Acta Materialia 100 (2015) 155–168

Contents lists available at ScienceDirect

Acta Materialia

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

Recrystallization behavior of a high-manganese steel: Experiments and simulations

Christian Haase [a,*], Markus Kühbach [a], Luis A. Barrales-Mora [a], Su Leen Wong [b], Franz Roters [b], Dmitri A. Molodov [a], Günter Gottstein [a]

[a] Institute of Physical Metallurgy and Metal Physics, RWTH Aachen University, Aachen 52074, Germany
[b] Max-Planck-Institut für Eisenforschung GmbH, Max-Planck-Str. 1, Düsseldorf 40237, Germany

ARTICLE INFO

Article history:
Received 25 June 2015
Revised 22 August 2015
Accepted 23 August 2015

Keywords:
TWIP steel
Recrystallization
Simulation
3D Cellular Automaton
CP-FEM
Texture
Grain boundary nucleation
Kinetics

ABSTRACT

The thermal treatment of a 30% cold-rolled Fe–28Mn–0.28C Twinning-Induced Plasticity (TWIP) steel was investigated. The low degree of rolling served to exclude the effect of shear banding but to capture the characteristic texture evolution. A detailed microstructure and texture characterization was performed by means of SEM/EBSD, X-ray texture analysis, and hardness measurements. Specifically, the dislocation density distribution was computed using a Crystal Plasticity Finite Element Method (CP-FEM) framework and the primary recrystallization was modeled by means of a Cellular Automaton (CA) approach. The macrotexture of the recrystallized state was controlled by (i) retainment of the deformation texture components during nucleation due to oriented nucleation and (ii) the formation of new orientations by recrystallization twinning. The nucleation of new grains occurred heterogeneously at grain boundaries. The experimental results were used as input data for simulations. The results from the CP-FEM simulations in the form of orientation-resolved dislocation densities and the orientation and density of recrystallization nuclei extracted from SEM/EBSD measurements were directly transferred into a 3D CA for the simulation of primary recrystallization. The results substantiated that the consideration of realistic simulation scenarios in terms of microstructural inhomogeneity and annealing twin formation is essential for an accurate prediction of the recrystallization behavior of the investigated high-manganese steel.

1. Introduction

During the past two decades the commercial and scientific interest in high-manganese Transformation- and Twinning-Induced Plasticity (TRIP/TWIP) steels has constantly increased due to their outstanding mechanical properties [1–3]. The combination of ultra-high strength, high ductility, and work-hardening capacity makes these steels especially suitable as crash-relevant structural components in automobiles in order to increase passengers' safety, to reduce the body-in-white weight and therefore, to contribute to meet CO_2 emission targets [4]. For this reason, most of the research dedicated to high manganese steels has focused on the characterization of the mechanical properties [5,6], the evolution of deformation microstructures [7,8], on the texture development during cold rolling and tensile testing [9–15], and modeling of the strain hardening behavior [16–18]. By contrast, recrystallization and its impact on texture and microstructure of high-manganese steels during heat treatment have been only sparsely studied experimentally so far [10,19–31]. In addition, only few simulation studies have been dedicated to the microstructural evolution of these materials during their thermo-mechanical processing, i.e. deformation and annealing [13,32,33]. The present contribution aims at removing this deficit by a combination of experiments and computer simulations. For this purpose, the microstructure and texture of a 30% cold-rolled Fe–28Mn–0.28C TWIP steel were comprehensively characterized experimentally and the obtained data were utilized as input for the simulations. The benefit of this strategy is that it allows clarifying the significance and the interplay of recrystallization mechanisms in a reproducible and well-controllable system.

Different models can be utilized to simulate the relevant physical processes, which lead to microstructural changes during processing of crystalline materials. For instance, plastic deformation can be simulated with cluster-type [34,35], viscoplastic [36,37] or Crystal Plasticity Finite Element Method (CP-FEM) models [38,39]. In turn, for recrystallization and grain growth level-set [40,41], phase-field [42,43], cellular automata [44], and vertex

* Corresponding author.
E-mail address: haase@imm.rwth-aachen.de (C. Haase).

http://dx.doi.org/10.1016/j.actamat.2015.08.057
1359-6454/

models [45–47] can be utilized. CP-FEM models for the simulation of deformation and Cellular Automaton (CA) models respectively for recrystallization have been shown to yield excellent time and space resolved mesoscopic microstructure predictions. Thus, both approaches were used in this study. They are summarized in the following:

(i) In the CPFEM simulations deformation twinning was considered in addition to crystallographic slip. Following the ideas in [48], twinning can be interpreted as an operation of additional, though, unidirectional deformation systems. The total plastic deformation gradient can thus be calculated as the sum of both crystallographic slip and deformation twinning according to Eq. (1)

$$L_p = \left(1 - \sum_{\beta=1}^{n_{twin}} f^{\beta}\right) \sum_{\alpha=1}^{n_{slip}} \dot{\gamma}^{\alpha} \boldsymbol{m}^{\alpha} \otimes \boldsymbol{n}^{\alpha} + \sum_{\beta=1}^{n_{twin}} \dot{f}^{\beta} \gamma_{twin} \boldsymbol{m}^{\beta} \otimes \boldsymbol{n}^{\beta} \qquad (1)$$

with n_{slip} and n_{twin} being the numbers of the slip and twin systems, respectively. f^{β} is the twin volume fraction of twin system β, $\dot{\gamma}^{\alpha}$ is the shear rate of slip system α with slip direction $\boldsymbol{m}^{\alpha}$ and slip plane normal $\boldsymbol{n}^{\alpha}$, γ_{twin} is the characteristic twinning shear and $\dot{f}^{\beta}$ is the twinning rate on twin system β with direction $\boldsymbol{m}^{\beta}$ and plane normal $\boldsymbol{n}^{\beta}$. For calculating $\dot{f}^{\beta}$ an adaption of the twin nucleation and growth model described in [18], as presented in [25], is used. The evolution equations for the dislocation densities are outlined in [38].

(ii) Cellular automata for recrystallization are based on the idea that recrystallization can be abstracted as a simple change of state, i.e. from the deformed to the recrystallized one. We used an advanced CA code [49] that treated the change of state as a discrete local process which was controlled by the thermally activated physical velocity of a moving grain boundary segment [50]:

$$v = m \cdot p = m_0 \exp(-H/kT) \cdot \left(\frac{1}{2} G b^2 \rho_{def}\right) \qquad (2)$$

where m is the mobility of the grain boundary, p is the driving force, and H and m_0 are the migration activation enthalpy and the preexponential factor of that boundary segment, respectively. The driving force is controlled by the local dislocation density ρ_{def} in front of the boundary. The model was recently tailored to massive parallel computation for high-speed simulations of significantly larger systems with outstanding spatial resolution [51].

In previous studies [52,53], a 3D CA was used to simulate the macrotexture evolution during recrystallization of TRIP/TWIP steels taking the experimental deformation texture but assuming an overall homogeneous dislocation density as input data, and thus, low predictive power, since the simulation setups departed essentially from realistic scenarios. In order to perform simulations closer to experiments, it is necessary to feed the simulation models with real data. For this reason, we combined a parallel 3D CA (on the basis of the CA used in [51–53]) and comprehensive experimental characterization. The preceding deformation of 30% thickness reduction by cold rolling was simulated using DAMASK code developed by Roters at Max-Planck-Institut für Eisenforschung GmbH [38,54] and Steinmetz et al. [18], which was proven to predict with excellent accuracy the work-hardening behavior of TWIP steels. In typical industrial processes higher deformation degrees are normally applied. In the present study, the cold rolling degree was restricted to 30% to avoid the complications of shear banding at higher strains on the modeling of the deformed structure, so that only the dislocation density variation contributed to the microstructural inhomogeneity. On the other hand, the essential deformation texture components develop already at relatively low degrees of deformation, so that the rolling texture can be accounted for in the CA simulations. From the CP-FEM simulations, grain orientations and dislocation densities were obtained and input into the CA. Nucleation phenomena and microstructure evolution during recrystallization were characterized by experimental methods and served as the basis for both the initial CA setup and the final critical assessment.

2. Applied methods

2.1. Experimental

2.1.1. Material chemistry and processing

The exact chemical composition of the investigated Fe–28Mn–0.28C TWIP steel as well as a detailed description of the processing scheme are given in [11]. The stacking fault energy (SFE) of this alloy was estimated to be about 27 mJ/m^2 using a sub-regular solution thermodynamic model [55].

The recrystallization behavior was studied on 30% cold-rolled sheet specimens. After deformation the samples were annealed in an air furnace at 700 °C for different annealing times. In addition, the microstructure evolution in a randomly chosen but identical sample area was tracked by repetitive annealing in an argon furnace followed each time by 'quasi in-situ' electron backscatter diffraction (EBSD) analysis.

2.1.2. Specimens and characterization techniques

Steel specimens of dimensions 10 mm × 12 mm (transverse direction (TD) and rolling direction (RD)) were cut from the cold-rolled and annealed sheets. Subsequently, the specimens were ground mechanically with 800, 1200, 2400, and 4000 SiC grit paper followed by mechanical polishing using 3 and 1 μm diamond suspension, respectively. For microstructure investigations by SEM/EBSD performed in the RD–ND (normal direction) plane, the samples were further electropolished at room temperature for 22 s at 20 V using an electrolyte consisting of 700 ml ethanol (C_2H_5OH), 100 ml butyl glycol ($C_6H_{14}O_2$), and 78 ml perchloric acid (60%) ($HClO_4$). Hardness testing and X-ray diffraction were performed on the center layer of the sheets, which were prepared as described above but finally electropolished for 120 s at 20 V.

EBSD analyses were carried out in a LEO 1530 field emission gun scanning electron microscope (FEG-SEM). The SEM was operated at 20 kV accelerating voltage and a working distance of 10 mm. EBSD mappings were visualized and post-processed using the HKL Channel 5 software. Wild spikes and non-indexed points were corrected by considering the orientation of neighboring pixels, taking at least five neighbor pixels into account. Subdivision of EBSD mappings into subsets containing only non-recrystallized (non-RX) or recrystallized (RX) grains was realized using an algorithm of the MATLAB®-based MTEX toolbox [56–58], as described in [24,59]. The internal grain/subgrain misorientation was calculated based on the grain reference orientation (GROD-AO) value, which takes the average grain/subgrain orientation as a reference. The misorientation threshold value for subdivision was chosen as RX < 1.5° < non-RX. Grains containing less than 10 EBSD data points were disregarded. Furthermore, MTEX was also utilized to calculate the microtexture orientation distribution functions (ODFs) and the corresponding volume fractions of specific texture components.

The crystallographic macrotexture was determined by X-ray pole figure measurements, where three incomplete (0–85°) pole figures, {111}, {200}, and {220}, were acquired on a Bruker D8 Advance diffractometer, equipped with a HI-STAR area detector.