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Modeling and Simulation of Quenching and Tempering Process in steels

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Abstract

Quenching and tempering (Q&T) is a combined heat treatment process to achieve maximum toughness and ductility at a specified hardness and strength. It is important to develop a mathematical model for quenching and tempering process for satisfy requirement of mechanical properties with low cost. This paper presents a modified model to predict structural evolution and hardness distribution during quenching and tempering process of steels. The model takes into account tempering parameters, carbon content, isothermal and non-isothermal transformations. Moreover, precipitation of transition carbides, decomposition of retained austenite and precipitation of cementite can be simulated respectively. Hardness distributions of quenched and tempered workpiece are predicted by experimental regression equation. In order to validate the model, it is employed to predict the tempering of 80MnCr5 steel. The predicted precipitation dynamics of transition carbides and cementite is consistent with the previous experimental and simulated results from literature. Then the model is implemented within the framework of the developed simulation code COSMAP to simulate microstructure, stress and distortion in the heat treated component. It is applied to simulate Q&T process of J55 steel. The calculated results show a good agreement with the experimental ones. This agreement indicates that the model is effective for simulation of Q&T process of steels.

Keywords: Quenching and tempering; phase transformation kinetics; tempered martensite; carbide; hardness

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1. Introduction

Quenching and tempering (Q&T) is a combined heat treatment process which consists of quenching and high temperature tempering. It is a common process used in the manufacture of steel components. During Q&T process,

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as-quenched steels are tempered to achieve optimum mechanical properties tailored to fit specific application (Babu, 2007). The final properties of a quenched and tempered steel part depend on the microstructure that evolves during the Q&T process. In practice, the Q&T process is designed by empirically determining and trail-and-error methods. However, there is much less predictive ability can be employed to components that vary in material composition and geometry or both (Bhadeshia et al., 2006). Furthermore, the thermodynamic and kinetic mechanisms have not been developed perfectly. Therefore, computer simulations are employed to model microstructural evolutions during Q&T process of steels.

In the past decade, many researchers have developed various theoretical and numerical models for Q&T process. In the 1990s, Ju and Inoue (Inoue et al., 1992; Ju et al., 1996) proposed a metallo-thermo-mechanical model to predict the kinetics of quenching-tempering process. Around the same time, Aubry and Denis (Aubry et al., 1997; Denis et al., 1999) have developed the global kinetics of tempering in low-alloy steels. The tempering kinetics on heating was calculated by isothermal transformation (IT) tempering diagram additivity. Then Wang and Denis (Wang et al., 2004; Wang et al., 2006) presented a model for describing the concomitant precipitation of ε--carbide and cementite during the tempering of martensite, including the nucleation, growth, coarsening process of carbides. Liu et al. (Liu et al., 2003; Shi et al., 2004) developed a model based on tempering parameter to predict the micro-structural evolution during Q&T process. In their model, tempering parameters presented the combined effects of both heating time and temperature on tempering process. Recently, the tempering kinetics equation was developed by Lee et al. (Lee et al., 2008; Jung et al., 2009) using tempered martensite fractions (calculated by experiment) and the measured strain changes at each tempering stage. Rajeev and Jin (Jin, 2001; Rajeer et al., 2009) presented a mathematical model implemented using the finite element (FEM) method. The model could predict microstructure, distortion, and residual stress distribution in quenched and tempered steel. Smoljan (Smoljan et al., 2009; Smoljan et al., 2010) developed an experimental regression model to predict hardness, strength and fatigue properties of quenched and tempered steel. However, these models modeled only some aspects of phase transformation during Q&T process.

In the present study, a quantitative model is constructed to simulate the micro-structural evolution during the tempering process of carbon steel by modifying the previous model in COSMAP (Computer Simulation of Manufacturing Process). The paper is organized as follows: the transformation kinetics model and hardness regression equation are described in section 2, the model validation are presented in section 3, and the conclusions are given in the final section.

2. Model description

In the present model, the microstructure evolutions are modeled for quenching process and tempering process respectively. The product phases in quenching consist of bainite, pearlite and martensite. If the steel is cooled slowly, the austenite would transform to relatively soft pearlite, which is the equilibrium phase at room temperature. If the steel is cooled very rapidly, a very hard and strong structure called martensite forms that is a metastable phase of carbon dissolved in iron. It may be tempered to produce lower hardness structures that are less brittle. Intermediate cooling rate would produce other structures referred to as bainite. The transformation in tempering involves mainly precipitation of carbides and decomposition of retained austenite.

2.1. Transformation kinetics model during quenching

During quenching, steels are heated and maintained above the austenitizing temperature and then rapidly cooled to the ambient temperature. There have two kinds of phase transformation mechanism in quenching process, namely diffusional transformation and diffusionless transformation. The detail of introducing for transformation kinetics model is already presented in the previous articles (Inoue et al., 1992; Ju et al., 1996).

2.2. Transformation kinetics model during tempering

Tempering is the process of heating martensitic steels to elevated temperature to obtain more ductile. It involves the segregation of carbon to lattice defects, the precipitation of carbides and the decomposition of retained austenite. It is general accepted that the tempering can be divided into four distinct but overlapping stages (Liu et al., 1988).

It is assumed that carbon is partitioning between martensite, ε-carbide and cementite. The carbon concentration in martensite can be calculated by the following equation

$$C_0 = (1-\xi_\varepsilon-\xi_\theta)C_{\alpha'} + C_\varepsilon\xi_\varepsilon + C_\theta\xi_\theta$$

* MERGEFORMAT (1)

where, C_0 is the nominal carbon concentration of the steel, C_ε and C_θ are the carbon concentration in ε-carbide and cementite respectively, ξ_ε and ξ_θ are the volume fraction of the predicted ε-carbide and cementite respectively.

It is assumed that the precipitation process of ε-carbide and cementite are independent of each other. Since the solute concentration in the matrix in equilibrium with the metastable ε-carbide is higher than that of cementite, and as the cementite appear, ε-carbide gradually disappear. The kinetics of precipitation of cementite can be described by Johnson-Mehl-Avrami (JMA) for heterogeneous solid-state reactions

$$\xi_\theta = \xi_{\theta,\max}(1-\exp\left\{-\beta_\theta^{\,n_\theta}\right\})$$

* MERGEFORMAT (2)

where β_θ is a state coefficient of cementite.

It is assumed that the precipitation process of ε-carbide and cementite are independent of each other. Since the solute concentration in the matrix in equilibrium with the metastable ε-carbide is higher than that of cementite, and as the cementite appear, ε-carbide gradually disappear. The kinetics of precipitation of cementite can be described by Johnson-Mehl-Avrami (JMA) for heterogeneous solid-state reactions

$$\xi_\varepsilon = \xi_{\varepsilon,\max}\left[(1-\exp\left\{-\beta_\varepsilon^{\,n_\varepsilon}\right\})\Big/(1-\exp\left\{-\beta_\theta^{\,n_\theta}\right\})\right]$$

* MERGEFORMAT (3)

During tempering stage 2, retained austenite after quenching decomposes into a mixture of cementite and ferrite. Decomposition of retained austenite is similar with the original austenite transformation in quenching process. The kinetics of decomposition of retained austenite can be described by a modified Avrami equation

$$\xi_i = \xi_{i,\max}\left\{1-\exp(-\frac{4}{3}\pi\int_0^t f(T)(t-\tau)^{n_i}\,d\tau\right\}$$

* MERGEFORMAT (4)

For ferrite and cementite, n_α and $n_{\theta 2}$ is 2.5 and 3 respectively. The critical temperature of decomposition for the retained austenite is regressed and given by $T_C = 490.50 + 977.65C_0 - 417.57{C_0}^2$.

2.3. Hardness regression equation

The hardness during quenching and tempering (Q&T) process can be predicted by the experimental regression equation

$$H_v = \sum_{M=1}^{M_P}\gamma_M\xi_M + \sum_{K=1}^{K_N}\eta_K \mathrm{C}_K$$

* MERGEFORMAT (5)

where, ξ_M and γ_M are iron-carbon phase (including martensite, ε-carbide, cementite, bainite and ferrite) composition and weighted coefficient, C_K and η_K are alloy element content and weighted coefficient.

3. Model Validation

3.1. Precipitation kinetics during tempering process

The precipitation kinetics of ε-carbide and cementite are simulated by the present model for tempering of 80MnCr5 (0.8C-1.25Mn-1.25Cr) steel. The tempering treatment are modeled at different tempering temperature (673 K, 873 K) with a heating rate of 10 K/s. Fig.1 shows that the simulated precipitation kinetics of carbide for different tempering temperature. It can be seen that the volume fraction of cementite increases and reaches the maximum value $\xi_\theta^{\max}$, and as the cementite concentration increase, the ε-carbide gradually disappear. The simulated results are consistent with the previous literature results (Wang et al., 2004; Wang et al., 2006). Therefore, the tempering kinetics model can be employed to simulate the tempering process of steel.

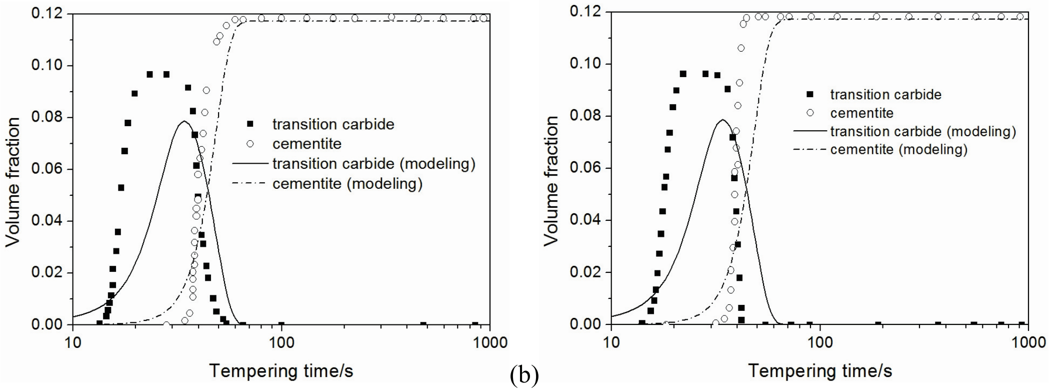

Fig. 1. Simulated volume fraction in different tempering temperature for 80MnCr5 (a) 673K; (b) 873K.

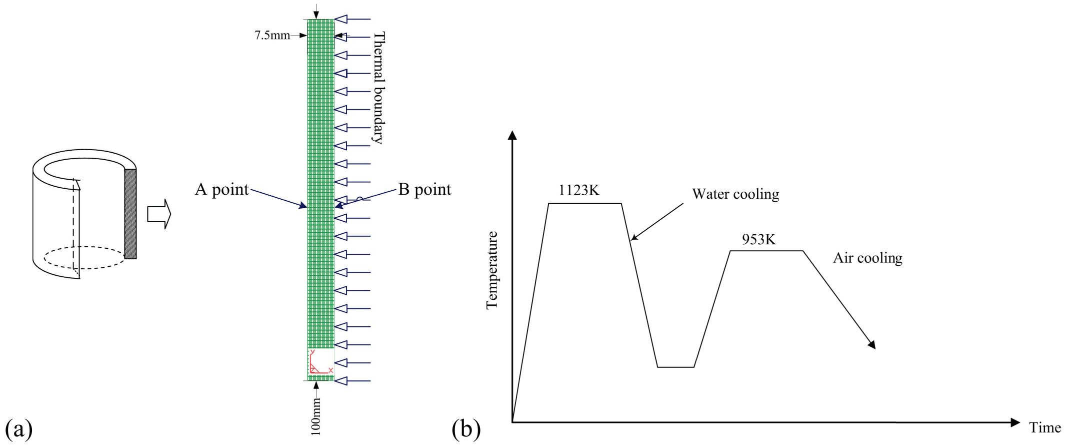

Fig. 2. (a) 2-D finite element mesh of a steel pipe, (b) Temperature history during quenching and tempering process.

3.2. Precipitation kinetics during tempering process

Table 1. Chemical compositions of J-55 steel.

Chemical elements	Fe	C	Si	Mn	P	S
Wt%	98.04	0.25	0.03	1.60	0.03	0.03

The series of equations governing the Q&T process, developed above, are to be numerically solved by the finite element (FEM) code COSMAP. To validate further the transformational dynamic model, the simulations are presented for Q&T process of J-55 steel. In this paper, the FEM model of a steel pipe of J-55 steel for Q&T is used as shown in Fig. 2 (a). The mesh division is depicted in Fig. 2 (a) for FEM calculation of steel pipe. Due to the symmetry, one half of the cross-section is adopted for meshing by nodes and elements. An axisymmetric quadrilateral iso-parameter element with four nodes is employed. The thermal boundary conditions are the flux type and shown in Fig. 2(a). The chemical composition of J-55 is listed in Table 1. The schematics of Q&T process are shown in Fig. 2(b). During quenching stage, the specimen is heated up to 1123K and then quenching into water quenchant of 25℃. During tempering stage, the specimen is reheated up to 953 K and finally air cooled to room temperature.

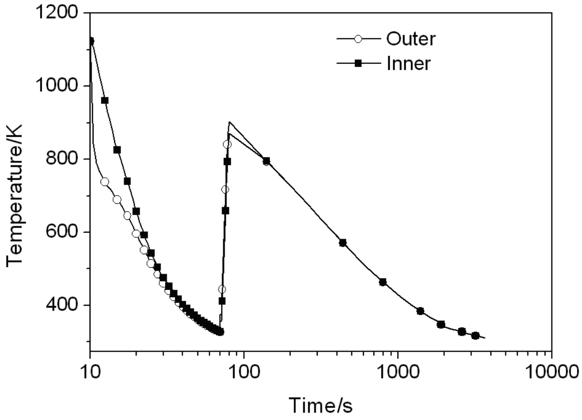

Fig.3. Simulated temperature variations with time during Q&T process.

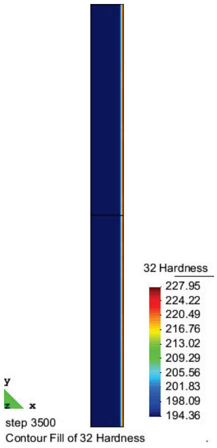

Fig. 4. Hardness distributions after Q&T process.

Fig. 3 shows the temperature variation at both outer (point B) and inner (point A) surface of pipe. During the quenching process, the temperature drops quickly at the outer surface, whereas the cooling velocity at inner surface is relatively slow. It is indicated that the temperature history between outer and inner surface has a difference.

Fig. 4 shows the hardness distributions after Q&T process. The simulated hardness results are in good agreement with the measured data 224 HV (outer surface) and 195 HV (inner surface). The hardness results are dependent on volume fraction of iron-carbon phase. Hardness of outer surface is higher owing to the martensite and cementite phase is harder than bainite.

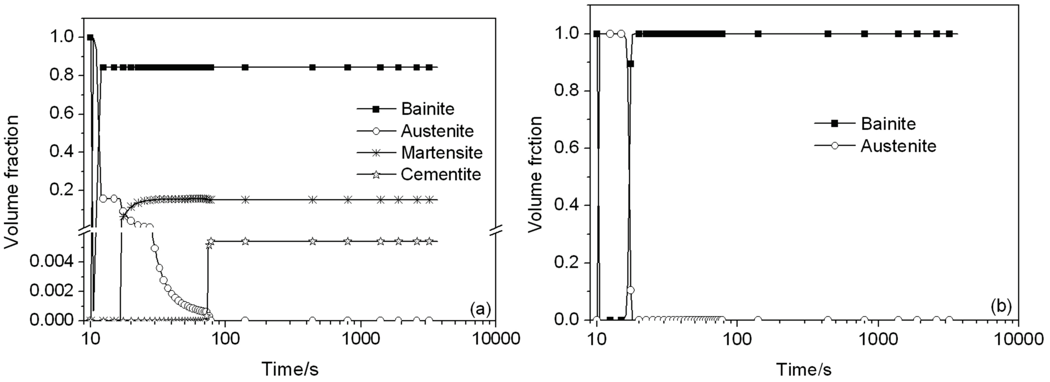

Fig. 5. Iron-carbon phases variations with time (a) Outer surface; (b) Inner surface.

Fig. 5 shows the microstructure evolutions of iron-carbon phases during quenching and tempering (Q&T) process at outer (point B) and inner (point A) surface respectively. It can be seen from Fig. 5(b) that the bainite formed by austenite-bainite transformation and there is no other transformation. The reason is that the temperature drops slowly and the movement of carbon atoms can be occurred. Fig. 5(a) shows both bainite and martensite form after quenching. At the outer surface, the temperature drops sufficiently fast so that martensite can be formed by the austenite-martensite transformation. It is observed from Fig. 5(a) that cementite precipitated from martensite during tempering process. The volume fraction of ε-carbide is negligible owing to the low carbon content and martensite. The final microstructures after Q&T consist of bainite, low-carbon martensite and cementite.

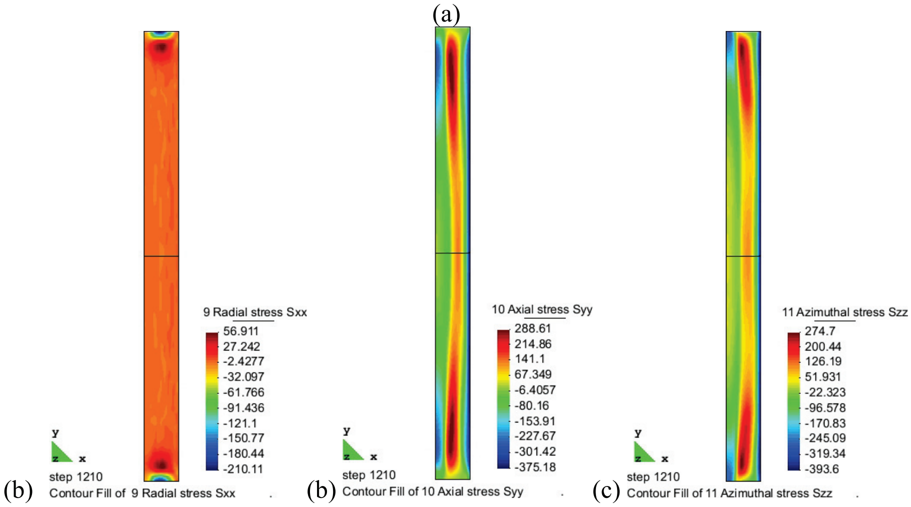

Fig. 6. Stress distributions after quenching (a) Radial stress; (b) Axial stress; (c) Circumferential stress.

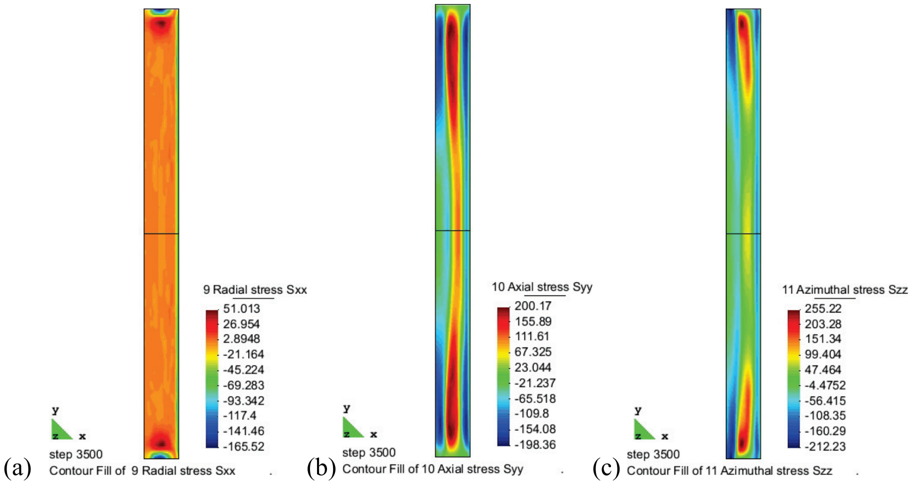

Fig. 7. Stress distributions after tempering (a) Radial stress; (b) Axial stress; (c) Circumferential stress.

Stress distributions after quenching and tempering are depicted in Fig. 6 and Fig. 7 respectively. In the present model, total strain rate is composed of elastic, plastic, thermal, transformation plasticity strain rates and the strain due to the volume dilatation associated with the different phase transformations. The model considers both the effect of temperature history and phase transformations on the stress behavior. During quenching process, due to the dilatation caused by martenstic and bainitic transformation on the surface of pipe, large compressive stress is induced near the inner and outer surface. Compared with Fig. 6, the stress significantly reduces after tempering is shown in Fig. 7. The reason tempering reduces the residual stress is that transformations in tempering process cause a volume and transformation strain decrease. It is indicated that precipitation of ε-carbide causes a volume decrease by 0.52 pct and precipitation of cementite causes a volume decrease by 0.66 pct. The volume decrease has considerably greater than volume increase caused by the decomposition of retained austenite (0.33 pct) (Liu et al., 1988). The simulated stress results are consistent with the theoretical analysis. From the above results, it can be concluded that tempering heat treatment can relax the residual stress.

4. Conclusions

A modified transformation kinetics model and hardness equation were developed and implemented in finite element code COSMAP. The model could predict the distributions of temperature, iron-carbon phases, hardness and residual stress. The precipitation kinetics of tempering process for 80MnCr5 steel is simulated and agrees well with previous literature results.

To validate further model, the COSMAP were employed to simulate Q&T process of J-55 steel pipe. The simulated results indicated that the volume fraction of iron-carbon phases were dependent on temperature history and carbon content. The final microstructure had a significant difference between outer and inner surface. This phenomenon was caused by the different cooling velocity. The simulated stress results confirmed that the tempering can relax the residual stress caused by quenching and were consistent with the theoretical conclusions. The hardness distributions could be predicted based on phase composition and alloy elements content. The simulated hardness results agreed well with the measured ones. Therefore, the transformation kinetics model can be predicted the microstructural evolution and mechanical properties in Q&T process of steels.

Acknowledgements

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