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Typical Heat Treatment Defects of Gears and Solutions Using FEA Modeling

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Steel gears are heat treated to obtain enhanced properties and improved service performance. Quench hardening is one of the most important heat treatment processes used to increase the strength and hardness of steel parts. Defects seen in quenched parts are often due to high thermal and phase transformation stresses. Typical defects include excessive distortion, surface decarburization, quench cracks, large grain growth, and unfavorable residual stresses. Gear geometries with large section differences may suffer high stress concentrations and crack during quenching. Surface decarburization before quenching may lead to high surface residual tension and possible post heat treatment cracking. In this paper, the commercial heat treatment software DANTE is used to investigate three examples of heat treatment defects. Improved processes are suggested with the help of modeling. The first example is an oil quench process for a large gear. Peeling cracks were observed on the gear surface during grinding of the quench hardened gears. Computer modeling showed that surface decarburization was the cause. The second example is a press quench of a large face gear. Unexpected large axial bow distortion was observed in quenched gears, and computer modeling indicated that an incorrect press load and die setup were the reasons. The third example is an in-process quenching crack caused by high concentrated tensile stress from unbalanced temperature and phase transformations in a spiral bevel pinion gear. The quenching process was modified to solve the problem. This example also emphasizes the need for heat treatment modeling in gear design to reduce the possibility of heat treatment defects. The three examples illustrate how to effectively use heat treatment modeling to improve the quality of the gear products.

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Introduction

During heat treatment of steel gears, thermal gradient, phase transformation, and the resultant internal stress interact with each other to contribute to distortion and residual stress in the quench hardened parts. Both distortion and internal stress during quenching are complicated and not intuitively understandable in most cases, which make process troubleshooting and improvement difficult. To reduce the machining cost after heat treatment, minimum distortion is preferred. Minimum distortion can be obtained by tuning up the heat treatment process parameters, such as heating and cooling rates, and carburization schedules, etc., although such tune ups are usually costly and time consuming. The increasing demand of gear performance requires the designer to take advantage of the favorable residual stresses obtained from carburized and quenching processes. To achieve these goals, computer modeling is being more widely used in the heat treat industry to optimize the heat treatment process [1-3]. DANTE is a commercialized heat treatment software based on the finite element method [4]. It can be used to predict the phase transformations, deformation, residual stresses, hardness, and distortion for heating, carburization, cooling, and tempering processes.

Surface decarburization affects the surface hardness achieved by the quenching process. Many heat treaters believe that the decarburized layer can be ground off to regain higher surface hardness and the effect of decarburization is totally eliminated. Decarburization also affects the surface residual stresses [5]. Favorable residual compression is expected on the surface of steel parts from carburization and quenching processes. Decarburization can shift the surface stress from compression to tension, and the effect on the depth of tensile stress is normally deeper than the depth of the decarburized layer. A grinding process may not be able to effectively remove the surface tension and regain favorable residual compression. Computer modeling can be used to understand the relationship between the depth of decarburized layer and its effect on residual stresses.

A press quench is often used to reduce the distortion of gears larger than eight inches in diameter. The press quench is more complicated than the traditional oil quench, and distortion can be affected significantly by the selection of the quench press, die geometry and quench channel design, and the process setup.

Excessive distortion and quench cracks are often seen in gears with large section differences. Nonuniform phase transformation between thin and thick sections can lead to stress concentration in a gear during the quenching process, and excessive stress can crack the part at the worst, or distort the part at the least. The quenching process can be modified to reduce the possibility of cracking or to control size and shape change.

Quenching is a highly nonlinear process due to phase transformations and plastic deformation. Effective computer modeling is required to understand the part response during quenching before solutions to problems can be obtained [6]. A gear can rarely be designed with perfectly uniform section, so knowledge of the effects of gear geometry on potential heat treatment defects is critical for the gear designer. Heat treatment models can be used in the gear design process to reduce cost, improve quality, as well as shorten the design cycle.

Effect of decarburization on residual stresses

A ring gear made of AISI 4320 was carburized, quench hardened, tempered at a relatively low temperature, and then finished by a grinding process. Peeling cracks on the tooth face were observed during the grinding of the hardened gears. The axial height of the ring gear is 650 mm, the inner diameter is 950 mm, the tip diameter is 1300 mm, the root diameter is 1210 mm, and the gear has 60 outer straight teeth. Because of the gear geometry and the observed cracking mode, a plane strain FEA model of a single tooth with cyclic boundary

conditions was created to investigate the causes of cracking. Figure 1 shows a CAD model of this ring gear and the finite element model created for heat treatment simulations. To model the decarburization effect, very fine elements are required in the shallow surface to ascertain the carbon, temperature, phase, and stress gradients during quenching. Point A in Figure 1 is located right on the tooth surface, and point B is located at a 6 mm normal depth from the surface. The material response along the straight line AB is used to investigate the effect of decarburization. The gear face from tip to root cools at different rates during quenching. Contour plots of carbon, temperature, metallurgical phases, and stresses are used to understand the part response. Modeling results indicate that the grinding cracks are caused by high residual tensile stresses in the tooth surface due to decarburization.

The carburization temperature was 950° C, and a boost/diffuse process was used to expedite the carbon diffusion rate. The boost step was 35 hours with a 1.0% carbon potential, and the diffuse step was 15 hours with a 0.85% carbon potential. At the end of the carburization process, the predicted carbon distribution is shown by the curve with solid markers in Figure 2a. At high temperature when the gear is entirely austenite, its surface may decarburize in an atmosphere containing oxygen. An oxidizing atmosphere can be found in a poorly maintained furnace. During the transfer from furnace to quench tank, gears are exposed to air. For large parts, the transfer time in air is usually longer than for small parts, which makes the decarburization effect more significant due to the reaction time between the oxygen and surface carbon. The transfer time from furnace to the quench tank is 2 minutes. However, an oxygen atmosphere in the furnace can cause surface decarburization. In this study, it is assumed that the ring gear is exposed to an oxygen atmosphere for 10 minutes before being quenched, which is a combined effect of furnace atmosphere and air transfer. The surface carbon is assumed to drop to 0.4% due to the carbon-oxygen reaction. The carbon distribution within the decarburization zone is shown by the curve with hollow diamond markers in Figure 2a. The depth of decarburized layer is about 0.10 mm using 0.65%C as the initial threshold. Without decarburization, the predicted axial and tangential stresses after quenching are 160 MPa and 350 MPa in compression, respectively. With decarburization, the axial and tangential surface stresses are 400 MPa and 250MPa in tension. The change in axial residual surface stress due to decarburization is 560MPa. The tensile stresses will contribute to the cracking probability during the grinding process.

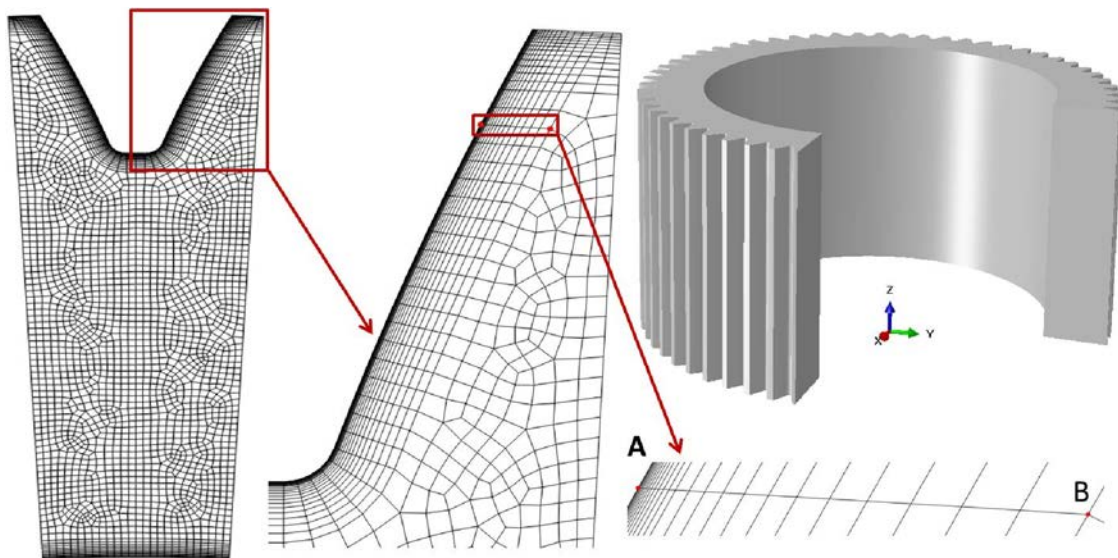


Figure 1. Gear geometry and finite element model

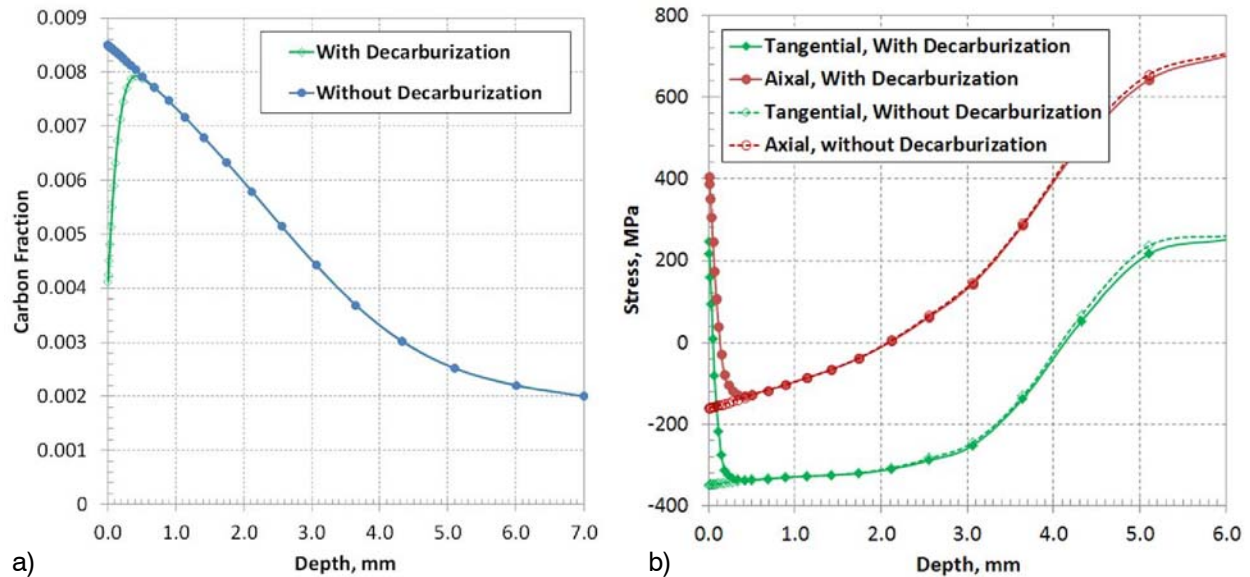


Figure 2. a) Carbon and b) residual stress distribution after quench

During quenching, both the thermal gradient and phase transformations contribute to the stress evolution in the part. Contours of carbon profile and martensite distribution after quenching are shown in Figure 3. The carburized case contains mainly martensite with about 10% retained austenite in the as-quenched condition. The retained austenite will transform to bainite during tempering process. The depth of the hardened case increases from the root to tip along the tooth face due higher cooling toward the tooth tip and the deeper martensite distribution. The gear body microstructure is about 90% bainite and 10% martensite.

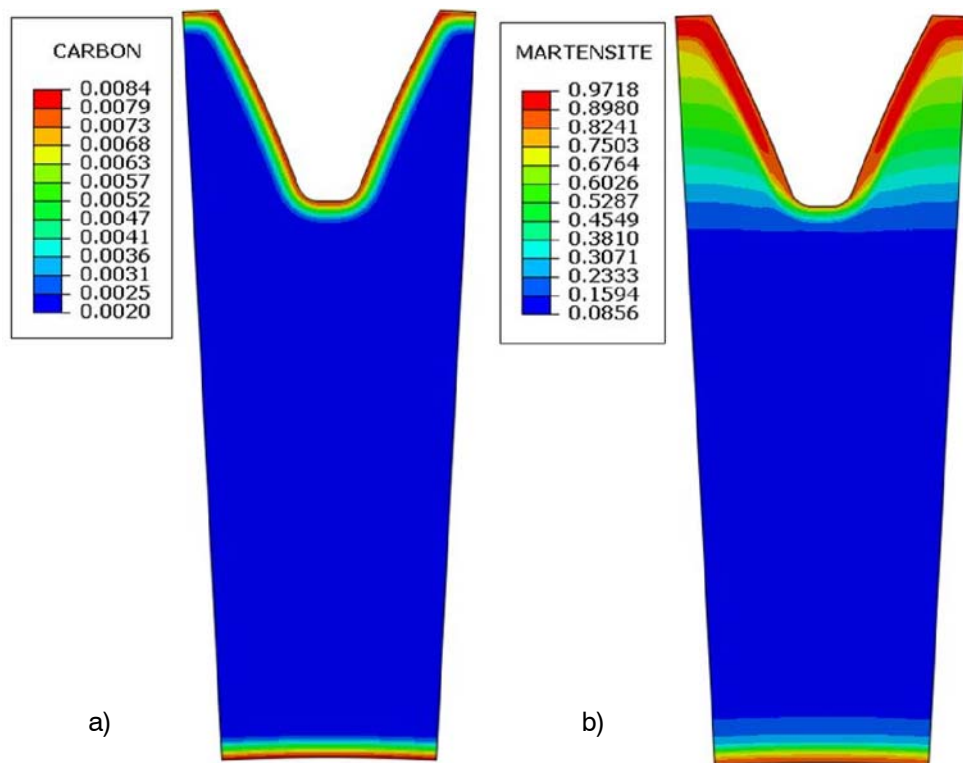


Figure 3. a) Carbon distribution, and b) martensite distribution at the end of quenching