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Correlation between grain size and flow stress during steady-state dynamic recrystallization

Houquan Liang [a,*], Hongzhen Guo [a], Kai Tan [a], Y.Q. Ning [a], Xin Luo [a], Gang Cao [a], Jiajun Wang [a,b], Pengliang Zhen [a]

[a] *School of Materials Science and Engineering; Northwestern Polytechnical University, 127 Youyixi Street; Xi'an 710012, PR China*
[b] *China Electronics Technology Group Corporation No. 39 Research Institute, 30, 3nd Zhangba Road; Xi'an 710077, PR China*

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ABSTRACT

The mechanical behaviour and microstructure evolution during hot deformation remain a fundamental industrial topic for metallic materials. In the present paper, the correlation between grain size and flow stress during steady-state dynamic recrystallization (DRX) has been investigated from an internal-variable perspective. From the competition between work-hardening and recrystallization softening, a dynamic model of DRX evolution has been generalized by proposing an identification criterion on DRX continuity or periodicity. The dependence of grain size on deformation parameters under the DRX steady state has been obtained from the dynamic balance. An Arrhenius constitutive model for the DRX steady state has also been constructed from the Estrin-Mecking formula, and the stress exponent has been fixed as a constant equal to 6. The correlation between grain size and flow stress has been validated as an inverse proportion with the relevant exponent $n = 1/2$. In addition, the influence of deformation parameters on flow curve shapes and grain coarsening/refinement has been characterized correspondingly.

1. Introduction

The thermomechanical processing of metallic materials has attracted considerable interest from the research community and industry due to the integrated influence of plastic deformation and microstructural evolution [1]. Dynamic recrystallization plays a significant role in the thermomechanical processing of metals owing to the improvement in component properties through stress relief and texture control, such as enhancing grain refinement and promoting matrix uniformity [2,3]. Both the mechanical behaviour and microstructure evolution are significantly influenced by DRX evolution during hot deformation, which directly determine the processing path and ultimate component performance. Therefore, the mechanical and microstructural investigation of DRX evolution is of fundamental technological importance for the hot deformation of metallic materials.

The complexity of the mechanical behaviour and microstructure evolution is due to the concurrent effects of work-hardening (WH), dynamic recovery (DRV) and recrystallization during hot deformation [4]. The mechanical behaviour exhibits a corresponding response to different microstructure evolutions, with the flow stress clearly increasing during WH and decreasing with DRX softening. The DRX steady state, a dynamic balance of work-hardening and DRX softening at larger strains of hot deformation, remains a metallurgical topic due to the establishment of an ultimate stress level and microstructure state. Once the DRX steady state is achieved during hot deformation, a constant average grain size and flow stress could be reached with some interdependence [5].

Several previous papers have investigated the steady-state mechanical behaviour and microstructural features during hot deformation undergoing DRX inform the experimental and theoretical perspectives. Frommert and Gottstein [6] demonstrated the dependence of flow stress and grain size on deformation parameters during steady-state DRX through the isothermal compression of austenitic steel 800 H. The single peak and multiple peaks in flow curves have been individually observed with low and high Zener-Hollomon parameters $(Z = \dot{\varepsilon} \cdot \exp(Q/RT)^{1})$. In addition, the reverse relationship between DRX grain size D_S and steady-state stress has been obtained under steady state, and the relevant exponent between $\ln\sigma$ and $\ln D_S$ has been calculated to be less than 1. Graetz et al. [7] characterized the DRX steady-state behaviour during hot deformation for pure copper and 800 H steel. The DRX grain size sensitivity to flow stress at steady state has been identified as inversely proportional, with the relevant exponent fixed at 1/2. Their research results also confirmed

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* Corresponding author. Fax: +86 29 88493744.
E-mail address: oursummer@mail.nwpu.edu.cn (H. Liang).

[1] $\dot{\varepsilon}$ and T denotes the strain rate and deformation temperature, respectively. R is the gas constant, and Q represents the deformation activation energy.

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the inheritance relationship between DRX grain size and the deformation-induced subgrain size. Furthermore, the grain size distribution during steady-state DRX has been evaluated and found to remain constant. Huang et al. [8] constructed a single irreversible thermodynamics-based formulation to discuss the correlation between steady-state stress and deformation parameters during hot deformation. The influence of DRX and DRV on dislocation annihilation has been comprehensively considered. The steady-state stress dependence on temperature and strain rate has been characterized by introducing Zener-Hollomon parameters under experimental verification by pure copper creep loading. Montheillet et al. [9] developed a grain-scale approach to demonstrate the mechanical and microstructural behaviour during steady-state discontinuous dynamic recrystallization (DDRX) by isothermal compression of 304 L stainless steel. The steady-state stress and grain size have been observed with less sensitivity to the initial microstructure conditions than to the deformation parameters. Lin et al. [10] investigated the DRX kinetics for the isothermal deformation of a Ni-based superalloy, and a corresponding physical constitutive model has been proposed to characterize the influence of deformation parameters on the flow stress. A stable stress variation has been observed at larger strains, and its relationship with the steady-state DRX grain size has been demonstrated by introducing Zener-Hollomon parameters.

In the present paper, the dependence of the grain size on flow stress under the dynamic recrystallization steady state has been investigated for the hot deformation of metallic materials. Their correlation has been analysed from the dynamic balance achieved by DRX grain expansion and shrinkage. The dynamic model of DRX continuity or periodicity has been generalized by constructing an identification criterion from the deformation parameters. The interdependence between flow stress and grain size under steady-state DRX, characterized by the Derby function, has been interpreted from an internal-variable perspective. An Arrhenius constitutive model for the DRX steady state has been proposed using the Estrin-Mecking formula, and the stress exponents are discussed. The influence of the deformation parameters on the DRX steady-state stress and grain size has also been characterized correspondingly.

2. Function and verification

A dynamic balance between work-hardening and DRX softening is achieved under the DRX steady state of hot deformation, where the flow stress and DRX grain size are both stable with strain [11]. There exists a phenomenological function to characterize the dependence between these balanced variables, as illustrated by Fig. 1, proposed by Derby [12]:

$$\frac{\sigma}{\mu}\left(\frac{D_S}{b}\right)^n = K \tag{1}$$

where D_S denotes the DRX steady-state grain size. μ is the material shear modulus. σ/μ represents the normalized flow stress. b is the magnitude of the Burgers vector. K denotes a constant, usually within the range from 1 to 10, and n is a relevant exponent equal to $1/2 \sim 2/3$. The Derby function has been validated with excellent application for the hot deformation of various alloy systems [12,13].

Stress-strain curves for the isothermal compression of austenitic steel alloy 800 H [6,7] are exhibited in Fig. 2 under different conditions, with the steady state achieved at a true strain of approximately 0.4. With increasing temperature T or decreasing strain rate $\dot{\varepsilon}$, the flow curves were shifted to lower stress levels. An obvious stress decrease after the peaks in most curves could be observed as the result of DRX softening. A notable difference could also be identified for the DRX steady state in that stress fluctuations (multiple peaks) appeared in flow curves during hot deformation with high temperatures and low strain rates, while curves with the opposite conditions exhibited a continuous softening trend after the stress peak (single peak). This phenomenon could be associated with the dependence of the DRX type on the deformation parameters.

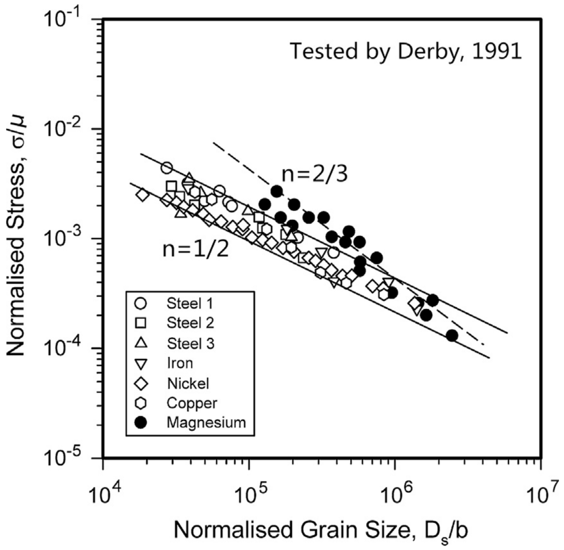

Fig. 1. Relationship between flow stress normalized by the shear modulus and DRX grain size normalized by the Burgers vector for metallic materials, in verification of the Derby function.

Fig. 3 demonstrates the microstructural and textural evolution under continuous deformation at strains of (a) 50%, (b) 70% and (c) 90% for alloy 800 H deformed with $\dot{\varepsilon}=0.001\mathrm{s}^{-1}$ at 1100 °C. A true strain of 0.4 during hot deformation, with the DRX steady state achieved from flow curves in Fig. 1, corresponds to a 70% deformation. From comparison between strains of 50% and 70%, the enhanced deformation level could provide sufficient distortion storage for boundary combination and migration, correspondingly resulting in an obvious DRX-formed grain growth. A clear grain expansion could be identified in the $<0\,0\,1>$ component owing to DRX directional growth under a fixed driving pressure gradient (from comparison between Fig. 3(a) and (b)). With the DRX steady state established, a relatively stable grain size could be maintained. Little grain size variation could be observed from 70% to 90% deformation, with a certain orientation distribution change (from comparison between Fig. 3(b) and (c)).

Fig. 4 exhibits the microstructural and textural evolution for alloy 800 H [6] deformed at 1100 °C with (a) $\dot{\varepsilon}=0.01\mathrm{s}^{-1}$ at 98%; (b) $\dot{\varepsilon}=0.001\mathrm{s}^{-1}$ at 98%; (c) strain rate change from $0.001\ \mathrm{s}^{-1}$ to $0.01\ \mathrm{s}^{-1}$ at 56% and further deformation to a total strain of 96%; (d) strain rate change from $0.01\ \mathrm{s}^{-1}$ to $0.001\ \mathrm{s}^{-1}$ at 57%, total strain 96%. From comparison between Fig. 4(a) and (b), lower strain rates result in a prolonged deformation time for sufficient grain growth under high temperatures. A clear grain size sensitivity to strain rate could be observed as the DRX-formed grain expands from high to low rate. Furthermore, lower strain rates mean a lower deformation resistance under the same conditions. Therefore, the correlation between the grain size and flow stress under different strain rates keeps consistent with the Derby function, in which lower stress levels correspond to larger DRX grain sizes. Comparing Fig. 4(a, c) and (b, d), respectively, an interesting phenomenon could be observed in which the DRX steady-state grain size is insensitive to the processing route of deformed materials and is only significantly dependent on the deformation parameters at steady state. This phenomenon could also validate the Derby function, showing that the same stress levels under the DRX steady state correspond to similar grain sizes during hot deformation.