

Crystal size effect in two dimensions – Influence of size and shape

R. Maaß,^{a,*} C.A. Volkert^a and P.M. Derlet^b

^a*Institute for Materials Physics, University of Göttingen, Friedrich-HundPlatz 1, 37077 Göttingen, Germany*

^b*Paul Scherrer Institut, Condensed Matter Theory, 5232 Villigen PSI, Switzerland*

Received 1 January 2015; revised 30 January 2015; accepted 1 February 2015

Available online 19 February 2015

Based on the statistics of both the stress and strain of a plastic event, the well known size-effect in strength can be linked to a crystal's critical stress distribution and the universal scaling exponent of intermittent plasticity. We successfully test these hypotheses with small-scale deformation experiments as a function of diameter and aspect ratio, and find that the latter affects the material's strength in a way that gives direct insight into the underlying critical stress distribution of the deforming volume.

© 2015 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

Keywords: Size effect; Plasticity; Single crystals; Stress scaling

Classical laws on strength of crystalline materials did consider strength to be independent of external dimensions of the tested material. About 10 years ago it was convincingly demonstrated that there is an extrinsic size-strength scaling in crystal plasticity at small scales that is well described by a power-law: $\sigma \propto d^{-n}$, where σ is the flow strength and d is some measure of crystal size. Today's consolidated picture of this strength-size scaling shows that n is strongly dependent on the initial microstructure of the material [1–3].

While no size-scaling exists at the macroscopic scale, bulk crystals have in common with their small counterparts that their elastic to plastic transition is also very much dependent on the details of the underlying microstructure. More specifically, it is the initial defect structure that determines strength across all length scales. The mobile part of the dislocation network will facilitate plastic deformation by collectively moving and multiplying within the crystal. Such plastic activity – may it be in a bulk or small-scale crystal – can be characterized by the external stress at which it occurs and thus the statistical properties of the early stages of a deformation sequence should be strongly influenced by a distribution $P(\sigma_c)$ of such critical stresses. $P(\sigma_c)$ therefore characterizes the underlying dislocation network microstructure in terms of the stress scale at which plastic evolution occurs.

In addition to the strength determining initial defect distribution, crystals at all length scales deform plastically in a discrete fashion in terms of both stress and plastic strain [4]. At the bulk scale this is hard to observe in a regular

straining experiment, with the exception of some cases of ultra high strain resolution [5]. Reducing sample size, the intermittency of the discretely evolving dislocation structure can be readily observed with nano-scale extensometry, which reinvigorated numerous efforts investigating scale-free slip events [6,7] as well as the temporal dynamics of avalanches [8,9] occurring in critically evolving dislocation systems. The general conclusion became that a plastically evolving dislocation structure exhibits power-law slip-size (plastic strain) distributions, $P(S) \propto S^{-\tau}$, where τ is a critical exponent, suggesting that dislocation based plasticity belongs to a class of phenomenon that is fundamentally scale free and universal [4,10].

Such universality in the statistics of plastic strain implies an insensitivity to the microscopic details, while on the other hand the stress scale at which such plastic events occur does appear to be very dependent on the microstructural details. The emerging questions are how these two very different aspects of deformation can be linked, and how this may result in the “smaller is stronger” paradigm observed in micro-compression experiments? One recent statistical approach which relates these aspects in a unified way gives the simple expression $n = (\tau + 1)/(\alpha + 1)$ [11], for the size-effect exponent, where α is the leading order exponent of the low critical stress side of $P(\sigma_c)$ and τ is the aforementioned critical exponent for scale-free plastic activity. This expression relates material strength (as a function of deforming volume) directly with the universal behavior of intermittent plastic strain activity and the statistics of the critical stresses at which it occurs. As will be subsequently discussed, the developed connection also infers a broader class of scaling laws in which both size and shape can affect material strength. In particular the aspect ratio of a

* Corresponding author; e-mail: robert.maass@ingenieur.de

micron-sized crystal should affect strength via a scaling law with an exponent equal to $1/(\alpha + 1)$. Motivated by these theoretical developments, the present work undertakes an experimental investigation demonstrating that the aspect ratio does indeed affect material strength, and via the above expression it becomes possible to access α and τ from one test series probing crystal size and shape. This combined experimental and theoretical approach links for the first time a universal scaling parameter to simple stress measurements, and indicates that the size-effect in strength partly is universal to crystalline metallic materials.

Cylindrical nano- and micro-crystals with a compression axis along the $\langle 001 \rangle$ -axis were prepared by focused ion beam milling from a single crystal (Mateck). The specimens were compressed at a nominal strain rate of $5 \times 10^{-3} \text{ s}^{-1}$ inside a Hysitron Nanoindenter or in an Agilent G200 Nanoindenter using the DCM module at a nominal force

rate of $1.0 \mu\text{N s}^{-1}$. The obtained data were converted to engineering stress–strain data, and the flow stress at a plastic strain of 3% was used to construct Figures. 1a, 2a and 3a.

The size-effect model developed in Ref. [11] is based on two distinct size effects – one in stress and one in strain. For the size effect in stress, it is realized that the number of available plastic events, M , should scale linearly with the volume of the deforming material. Sampling the assumed critical stress distribution, $P(\sigma_c)$, M times results in a critical stress sequence whose order statistics is important. Indeed, the characteristic i th smallest critical stress is given by $i = M \int_0^{\sigma_c} P(\sigma) d\sigma$, reflecting the extreme value statistics when M is not small. Thus when the sample volume (and thus M) decreases, the scale of the lowest critical stresses increases. For the case of plastic strain, it was further recognized that under the assumption of self-organized criticality, the magnitude of a plastic strain event is only weakly correlated with the applied stress and that their distribution is truncated by the finite size of the sample. Together this results in an average plastic strain magnitude which scales with volume via the universal critical exponent τ . When combined, the size effects in stress and plastic strain give a simple expression for the stress scaling with respect to system size as (Ref. [11])

$$\sigma \sim \left(\frac{1}{L}\right)^{(1+\tau)/(1+\alpha)} \quad (1)$$

Here L is a characteristic dimension of the system. For the case of a cylindrical pillar of height h and diameter d , the stress scaling of Eq. (1) is with respect to the minimum external length scale, the pillar diameter ($d = L$) at a fixed aspect ratio. Since the critical strain scaling depends only on this minimum external length, changing the pillar height only affects the stress scaling (since it depends on the total sample volume) resulting in an overall stress scaling:

$$\sigma \sim \left(\frac{1}{h}\right)^{\frac{1}{1+\alpha}} \times \left(\frac{1}{d}\right)^{\frac{\tau}{1+\alpha}} = \left(\frac{1}{A_r}\right)^{1/(1+\alpha)} \times \left(\frac{1}{d}\right)^{(1+\tau)/(1+\alpha)} \quad (2)$$

where in the last equality, the scaling has been written in terms of the aspect ratio $A_r = h/d$. Eq. (2) indicates a dependence on A_r , arising solely from the extreme value statistics of critical stress, thereby providing direct insight into the distribution $P(\sigma_c)$. It is this new aspect of the size-effect in crystal strength which forms the central theme of the present work.

As a first step, the compressive strength at 3% plastic strain of cylindrical gold crystals with diameters ranging between 300 nm and 10 μm is tested and yields the expected trend depicted in Fig. 1a. The very robust scaling for the here studied $\langle 001 \rangle$ -oriented single crystalline material can be expressed as $\sigma \propto d^{-n}$, with $n = 0.44 \pm 0.1$ ($R^2 = 0.976$, root mean square error (RMSE) = 0.082). This trend includes all investigated aspect ratios and is the essence of many studies of similar sample geometries whose bounds in n are indicated with dashed lines for $n = 0.16$ [3] and ca. 0.9 [12]. For later purposes we display in Fig. 1a the standard $A_r \approx 3$ as one data set and the other A_r covering smaller and larger values in another set. Irrespective of the data sets, all strength values seem to align well with the established power-law scaling and cannot be distinguished from each other.

Before turning our attention to how the data summarized in Fig. 1a can be recast to express scaling with respect

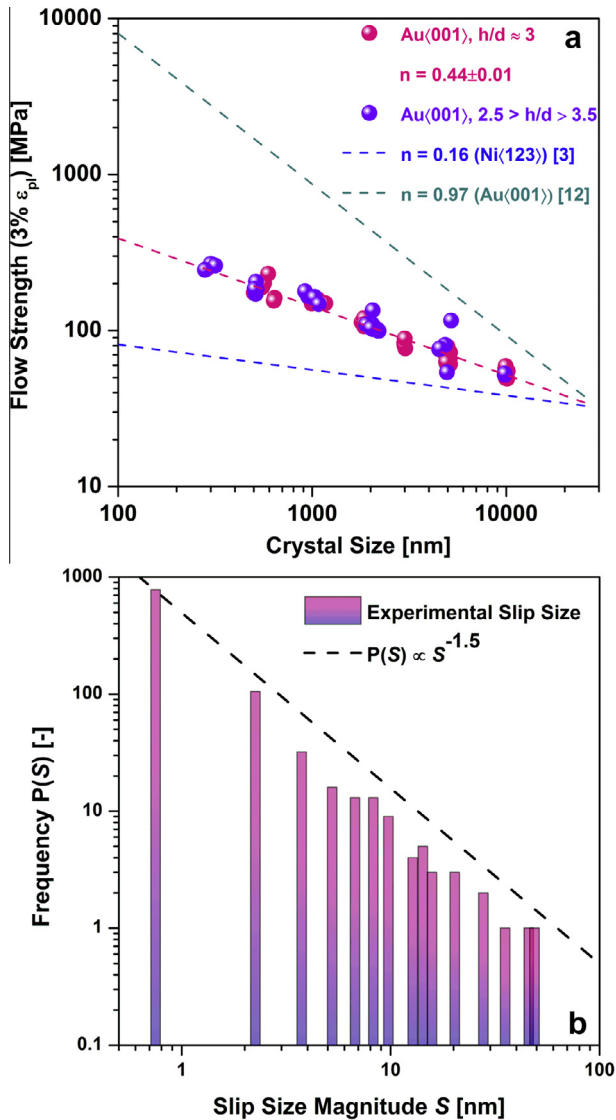


Figure 1. (a) Strength-size scaling for $\langle 001 \rangle$ -oriented Au crystals, fit to a power-law with a scaling exponent of 0.44. Two different data sets are presented: one with an $A_r = 3$, and one with an $2.5 > A_r > 3.5$. The dashed lines bound the reported experimental limits reported so far. (b) A slip-size distribution obtained from the intermittent slip activity of the deforming Au crystals with $A_r = 3$.

Download English Version:

<https://daneshyari.com/en/article/7913054>

Download Persian Version:

<https://daneshyari.com/article/7913054>

[Daneshyari.com](https://daneshyari.com)