

A large strain rate effect in thin free-standing Al films

E. Ben-David,^{a,*} T. Tepper-Faran,^b D. Rittel^a and D. Shilo^a

^aDepartment of Mechanical Engineering, Technion- Israel Institute of Technology, Haifa 32000, Israel

^bMicrosystems Department, R&D and Technology Center, MANOR A.D.T Div., Rafael Advanced Defense Systems, Israel

Received 26 May 2014; revised 18 June 2014; accepted 18 June 2014

Available online 2 July 2014

We present tensile tests of thin aluminum films under quasi-static, medium and high strain rates. A large strain rate effect is revealed, as the ultimate tensile strength increases by more than 400% compared to quasi-static tests. An analysis of the kinetic relation for plastic flow shows that all commonly used kinetic laws cannot explain our results. Instead, we suggest a newly elaborated kinetic law that is in good agreement with the results over the entire range of strain rates.

© 2014 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

Keywords: High strain rate; Thin films; Mechanical properties; Tension tests; MEMS

Thin metallic films are commonly employed in micro/nanoelectromechanical systems (MEMS/NEMS) and are frequently subjected to various mechanical constraints [1,2]. A main characteristic of thin films is that the specimen dimensions become comparable to the characteristic length scales that govern the mechanical behavior. Therefore, specimens at the micrometer and sub-micrometer scales often exhibit a mechanical behavior that may be different from that of bulk specimens, which is referred to as the “size effect” [3].

MEMS and NEMS devices may be subjected to a wide range of operating velocities and frequencies, depending on their use, environmental conditions and method of actuation. A device can be used as a transducer for long-term measurements, which implies quasi-static loads, or alternatively as a switch [4–6], which mostly dictates high rates and dynamic loads. As a rule, the resonance frequency of mechanical devices increases as their size decreases. In accordance, smaller devices are subjected to higher strain rates during vibrations or other dynamic motion. In particular, vibrating metallic nanowires, which are of great interest for resonator applications (see e.g. Refs. [7,8]), are subjected to very high strain rates on the order of 10^3 – 10^6 s^{−1} during their operation. Hence, to design devices that may last and perform well under various loading regimes, the

investigation of the mechanical properties of thin films at various and high strain rates is crucial.

Strain rate sensitivity is also a fundamental problem in materials mechanics. At the microscopic scale, plastic deformation occurs through the motion of crystal defects (usually dislocations). Quasi-static tests usually demonstrate a critical stress, called the yield stress, below which dislocations are pinned and above which accumulated dislocation motions result in significant plasticity. Under higher strain rates, dislocations are forced to move at some velocity to produce an accumulated plastic strain rate equal to the strain rate applied in the test. From the physical point of view, there is some fundamental kinetic relation between the force acting on a dislocation and its velocity. As a result, a larger stress is required to produce a higher plastic strain rate. Thus, material characteristics such as the yield and ultimate stress values may depend on the strain rate.

The study of strain rate effects is hampered by limitations of the existing experimental methods. Experimental methods for testing bulk specimens (with typical dimensions above the millimeter scale) allow the application of strain rates either below ~ 1 s^{−1} using large-scale tensile instruments or above ~ 500 s^{−1} using impact techniques. Thus, there is a range of strain rates spanning roughly two orders of magnitude, from macroscopic specimens to microscopic specimens such as thin films, over which it is difficult to obtain reliable mechanical characteristics. Many common engineering

*Corresponding author. Tel.: +972 48295911; e-mail: bderan@tx.technion.ac.il

applications, including automotive crash and low-velocity impact testing, lead to strain rates in this range.

In principle, the tensile testing of thin free-standing films has the ability to bridge the above-mentioned gap of strain rates and allows testing at a variable rate from the quasi-static regime up to approximately 1000 s^{-1} . The strain rate in tensile tests is given by $\dot{\epsilon} = v/L$, where v is the cross-head velocity and L is the specimen length. Commercial small-scale actuators can provide adjustable velocities of up to $\sim 0.1 \text{ m s}^{-1}$. Thus, for a specimen length of $\sim 100 \mu\text{m}$, a strain rate of up to 10^3 s^{-1} can be obtained in principle.

The main problems associated with tensile testing of free-standing films at high strain rates come from the short duration of the overall test. The latter can be estimated by $\Delta t = \epsilon_f / \dot{\epsilon}$, where ϵ_f is the strain at failure. Thin metallic films tend to be less ductile than bulk materials and usually exhibit an ϵ_f of approximately 5% [9,10]. Thus, the overall test duration at a strain rate of 1000 s^{-1} is expected to be $50 \mu\text{s}$. This short duration imposes a severe requirement for the bandwidth and the sampling rate, which should be much larger than $1/\Delta t$ for all measuring devices.

Recently, we presented a novel apparatus and a method for the tensile testing of free-standing thin films under adjustable strain rates [11] from the quasi-static regime to approximately 500 s^{-1} . To provide this capability, a unique displacement measurement method [12] that provides a resolution of 25 nm, a bandwidth above 1 MHz and a sensing range above 1 mm was implemented. In addition, a microdevice that meets several strict requirements was implemented and a testing methodology was developed [11]. However, because of rupture of the thin films during their preparation process, Ref. [11] demonstrates the capabilities of the apparatus and method using microdevices without thin-film specimens. Thus, while the apparatus and method have been demonstrated to function properly, there has been no report on high strain rate tensile tests of thin free-standing films.

In this paper, we apply the above-mentioned experimental system and methodology to study the mechanical response of thin Al films under various strain rates from 0.001 to 170 s^{-1} . We report an unusually large strain rate effect, which results in a greater than fourfold increase in the ultimate strength. Furthermore, we show that our results do not fit the commonly used exponential and power-law kinetic relations. Instead, we suggest an elaborated power law, which takes into account a threshold stress for the plastic strain and is in good agreement our results over the entire range of strain rates.

The samples used in this study are free-standing Al films $1.2 \mu\text{m}$ thick, $25 \mu\text{m}$ wide and $70\text{--}120 \mu\text{m}$ long; they were fabricated on a microdevice that includes Si springs positioned to protect the sample (Fig. 1). Two circular holes located at both ends of the microdevice allow it to be mounted on gripper pins. The moveable part of the microdevice has a metallic grating on its surface to allow for the measurement of its displacement by an optical linear encoder located above the grating. A piezoelectric force sensor is connected to the static gripper, while the moving gripper is connected to a linear stage actuator. An XYZ stage and an optical stereoscope serve to

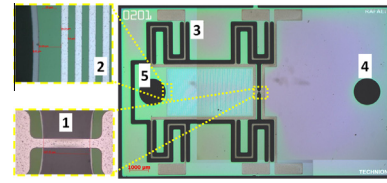


Figure 1. A top view of the microdevice (dimensions $13.8 \times 8.5 \text{ mm}^2$), showing (1) the thin film, (2) the encoder grating, (3) the “S”-shaped silicon springs and (4, 5) the holes for the static and moving grippers, respectively.

align the microdevice along the tensile direction. Dedicated software and a user interface are used to operate the entire system and to record the measured response.

Displacement control tensile tests were performed. As the gripper that is attached to the linear stage starts moving, tension is applied to the microspecimen until it is torn. Unloading is then performed, followed by a reloading step to measure the response of the springs alone. Thus, two tests are performed in series. In the first test, the responses of both the springs and the specimen are measured. In the second test, after the specimen is torn, only the spring's response is measured. The force measured over the springs alone is subtracted from the force measured over the springs and the specimen to extract the specimen's response alone. The experimental setup and procedure are described in detail in our recent study [11].

Five stress–strain curves measured under different strain rates from 0.0012 to 170 s^{-1} are presented in Figure 2. Significant increases in the yield and ultimate stresses are observed at high strain rates. At the highest rate, the ultimate stress is more than fourfold larger than the ultimate stress that is measured in the quasi-static experiment.

At strain rates between 0.0012 and 5.4 s^{-1} , the maximal slopes of the stress–strain curves are between 16 and 20 GPa . These values are considered to be very low for aluminum in comparison to the reported Young's modulus of 70.6 GPa for pure bulk samples [13]. An accurate measurement of Young's modulus of thin free-standing films is a major experimental problem, and several previous studies have reported values much lower than the known value for bulk materials [14–18]. In testing methods where the strain is determined by measuring the overall sample elongation, even a small compliance of the sample grippers may result in a significant underestimation of Young's modulus. In our case, we calculate the total sample elongation by assuming that the

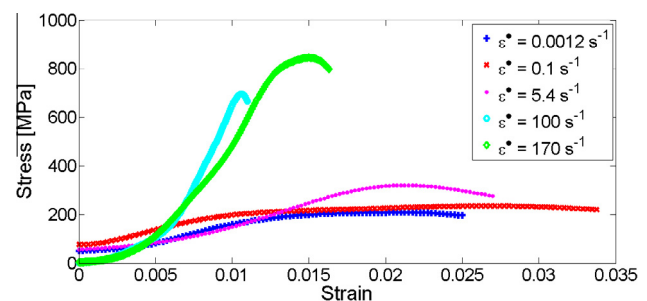


Figure 2. Stress vs. strain curves for different strain rates.

Download English Version:

<https://daneshyari.com/en/article/1498540>

Download Persian Version:

<https://daneshyari.com/article/1498540>

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