance.

Uniform pre-heating temperature by furnace is assumed in this paper, but induction heating with lower frequency and lower power inductor can also be used to preheat the opposite side of gear teeth. The temperature distribution at the end of pre-heating doesn't need to be uniform.

With different gear geometry, steel grade and service condition, different inductor designs and pre-heating processes could be designed to enhance the residual compression at critical regions.

Future Works

In this conceptual modeling study the spray quench is applied right after induction heating — without delay. Past experience has shown that delay can have a significant effect on residual stresses, and further studies should consider delay time as one of the process parameters to optimize the induction hardening process with pre-heating. Experimental validation of this process should also be implemented.

Uniform pre-heating temperatures are assumed in this paper, which can be done by furnace heating for experimental studies. To be practical, the bore of the gear can be preheated using low power and low frequency inductor, and the pre-heating temperature doesn't need to be uniform throughout the part. Further modeling studies should be implemented to investigate the pre-heating by inductors.

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