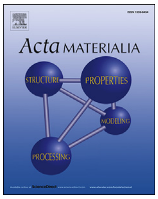
Acta Materialia 144 (2018) 666–678

Contents lists available at ScienceDirect

Acta Materialia

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



Elucidating the effect of Mn partitioning on interface migration and carbon partitioning during Quenching and Partitioning of the Fe-C-Mn-Si steels: Modeling and experiments

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ARTICLE INFO

Article history:
Received 23 September 2017
Received in revised form
7 November 2017
Accepted 13 November 2017
Available online 17 November 2017

Keywords:
Advanced high strength steels
Martensite
Austenite
Quenching and Partitioning

ABSTRACT

A fundamental understanding of carbon partitioning and the martensite/austenite interface migration during the Quenching & Partitioning (Q&P) process is essential for tailoring the microstructures of the advanced Q&P steels. In this study, two Q&P models (QP-LE and QP-PE), in which effects of substitutional alloying elements have been considered by assuming Local Equilibrium (LE) or Paraequilibrium (PE) at the interface, are proposed to simulate the kinetics of martensite/austenite interface migration and carbon partitioning in the Fe-C-Mn-Si steels. The QP-LE and QP-PE models predict that whether the interface migrates or not and its moving direction are dependent on quenching/partitioning temperature (QT/PT) and alloy composition. A careful comparison between experiments and model predictions indicates that the dependence of interface migration behavior on QT/PT indirectly measured by experiments during the Q&P process could be explained reasonably well by the QP-LE model, rather than the Constrain Carbon Equilibrium (CCE) model and the QP-PE model. The carbon partitioning behavior is also well predicted by the QP-LE model while the QP-PE model predictions deviate significantly from experiments. The current study suggests that interfacial partitioning of Mn plays a significant role in carbon partitioning and interface migration during the Q&P process.

1. Introduction

Quenching and Partitioning (Q&P) steel has been regarded as the 3rd generation advanced high strength steels (AHSS), and it is a promising candidate for future automobile applications. In the Q&P process, the steel is first quenched to a temperature between Martensite start temperature (Ms) and Martensite finish temperature (M_f) to obtain a mixture of martensite and austenite, and then reheated to a temperature above Ms to allow carbon partitioning from martensite into the preserved austenite [1,2]. The stability of austenite is enhanced by carbon partitioning, which will allow more austenite to be retained to room temperature. In order to describe carbon partitioning behavior during the partitioning process, a Constrain Carbon Equilibrium (CCE) model was initially proposed by Speer et al. [1,2]. In the CCE model, it is assumed that the martensite/austenite interface is immobile while carbon has equal chemical potential across the martensite/austenite interface. The martensite/austenite interface was indeed deduced to be immobile based on some dilatometer and X-Ray diffraction (XRD) experiments [3–6]. However, several recent experimental studies suggested that the martensite/austenite interface could be mobile during the Q&P process [7–11]. Zhong et al. [7] deduced that the martensite/austenite interface could migrate based on the observations that the straight martensite/austenite interface became curved after the partitioning process. In Refs. [8–11], an increase of body-centered cubic phase during the partitioning process was detected by the dilatometer or in-situ High Energy X-Ray diffraction (HE-XRD) experiments, which indicates interface migration from martensite into austenite or bainite formation. Austenite formation during the Q&P process in the high carbon steels was also detected by the in-situ neutron diffraction [12] and in-situ high resolution transmission electron microscope [13]. Based on the above analysis, the interface migration behavior during the Q&P process is still quite controversial, and the existing experimental results indicate that quenching/partitioning temperature and composition seem to play a very important role.

Besides experimental studies, much effort has also been made to develop theoretical models to simulate the martensite/austenite

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https://doi.org/10.1016/j.actamat.2017.11.025

Table 1
Chemical composition of the investigated steels (wt.%).

	C	Mn	Si	Fe
A	0.25	2.1	1.1	Bal.
B	0.59	2.9	2.0	Bal.

interface migration and carbon partitioning during the Q&P process [14,15]. It is usually assumed in the models that during the Q&P process only carbon would partition from martensite to austenite while substitutional alloying elements such as Mn do not partition due to their low diffusivity. However, recently, thanks to the fast development of three-dimensional atom probe tomography (3D-APT), nanoscale interfacial partitioning of substitutional alloying elements was detected at the martensite/austenite interface after the Q&P process [4,5,16–18], which is expected to affect the kinetics of martensite/austenite interface migration and carbon partitioning. In the past decades, much effort has been made to investigate substitutional alloying elements effects on the kinetics of ferrite/austenite interface migration during the austenite to ferrite transformation [19–29], and the progress on this topic has been well reviewed in Ref. [30]. It has also been experimentally and theoretically proven that interfacial partitioning of substitutional alloying elements could play a significant role in the kinetics of bainitic ferrite/austenite interface migration and carbon partitioning [31–35]. Despite its great importance for the design of Q&P steels, the effect of substitutional alloying element on the martensite/austenite interface migration has been relatively less studied [36–39].

In the current study, the so-called QP-PE and QP-LE models, in which the interface condition are assumed to be Paraequilibrium (PE) and Local Equilibrium (LE), respectively, have been proposed to investigate the effect of interfacial partitioning of substitutional alloying elements on interface migration and carbon partitioning during the Q&P process of the Fe-C-Mn-Si steels. A detailed comparison among the QP-LE, QP-PE and CCE models is made, and these three models are benchmarked by experiments. The importance of interfacial Mn partitioning on interface migration and carbon partitioning are discussed in details.

2. Experimental

In this study, two Fe-C-Mn-Si steels were selected to investigate the kinetics of interface migration and carbon partitioning during the Q&P process. Their chemical compositions are listed in Table 1. A Bahr DIL-805 dilatometer was used to measure the dilatation of the cylindrical dilatometric specimens with a size of ϕ4 × 10 mm during the Q&P process. The temperature programs during the Q&P process applied to steel A and B are illustrated in Fig. 1. Three quenching temperatures, 230 °C, 260 °C and 290 °C, were selected for steel A to study the influence of quenching temperature on interface migration and carbon partitioning. In order to evaluate the volume fractions of martensite at different quenching temperatures, the dilatation of one steel A sample quenched to room temperature at a rate of 10 °C/s to obtain full martensitic microstructure and then heated up at a rate of 20 °C/s to 400 °C was also recorded. Quenching temperature (QT), partitioning temperature (PT) and partitioning time (Pt) for steel A and B are indicated in Fig. 1.

The relative length change during the Q&P process could be attributed to carbon partitioning and phase transformations. Carbon partitioning from martensite into austenite will change the crystal lattice parameters and thus induce the dilatation [40,41]. The dilatation due to carbon partitioning can be estimated by the method in Refs. [37,42,43]. Assuming that the sample is isotropic, the relative length change$\Delta L/L_0$, could be estimated by:

$$\frac{\Delta L}{L_0}=\frac{L-L_0}{L_0}\approx\frac{1}{3}\frac{V-V_0}{V_0} \tag{1}$$

where L_0 and V_0 are the length and volume of sample at a reference state, respectively, L and V are the length and volume of sample at a certain state, respectively. Volume of sample is proportional to average atomic volume, V_a. According to the rule of mixture, V_a can be expressed as:

$$V_a=\frac{1}{4}a_\gamma^3(1-f_{\alpha'})+\frac{1}{2}a_{\alpha'}^2c_{\alpha'}f_{\alpha'} \tag{2}$$

where $f_{\alpha'}$ is the phase fraction of martensite, a_γ is the austenite lattice parameter, $a_{\alpha'}$ and $c_{\alpha'}$ are the martensite lattice parameters. The lattice parameters for austenite and martensite as a function of chemical composition and temperature are given by:

$$a_\gamma=\left(a_{\gamma,\mathrm{Fe}}+\sum_i k_i^\gamma x_i^\gamma\right)\left[1+\beta_\gamma(T-298)\right]\ (\mathrm{nm}) \tag{3A}$$

$$\beta_\gamma=\alpha_{\gamma,\mathrm{Fe}}+\sum_i \kappa_i^\gamma x_i^\gamma\ \left(K^{-1}\right) \tag{3B}$$

$$a_{\alpha'}=\left(a_{\alpha',\mathrm{Fe}}+k_{\mathrm{C}1}^{\alpha'}x_{\mathrm{C}}^{\alpha'}+\sum_i k_i^{\alpha'}x_i^{\alpha'}\right)[1+\beta_{\alpha'}(T-298)]\ (\mathrm{nm}) \tag{3C}$$

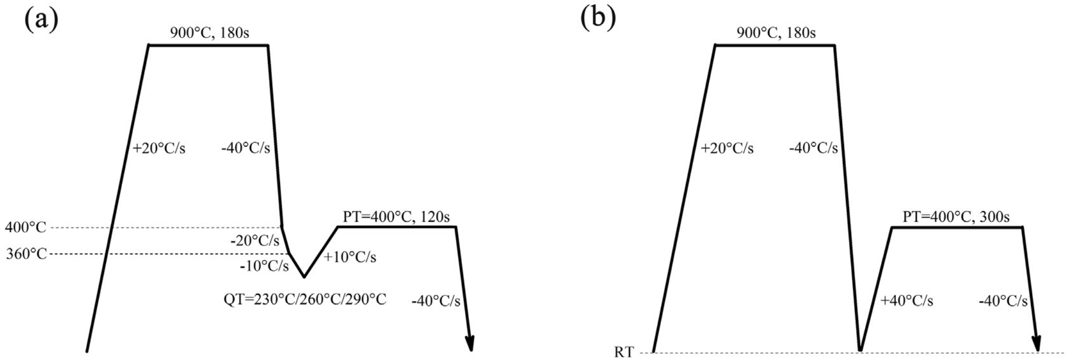

Fig. 1. Sketch of the Q&P process applied to (a) steel A and (b) steel B. QT: quenching temperature; PT: partitioning temperature; RT: room temperature.