USING SIMULATION TO EVALUATE PART GREEN SHAPE TO REDUCE DISTORTION DURING PLUG QUENCHING
The commercially available heat-treatment simulation software, DANTE, has been used successfully to improve heat-treat processes and steel-part characteristics; this case study follows an example of applying the software to evaluate a real-world challenge.

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Determining the heat-treatment geometry (green shape) for complex gears is not a trivial task. Mass distribution becomes critical in determining the uniformity of heat removal, and subsequently, the uniformity of solid-state phase transformations. The uniformity of transformation directly affects the distortion after quenching. For decades, distortion control during heat treating has been based on experience. However, simulation of complex processes and geometries is now feasible due to improved material models, improved computational power, and the reduced cost of computer hardware [1]. Heat-treatment processes are no longer black boxes but become transparent and pliable with the use of heat-treatment software.

The commercially available heat-treatment simulation software, DANTE, has been used successfully to improve heat-treat processes and steel-part characteristics [1-3]. The following is an example of applying DANTE to evaluate a real-world challenge. Several green shapes are explored in an effort to reduce distortion of a complex gear shape that is quenched in oil using a plug. The ability to simulate the effects of quenching on the gear shape quickly, cheaply, and accurately cannot be overstated. The time and cost to perform physical trials on various gear shapes would be a daunting task. Simulation can help guide the physical trials, substantially reducing the total number.

HEAT-TREATMENT PROCESS MODELING

Accurately 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 commercially available heat-treatment simulation software DANTE accounts for all of these phenomena [4]. These models, resident in DANTE, exist as libraries that link with commercial finite element packages ANSYS Mechanical or ABAQUS/STANDARD. Necessary process data, defined as heat-transfer coefficients as functions of part-surface temperature, are contained in supplied databases to describe the heating and cooling processes. The effects of the oil-fill rate also can be considered, as they are here.

COMPONENT GEOMETRY

An internal gear with a spline and a smooth outer diameter was suffering from excessive radial growth and bow distortion of the spline during a plug quenching operation. A redesign of the green shape was proposed. DANTE heat-treatment simulation software was used to evaluate several different green shapes and how the green shape affects the distortion modes and magnitudes of the spline. The gear was simplified for this initial study by replacing the spline and teeth with an equivalent thermal mass, as shown in Figure 1. This allowed the model to be reduced to 2D axisymmetric for quicker computation times and the evaluation of many geometric changes in a short period of time. A 3D model would be needed to validate the 2D results, but it is not discussed here. The component has a 37 mm OD, 5.7 mm wall thickness, and 90 mm height. The wall thickness at the spline and gear teeth is 8.7 mm. There is also a flange at one end that adds to the difficulty in controlling the distortion during quenching. The component is made from AISI 9310.

The four main geometries evaluated and discussed in this article are shown in Figure 2. From left to right:

- The original geometry described in Figure 1.
- A geometry with 2 mm added to the entire outer diameter, increasing the total mass to reduce the overall cooling rate.
- A geometry with 2 mm added to the outer diam-
A geometry that removed material near the spline, making the cross-section more uniform throughout the part.

These geometry modifications were for the initial trial and should not be considered optimized for each case. Once a geometry proves better than the current green shape, further optimization can be performed. This optimization was not considered in this study.

HEAT TREAT PROCESS CONDITIONS

Selective carburization was performed on the spline only and was the same for each geometry modification, as shown in Figure 3. The component has a surface carbon value of 0.86 percent and an effective case depth of 0.4 mm.

The quenching process consists of several steps, as shown in Table 1. All steps were modeled and consist of:

- Austenitize at 830°C for 1 hour.
- Transfer from the heating furnace to the quench vessel in 7 seconds.
- Immerse the part into the 55°C oil.
- Hold for 1 sec before oil flow begins.
- Flow the oil to quench the component.
- Cool to room temperature after removing the part from the oil.

The 400°C transfer temperature is due to the close proximity of the hot-fixture mass, which acts to substantially heat the air around the part during transfer. It should be noted that during the immersion and hold processes, the plug blocks oil from contacting the spline and traveling past it up the bore. This has an impact on the temperature profile when the quenching starts, and hence, the transformation timings.

Figure 4 shows contour plots of temperature in Celsius at the end of each step in the process: heating, transfer, immersion, quench hold, quench, and cool to room temperature. Of particular note, the temperature at the tip of the flange after the transfer from the furnace to the quench vessel has dropped below 800°C. After the 1-second hold, the tip of the flange has dropped below 400°C, while the spline is still more than 800°C. The martensite start temperature for 9310 is approximately 425°C. Martensite has started to form in the flange before the oil flow even begins. Once the oil flow is initiated, the oil is able to flow between the component and the plug.

GREEN SHAPE SENSITIVITY ANALYSIS

The bow distortion and radial growth of the spline were the main concerns, with the radial growth taking precedent due to the component not mating to other parts properly without too much finish machining. Understanding where these distortions came from and the sensitivity of the geometry to the quenching conditions were the main goals of these models. Figure 5 shows a plot of the radial displacement of the spline for the four geometries. A radial displacement of zero is the original green-shape dimension. Positive displacement is growth, and negative displacement is shrinkage. Figure 5 shows that all four geometries experience radial growth. Figure 6
shows contour plots of the radial displacement for the four geometries. The lower limit of the contours is set at 0.040 mm, and the upper limit is set at 0.090 mm for all geometries to better illustrate the differences between them.

Figure 5 shows that adding additional material to the outer diameter can significantly reduce the overall growth of the spline while maintaining approximately the same bow distortion. Removing material, as is the case with the scallop geometry, made the radial growth and the bow distortion worse than the original geometry. Thanks to the DANTE model, the causes leading to these outcomes can be ascertained. The radial growth differences will be examined first.

The component is restricted at the green-size inner-diameter dimension during quenching by the plug, which means that growth will always occur since the transformation to martensite should allow the part to expand off the plug. Figure 7 shows the predicted radial displacement (solid lines) and temperature (dashed lines) histories for the four geometries during the cooling steps of the process at a single node. The node is on the surface and at mid-height of the spline. Figure 8 is a close-up of the time when the part makes contact with the plug.

As can be seen in Figure 8, the four geometries contact the plug at different times. This seemingly minor difference is ultimately the cause of the different final radial dimensions of the four geometries. An interesting point can be gleaned from Figure 8: Different geometries clearly contact the plug at different times and for different amounts of time, with the smallest growth occurring for the geometry that remains in contact with the plug for the longest period of time. The scallop geometry remains in contact for approximately
4 seconds, the original geometry for approximately 6 seconds, and the two geometries with added mass for approximately 7 seconds.

This means that, in order to keep the radial growth to a minimum, the component should remain in contact with the plug for as long as possible. Since the part appears to contact the plug at the same temperature, the slower the part can cool, the longer it will stay in contact with the plug and the smaller the overall radial growth. This is why adding material to the part near the spline helped, because it slowed the cooling rate of the spline. By adjusting the size of the green shape and the plug size, the part could be made to expand to the required dimension instead of being machined to the final shape. Heat-treatment modeling could help determine these sizes.

The bow distortion is strictly a result of the unbalanced mass in the axial direction, resulting in the top and bottom of the gear transforming to martensite before the center section. Figure 9 shows snapshots at key times for the progression of the martensite and temperature histories. All figures have a displacement magnification of 25X. Figures labeled A# are of temperature in Celsius, and those labeled B# are of martensite in volume fraction.

Figures A1 and B1 show the profiles at the end of the transfer step. A minor temperature gradient exists at this stage with no martensite transformation. The part is also straight at this time. Figures A2 and B2 show a snapshot at 1.8 seconds into the quench. At this stage, a large temperature profile exists, and the transformation to martensite has started at the very edges of the flange and at the top corner. The bow distortion shown is strictly from the thermal effects and is mostly elastic. Figures A3 and B3 show a snapshot at 8.3 seconds into quench. At this point, the martensite transformation in the flange and at the top of the part bow the part in the opposite direction and begin to straighten the spline. There is still no phase transformation happening in the core of the spline. At approximately 14 seconds into quench, Figures A4 and B4 show the martensite transformation has started in the core. The expansion in the core pushes outward and actually make the component straight. The transformation is nearly complete at the ends of the component at this time, yet is only approximately 35 percent complete in the core. The transformation to martensite is completed in the core at approximately 30 seconds, shown in Figures A5 and B5. The 65-percent martensite transformation in the core that occurred over the previous 16 seconds with the ends already completely transformed has acted to bow the component in to the final shape. There is still a small temperature gradient at this point, but it is not large enough to significantly change the shape once the component has cooled to room temperature. Figures A6 and B6 show the component at room temperature.

CONCLUSIONS

The analysis showed that additional material is needed to reduce the overall radial growth. The increase in mass also slightly improved the bow distortion. Removing material from the green shape, as was the case with the scallop geometry, increased the radial growth and bow distortion. The next step would be to optimize the mass needed to reduce the radial growth to manageable levels while keeping the bow distortion to a minimum. Once optimized, a 3-dimensional model would be executed to confirm the 2-dimensional modeling results. These conclusions were reached through the use of heat-treatment simulation software DANTE and were relatively inexpensive trials.

REFERENCES


ABOUT THE AUTHORS

Justin Sims, Charlie Li, and B. Lynn Ferguson are with DANTE Solutions Inc., in Cleveland, Ohio. Sims is a graduate Mechanical Engineer from Cleveland State University. His project work includes development and execution of carburization and quench-hardening simulations of steel components, analysis of heat-treat racks and fixtures, and upgrading the company computers. He has developed the DANTE HELP package for both ABAQUS and ANSYS versions of the software, and he is the primary trainer and software support person. DANTE Solutions is an engineering consulting and software company, specializing in metallurgical process engineering and thermal/stress analyses. Founded in 1982 by Dr. B. Lynn Ferguson as Deformation Control Technology, the company has evolved into the premier thermal process modeling company.
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Figure 9: Contour plots of A) Temperature, in Celsius, and B) Martensite, in volume fraction, at various times during the hardening process.