

Modeling Application to Reduce Distortion of a Carburized and Quenched Steel Gear

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Abstract

During quench hardening processes for steel components, both the thermal gradient and phase transformations in the part contribute to distortion and residual stresses in the final part. Most transmission gears have unbalanced geometry, which will cause a temperature difference from one region to another during quenching, aside from the temperature gradient from surface to core. The unbalanced temperature distribution in the part will lead to different phase transformation timing and final phase composition in the quenched part. The material volume expands with different ratios when austenite transforms to different phases at different temperatures. By modifying a quenching process, such as quenchant type, agitation, immersion direction and speed, the distortions of the final part are expected to be different. In this paper, the commercial heat treatment software, DANTE, is used to model the quenching process of a transmission gear. This transmission gear is gas carburized by using a boost/diffuse process, followed by an immersion oil quench process. The predicted carbon distribution and distortion are compared against the experimental measurements. The correlations between temperature, carbon distribution, phase transformation, and stress changes are described using the modeling results. The causes of distortion and residual stresses are discussed.

Introduction

Heat treatment is used to improve the quality and performance of steel components. A combination of carburizing and quenching can generate residual compression in the hardened case of parts, which benefits the fatigue performance [1]. However, distortion caused by heat treatment may increase the noise and reduce the fatigue life of gears during service. Both distortion and internal stresses during quenching are complicated and not intuitively understandable in most cases, which make it more difficult for process troubleshooting and improvement. It is both difficult and expensive to experimentally investigate the heat treatment process of a real part with complex geometry.

Heat treatment results that are of common interest include the volume fractions of phases, hardness, residual stresses, and part distortion. Heat treatment is a transient thermal process, and

most of these results can only be measured after heat treatment has been completed. The thermal gradient during both heating and cooling works together with phase transformations to continually change the internal stresses and shape of the part being heat treated. The material response of a specific part during the heat treatment process is difficult to document by just using the final measurements. The development of heat treatment simulation software makes it possible to understand the material response during the heat treatment process, including the evolution of internal stresses and deformation, the phase transformation sequences, and the probability of cracking, etc. DANTE is a commercial heat treatment software tool based on the finite element method that has been used to predict steel phase transformations, dimensional change, residual stress, and hardness for heating, carburization, cooling, and tempering processes [2]. Computer simulation has increased the level of understanding of heat treatment processes because the events that occur during heating and cooling can be accurately modeled. In turn, advances in computer hardware, in combination with accurate simulation, has made the design and optimization of the heat treatment processes more cost effective than traditional experimental trial-and-error methods. By increasing the carbon content of an alloy steel, the diffusive transformations are retarded, and the martensitic phase transformation starting temperature is depressed. As a combined effect of the thermal gradients and phase transformation sequences, quenching of carburized steel parts generates compressive residual stresses in the carburized case, in general. However, the relations among the carburization schedule, residual stress state, and fatigue life are not well understood quantitatively. This paper applies heat treat simulation to investigate the effect of different carburization schedules on the residual stress, distortion, and fatigue life of a shaft component. The simulation results are validated against experimental measurements.

Mathematical Models for Steel Quenching Processes

Temperature, phase transformation and stress are the three main fields for modeling the heat treatment of steel parts. In this section, the phase transformation models, mechanical models, and TRIP models used in DANTE are briefly described. To accurately model the heat treatment process, the detailed process information should be converted to the thermal and mechanical boundary conditions. The thermal boundary conditions for quenching processes are briefly described.

Phase Transformation Models

Phase transformations during quenching of steel parts are classified as diffusive and martensitic transformations. The diffusive transformation is time and temperature dependent, and martensitic transformation is temperature driven. The two types of phase transformations are described in equations (1) and (2).

$$\frac{d\Phi_d}{dt} = v_d(T)\Phi_d^{\alpha_1}(1 - \Phi_d)^{\beta_1}\Phi_a \dots\dots\dots (1)$$

$$\frac{d\Phi_m}{dT} = v_m(1 - \Phi_m)^{\alpha_2}(\Phi_m + \varphi\Phi_d)^{\beta_2}\Phi_a \dots\dots\dots (2)$$

where Φ_d and Φ_m are the volume fractions of individual diffusive phase and martensite; Φ_a is the volume fraction of austenite; v_d and v_m are the mobilities of the transformation; α_1 and β_1 are the

constant parameters of diffusive transformation; α_2 , β_2 and φ are the parameters for martensitic transformation. For each individual phase transformation, one set of kinetics parameters is required.

During cooling of steel parts, austenite transforms to ferrite, pearlite, bainite, and martensite under different cooling rates. TTT/CCT diagrams, Jominy End-Quench, and dilatometry tests have been used to characterize these phase transformations. The dilatometry test is considered to be the most effective method to characterize the cooling transformation kinetics. The phase transformation kinetics parameters can be fit from dilatometry tests using design optimization method [3]. Dilatometry tests with periods of isothermal holding and continuous cooling under different rates are required in order to fit the transformation kinetics parameters. Slower cooling rates and isothermal holding at various temperatures are required to characterize the diffusive transformations. Using DANTE utility tools, dilatometry curves can also be generated from the database. Using AISI 4320H as an example, Figure 1 shows the dilatometry curves for a fast cooling rate generated from DANTE database. In this case, the cooling rate is fast enough to avoid diffusive phase transformations. The martensitic transformation starting temperatures (M_s) are around 400° C, 325° C, and 195° C for 0.2%, 0.4%, and 1.0% carbon contents, respectively. The martensitic transformation finishing temperatures (M_f) are higher than room temperature for AISI4320H with 0.2% and 0.4% carbon levels. For carbon levels above 0.7%, the M_f is higher than room temperature, and retained austenite is observed in parts after fast cooling to room temperature. Besides phase transformation kinetics, the dilatometry tests also provide coefficients of thermal expansion and phase transformation strains. These data are critical for the modeling accuracy of residual stresses and distortion from quenching processes.

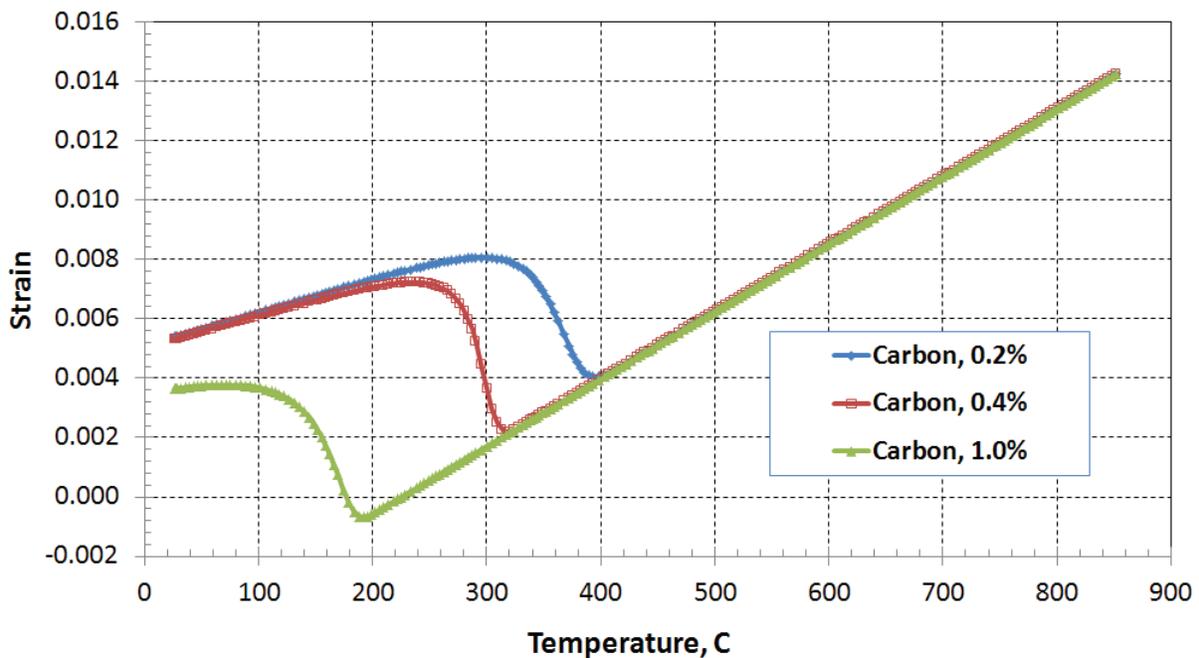


Figure 1: Dilatometry curves of carburized AISI 4320H from DANTE database

Multiphase Mechanical Model

To properly characterize the quenching process of carburized steels, an effective multiphase plasticity model is essential. The mechanical properties of individual phases should be defined as functions of temperature and carbon contents. The composite behavior of multiple phases in the part can be modeled using a nonlinear mixture law. In DANTE, the plastic behavior of each individual phase is described by the Bammann–Chiesa–Johnson (BCJ) model. A tensor variable and a scalar variable are used to describe the conditions of each phase. The yield criterion of each phase is modeled by equation (3).

$$D_p = \left\| \left(\sigma_i - \frac{2}{3} \alpha_i \right) \right\| - \frac{2}{3} \left[Y + \kappa + V * \text{Ln} \left(\frac{\|\dot{\epsilon}\| + \sqrt{\|\dot{\epsilon}\|^2 + f^2}}{f} \right) \right] \quad (3)$$

If $D_p \geq 0$, the phase reaches its yield point, otherwise, the phase is in the elastic region. In equation (3), α is the tensor internal variable, κ is the scalar internal variable, σ is the deviatoric stress, $\dot{\epsilon}$ is the strain rate, Y is rate independent function, V and f are rate dependent functions.

Traditional tensile and compressive tests can be used to characterize the parameters in the mechanical model for each individual phase. The tensile or compressive tests should cover the ranges of temperature, carbon content, and strain rate experienced during heat treatment.

Transformation Induced Plasticity (TRIP) Model

During a heat treatment process, there is a volume change along with phase transformation, and the original and product phases have different mechanical properties. The interaction between different phases while phase transformation is in progress causes TRansformation Induced Plasticity (TRIP), which is defined as plastic deformation under an external load that is lower than the yield of the weak phase. The TRIP model applied in DANTE is shown in equation (4).

$$\Delta \epsilon = \left(A_1 \bar{\sigma} + A_2 \bar{\sigma}^2 \right) \frac{A_3}{A_4} \left(\frac{A_4}{1 - \Delta \Phi} \right)^{(1-A_3)} \frac{\Delta \Phi}{\text{Exp} \left(\frac{\Delta \Phi}{A_4} \right)^{A_3}} \frac{\sigma_{ij}}{\bar{\sigma}} \dots \quad (4)$$

where $\Delta \epsilon$ is TRIP plastic strain, $\bar{\sigma}$ is effective stress, σ_{ij} is deviatoric stress tensor component, $\Delta \Phi$ is the volume fraction of phase transformation, A_i ($i=1$ to 4) are constant parameters. The parameters in the TRIP model are fit from tensile or compressive tests while phase transformations are occurring.

Thermal Boundary Conditions

Thermal boundary conditions are the driver of heat treatment models. Detailed and accurate process information is essential to describe the thermal boundary conditions. Using an immersion oil quench process as an example, the critical process information includes quenchant type and temperature, quench tank design and agitation, and quench holding time. Thermocouple measurements are typically used to characterize the thermal boundary conditions. Surface heat transfer coefficients can be fit from the thermocouple measurements using an optimization method, and a minimum of two thermocouple points located at different depths are required for an accurate fitting.

CFD analyses have also been used to investigate the quenchant flow pattern [4]. Both CFD modeling and thermocouple measurements can be used to convert to thermal boundary conditions including heat transfer coefficient and ambient temperature, as shown in equation (5).

$$q = h_f (T_{surf} - T_{ambient}) \dots\dots\dots (5)$$

where q is the heat flux, h_f is the heat transfer coefficient, T_{surf} is the part surface temperature, and $T_{ambient}$ is the ambient temperature. It has been established that heat transfer coefficients of liquid quenchants are highly dependent on the part surface temperature, which includes three main cooling phases: vapor blanket, nucleate boiling, and convection [5].

Case Study: Modeling Oil Quench Process of Gear Component

A gear made of AISI 4320H was carburized and oil quenched. The chemical composition of 4320H is shown in Table 1. The thermal/mechanical properties and phase transformation kinetics from DANTE database were used directly in this modeling study.

Table 1 Chemical composition of AISI 4320H

Element	C	Mn	Cr	Ni	Mo
%	0.20	0.55	0.50	1.75	0.25

A simplified CAD model of the gear is shown in Figure 2(a). The inner diameter is 90mm, the outer/tip diameter is 225mm, the height is 70mm and the gear has 40 teeth. The main distortion mode resulting from the oil quench was tapering of the bore and gear tooth in the radial direction. The out-of-round distortion was not an issue in this specific case. Therefore, it was assumed that all the gear teeth responded the same during an axial immersion quenching process. A finite element model of a single tooth with cyclic boundary conditions was used to represent the whole gear, as shown in Figure 2(b). This finite element mesh contains 32,474 nodes and 29,545 linear hexagonal elements. Fine surface elements were used to effectively model the carbon and thermal gradients during quenching.

A boost/diffuse process was used to reduce the carburization furnace time. The desired case depth was 1.2mm. The carburization schedule is listed below:

- Boost step: furnace temperature: 927° C; carbon potential: 0.97%; time: 12 hours.
- Diffuse step: furnace temperature: 927° C; carbon potential: 0.88%; time: 3 hours.
- Drop furnace temperature to 857° C; carbon potential: 0.88%; time: 1 hour.

The predicted final carbon distribution is shown in Figure 3(a). The carbon profile in terms of depth from the bore surface, measured using the combustion method, is shown in Figure 3(b) by the curve with solid diamond marks. A straight line ABC was selected to plot the predicted carbon in terms of depth. The line ABC is located at approximately the middle height position. Point A is on the part surface; point B is at a depth of 1.5mm, which is the case-core interface depth; and the depth of point C is 2.8mm. The predicted carbon along the line ABC is plotted in Figure 3(b) to compare with the measured values. The prediction and measurement agree reasonably.

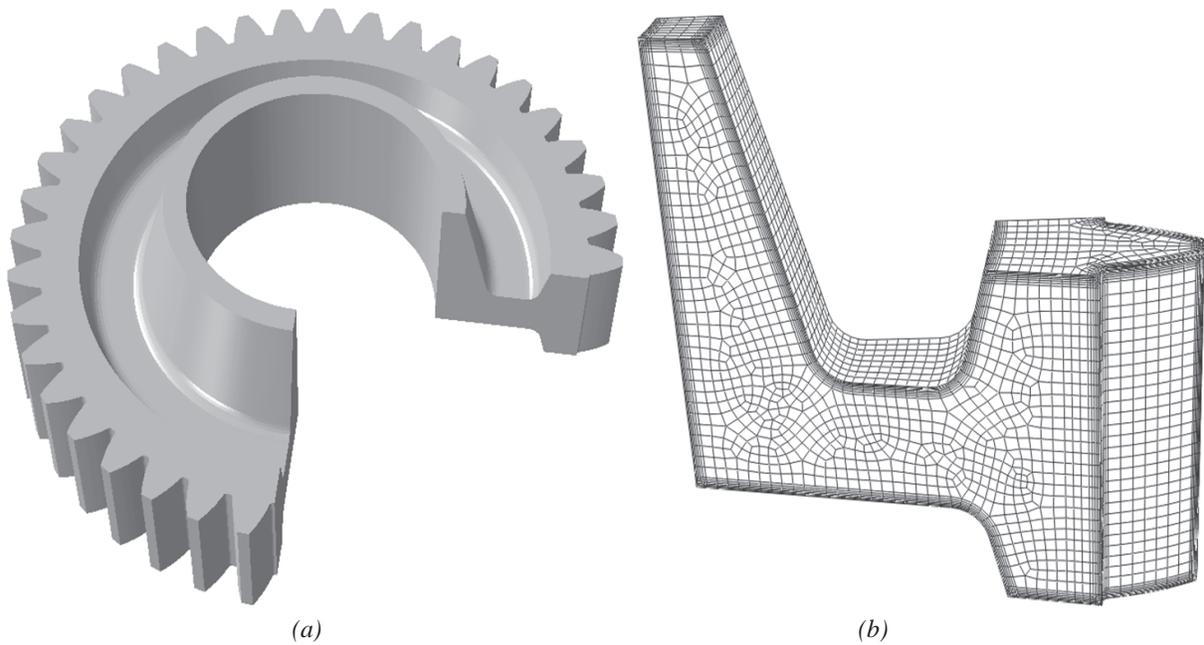


Figure 2 (a) Gear CAD model, and (b) single tooth FEA model

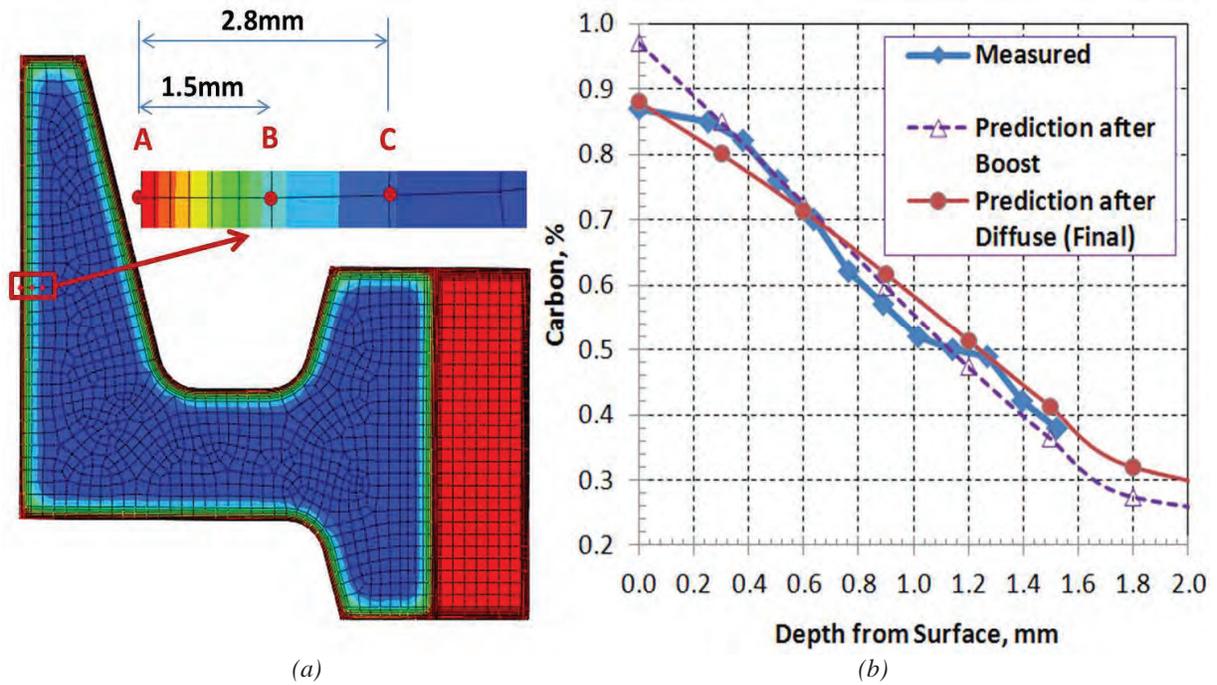


Figure 3 Comparison of measured and predicted carbon distribution profile
 (a) Location of carbon measurement, and (b) carbon distribution

The gears were racked horizontally during the furnace heating and carburization processes. After carburization, the rack of gears was transferred to the quench tank over a 42 second period. The gears were immersed into the oil tank at a speed of 200mm/second in the

direction shown in Figure 4(a). A snapshot of temperature distribution during the immersion process is shown. The temperature difference between the bottom and top ends of the gear due to immersion affects the tapering distortion in radial direction. Therefore, it is important to include the immersion process in the quenching models. Due to the gear geometry and rack design, stagnant oil flows are expected in the highlighted regions shown in Figure 4(a), and lower cooling rate is expected in these regions. Figure 4(b) shows the heat transfer coefficients in terms of part surface temperature for both regular and stagnant oil flows used in this model. The temperature of the quenching oil is 70° C. After quenching, the gears are taken out of quench tank, washed, and cooled to room temperature. The gears are then tempered at a low temperature. The low temperature tempering process has a minor effect on both residual stress and distortion, so this process was not modeled in this study.

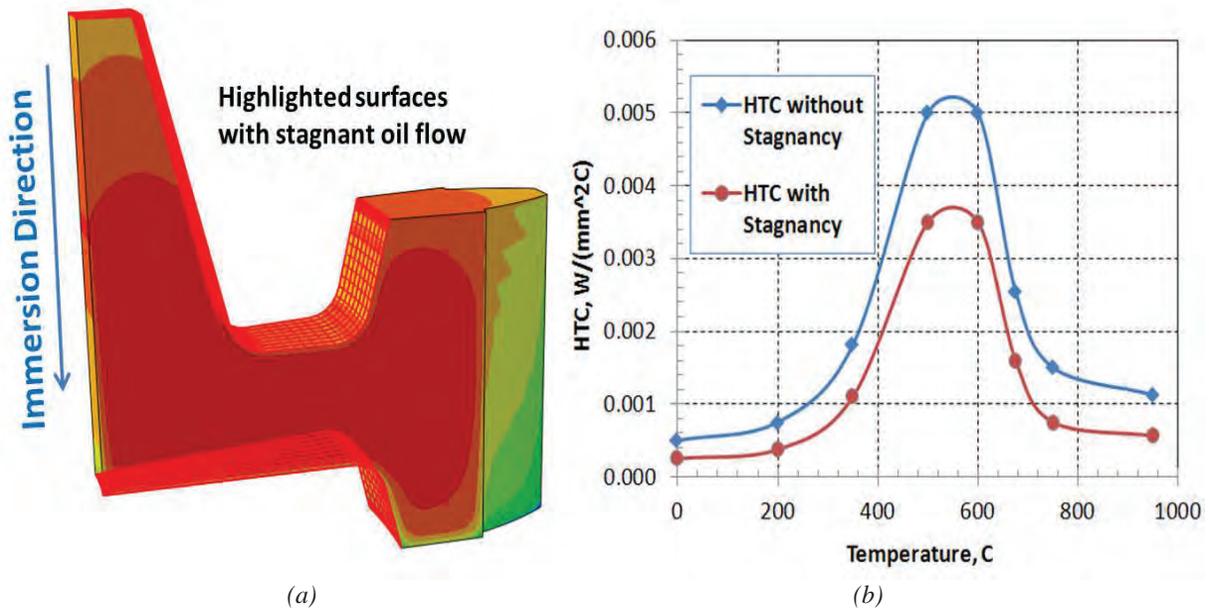


Figure 4 Thermal boundary conditions during quenching process
 (a) Surface definition for stagnant oil flow region, and (b) heat transfer coefficients

The predicted carbon content on the gear surface is 0.88%. The martensitic transformation finishing temperature (M_f) for this high carbon content is below room temperature, and about 15% retained austenite is predicted at the carburized surface after the gear is cooled to room temperature, as shown in Figure 5(b). The predicted martensite distribution is shown in Figure 5(c). A high percentage of martensite, about 97%, is predicted at the case-core interface. This is due to the combination of cooling rate and carbon content. Right at the gear surface, about 15% retained austenite and 85% martensite is predicted for the as-quenched condition. The core of the web has about 65% martensite and 35% bainite, as shown in Figures 5(c) and (d). An accurate phase transformation kinetics model is essential to predict residual stresses and distortion caused by the quenching process.

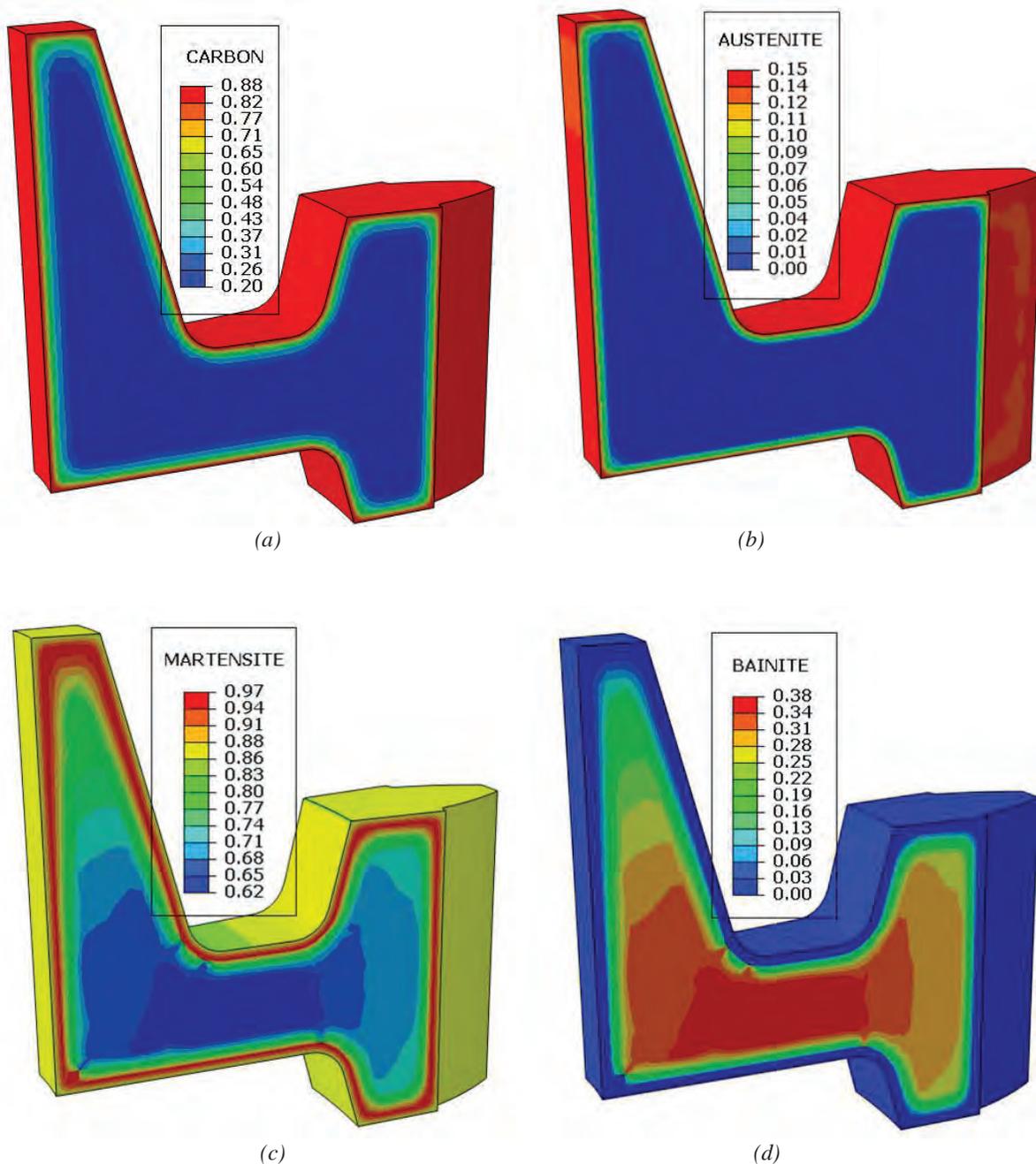


Figure 5 Predicted phase distribution contours of as-quenched condition
 (a) Carbon, (b) retained austenite, (c) martensite, and (d) bainite

The predicted axial and circumferential residual stresses are shown in Figure 6. The axial residual stresses at both the bore and tooth surfaces are approximately 700MPa in compression. A combination of carburization and quenching process not only increases the strength and hardness, but also introduces residual compression in the carburized surface. The surface residual compression benefits fatigue performance of the gear components [1].

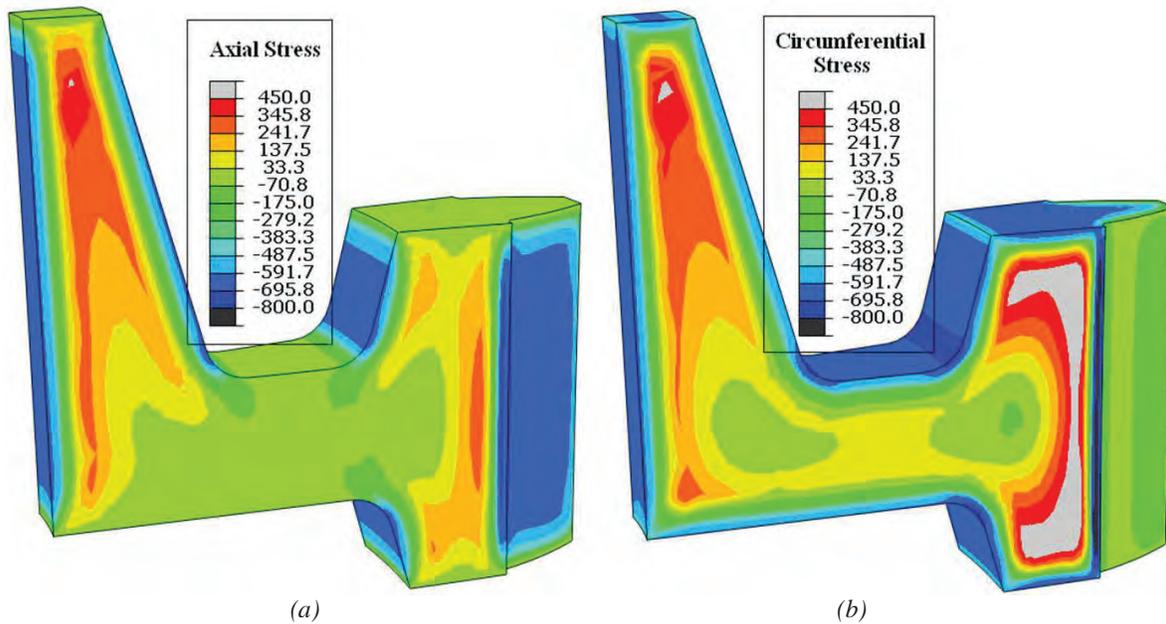


Figure 6 Predicted residual stresses (unit: MPa)
 (a) Axial stress, (b) circumferential stress

The quenching process of steel components is highly nonlinear due to part geometry, carbon gradient, temperature gradient, and phase transformations. In general, it is not intuitive to predict the response of the part during a quenching process. Computer modeling has proven to be an effective method for understanding and improving heat treatment processes [6]. Using the three selected points, A, B, and C shown in Figure 3(a), the interrelations of temperature, carbon, phase transformation, and stress evolutions during quenching process were investigated. Recall that the depths of the three points are 0.0mm, 1.5mm, and 2.8mm from the bore surface, respectively. The X-axis in Figure 7 is cooling time in seconds, starting at the beginning of air transfer (taking the part out of furnace).

After the 42 second air transfer, the temperature at the surface has dropped to about 825° C, and the temperature gradient along line ABC is negligible. After 42 seconds, the immersion process starts. With an immersion speed of 200 mm/second, the gear is immersed into the oil tank in about 0.35 seconds. In Figure 7(a), the primary Y-axis is temperature, and the secondary Y-axis is volume fraction of phases. The secondary Y-axis in Figure 7(b) is circumferential stress. During air transfer, a small temperature gradient is generated in the gear, and the internal stresses are negligible. The circumferential stresses at the three points at the end of air transfer are close to zero, as shown in Figure 7(b). No phase transformation is predicted during this step. During the early stage of quenching, before phase transformation starts, the thermal gradient is the main contributor to internal stress. Right at the beginning of quenching process, the cooling rate at the gear surface point A is higher than internal points B and C, and the cooling rates at points A, B, and C are higher than that of a central core point. All three locations, A, B, and C are in tension at this stage due to the thermal shrinkage. The magnitude of the tensile peak is highest at point A. With further cooling, the cooling rate at the surface drops, and the cooling

rate at the core increases. When the cooling rate at the core exceeds the cooling rate at the surface, the core shrinks more, and the surface stress shifts from tension to compression.

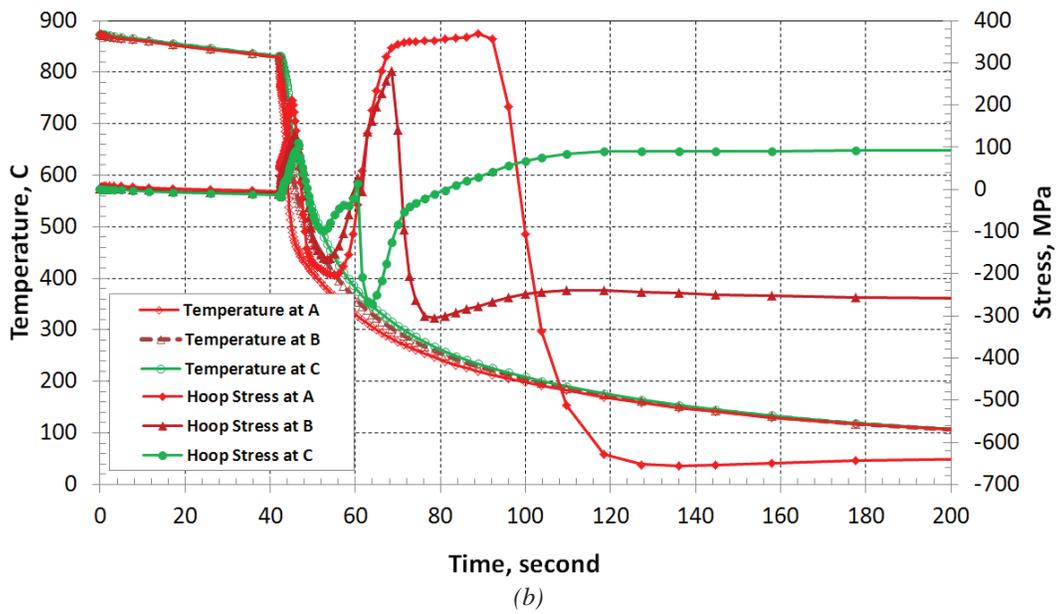
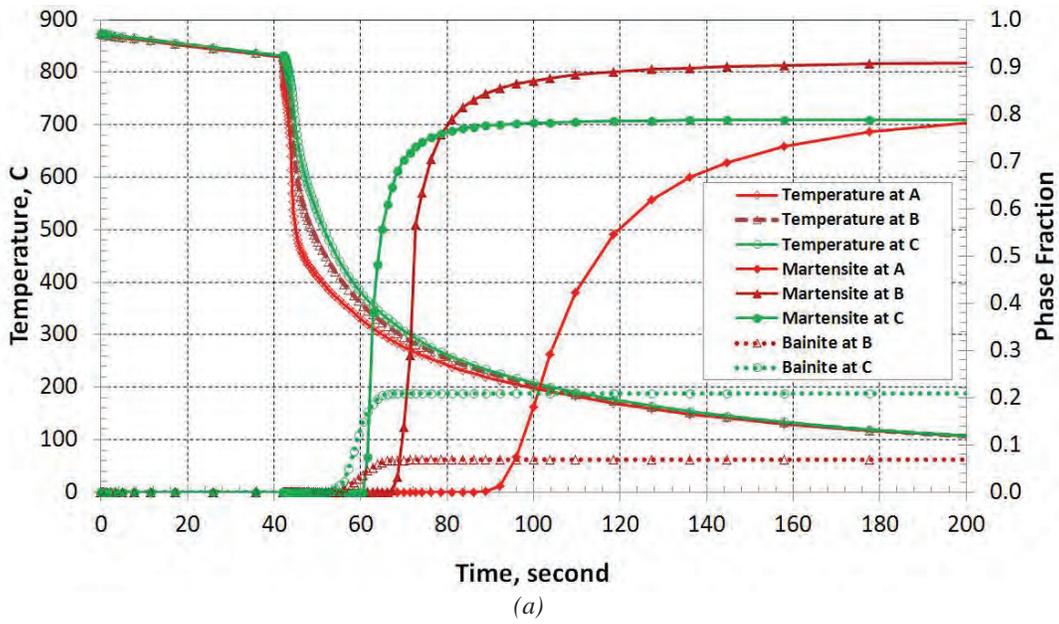


Figure 7 Relations between temperature, phase transformation and stress evolution during quenching
 (a) Phase transformations, (b) evolution of hoop stresses

The definition of surface and core is relative. For example, point A is a surface point compared to B and C. Points A, B, and C can all be considered as surface points relative to points at greater depths. At about 60 seconds during cooling (18 seconds during quenching), martensitic transformation starts at point C when its temperature has dropped below M_s due to its lower carbon content. There is a volume expansion accompanying martensitic phase formation,

and this converts the stresses at point C from tension to compression. To balance the compressive stress at point C, stresses at points A and B are shifted to tension. The phase transformation at point C is nearly completed before point B drops below its martensitic transformation starting temperature (M_s). With further cooling, martensite formation at point B reduces the level of compression and converts stress at point C from compression to tension. At the same time, the volume expansion at point B further increases the tensile stress at the surface, point A. The martensitic phase transformation starts at a location under the carburized case, and moves toward both the surface and the core of the part. The martensitic transformation in the carburized case is delayed due to its higher carbon content, and the delayed transformation is the main reason of residual compression in the surface of the gear. The predicted volume fractions of bainite are 20%, 6%, and 0% at point C, B, and A respectively, as shown in Figure 7(a).

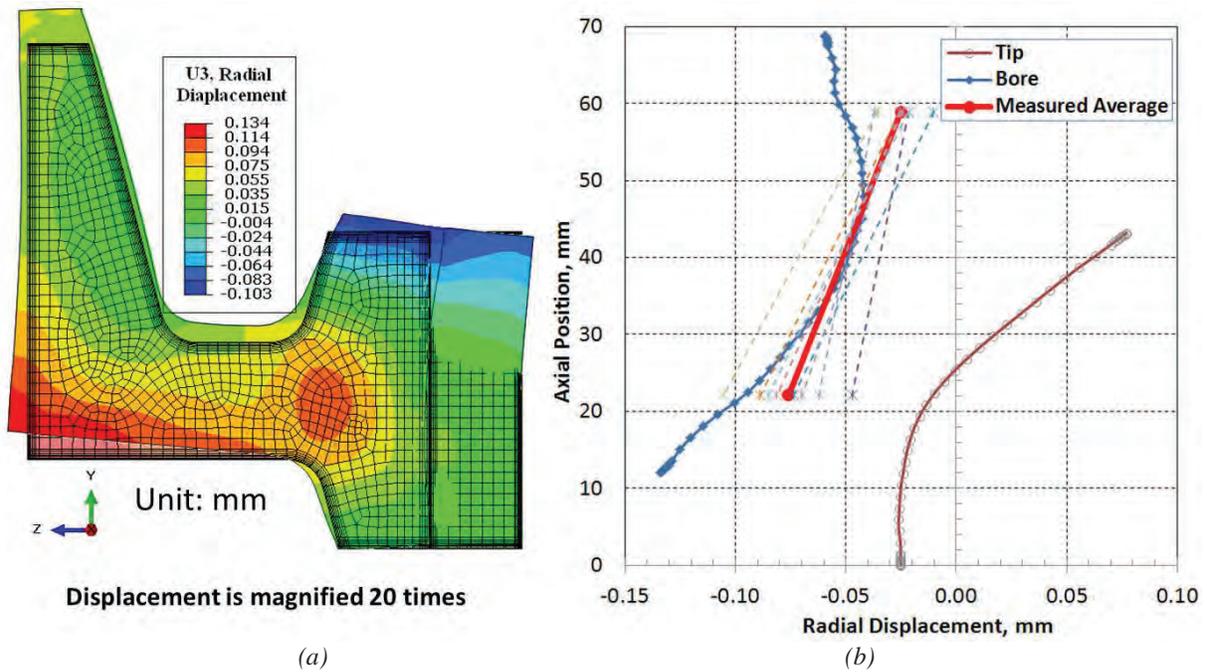


Figure 8 Comparison of predicted and measured distortion
 (a) Contour of radial displacement, (b) line plots of bore and tip distortion

The effect of low temperature tempering on the distortion is negligible in this case, and the predicted radial displacements of as-quenched condition is compared with the measurements. Figure 8(a) is the contour plot of the predicted radial displacement, with a shape magnification of 20 times. The mesh in Figure 8(a) denotes the original gear geometry for a comparison purpose. A straight line of points on the bore in the gear axial direction was selected to plot the predicted taper distortion as shown in Figure 8(b). The Y-axis is axial position, and X-axis is radial displacement. A negative radial displacement indicates shrinkage, a positive radial displacement indicates radial growth, and $X=0$ mm represents the zero radial displacement line. The dotted lines are the measured taper distortions of the bore from different gears and multiple quenching practices. The heavy line with solid round marks is the average taper distortion from all the measurements. Both prediction and experiments show a radial shrinkage of the bore, and the prediction and measurements agree reasonably. The lower end of the gear tooth is predicted to

shrink, and the top end of the gear tooth is predicted to grow in the radial direction. Further experiment study is required to validate the tooth profile predicted for the model.

Conclusions

A carburization and oil quenching process for a gear component made of AISI 4320H was modeled using finite element analysis. The predicted carbon distribution and radial distortion reasonably agree with the experiments. With the help of modeling, the interactions between temperature, carbon distribution, phase transformation and stress evolutions during quenching process have been discussed. The reasons why a combination of carburization and oil quenching can produce surface compressive residual stresses have been explained. In the past decade, computer modeling has proven to be an effective technology for understanding and improving heat treatment processes. With high demands of lean manufacturing and increasingly tighter part tolerance requirements, cutting edge computer modeling technology will be more accepted by the modern manufacturing industry. Heat treatment modeling will be used more intensively in the component design stage to optimize the geometry, improve part dimensional consistency, control residual stress state, and reduce the potential for defects caused by heat treatment.

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