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Thermomechanical analysis of steel cylinders quenching using a constitutive model with diffusional and non-diffusional phase transformations

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ABSTRACT

Quenching is a commonly used heat treatment process employed to control the mechanical properties of steels. In brief, quenching consists of raising the steel temperature above a certain critical value, called austenitizing temperature, and then rapidly cooling it in a suitable medium to room temperature. The resulting microstructures formed from quenching (ferrite, cementite, pearlite, upper bainite, lower bainite and martensite) depend on cooling rate and on steel characteristics. This article deals with the themomechanical analysis of steel cylinder quenching. A multi-phase constitutive model is employed for its modeling and simulation. Experimental analysis related to temperature evolution during the process and its resulting microstructure is used as a reference for the modeling effort. The thermomechanical coupling terms of the energy equation are included in the formulation. The through hardening of a cylindrical body is considered as an application of the proposed general formulation. Numerical simulations present good agreements with experimental data, indicating the model capability to capture the general thermomechanical behavior of the quenching process.

1. Introduction

Quenching is a heat treatment usually employed in industrial processes in order to control mechanical properties of steels as toughness and hardness. The process consists of raising the steel temperature above a certain critical value, holding it at that temperature for a specified time and then rapidly cooling it in a suitable medium to room temperature. The resulting microstructures formed from quenching (ferrite, cementite, pearlite, upper bainite, lower bainite and martensite) depend on cooling rate and on chemical composition of the steel. The volume expansion associated with the formation of martensite combined with large temperature gradients and non-uniform cooling can promote high residual stresses. Since these internal stresses can produce warping and even cracking of a steel body, the prediction of such stresses is an important task.

Phenomenological aspects of quenching involve couplings among different physical processes and its description is unusually complex. Basically, three couplings are essential: thermal, phase transformation and mechanical phenomena. The description of each one of these phenomena has been addressed by several authors by considering these aspects separately. Sen et al. (2000) considered steel cylinders without phase transformations. There are also references focused on the modeling of the phase transformation phenomenon (Hömberg, 1996; Chen et al., 1997; Çetinel et al., 2000; Reti et al., 2001). Several authors have proposed coupled models that are usually applicable to

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simple geometries as cylinders (Inoue and Wang, 1985; Melander, 1985; Sjöström, 1985; Denis et al., 1985, 1987, 1999; Denis, 1996; Fernandes et al., 1985; Woodard et al., 1999; Ju et al., 2006). Moreover, there are some complex aspects that are usually neglected in the analysis of quenching process. For example, one could mention the heat generated during phase transformation, transformation induced plasticity and volumetric expansion associated with phase transformation. The heat generated during phase transformation is usually treated by means of the latent heat associated with phase transformation (Inoue and Wang, 1985; Denis et al., 1987, 1999; Sjöström, 1994; Woodard et al., 1999). Meanwhile, other coupling terms in the energy equation related to other phenomena as plastic strain or hardening are not treated in literature and their analysis is an important topic to be investigated. Silva et al. (2004) analyzed the thermomechanical coupling during quenching considering austenite-martensite phase transformations. Afterwards, Silva et al. (2005) employed the finite element method to the quenching analysis. Kang and Im (2007a,b,c) presented a modeling effort employing the finite element model to perform numerical simulations. Results are in close agreement with experimental tests available in literature. Sinha et al., (2007) and Huiping et al. (2007) are others interesting contributions considering multi-phase models.

This article deals with the themomechanical analysis of steel cylinder quenching. A multi-phase constitutive model is employed for its modeling and simulation. Diffusional and non-diffusional phase transformations are considered in the formulation. Experimental analysis related to temperature evolution during the process and its resulting microstructure is used as a reference for the modeling effort. The kinetics of the diffusive transformations is described by the Johnson, Mehl, Avrami and Kolmogorov (JMAK) law (Avrami, 1940; Cahn, 1956), while non-diffusive transformations are described by the Koistinen–Marburger law. The thermomechanical coupling terms of the energy equation are analyzed considering the latent heat associated with phase transformation. This model is a first approach to represent thermomechanical couplings in the energy equation associated with phase transformation, plasticity and hardening, allowing the investigation of the effects promoted by these coupling (Silva et al., 2004).

A numerical procedure is developed based on the operator split technique (Ortiz et al., 1983) associated with an iterative numerical scheme in order to deal with nonlinearities in the formulation. Under this assumption, the coupled governing equations are solved from four uncoupled problems: thermal, phase transformation, thermoelastic and elastoplastic. The proposed general formulation is applied to the through hardening of steel cylinders. Numerical results show that the proposed model is capable of capturing the general behavior observed on experimental data. Besides, numerical results present a good agreement with those of experimental data (Oliveira et al., 2003; Oliveira, 2004).

2. Phenomenological aspects of phase transformations

Quenching of steel is the rapid cooling of steel heated to the austenitizing temperature. Depending on the cooling rate imposed by the type of quenching medium and chemical composition of the steel, transformation of the austenite phase into different microstructures can arise as: ferrite, cementite, pearlite, upper bainite, lower bainite and martensite. In order to deal with all these microstructures in a macroscopic point of view, the volume fraction of each one of these phases is represented by β_m (austenite $m = 0$, ferrite $m = 1$, cementite $m = 2$, pearlite $m = 3$, upper bainite $m = 4$, lower bainite $m = 5$ and martensite $m = 6$). All of these phases may coexist, satisfying the following constraints: $\sum_{m=0}^{6}\beta_m = 1$ and $0 \leqslant \beta_m \leqslant 1$ $(m = 1, .., 6)$, where $\beta_0 = \beta_A$ and $\beta_6 = \beta_M$. Reverse transformations from parent to the austenitic phase ($\beta_m \to \beta_A$; $m = 1, .., 6$), which occurs during heating, are not considered.

Phase transformation from austenite to martensite is a non-diffusive process, which means that the amount of volume fraction is only a function of temperature (Chen et al., 1997; Çetinel et al., 2000; Reti et al., 2001). This process may be described by the equation proposed by Koistinen and Marburger (1959),

$$\beta_M = \beta_A^0[1 - e^{-k(M_s - T)}] \tag{1}$$

where β_A^0 is the amount of austenite at the beginning of martensitic transformation, k is a material property and T is the temperature. Under a stress-free state, M_s and M_f are the temperatures where martensitic transformation starts and finishes its formation. Assuming M_f as the temperature where martensitic phase reaches an amount of 99%, from Eq. (1), $k = 2\ln(10)/(M_s–M_f)$. In order to incorporate these limits in Eq. (1) and also to assure that the martensite transformation only occurs during cooling, the following condition is defined by using the Heaviside function, $\Gamma(x)$, (Hömberg, 1996; Chen et al., 1997):

$$\varsigma_{A \to M}(\dot{T}, T) = \Gamma(-\dot{T})\Gamma(M_s - T)\Gamma(T - M_f) \tag{2}$$

where dot represents the differentiation with respect to time t. Therefore, the evolution of martensitic phase can be rewritten in a rate form as follows:

$$\dot{\beta}_M = \varsigma_{A \to M}\beta_A^0[(1 - \beta_M)k\dot{T}] \tag{3}$$

Pearlite, cementite, ferrite and bainite formations are diffusion-controlled transformations, which mean that they are time dependent. The evolution of these phase transformations can be predicted through an approximate solution using data from Time–Temperature-Transformation diagrams (TTT) (Çetinel et al., 2000; Reti et al., 2001). The analysis of phase transformation using this diagram is done by assuming that the cooling process may be represented by a curve divided in a sequence of isothermal steps, with a duration Δt, as shown in the Continuous-Cooling-Transformation diagram (CCT) of Fig. 1a. Through each isothermal step, the phase evolution is calculated by considering isothermal transformation kinetics expressed by the JMAK law (Avrami, 1940; Cahn, 1956; Çetinel et al., 2000; Reti et al., 2001):

$$\beta_m(t) = \hat{\beta}_m^{\max}[1 - e^{-b_m(t)^{N_m}}] \quad (m = 1, \ldots, 5) \tag{4}$$

where