International Federation of Heat Treatment and Surface Engineering 2016
Proceedings of the 23rd IFHTSE Congress
April 18–21, 2016, Savannah, Georgia, USA

Press Quench Process Design for a Bevel Gear using Computer Modeling

Zhichao Li, Andrew M. Freborg, and B. Lynn Ferguson
DANTE Solutions, Inc.
7261 Engle Road, Suite 105, Cleveland, OH 44130
Charlie.Li@Dante-Solutions.com

Peiran Ding, and Mike Hebbes
ANSYS, Inc.
900 Victors Way, Ann Arbor, MI 48018

Abstract

Press quenching is used to harden steel gears for tight dimensional control. The process is especially used when quenching thin-wall gears, face gears, and bevel gears with large dimensions. The dimensional control aims at maintaining flatness, circularity, and radial dimensional changes. The press quench process tooling design has been mainly based on experience, with trial and error used for implementation of new processes, new gear materials and configurations. Computer simulation provides a means for eliminating or at least reducing the number of try-outs that are needed to achieve the desired process results. In comparison to traditional oil quenching, the oil flow pattern and cooling rates along different gear surfaces in press quenching are more dependent on the tooling design, oil channels, and oil pump rate, and these should be considered in design of the process. Other process parameters include the die and expander loads and the locations of load application. In this paper, the gear responses during a press quench of a spiral bevel gear made of carburized AISI 9310 are assessed for reduced distortion using the commercial heat treatment software DANTE, linking with ANSYS Mechanical solver. Radial shrinkage and taper of the internal spline are observed from the trials, and the causes of the distortion are simulated and analyzed by the models. The modeling results have shown that the expanders do not effectively control the radial size change in this case. Based on the simulation results, an effective method is proposed to control the radial shrinkage of the spline by using a plug with a slightly oversized dimension, which is demonstrated by computer models.

Introduction

Heat treatment is used to improve the strength and service performance of steel components, such as gears, shafts, and bearings, etc. A combination of carburizing and quench hardening can generate beneficial compressive surface residual stresses in the hardened case, which improves the fatigue performance. [1-3] During quenching, stresses caused by the thermal gradient and phase transformations will generate plastic deformation and 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. [4]

Heat treatment is a transient process, and the thermal gradient and phase transformations act together to cause distortion. It is both difficult and expensive to experimentally investigate the part responses during a quench hardening process, and most of these results can only be measured after heat treatment has been completed. 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. HEARTS is one of the earliest finite element based quench hardening process modleing package. [5] DANTE was developed to reduce the distortion casued by heat treatmnet processes, and the processes inmclude austenitization, carburizing, quench hardening, and tempering , etc. [6-7] Recently, DANTE was developed as a set of user subroutines linking to ANSYS Mechanical, with the capabilities of modeling phase transformations, dimensional change, residual stress and hardness. [8] 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. [9-10] In turn, advances in computer hardware, in combination with accurate simulation, have made the design and optimization of the heat treatment processes more cost effective than traditional experimental trial-and-error methods. In this paper, DANTE and ANSYS are coupled to model the carburization and press quenching of a spiral bevel gear component. The modeling results are used to understand the causes of distortion, and further studies of the press quench models are used to improve the effectiveness of the press quench tooling design.

DANTE ANSYS Coupling and Workflow

DANTE user subroutines have been developed to link with ANSYS Workbench for modeling carburizing and quench hardening processes. ANSYS customized USERMATTH subroutine is used for carburizing and thermal analyses with phase transformations, and USERMAT with customized mechanical models is used for stress analysis. As shown in Figure 1(a), the hardening process is coupled sequentially for improved computational efficiency, and the rationale is that heat treatment processes have small deformation in general. The carburization model is executed first, and the predicted carbon distribution profile is imported to the thermal model. Once the thermal model is completed, the temperature history of the entire component will be imported to the stress model together with the carbon distribution profile. The predicted results from the stress model include microstructure phases, hardness, residual stresses, and distortion.

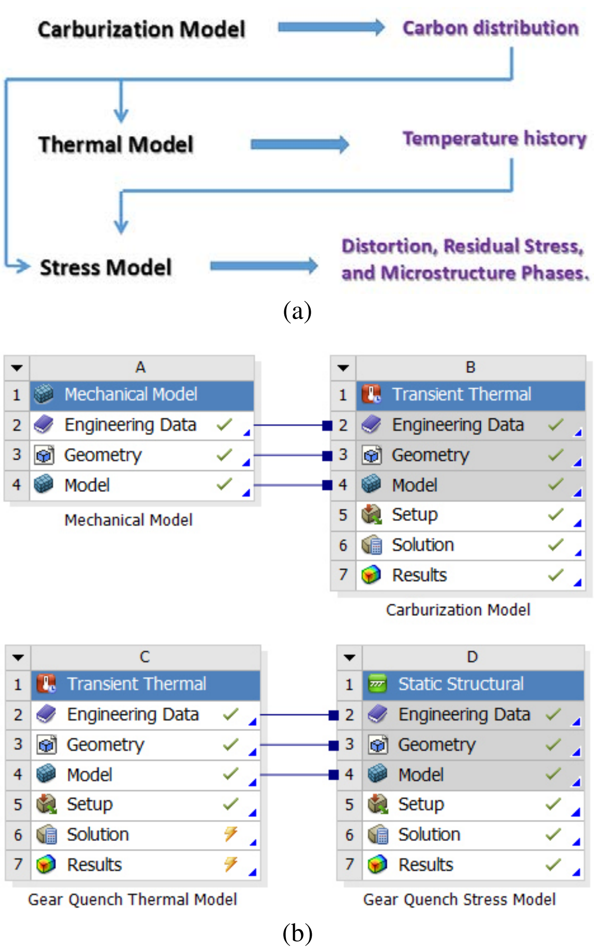


Figure 1: *(a) Sequentially coupled procedure of carburizing, thermal and stress models in DANTE, and (b) implementation of the coupling procedure in ANSYS Workbench.*

ANSYS Mechanical is used as the solver by linking to DANTE user subroutines with phase transformations and mechanical models. Both pre-processing and post-processing are done under ANSYS Workbench as shown in Figure 1(b). ANSYS Application Customization Toolkit (ACT) has been developed for setting up heat treatment models and post-processing using Workbench.

Phase Transformation Kinetics

Quench hardening is a highly nonlinear process due to the solid state phase transformations, 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.

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

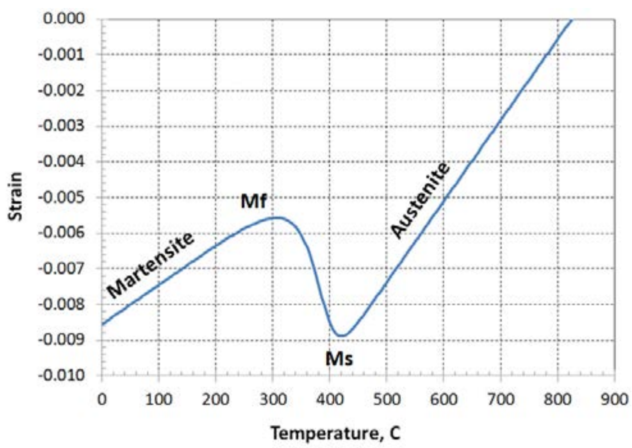
$$\frac{d\Phi_m}{dT} = \nu_m(1-\Phi_m)^{\alpha 2}(\Phi_m+\varphi\Phi_d)^{\beta 2}\Phi_a \qquad (2)$$

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; ν_d and ν_m are the mobilities of tranformation products, where ν_d is a function of temperature, and ν_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.

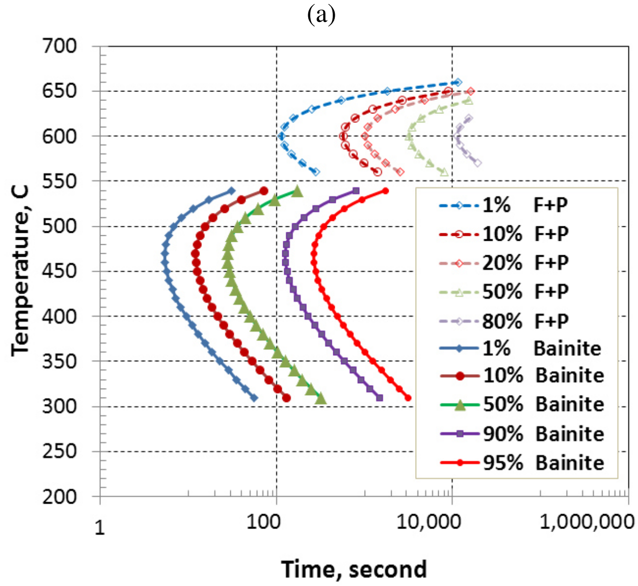
Dilatometry data are often used to describe the phase transformation behavior of steels. Figure 2(a) is a continuous cooling dilatometry strain curve generated from the DANTE database representing the martensitic formation of AISI 9310. The horizontal axis in Figure 2(a) is temperature, and the vertical axis is strain caused by temperature change and phase transformation. The strain change due to martensitic transformation is clearly quantified.

When the dilatometry test sample cools to the martensite start (Ms) temperature, its volume expands with the crystal strucure change from austenite's face centered cubic (FCC) lattice to martensite's body centered tetragonal (BCT) lattice. Martensite's BCT structure has a lower density than austenite's FCC structrue. The strain change during transformation is a combination of thermal strain, phase transformation volume change, and strain induced by stresses generated during the transformation. The latter strain is referred to as TRansformation Induced Plasticity or TRIP. The data obtained from this specific type of dilatometry test include coefficient of thermal expansion (CTE) for austenite and martensite, martensitic transformation starting (Ms) and martensitic transformation finishing (Mf) temperatures, transformation strain, and phase transformation kinetics (transformation rate) from austenite to martensite. These data are critical to the accuracy of modeling the internal stress and deformation caused by quenching.

Diffusive transformations are also characterized by dilatometry tests. A series of dilatometry tests with different cooling rates are required to fit a full set of diffusive and martensitic phase transformation kinetics parameters. Once the full set of phase transformation kinetics paratmeters are fit from dilatometry tests, isothermal transformation (TTT) and continuous cooling transformation (CCT) diagrams can be generated for users to review. TTT/CCT diagrams are not directly used by DANTE phase transformation kinetics models, but they are useful because users can see the hardenability of the material graphically. Figure 2(b) is an isothermal transformation diagram (TTT) for 9310 steel created from the DANTE database.



(a)

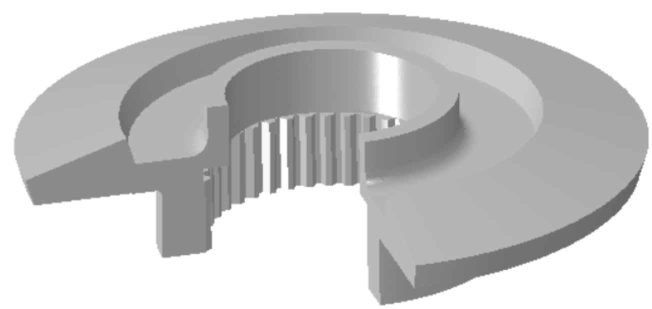


(b)

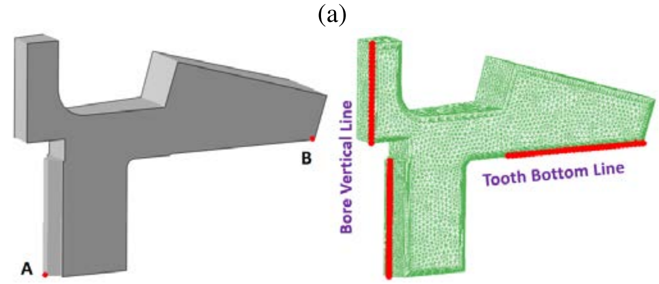
Figure 2: *(a) Dilatometry strain curve during continuous cooling, and (b) TTT diagrams of AISI 9310 generated from DANTE material database.*

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 major issue observed from the first hardening process try-out is 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. The hardened gear does not have 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). Ten layers of fine elements were applied to a 3 mm depth in the gear surface for the purpose of catching the temperature and carbon gradients effectively during the heat treatment process. Six-node wedge elements were used in these surface layers of elements, and tetragonal elements were used inside the part where the thermal gradient was mild. 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.



(a)



(b)

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

GLEASON press quench is often used in industry to quench harden steel parts requiring a tight dimensional tolerance. [11] In this paper, the finite element model of the press quench tooling is created by ANSYS Workbench, as shown in Figure 4 [11]. The press quench tooling include an upper outer die, an upper inner die, a lower outer die, a lower inner die, an upper expander, and a lower expander. All the tooling are modeled as rigid surfaces, and the Augmented Lagrange contact in ANSYS Mechanical is used to define the mechanical constraints between the gear and the tooling contact surfaces. 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.

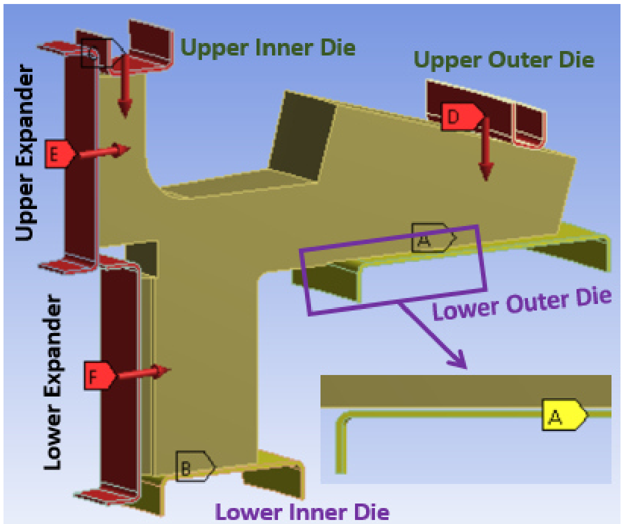


Figure 4: Press quench tooling set up used in the finite element model.

Baseline Press Quench Process Modeling

The gear is gas carburized and cooled prior to reheating and press quenching. The carburizing process is briefly described below.

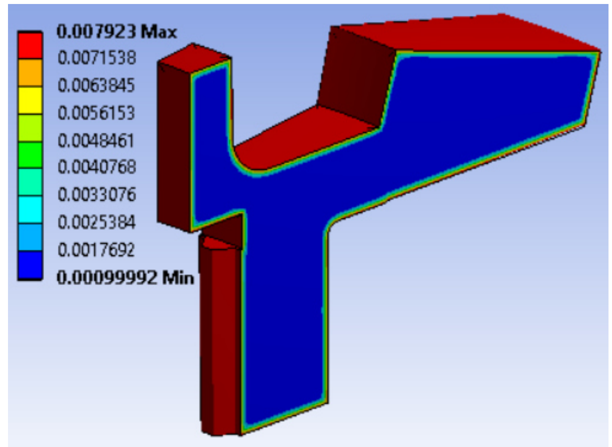
- Carburization temperature: 954.5° C.
- Carburization furnace time: 54,000 s.
- Furnace carbon potential: 0.8 wt.%.

The predicted carbon distribution contour is shown in Figure 5(a), with the entire surface being carburized. The carbon distribution is important to the residual stresses and distortion obtained due to its effect on the 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) criterion, the predicted ECD is 1.3 mm, which meets the specification.

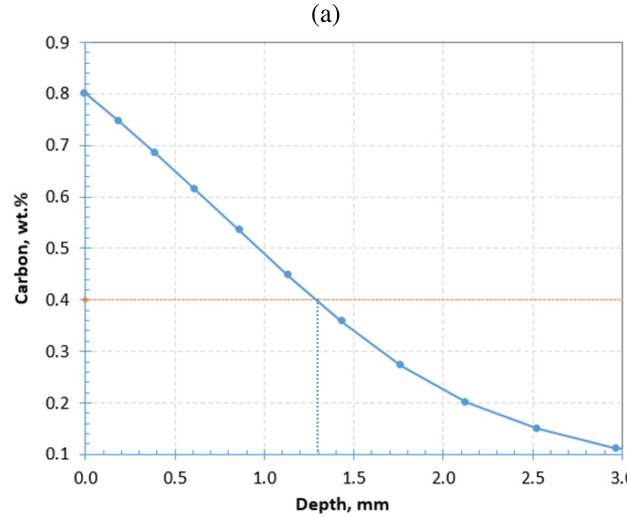
After carburizing, the gear is cooled to room temperature, followed by reheating and press quenching. The hardening process is briefly described below.

- Austenitization temperature: 850° C; Total furnace time: 10800 s.
- Transfer time from furnace to press quench prior to pumping oil: 15 s.
- Oil temperature: 54.5° C.
- Quenching time duration: 600 s.
- Remove and cool to room temperature (20° C).

During reheating, before the material reaches the austenitization temperature, phase transformation to austenite occurs. Snapshots of temperature and austenite distribution contours during reheating are shown in Figure 6. The thin section of the gear has a higher temperature during heating as shown in Figure 6(a), which leads to earlier phase transformation to austenite in this region. The gear surface is carburized, and the phase transformation to austenite is earlier in the carburized case due to its high carbon content as shown in Figure 6(b). Along with the phase transformation to austenite, the volume of the material decreases, which contributes to internal stresses and distortion.



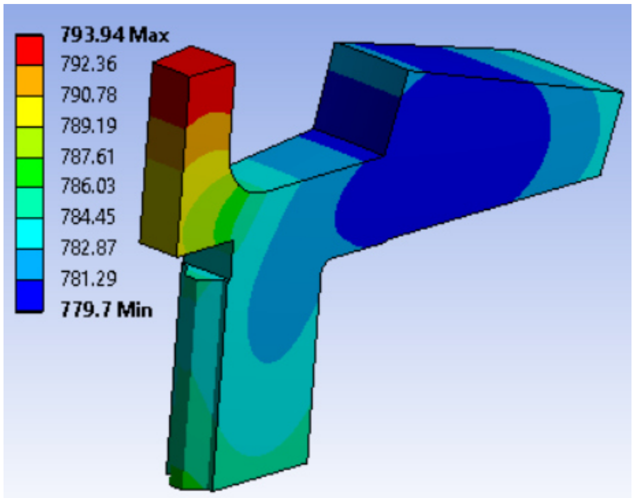
(a)



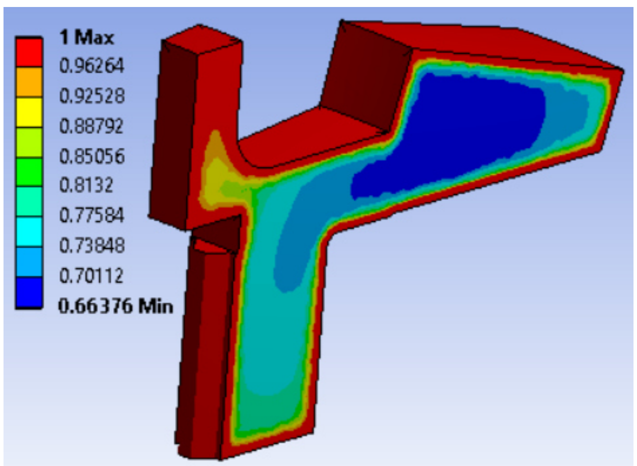
(b)

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

After achieving full austenite and soaking in the furnace at 850° C, the gear is removed from the furnace for press quenching. The transfer time of 15 s can affect the final distortion of hardened parts, and it is important to keep the transfer time consistent. 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. Final steps are deep freezing to reduce retained austenite levels and low temperature tempering in a furnace. Because the deep freeze and low temperature tempering process steps have an insignificant effect on the shape change, the deep freeze and tempering processes are not modeled in this paper. If gear performance is the purpose of the model, these steps must be included in the model.



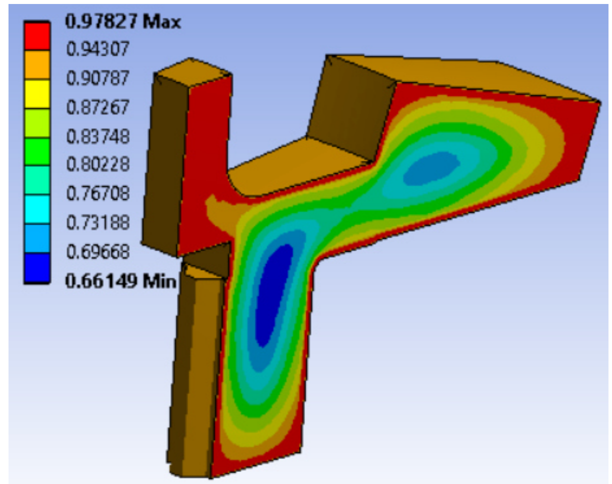
(a)



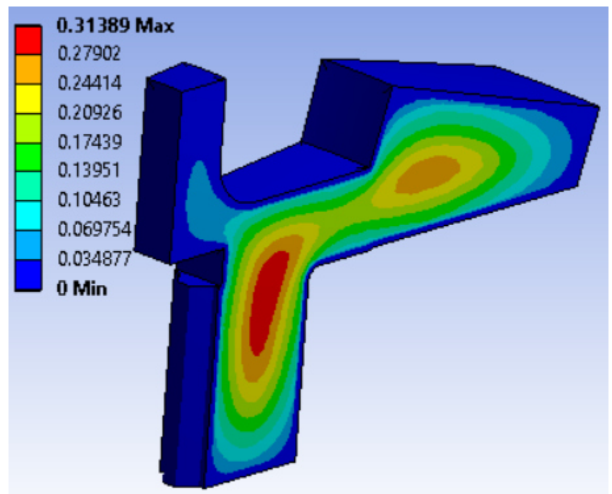
(b)

Figure 6: Phase transformation to austenite at 4085.1 s during heating: (a) temperature distribution, and (b) austenite distribution.

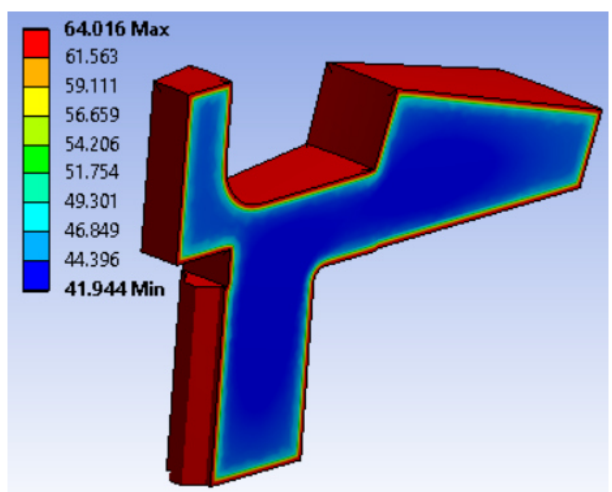
After the press quenched gear has cooled to room temperature, the predicted martensite and lower bainite distribution contours are shown in Figure 7(a) and 7(b), respectively. The core has about 70% martensite and 30% lower bainite, and other phases are ignorable in this location. In a location slightly deeper than the case, about 97% martensite is predicted with a small amount of lower bainite. In the carburized case, the maximum amount of retained austenite is about 15%. The existence of retained austenite in the carburized case is due to the low martensite formation starting and finishing temperatures for AISI 9310 with higher carbon content. As mentioned, the amount of retained austenite can be further reduced by deep freezing and tempering processes. In DANTE, the hardness of as-quenched parts is calculated from the obtained volume fractions of various phases and the carbon content. The predicted hardness distribution of the as-quenched gear is shown in Figure 7(c) with Rockwell C hardness unit (HRC). The hardness of the carburized case is 64 HRC, and the core is about 41 HRC, which agrees with the measured data.



(a)



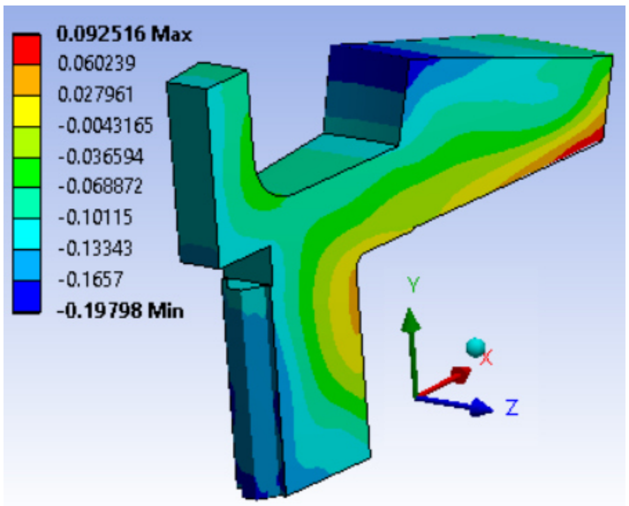
(b)



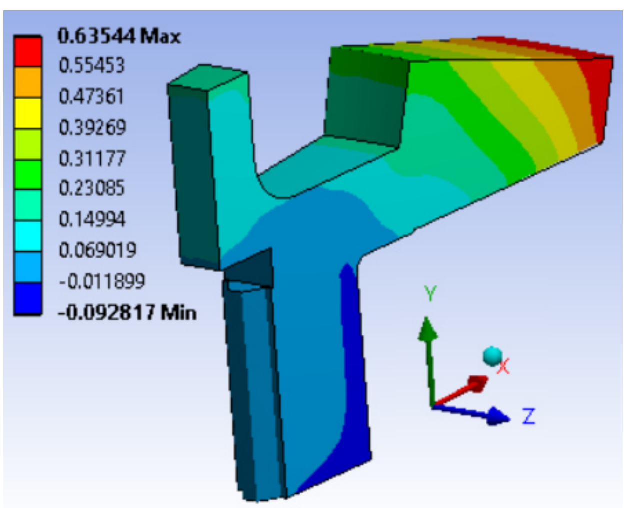
(c)

Figure 7: Phase and hardness distributions at the end of quenching: (a) martensite, (b) lower bainite, and (c) hardness.

A virtual quench hardening model without the press quench tooling constraints (free oil quench) was run with the same thermal boundary conditions applied. The purpose of this free oil quench model was to understand the effect of the tooling constraints on distortion by comparing the free quench and baseline press quench models. The free 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 for the free quench model is shown in Figure 8(a). The internal spline tooth is predicted to shrink radially about 0.19 mm. The axial displacement is shown in Figure 8(b), and the spiral bevel teeth axial warp upward about 0.635 mm.



(a)

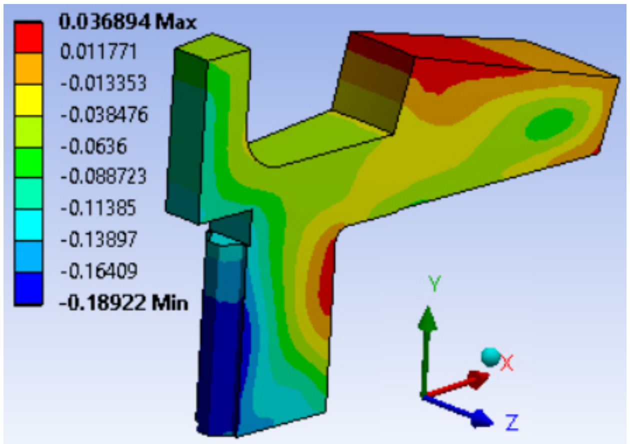


(b)

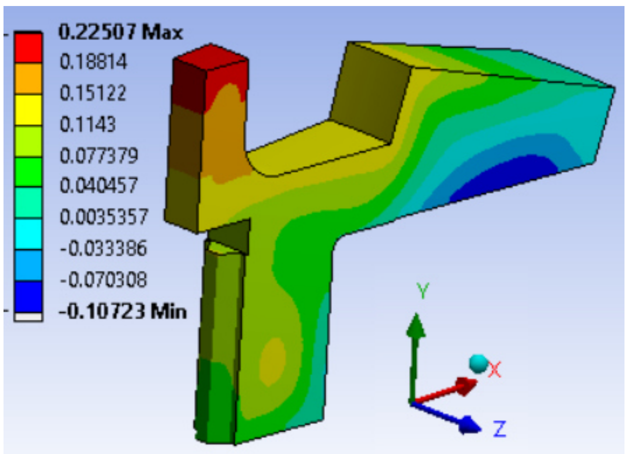
Figure 8: (a) Radial distortion, and (b) axial distortion at the end of oil quench (without the mechanical constraints and loads from the tooling).

The predicted axial distortion from the free quench model is an important value for setting up the lower die positions for the press quench. It is worth mentioning that the lower inner and the lower outer die positions are fixed during press quench, and the temperature of the tooling is negligible (remember the oil cools the tooling as well as the part) in comparison to the gear size changes during quenching due to part temperature change (heat lost to the oil) and the phase transformations. As a result of the part temperature change, the axial dimension of the gear changes between the bottom face of the spiral bevel tooth and the lower end face of the bore, and it is not expected that the lower outer die contacts the gear during the entire quench process unless extremely high die load from the upper outer die is applied. In general, the press load applied in a press quench process is much lower than the required load of causing plastic deformation of high temperature austenite. The low load applied is also a guarantee of not damaging the gear teeth locally. The axial loads are applied on the expanders to control the oval or out-of-round distortion. The axial loads applied on the upper dies are to control the axial warping of the spiral bevel teeth, together with the lower die position setting. To compensate for the predicted axial distortion of the spiral bevel teeth, as shown in Figure 8(b), the lower outer die is positioned 0.635 mm lower than the bottom face of the spiral bevel tooth at room temperature, as shown in Figure 4. In other words, if the room temperature gear is positioned on the lower dies of the press tooling, the lower end face of the bore contacts with the lower inner die, and the bottom face of the spiral bevel tooth section has a 0.635 mm gap with the lower outer die surface. This is designed to reduce the axial upward warpage predicted from the free quench hardening model.

Using the press quench tooling setting shown in Figure 4, the predicted radial and axial distortions after quenching and cooling to room temperature are shown in Figure 9. The predicted radial distortion of the internal spline tooth is approximately 0.19 mm shrinkage, which is slightly less than the value of 0.198 mm predicted by the free oil quench model. In general, the axial load applied on the expander is low, and its effect on the 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. Minimal plastic strain due to the expander is desired. An expander load that is too high will cause inconsistent radial size and possible shape distortion. The predicted axial distortion of the baseline press quench model is shown in Figure 9(b), and the contour plot shows the press quench tooling is effective in reducing the axial distortion of the spiral bevel tooth section. By studying the contact history between the lower outer die and the bottom face of the spiral bevel tooth during the entire press quenching process, a conclusion can be made that the load applied on the upper outer die is much lower than the necessary load required to plastically bend the spiral bevel tooth section, even when the section is austenite at the high temperature. However, the spiral bevel tooth section can be bent downward sufficiently under a low die load when phase transformation occurs. The transformation induction plasticity (TRIP) is an important phenomenon for making the press quench process effective.



(a)



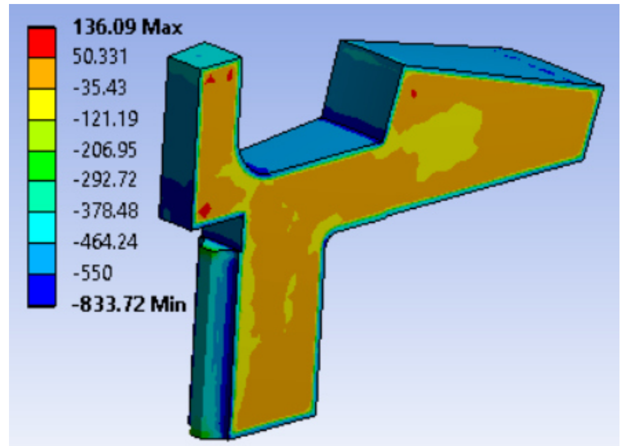
(b)

Figure 9: (a) Radial distortion, and (b) axial distortion predicted at the end of press quench.

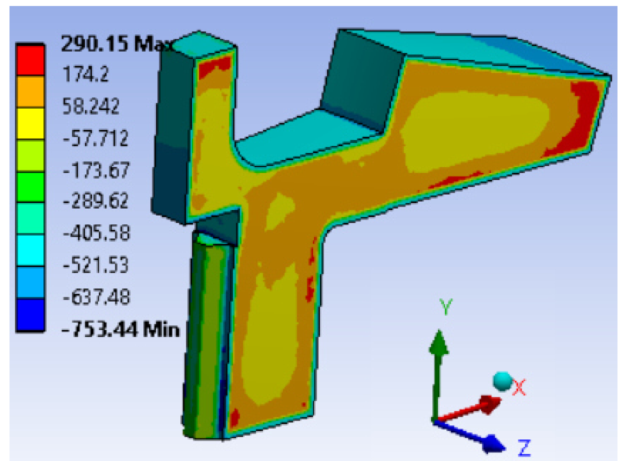
Figure 10 shows the predicted minimum principal and the circumferential residual stresses of the hardened gear in the as-quenched condition. The carburized case is under residual compression due to the delayed martensite transformation in the case. It is also worth mentioning that the press quench tooling has an insignificant effect on the residual stress state if performed properly. The stress magnitude generated by external loads from the tooling is insignificant compared to the thermal stress and phase transformation stress generated from the quenching process.

Distortion Reduction by Modifying the Press Quench Set Up

The axial shrinkage of the internal spline tooth predicted from the baseline press quench model is about 0.19 mm, which is significant relative to the designed case depth and allowed final machining stock. Higher loads can be applied to the expanders to counter the radial shrinkage. However, the required load magnitude will be high, which can cause inconsistent radial size change after hardening. Too high of a load on spline tooth surface prior to transformation to



(a)



(b)

Figure 10: (a) Minimum principal residual stress, and (b) circumferential residual stress distributions predicted at the end of press quench.

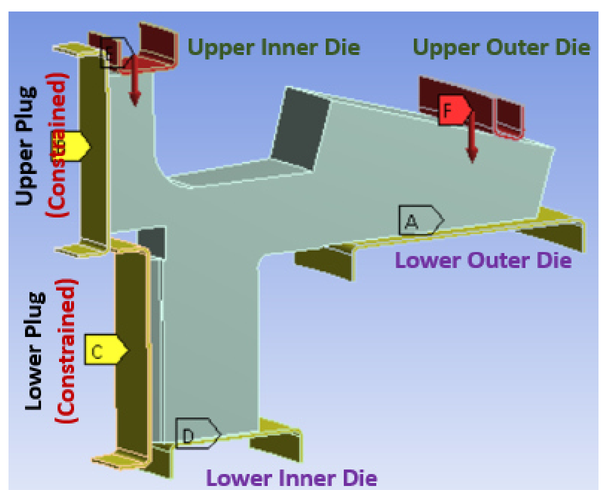
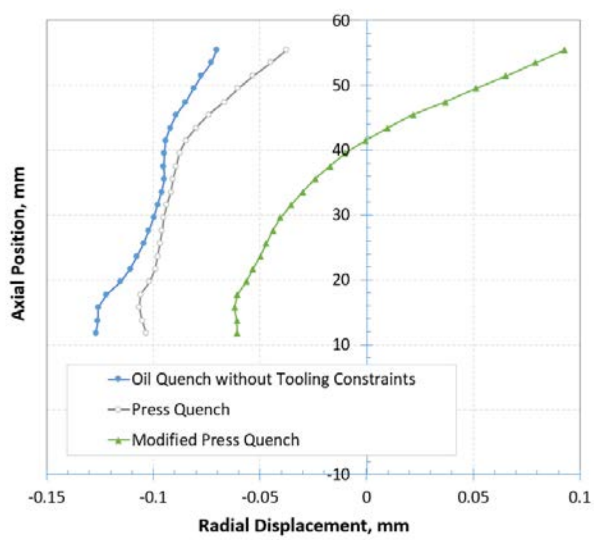


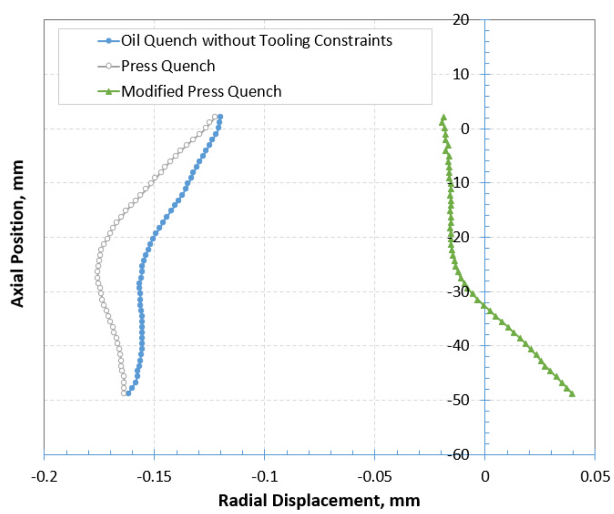
Figure 11: Modified press quench tooling set up.

martensite can damage the tooth shape. One effective method is to replace the expanders by plugs, as shown in Figure 11. In this modified press quench setting, the lower outer die and the lower inner die are kept at the same positions as those of the baseline model, and the loads applied by the upper dies are not changed either. As shown in Figure 11, the upper expander is replaced by an upper plug; the size of the upper plug is the same as desired bore dimension at room temperature. The lower expander is replaced by a lower plug, and the plug's radial size is 0.060 mm larger than the internal tooth tip size at the room temperature (an overclosure of 0.060 mm). After the gear is heated, enough gap will be generated between the plug and the gear due to the thermal expansion, so the plugs can be inserted into the gear for quenching.

The effectiveness of the baseline and the modified press quench settings on the radial displacements of the internal spline tooth and the bore after hardening are studied by selecting two lines of points from the bore and the internal spline tooth tip of the FEA model, as shown in Figure 3(b). The predicted radial displacements from the three models are compared in Figure 12.



(a)



(b)

Figure 12: Comparison of the tooling effect on the bore radial distortion along (a) the upper bore line, and (b) the lower spline tooth tip line as shown in Figure 3(b).

The X-axis in Figure 12 is the radial displacement after cooling the gear to room temperature, with X = 0.0 mm representing the original position of the upper bore and the internal spline tooth tip. The Y-axis of Figure 12(a) is the axial position of the upper bore, and the Y-axis of Figure 12(b) is the axial position of the internal spline tooth tip. The free quench model and the baseline press quench model have similar radial distortions along the internal spline tooth tip and the upper bore. With the modified press quench, the radial shrinkage of the internal spline tooth is significantly reduced, as shown in Figure 12(b). The radial distortion of the upper bore is also reduced. However, the tapered distortion along the upper bore is more severe with the plug design. This can be partially caused by the part and plug interaction along the spline tooth tip.

One line of points located along the bottom face of the spiral bevel tooth section as shown in Figure 3(b) is selected to compare the axial distortion obtained from the three models, and the results are plotted in Figure 13. The X-axis is the radial position of the selected points, and Y-axis is the axial displacement, with a positive value representing warping upward. With free oil quench, the predicted axial displacement is about 0.6 mm at the end face of the spiral bevel tooth section. Both the baseline and the modified press quench models can effectively reduce the axial distortion of the spiral bevel tooth section.

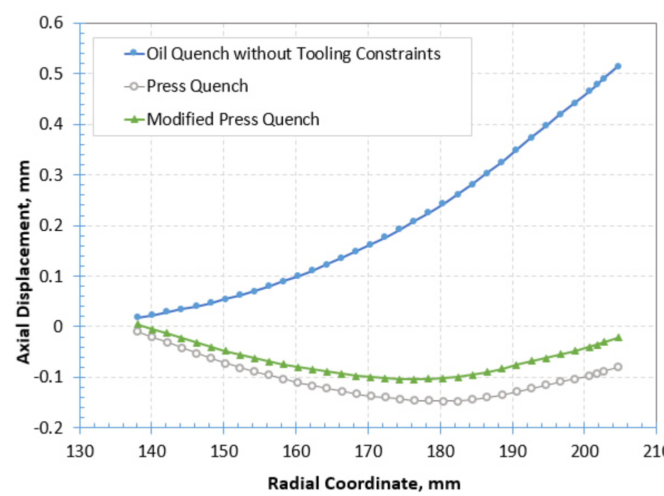


Figure 13: Comparison of the tooling effect on the axial distortion of the tooth bottom face.

Understanding the gear response during a quenching process is important to interpret the causes of distortions, and give ideas of process improvement for reduced distortion. As shown in Figure 3(b), two points are selected to plot the radial and axial displacements during the entire quenching processes. Point A is located at the lower end of the internal spline tooth tip surface, and the point B is located at the far end of the bottom face of the spiral bevel tooth.

Figure 14 plots the radial displacements of the point A for the three models. The X-axis is the time, and the Y-axis is the radial displacement. With the same thermal boundary conditions applied for the three models, the effects of the expander and the plug are clearly compared. The expander has an insignificant effect on the radial displacement. However, if the gear has an out-of-round shape during quenching before the martensitic transformation is completed, the radial force will concentrate on the least radial size section to make it round. By using the plug, the upper bore and the internal spline tooth tip surface of the gear will contact with the plug due to the thermal shrinkage. The reaction force between the plug and the gear is much higher than the force applied on the expander of the baseline press quench process, which leads to elongated circumferential plastic strain in the gear, and the gear ends up with a larger radial dimension. With further cooling, the gear expands when bulky martensitic phase transformation occurs in the gear, and the gear detaches from the plug.

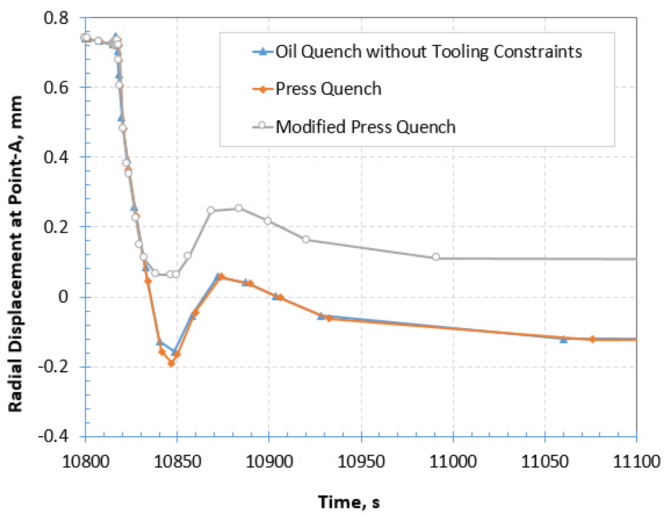


Figure 14: Radial displacement of the point-A as shown in Figure 3(b) vs. time during quenching for the three models.

Figure 15 shows the axial displacements of the point B during quenching for the three models. After furnace heating, air transfer, and before quenching, the radial displacements of point B are the same for the three models. During quenching, the same axial load is applied to the upper outer die to control the axial distortion, and no load is applied for the free quench model. Because the gear has an unbalanced geometry, the spiral bevel tooth section warps upward at the early stage of quenching. However, the amount of the upward warpage is reduced with die load applied on the upper outer die. With further cooling, the die load is sufficient to push the spiral bevel tooth section downward contacting with the lower outer die with the help of internal thermal and phase transformation stresses. It is worth mentioning again that the transformation induced plasticity (TRIP) phenomenon plays an important role in the press quenching process. When phase transformation is going on, a lower magnitude external load can be applied to introduce plastic deformation to the part.

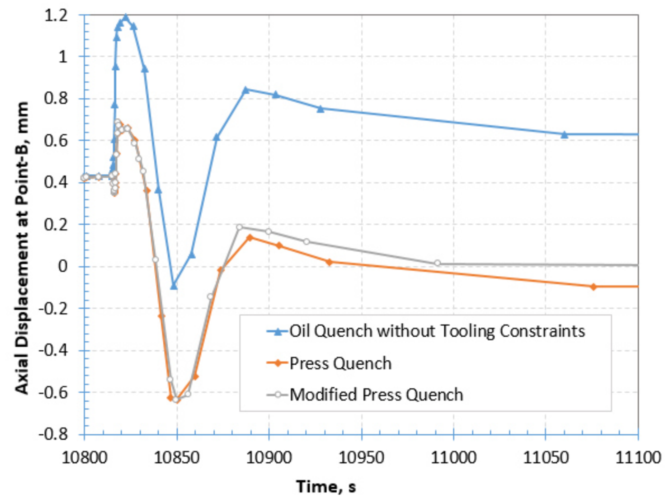


Figure 15: Axial displacement of the point-B as shown in Figure 3(b) vs. time during quenching for the three model scenarios.

Conclusions

The dimensional responses of the spiral bevel gear to press quench processes were 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 not causing damage to the part, e.g. plastic deformation of spline or gear teeth. 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 have shown that the radial distortion of the internal tooth can be consistently and effectively controlled. In this study, straight (stepped) plugs with different radial sizes were used for the internal spline tooth section and the upper bore section. It is expected that the reaction force for a plug is much higher than that from an expander of a traditional press quench, and its effect on the neighbors (regions without plug contact) is also more severe. Plugs with tapered or profiled configurations will be designed to further reduce the tapered distortion of the upper bore location in future works.

References

[1] B.L. Ferguson, A.M. Freborg, and Z. Li, "Residual Stress and Heat Treatment – Process Design for Bending Fatigue Strength Improvement of Carburized Aerospace Gears", Journal of HTM. Härterei-technische Mitteilun, 62(6), 2007, p 279-284.

[2] Zhichao Li, Andrew M. Freborg, Bruce D. Hansen, T. S. Srivatsan, "Modeling the Effect of Carburization and Quenching on the Development of Residual Stresses

and Bending Fatigue Resistance of Steel Gears", Journal of Materials Engineering and Performance, March 2013, Volume 22, Issue 3, pp 664-672.

[3] A. Freborg, B. Ferguson, and Z. Li, "Modeling Heat Treatment for Characterizing Distortion, Residual Stress, Loading Response and Fracture in a Vacuum Carburized and Gas Quenched Steel Coupon", Proceedings from the 5th International Conference on Thermal Process Modeling and Computer Simulation, June 16–18, 2014, Gaylord Palms Resort & Convention Center, Orlando, FL, USA.

[4] Reardon, A.C. "Press Quenching," ASM Handbook, Volume 4a, Steel Heat Treating Fundamentals and Processes, J. Dossett and G. Totten, Editors, ASM International, Nov. 2013.

[5] T. Inoue, S. Nagaki, T. Kishino, and M. Monkawa, "Description of transformation kinetics, heat conduction and elastic-plastic stress in the course of quenching and tempering of some steels", Ingenieur-Archiv, Vol.50, 1981, Springer, pp 15-327.

[6] Ferguson, B.L., Freborg, A., Petrus, G., Software Simulates Quenching, Advanced Materials and Processes, H31-H36, August (2000).

[7] D. Bammann, et al., "Development of a Carburizing and Quenching Simulation Tool: A Material Model for Carburizing Steels Undergoing Phase Transformations," 2nd Int. Conference on Quenching and Control of Distortion, ASM Int., 1996.

[8] ANSYS Mechanical User's Guide, R16.

[9] Z. Li, A. Freborg, B. Ferguson, "Application of modeling to heat treat processes". Heat Treating Processes, May/June 2008.

[10] MacKenzie, Scott, Li, Zhichao and Ferguson, B. Lynn, "Effect of Quenchant Flow on the Distortion of Carburized Automotive Pinion Gears", Proceedings of the 5th International Conference and European Conference on Heat Treatment, eds. Johann Grosch, Jorg Kleff and Thomas Lubben, Berlin, Germany, pp 119-129, 2007.

[11] Reardon, A.C. "Press Quenching and Effects of Prior Thermal History on Distortion during Heat Treatment," Gear Technology, March/April, 2014, pp. 50-53.