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Coupling CFD and Oil Quench Hardening Analysis of Gear Component

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Abstract

During the liquid quenching process, there are three main phases between the solid and the liquid interface: film boiling where vapor blanket covers the entire solid structure, transition or nucleate boiling, and single phase convection. The type of the quenching media, the agitation, and the flow pattern of a quench tank have significant effect on the cooling behavior during these three phases, which will affect the cooling rate, phase transformation, stress evolution and shape change of the quenched components. In this paper, transient CFD analysis using AVL FIRE® is coupled with heat treatment analysis using DANTE® to simulate an oil quench hardening process of a test gear made of Pyrowear® 53. The gear is carburized prior to quench hardening. During the coupling analyses, the heat flux between the gear and the oil calculated in the CFD model is applied to the solid heat treatment model, and the gear surface temperature predicted by the heat treatment model is passed back to the transient CFD model. The aforementioned CFD tool is capable of considering the entire quenching domains without considering phase transformations in the quenched components. In the present case the gear is treated with a finite element tool in combination with DANTE to account for the latent heat release, which slows down the cooling. The relations between carbon content, temperature field, phase transformation, internal stress, and shape change during quenching are explained from the heat treatment modeling results. The coupling of CFD and heat treatment analyses provides a more robust application of computer modeling in the heat treatment industry.

Introduction

Nowadays powertrain development is driven in direction of weight reduction by replacing heavier metals with low-cost alloys for industries such as automotive, aerospace and process engineering. Accurate prediction and optimization of the heat treatment process of metal parts is important in order to achieve optimum surface material properties or to increase the magnitude of surface compressive residual stress from local thermal gradients and solid phase transformation timing during hardening processes and thereby prevent component failure during operation. Among all other heat treatment techniques, immersion quenching process has long been identified as one of the most important methods to fulfill the aforementioned requirements. In order to achieve the desirable microstructure and mechanical properties of the metal piece, steel components are heated to an austenitization temperature, followed by immediate submerging into quenching media. [1]. The common austenitization and soaking temperature of steel gears is about above 900 °C. The temperature varies based on the steel grades. During quenching hardening of steel components, the latent heat released during solid phase transformations affects the cooling significantly, which needs to be considered in heat treatment process modeling.

The paper features the results of the Eulerian multi-fluid model implemented within the commercial CFD code AVL FIRE® coupled with DANTE®, using ABAQUS finite element solver. The coupled modeling is capable of considering the solid phase transformation kinetics, which affects the microstructure, thermal and mechanical properties. Phase transformation during quench hardening also involves releasing latent, which is considered in this study.

In this paper, a test gear component made of Pyrowear 53 is simulated, and the modeling results include the entire history of the part response during hardening including heating and quenching. The temperature gradients predicted by the presented model reproduce the latent heat release during the phase transformation. It is clear that neglecting the additional heat source would result in very different thermal gradients and consequently very different thermal stresses and surface properties of the treated component.

Theoretical Background and Simulation Set Up

Eulerian multi-fluid model considers each phase as interpenetrating continua coexisting in the flow domain, with interfacial transfer terms accounting for phase interactions where conservation laws apply [2]. The averaged continuity, momentum, energy and boiling models equations are well described in work of Srinivasan *et al*. [3] and Greif *et al*. [4]. The methodology is applied in industrial environment, as described by Jan *et al*. [5] and Mulayim Kaynar *et al*. [6].

The gear geometry is shown in Figure 1. The bore diameter of the gear is 48.35 mm, the tip diameter is 106.25 mm, and the total number of teeth is 41.

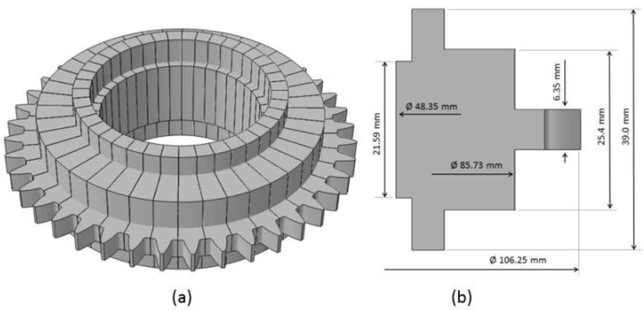
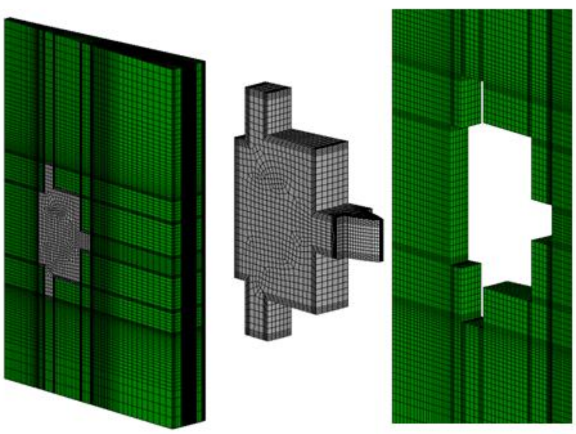


Figure 1. (a) CAD model, and (b) the dimensions of the gear.

Figure 2 shows finite element meshing of the computational model. In this coupled modeling, the fluid and the solid structure are modeled by different computational codes, and their geometries are shown in Figure 2. It is assumed that all the gear teeth behave the same during quenching, so the gear is modeled using a single tooth with cyclic symmetry boundary conditions.

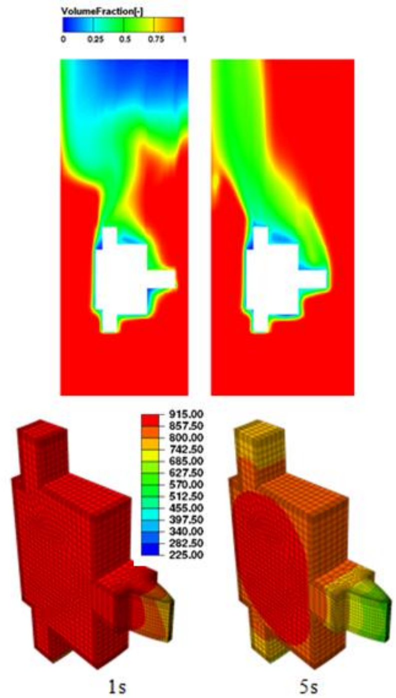


(a) (b)

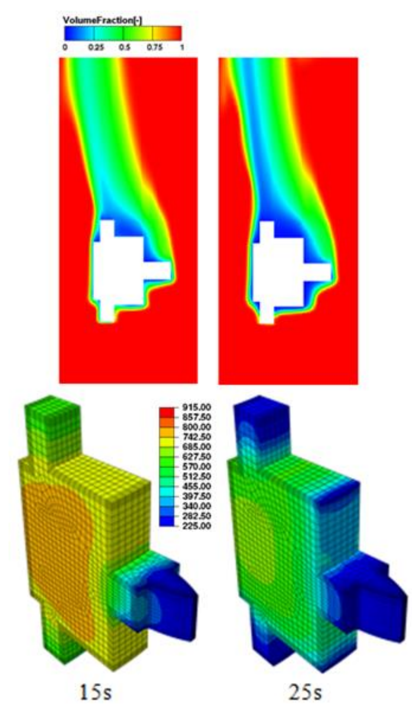
Figure 2. (a) Computational model, and (b) coupled solid domain using DANTE and liquid domain using AVL Fire.

CFD Simulation Results and Discussion

The modeling results shown in Figure 3 are the volumetric fraction of oil to illustrate the boiling process, and the temperature distribution of the solid gear at four time snapshots during quenching. The results are shown on the planar cut through the fluid domain (top row) and on the surface of the structure. The gear temperature prior to quenching is 915 °C.



(a) (b)



(c) (d)

Figure 3. Oil phase volume fractions and solid gear temperature distributions at four different snapshots during quenching: (a) 1.0s, (b) 5.0s, (c) 15s, and (d) 25s.

Figure 4 shows two points selected to study the cooling history of the gear during quenching. The surface point locates at the bore surface, and the core point locates at approximately the center of the cross section.

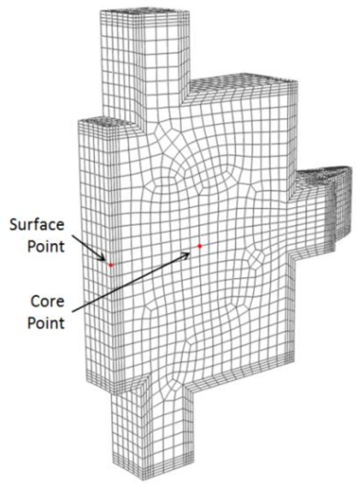


Figure 4. Surface point and core point selected to study the cooling history of the gear during quenching.

The thermal properties during quenching are affected by the temperature, as well as the phase transformations because different phases have different thermal properties. The overall thermal properties are calculated from the volume fractions of individual phases and their properties. The cooling history of the part is also significantly affected by the latent heat released due to phase transformation. By turning off the latent heat in the quenching model (the phase transformations included), the effect of latent heat is shown in Figure 5. The bump in the time-temperature profile after 15-20 s represents the latent heat release. Slower cooling is clearly visible (yellow and gray profile) affecting the local cooling and overall temperature gradients. Orange and blue curves show the case without latent heat consideration.

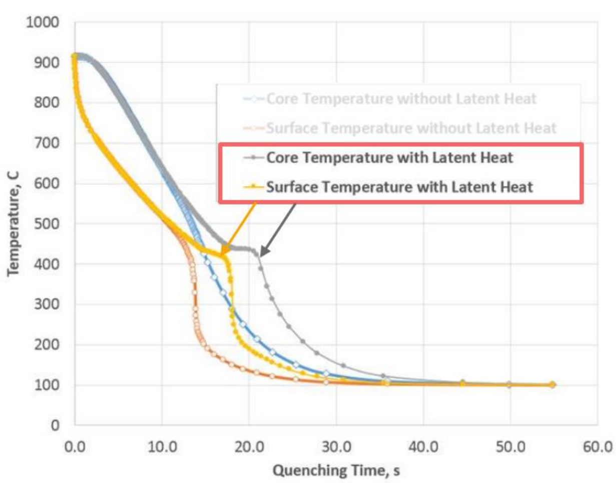


Figure 5. Temperature profiles at monitoring locations.

Thermal and Stress Modeling using DANTE

Prior to quench hardening, the gear tooth is gas carburized with all other surfaces being copper plated. After carburization, the gear is reheated for hardening. It is important to include the carbon distribution profile in the quench hardening model because the carbon content has significant effect on the phase transformation kinetics. The carbon distribution profile after carburization is shown in Figure 6.

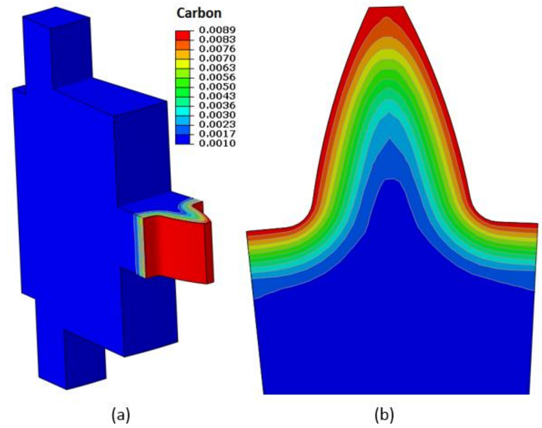


Figure 6. Carbon distribution after gas carburization process: a) overall view, and b) zoomed in view of the tooth section.

The heating process is modeled by applying a uniform heat transfer coefficient on the gear surface with the furnace temperature being 915 °C. Figure 7 shows temperature, austenite and circumferential stress distributions at 673 s during heating. The tooth tip has a higher heating rate, and the austenite transformation is earlier at the tip.

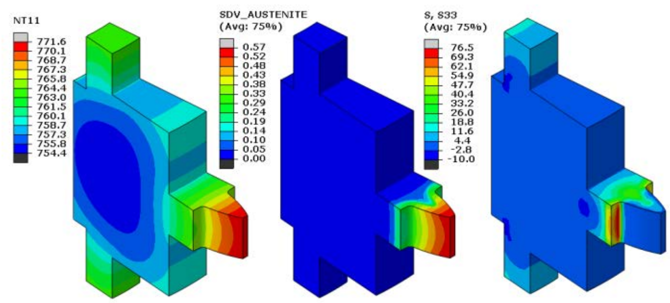


Figure 7. Temperature, austenite and circumferential stress of the gear at 673 s during heating.

Figure 8 is a snapshot of the gear at 820 s during heating. The austenite distribution clearly shows the effect of carbon on the austenite forming. The growth of the gear due to heating is shown also shown.

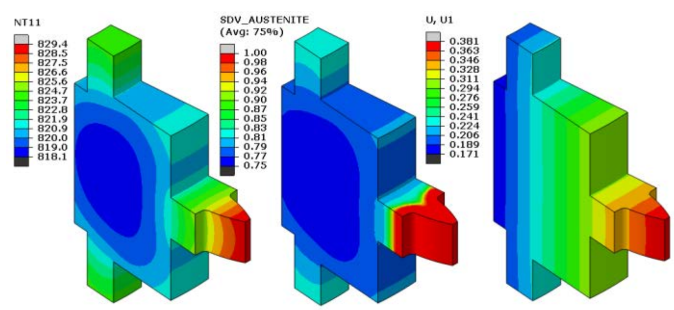


Figure 8. Temperature, austenite and radial displacement at 820 s during heating.

At the end of heating, the gear temperature is 915 °C with full austenite. The radial growth is 0.431 mm.

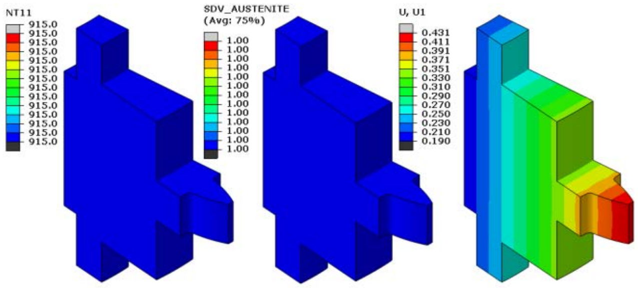


Figure 9. Temperature, austenite and radial displacement at the end of heating (3600 s).

Using the predicted temperature from coupled AVL-Fire and DANTE thermal model, the stress model of quenching process is executed. Figure 10 shows the temperature, martensite, and circumferential stress distributions at 3.7 s during quenching. When austenite transforms to martensite, the material volume increases because martensite has a lower density. As shown in the Figure 10, the region with martensite forming shows a compression stress, and its neighbor is under tension to balance the stress.

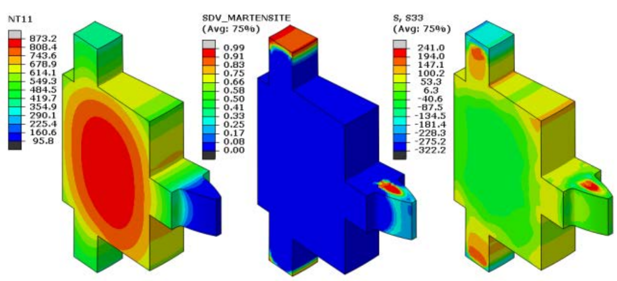


Figure 10. Temperature, martensite, and circumferential stress at 3.7 s during quenching.

At the end of quenching, the volume fraction of martensite and residual stress in the circumferential direction is shown in Figure 11. Pyrowear 53 has high hardenability, and the austenite transforms only to martensite during quenching. The gear tooth is carburized, and the retained austenite at the gear tooth is about 12% due to the lower Ms and Mf temperatures with high carbon content.

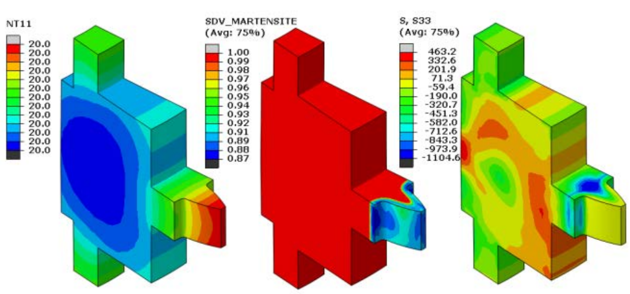


Figure 11. Temperature, martensite and circumferential stress at the end of quenching.

Conclusions

The applied CFD code AVL FIRE is coupled with DANTE® to predict the latent heat release, distortion and residual stresses during quench hardening process. The latent heating release has significant effect on the temperature distribution during quenching, which will affect the rate of phase transformation, distribution, and residual stresses of the quenched part. The study show the possibility of coupling CFD transient analysis with heat treatment model of solid part, which is valuable to understand the cooling uniformity around the part and its effect on the part response during liquid quenching processes.

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