ICME TOOLS CAN HELP CONTROL GEAR DISTORTION FROM HEAT TREATING

INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING TOOLS ENABLE ACCURATE SIMULATION OF GEAR HEAT TREATMENT TO PREDICT PHASE TRANSFORMATION KINETICS AND DISTORTION.

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Most gears used in industrial applications are carburized and quenched to meet surface and core hardness and overall fatigue strength requirements. Low pressure vacuum carburizing (LPC) combined with high pressure gas quenching (HPGQ) offers the opportunity to minimize environmental impact, eliminate oxidation and surface decarburization, accurately control case depth and core hardness, and produce consistent microstructure, and thus, fatigue performance from batch to batch.

LPC/HPGQ has the potential to minimize distortion by controlling such parameters as gas flow velocity, operating pressure, chamber geometry, and fixture materials. A time-efficient, cost-effective way to optimize those parameters is to integrate various computational tools such as computational fluid dynamics (CFD), finite element analysis (FEA), and microstructure modeling to perform numerical tests for specific type of gears. This article discusses the development of an integrated computational materials engineering (ICME) tool and its practical application in product development.

Manufacturing challenges
Increasing demand for vehicle fuel efficiency has led to weight reduction of transmission components, and transmission gears of thinner cross section are more sensitive to distortion during manufacture[1-2]. Transmission gears have very tight dimensional tolerances to meet durability, as well as noise, vibration, and harshness (NVH) requirements. This creates processing challenges from machining through heat treating. Along with the effects of residual stresses from machining, distortion is caused by nonuniform plastic deformation due to thermal and phase-transformation stresses during heat treatment. Parts that do not meet quality control specifications may require additional grinding and other corrective measures to meet dimensional tolerances, which significantly increases costs.

Low pressure carburizing combined with high pressure gas quenching produces less distortion compared with other heat treating methods[3-4]. It consists of vacuum carburization at an austenitizing temperature of ~930°C followed by high pressure nitrogen gas quenching at 1–20 bar (Fig. 1a). Acetylene is supplied at low pressure in several boost intervals, because its decomposition is catalyzed by iron atoms at the gear surface, providing high carbon potentials for diffusion into the austenitic structure[5]. After achieving the desired 0.3–1.0 mm carburized case depth, the workload is transported into the quenching chamber where controlled cooling using high pressure, turbulent nitrogen gas flow produces the desired microstructure[6]. Surface and core hardness, as well as properties such as fatigue strength, wear resistance, and pitting corrosion resistance are determined by the microstructural constituents resulting from different cooling rates and carbon profile[6].

For example, a straight quench at constant pressure and velocity leads to a large temperature difference between the gear surface and core, introducing nonuniform thermal and martensite-transformation stresses, which can cause distortion as shown in Fig. 1b. Stop quench, dynamic quenching, and reversing quench are recent developments[1-5] used to control cooling rate (and thus phase transformation) in three steps: (1) high quench severity prior to martensite phase transformation to

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Fig. 1 — (a) LPC and HPGQ heat treating process and schematics of (b) straight quench and (c) step quench.
The prediction of heat transfer in combination with the phase-transformation process during HPGQ has become increasingly important as more attention is paid to optimizing the quenching process to minimize distortion[8-10]. The need for CAE tools that can predict the conjugate heat transfer during high pressure gas quenching and couple it with phase transformation distortion analysis led to the development of ICME-GearHT.

**Computational tool development**

The ICME-GearHT tool enables accurate simulation of the transmission gear heat-treatment process, predicts phase transformation kinetics and distortion, and provides cost-effective, time-efficient evaluation of new equipment designs. These will ensure high quality product launch and help achieve a “first-time-through” manufacturing vision (Fig. 2). This was accomplished by gaining a clear understanding of the fundamentals of carburizing, conjugate heat transfer, phase transformation, and micromechanics during the gear heat treatment process; and integration with the most advanced models in different disciplines[8-10] and related leading industrial experimental validations.

ICME-GearHT analysis is broken down into four parts: carburizing, CFD, phase transformation, and mechanical analysis. Figure 2 shows the data requirements and how the analyses are coupled. Each analysis starts from diffusion-based carburization at high temperature using carbon potentials and diffusivities measured from experiments. The Abaqus (Dassault Systèmes) FEA model calculates the kinetic process of carbon diffusing into austenitic interstitial sites, which expands the lattice, and introduces a carbon gradient into the gear. The resulting nodal carbon concentrations serve as input to the subsequent high pressure-gas quench analysis. Transient heat transfer is calculated using the Fluent (Ansys Inc.) CFD model, in which the latent heat of phase transformation is implemented as a subroutine. Carbon concentration (from FEA) and temperature values (from CFD) are fed into the DANTE (Deformation Control Technology Inc.) microstructure model. Finally, the coupled Abaqus CAE and DANTE database performs structural analysis for mechanical properties of each phase. As shown experimentally by previous authors[1-4], surface carbon concentration has little effect on gear distortion. Temperature and phase evolution at different locations/orientations control thermally and transformation-induced plasticity.

**Model validation**

The following example case illustrates thermal model validation and compares predicted and experimental results. Because different cooling rates result in different volume fractions of martensite, nonuniform cooling rate on a single gear results in nonuniform distribution of martensite in the gear (Fig. 2). Martensite transformation causes a 2–5% volume increase[11] depending on the composition and releases about 3.1 x 10⁸ J/m² latent heat[12], which complicates the temperature profile of each gear. Therefore, it is important to include transformation kinetics in modeling the transient temperature history of gears during quenching[13]. However, commercial CFD codes are intrinsically unable to accurately predict the thermal history of the gear quenching process due to the lack of a phase-transformation model. We implemented a subroutine in the commercial Fluent CFD code to take the latent heat effect due to phase transformation into account.

Model validation is accomplished using experimentally measured temperature data (Fig. 3 I-a) at 40 and 100% fan speeds. Figure 3 I-b shows that higher cooling velocity results in higher heat-transfer coefficient. The predicted thermal profile captures the effect of latent heat release, agreeing well with experiments for different gear orientations (Fig. 3 I-c). Temperature uniformity during HPGQ is critical for improving process performance to minimize distortion and maximize gear service life. Therefore, the ICME-GearHT model was used to evaluate properties of furnace-fixture materials, chamber configurations, and parts loading in the furnace.

**Experimental validations**

New kinetic parameters were developed for 5130 alloy steel, which is widely used for transmission gears. Kinetic parameters in the phase transformation models were determined using an optimization approach that matches model predictions with experimental measurements. The parameters were implemented into the DANTE materials database, allowing accurate prediction of phase transformation and seamless integration with the micromechanical model for calculating both thermal and transformation plasticity during the gear quenching process.

Distortion analysis using ICME-GearHT is validated by mapping the distortion at various locations of the load and at three different quenching conditions including step quench, 40% fan speed, and 100% fan speed. The experimental setup is shown in Fig. 3 II-a. Experimentally measured distortion at three different conditions (Fig. 3 II-b) agrees well with previous studies[7]. Step quenching produces less distortion and better product quality. Distortion calculations determined using the ICME-GearHT approach are compared with experimental results to provide efficient, effective solutions for process design and optimization. Figure 3 II-c shows predicted gear...
circularity, replicating the influence of gear location on distortion and matching experimental measurements in locations 8 and 9. Results show the model can be used to optimize production processes and identify the best heat-treatment recipe for minimized distortion.

Recent experimental studies by others\cite{1-4} have shown that use of carbon-fiber composite (CFC) fixtures reduces distortion by 25%, and by 50% by combining CFC fixtures with a step quench. Computations were performed using both alloy and CFC fixtures to quantitatively evaluate the benefits of new fixture materials. CFC fixtures significantly improve temperature uniformity within the load and within individual gears with the same load volume as in a steel basket. An improvement of 20–25% in temperature uniformity is possible using CFC fixtures. Evaluation of modifications to the quenching system using ICME-GearHT shows that a proposed new cooling fan and stator design along with velocity filtering improves temper-
ature uniformity prior to martensite transformation by more than 20%.

Summary
The ICME-GearHT model incorporating latent heat release due to phase transformation was validated using experimental data. The entire workload is a complex thermal body subjected to large temperature variations during quenching. ICME-GearHT captures those variations. It was used to investigate and validate a new gas quenching process, propose cost-effective, time-efficient recommendations for new transmission-product development, and accelerate new process development. It was also used to evaluate the benefits of using different heat treating furnace-fixture materials and different quenching furnace stator and fan designs to improve temperature distribution uniformity for reduced distortion.

Fundamental and experimental methods developed using ICME-GearHT can be extended to any high pressure gas quenching process such as sun-gear and pinion-gear heat treatments. It can be extended to any case-hardening process such as induction hardening, oil quenching, and molten salt quenching.

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References

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