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Analysis of steady-state dynamic recrystallization

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Abstract

The steady-state behavior of dynamic recrystallization (DRX) was studied in commercially pure copper and the austenitic steel alloy 800H. Investigations on the flow stress behavior during strain-rate and temperature-change tests in the steady-state regime regarding the grain size sensitivity of the flow stress were analyzed. The results confirmed the predicted connection of DRX grain size and deformation-induced subgrain size. Furthermore, the grain size distribution during steady-state DRX was evaluated and found to remain constant. A continuity equation of the growing and shrinking grain distributions is proposed which allows the steady-state flow stress to be calculated.

Keywords: Dynamic recrystallization; Steady-state flow stress; Grain size distribution; Flow stress continuity equation

1. Introduction

If recrystallization (RX) occurs during high-temperature deformation it is referred to as dynamic recrystallization (DRX). Owing to its importance for thermomechanical processing of metallic materials, DRX has attracted much attention and has been frequently addressed in the past both experimentally and theoretically [4,7,9]. Since the first attempts by Stuewe and Ortner [14] or Luton and Sellars [8] DRX has been considered as a superposition of static recrystallization on the dynamics of the deformation process. Particular attention has been paid to the prediction of the flow curve and the dynamically recrystallized grain size [12]. Typically, the flows curves reveal one maximum or a damped oscillation before they attain a constant value. The strain regime of constant flow stress at constant strain rate is referred to as steady-state deformation [7,8]. In addition to early empirical descriptions of the flow curve in terms of strain as a state parameter [8], more recent models are based on the evolution of the dislocation density during deformation and typically define an energy criterion for the initiation of dynamic recrystallization [3,6,10,13,14]. In a recent publication [5] we have contended that DRX is a true dynamic phenomenon which is caused by the evolution of the dislocation arrangement (rather than its density), and we presented a theoretical approach which considers the kinetics of grain boundary motion as an essential character of DRX. In this model the evolution of the DRX structure is closely related to the development of the subgrain structure during deformation. This allowed the critical conditions for initiation of DRX to be defined.

In this contribution we will focus on DRX during steady-state deformation. Typically, the DRX grain size d_{DRX} is related to the steady-state flow stress σ_s by a power law $\sigma_s = K \cdot d_{DRX}^{-\alpha}$ [8]. However, usually α is some real number with no particular physical meaning and changes from material to material. Moreover, the power law is only a convenient way to express monotonic functional behavior but does not necessarily reflect an underlying physical principle. We have proposed recently that the grain size dependence of the flow stress can be interpreted in terms of the grain-size sensitivity of the flow stress [5]. In this study we will corroborate the hypothesis by expanding the

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experimental results significantly. For this, the database is extended to a second material, commercially pure copper, and to contain data for an advanced experimental setup to perform not only strain-rate but also temperature-jump tests.

2. Experimental procedure

A commercially pure Cu and the austenitic steel X10NiCrAlTi3220, also referred to as alloy 800H, have been used for the investigations. Their exact chemical compositions are given in Tables 1 and 2.

Cylindrical samples of 5 mm diameter and 7.7 mm height were machined from statically recrystallized material with Rastegaev geometry [11]. The uniaxial compression tests were performed on a servohydraulic Schenck Hydropuls testing machine with true strain rates of $5 \times 10^{-4}\ s^{-1} \leqslant \dot{\epsilon} \leq 5 \times 10^{-2} s^{-1}$ at temperatures of $450\ ^{\circ}C \leqslant T \leqslant 500\ ^{\circ}C$ for Cu and $1100\ ^{\circ}C \leqslant T \leqslant 1150\ ^{\circ}C$ for alloy 800H at constant and transient deformation conditions. Boron nitride was used as lubricant to avoid barreling. For microstructure analysis the samples were quenched with water (Cu) or cold helium gas (alloy 800H) immediately after deformation.

The microstructures of the quenched samples were examined on center sections perpendicular to the compression axis via electron backscatter diffraction (EBSD) measurements using a field emission gun scanning electron microscope (FEGSEM). The scanned areas were evaluated with the MATLAB toolbox MTEX [1] to determine the crystallographic texture and the grain sizes.

3. Results

3.1. Constant deformation conditions

Flow curves at different strain rates and temperatures of both materials were recorded and are displayed in Fig. 1. The characteristic shapes of these curves with either single- or multiple-peak behavior depending on the Zener–Hollomon parameter $Z = \dot{\epsilon} \cdot exp(Q/kT)$ [8] and the occurring steady-state regimes are clearly visible. Increasing deformation temperature or decreasing strain rate lead to a multiple peak behavior and lower flow stresses, whereas single-peak flow curves and higher stresses occur at lower temperatures or higher strain rates.

The initial grain sizes of the statically recrystallized materials were $33 \pm 2\ \mu m$ for Cu and $62 \pm 6\ \mu m$ for alloy 800H. Both microstructures contained large fractions of annealing twins.

Table 1
Chemical composition of the commercially pure Cu (alloying elements in ppm).

O	Fe	Bi	Co	C	Cu
126	31	29	26	25	Bal.

Samples were deformed to various strains in the steady-state flow stress regime and immediately quenched to determine the microstructure and texture. Figs. 2 and 3 show the microstructures and the histograms of the grain size distributions after 50%, 70% and 90% strain for Cu deformed with $\dot{\epsilon} = 10^{-2}\ s^{-1}$ at $T = 450\ ^{\circ}C$ and alloy 800H deformed with $\dot{\epsilon} = 10^{-3}\ s^{-1}$ at $T = 1100\ ^{\circ}C$. The average grain sizes are listed in Table 3. The color coding in the orientation images of the microstructure with respect to the compression axis corresponds to the displayed standard triangle.

3.2. Transient deformation conditions

Strain-rate jump tests of one and two orders of magnitude were conducted in the steady-state regime for both materials. Two typical flow curves of jumps between strain rates of $\dot{\epsilon} = 10^{-2}\ s^{-1}$ and $\dot{\epsilon} = 10^{-3}\ s^{-1}$ are given in Fig. 4. For comparison, the flow curves at constant strain rates are also shown on the diagram as gray curves.

Additionally, temperature jump tests were carried out on alloy 800H. The heating and cooling system used allowed temperature change rates of $1.5\ K\ s^{-1}$. Therefore, sufficiently fast temperature changes from 1100 to 1150 °C and vice versa at strain rates of $5 \times 10^{-4}\ s^{-1}$ and $10^{-3}\ s^{-1}$ could be achieved with respect to the elapsed strain during that time, i.e. the microstructure did not change notably owing to the small strain interval. A characteristic flow curve is displayed in Fig. 5. Such fast temperature jumps could not be realized in the case of Cu because this material was studied with a different heating system and over a different temperature range.

4. Discussion

4.1. Grain-size sensitivity

Whereas traditional models of DRX typically assume a critical energy criterion to define the initiation of DRX, Frommert and Gottstein [5] have recently proposed a model based on a mobility criterion for the initiation of DRX. This model is based on the observation that during high-temperature deformation the dislocation structure undergoes a change from a cell structure to a subgrain structure when approaching steady-state deformation. Subgrain boundaries are essentially low-angle grain boundaries and have specific thermodynamic and kinetic properties such as surface tension and mobility in contrast to cell walls that comprise immobile dislocation tangles. The conversion of cell walls to subgrain boundaries takes place locally when deformation approaches steady state. The surface tension of subboundaries introduces an imbalance at grain boundaries which causes bulging and therefore nucleates the first necklace of a typical DRX structure. As DRX grains become deformed, their dislocation structure undergoes the same development and successive necklaces will form until the original grain structure prior to deformation is completely replaced by DRX grains and a new steady