Heat Treat 2017: Proceedings of the
29th ASM Heat Treating Society Conference
October 24–26, 2017, Columbus, Ohio, USA



# Solving Critical Heat Treatment Challenges with Practical Process Modeling

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## Abstract

Heat treaters are encountering an ever-increasing need for practical process design and troubleshooting methods to effectively address quality, cost and production time requirements for thermal treatment of steel parts. Over the last two decades, substantial advances have been made in heat treatment process modeling, now permitting user-friendly and robust means for process engineers, designers, and other heat treatment technical professionals to readily apply advanced modeling technology to address complex, "real-life" heat treatment challenges. DANTE modeling software has now been implemented for ready application to carburizing and hardening processes with the consideration of phase transformation, following the process parameters input from heat treaters. This paper highlights a user-friendly and advanced modeling tool now available for solving practical heat treatment challenges. Several case studies using DANTE will cover induction hardening, press quenching and plug quenching, and low pressure carburizing. Also shown are the important benefits received from this technology, including minimization of the costly "trial and error" approach to troubleshooting, and evaluating the effect of process parameters on part quality.

## Introduction

Improving in-service performance of steel components is the ultimate goal of heat treating. For decades, heat treating has been based on experience. However, with computational power improving every year, and computer hardware becoming less costly, simulation of complex processes and geometries is now feasible.[1] Heat treatment processes are no longer a black box, but become transparent and malleable with the use of heat treatment software.

With the use of computer based heat treatment software such as DANTE, modeling has been used successfully to improve part performance and process control.[1-7] This paper looks at four examples of using the DANTE heat treatment software to solve real-world challenges.

## Heat Treatment Process Modeling

Modeling the heat treatment process requires the solution to several physical phenomena: Mass diffusion for the carburization process, heat transfer for heating and cooling processes, stress and strain for the prediction of deformation and residual stress, and solid-state phase transformations for microstructural evolution predictions. The heat treatment modeling software, DANTE, accounts for all of these phenomena.[4]

The most computational efficient method of solution for heat treatment modeling using DANTE is by sequentially coupling the required analyses. Figure 1 shows a schematic of the models required to successfully simulate the heat treating process, their outputs, and the flow of the outputs from one model to the next.

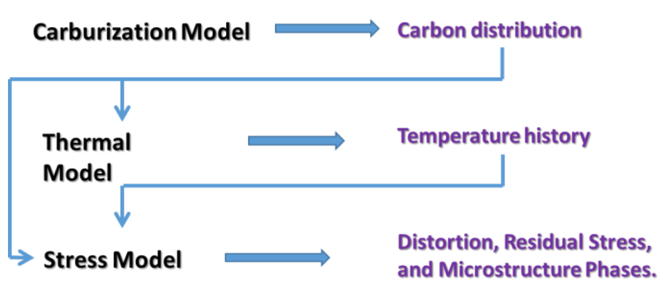


*Figure 1: Sequential coupling method for modeling heat treating processes.*

The carburization model calculates the carbon diffusion and determines the carbon distribution for the entire component; this model can be skipped if there is no carburizing process. The thermal model is the most important for the proper modeling of the heat treating process. The boundary conditions for this model are absolutely critical, as the thermal model determines the entire thermal history of the component. The thermal model uses the carbon distribution to determine phase transformation timing and the subsequent thermal properties as a function of phase, carbon level, and temperature. The stress model then uses the carbon distribution and the thermal history to calculate the displacements and stresses in the component throughout the entire process, including the final distortion and residual stress.

ANSYS Workbench allows for an intuitive approach to the sequentially coupled method of modeling the heat treating process. Figure 2 shows the Workbench Project Schematic for four different DANTE heat treatment models, with the models all using the same geometry. ANSYS Workbench allows the user to define different processes for the same geometry without having to redefine or recreate the geometry again, simplifying process parameter investigations; i.e., sensitivity analyses.

Figure 2A is for a gas carburization process followed by oil quenching. The oil quench can be either a free quench or a press quench, the only difference being the geometry and mechanical boundary conditions used in the stress model. One can see how easy it would be to create the part geometry with all the necessary tooling to complete a press quench model, suppress all the tooling to run the carburization and thermal model. A free oil quench stress model could then be executed with the tooling still suppressed to determine the components unrestrained behavior. The stress model could then be duplicated, the tooling unsuppressed, and a press quench model executed to determine the effects of the tooling constraints on stresses and displacements.

Figure 2B is for a low pressure carburization process, followed by a high pressure gas quenching operation. Figure 2C is for an induction hardening process. Notice the lack of the carburization model, the base carbon of the material is all that is needed for the induction hardening model, and the addition of External Data. The External Data is a file containing the joule heating distribution for the component. The joule heating file can be generated from micrographs of the hardened component, if they exist, and experience or by using a software which solves electromagnetic phenomena. Figure 2D is for a loading model which considers the residual stresses from the heat treatment process. The residual stress profile for the entire model is generated in an external file that is read into the loading model.

Modeling heat treatment processes using DANTE has become increasingly user-friendly when used with the ANSYS finite element package. Taking the intuitive, step-by-step approached utilized by ANSYS Workbench, DANTE has developed an extension within the ANSYS Application Customization Toolkit (ACT), allowing the process engineer, designer, or heat treat professional to build up and view the results of the model in a very intuitive way. Figure 3 shows the DANTE ACT and the various inputs required to build up the sequential models; buttons to the left of the double bars are for pre-processing and the buttons to the right of the double bars are for post-processing.

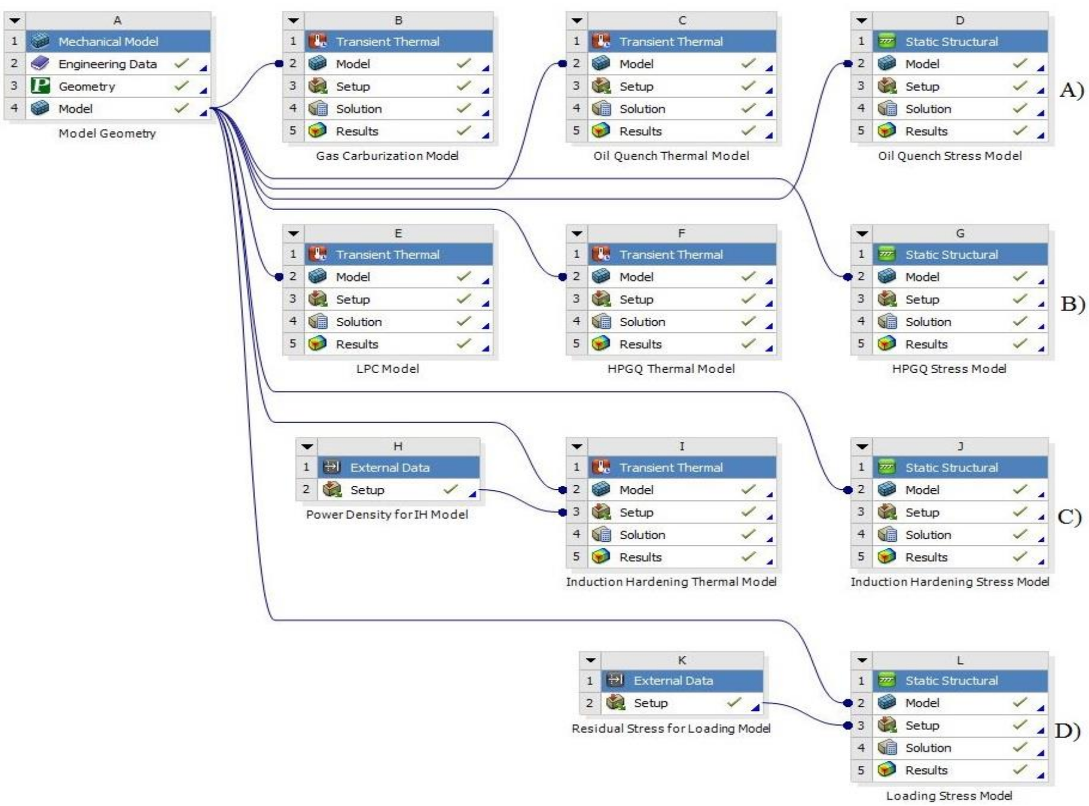


*Figure 2: Workbench Project Schematic for four DANTE heat treatment models: A) Gas carburizing, followed by oil quenching; B) Low pressure carburizing, followed by high pressure gas quenching; C) Induction hardening; D) Static loading, considering the residual stress from heat treatment.*

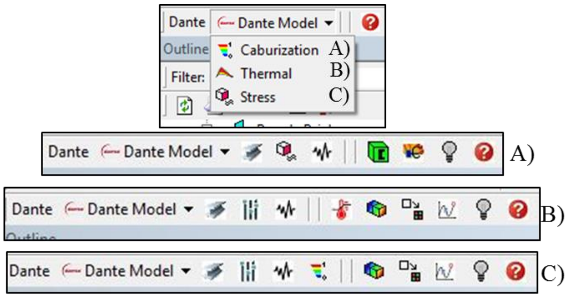


*Figure 3: Ansys ACT for DANTE Heat Treatment Software. The layout allows for a natural progression of building the models and viewing the results.*

The ANSYS ACT buttons, shown in Fig. 3, for pre-processing, include material selection from the DANTE material database, and defining of process details that are needed for the carburization model, thermal model and the final stress/displacement model. These details include modeling instructions such as when the carbon distribution is added to the thermal and stress models, how often the results are saved for later viewing graphically, and so forth. The ACT is meant to remind the user as to what process steps must be defined and what model control parameters must be defined.

The DANTE Carburization Model ACT buttons, Fig. 3A, include material selection from the DANTE material database, carburization temperature definition as a function of time, and a definition for how often the model results are saved for post-processing. The post-processing buttons for the Carburization Model include a function to automatically generate the carbon profile file and a button to view the amount of carbon in carbide form, a normalized carbide size, and the carburization temperature.

The DANTE pre-processing buttons for the Thermal Model, Fig. 3B, and Stress Model, Fig. 3C, include a material definition, a button for defining the carbon profile file, and a result output frequency definition. The Stress Model adds a button to select the temperature history file generated during the post-processing of the Thermal Model.

The DANTE post-processing buttons for the Thermal and Stress Model include a button to view the DANTE variables, which include carbon, hardness, microstructural phases, and plastic strain; a button to create a path at a particular time for the DANTE variables; a button to create a time history at a single node for the DANTE variables, and a link to the DANTE help file.

## Induction Hardening Quench Cracks

**Problem Statement**

A thick-walled component made of AISI 4150 steel suffered cracking on the inner bore from a scanning induction hardening process.[5] The cracks were visible immediately after quenching and were a persistent problem.

**Solution**

A finite element model was constructed and the scanning induction hardening process was modeled using DANTE. Using micrographs from a previously hardened and cracked part, along with the inductor scan speed, the joule heating, as a function of time was determined.

The joule heating input is required to determine the thermal history of the component during the hardening process. A program that solves electromagnetic phenomena can also be used to get the joule heating in terms of time for the model inputs. The joule heating in terms of time for each node in the model is then prepared in an external file, which can be generated using several different methods, and read into the DANTE Thermal Model.

Armed with the thermal history, a stress model was executed and the root cause of the cracking was ascertained to be a result of bending stresses induced during the solid-state phase transformation from austenite to martensite. Figure 4 shows the crack location in a component and the results of the DANTE model showing high tensile stresses corresponding to the crack location.

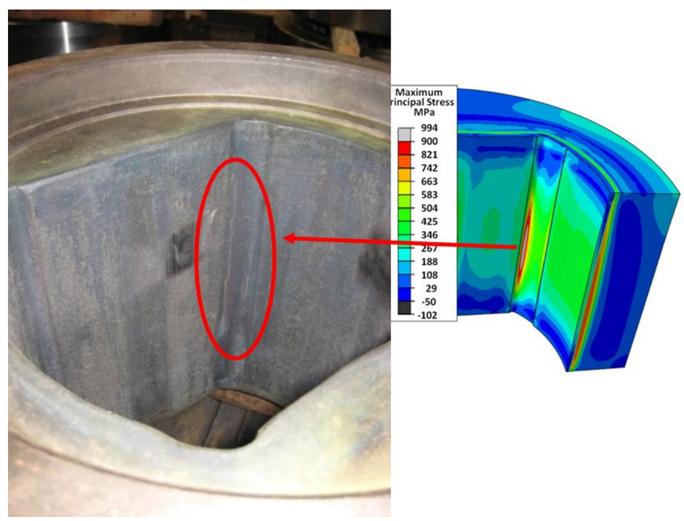


*Figure 4: Crack on ID of induction hardened steel component (left) and DANTE heat treat model of component showing area of high maximum principal stress corresponding to crack location (right).*

Knowing the root cause of the cracking, several low cost virtual trials, DANTE models, were conducted to find a solution. Several DANTE models were executed to examine the effects of reducing the case depth on the in-process stresses. Another model examined the effects of a low temperature preheat prior to the induction hardening process. The hoop stress, as a function of time, is shown in Fig. 5 for two of the virtual trials, as well as for the original process.

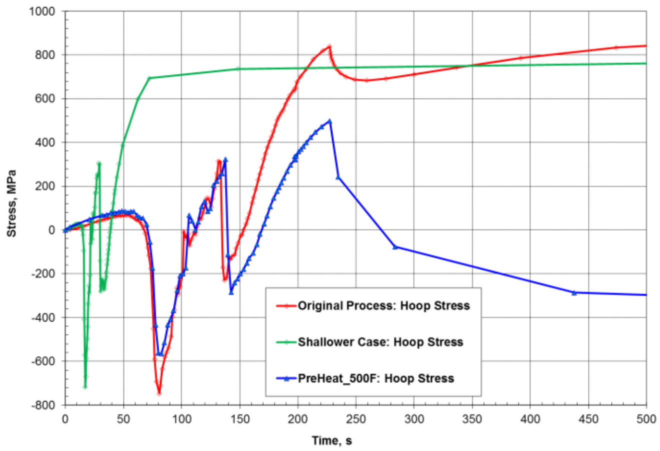


*Figure 5: Hoop stress at the inner bore point of maximum stress for the original process and two process modifications examined using heat treat modeling.*

As can be seen from Fig. 5, the effects of reducing the case depth are minimal and will most likely still result in cracking issues. Including a low temperature preheat step to the induction hardening process, either in a furnace or with a through heating induction process, has tremendous benefits. Not only does the preheat method eliminate the propensity for cracking by reducing the in process bending stress, but using a low temperature preheat actually places beneficial residual compressive stresses on the surface of the component.

### Additional Studies

Although the addition of a preheating step rendered a solution, further virtual trials could be conducted to optimize the preheat temperature. The ideal way to preheat the component would be with induction, and heat treatment modeling with DANTE could determine the ideal conditions to achieve maximum compressive stresses. The virtual trials conducted in a virtual environment are ideal for process design in that the designer is given the opportunity to view the causes of the outcome. Understanding the causes allows for the design of a more robust process.

## Press Quenching Quench Cracks

### Problem Statement

Inner bearing rings manufactured from AISI 52100 steel were experiencing excessive cracking in the outer raceway at mid-height during a press quenching process.[6] The number of rings cracking during the quenching process was high, and a study was undertaken to determine the cause of the cracking and to find a solution. Figure 6 shows an austenitized bearing ring used in the study on the lower die of the press quench machine just prior to quenching.

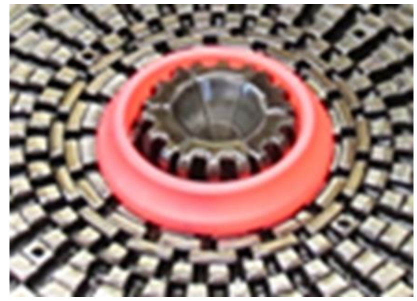

*Figure 6: Hot bearing ring on lower die of the press quench machine just prior to quenching.*

### Solution

The study that was conducted to determine the cause of the cracking examined the ring's sensitivity to various process parameters. Review of experimental trials and DANTE modeling were used during the study. Figure 7 shows a quench crack in one of the actual rings (left) and the high tensile stress in the area of cracking predicted by the DANTE model (right).

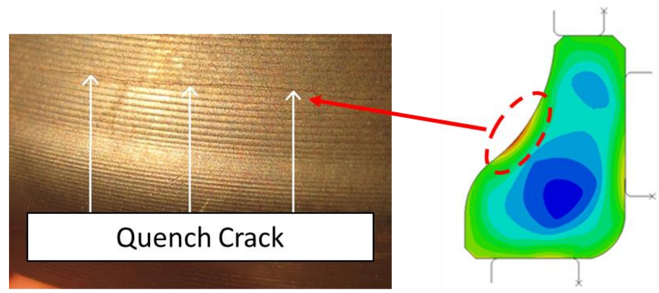


*Figure 7: Quench crack in bearing ring (left) and heat treat model with high tensile stresses in location corresponding to crack location (right).*

Nine different cases were simulated and are listed in Table 1. Of particular interest in this study were the frictional effects, including sticking due to excessive friction, between the die and the ring, as well as the effects of oil flow rate.

*Table 1: The friction coefficient, generic quench flow, and the press load used for the nine cases examined in the study.*

| Case | Friction Coefficient | Quench Practice | Press Load |
|---|---|---|---|
| 1 | 0.05 | Std. Flow | 4000 lbs. |
| 2 | 0.05 | Low Flow | 4000 lbs. |
| 3 | 0.2 | Std. Flow | 4000 lbs. |
| 4 | 0.5 | Std. Flow | 4000 lbs. |
| 5 | 0.05 | High Flow | 4000 lbs. |
| 6 | Sticking – Top & Bottom | Std. Flow | Not Applicable |
| 7 | Sticking – Top | Std. Flow | Not Applicable |
| 8 | Sticking – Bottom | Std. Flow | Not Applicable |
| 9 | 0.05 | ID – Low Flow; OD – Std.Flow | 4000 lbs. |

Frictional effects were considered by using a friction coefficient at the boundary between the ring and the press quench tooling. Sticking of the ring to the die, as a result of increased friction, was modeled by fixing the top surface, bottom surface, or top and bottom surface nodes on the ring which were in contact with the die. The interaction between the top and bottom dies with the corresponding ring surfaces were of the most concern, due to the restriction created by friction as the ring contracted and expanded during the quenching process due to thermal and phase transformation effects, respectively.

The effects of flow rates on the in-process and residual stresses near the area corresponding to the crack location were also of interest and modeled for this study. The Standard (Std.) Flow rate was the flow rate being used at the time of the study, with the High Flow and Low Flow simply multiples of the Std. Flow, as shown in Table 1.

Table 2 shows the maximum axial stress occurring in the bearing ring during the process and the final maximum residual axial stress predicted by the DANTE models for all 9 cases examined during the study.

*Table 2: Maximum in-process axial stress and the maximum residual axial stress predicted by the DANTE models.*

| Case | Max. In-Process Stress, MPa | Max. Residual Stress, MPa |
|---|---|---|
| 1 | 642 | 400 |
| 2 | 400 | 236 |
| 3 | 668 | 403 |
| 4 | 691 | 422 |
| 5 | 746 | 472 |
| 6 | 882 | 338 |
| 7 | 680 | 393 |
| 8 | 860 | 371 |
| 9 | 325 | 230 |

As can be seen by Table 2, Case 6, sticking of the top and bottom die, and Case 8, sticking of the bottom die, both generate in-process stresses in excess of 850 MPa. These stresses are believed to be great enough to result in quench cracks. The sensitivity to increased friction, or a sticking top die, does not seem to become an issue until the bottom die sticks. Also, gleaned from Table 2 is the sensitivity to higher and lower quench oil flow rates, resulting in a 16% increase and a 62% decrease in maximum in-process stresses, respectively. However, while the in-process stresses for the high flow rate are approximately 750 MPa and could lead to cracking, the flow is much easier to control than the friction between the die and the ring.

Armed with the prediction that die-part interface sticking could be a major contributor to the quench cracking of the ring, a trial involving 209 rings manufactured from the same heat was conducted to try and explore the possibility of die-part sticking. The press quench machine utilized for the study had a pulsing feature which allowed the force applied to the tooling to be momentarily released and reapplied. This pulsing function had not been engaged in prior trials.

A total of four trials were conducted, two without pulsing and two with pulsing. The two without pulsing had a scrap rate of approximately 61%, with good agreement between the two trials. The two trials with the pulsing function activated had a failure rate of approximately 4%, with good agreement between the two trials. The effects of flow rate were not examined during the physical trials.

**Additional Studies**

Although friction and die sticking had been the main focus of the modeling investigation, the DANTE model could have been applied to examine and optimize other process parameters. Of particular interest to the manufacturing of bearing rings is circularity. A model could have been developed to determine optimum press quench loading conditions to ensure circularity. Yet another study could have focused on optimizing the shape of the expander to ensure a consistently straight inner bore. Performing sensitivity studies of a specific process can shed light on those parameters that must be closely monitored to maintain a consistent process, and those parameters that can meet consistency requirements without being tightly controlled.

## Press/Plug Quench Tooling Design

**Problem Statement**

Press quenching of a carburized bevel gear was resulting in excessive radial shrinkage of the inner bore.[7] Due to the carburized case on the inner bore spline teeth, final grinding could not be used to meet dimensional specifications and still meet the mechanical property requirements. Figure 8 shows the actual component (left) and the simplified CAD model (right). Since the inner bore was the area of interest, the bevel teeth could be removed from the model and replaced with a thermal equivalent mass for modeling purposes without degrading accuracy.

*Figure 8: Bevel gear (left) and corresponding simplified CAD model (right) used for heat treat model.*

**Solution**

DANTE was used to explore the effects of the tooling constraints on the radial shrinkage. Figure 9 shows the simplified bevel gear, further simplified to represent a single tooth, with the press quench tooling also shown. The simplification to a single tooth is warranted due to radial shrinkage being the primary concern; out-of-round distortion is not considered and was not an issue. The assumptions of cyclic symmetry and uniform cooling in the circumferential direction form the basis of the single tooth model.

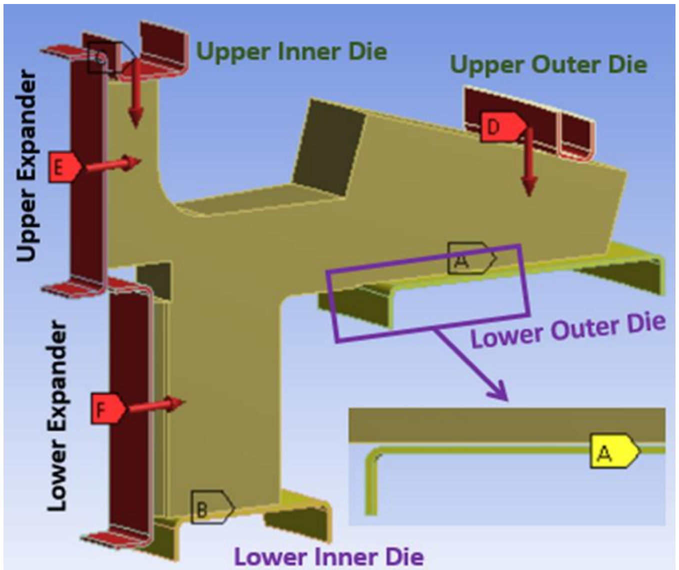


*Figure 9: Simplified bevel gear, single tooth press quench heat treat model with all tooling shown.*

A baseline immersion quench model was constructed to observe the gear's behavior in the absence of tooling constraints. These DANTE model results were then compared to the current tooling load conditions used to process the gear. As can be seen in Fig. 10, the tooling with the current loading conditions, grey curve, did not offer much benefit over a free oil quench process, blue curve, and actually may have been making the shrinkage of the bore worse.

Using a plug, or a locked expander, does a much better job of controlling the radial dimension than a loaded expander. Figure 10 also shows the results of the DANTE model using a plug (Modified Press Quench data points), green curve, to control the radial dimension. Using a plug in this instance greatly reduced the radial shrinkage and brought the radial dimension within tolerance, while maintaining the desired mechanical properties.

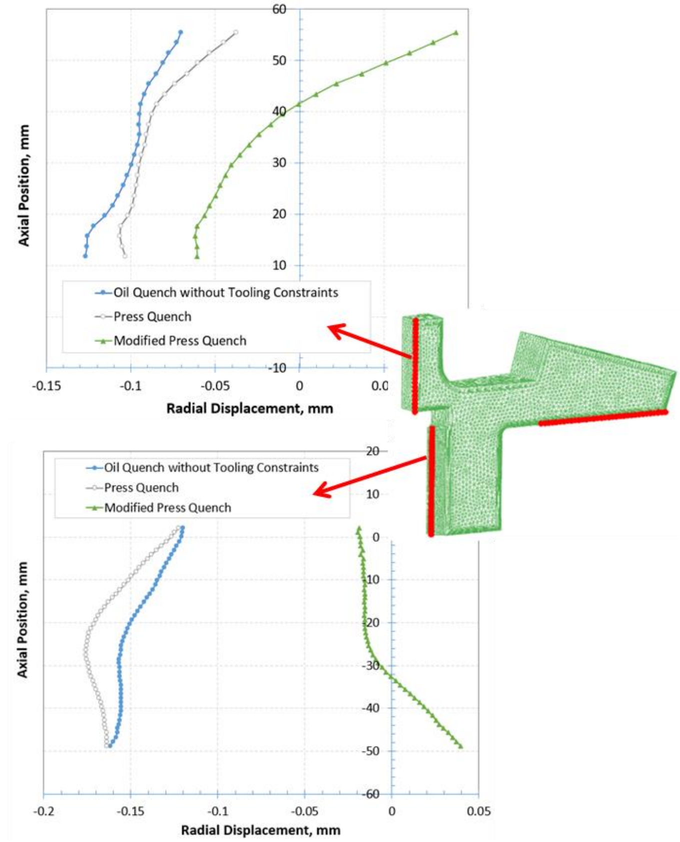


*Figure 10: Plots of axial and radial position (left) for the line of nodes shown (right). The plots show the shape of the two sections of the bore for a free oil quench (blue line), original press quench process (grey line), and a plug quench process designed using DANTE (green line).*

**Additional Studies**

Although the use of a plug brought the radial dimension within tolerance, a few more model variations could easily determine the plug shape which would also eliminate the taper. By controlling the size of the bore, as well as the shape, the process can be made more consistent from component to component by being less sensitive to process parameters. DANTE could also be used to explore which process parameters have the most effect on dimensions, residual stress, and in-process stress. These findings can then be used to steer operator focus to those parameters that have the greatest effect on final part performance.

## Carbide Formation During LPC Process

**Problem Statement**

Understanding possible carbide formation sites in a component processed using low pressure carburizing (LPC) is critical to ensure optimal part performance during service. These carbides can be a result of poorly designed boost/diffuse steps for the LPC process, or from geometric features not conducive to uniform carbon diffusion into the component. Sharp corners, in particular, can be severely detrimental to proper carbon diffusion. Carbon diffusion from both surfaces of the corner can lead to a carbon buildup and a subsequent area of increased carbide formation. Machining off the areas of excessive carbide formation can remove the unwanted microstructure, but can also remove the carburized case that gives the component the desired mechanical properties.

**Solution**

Modeling of the LPC process using DANTE can help understand when geometric features create a strong possibility to form unwanted carbides. DANTE can also be used to design the boost/diffuse cycles of the LPC process, but is not discussed here. These carbides either need to be avoided in the first place, or their location should be known well enough that finish machining can remove them without degrading the mechanical properties of the component.

Using an axisymmetric ring made from X-2M with a 101.6 mm OD and a 12.7 mm wall thickness, an LPC process was used to achieve a surface carbon value of 1.0% and an ECD of 1.0 mm. The first geometry investigated used sharp corners on the ID and OD surface. Several plots were generated to show the amount of carbon within the austenite matrix, the amount of carbon locked in carbides, and the total amount of carbon. Figure 11 shows the full cross-section (left) and a close-up view of the top-right corner (right). The nodes used to generate the plots are highlighted in red.

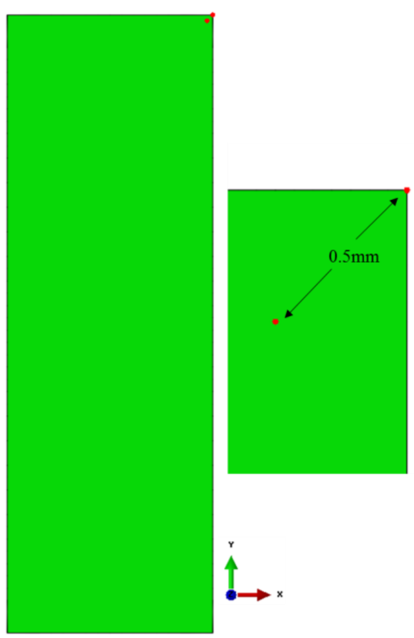


*Figure 11: Full cross-section of sharp corner ring model (left) and a close-up of the top-right corner of the cross-section (right) to better show the relationship between the nodes used to generate plots of the carbon.*

Figure 12 is a plot of the three carbon variables on the surface of the sharp corner model plotted over the entire LPC process. There is reason to be concerned about the carbide formation at this location using the current LPC schedule with the sharp corner geometry; the amount of carbon in carbide form is more than the amount of free carbon in the austenite matrix.

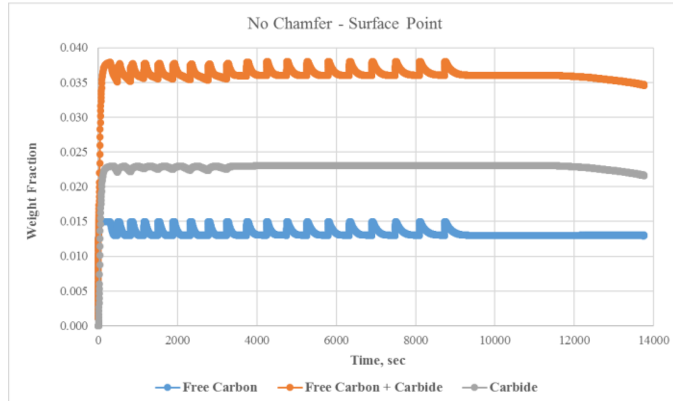


*Figure 12: Plot of carbon as carbon in the austenite matrix (free carbon), carbon in carbides (carbide) and the total amount of carbon (free carbon + carbide) at the corner of the OD on the surface of the ring with sharp corners.*

Figure 13 is a plot of the three carbon variables at a location 0.5 mm from the surface of the sharp corner model plotted over the entire LPC process. The amount of carbon in carbide form is considerably less at this depth than on the surface, but the carbon in carbide form is steadily growing. This steady growth indicates that the carbides are forming, not dissolving, and should raise some concern.

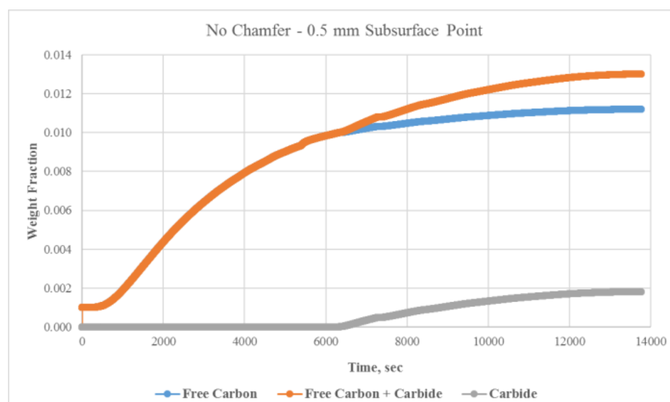


*Figure 13: Plot of carbon as carbon in the austenite matrix (free carbon), carbon in carbides (carbide) and the total amount of carbon (free carbon + carbide) at a 0.5mm depth from the corner of the OD of the ring with sharp corners.*

To remove the unwanted carbides, a post-heat treatment machining operation would need to be conducted. Besides the added costs of additional procedures, the carburized case that was worked so hard for is machined away. This reduction of the carburized case would have serious implications on the hardness and mechanical properties of the martensite. To make matters worse, the beneficial compressive stresses placed in the surface layer would be significantly reduced.

With the ability to thoroughly interrogate the modeling results, an area can be found where the amount of carbide formation is acceptable. The area corresponding to this criterion occurs at 0.5 mm from the corner on the OD surface for this geometry. Figure 14 shows this location with the node highlighted in red for the full cross-section (left) and a close-up of the top-right corner (right).

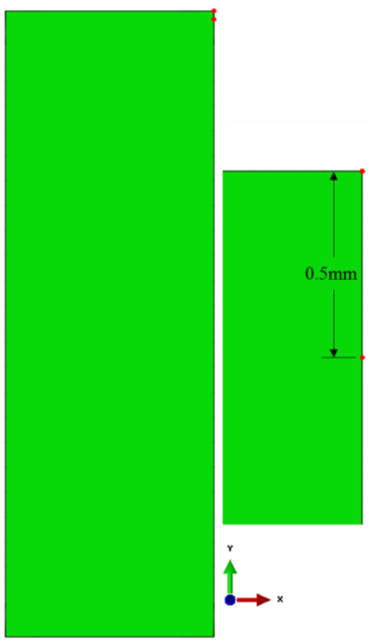


*Figure 14: Full cross-section of sharp corner ring model (left) and a close-up of the top-right corner of the cross-section (right) to better show the relationship between the nodes used to generate plots of the carbon.*

Figure 15 is a plot at the 0.5mm location, shown in Fig. 14, for the carbon in the austenite matrix, carbon in carbide form, and the total amount of carbon. Although there is still some carbon in carbide form, it is decreasing and is relatively small.

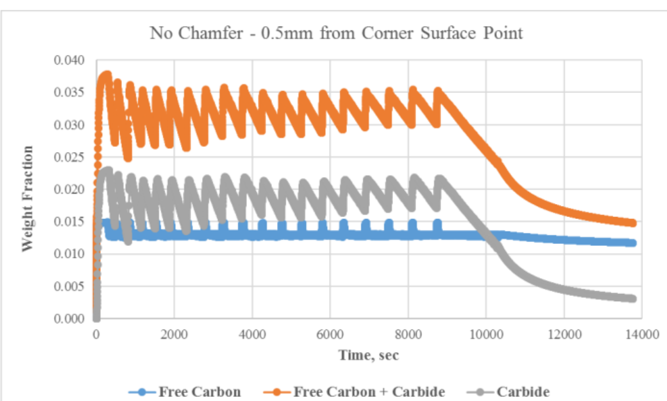


*Figure 15: Plot of carbon as carbon in the austenite matrix (free carbon), carbon in carbides (carbide) and the total amount of carbon (free carbon + carbide) at 0.5 mm from the corner of the OD on the surface of the sharp corner ring model.*

Knowing the location and distribution of possible carbide formation, the component can be designed to significantly reduce the possibility of carbide formation. Figure 16 shows the same ring with a 0.5 mm x 0.5 mm chamfer. The addition of the chamfer reduces the carbon build-up at the corner and significantly reduces the risk of carbide formation.

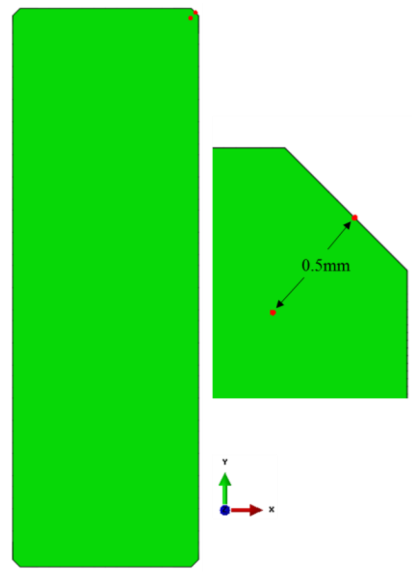


*Figure 16: Full cross-section of 0.5 mm x 0.5mm chamfer ring model (left) and a close-up of the top-right corner of the cross-section (right) to better show the relationship between the nodes used to generate plots of the carbon.*

Figures 17 and 18 show the three carbon variables for the 0.5mm chamfer model, shown in Fig. 16, at the surface and 0.5 mm under the surface, respectively.

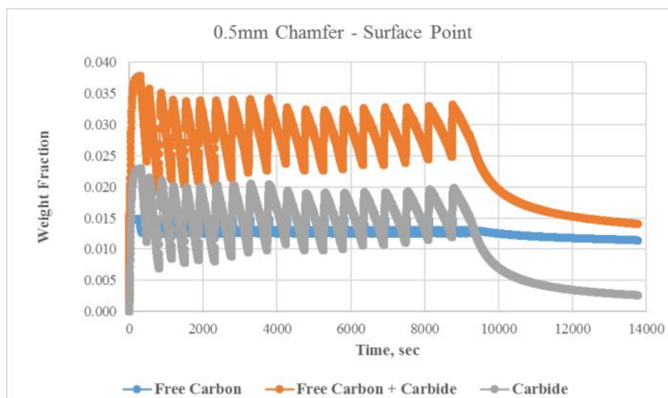


*Figure 17: Plot of carbon as carbon in the austenite matrix (free carbon), carbon in carbides (carbide) and the total amount of carbon (free carbon + carbide) at the flat of the 0.5mm x 0.5mm chamfer on the OD surface of the ring.*

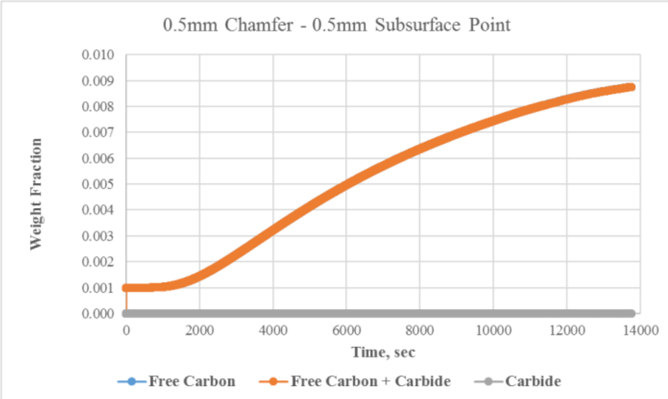


*Figure 18: Plot of carbon as carbon in the austenite matrix (free carbon), carbon in carbides (carbide) and the total amount of carbon (free carbon + carbide) at a point 0.5 mm below the surface of the ring with a 0.5mm x 0.5mm chamfer.*

As can be seen from Fig. 17, there is still a small amount of carbon locked up in carbide form on the surface of the ring. The amount is small and will likely be removed by the final grinding operation. Figure 18 reveals that at a distance of 0.5mm from the surface, all of the carbon present is in the austenite matrix. This indicates no unwanted carbides will be formed at this depth.

**Additional Studies**

Material composition, carburizing schedule, and part geometry all affect carbide formation. Using DANTE to explore the effects each of these parameters has on the final carburized case, with respect to carbide growth and dissolution, can help determine carbide formation severity and location before production of a component begins. Taking a proactive approach to low pressure carburizing, with the help of heat treatment modeling, can have major cost benefits. By understanding the component's sensitivity to boost/diffuse schedules, geometric features, carburizing temperatures, and alloying elements, a reduction in processing time, post-heat treatment machining, and scrap rates can be achieved.

## Summary

Modeling of heat treating processes was briefly discussed. The ease of use offered by utilizing software such as DANTE, as it is implemented in ANSYS, with a customized interface specific to heat treatment, was also briefly described. This combination is ideal for designers, process engineers, and other heat treat professionals looking to troubleshoot, improve, or design their heat treating processes.

Four real-world examples were then examined, with solutions derived through the use of DANTE simulation. These examples covered scanning induction quench cracks, friction related issues during press quenching, designing a process to handle unacceptable shrinkage during a press quenching operation, and geometry influenced carbide growth during a low pressure carburizing process.

With the help of accurate heat treatment simulation and intuitive software interfaces for model building and executing, computer modeling has become a useful tool for troubleshooting and improving heat treatment processes. Simulation capability, at least for steel parts, has improved to the point that many captive shops either have acquired such tools or are actively assessing how they might be beneficially used. Commercial heat treaters are also evaluating the capabilities of these tools, largely by supporting projects to fix heat treat related problems. Realizing their potential, computer based tools like DANTE are helping to improve the state of our heat treat industry.

## References


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