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Sources of Heat Treatment Distortion and Approaches for Distortion Reduction during Quench Hardening Process

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Abstract

Heat treatment of steels is a process of modifying the mechanical properties by solid-state phase transformations or microstructural changes through heating and cooling. The material volume changes with phase transformations, which is one of the main sources of distortion. The thermal stress also contributes to the distortion, and its effect increases with solid-state phase transformations, as the material stays in the plastic deformation field due to the TRIP effect. With the basic understanding described above, the sources of distortion from a quench hardening process can be categorized as: 1) nonuniform austenitizing transformation during heating, 2) nonuniform austenite decomposing transformations to ferrite, pearlite, bainite or martensite during quenching, 3) adding of carbon or nitrogen to the material, and forming carbides or nitrides during carburizing or nitriding, 4) coarsening of carbide in tempered martensite during tempering, 5) stress relaxation from the initial state, 6) thermal stress caused by temperature gradient, and 7) nonhomogeneous material conditions, etc. With the help of computer modeling, the causes of distortion by these sources are analyzed and quantified independently. In this article, a series of modeling case studies are used to simulate the specific heat treatment process steps. Solutions for controlling and reducing distortion are proposed and validated from the modeling aspect. A thin-walled part with various wall section thickness is used to demonstrate the effectiveness of stepped heating on distortion caused by austenitizing. A patented gas quenching process is used to demonstrate the controlling of distortion with martensitic transformation for high temperature tempering steels. The effect of adding carbon to austenite on size change during carburizing is quantified by modeling, and the distortion can be compensated by adjusting the heat treat part size.

Introduction

Distortion from a quench hardening process of steel components is inevitable because the phase transformations, or crystal structure changes, put the material in the plastic deformation field. The phenomenon of plastic deformation below the material's yield during phase transformations is called transformation induced plasticity (TRIP) (ref 1). However, the distortion can be controlled and minimized if the part design is heat treatment friendly, and the heat treatment process is properly designed. Distortion by heat treatment can be virtually classified as size change and shape change (ref 2). The size change is caused by the crystal structure difference (or density difference) of the material before and after heat treatment. The shape change is caused by the gradients of temperature and phase transformation during the process, including both the heating and quenching steps. These gradients will cause internal stresses, which could lead to plastic strain (distortion) if the stress magnitude exceeds the material's yield, or if there are phase transformations. The size change caused by a quench hardening process can be compensated by adjusting the initial part size before heat treatment. The shape change is more complicated, as it is affected by the steel grade, part geometry, and the detailed processing steps. The shape change is the main reason that the heat treatment process, especially a quench hardening process, is considered a black box. With the help of computer modeling, the causes of both size and shape distortions during different heat treatment processing steps are better understood. This, in turn, supports material section, part design, and process design for reduced cost and improved quality.

The distortion caused by the quenching step of a hardening process is well known and recognized. Different processes have been used to reduce the distortion by improving the uniformity of phase transformation in the part, including martempering and austempering processes. The distortion caused by the heating process is more forgiving. However, for components with complex geometries, such as features with combined thin and thick wall sections, the heating and austenitizing process may lead to unacceptable distortion if the process is not properly designed. Stepped heating is often used to reduce distortion by obtaining more uniform austenitizing transformation. During a carburizing step, carbon flux enters in the part through the surface, and diffuses inward. By adding carbon atoms in the austenite matrix, the material volume increases, which leads to part distortion. The research on distortion caused by the carburizing step is limited. Most distortion studies combined the carburizing and quenching, and it is difficult to separate the pure carburizing effect (ref 3). With computer modeling, all the individual processing steps can be analyzed separately, helping to quantify their effects on distortion, and support finding solutions to improve the process and reduce distortion. In this paper, a thin-walled gear blank is selected to apply modeling technology for quantifying the distortion and demonstrating solutions for distortion reduction.

Description of Part, Heat Treatment Process, and Modeling Basics

The part selected for this study is a thin-walled bevel gear, and the gear tooth is simplified as shown in Figure 1. The outer diameter of the gear is 150 mm, the inner diameter is 106 mm, and the height is 57.5 mm. The cross-section of the wall has various thicknesses: 2.0 mm (bottom), 4.5 mm (middle), and

7.0 mm (top). The distortion control during the heat treatment processes is often challenging for this type of gear geometry.

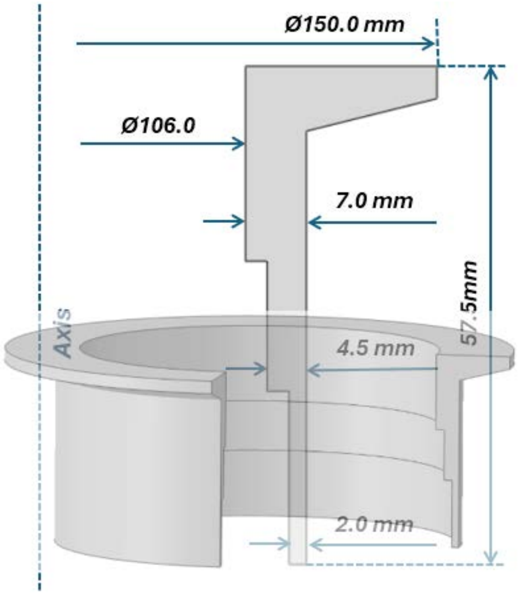


Figure 1: Brief description of the ring gear blank dimensions.

The gear is made of Ferrium C64 steel, and its chemical composition is shown in Table 1. The general heat treatment process steps for Ferrium C64 include carburizing, quenching, deep freeze, and high temperature tempering.

Table 1: Chemical composition of Ferrium C64 (ref 4).

C	Cr	Mo	Ni	Co	V	W	Fe
0.11	3.5	1.75	7.5	16.3	0.02	0.2	Bal.

An axisymmetric finite element model using the cross-section of the gear blank is shown in Figure 2. The finite element mesh contains 8,011 nodes, and 7,686 hexagonal elements, with fine elements on the top surface and the middle inner surface, which are carburized selectively.

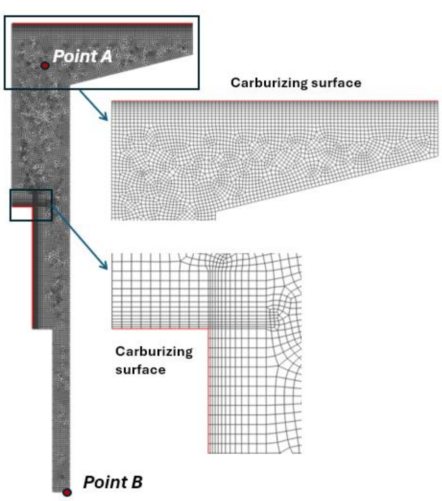


Figure 2: Finite element model of the ring gear blank.

For all the heat treatment process steps, a uniform thermal boundary condition is applied to the entire exposed *part* surface. As shown in Figure 2, Point-A is located in the center of the top wall section, where the heating rate and the cooling rate are expected to be the slowest. Point-B is at the bottom of the wall section, where the heating rate and the cooling rate are expected to be the highest. The two points are selected to understand the effect of different processes on the temperature uniformity and distortion.

Figure 3 shows the calculated dilatometry (time-temperature-strain) curves for Ferrium C64 base carbon steel from the DANTE material database. Ferrium C64 has a high hardenability, and the austenite transforms only to martensite during quenching or even during slow air cooling (ref 4). The austenitizing temperature is heating rate dependent, and the austenitizing temperature is between 800° C to 850° C with 5° C/s heating rate, as shown in Figure 3. The blue dash curve assumes the material starts with a 100% pearlite structure. The final strain after heating and quenching is positive because the formed martensite has lower density than the initial pearlite phase. The orange curve assumes the material starts with a martensite structure, and the final strain after the same thermal cycle is near zero. The different final strains due to the different initial microstructural phases in Figure 3 demonstrate the importance of knowing and controlling the initial microstructure for the quench hardening distortion control. Starting with as-quenched martensite, the material during heating will be tempered, and the coarsening of iron carbide in the tempered martensite can lead to material volume shrinkage, as shown in Figure 3 by the brown curve. It is highly recommended to sub critical annealing the material after rolling or forging before machining the parts.

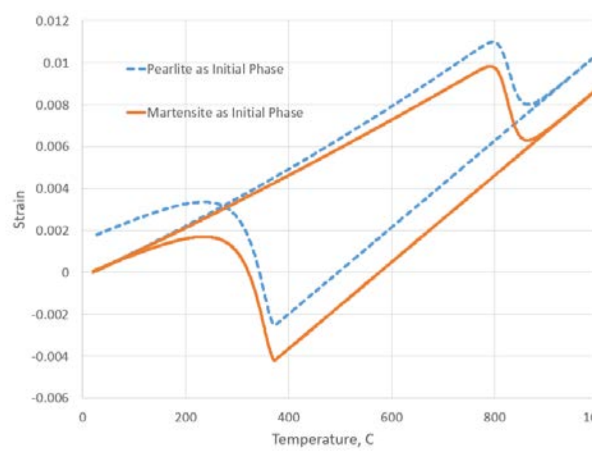
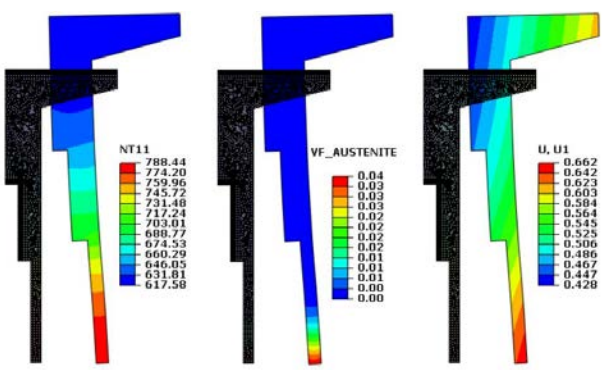


Figure 3: Comparison of dilatometry strain curves during heating and continuous cooling with pearlite or martensite as initial phases.

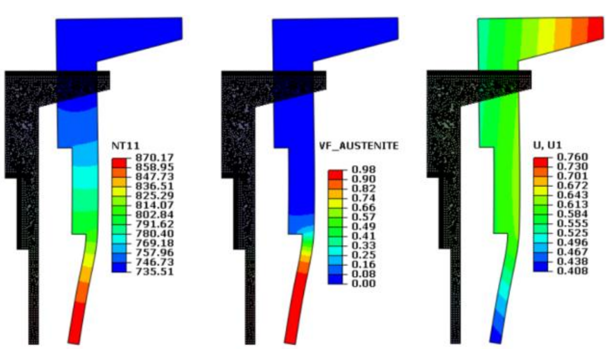
Effect of Austenitizing Process on Distortion

The distortion caused by the austenitizing step is often ignored. For bulky parts with slow heating rate, the distortion caused by the heating is ignorable. However, for complex part geometries with a combination of thin and thick sections, the uniformity of temperature and austenitizing transformation in the part cross-section may lead to unacceptable distortion by heating and austenitizing if the process is not properly designed or controlled.

Using the thin-wall gear model in Figure 2 as an example, the part is heated in a hot furnace with the furnace temperature set to 1000° C (straight heating). The temperature of the bottom wall (thinnest section) has the highest temperature during heating, as shown in the left figure of Figure 4(a). The displacement is magnified 20 times for an easier view. About 4% of austenite is formed at the bottom wall at this snapshot time, and its effect on the shape change is ignorable. At this snapshot during heating, the displacement is caused only by thermal expansion of the material. For most furnace heating processes, the thermal stress in the part is below the material's yield, and the deformation in the part is elastic without the phase transformation. It is expected that the part ends up with a perfect shape with isotropic thermal expansion only at the end of the heating step when the part reaches the equilibrium temperature if there is no austenitizing transformation involved. With the phase transformation to austenite, the material is in the plastic deformation field due to TRIP effect, and both thermal stress and stresses caused by phase transformation strain will lead to plastic strain, which contributes to the distortion. As shown in Figure 4(b), the shrinkage of the bottom wall generates plastic strain in its connection region to the middle wall, which leads to distortion at the end of heating.



(a)



(b)

Figure 4: Simulated temperature, austenite, and radial displacement profiles during straight heating. (a) Right before austenitizing, and (b) forming partial austenite at the thin-walled section.

The time-temperature history of the two points (Point-A and Point-B in Figure 2) are plotted for the straight heating process, as shown in Figure 5. With a furnace heating, the austenitizing temperature range is about 100° C, with A_{C1} and A_{C3} being ~750° C and ~850° C, respectively. The temperature difference between Point-A and Point-B is over 130° C while austenitizing transformation is happening during the straight heating process.

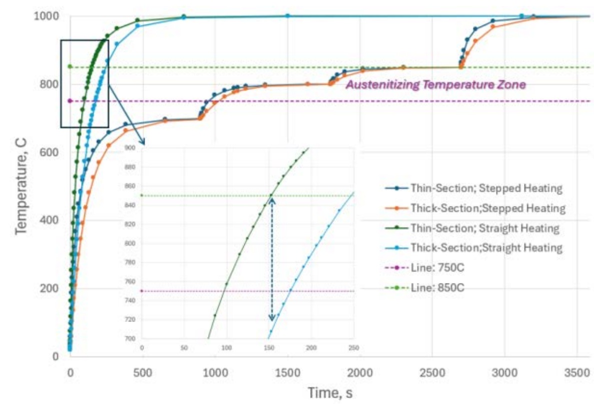
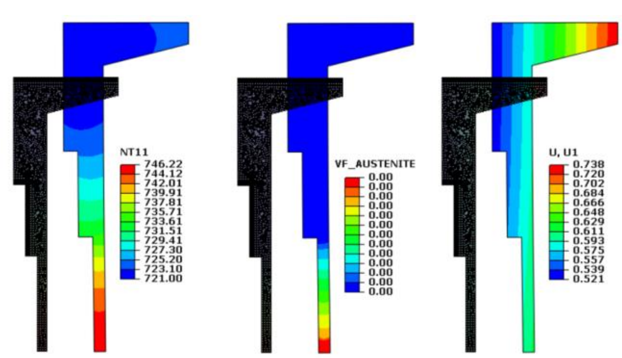
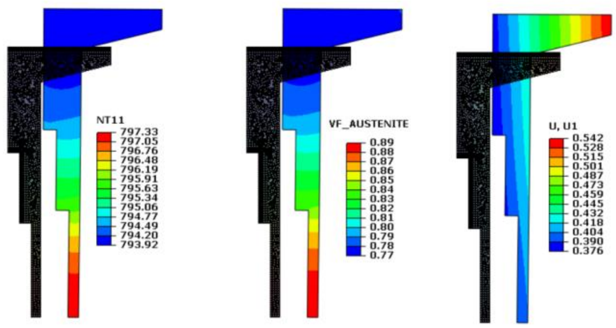


Figure 5: Simulated time-temperature histories of straight heating and stepped heating process.

To reduce distortion caused by the austenitizing process, a stepped heating process is recommended. Most stepped heating processes will heat the part to ~650° C, soaking for a certain amount of time according to the part size, then heat to the final target temperature directly. The temperature uniformity while the part is going through the austenitizing transformation is more uniform than that of the straight heating process. However, for the challenging part geometry in Figure 1, the modeling results show the normal stepped heating described above is insufficient to reduce the distortion effectively from the austenitizing process. An improved stepped heating process is proposed: 1) Heat to 700° C, and soak for enough time for the temperature to reach its equilibrium, 2) heat to 800° C, and soak for equilibrium, 3) heating to 850C, and soak for equilibrium, and 3) heat up 1000° C. The simulated time-temperature histories of Point-A and Point-B are shown in Figure 5, with a much more reduced temperature difference between the two points during the austenitizing transformation. Figure 6 shows simulated contours of temperature, austenite fraction, and radial displacement at the end of the 700° C and 800° C heating steps.



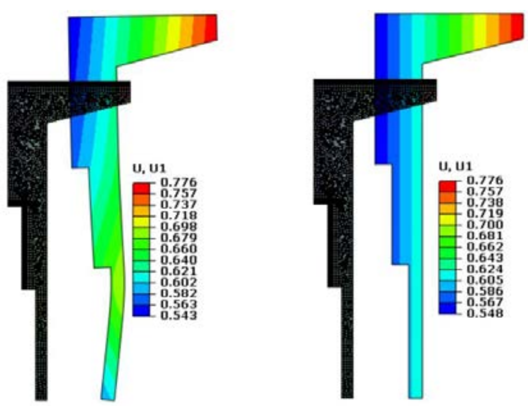
(a)



(b)

Figure 6: Simulated temperature, austenite, and radial displacement profiles during stepped heating. (a) Right before austenitizing, and (b) forming partial austenite at both the thin-walled and thick wall sections.

Figure 7 compares the simulated distortions at the end of the straight heating and the proposed stepped heating processes. With the straight heating, the wall OD is bent, as shown in Figure 7(a), compared to a straight wall using the stepped heating process, as shown in Figure 7(b). The displacement in Figure 7(a) is a combination of thermal expansion and volume change caused by phase transformation to austenite. The amount of plastic deformation using the stepped heating process is ignorable.

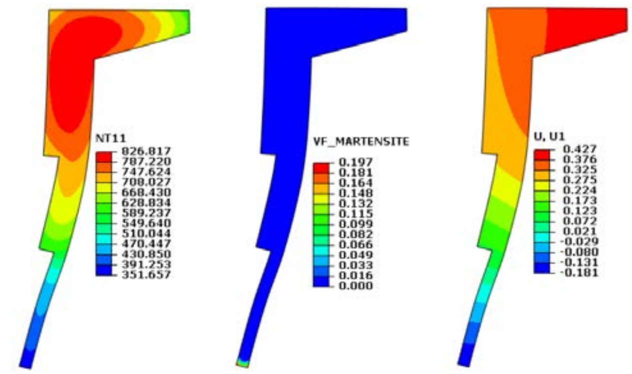


(a) *(b)*

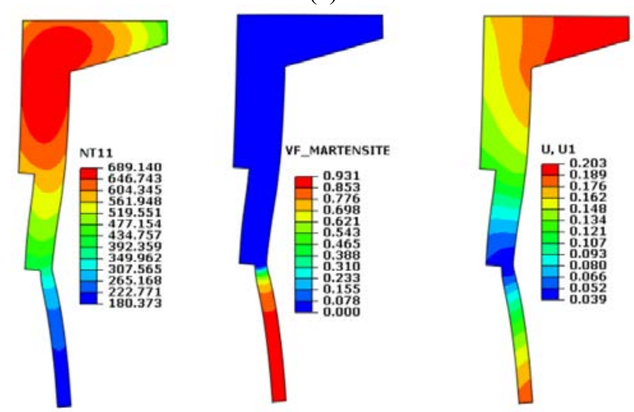
Figure 7: Simulated part radial displacement contours at the end of austenitizing process. (a) straight heating, and (b) stepped heating.

Effect of Quenching Process on Distortion

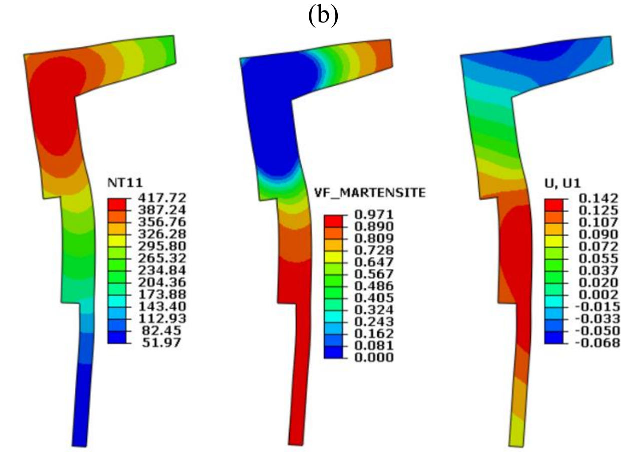
After austenitizing, the thin-walled gear blank is high pressure gas quenched (HPGQ) using an 8-bar nitrogen to room temperature. In this section, the gear blank is not carburized. The heat treatment model uses the stepped heating process described in the last section, and the shape distortion caused by heating and austenitizing is negligible. The contours of simulated temperature, martensite volume fraction, and radial displacement at four different time snapshots during quenching are shown in Figure 8. Figure 8(a) shows the results when martensitic transformation at the bottom wall is about to start. The temperature difference in the part is significant, and the gear wall is tapered about 0.45 mm radially. The thermal stress is high enough to cause plastic strain in the part, mainly concentrating in the connection region between the bottom and middle wall. With further quenching, a significant amount of martensite is obtained at the bottom wall, while the middle wall temperature is still above martensite start temperature (*Ms*), as shown in Figure 8(b). The volume expansion of the bottom wall at this time snapshot causes a reversed bending and plastic deformation in the connection region between the bottom wall and middle wall. Figure 8(c) and 8(d) show simulated results when the middle wall and the top wall martensitic transformations are about to complete, respectively. The nonuniformity of the martensitic phase transformation is the main cause of distortion during the quenching process.



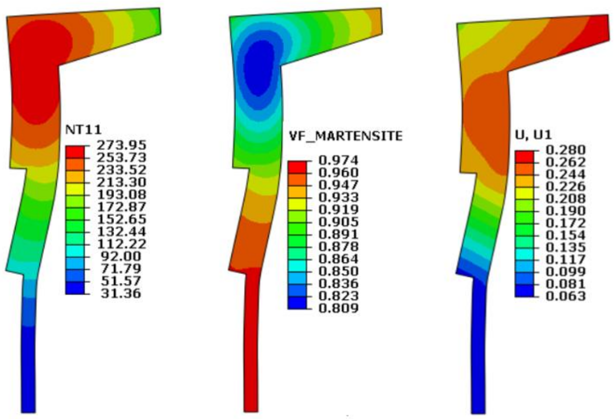
(a)



(b)



(c)



(d)

Figure 8: Simulated temperature, austenite, and radial displacement profiles during HPGQ quenching with pearlite as initial phase, and no carburizing. (a) Right before forming martensite, (b) forming martensite at the bottom (thin) wall section, (c) forming martensite at the mid wall section, and (d) forming martensite at the top (thick) wall section.

Figure 9 plots the time-temperature histories of Point-A and Point B from the simulated HPGQ results. The martensite transformation temperature zone is from ~375° C to ~200° C, while the temperature difference between Point-A and Point-B is over 200° C during the martensitic phase transformation zone. The thermal stress generated during this HPGQ exceeds the yield of austenite, which leads to plastic strain and distortion. However, the nonuniform martensitic phase transformation is still the main cause of the quenching distortion. A patented process, DANTE Controlled Gas Quench (DCGQ), is proposed to minimize the quench distortion for this high alloy steel gear blank (ref 5). To reduce the magnitude of thermal stress, the gear blank is cooled from 1000° C to 800° C before further quenching. During the DCGQ process, the ambient gas temperature is controlled following a preset time-temperature recipe. As shown in Figure 9, the temperature difference between Point-A and Point-B during the martensitic transformation range is minimized.

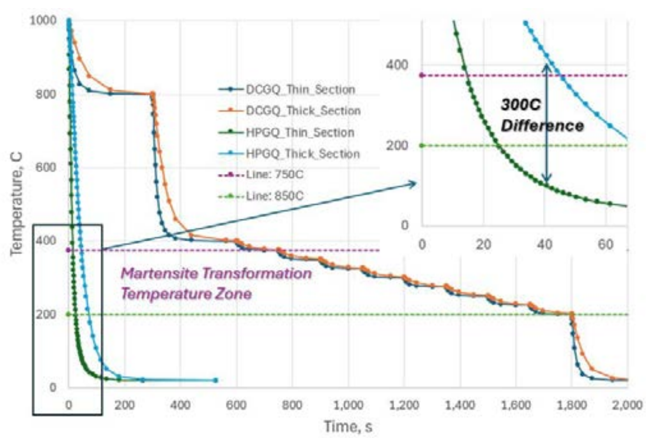
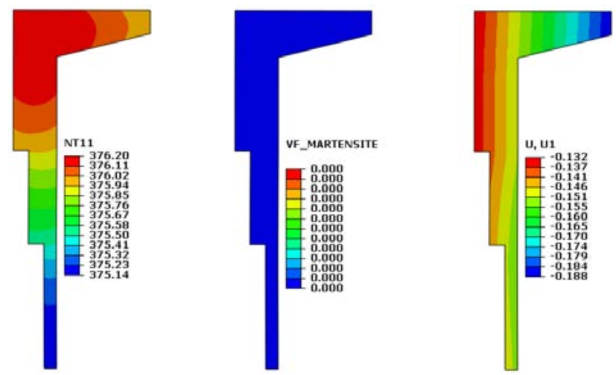
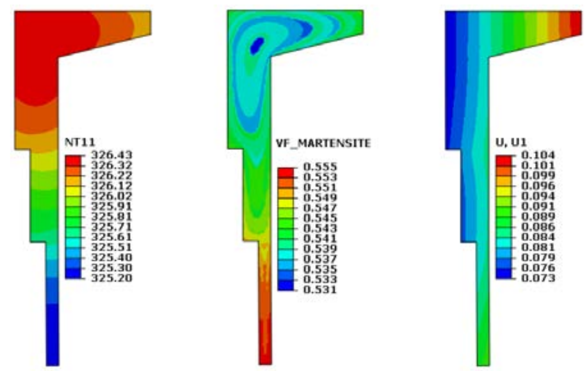


Figure 9: Simulated time-temperature histories of HPGQ process and DCGQ process.

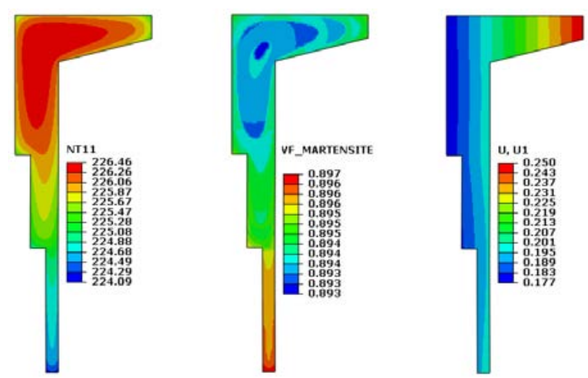
When the part is cooled to about 375° C, as shown in Figure 10(a), the temperature difference in the part is less than 1.5° C, and the radial displacement relatively uniform (linear to its radial position). With further cooling to ~325° C, the volume fraction of martensite obtained is about 55%, with less than 2% of difference in the part section, as shown in Figure 10(b). When the part cools down to 225° C, about 90% martensite is obtained, the wall OD has about 0.2 mm radial displacement.



(a)



(b)

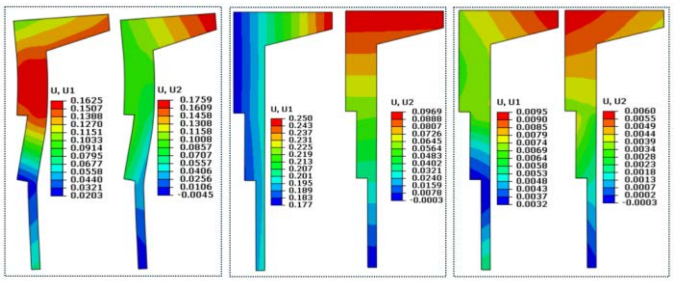


(c)

Figure 10: Simulated temperature, austenite, and radial displacement profiles during DCGQ quenching with pearlite as initial phase and no carburizing. (a) Right before forming martensite, (b) forming about 55% martensite uniformly through the cross-section, and (c) forming about 90% martensite uniformly through the cross-section.

The distortion can be classified as shape change and size change (ref 6). Shape change is caused by the plastic strain from thermal stress and nonuniform phase transformations. The size change is caused by the volume or density difference between the starting phase and the end phase, and the material volume expansion by adding carbon or nitrogen to the matrix.

The HPGQ and DCGQ models described above assume the initial phase is pearlite, and their final distortions using the stepped heating process are shown in Figure 11 (a) and 11(b), respectively. The HPGQ process generates large and ununiform distortions (both shape change and size change) in both the radial and axial directions. The DCGQ process generates uniform distortions (mainly size change) in the radial and axial directions. While more uniform radial displacement with the DCGQ process using pearlite as the initial phase, the magnitude of the radial distortion (mainly size distortion) is still large. Figure 11(c) assumes the initial phase is martensite, and the modeling results of DCGQ process show negligible radial and axial distortions.



(a) (b) (c)

Figure 11: Comparison of simulated distortion profiles with stepped heating process and no carburizing. (a) Direct HPGQ quench with pearlite as initial phase, (b) DCGQ quench with pearlite as initial phase, and (c) DCGQ quench with martensite as initial phase.

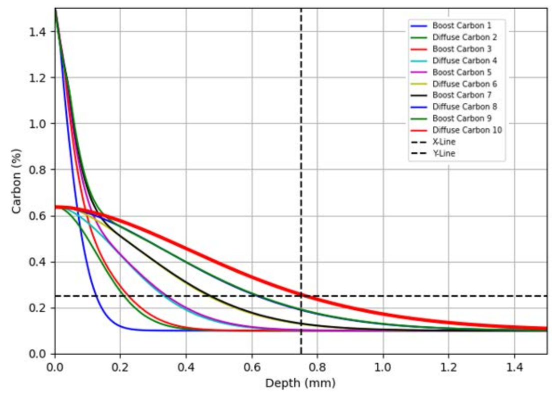
LPC Process Design and Its Effect on Distortion

The models described in the last section assume that the gear blank is uncarburized. Carburization has two major effects on distortion: 1) material volume expansion by diffusing and dissolving carbon atoms into the austenite matrix, and 2) the carbon effect on the change of austenite decomposing during quenching. DANTE material models have accounted for both effects. The second effect is more significant in most cases, especially if a selective carburization is used with unbalanced carburizing surfaces. For this specific gear blank, the top surface and the middle of the inner surface are selectively carburized, as described in Figure 2. DANTE VCarb is used to design the LPC schedule for ~0.75 mm effective case depth (ECD), and the schedule is shown in Table 2.

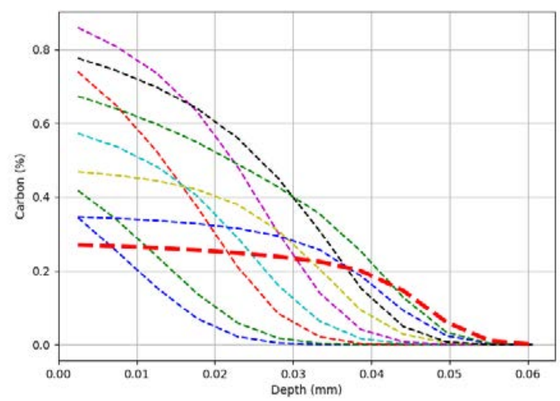
Table 2: LPC recipe designed by using DANTE VCarb tool.

Step Number	*Boost/Diffuse*	*Time, s*
1	*Boost*	*75.0*
2	*Diffuse*	*155.0*
3	*Boost*	*45.0*
4	*Diffuse*	*360.0*
5	*Boost*	*45.0*
6	*Diffuse*	*660.0*
7	*Boost*	*45.0*
8	*Diffuse*	*1050.0*
9	*Boost*	*45.0*
10	*Diffuse*	*1400.0*

Figure 12(a) shows the predicted carbon profile in terms of depth after each boost and diffuse step, and the final carbon profile is shown as the heavy red curve. The predicted ECD is 0.75 mm, with about 0.25% carbon. Figure 12(b) shows the simulated primary carbide profile in terms of depth after each boost and diffuse step, and the depth of the primary carbide is about 0.050 mm.



(a)



(b)

Figure 12: Predicted (a) carbon, and (b) carbide distribution profiles after each LPC boost/diffuse step.

The carbon distribution contour at the end of carburizing is shown in Figure 13, and the predicted surface carbon is about 0.65%.

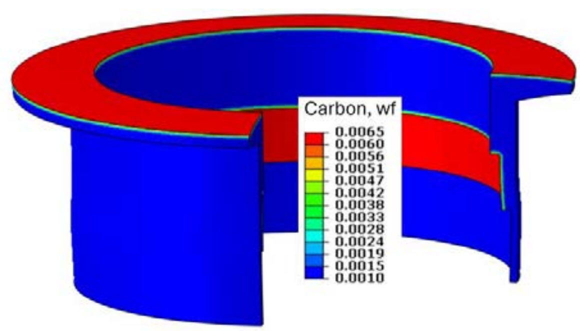


Figure 13: Simulated carbon distribution profile of the ring gear blank with selectively carburized surfaces.

Using the stepped heating and DCGQ process as described in the previous section, the temperature, martensite transformation and the radial displacement at different times during quenching are shown in Figure 14. Before martensite transformation starts, the radial displacement is uniform with size distortion only, as shown in Figure 14(a). When martensite transformation starts, the carburized areas have a delayed transformation even if the temperature is uniform, as shown in Figure 14(b). After the part is cooled to room temperature, the radial displacement of the OD wall is about 0.025 mm radially. To reduce the effect of carburized case on distortion, the part should be designed with more balanced carburizing surfaces.

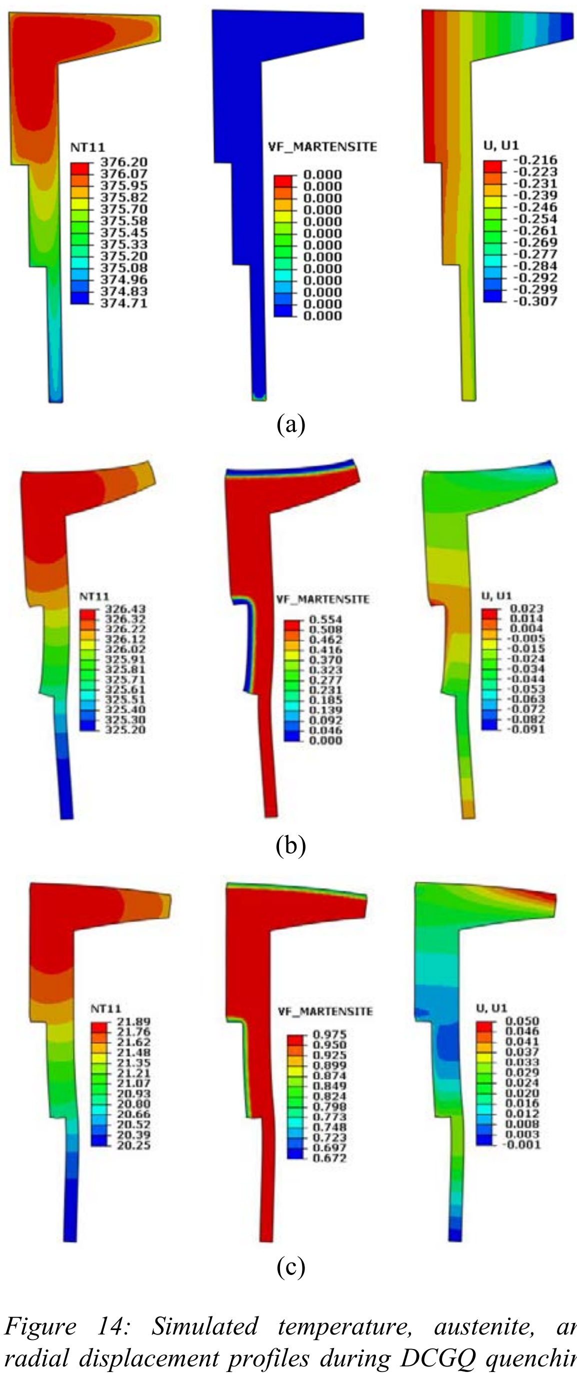


Figure 14: Simulated temperature, austenite, and radial displacement profiles during DCGQ quenching including a carburizing process and martensite as the initial phase. (a) Right before forming martensite, (b) forming about 55% martensite uniformly through the cross-section, and (c) forming about 90% martensite uniformly through the cross-section.

Conclusions

Using a thin-walled gear blank as an example, the effects of heating, quenching and carburizing process steps on distortion are analyzed using computer modeling. The simulation results show that stepped heating can be used to reduce the distortion caused by nonuniform austenitizing transformation, DCGQ can be used to minimize the distortion caused by the quenching process for high thermal resistance steels, and balanced carburizing surfaces should be designed to avoid the ununiform martensite transformation due to the carbon gradient.

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