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Interaction between recrystallization and phase transformation during intercritical annealing in a cold-rolled dual-phase steel: A cellular automaton model

Chengwu Zheng [a,b,*], Dierk Raabe [b,*]

[a] Institute of Metal Research, Chinese Academy of Sciences, Wenhua Road 72, Shenyang 110016, China
[b] Max-Planck Institut für Eisenforschung, Max-Planck-Straße 1, Düsseldorf 40237, Germany

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Abstract

The concurrent ferrite recrystallization and austenitic transformation during intercritical annealing of cold-rolled DP steels is investigated by cellular automaton (CA) modeling. The simulations provide insight into the microstructural phenomena that result from the interaction of primary recrystallization and phase transformation. We find that the interaction between ferrite recrystallization and austenite formation affects not only the transformation kinetics but also the morphology and spatial distribution of the austenite. From this we can interpret experimental data of the observed temperature-dependent hardness and its dependence on the two metallurgical processes. The influence of the initial heating rate on subsequent isothermal transformation kinetics and the microstructure evolution is also obtained by the model.

Keywords: Intercritical annealing; Ferrite recrystallization; Austenitization; Cellular automaton; Mesoscopic modeling

1. Introduction

Owing to a favorable combination of high strength and good formability, dual-phase (DP) steels are currently receiving high interest in the automotive industry for low energy consumption vehicle design through weight reduction [1–6]. The microstructure of DP steel is characterized by hard martensite islands dispersed in a soft and ductile ferrite matrix [7]. To generate DP microstructures, a continuous annealing process that includes reheating of a cold-rolled ferrite/pearlite microstructure followed by intercritical annealing is implemented to form an austenite/ferrite mixture, which after final quenching results in a DP microstructure [8]. During this process, microstructure formation is determined by a number of interacting metallurgical phenomena, of which ferrite recrystallization, austenite formation and carbon diffusion are the most important. What makes the prediction of DP microstructures challenging is the fact that these phenomena may proceed consecutively or simultaneously, i.e. complex local interactions between the metallurgical diffusion and transformation phenomena occur. The nonlinear character of the phenomena involved minor changes in these interactions, and this may have a profound influence on the resulting microstructure. On the other hand, from a theoretical point of view, it is also an essential challenge to quantitatively understand and evaluate the interdependence and competition between these two metallurgical processes.

In earlier studies, such potential interactions between recrystallization and phase transformation have been reported to occur for various intercritically annealed steels on materials that had been initially cold rolled [9–11]. Yang

* Corresponding authors. Address: Institute of Metal Research, Chinese Academy of Sciences, Wenhua Road 72, Shenyang 110016, China. Tel.: +86 24 83970106; fax: +86 24 83970097 (C. Zheng), tel.: +49 211 6792 340; fax: +49 211 6792 333 (D. Raabe).
E-mail addresses: chwzheng@hotmail.com (C. Zheng), d.raabe@mpie.de (D. Raabe).

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et al. [9] observed austenite nucleation both on grain boundaries of unrecrystallized ferrite and at the interfaces between recrystallized and unrecrystallized grains. This work revealed an influence of ferrite recrystallization on the formation and distribution of austenite. Huang et al. [10] systematically investigated the effect of the initial heating rate on austenite formation and ferrite recrystallization in two steels with chemical compositions that are typically used for DP and transformation-induced plasticity (TRIP) steels. They suggested that there was a strong interaction between ferrite recrystallization and austenite formation, which could affect the kinetics of austenite formation as well as its spatial distribution. Their findings were recently verified by Azizi-Alizamini et al. [11] in a plain low-carbon steel, including a similar morphology shift from randomly distributed to a banded structure of austenite when increasing the initial heating rate. Despite these important findings and their potential practical relevance, further investigations of such interaction phenomena as well as their potential effect on the final microstructure and properties of the steels annealed in the intercritical region are still required. More specifically, the interaction between the two metallurgical processes may cause property variations and makes it difficult to identify the relation between direct thermal processing settings and the final product properties. However, the approach of integrated microstructural simulation that includes all relevant metallurgical processes is ideally suited to provide the desired insight for this problem, which hence enables us to conduct quantitative microstructure design for optimal properties.

With the recent development of mesoscale microstructure-based transformation models [12], e.g. the cellular automaton (CA), the Monte Carlo (MC) and the phase field (PF), simulations can now provide deeper insight into the mechanism and morphological complexity of both the phase transformation and recrystallization in steels [13,14]. Numerical modeling is thus emerging as an alternative tool to investigate the interaction mechanism of recrystallization and phase transformation in DP steels. Recently, Rudnizki et al. [15] developed a PF model to describe the austenite formation from a ferrite–pearlite aggregate during the annealing of a cold-rolled DP steel. However, their simulation started from an already recrystallized microstructure. Hence, the approach did not consider the interaction between recrystallization and phase transformation. Bos et al. [16,17] presented an integrated three-dimensional (3-D) CA model to describe the through-process microstructure evolution during the entire processing of DP steels. In their model, simulation of concurrent ferrite recrystallization and austenite formation was involved. However, their interest was placed on the model development [16] and its usage on a study of the influence of individual transformation processes on the final DP microstructure [17], whereas the interaction between recrystallization and phase transformation was not addressed. Okuda et al. [18] performed an MC simulation to examine the competition between recrystallization and transformation in several DP microstructures. However, their model did not involve detailed thermodynamic criteria of either recrystallization or phase transformation.

In this work, we present a modified two-dimensional (2-D) CA model to investigate the competition between ferrite recrystallization and austenitic transformation during the intercritical annealing of cold-rolled DP steels. In this model, discrete microstructural constituents either in recrystallization or in phase transformation are depicted through involving relevant thermodynamic criteria (stored deformation energy, chemical transformation driving force, etc.) and kinetic effects (grain boundary mobility, carbon diffusion, etc.), so that a detailed microstructural insight into the mutual interactions between these various metallurgical processes can be obtained. This model also enables us to study the influence of initial heating rate and annealing temperature on subsequent isothermal transformation kinetics and the associated microstructure evolution.

2. Model concept

2.1. Austenite transformation

During the intercritical annealing of DP steels, two different situations of austenite nucleation are usually considered [19,20]. One is related to the austenite formation at the ferrite/cementite interfaces within the carbon containing colonies, e.g. within the pearlite. The other is the nucleation on the ferrite/ferrite grain boundaries. In general, nucleation of austenite starts from the pearlite colonies. The newly formed austenite nuclei grow rapidly at the expense of the pearlite and subsequently of the ferrite. During this process, austenite growth is mainly limited by carbon diffusion inside the austenite, as schematically represented in Fig. 1. The transformation proceeds much faster for the pearlite-nucleated austenite than that in ferrite due to the

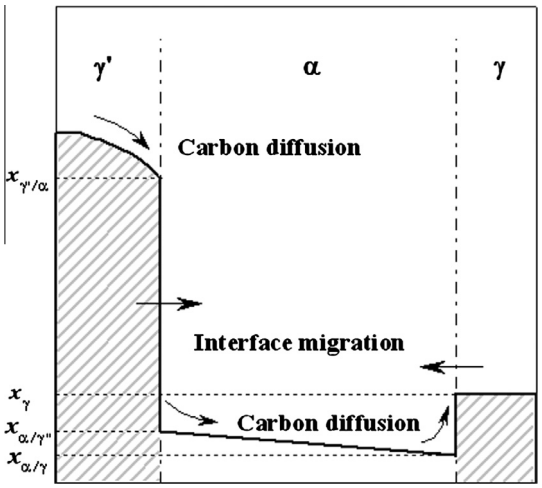

Fig. 1. Schematic drawing about the variation in the carbon content across the austenite–ferrite boundary [20]: γ' = pearlite-nucleated austenite, α = ferrite and γ = grain-boundary-nucleated austenite.