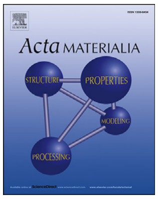
Acta Materialia 128 (2017) 351–364

Contents lists available at ScienceDirect

Acta Materialia

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



Full length article

Taming intermittent plasticity at small scales

Peng Zhang [a, 1], Oguz Umut Salman [b, 1], Jin-Yu Zhang [a, 1], Gang Liu [a, *], Jérôme Weiss [c, **], Lev Truskinovsky [d, ***], Jun Sun [a, ****]

[a] *State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an, 710049, China*
[b] *CNRS, LSPM UPR3407, Université Paris 13, Sorbonne Paris Cité, 93430, Villetaneuse, France*
[c] *IsTerre, CNRS/Université Grenoble Alpes, 38401, Grenoble, France*
[d] *PMMH, CNRS – UMR 7636, ESPCI ParisTech, 10 Rue Vauquelin, 75005, Paris, France*

ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form
20 January 2017
Accepted 13 February 2017
Available online 20 February 2017

Keywords:
Dislocation dynamics
Size effects
Plastic fluctuations
Hardening

ABSTRACT

The extreme miniaturization in modern technology calls for deeper insights into the non-conventional, fluctuation dominated mechanics of materials operating at microscale. For instance, both experiments and simulations show that sub-micron face-centered-cubic (FCC) crystals exhibit high yield strength accompanied by intermittent, power law distributed strain fluctuations. At macro-scales, the same bulk materials show bounded, uncorrelated fluctuations. Both anomalous strength and intermittency appear therefore as size effects: while the former is highly desirable, the latter is detrimental because stochastic dislocation avalanches interfere with forming processes and endanger structural stability. In this paper we quantify the coexistence of correlated and uncorrelated fluctuations in compressed Al alloys micro-pillars, demonstrate that the partition between the two is determined by sample size, and propose quantitative strategies allowing one to temper plastic intermittency by artificially tailored disorder. Our experimental results are rationalized using a theoretical framework that quantifies the competition between external (size related) and internal (disorder related) length scales.

1. Introduction

The classical paradigm of dislocation-mediated plasticity in crystalline solids is that of a smooth *flow* [1,2] where strain fluctuations are small and uncorrelated. This vision of *mild* plasticity was fundamentally challenged by the discovery that plastic fluctuations may be power law distributed in size and energy [3–6], with clustering in space [7] and time [8]. The fact that dislocations self-organize and plasticity proceeds through collective avalanches implies that the flow is *wild* in the terminology of Mandelbrot who distinguished in this way stochastic processes with infinite moments [9]. Following Ref. [10] we use this language to differentiate between Gaussian (mild) and power law distributed (wild) plastic fluctuations.

The two apparently conflicting pictures of smooth and jerky plasticity have been recently reconciled as it was shown that, in bulk materials, mild and wild fluctuations can coexist, with a degree of wildness depending on crystal structure [10]. In hexagonal close-packed (HCP) crystals, long-ranged elastic interactions dominate, leading to cooperative behavior of dislocations. Instead, in face-centered cubic (FCC) crystals, short-range interactions, enhanced by the multiplicity of slip systems, quench plastic avalanches. Plastic flow then proceeds through mainly small and uncorrelated dislocation motions, confined inside the transient microstructural features (e.g. dislocation cells), which give rise to Gaussian (mild) fluctuations. Those coexist with rare power-law distributed (wild) fluctuations associated with sudden rearrangements of the dislocation substructures [10].

In view of the growing interest towards building progressively smaller technological devices, classical approaches of size-independent material engineering have to be reconsidered [1]. In particular, metal plasticity has to be reassessed to meet the demands posed by the manufacturing of components at the micro/nano scales [11] and experiments with ultra-small pillars have become a standard tool in the study of the corresponding fluctuations and size effects [6,12–15]. Besides the initial observation that “smaller is stronger” [12], it has been recently argued that “smaller

---

* Corresponding author.
** Corresponding author.
*** Corresponding author.
**** Corresponding author.
E-mail addresses: lgsammer@mail.xjtu.edu.cn (G. Liu), jerome.weiss@ujf-grenoble.fr (J. Weiss), lev.truskinovsky@espci.fr (L. Truskinovsky), junsun@mail.xjtu.edu.cn (J. Sun).
[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.actamat.2017.02.039

is wilder" [10], as, in contrast to the observations showing Gaussian plastic fluctuations in bulk FCC samples [10], scale-free intermittency has been confirmed at micro and nano scales for the same materials by a wealth of experiments [6,13,15–17] and simulations [11,18]. The abrupt strain jumps in quasi-statically loaded micro-/nano-components endanger structural stability and the associated unpredictability raises serious challenges for plastic-forming processes [18]. It has been realized that tempering plastic deformation at ultra-small scales requires new approaches going beyond the phenomenological continuum theory [19].

In bulk materials, grain boundaries (GBs) hinder the propagation of dislocation avalanches, introducing grain-size related upper cut-offs on their size distribution [20]. At micro- and nano-scales, the level of poly-crystallinity cannot be controlled with the same confidence as in bulk materials [21], which limits our ability to use GB for mitigating size-induced intermittency. Considering these limitations, we focus here on a different strategy of controlling deleterious intermittency, motivated by recent simulations which showed that quenched disorder may suppress scale-free behavior in bulk materials [22]. We use the fact that the pinning strength of solutes and precipitates can be artificially tailored within metals by simple aging treatments [23].

Despite many observations that at sub-micro scales quenched disorder suppress plastic fluctuations [24–27], this effect has not been quantified so far in terms of avalanche statistics. We begin by studying the effects of miniaturization on strain fluctuations in Al-alloys single crystals strengthened by different types of solutes or precipitates in the conditions when the grain size is not a relevant length scale of the problem. We experimentally *quantify* the "smaller is wilder" effect in pure crystals, tracing the evolution from mild plastic behavior at large pillar diameters L, to wild plasticity at small L. We then provide evidence that the transition between mild to wild regimes shifts towards smaller L with the increase of the pinning strength of quenched disorder. Translating the pinning strength into a characteristic length scale l, we show that the competition between *external* (due to L) and *internal* (due to l) scale effects can be quantified by a single nondimensional parameter $R = L/l$ allowing one to collapse the data for materials with different degree of defectiveness on a single curve. We rationalize this collapse within a simple theoretical framework that builds an unexpected bridge between wildness and strength. Our study suggests specific semi-quantitative strategies for controlling intermittency in sub-μm plasticity.

2. Experimental procedures

2.1. Materials

The experiments were performed on four different types of Al crystals: (i) pure Al, (ii) Al-0.3 wt%Sc alloy with Sc solute clusters (referred to as Al-Sc cluster in Fig. 1a), (iii) Al-0.3 wt%Sc alloy with fine sphere-like Al_3Sc precipitates of size ~ 3–8 nm (referred to as Al-Sc precipitate in Fig. 1b), and (iv) Al-2.5 wt%Cu-0.1 wt%Sn with coarse plate-like θ'-Al_2Cu precipitates of diameter ~ 10–40 nm (referred to as Al-Cu-Sn in Fig. 1c). The pure Al, Al-0.3 wt%Sc alloy, and Al-2.5 wt%Cu-0.1 wt%Sn alloys were respectively melted and cast in a stream argon, by using 99.99 wt% pure Al, mast Al-50 wt% Cu alloy, 99.99 wt% pure Sn, and mast Al-2.0 wt% Sc alloy. The cast Al-Sc ingots were solutionized at 921 K for 3 h and then quenched in cold water. Immediately after quenching, one part of the Al-Sc ingots was aged at relatively low temperature of 523 K for 8 h to form Sc clusters. The other part of the Al-Sc ingots was aged at high temperature of 623 K for duration of 24 h, in order to precipitate Al_3Sc particles. The cast Al-Cu-Sn ingots were solutionized at 823 K for 3 h, followed by a cold water quench and subsequently aged at 473 K for 8 h to precipitate plate-like θ'-Al_2Cu particles. Minor addition of micro-alloying element Sn was used to catalyze the precipitation of θ'-Al_2Cu particles with relatively uniform size and homogeneous distribution.

2.2. Microstructure characterization

Three-dimensional atom probe tomography (3DAP) analyses were performed using an Imago Scientific Instruments 3000HR

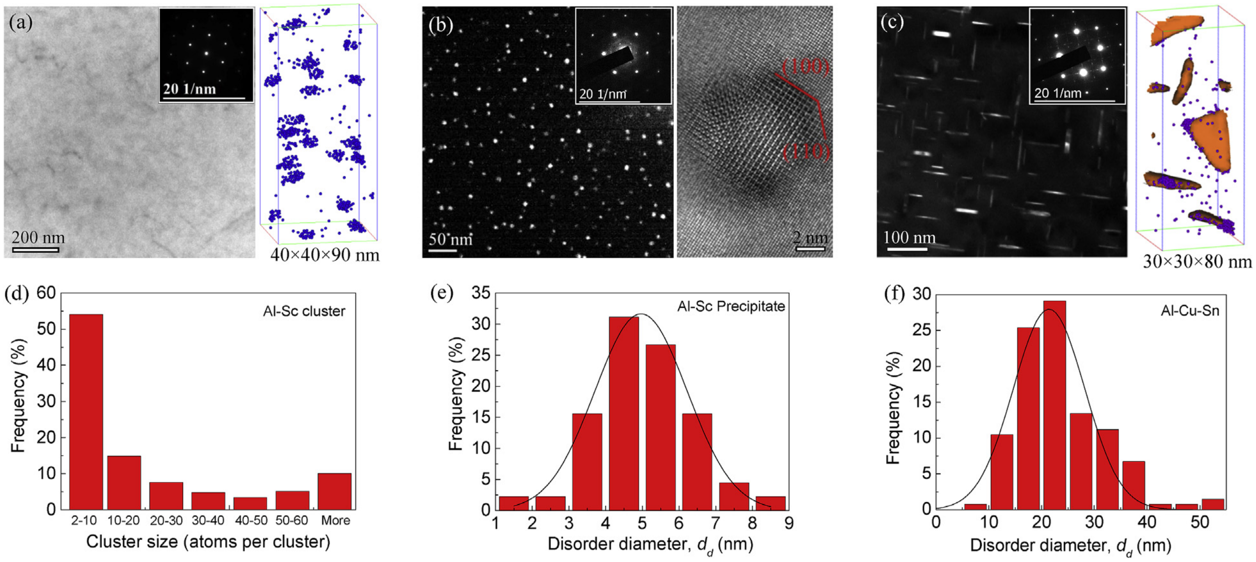


Fig. 1. Microstructural characteristics of Al alloys. (a) Bright field TEM image (left) and 3DAP result (right) for the Al-Sc alloy. No precipitates can be observed but a large number of Sc atom clusters are detectable (referred as Al-Sc cluster alloy). The blue points represent Sc atoms. **(b)** Dark field TEM image (left) and HRTEM image (right) for the Al-Sc alloy dispersed with spherical Al_3Sc precipitates with average diameter ~5 nm (referred as Al-Sc precipitate alloy). **(c)** Dark field TEM (left) and 3DAP (right) images for the Al-Cu-Sn alloy with plate-like θ'-Al_2Cu precipitate with a diameter ~25 nm (Al-Cu-Sn). The purple points represent Sn atoms and orange ones are & precipitates. Insets in the TEM images are the corresponding selected area diffraction patterns. The statistical results of obstacle size in Al-Sc cluster (a), Al-Sc precipitate (b), and Al-Cu-Sn alloys (c) are shown in **(d), (e), (f)** respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)