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Innovative Induction Hardening Process with Preheating for Improved Fatigue Performance of Gear Component

By Dr. Z. Li, Dante Software

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Dr. Zhichao (Charlie) Li, Dante Software

[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Contact fatigue and bending fatigue are two main failure modes of steel gears. Surface pitting and spalling are two common contact fatigue failures, which are due to the alternating subsurface shear stresses from the contact load between two gear mates. When a gear is in service under cyclic load, concentrated bending stresses exist at the root fillet, which is the main driver of bending fatigue failures. Heat treatment is required to increase the hardness and strength of gears to meet the required contact and bending fatigue performance. Induction hardening is becoming more popular due to its process consistency, reduced energy consumption, clean environment, and improved product quality. It is well known that an induction hardening process of steel gears can generate compressive residual stresses in the hardened case. Compressive residual stresses in the hardened case of tooth flank benefit the contact fatigue performance, and residual compression in the root fillet benefits the bending fatigue. Due to the complex gear geometry, the residual stress distribution in the hardened case is not uniform, and different induction hardening process can lead to different residual stress pattern and significant variation of fatigue performance. In this paper, an innovative approach is proposed to flexibly control the magnitude of residual stress in the regions of root fillet and tooth flank by using the concept of preheating prior to induction hardening. Using an external spur gear made of AISI 4340 as an example, this concept of innovative process is demonstrated with finite element modeling, using commercial software DANTE.

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American Gear Manufacturers Association
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Alexandria, Virginia 22314

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Introduction

Residual stresses embedded inside a hardened gear are critical to its fatigue performance. There are two main failure modes for gear components: contact fatigue and bending fatigue. In service, one pair of gears transfer torque load through the contact of two teeth. High shear stresses co-exist with high hydrostatic pressure under the contact surface. Depending on the load magnitude and the gear size, the depth of the highest shear stress point varies. To improve the contact fatigue life, the hardened case depth needs to be deeper than the highest shear stress point. Compressive residual stresses located inside the hardened case benefit the contact fatigue performance [1]. The bending fatigue failures are commonly found at root fillet location where tooth flank and root meet. Under the contact load between two gears, the root fillet experiences cyclic stresses, which is the driver of bending fatigue failure. Compressive residual stresses from heat treatment or other surface processing can significantly improve the bending fatigue performance [2].

Induction hardening is more environmentally friendly than conventional furnace heating and liquid quenching. It also provides flexibility in control of case depth, residual stresses, and part distortion. Due to these advantages, the induction hardening process is becoming more popular to harden steel gears. During induction heating, the energy to heat the part is generated inside the part by eddy currents in response to the imposed alternating magnetic field. The energy distribution in the part is directly related to the distance between the inductor and the part, the frequency and power of the inductor. Lower frequency and lower power heat the part deeper over longer time period. Higher frequency and higher power heat a shallower layer over shorter time period. The temperature distribution in the part is a combined result of induction heating and thermal conduction. During induction hardening of steel components, both thermal gradient and phase transformations simultaneously contribute to the evolution of internal stresses and shape change. Recent developments in heat treatment modeling technologies make it possible to understand the material's responses during heat treatment processes, such as how the internal stresses and distortion are generated. DANTE is a commercial heat treatment software based on finite element method [3-5], which was designed to model the responses of steel parts during heat treatment processes. The material's responses include phase transformations, deformation, residual stresses, and hardness, etc. Typical heat treatment process steps include austenitization, carburization, quench hardening, and tempering. Phase transformation kinetics and mechanical properties are required for modeling the heat treatment processes [6,7]. DANTE has a validated database for most common low and medium alloy carbon steel grades, which have been used successfully in the past to model induction hardening processes [8,9]. With the help of computer modeling, engineers with DANTE Software have discovered that residual compression at the root fillet of a gear can be enhanced by applying preheating prior to induction hardening process. The preheating process can be implemented either by furnace or induction heating. In this paper, this innovative process is demonstrated by computer modeling, using an AISI 4340 spur gear example.

Phase transformation kinetics

Phase transformations are involved in most heat treatment processes of steel components. During heating, initial phases transform to austenite, and carbides dissolve while being held at the austenitization temperature. During cooling or quenching steps, austenite transforms to ferrite, pearlite, bainite, or martensite, depending on the cooling rate and hardenability of the steel grade. At different heat treatment stages or at different regions in a part, the material can be composed of different phases, and the volume fractions of individual phases are functions of chemical composition and thermal history. To model the heat treatment process of steel components, accurate descriptions of material properties and process information are required. The basic material property data includes phase transformation kinetics, thermal and mechanical properties of individual phases.

Phase transformations during quenching are classified as diffusive and martensitic transformations. The diffusive transformation is time and temperature driven, and the martensitic transformation is mainly

temperature driven. The two types of phase transformation models used in DANTE are described in equations (1) and (2).

$$\frac{d\phi_d}{dt} = v_d(T) \phi_d^{\alpha 1} (1 - \phi_d)^{\beta 1} \phi_a \quad (1)$$

$$\frac{d\phi_m}{dT} = v_m (1 - \phi_m)^{\alpha 2} (\phi_m + \varphi \phi_d)^{\beta 2} \phi_a \quad (2)$$

where

ϕ_d is the volume fractions of individual diffusive phase and martensite transformed from austenite;

v_d is a transformation mobility and is a function of temperature;

$\alpha 1, \beta 1$ (superscripts) are constants of diffusive transformation;

ϕ_a is the volume fraction of austenite;

ϕ_m is the volume fractions of individual diffusive phase and martensite transformed from austenite;

v_m is a transformation mobility and is a constant;

$\alpha 2, \beta 2$ (superscripts) are constants of martensitic transformation;

φ is a constant of martensitic transformation.

For each individual phase formation, one set of transformation kinetics parameters is required.

Different experiments can be used to characterize phase transformations, such as dilatometry test, Jominy End-Quench test, and metallographic characterization, etc. Among these experiments, dilatometry test is preferred due to its accuracy, economic advantage, as well as more useful data obtained [7]. Figure 1a is a strain curve of martensitic phase transformation dilatometry test for AISI 4340. The X-axis is temperature in Celsius, and the Y-axis is strain from the combined effects of thermal shrinkage and phase transformations. During this specific cooling test, the cooling rate of the sample is fast enough to avoid diffusive phase formations. During cooling, the dilatometry sample shrinks with the temperature dropping. When the sample reaches the martensitic transformation starting temperature (M_s), martensitic formation starts with volume expansion. The strain change during transformation is a combination of thermal strain and phase transformation volume change. The data obtained from this specific dilatometry test include coefficient of thermal expansion (CTE) for austenite and martensite, martensitic transformation starting and finishing temperature (M_s , M_f), transformation strain, and phase transformation kinetics (transformation rate) from austenite to martensite. These data are critical to the accuracy of modeling the internal stresses and deformation during quenching.

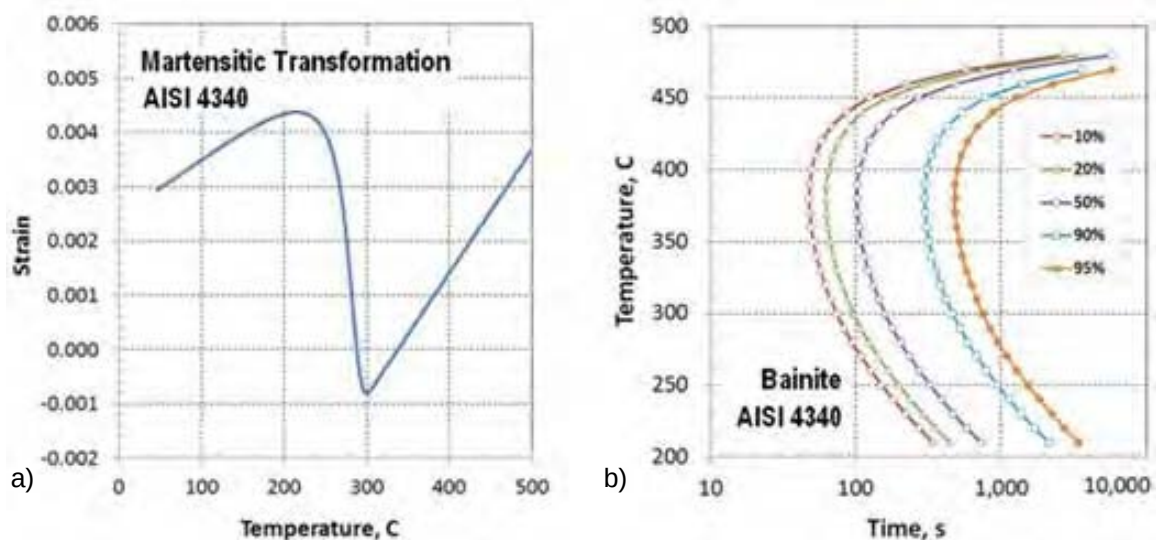


Figure 1. a) Dilatometry strain curve during continuous cooling; b) bainitic TTT diagram of AISI 4340 generated from DANTE database