Data Needs for Modeling Heat Treatment of Steel Parts

Z. Li, B. L. Ferguson, and A. M. Freborg

Deformation Control technology, Inc. 7261 Engle Road, Suite 105
Cleveland, OH 44130

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Abstract

Heat treatment of steel parts, or more specifically hardening of steel parts, involves controlling the microstructural phases by heating and cooling at particular rates and holding times. The microstructure changes from initial phases, such as ferrite, pearlite, to austenite at elevated temperatures, and to combinations of martensite, bainite, pearlite and ferrite upon cooling (usually rapid) and tempering. There is associated thermal expansion/contraction of these phases with temperature, changes in density with phase transformation, and resultant stress that accompanies both nonuniform heating/cooling and the changes in phase. Simulation of such a process requires that the material behavior be known or defined for all possible conditions experienced during heat treatment. Complex parts with a non-constant cross-section will go through a nonuniform austenitization history, and this is the main cause of distortion during austenitization. Similarly, nonuniform cooling causes nonuniform phase transformation histories, which is the main reason for distortion during quenching. This paper discusses the nature of the testing and data required to characterize the phase transformation kinetics for both heating and cooling processes. Several simplified methods for checking the accuracy of the transformation kinetics are presented. The methods discussed in this paper were implemented as part of the DANTE® software for simulation of heat treatment. Simulation results for a two-dimensional gear blank model are presented to demonstrate the effect of phase transformations on the part distortion during heat treatment.

Introduction

Modeling the heat treatment of steel components includes the calculation of transient temperature fields, changing metallurgical phases, and resultant stress and deformation caused by the thermal gradients and phase transformations. Numerical analyses using finite element method were conducted previously to simulate the quenching process for alloy steel parts.[1,2,3,4] These studies, supported by experimental investigations, showed that phase transformation increases the possibility of large distortion during steel heat treatments. While there are many potential sources of distortion, the material volume change and the stress caused by phase transformation during both heating and cooling processes are primary causes of distortion. During phase transformations, the material will go through loading, unloading, and reverse loading because of the volume change. To model the material response during heat treatment, the mechanical model should capture the loading and reverse loading processes.[5] Phase transformation is the driver for stress and deformation changing during heat treatment. The accuracy of the phase transformation kinetics is one key that affects the accuracy of the model. However, most modeling studies have focused on the cooling process, and have reported distortion and stress states for quenching step(s) of the heat treat process. Recently, ASTM Standard A1033-04 has been published to document two dilatometric methods for characterizing the phase transformation of hypoeutectoid steels, and this standard focuses on the transformations that occur during cooling of austenite. The effect of the heating process on distortion is generally ignored, other than the size change that occurs due to heating to austenite. Papers and reports on experimental methods for obtaining the phase transformation kinetics are rare.

In the present paper, an effective method of deriving the phase transformation kinetics from dilatometry experiments is discussed. Jominy End-Quench data and Temperature-Time-Transformation (TTT) diagrams and Continuous-Cooling-Transformation (CCT) diagrams may be used to check the accuracy of the cooling kinetics. A two-dimensional gear blank model is used to investigate how the phase transformations affect the distortion and residual stress.

Phase Transformation Kinetics during Heating

During the heating process of a steel component, the thermal gradient generates internal stresses. For typical furnace heating, the thermal gradient is relatively small and the thermal stress is below the steel yield stress. The deformation caused by the thermal stress remains in the elastic region. However, when the phase transformation to austenite starts, the volume contraction causes higher levels of internal stress, which may cause plastic deformation. The transformation induced plasticity allows the material be deformed under small deviatoric stress.[6] For a component with significantly changes in cross-section, the timing of austenite formation will vary throughout the part. In this case, the effect of austenitization on distortion cannot be ignored. The austenite formation kinetics are key to improving the accuracy for deformation prediction during heat up. The TTT or CCT diagram for heating is one source for deriving the transformation kinetics. However, the availability of these diagrams for heating is limited [7,8], the strain data are typically not available, and the diagram accuracy is questionable.

In comparison to TTT or CCT diagrams, dilatometry is a more accurate method for deriving the transformation kinetics during heating. Figure 1 shows the dilatometry curves for 5140 steel during heating. The starting phases prior to heating are bainite and martensite, respectively. The heating rates for both cases are the same. The starting temperature for transforming martensite to austenite is about 10 ºC lower than that of bainite transforming to austenite. The difference between austenitization starting temperature and finishing tempering is around 30 ºC in this case. The transformation time period usually takes several seconds. The material volume reduces during austenitization, as shown by the strain in Figure 1. Another benefit from the dilatometry experiment for heating is the accurate measurement of the transformation strain, which is the key for accurately modeling the internal stress and distortion during austenitization.

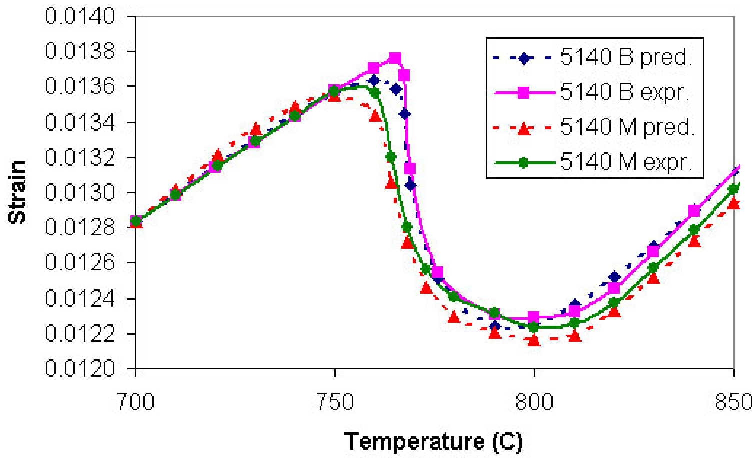


Figure 1. Phase Transformation Kinetics Fitting during Heating using Dilatometry.

The heat treat simulation software DANTE provides a utility to fit the phase transformation kinetics for heating using the heating portions of dilatometry experiments. In Figure 1, the solid lines are the experimental data, and the dotted lines are the predicted curves from the DANTE utility. The austenitization temperature increases with increased heating rate. For a component going through a rapid heat up, such as induction heating, the dilatometry experiments using rapid heating rates are required to accurately determine the transformation kinetics. To generate robust heating kinetics for a specific steel, a series of heating rates with different starting phases is required.

Phase Transformation Kinetics during Cooling

During cooling of a steel component, austenite transforms to ferrite, pearlite, bainite, and martensite according to the cooling rate and the hardenability of the alloy. TTT and CCT diagrams, Jominy End-Quench data, and dilatometry data may be used to characterize the phase transformations during cooling. Of these, dilatometry is the most effective method because time, temperature and strain are recorded, and the cooling transformation kinetics parameters must be fit using these data. Figure 2 shows a dilatometry curve of 5140 during rapid cooling where the cooling rate is fast enough to avoid the formation of diffusive phases. Therefore, the curve in Figure 2 provides only martensite formation data. To characterize diffusive transformations, i.e. formation of ferrite, pearlite and bainite, dilatometry experiments using slow cooling or isothermal holds are required. DANTE provides a utility to determine the cooling transformation kinetics parameters from dilatometry experiments. In Figure 2, the solid line is the experimental data, and the dotted line is the predicted curve. In addition to the data needed to characterize phase transformations, the dilatometry curve also provides the coefficient of thermal expansion data and the transformation strains for the various transformations at different temperatures. These data are critical for modeling the internal stress and deformation during quenching.

Jominy End-Quench Hardness data, TTT diagrams and CCT diagrams can also be used to determine the phase transformation kinetics parameters. TTT diagrams are limited to the determination of diffusive phase transformation kinetics only. Determining martensitic transformation kinetics from the M_s and M_{50} reported in TTT diagrams is not recommended. CCT diagrams are preferred for fitting martensite kinetics, and they provide an additional source of data for characterizing diffusive phase transformations. To determine kinetics parameters using Jominy hardness data, the hardness values of different phases formed at different temperatures are required as these provide the bridge between the Jominy hardness values and volume fractions of phases. These methods all are lacking a major data component, namely the strain – time data.

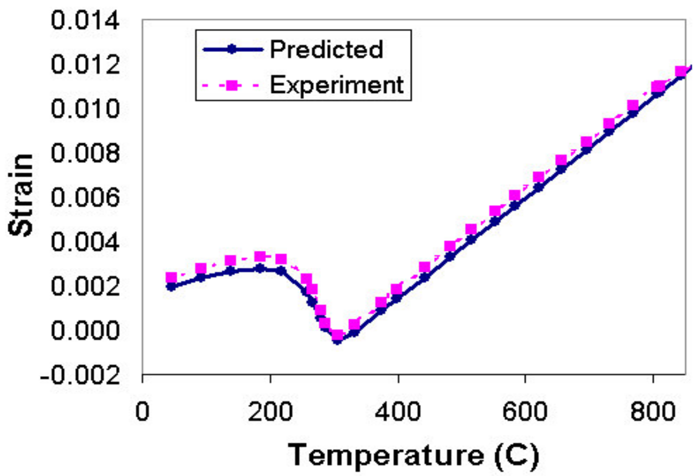


Figure 2. Martensitic Transformation Kinetics Fitting using Dilatometry.

As mentioned, the accuracy of the phase transformation kinetics is key to the accuracy of the model results. DANTE provides two utilities for checking the accuracy of the cooling kinetics. While the Jominy test and the TTT diagram are not preferred for determining the transformation kinetics parameters, they provide excellent checks of the parameter accuracy. A Jominy End-Quench simulation can be run to generate a hardness curve, which can then be compared with available Jominy hardness experimental data. Similarly, a simple model may be used to generate a TTT diagram using the kinetics parameters determined from dilatometry tests. The predicted TTT diagram can then be compared to experimentally deterived TTT diagrams.

Figure 3 shows the Jominy End-Quench hardness and phase distributions generated for 5140 steel using kinetics parameters contained in the DANTE database that were fit from dilatometry tests. The experimental Jominy data provides hardness only, while the simulation predicts hardness and the distribution of phases. The Jominy End-Quench hardness comparison is very helpful for checking the accuracy of the kinetics parameters, especially the bainite transformation kinetics. In Figure 3, the hardness drops at J5, which indicates the increasing amount of bainite and decreasing amount of martensite. If the bainite transformation speed in the model is faster than reality, the predicted hardness at J positions below J5 will be lower than measured. On the other hand, a higher predicted hardenability indicates that the bainite transformation rate is lower than reality. In Figure 3, the hardness curve becomes flat when the J position exceeds J20, which indicates the dominance of ferrite and pearlite. Generally, the hardness comparison at high J positions characterizes the accuracy of the transformation kinetics of ferrite and pearlite.

Many TTT and CCT diagrams have been published; for example, see reference [9]. These diagrams can be used in combination with the Jominy End-Quench data to check the accuracy of the transformation kinetics. The TTT diagram of 5140 steel generated by simulation is shown in Figure 4. The top curves are the volume fraction combinations of ferrite and pearlite formed by isothermal holds, and the bottom curves are fractions of bainite formed.

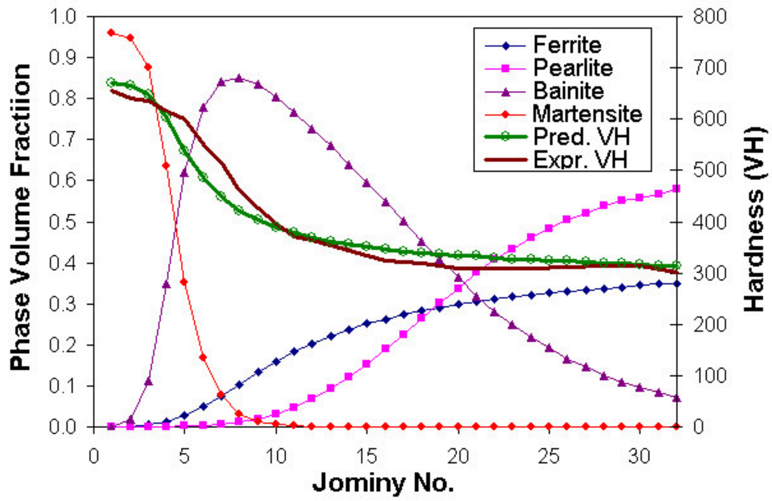


Figure 3. Jominy Hardness and Phase Distributions of 5140 Generated using DANTE Utility.

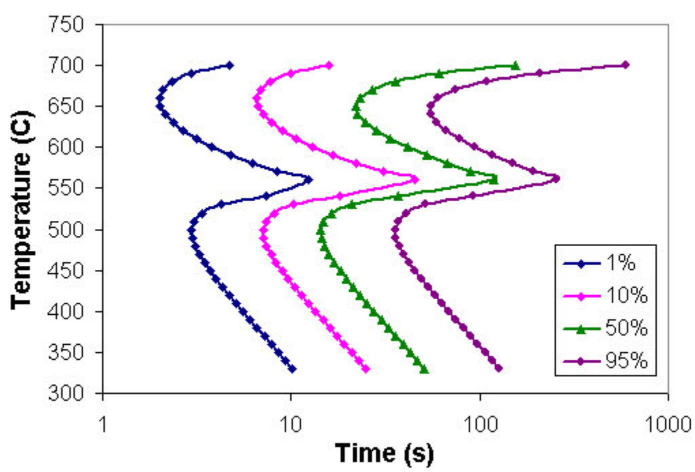


Figure 4. TTT curves of 5140 Generated using DANTE Utility.

Gear Blank Case Study

Finite Element Model

The effects of phase transformations during both heating and cooling on the heat treat simulation results are illustrated by a two-dimensional axisymmetric gear blank example. The radius of the gear is 100 *mm*, and the gear is 5140 steel. The material phases before heating are a combination of ferrite and pearlite. Figure 5 shows the finite element model. A half section of the gear blank is modeled with 528 nodes and 473 elements. Fine elements on the surfaces are used to effectively capture the thermal gradients. The heat treatment process is specified as: furnace heating (600 seconds), hot oil quenching (600 seconds), and air cooling to room temperature (600 seconds). 19 points located on the bottom surface as shown in Figure 5 are used to check the temperature profile, phase distribution, and deformation.

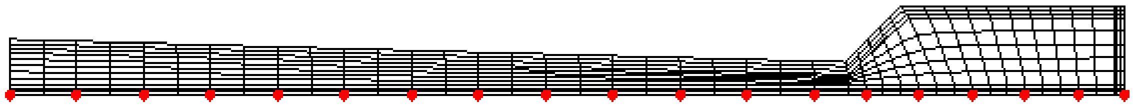


Figure 5. Finite Element Model of the Gear Blank with 528 Nodes and 473 Elements.

Effect of Heating Kinetics on Stress Changing and Deformation

Figure 6 shows the temperature (dotted lines) and austenite fraction (solid lines) of the 19 bottom points at various times during heating. The shape of the lines indicates the level of nonuniform heating and the nonuniform formation of austenite due to part thickness variations. At 40.5 seconds austenite is forming at locations in the thin web section but not in the center or rim sections. Because the austenite formation is fast, the transformation in the thin web section is nearly completed before the transformation at the center starts. The rim section of the gear blank is the thickest, and its temperature is the lowest during heating. The austenite volume fraction curve at 52.8 second shows a complete austenite transformation across the web, while the transformation at the rim has just started.

As shown by the dilatometry curves in Figure 1, the material volume reduces during austenite formation. The stresses caused by the thermal gradient and volume change are the drivers for plastic deformation. Figure 7 shows the gear blank shape change during furnace heating. The displacement in this figure is magnified by 10 times.

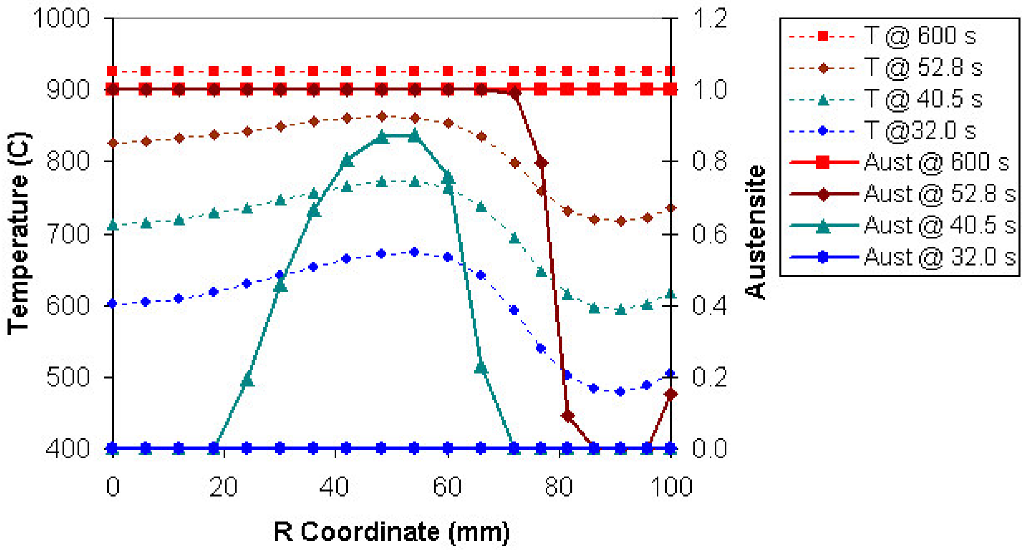


Figure 6 Austenitization Transformation during Heating

Figure 7(a) shows the simulation results with the phase transformation kinetics activated, while the series in Figure 7(b) has the transformation kinetics turned off, thus isolating the effect of thermal stress on distortion. The temperature histories for both cases are same. Figure 7(b) shows that the thermal stress generates only elastic deformation during heating in this case. At time 40.5 second, austenite formation has started in the thin web section as shown by the shaded area. The transformation in the thickness direction of the web is almost uniform. The volume reduction caused by the transformation generates tensile stress at this location, and plastic deformation occurs locally. As a result, the rim of the gear blank moves downward. The effect of the austenite formation is shown clearly by comparing the modeling results of the gear blank shapes between Figure 7(a) and Figure 7(b) at time 48.5 second. When austenite formation starts in the rim location, the stress at this location converts from compression to tension due to the material volume reduction, and the rim moves upward. During austenitization, the phase transformation has a significant effect on the state of internal stress, which usually has more contribution to the deformation than the thermal stress alone. For a component with a more uniform cross section, the deformation caused by austenitization is smaller. However, if the component has large section thickness differences, the effect of austenite formation will be more significant, and the accuracy of the heating kinetics will play an important role on the simulation results.

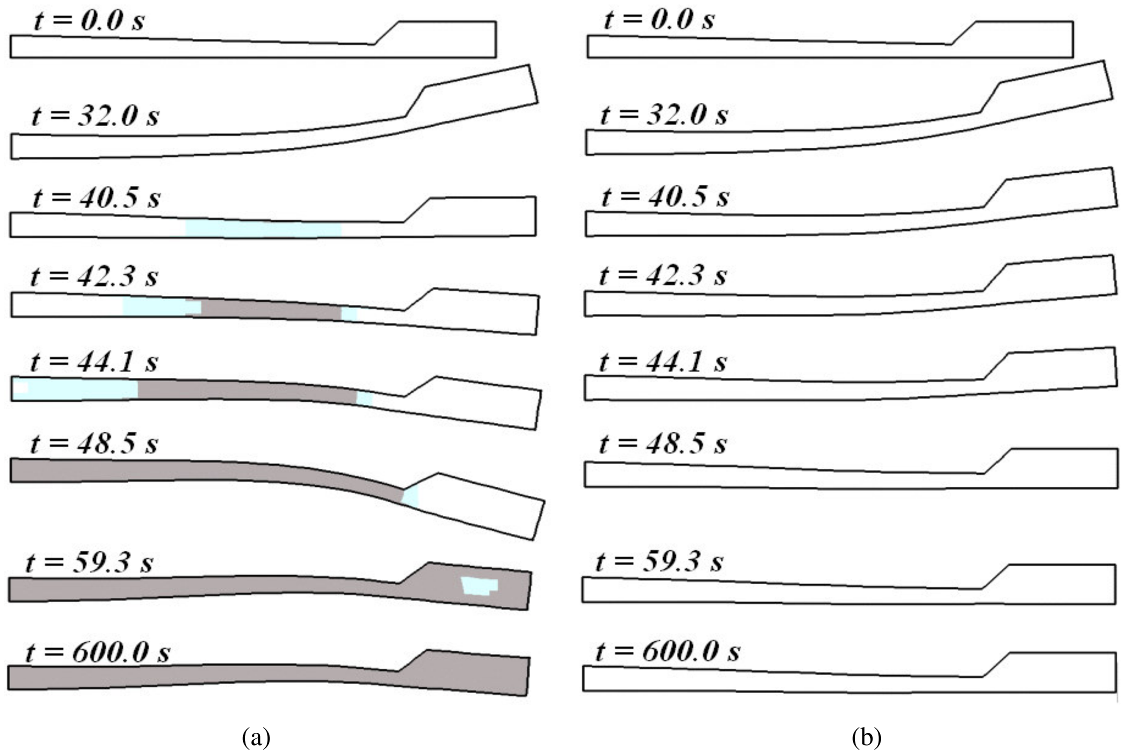


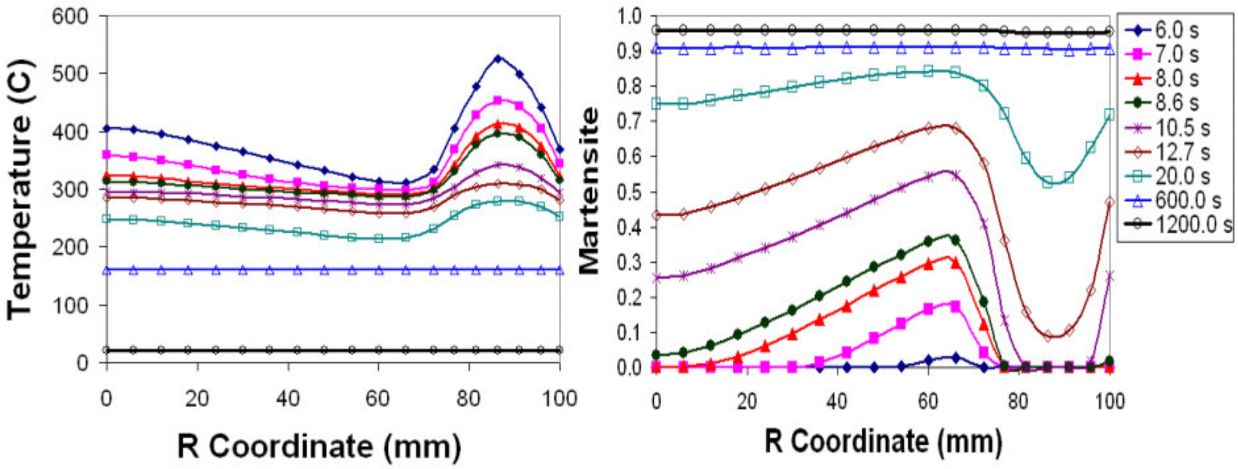
Figure 7. Comparison of the Distortion History (Displacement is magnified by 10X)

(a) with phase transformation (b) without phase transformation.

Effect of Cooling Kinetics on Stress and Deformation

After austenitization, the gear blank is quenched into hot oil (160 °C) and held for 600.0 seconds, and then air cooled to room temperature. Martensitic transformation is the main phase transformation during cooling in this case. The simulation shows that the total volume fraction of the diffusive phases is less than 1%. Figure 8(a) shows the nonuniform cooling history along the radial direction of the gear blank. The thin web section is cooled faster than the center of the gear, and the rim section is cooled the slowest. Figure 8(b) shows the martensitic transformation in the thin web section starts earlier than in the gear center. After 12.7 seconds in oil, the thin web section achieves about 70% martensite, the center is 45% martensite, and the rim section contains only 10% martensite. The nonuniform transformation history at different locations is the main driver of internal stress and deformation.

Figure 9 shows the changes in hoop stress and deformation during oil quenching and air cooling. The displacement is magnified by 5 times. The stress and deformation at 0.0 second are from the furnace heating and austenitization step; the distortion is relatively high, and the stress values are vary around zero. At 6.0 second after quenching, the martensitic transformation in the thin web section starts. The changes in stress and deformation before 6 seconds are caused by thermal stress. Compared to the furnace heating case, the thermal stress during quenching has more contribution to the changing stress state and deformation. At the beginning of oil quenching, the temperature in the thin web section drops faster than in the center of the gear and the rim section, as shown in Figure 8(a). The thermal contraction at this location causes the increase in tensile stress, which is shown in Figure 9 at *t = 3.6s*. To balance the overall stress, the center of the web and the rim section suffer an increase in compressive stress. As cooling progresses, the hoop stress shifts from compression to tension at the center of the gear because the cooling rate here exceeds the cooling rate of the colder thin web section. At around 6 seconds, the martensitic transformation starts in the thin web section. The volume increase caused by martensite formation contributes to a compressive hoop stress at this location. The change in stress is shown in Figure 9 at *t = 6.6 s* and *t = 8.6 s*. Another contribution to the compressive stress at this location is the now higher cooling rate at the center of the gear than in the thin web section. **Both thermal stress and stress caused by phase transformation are significant during quenching, and neither can be neglected.** At 8.6 second, the martensitic transformation at the rim section has not started. The change in stress at the rim section before 8.6 second is due to the combined contributions of both thermal contraction and phase transformation from the gear web. Before the martensitic transformation starts in the web section (6s), the cooling rate of the web is higher than in the rim section. The stress at the rim is a higher compressive stress. When the transformation starts in the web section, the volume increase contributes more to the stress than the thermal contraction. Therefore, the web section stress becomes more compressive, while the rim section stress shifts from compression to tension to balance the overall equilibrium. At 10.5 second, the martensitic transformation starts in the rim section, and the rim section's stress pattern shifts from tension to compression because of the volume increase caused by transformation. The web section shows a low tensile stress. During the air cooling process, the stress does not change significantly because of negligible phase transformation and relatively uniform temperature throughout the part.



(a) (b)

Figure 8 Relation between Temperature Changing and Martensitic Transformation

(a) Temperature (b) Martensite Volume Fraction

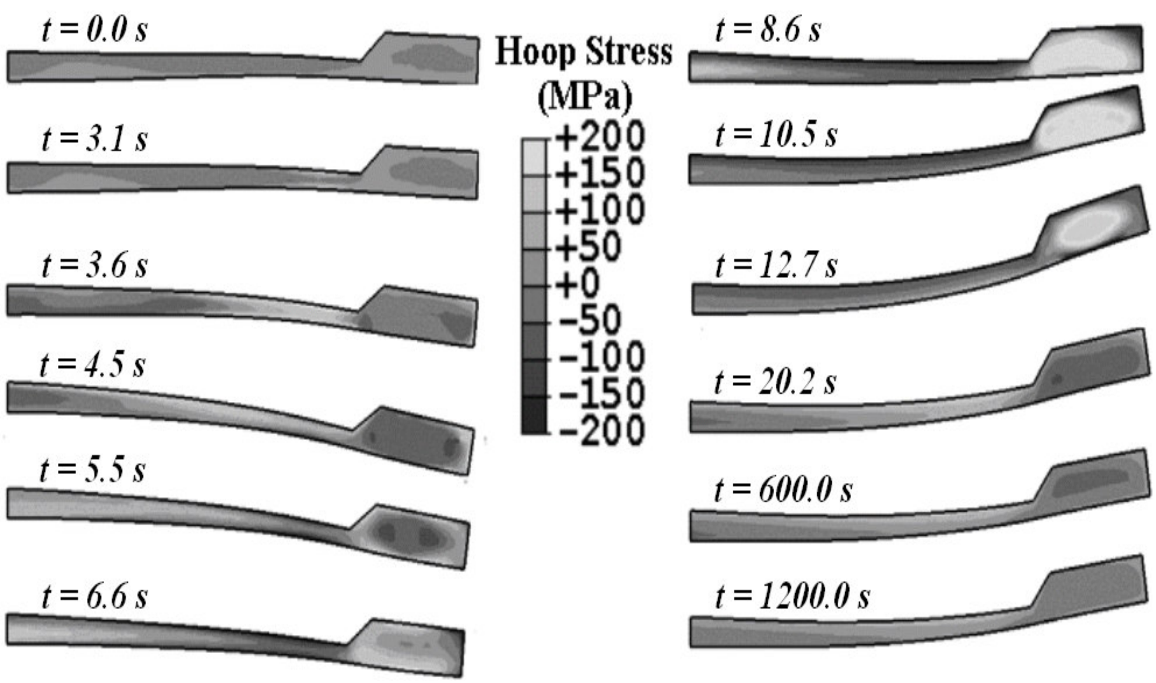


Figure 9 Internal Hoop Stress and Deformation during Oil Quenching (displacement is magnified by 5X)

Conclusions

The experimental data required for phase transformation kinetics fitting has been discussed. Dilatometry is the most effective method to characterize the phase transformations during both heating and cooling because time, temperature and strain data are obtained. Jominy End-Quench hardness data, TTT and CCT diagrams are effective methods for checking the accuracy of kinetics parameters. Methods for determining kinetcis parameters from dilatometry data and available TTT diagrams have been implemented as DANTE utilities.

Heat treatment of a two-dimensional axisymmetric gear blank model has been simulated using DANTE. The effect of phase transformation has been shown to be important in the prediction of stress and deformation for both austenitization and quenching processes. For both heating and cooling, phase transformation has a significant effect on the changes in stress state during heat treatment. The austenite formation rate during heating is high, and the transformation can be completed in several seconds, depending on the initial microstructure and heating condition. The effect of austenite formation on the internal stress state and the resultant deformation is significant and accurate prediction of distortion caused by heat treatment must consider the heating process. Because austenite formation is an important driver of deformation during heating, accurate austenite formation models and data are critical. The stress distribution and deformation during quenching has been plotted and compared to temperature and phase transformation histories. The simulation results have shown that both the thermal stress and stress caused by phase transformation are important.

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