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Excessive distortion can be a problem during heat treatment of parts. Modeling can help understand the factors that contribute to part distortion.

Bending under pressure: Controlling distortion

Distortion from heat treatment is a main concern because heat treatment is often one of the last steps in the manufacturing process. Excessive distortion can ruin hours of work on parts that are machined and hardened. Reworking the parts may be challenging, and scrapping the parts leads to lost revenue. In 1995, the German Research Association of Drive Engineering estimated annual losses of ~850M Euros to remove distortion from manufacturing [1]. Around the same time DANTE, a heat-treatment process modeling tool, was born from a project with the American automotive industry, academia, and the national labs, to combat distortion in excess of hundreds of millions of dollars annually.

All distortion from heat treatment can be broken down into two categories: shape change and size change. Size-change distortion is caused by the reorientation of the crystal structure as the steel changes phase and is unavoidable. Shape change is the difference in part dimensions before and after hardening, assuming no volume change. Shape and size change is caused by material, geometry, and process effects. Material effects refer to the initial state of the steel, including the microstructure phases, chemical composition, carbide phases and sizes, alloy segregation, grain size, and the effects from the material fabrication process. Part geometry affects distortion due to differences in heating and cooling between thick and thin sections, causing material strain. Process uniformity and consistency directly affect part distortion during heating and cooling due to the accompanying phase transformations. Chemical gradients of carbon and nitrogen play a role in nonuniform phase transformations due to their effect on martensite start temperature. The volume change from tempering martensite can have a similar effect if the thermal gradient is high. Process consistency and residual stresses from previous processes also impact process distortion.

To accurately model the distortion from heat treatment, the model must include thermomechanical and phase transformation behavior. A multi-phase plasticity model captures the stress and deformation during the phase transformations and must include the mechanical properties over a wide range of parameters such as carbon level and temperature. Understanding the equipment behavior and the equipment/part interaction in the form of heat transfer coefficients is needed to accurately describe the heat transfer, and temperature gradients, within the part. Heat-treat process modeling can show the root causes of part distortion and potential measures that can be taken to reduce it.

CASE STUDY

A Ferrium C64 bevel gear was selected for a modeling case as it is known to have difficulty in controlling the taper distortion in the teeth during heat treatment. All exposed surfaces are carburized using a low-pressure carburization process, typical of aerospace heat-treatment methods for these types of gears. Since taper distortion is the main modeling objective, the gear geometry can be simplified by modeling only a single tooth to reduce computational costs. A finite-element mesh consisting of nodes and elements is created to simulate the car-

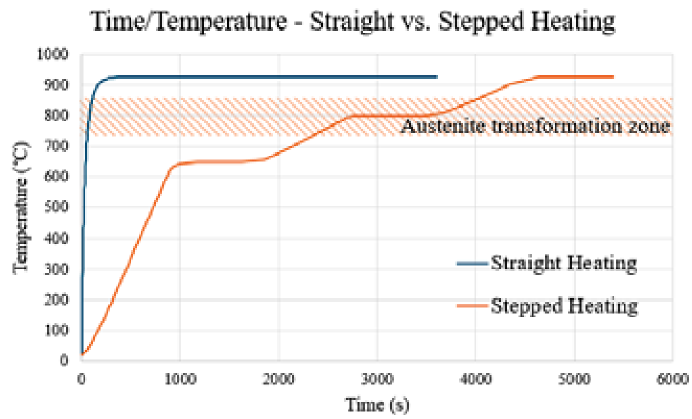

Figure 1: Time/Temperature plots for straight heating and stepped heating models.

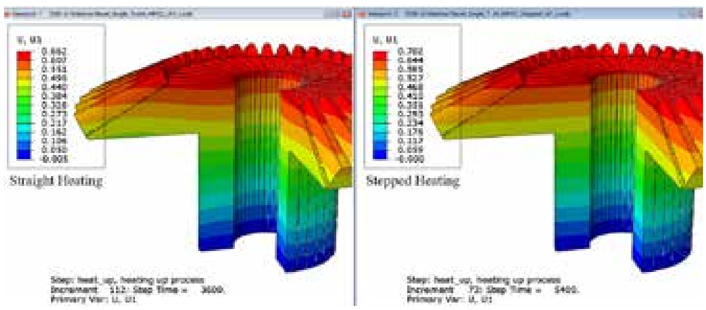

Figure 2: Axial distortion contours for the straight heating and stepped heating models.

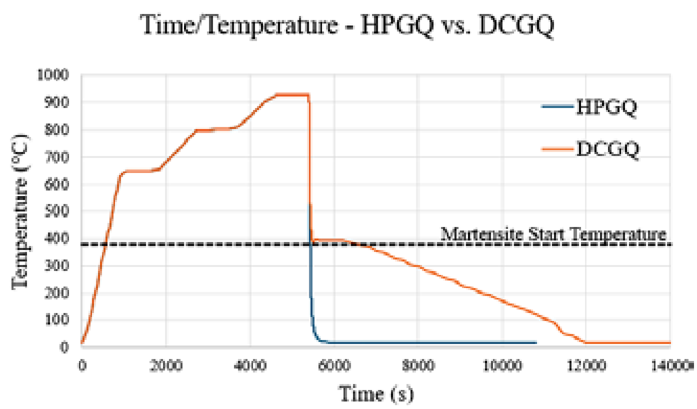

Figure 3: Time/Temperature plots for the HPGQ and DCGQ models.

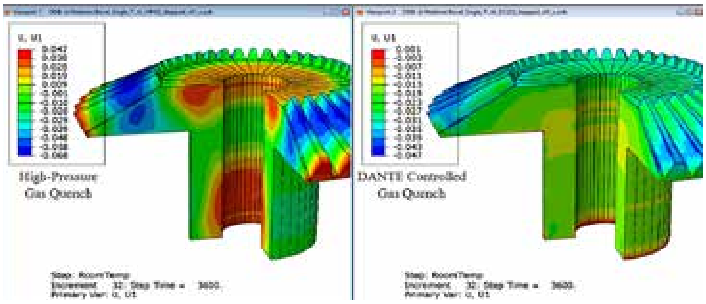

Figure 4: Axial distortion contours for the HPGQ and DCGQ models.

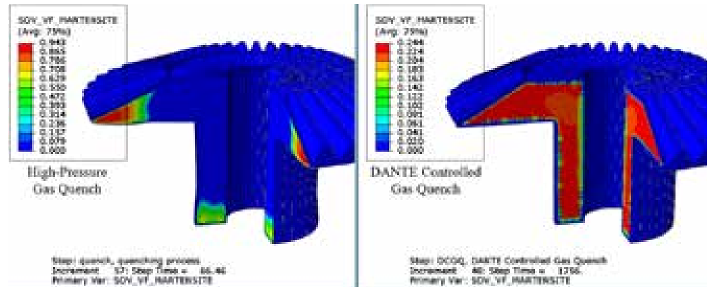

Figure 5: In-process martensite contours for HPGQ and DCGQ processes.

bon, thermal, phase transformation, and stress gradients developed within the part. Additional model assumptions include martensite as the initial phase and a uniform heat-transfer coefficient applied to the outer surfaces for simulating the heating and quenching processes. The study starts with a furnace heating model to predict distortion during heating. Two models were developed, with a straight-furnace heating and a stepped heating to compare the distortion from heating alone. The time/temperature history of a surface point, or node, from each of the models is shown in Figure 1. The straight heating model assumes the part is placed into a furnace preheated to 912°C. The stepped heating model assumes the part is heated to 650°C and is allowed to reach thermal equilibrium. The furnace is then heated to 800°C and held for another 15 minutes until finally heating to the 912°C holding temperature. The temperature holds help control the thermal gradient in the part before and during the transformation to austenite ensuring the phase transformation happens more uniformly throughout the part.

This case study reinforces the need to understand the factors that contribute to part distortion, such as part geometry, thermal uniformity, material condition, surface chemistry, and phase transformations.

The results of the two heating models are shown in Figure 2. The contours show axial distortion, to capture the tooth-taper mode, and both models are at the end of heating while the part is uniformly at 912°C. At first glance, the stepped heating model, right, shows a slightly higher magnitude of axial distortion. However, each of the color divisions in the contour are almost perfectly horizontal, showing a uniform expansion from heating in the axial direction. In contrast, the straight heating contour, left, has a "wavier" appearance to the color divisions in the contour, showing non-uniform distortion from heating compared to the stepped heating model.

Following heating, two quench methods are modeled, one with a standard high-pressure gas quench (HPGQ) process and another with a DANTE Controlled Gas Quench (DCGQ) process. The DCGQ process is determined by modeling the quench with a hold just before the martensite transformation to achieve thermal equilibrium, and a design requirement of no greater than 10°C temperature gradient in the part during the martensite transformation. For the DCGQ process, the ambient temperature is controlled to maintain the thermal equilibrium in the part with a series of temperature holding steps. The time temperature plots for the surface node during the two quench models in Figure 3 illustrate the difference in quenching methods. Due to the complexity of the part geometry and the tight temperature gradient requirement, the quench holding steps appear to ramp the temperature down.

Figure 4 shows the stark contrast in axial distortion between the HPGQ and DCGQ models. The HPGQ model shows that the tip of the tooth curls up while the middle of the tooth dips down, contributing to an overall curl of about 115 µm. The bore of the gear also shows some nonuniform axial distortion. The DCGQ model shows an overall shrinkage in the part with the tooth tapering down about 47 µm near the tip. Because of the controlled heating and quenching, the distortion from the DCGQ process is more uniform than from the HPGQ process. If corrective machining were needed to bring the parts within spec, the HPGQ processed gear may need to remove material from the case nonuniformly, reducing the effectiveness of the case-hardening process.

The mechanism behind the increased distortion shown in the HPGQ model can be seen in the in-process martensite contours, Figure 5. When martensite begins to form in the HPGQ model, a large thermal gradient is present in the part. This gradient causes the martensite to form first in the thinner cross sections of the part, such as the tips of the gear teeth, where the cooling is fastest. The temperature is low enough to have a nearly complete martensite transformation, and the associated volume expansion bends the tip of the tooth upwards, causing the taper shown in the final distortion contour. The DCGQ model specifically aims to keep the thermal gradient to a minimum during the martensite transformation, so the transformation occurs more uniformly through the core of the gear, as shown in the right contour in Figure 5.

This case study reinforces the need to understand the factors that contribute to part distortion, such as part geometry, thermal uniformity, material condition, surface chemistry, and phase transformations. Minimizing the thermal gradient within a part during phase change can reduce the nonuniform size and shape change leading to more uniform, or even reduced, distortion. The DCGQ method presented here is particularly suited for high-hardenability steels in which the holding steps during quench can reduce the part thermal gradient while still forming the desirable martensite phase. In applications where tolerances are tight, such as aerospace components, the distortion from heating should also be considered. Heat-treat process modeling can help to gain a better understanding of what is going on behind the black box of heat treatment to get to the root causes of distortion.

REFERENCES:

[1] [1] Zoch, Hans-Werner & Lübben, Thomas. (2012). Distortion Engineering - A New Concept to Control Distortion Problems.

ABOUT THE AUTHOR

Jason Meyer joined DANTE Solutions full time in May 2021 after receiving his Master's degree in mechanical engineering from Cleveland State University. His main responsibilities include marketing efforts, project work, and support and training services for the DANTE software package and the DANTE utility tools. Contact him at jason.meyer@dante-solutions.com.