

Distortion Minimization of Bevel Gear Press Quench Hardening Process Using Computer Modeling

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Abstract

Press quenching is used to harden gears with large sizes or thin-wall sections while keeping distortion under control. For carburized gears, controlling distortion is critical because only a limited amount of the carburized case can be machined off after hardening. In comparison to immersion oil quenching, the press quench process involves more process parameters due to the thermal and mechanical effects from the tooling on the parts. The press quench tooling and process designs are mainly experience based, with iterative trials needed before obtaining an acceptable process. Computer modeling provides a means for understanding the effects of tooling and process parameters on distortion, which can be used to optimize the process and tooling design. One paper using modeling to simulate the gear responses during a press quench process was published in the 23rd IFHTSE Congress, Savannah, Georgia, USA, 2016.[1] The bevel gear was made of carburized AISI 9310, and the radial shrinkage and taper of the inner diameter were the main distortion modes. The modeling results showed that the expanders were not effective in controlling the distortion of the inner diameter of this gear. Based on the simulation results, an oversized plug was proposed to replace the expanders to effectively control the inner diameter of the gear. However, the taper distortion of the bore was not corrected effectively. In this follow-up paper, the effect of a customized plug configuration is modeled, and an optimized plug configuration is designed to further reduce the distortion of the bore from the quench hardening process.

Introduction

A combination of carburization and quench hardening is often used to increase the strength and improve the fatigue performance of steel parts. A carburized case can generate beneficial compressive surface residual stresses in the hardened case due to the delayed martensitic transformation with higher carbon content. [2-4] During quenching, stresses caused by the thermal gradient and phase transformations will generate plastic deformation, which will lead to distortion in hardened parts. Gear components with large distortion will increase gear noise and reduce the fatigue life in service. Final machining of case hardened gears often leads to nonuniform case depth distribution, so a maximum amount of distortion caused by hardening is often specified, and parts with distortion exceeding the specification will be scrapped. Press

quenching is one effective way to reduce the distortion amount from a hardening process. [5]

Quench hardening is a transient thermal stress process with phase transformations. The effect of various factors on distortion is nonlinear, and the distortion can only be measured after the process is done. Heat treatment results that are of common interest include the volume fractions of phases, hardness, residual stress profile, and part dimensional change. The thermal gradients during both heating and cooling work together with the phase transformations to continually change the internal stress and deformation of the part being heat treated. The material response of a specific part during the heat treatment process is difficult to document 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. DANTE has been developed as a set of user subroutines linking to Ansys Mechanical with the capabilities of modeling phase transformations, dimensional change, residual stress and hardness. [6] Computer simulation has increased the level of understanding of heat treatment processes because the events that occur during heating and cooling. [7-12] In the previous paper published in the 23rd IFHTSE Congress, [1] DANTE and ANSYS were coupled to model the carburization and press quenching of a spiral bevel gear component. The modeling results were used to understand the causes of distortion, and the further studies of the press quench models were used to improve the process by replacing the expander with an oversized plug. In this paper, the plug configuration is further optimized to reduce the distortion.

DANTE Workflow Linking to ANSYS

DANTE user subroutines have been developed to link with ANSYS Mechanical for modeling carburizing and quenching processes. ANSYS subroutine USERMATTH is used for modeling carburizing and thermal processes, and the subroutine USERMAT is used for stress modeling. The carburization model calculates carbon diffusion and any carbide formation/decomposition that may occur during the process. Phase transformation models are included in the thermal and stress models. As shown in Figure 1(a), the hardening process is coupled sequentially, which is rationale for small geometry change problems. The carburization model is executed first, and the predicted carbon distribution profile

is mapped to the thermal model. Once the thermal model is completed, the temperature history of the entire component is mapped to the stress model, along with the carbon distribution profile. The predicted results from the stress model include volume fractions of microstructural phases, hardness, residual stresses, and distortion. Both pre-processing and post-processing are done under ANSYS Workbench as shown in Figure 1(b). An ANSYS Application Customization Toolkit (ACT) has been developed for setting up heat treatment models and post-processing using Workbench.

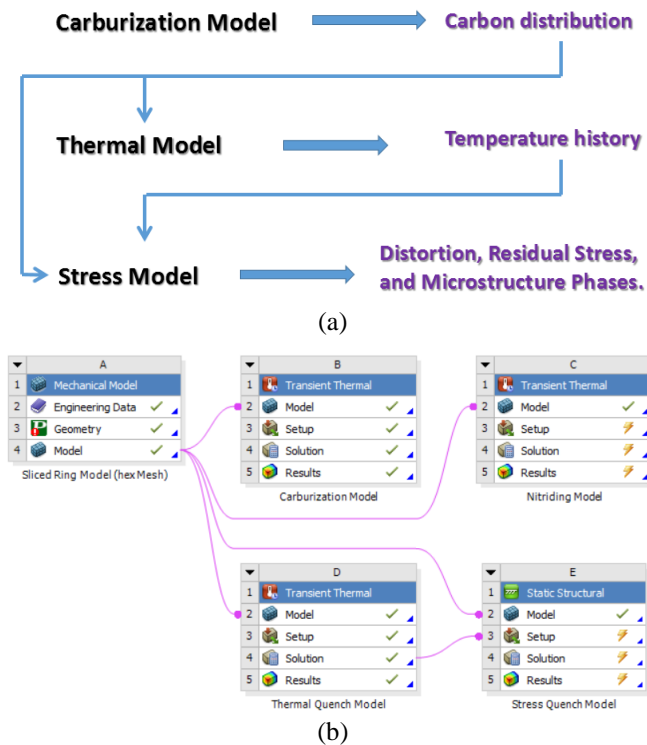


Figure 1: (a) Sequentially coupled modeling workflow of carburizing, thermal and stress models in DANTE, and (b) implementation of the coupling procedure using ANSYS Workbench.

Phase Transformation Kinetics

Quench hardening is a highly nonlinear process due to the solid state phase transformations that occur, and the accuracy of the phase transformation models is critical to the modeling results. The diffusive and martensitic transformation models in DANTE are described in equations (1) and (2) below.

$$\frac{d\Phi_d}{dt} = v_d(T)\Phi_d^{\alpha 1}(1-\Phi_d)^{\beta 1}\Phi_a \quad (1)$$

$$\frac{d\Phi_m}{dT} = v_m(1-\Phi_m)^{\alpha 2}(\Phi_m + \varphi\Phi_d)^{\beta 2}\Phi_a \quad (2)$$

where Φ_d and Φ_m are the volume fractions of individual diffusive phase and martensite transformed from austenite; Φ_a is the volume fraction of austenite; v_d and v_m are the mobilities of transformation products, where v_d is a function of temperature, and v_m is a constant; $\alpha 1$ and $\beta 1$ are material related constants of diffusive transformation; $\alpha 2$, $\beta 2$ and φ are

constants of martensitic transformation. For each individual phase formation, one set of transformation kinetics parameters is required. Dilatometry data are used as the main source to characterize the phase transformation behavior of steels for DANTE material database. Figure 2(a) is a continuous cooling dilatometry strain curve generated from the DANTE database representing the martensitic formation of AISI 9310. The horizontal axis in Figure 2(a) is temperature, and the vertical axis is strain caused by temperature change and martensitic phase transformation. The martensitic transformation starting temperature is about 425° C. Diffusive phase transformations are also characterized by dilatometry tests. A series of dilatometry tests with different cooling rates is required to fit a full set of diffusive and martensitic phase transformation kinetics parameters. Once the full set of phase transformation kinetics parameters is fit from dilatometry tests, isothermal transformation (TTT) and continuous cooling transformation (CCT) diagrams can be generated for users to review. TTT/CCT diagrams are intuitive for assessing the hardenability of specific steel grades found in the material database. Figure 2(b) is an isothermal transformation diagram (TTT) for 9310 steel created from the DANTE database.

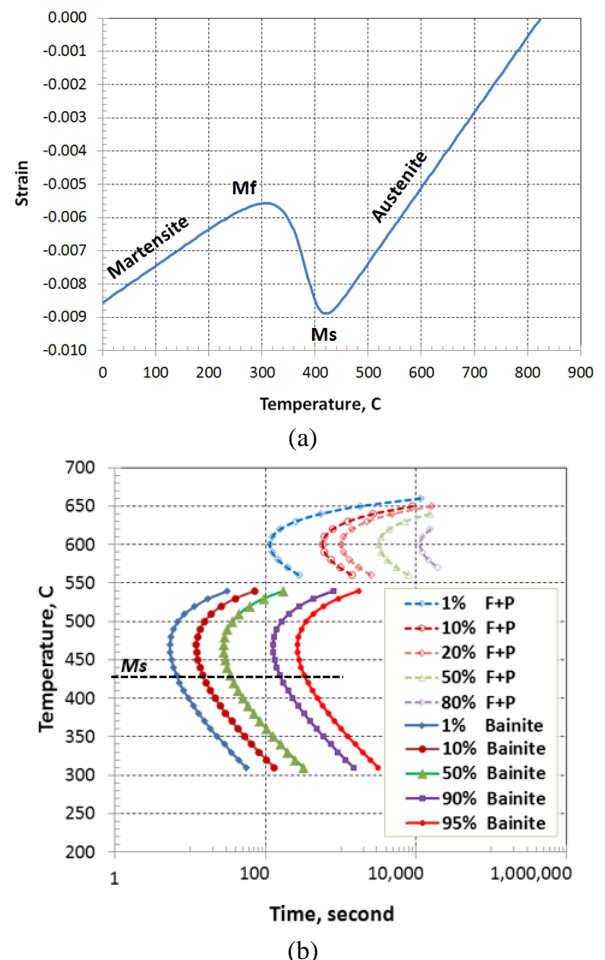


Figure 2: (a) Dilatometry strain curve during one continuous cooling, and (b) TTT diagrams of AISI 9310 generated from DANTE material database.

Finite Element Model and Heat Treatment Process Description

The CAD model of the spiral bevel gear used in this study is shown in Figure 3(a). The outer diameter of the gear is 421 mm, and its height is 100 mm. Carburization and press quenching are used to harden the gear, and the main issue observed from the press quench trials was the excessive radial shrinkage of the internal spline teeth. To simplify the model, the internal teeth of the gear are modeled, but the tapered spiral bevel teeth are not modeled. After hardening, the gear did not experience oval or out-of-round distortion exceeding the specification. Therefore, a single tooth model was developed to represent the entire gear to further reduce the model size. The single tooth CAD model and the generated finite element mesh model are shown in Figure 3(b). Fine elements are used in the gear surface to catch the temperature and carbon gradients effectively during the heat treatment process. Six-node wedge elements are used in the surface, and tetragonal elements are used in the core. The mesh was generated using ANSYS Mechanical. The finite element mesh model contained 59,862 nodes, 72,600 wedge elements, and 105,625 tetragonal elements. The “Upper Bore”, “Lower Bore”, and the three points labeled in Figure 3(b) are used for post-processing in later sections of this paper.

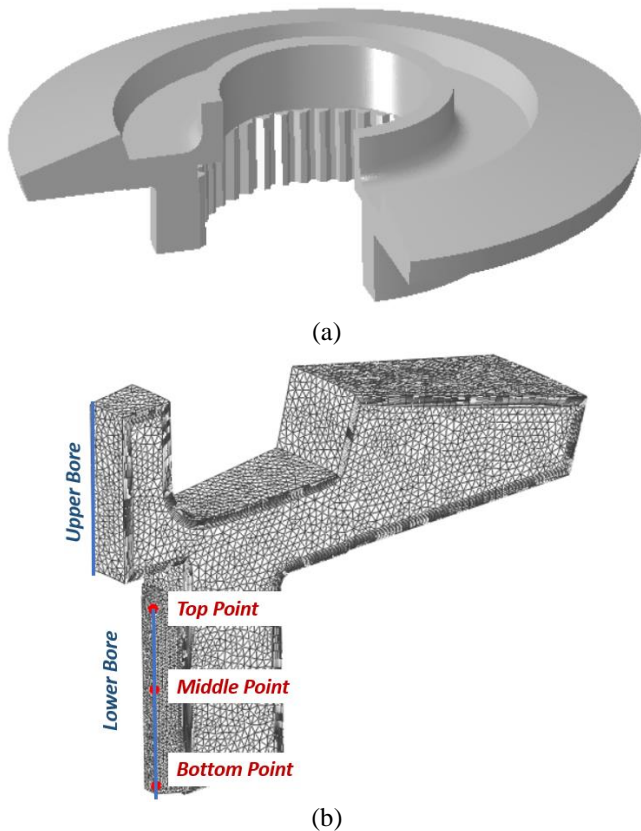


Figure 3: (a) Gear CAD model, and (b) single tooth finite element mesh model.

The finite element model of the press quench tooling is created by ANSYS Workbench, as shown in Figure 4. The press quench tooling includes an upper outer die, an upper

inner die, a lower outer die, a lower inner die, and an expander. To make the model investigation easier, the expander is separated as one upper expander and one lower expander, so their dimensions can be adjusted independently. All the tooling components are assumed to be rigid, and the temperature change of the tooling is neglected. During press quenching, the positions of the lower inner die and the lower outer die are fixed. Constant axial loads are applied to the upper inner die and the upper outer die to reduce the axial distortion of the spiral bevel tooth section. Radial loads are applied to the expanders to control the radial size and reduce the out-of-round distortion.

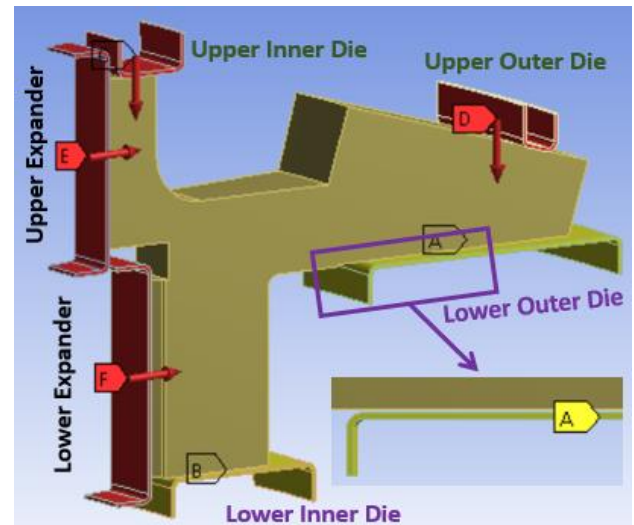


Figure 4: Press quench tooling set up used in the finite element model.

Process Description and modeling of Baseline Press Quench Process

The entire surface of the gear is gas carburized, and the carburizing process is briefly described below:

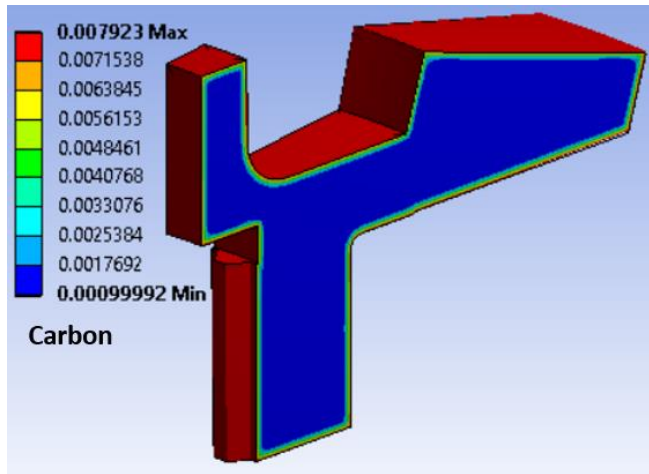
- Carburization temperature: 954.5° C.
- Carburization time: 54,000 seconds.
- Furnace carbon potential: 0.8 wt. %.

The predicted carbon distribution is shown in Figure 5(a). The carbon distribution is important to the residual stresses and distortion due to the carbon effect on phase transformations. The predicted carbon distribution in terms of depth from the surface is plotted in Figure 5(b). With the assumption of 0.4 wt. % carbon as the effective case depth (ECD), the predicted ECD is 1.3 mm, which meets the specification.

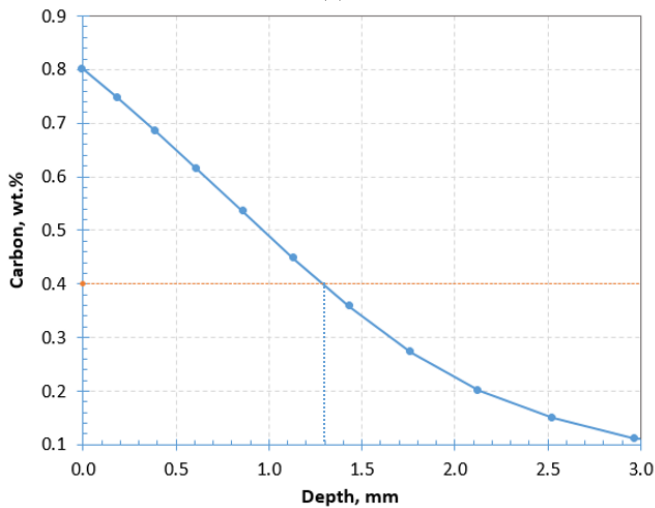
After carburizing, the gear is cooled slowly to room temperature, followed by reheating and press quenching. The hardening process is briefly described below:

- Austenitization temperature: 850° C; Total furnace time: 10800 seconds.
- Transfer time from furnace to press quench prior to pumping oil: 15 seconds.
- Oil temperature: 54.5° C.

- Quenching time duration: 600 seconds.
- Remove and cool to room temperature (20° C).



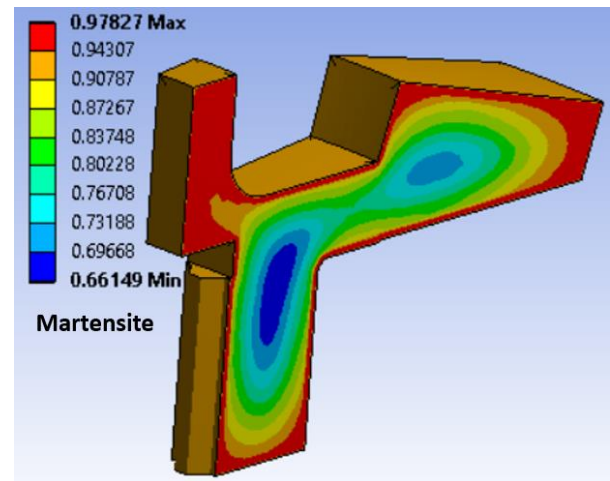
(a)



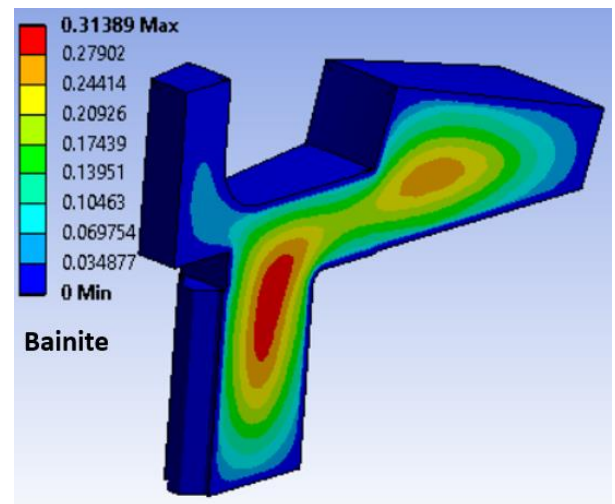
(b)

Figure 5: (a) Carbon distribution contour plot, and (b) carbon distribution in terms of depth.

The detailed modeling results of temperature and phase transformations during hardening process were described in the previous paper.[1] In this paper, the modeling results are briefly summarized. After achieving full austenite and soaking in the furnace at 850° C, the gear is removed from the furnace for press quenching in 15 seconds. Once the gear is placed on top of the lower dies and shuttled into position, the top dies move downward to closed die positions with specific loads applied, and then oil flow begins. The quenching process continues for 600 s, then loads are released, dies are opened, and the gear is taken out and cooled to room temperature. After the gear cools to room temperature, the predicted martensite and bainite distributions are shown in Figure 6(a) and 6(b), respectively. The core has about 70% martensite and 30% bainite, and other phases are negligible in the core. The amount of retained austenite is about 15% on the surface, which is due to the lower martensite transformation finishing



(a)



(b)

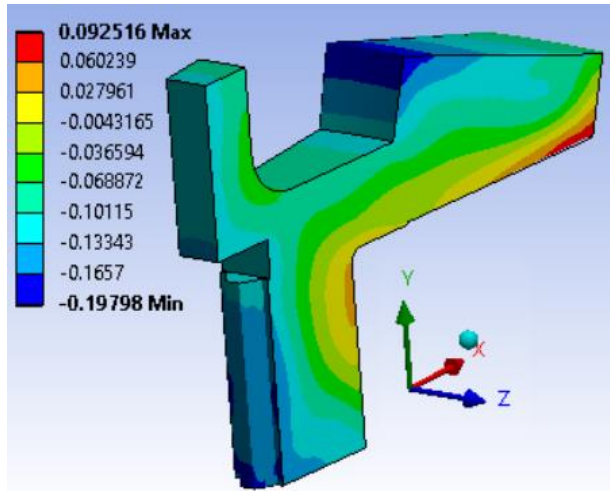
Figure 6: Predicted phase fractions at the end of quenching: (a) martensite, and (b) bainite.

temperature of AISI 9310 with higher carbon content. The amount of retained austenite in the carburized case can be further reduced by deep freezing and tempering processes.

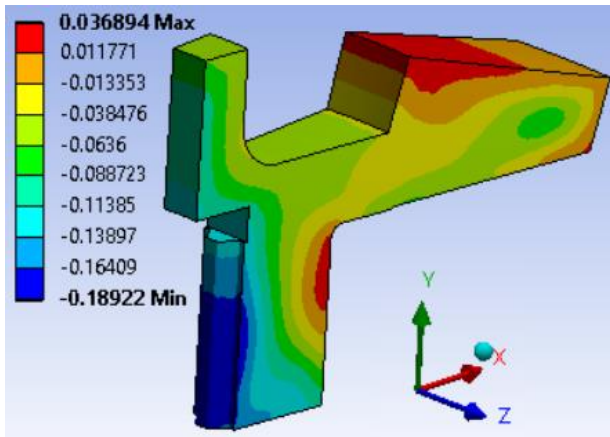
A virtual quench hardening model without the press quench tooling constraints (immersion oil quench) was run with the same thermal boundary conditions applied. The purpose of this oil quench model was to understand the effect of the tooling constraints on distortion by comparing the free quench and baseline press quench modeling results. The immersion oil quench model is also helpful for setting up the position of the lower outer die to compensate for the axial distortion of the spiral bevel tooth section. The predicted radial displacement after cooling the gear to room temperature from the immersion quench model is shown in Figure 7(a). The internal spline tooth is predicted to shrink radially about 0.198 mm.

Using the press quench tooling setting shown in Figure 4, the predicted radial distortion after quenching and cooling to room temperature is shown in Figure 7(b). The predicted radial distortion of the internal spline tooth is approximately 0.190 mm shrinkage, which is slightly less than the value of 0.198

mm predicted by the immersion oil quench model. In general, the axial load applied on the expander is low, and its effect on the averaged radial size should be insignificant. However, the expander load applied should be sufficient to control the oval or out-of-round distortion due to the concentrated radial force on the sector with lowest radial dimension of out-of-round parts.



(a)



(b)

Figure 7: Predicted radial distortions at the end of quench: (a) without the mechanical constraints and loads from the tooling, and (b) press quench using expander.

Gear Bore Distortion Minimization by Plug Configuration Design with Press Quench

The effectiveness of using an oversized plug for controlling the bore distortion was described in the previous published paper.[1] The press quench setup using the oversized plug is shown in Figure 8. The upper expander is replaced by an upper straight plug with its size being the same as the desired bore dimension at room temperature. The lower expander is replaced by a lower straight plug that is 0.060 mm larger radially than the room temperature dimension. To make the

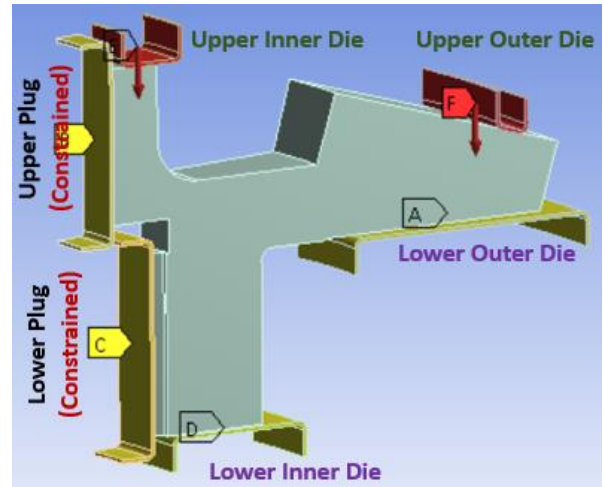


Figure 8: Modified press quench tooling setup by replacing the expander using oversized plugs.

model easier to investigate the effect of plug configuration on distortion, the plug is modeled as separate upper and lower plugs. During tooling manufacturing process, the plug can be machined as one piece or two pieces with assembly. All the other press quench process settings are kept the same.

The predicted radial displacements of the “Upper Bore” and “Lower Bore,” as shown in Figure 3, are summarized in Figure 9 for the three processing conditions: 1) immersion oil quench (without mechanical constraints from tooling); 2) press quench using expander; and 3) press quench using oversized straight plug to replace the expander. In this study, a radial displacement of 0.0 mm is ideal (no distortion). The results in Figure 9 have shown that the expander is not effective for controlling the radial size the bore. By using oversized straight plugs (upper plug: +0.0 mm; lower plug: +0.060 mm), the bore size is effectively controlled. However, a significant taper is predicted for the upper bore, and the lower bore is tapered in the opposite direction.

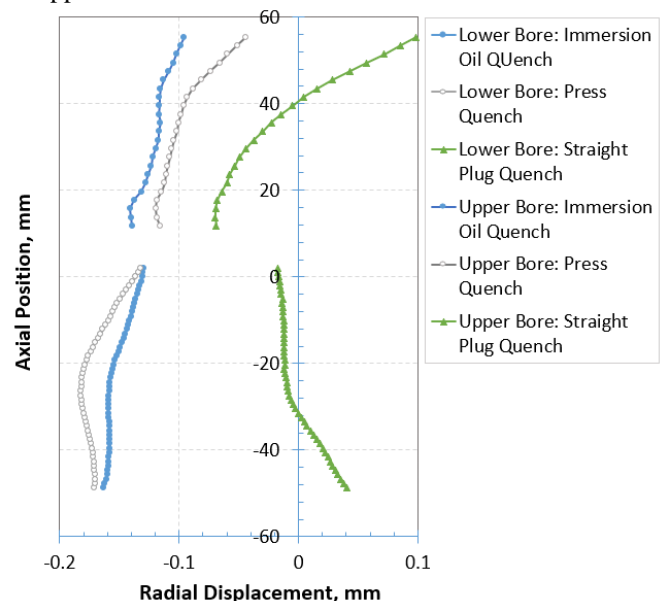


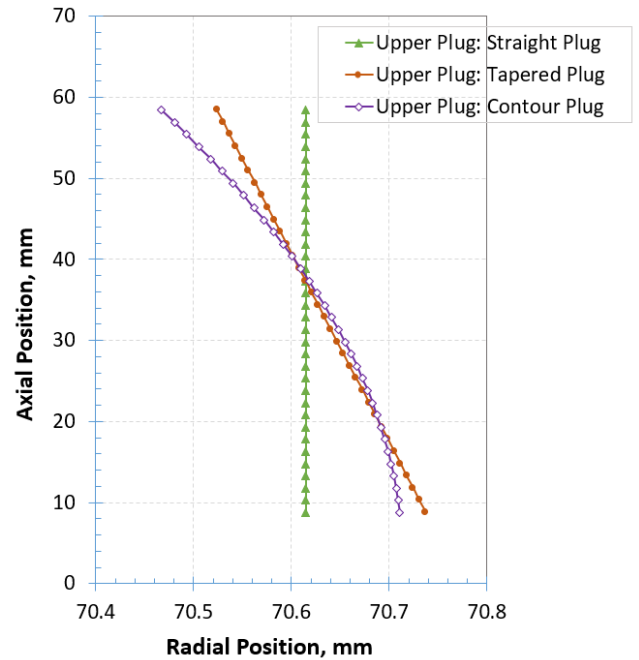
Figure 9: Effect of oversized straight plug on controlling the bore distortion of the gear.

The effect of plug configuration on the bore size and straightness is investigated by computer modeling. As described in the previous section, the quench hardening is a highly nonlinear process, and the tooling effect on distortion is also nonlinear. For example, the interaction between the lower plug and the bore affects the interaction between the upper plug and the bore, and vice versa. To minimize the distortion, model iterations with different plug configurations were executed. In this paper, representative results are described for users to understand the gear responses from temperature change, phase transformation and tooling effects.

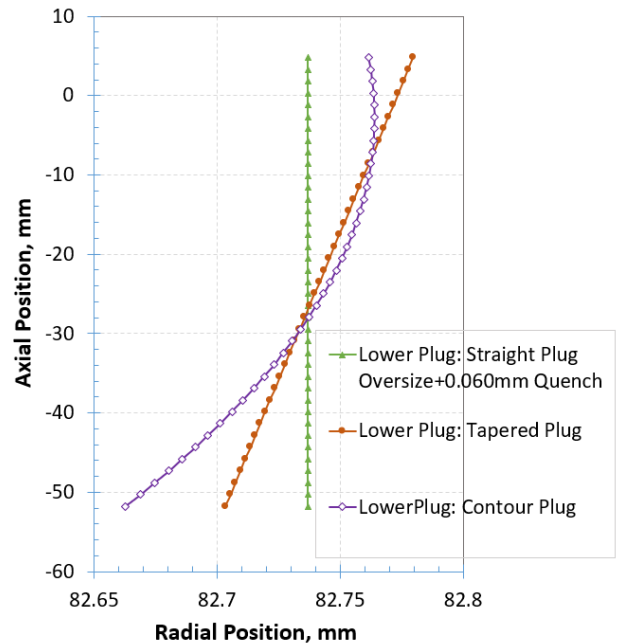
As shown in Figures 10(a) and 10(b), three representative configurations of the upper and lower plugs are plotted. The X-axis is the radial position of the plug, and the Y-axis is the axial position of the plug. For the straight plug configurations, the upper plug size matches the upper bore of the gear at room temperature, while the lower plug has a radial oversize of +0.060 mm relative to the lower bore of the gear at room temperature. From the amounts of the bore taper predicted using the straight plugs, tapered plugs are designed to pursue straight bore from the quench hardening process. Because the effect of the plug taper on the bore shape of the final gear is nonlinear, several iterations are required by adjusting the plug taper amount using modeling before the distortion can't be further reduced. The taper directions of the upper plug and the lower plug are opposite as shown in Figure 10. For both the upper and lower plugs, the final taper directions are also counteractive to the predicted bore taper directions with oversized straight plugs. The contour plug configurations are designed for the purpose of removing the barrel shape distortion of the upper bore and the lower bore (spline tip). Constant radii are used in designing the upper and lower plug configurations individually for easier manufacturing.

Figure 11 summarizes the predicted radial distortions of the upper and lower bores after hardening for all the five (5) tooling conditions: 1) Immersion quench without mechanical constraints from the tooling, 2) Press quench using expander, 3) Press quench using oversized plug, 4) Press quench using oversized plug with taper, and 5) Press quench using oversized plug with contour configuration. The blue lines in Figure 11 represent the distortion without mechanical constraints from the tooling, and the grey lines are from the press quench with expander. As shown, the radial shrinkage of the upper bore is reduced slightly. However, there is no improvement on the radial shrinkage of the lower bore. Instead, more barrel distortion is predicted on the lower bore (spline tip). By increasing the expander load, the radial sizes of both the lower and upper bores can be increased. However, an expander load that is too high is considered to cause process inconsistency. [12] In this case, oversized plugs are used to control the radial shrinkage of the bore. If the same amount of oversize is used for the lower and upper plugs, the interaction between the upper plug and the bore occurs earlier relative to the lower plug, which is because the upper section of the gear is thinner and it cools earlier than the lower section of the gear. As a result, the plug oversize will have a more significant effect on increasing the upper bore radial size. After several modeling iterations, the oversized straight plug sizes are optimized:

upper plug +0.0 mm oversize, and lower plug: +0.060 mm oversize radially. The predicted radial distortions from the oversized straight plug are shown as the green curves in Figure 11. The radial size is well controlled, but the upper bore and the lower bore have significant tapers.



(a)



(b)

Figure 10: Plug configuration designs with oversized straight plug, tapered plug, and contour plug: (a) upper plug, and (b) lower plug.

Tapered plugs are used to correct the taper distortions of the bore. The taper distortion is effectively corrected after several modeling iterations, as shown by the brown curves in Figure

11, and the dimensions of the tapered plugs are shown in Figure 10.

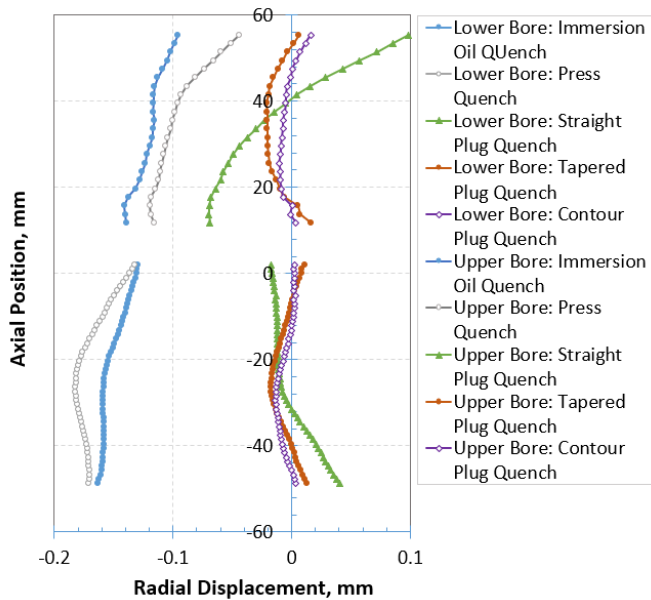


Figure 11: Summary of predicted bore distortion using various hardening processes: 1) Immersion quench assuming no mechanical constraints from the tooling, 2) Press quench using expander, 3) Press quench using oversized plug, 4) Press quench using oversized plug with taper, and 5) Press quench using oversized plug with contour configuration.

With tapered plugs, the taper distortions of both the upper bore and the lower bore (spline tip) are effectively corrected, but the barrel distortions still exist. Is it possible to further correct the barrel distortion by using contoured plug configurations? As shown in Figure 10, several iterations with adjusting the contour plug configurations were executed using modeling. The curvatures used in the plugs are from the intermediate modeling results. The contour profiles of the plugs does not effectively reduce the barrel (curvature) distortion of the bore, as shown by comparing the purple curves (tapered plug) and the brown curves (contoured plug) in Figure 11. The approximate barrel distortion is about 20 μm . With the plug quench, the radial size and the barrel distortion is more consistent when compared to the immersion quench or press quench with expander designs, and this distortion can be more reasonably corrected by adjusting the pre-heat treat gear configuration.

Figure 12 shows the predicted radial displacement of the gear using the tapered plugs. The barrel distortion of the bore is caused by the end effect on cooling. Using the upper bore of the gear as an example, the top and bottom of the upper bore cool earlier than the middle of the bore during quenching, and the martensite transformations are also earlier at the top and bottom of the upper bore. The material volume change due to the temperature change and phase transformations will generate high stresses in the gear during quenching, to cause barrel distortion. A higher magnitude of plug oversize is more effective for correcting the barrel distortion. However, the

magnitude of the plug oversize should be designed carefully to avoid other potential problems.

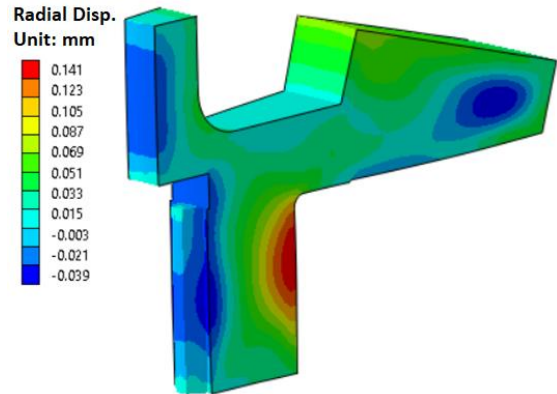
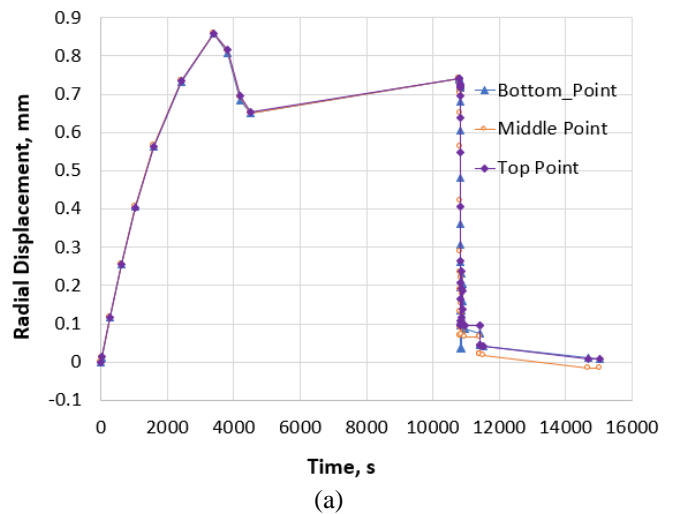


Figure 12: Predicted Contour plot of radial displacement Comparison of bore distortion using tapered plug.

Three node points on the spline tip are selected for post-processing to further understand the gear responses to the temperature change, phase transformations and mechanical interaction with the plug during the heat treatment process. The three points are “Top Point”, “Middle Point”, and “Bottom Point”, as shown in Figure 2(b). The radial displacements of the three points are plotted in Figure 13(a) covering the entire process. During heating, the maximum radial growth of the three points is about 0.85 mm before the gear transforms to austenite. After the gear transforms to austenite, there is a radial shrinkage from 0.85 mm to 0.65 mm. Once the transformation to austenite completes, the gear resumes expansion as it is heated to the soaking temperature.

The quenching portion of Figure 13(a) is magnified in Figure 13(b). During quenching, the “Bottom Point” contacts with the plug earlier than the “Middle Point” and the “Top Point”, even though the plug has a smaller dimension at the bottom, as shown in Figure 10(b). One important factor to consider in designing the plug dimension is to make sure there is a time period that all the three “Points” contact with the plug, as shown in Figure 13 (b).



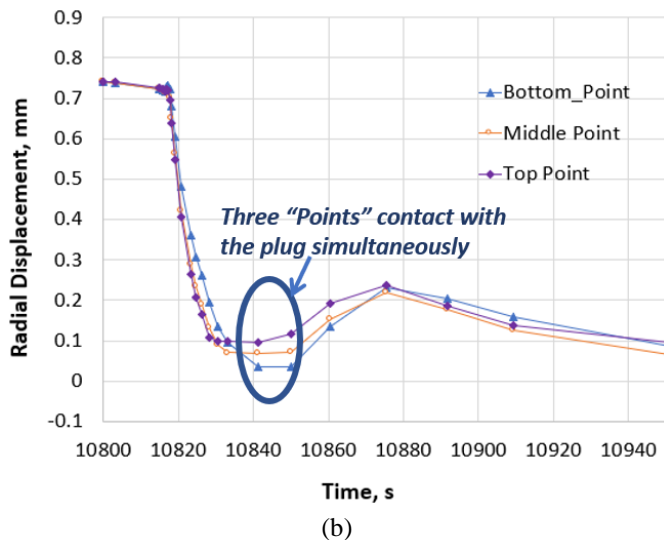


Figure 13: History of radial displacements of the lower bore during heat treatment process.

Conclusions

The dimensional responses of a spiral bevel gear to temperature, phase transformation, and tooling constraints during press quench have been investigated. The external loads applied to the gear by either dies or expanders are low in general to keep the gear dimensional response consistent, as well as to not cause damage to the part. Due to the TRIP effect, a low magnitude of tooling loads can be sufficient to constrain the gear during quenching for improved dimensions. However, the expanders in this specific press quench design do not effectively avoid radial distortion. With the help of computer modeling, the press quench tooling was modified by replacing the expanders with plugs, and the predicted results show that the radial distortion of the internal tooth can be consistently and effectively controlled. With oversized plug design, the radial dimensions of the gear bore are controlled effectively. In this paper, tapered plugs are designed to correct the tapered distortion of the bore effectively. However, by designing the plug with contour configurations, the barrel distortion cannot be removed effectively. To be practical, a tapered plug design should be used instead of contoured plug.

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