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New insight into the stable grain size of nanotwinned Ni in steady-state creep: Effect of the ratio of effective-to-internal stress

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ABSTRACT

Understanding the underlying physical mechanisms of grain growth/refinement in materials, in particular for nanotwinned (NT) metals with high stacking fault energy (SFE), to manipulate their microstructural stability for performance optimization is a grand challenge in the material community. The characteristic stable grain sizes of metals have been modeled in terms of various physical parameters, whereas there remains a lack of quantitative information regarding the correlation of stable grain size with the underlying mechanism(s) in the light of competition between effective and internal stresses. In this work, we systematically investigated the microstructural evolution of high SFE NT Ni at different loading rates during room temperature creep. It is found that both grain growth at low stresses and grain refinement at high stresses achieved via (de)twinning-mediated processes emerge in NT Ni. Unlike the general belief that the steady-state grain sizes are characteristics of single-phase metals, it is appealing that the stable grain size is strongly dependent on the effective stress. The effective-to-internal stress ratio η_{Stress} plays a critical role in the grain size evolution: grains grow at $\eta_{Stress} < 1$, while they refine at $\eta_{Stress} > 1$. A stable grain size is reached at $\eta_{Stress} = 1$. We further developed a dislocation-based unified model to quantitatively predict the stable grain size of NT Ni achieved in steady-state creep and the steady-state creep strain rate from the perspective of effective stress, which gains insight into plastic deformation processes associated with growth or refinement of grains.

1. Introduction

Nanotwinned (NT) materials with twin thickness (λ) < 100 nm, are particularly attractive for structural applications because they possess high strength and simultaneously considerable ductility (Anderoglu et al., 2010; Lu et al., 2009a; Zhu et al., 2015; Wang et al., 2012), two characteristics that are traditionally considered to be mutually exclusive and are closely correlated with their internal microstructures, such as grain boundaries (GBs), twin boundaries (TBs) and dislocations. To date, some investigators reported the superior stability of medium stacking fault energy (SFE, γ ~45 mJ m^{-2}) NT Cu with grain size (d) in the submicron regime (Lu et al., 2009a), whereas others uncovered the (de)twinning-mediated grain growth via GB and/or TB motion/migration in nanocrystalline (NC) NT Cu (Brons et al., 2013; Wang et al., 2013), even in fatigued NT

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Ni–Fe (Cheng et al., 2010) and tensile deformed NT Ni with high SFE (γ ~125 mJ m^{-2}) (Li et al., 2015). Compared with NT metals, similar phenomena have been unambiguously confirmed in their nontwinned siblings (Gianola et al., 2006; Rupert et al., 2009; Li et al., 2009); namely coarse-grained (CG) and ultrafine-grained (UFG) materials are more favorable to suffer from grain refinement dominated by dislocation activities and deformation twinning, while NC materials are more prone to suffer from grain growth via the formation of nanotwins, in particular under severe plastic deformation. However, no detailed micromechanisms at the physical level are available to illustrate how these GBs migrate through twinning as well as its reverse process, *i.e.*, detwinning, to achieve the coalescence of nanograins in these nanostructured (including NT and NC) face-centered cubic (FCC) metals.

Most importantly, these results mentioned above suggest that both NC and NT metals have a stable grain size (d_s) at steady state, which is generally believed to be a characteristic of each metal and very important to engineering materials. To date, the stable grain sizes in NC metals achieved during plastic deformation can be predicted by some theoretical models using material parameters (Mohamed, 2003; Edalati and Horita, 2011), such as hardness, atomic bond energy, melting temperature, diffusivity and SFE. Specifically, Mohamed (2003) proposed a dislocation-based model to quantitatively capture the correlation between d_s and physical parameters for pure metals processed by ball milling, given the similarities of ball milling and creep. Therefore, it is normally anticipated that d_s can be obtained once the steady-state creep strain rate ($\dot{\varepsilon}_{SC}$) is reached during creep. More details are shown by Mohamed (2003) and will not be presented here. Moreover, Mohamed's model seems to be applicable to predict d_s in other deformation processes, such as HPT and ECAP, because the occurrence of a steady state is also attributed to the balance between dislocation accumulation and grain refinement on the one hand, and dislocation annihilation and grain growth on the other (Edalati and Horita, 2011). However, it is a pity that this well-accepted model as well as others (Edalati and Horita, 2011; Eckert et al., 1992) ignores an important fact that due to the microstructural evolution in deformed pure metals, both ball milling (or HPT and ECAP) and creep process would unavoidably give rise to notable (long-range and short-range) internal stresses, which reflect variations in the structural parameters that control the deformation process (Ahlquist et al., 1970). The usage of applied stress (σ_a) in Mohamed's model renders that the roles of average internal stress (σ_i) driving recovery or average effective stress ($\sigma_e = \sigma_a - \sigma_i$) driving dislocation motion played in microstructural evolution during plastic deformation cannot be distinguished. In such a case, Mohamed's model would miss some critical information about the physical mechanism(s) for microstructural evolution, which is unfavorable for us to design engineering materials with stable grain size via tuning their initial microstructures and/or processing parameters. Although tremendous efforts have been dedicated to investigating d_s in nontwinned FCC materials (Mohamed, 2003; Edalati and Horita, 2011), few studies have focused on how the grain size d evolves during room temperature (RT) plastic deformation in NT metals. In particular, the theoretical prediction of d_s in NT metals involving the thickness and fraction of nanotwins is still absent.

Apart from modeling their microstructural evolution in terms of underlying deformation mechanism(s), quantifying the time-dependent plasticity (*i.e.*, creep) of nanostructured metals at RT has been at the forefront of mechanics and materials research. For pure metals with submicron- and micron-sized grains, creep deformation is generally accomplished by the generation, motion and annihilation of dislocations, and the cell walls and subboundaries formed by dislocation groups play critical roles in their creep behavior (Orlová and Čadek, 1986; Kassner, 2009; Basirat et al., 2012; Zhao et al., 2015). In contrast, the behavior of dislocation groups emerged in large grain-sized metals likely disappears in NC metals, because there is insufficient space for collective dislocation interactions and the emitted dislocations from a GB can easily travel within the grain interior and become absorbed by the opposite GB, leaving a dislocation starved state (without dislocation accumulation) (Van Swygenhoven et al., 2006; Van Swygenhoven et al., 2002). The present authors have revealed that the Cu freestanding foils with a wide grain size-range of ~25–250 nm exhibit the change from a creep stress exponent of ~5 in bulk Cu to an exponent of ~3, which can be attributed to the lack of subgrains or dislocation substructures in UFG and NC Cu (Guo et al., 2013). This result is consistent well with the experiments of Hasegawa et al. (1972), which have clearly established that the dynamic internal stresses correlate well with the formation of subgrains and the change of creep stress exponent at steady state. In fact, the high (creep) strain rate sensitivity indicates that the short-range internal stress becomes more important during plastic deformation of nanostructured FCC metals, such as Cu (Guo et al., 2013) and Ni (Blum and Li, 2007). Abundant investigations (Chauhan and Mohamed, 2007; Barai and Weng, 2008; Choi et al., 2013; Gollapudi et al., 2010) on the creep behavior of NC metals have uncovered that GB-related processes like GB dislocation emission, GB sliding and GB diffusion are the underlying creep mechanisms, rendering that they exhibit several orders of magnitude enhancement of $\dot{\varepsilon}_{SC}$ in comparison with their CG counterparts. Although the creep deformation of NC FCC metals has been widely studied as mentioned above, the lack of quantitative information on the effect of nanotwins leads to uncertainty in understanding the creep behavior of their NT counterparts.

This study is thus motivated by two main objectives: one is to model the stable grain size d_s in NT metals (Ni) with high SFE during creep at RT, and the other is to quantify the strain rate $\dot{\varepsilon}_{SC}$ of NT Ni in terms of the effective stress σ_e, since σ_e is actually responsible for the creep deformation instead of the applied stress σ_a. This paper is organized as follows. After this introduction, which presents the background and outlines the motivations, a dislocation-based model to quantitatively capture d_s of NT Ni and to predict $\dot{\varepsilon}_{SC}$ in terms of σ_e is constructed in Section 2. In Section 3, the experimental details about the NT Ni sample preparation, the creep tests and the methods of internal stress measurement are clearly presented. In Section 4, (de) twinning-mediated grain growth/refinement and the size-dependent $\dot{\varepsilon}_{SC}$ under different σ_a are shown. In Section 5, the