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Numerical investigation of asynchronous dual-frequency induction hardening of spur gear

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ABSTRACT

The asynchronous dual-frequency (ADF) induction hardening process was simulated based on the electromagnetic–thermal–metallic–mechanical coupled numerical model. Calculations of microstructure fraction and internal stress were introduced through the calculations of electromagnetic and temperature fields during heating, as well as through the calculation of temperature field during subsequent quenching. The isoconversional method and K-M equation were used to calculate the fraction of austenite and martensite, respectively. A thermal elastoplastic constitutive model associated with the transformation stress and transformation induced plasticity was developed to describe residual stress. The ADF induction hardening process for a 42CrMo spur gear of was studied to determine the microstructure and residual stress distributions. The cause of the gear tooth root hardening under medium frequency heating was revealed from the simulated temperature and microstructure results. The stress evolution showed that quenching cracks were most likely to occur at the beginning of martensite transformation. The effect of the residual stress distribution on the initiation and prolongation of the bending crack at gear root was analyzed in combination with the simulation of the gear mesh.

1. Introduction

A gear system transmits toque and power by means of teeth engagement and is one of the most important transmission forms for machinery and mechanical equipment. Wear resistance and fatigue resistance are considered the most critical factors influencing gear life and can be improved by induction hardening. Depending on the required hardness pattern and tooth geometry, gears can be case hardened by encircling with a coil (spin hardening) or by hardening them tooth-by-tooth with either gap-by-gap or tip-by-tip heating techniques. Due to the higher production rates, spin hardening is the most popular induction gear-hardening method which is particularly appropriate for fine- and medium-size gears [1]. The spin hardened gear is heated by the encircled inductors and then cooled. The cooling intensity is an important factor in induction gear hardening. Different selected inductor parameters such as; power, frequency and heating time, will produce different hardened layer distributions [2]. When high frequency is applied, for example, only the tip of the gear teeth will be hardened, while the root hardening is associated with lower frequency heating [3]. Therefore, it is difficult to obtain a uniform contour hardened zone for gears using a single-frequency current [4].

Compared to carburizing and conventional single-frequency induction hardening, contour hardened gears performed better in the bending fatigue test mainly due to superior residual compressive stress distribution [4]. To improve the hardened pattern uniformity, dual-frequency gear hardening has been developed which utilizes two separate power supplies with different frequencies. The dual-frequency current may be asynchronous and synchronous. The asynchronous dual-frequency (ADF) induction hardening process consists of preheating the gear tooth root with medium frequency then switching to a high frequency power supply for final heating. The synchronous dual-frequency (SDF) current fundamentally consists of a medium frequency oscillation superimposed with a high frequency oscillation. However, the relatively complicated design is one of the critical reasons for the limitation of the application of both techniques. With the development of computer technology and improvement of theoretical modeling, numerical computer simulation has provided important assistance in developing an optimal ADF and SDF induction hardening process recipe.

Induction hardening is a multi-physical coupled process, involving thermal, mechanical, metallurgical and electromagnetic process effects. The coupling model of magnetic–thermal fields has been intensively studied since 1980s. Some researchers are oriented toward qualitative analysis for process optimization based on the temperature simu-

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lation results of induction hardening. Li et al. [5], for instance, studied microstructure evolution and residual stress distribution of a continuous induction hardened ball screw in accordance with the temperature simulation work. References [6–8] dealt with the electromagnetic–thermal simulation of single-shot gear induction hardening with a single-frequency current. However, an accurate and realistic modeling of all the concurrent physical phenomena occurring within the workpiece during the induction hardening is problematic because of the interdependence and cross-coupling of material electrical, magnetic, thermal, metallurgical, and mechanical properties.

Hömberg et al. [9] simulated the full process of a multi-frequency induction hardening process for the case of discs and gears. In this study, phase transformation rate equations derived from JMA and K-M models were adopted to describe different phase transformations. The total strain was assumed to be the sum of purely elastic, thermal strain and transformation induced plasticity (TRIP). In classic theory, although the applied load is lower than the yield stress [10], TRIP is the phenomenon that the plasticity increases during a phase transformation. It has been considered to be essential during the modeling of heat treat [11]. However, the plasticity due to yielding (Von-Misses equivalent stress reaches to the yield strength) as well as the effect of temperature on mechanical properties (such as elastic modulus and yield stress), were not introduced in Hömberg's work [9] which will affect the accuracy of the simulation results.

In this study, the ADF induction hardening process of quenched and tempered 42CrMo steel (hardness is 327HV) spur gear was solved by the FE method based on the electromagnetics–thermal–metallurgy–mechanical coupled field. The metallurgical transformation kinetics was selectively chosen from the isoconversional model for the austenitizing process, whereas K-M equation was used for the diffusionless martensitic transformation to describe the evolution of phases during the relatively rapid cooling [12]. The isoconversional model describes the continuous heating process. Therefore, the effect of heating rate on critical temperature of austenitizing has been considered in the model. The thermal elastoplastic constitutive equations coupling the phase transformation were incorporated into the finite element model. Based on the suggested FE model, the evolution of temperature, microstructure and residual stress during dual-frequency induction hardening was studied. The property of surface hardness is more essential at the active face of the tooth to resist plastic deformation caused by contact. By combining the bending stress (as a result of gear engagement) and residual stress (as a result of ADF induction hardening treatment), the FE model was used to study the resultant stress distribution in the root to inhibit the initiation and propagation of cracks.

2. Numerical model

The computational model is based on a coupling strategy between an electromagnetic model, heat transfer, as well as phase transformation and mechanics. The classical Maxwell equations and derived global A–V potential formulations are routinely used to calculate the electromagnetic distribution and induced current in the workpiece [13]. Heat transfer can be calculated based on Fourier's law [13]. The coupling of electromagnetics and heat is achieved by using Joule Power due to induced eddy current. In this study, mathematical models of phase transformation and mechanical properties associated with temperature variation were studied.

2.1. Phase transformation model

In the case of gear contour hardening, only austenitizing and martensite transformation are involved in the phase transformation due to the large temperature variation rate during induction hardening. Therefore, the diffusional phase transformation (pearlite/bainite transformations) was not considered in this research.

2.1.1. Isoconversional model

During induction heating process, the critical temperature of austenitizing is difficult to determine due to the high heating rate. The continuous austenitizing process can be described by isoconversional theory, developed by Friedman [14]:

$$\ln\left(\frac{df_i}{dt}\right) = A\left(f_i\right) - \frac{\mathrm{E}\left(f_i\right)}{RT} \qquad i = 1 \tag{1}$$

where A and E are parameters relate to the residual austenite fraction [15]. f_i represents the fraction of the parent phase, austenite and martensite when $i = 0,\ 1,\ 2$. According to Eq. (1), it can be concluded that the logarithm of austenite transformation rate, $\ln(df_1/dt)$, is linearly related to the reciprocal of temperature, $1/T$, at a certain volume fraction f_1. Consequently, the curves of parameters A and E with the austenite fraction variation can be extracted from the continuous heating dilatometry of different heating rates.

2.1.2. Martensite transformation model

In the case of martensite transformation of low carbon steel, the content of martensite is a function of temperature and it is independent of time. According to Koistinen and Marbuger's study [12], the volume fraction of martensite can be calculated as:

$$f_2 = f_1\{1 - \exp[-a(M_s - T)]\} \tag{2}$$

where a is a constant and M_s is the critical temperature of martensitic transformation. f_1 denotes the volume fraction of residual austenite. In Denis' work [16], the relationship of M_s and hydrostatic pressure was proposed as: $dM_s/d\sigma = -0.05\ \mathrm{K\ MN^{-1}\ m^2}$, which can be considered as a negligible correction. Therefore, M_s is assumed constant and independent of the local stress field in this work.

Finally, the latent heat incremental during phase transformation, dq, can be calculated as follow:

$$dq = \frac{H_i \times df_i}{dt} \tag{3}$$

where H_i denotes the formation enthalpy of the ith new phase. The enthalpy of the austenite and martensite formation is introduced using the following values by reference [17] with the similar material: $H_1 = -6.2\mathrm{E}8\ \mathrm{J/m^3}$ and $H_2 = 6.5\mathrm{E}8\ \mathrm{J/m^3}$. The negative and positive values represent endothermic and exothermic process respectively.

2.2. Mechanical model

For steel, temperature variation has great effect on elastic and plastic modulus, E_e and E_p, while has little effect on Poisson's ratio μ [18]. Therefore, it is assumed that μ can be considered as a constant while E_e and E_p are functions of temperature in the numerical model.

The generalized Hook law in tensor form is presented as follows:

$$\{\sigma\} = [D_e]\{\varepsilon_e\} \tag{4}$$

where, $\{\sigma\}$, $[D_e]$, $\{\varepsilon_e\}$ are stress tensor, elastic matrix and elastic strain tensor, respectively. The total differential equation for Eq. (4) can be written as:

$$d\{\sigma\} = [D_e](d\{\varepsilon_e\} - d\{\varepsilon_0\}) \tag{5}$$

where $d\{\varepsilon_0\}$ indicates the additional strain due to the consideration of the effect of temperature on elastic modulus and can be expressed as:

$$d\{\varepsilon_0\} = \frac{\partial[D_e]^{-1}}{\partial T}\{\sigma\}dT \tag{6}$$

In the process of induction hardening, the total strain can be divided into elastic strain $\{\varepsilon_e\}$, plastic strain $\{\varepsilon_p\}$, thermal strain $\{\varepsilon_{th}\}$, strains due to phase transformation $\{\varepsilon_{tr}\}$ and transformation plasticity $\{\varepsilon_{tp}\}$. So, the total strain tensor, $\{\varepsilon\}$, can be described as:

$$\{\varepsilon\} = \{\varepsilon_e\} + \{\varepsilon_p\} + \{\varepsilon_{th}\} + \{\varepsilon_{tr}\} + \{\varepsilon_{tp}\} \tag{7}$$