Acta Materialia 109 (2016) 394–404

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Transformation kinetics and density models of quenching and partitioning (Q&P) steels

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ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form
23 November 2015
Accepted 27 November 2015

Keywords:
Isothermal heat treatments
Dilatometer
Phase transformation kinetics
Martensite transformation
Quenching and partitioning

ABSTRACT

Thermal dilatation during an isothermal partitioning process below the martensite start temperature (M_s) was characterized and modeled for quenching and partitioning (Q&P) steel sheet. The dilatations were attributed to changes in the phase composition and phase density due to austenitic decomposition and carbon partitioning. To develop a prediction model for the dilatation during the Q&P process, conventional kinetics models for non-diffusional and diffusional phase transformations were improved by introducing the evolution of the transformation rate parameters during the austenitic decomposition. Furthermore, a kinetics equation for carbon partitioning was also proposed after considering the effect of constituent martensite on the partitioning rate. Finally, variations of the phase densities in the partitioned phases were modeled to describe the effect of carbon partitioning on the dilatation. The proposed models were implemented in a finite element code, and simulated dilatometry tests could accurately capture the experimentally measured dilation behaviors under the Q&P process with single and 2-stage partitioning conditions.

1. Introduction

Conventional steels have been replaced with so-called advanced high strength steels (AHSS) to take advantage of their higher strength. However, the limited ductility of AHSS causes a lower crash performance, which leads to early fracture upon impact. For this reason, recent research activity to manufacture automotive parts by applying AHSS has focused on how to secure both structural strength and ductility as in-service properties of the product. As for the high strength steels consisting of martensitic phase, conventionally, embrittlement in martensite can be enhanced through the elimination of supersaturated carbon by the tempering process [1]. However, the carbon atoms released from martensite are consumed by the iron carbide precipitation, which results in extra ductility but a loss in strength.

To enhance the balance of strength and ductility, a new concept of carbon partitioning between quenched martensite and retained austenite was introduced; i.e., the so-called quenching and partitioning (Q&P) process [2]. Experimental evidence for carbon partitioning from martensite into austenite has been found during isothermal tempering in a Si-added steel [3]. Slowly diffusing substitutional atoms can modify the thermodynamic equilibrium for meta-stability by minimizing the free energy. During this process, the ratios of iron to substitutional atoms are unchanged, and the chemical potentials of carbon in austenite and martensite are equal in each phase (para-equilibrium) [4]. Speer and his coworkers [2] defined a new model for this metastable condition that prohibits the short-range movement of iron and substitutional atoms and allows the free migration of carbon (or interstitials) with constraints in the phase interfaces as a constrained para-equilibrium (CPE).

The Q&P process can be applied to steels alloyed with non-diffusional substitutionals such as Si or Al that effectively suppress the movement of iron atom. To apply the CPE condition, the Q&P process requires quenched martensite and untransformed austenite. Because of the diffusional nature of carbon partitioning, a subsequent isothermal process is required after quenching. Ultimately, carbon-enriched austenite and carbon-consumed martensite are obtained as final microstructures of the Q&P

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http://dx.doi.org/10.1016/j.actamat.2015.11.051
1359-6454/

process, resulting in better formability of the partitioned martensite compared to the as-quenched. Furthermore, the enriched carbon in untransformed austenite stabilizes the austenite and provides more retained austenite at room temperature. During the impact or subsequent plastic deformation, a higher volume fraction of retained austenite would help absorb more impact energy as the austenite transforms into deformation-induced martensite (DIMT) [5]. Furthermore, the enriched carbon concentration also strengthens the partitioned austenite phase.

Prior studies report evidence for isothermal austenitic decomposition in Fe–C alloys during the holding process at a temperature between the martensitic start (M_s) and finishing (M_f) temperatures. Bohemen et al. observed a mixed microstructure of martensite and bainite that was formed by an isothermal transformation of austenite below M_s in Fe–0.69Mn–0.66C steel [6]. Kim and his coworkers also studied an isothermal transformation below the M_s temperature during the Q&P process of Si and Al added low carbon (0.15C) steels [7] and they could found the difference between the isothermal transformation and bainite transformation.

In order to apply the Q&P process to practical industrial applications such as automotive part forming, proper modeling and understanding on the phase transformation and carbon partitioning kinetics associated with the Q&P mechanism are required. Therefore, as the first objective of the present study, the kinetics during the partitioning process will be newly modeled based on the thermal dilatation measurement of the Q&P steel. To enhance the prediction accuracy of the newly proposed model, the conventional kinetics model for the diffusionless transformation of martensite will be revised to provide accurate information on the volume fraction and dilatation change against temperature. The kinetics model for diffusional transformation below M_s temperature will also be practically modified to predict the isothermal austenite decomposition during the Q&P process. Furthermore, a modeling procedure describing evolution of density for the partitioned phase due to the change of carbon concentration is developed. The proposed models are implemented in the finite element (FE) software to validate the developed models by predicting the dilatations of single and 2-stage partitioning under various thermal histories.

2. Experimental procedure

2.1. Materials

Q&P steel developed by POSCO (0.3C 1.5Mn 1.6Si 1.0Cr) was used. The Q&P steel sheet could exhibit enhanced in-service mechanical properties in terms of strength and toughness through carbon partitioning. The 1.6 wt% of Si was added as a non-diffusional substitutional. The sheet thickness was 1.5 mm.

2.2. Dilatometry experiments

A series of dilatometry tests was conducted to characterize the effect of the Q&P process on thermal strains. The thermal strains develop from (1) non-isothermal martensitic transformation, (2) isothermal transformation below the martensitic start temperature (M_s) and (3) phase density change due to carbon partitioning. Therefore, length changes in the dilatometry specimens were measured for two different thermal histories; i.e., (1) complete quenching for the kinetics of the athermal martensitic transformation and (2) interrupted Q&P for the kinetics of isothermal transformation and density change. A hexahedral shaped specimen of 10 mm × 1.5 mm × 1.5 mm (length × width × depth) was prepared by wire cutting. A K-type thermocouple was welded onto the specimen surface to measure the temperature of the specimen. The dilatation change was measured by the linear variable differential transformer (LVDT).

The specimen was heated up to 900 °C at a heating rate of 5 °C/s and held for 240 s for full austenitization. Then, the specimen was cooled to the predefined target temperature at a cooling rate of −10 °C/s. For the full martensitic transformation, the target temperature after cooling was room temperature. To observe the austenitic decomposition and density change during the isothermal partitioning process, 14 quenching temperatures were selected; i.e., 400, 385, 370, 355, 340, 325, 310, 295, 280, 265, 250, 220, 190 and 160 °C. The specimen was kept at each quenching temperature for 1400 s. Finally, the specimen was cooled to room temperature at a cooling rate of −10 °C/s.

2.3. Magnetic saturation measurement

The volume fraction of each phase after heat treatment was measured using the magnetic saturation method, which evaluates the total volume fraction of the ferritic phases, including martensite and the transformed phase during the isothermal partitioning process. The magnetic saturation of the tested dilatometry specimen was measured by applying an external magnetic field that induces the maximum magnetization. The volume fraction of ferritic phases could be estimated by calculating the total volume of the specimen using the information of the specimen weight and the density based on the chemical composition of the material. To calibrate the measurement, a sample specimen of the IF steel with a full (≥99.9%) ferritic microstructure was used to identify the reference value for the ferritic volume fraction. A feritscope (MSAT30, Metis Instruments & Equipment NV, Belgium) was used to determine the ferritic fraction of a sample. The equipment measures the magnetic moment of the sample with the corrections for chemical composition and shape when put in an external magnetic field. Magnetic field strength is over than 300 kA/m and probe aperture is 30 mm × 8 mm. Each measurement was repeated 10 times, and the volume fraction was calibrated with the reference.

3. Martensite transformation kinetics

3.1. KM model

The dilatation change ($\Delta L/L_0$) from 900 °C to room temperature was used to calculate the fraction of the transformed martensitic phase as a function of temperature by applying the lever rule. Here, ΔL and L_0 are the length change and initial length of the specimen.

The temperature dependency of the athermal martensitic transformation has been frequently captured by the kinetics model proposed by Koistinen and Marburger (KM model) [8]. The KM model is an exponential equation as a function of the undercooling below M_s; i.e., $f_m = 1-exp[-\alpha(M_s-T)]$. Here, the rate parameter α is usually assumed to be 0.011 for pure iron-carbon alloys and plain carbon steels. For the material considered in the present study, Fig. 1a shows significant nonlinearity in the plot of $(ln(ln(1/1-f_m)))$ against $ln(M_s-T)$, which requires improvement of the KM model. The figure illustrates that the curve consists of two linear regions at the beginning and end of the martensitic transformation and a transition between the two regions. The alloying elements to achieve better material properties may lead to the discrepancy between the KM model and experiments.

3.2. Modified KM model

To modify the original KM model by considering the nonlinearity in Ref. $(ln(ln(1/1-f_m)))$ vs.$ln(M_s-T)$ curve, the following equation is proposed [9].