Controlled Cooling Improves Forging Quality, Throughput And Cost

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Computational fluid dynamics (CFD) can shorten the time to achieve optimum part specifications. By controlling the rate at which just-forged parts are cooled, the desired metallurgical properties can be obtained while eliminating an entire heating cycle.

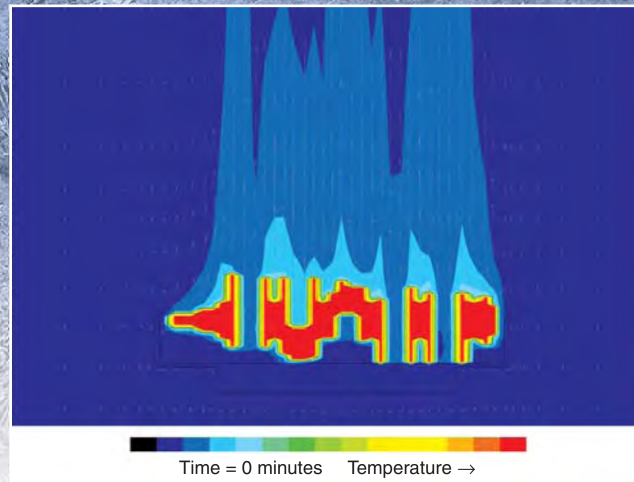


Figure 1. CFD predictions of forged part temperatures immediately after forging; color contour plot is for one slice of a full 3-D model

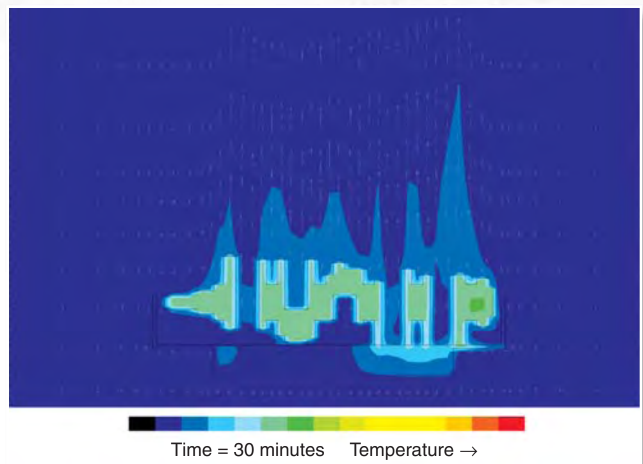


Figure 2. CFD predictions of forged part temperatures for the same slice as in Figure 1 after 30 minutes of cooling in still air

The controlled cooling of a hot forging has several advantages over the antiquated practice of piling the forgings into a bin until the bin is full, then repeating the same uncontrolled filling of another bin until the forging run is completed. Repeatable cooling for each forging produces a consistent microstructure, hardness and residual stress state in the parts as well as consistent dimensions at ambient temperature. If the cooling practice is controlled, these characteristics also can be controlled. The result is that finishing operations – such as the machining of the part and minimization of distortion both during cooling and during machining – can be optimized. For certain alloy steels, it is possible to use controlled cooling of the forging to achieve part properties without the need for additional heat treatment.

Acceptable cooling practice requires knowledge of cooling parameters and their effect on the forging as it cools in terms of phase transformations, consequent dimensional changes and stress-state changes. The combination of a computational fluid dynamics (CFD) model and a finite element model (FEM) that includes the metallurgical phase-transformation response offers a powerful tool for designing a well-controlled cooling process for hot forgings.

Controlled cooling of forgings is a "green" process that reduces unnecessary heating cycles and provides a tangible benefit to the forge operator's bottom line. In a study performed by the U.S. Department of Energy (DOE) on one forge facility regarding best practices, the savings from installing a controlled-cooling process represented over half of the projected savings resulting from the implementation of best practices.

ANALYTICAL PROCESS

The cooling rates provided by air passing over hot forgings can be simulated using CFD tools. These surface-cooling rates can then be applied to a finite element model for prediction of interior cooling, phase transformation, residual stress, distortion and hardness. A typical analysis cycle may include simulation of the flow field to define cooling rates followed by prediction of the resultant material properties. If the desired properties are not obtained, regions that need higher or lower cooling rates are noted, and modifications are made to the cooling-system design or operating conditions.

CFD ANALYSES – CRANKSHAFT COOLING

As part of the development of a controlled-cooling line for hot-forged crankshafts for Ford Motor Company, a CFD study was performed. In this case, it was known that if the crankshafts were cooled individually in still-air conditions (as opposed to being in a bin with many other crankshafts), the proper material hardness for downstream machining processes would be obtained. The challenge was to provide still-air cooling over the critical early time period when the desired microstructure is developed while accelerating the cooling for the balance of the cycle in order to reduce the footprint of the cooling enclosure. Since the target cooling rate was known in this case, there was no need to perform finite element modeling to predict phase transformation and hardness.

The analysis proceeded in three steps. First, a detailed model was constructed of the crankshaft in a still-air environment with the goals of establishing the cooling rate of a crankshaft in that environment and correlating to test data. Sample results for that simulation are shown in Figures 1 and 2. Good correlation with test data was achieved, as shown in Figure 3.

Since the cooling enclosure was to have a capacity of 480 crankshafts, it would not be possible to model the entire enclosure and all crankshafts with the level of detail used in the still-air cooling model. The second step of the analysis required the development of a simplified representation that exhibited the same cooling rate as the detailed model in still-air conditions.

Finally, transient simulations of the entire cooling enclosure were performed to determine the resulting cooling rate of the crankshafts. The design concept for the cooling enclosure called for the flow through the system to be driven completely by thermal buoyancy from the heat of the forgings rather than from a fan. This provided an additional challenge, and it meant that the flow through the enclosure was closely coupled to the temperature of the forgings and their cooling rates.

A number of simulations were performed before a configuration was found that provided the desired cooling rates. A schematic of the final configuration is shown in Figure 4. The cooling-system flow design consisted of two fresh-air inlets (blue), several flow-control devices (orange and gold) and a single-flow exit (red). The path taken by the crankshafts through the two-level cooling enclosure is outlined in black.

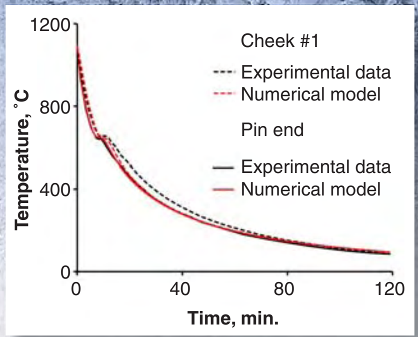


Figure 3. Comparison of empirical data and model predictions of time-temperature history of crankshaft cooled in still air

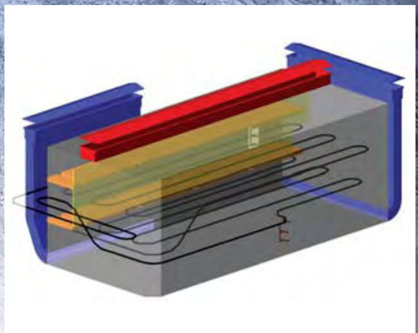


Figure 4. Schematic of final crankshaft-cooling enclosure design

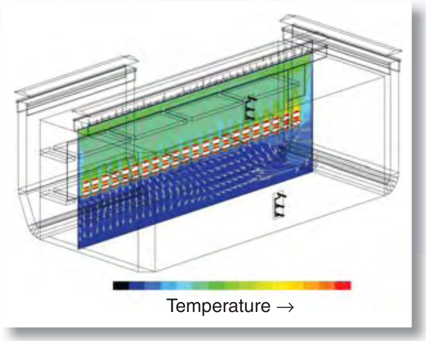


Figure 5. Simulation of crankshaft cooling in enclosure

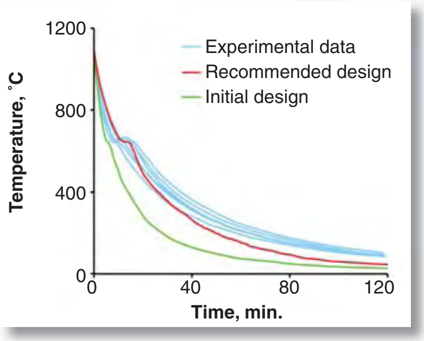


Figure 6. Actual cooling results obtained in cooling enclosure

Example flow field and air temperature results for the design case are shown in Figure 5. Figure 6 shows a comparison of the still-air test data, the crankshaft cooling results for the initial enclosure design and the cooling rate for the design case. As shown, the design case provides cooling that closely matches the still-air results through transition, followed by accelerated cooling for the balance of the cycle. In contrast, the initial design would have provided cooling rates that were too fast, making downstream machining more difficult or requiring a secondary heat-treating step.

The cooling enclosure was installed as designed and has been providing parts of the desired hardness since start-up. While proper design of the system required additional up-front engineering and associated expenses, the benefits of that engineering have been accruing in the form of reduced operating expenses ever since.

FINITE ELEMENT MODELING – GEAR COOLING

The DANTE heat-treatment-simulation software package is available from Deformation Control Technology Inc. It is a finite-element-based tool that can be used to predict metallurgical phase transformations, dimensional changes and the stress state of steel hot forgings as a consequence of cooling practices. The surface and internal temperatures of a hot-forged shape change in accordance with surface heat loss. DANTE uses local surface heat-transfer coefficients to calculate the nodal temperatures throughout the cooling processes. As cooling occurs, the austenite phase present during the forging operation will transform to combinations of ferrite, pearlite, bainite and martensite – depending on the cooling rate. By applying the local heat-transfer coefficients predicted by the CFD model for the cooling process, DANTE will predict the resulting metallurgical phase evolution, dimensional change, internal stress state and the hardness distribution of the cooled forging.

To use these tools for process design, a designer could specify desired dimensional and

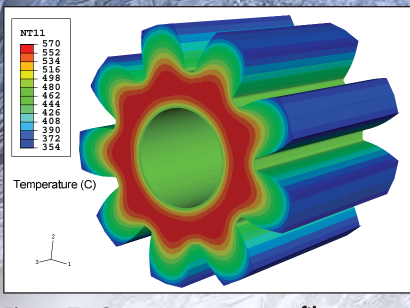


Figure 7. Gear temperature profile developed during controlled fan cooling

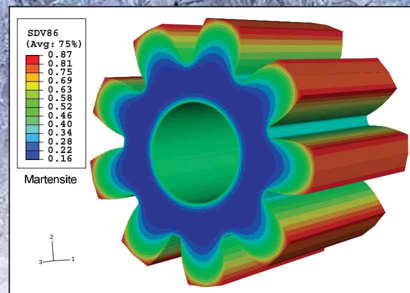


Figure 8. Martensite volume fraction across a gear section for fan-air cooling

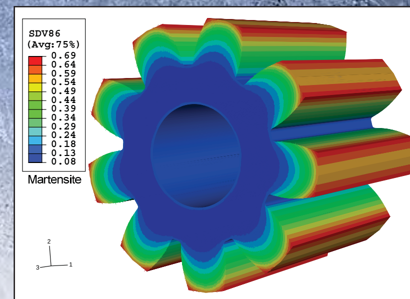
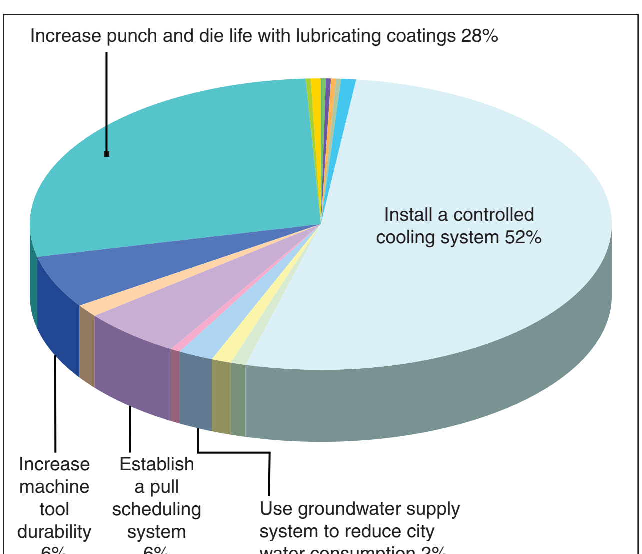


Figure 9. Martensite gradient on the gear surface for a still-air cool

desired hardness ranges. DANTE could be used, under the control of an optimization procedure, to determine the heat-transfer coefficients and post-forging temperature profile required to produce a part that meets desired conditions. The CFD model, run under the control of the same optimization procedure, could be applied to determine the conditions required to produce the needed heat-transfer coefficients, i.e. fan speed, blowing direction and circulation.

For example, a straight spur gear was hot forged to near-net shape from a high-hardenability-steel alloy. A fan-air cooling schedule was determined such that the forging transformed to nearly 100% martensite during cooling, thereby eliminating an austenitization and quenching heat-treatment step. A low-temperature tempering step was sufficient to complete the heat treatment. Figure 7 shows a temperature profile developed during the controlled fan cooling. Figure 8 shows the martensite volume fraction across a gear section for the fan-air cooling, with approximately 40% at the root surface and 50-88% on the tooth face – the remainder being bainite. For this gear, this microstructure would provide acceptable performance. For comparison, Figure 9 shows a large martensite gradient on the surface from 15% in the root to less than 50% on the tooth face for a still-air cool from the hot-forging temperature. This latter profile for still-air cooling was unacceptable, and a full heat treatment would be required.



COST JUSTIFICATION

In May 2005, the U.S. DOE released a best practices case study of the Metaldyne facility in Royal Oak, Mich. (now owned by FormTech Industries, LLC). That study (available on the web at http://www1.eere.energy.gov/industry/bestpractices/pdfs/37650.pdf) identified potential annual operating cost savings of $12.6 million, broken into several categories (Figure 10). Installation of the controlled-cooling systems – at $6.6 million – comprises more than half the annual cost savings. The DOE study estimated the cost of implementing controlled-cooling systems at $4.75 million, indicating a return on investment of less than one year.

This study shows that implementing controlled-cooling systems can be good for the bottom line as well as for the quality of the parts. Using the analytical methods described ensures that the cooling system will deliver the required part quality and provides confidence to implement a controlled-cooling system. The cost of performing these analyses represents a very small fraction of the total system cost.

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