Catastrophic vs. gradual collapse of thin-walled nanocrystalline Ni hollow cylinders as building blocks of micro-lattice structures

Supporting Information

Mechanical Testing

Two series of hollow cylinders with different wall thickness were prepared for uniaxial compression tests. For the first set (*thick* series), the wall thickness was ~ 400-600 nm, the diameter was 45-50 μm, and the height ranged from 31 to 64 μm. In the second set (*thin* series), the wall thickness was ~150 nm, with a diameter of ~30 μm and length of 39 μm. Uniaxial compression tests on the *thick* structures were performed in the XP module of a Nanoindenter G200 (Agilent Corp., Oak Ridge, TN, USA) with a custom-made flat punch diamond tip, while simultaneously measuring the contact stiffness by operating in continuous stiffness measurement (CSM) mode. The compression tests were performed at two nominal displacement rates of 50 nm/s and 10 nm/s, with the corresponding strain rates for each cylinder defined as $\dot{\varepsilon} = \frac{1}{h_0}\frac{dh}{dt}$, where h_0 is the original cylinder height. Uniaxial compressions on the samples from the *thin* set were performed in a custom-made *in situ* nano-mechanical deformation instrument, SEMentor [1]. In addition to compression tests, the mechanical properties of the electroless nickel thin films on flat substrates were also characterized by nanoindentation in the XP module of the Nanoindenter G200 with a Berkovich tip.

Finite Element Simulations

Given the inherently unstable nature of the problem, all Finite Elements simulations were performed with the dynamic solver ABAQUS Explicit. Two representative cylinders, one from the *thick* sample series and one for the *thin* sample series, were modeled. The *thick* sample had a diameter of 47.9 µm, a wall thickness of 579 nm and a length of 38.6 µm, whereas the *thin* sample had a diameter of 30 µm, a wall thickness of 150 nm and a length of 39 µm. Both cylinders were clamped at the bottom end, with the free top end impacted by a rigid platen (hard normal contact and frictionless tangential contact conditions). Initial imperfections with amplitudes of 50nm were introduced in the mesh prior to loading, according to buckling mode shapes obtained by an eigenvalue extraction. Strain rates of 260 and 512 s^{-}1 were adopted for the *thick* and *thin* samples, respectively, to simulate quasi-static loading: although these rates are 5 orders of magnitude higher than in the experiments, the kinetic energy in the system was *a posteriori* verified to be negligible compared to the internal energy throughout the entire simulation, confirming that no inertia effects were introduced. The material was modeled as an elastic-perfectly plastic solid, with a Young's modulus of 210 GPa, a Poisson's ratio of 0.3 and a yield strength of 1 GPa.

Figures

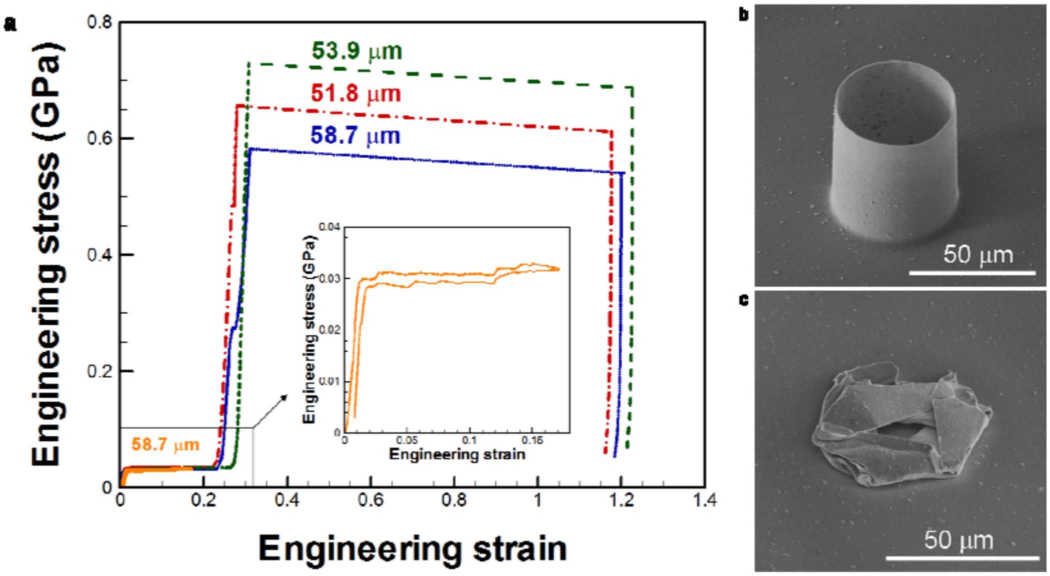

Figure S 1. Uniaxial compression results for the 500 nm-thick vertically oriented hollow Ni cylinder performed with a higher data acquisition rate of 500 Hz. (a) Engineering stress-strain curves of compression of different hollow cylinders with a low displacement rate of 10 nm/s. (b, c) SEM images of 500 nm thick hollow cylinder with height of 52 µm before (b) and after the compression (c).

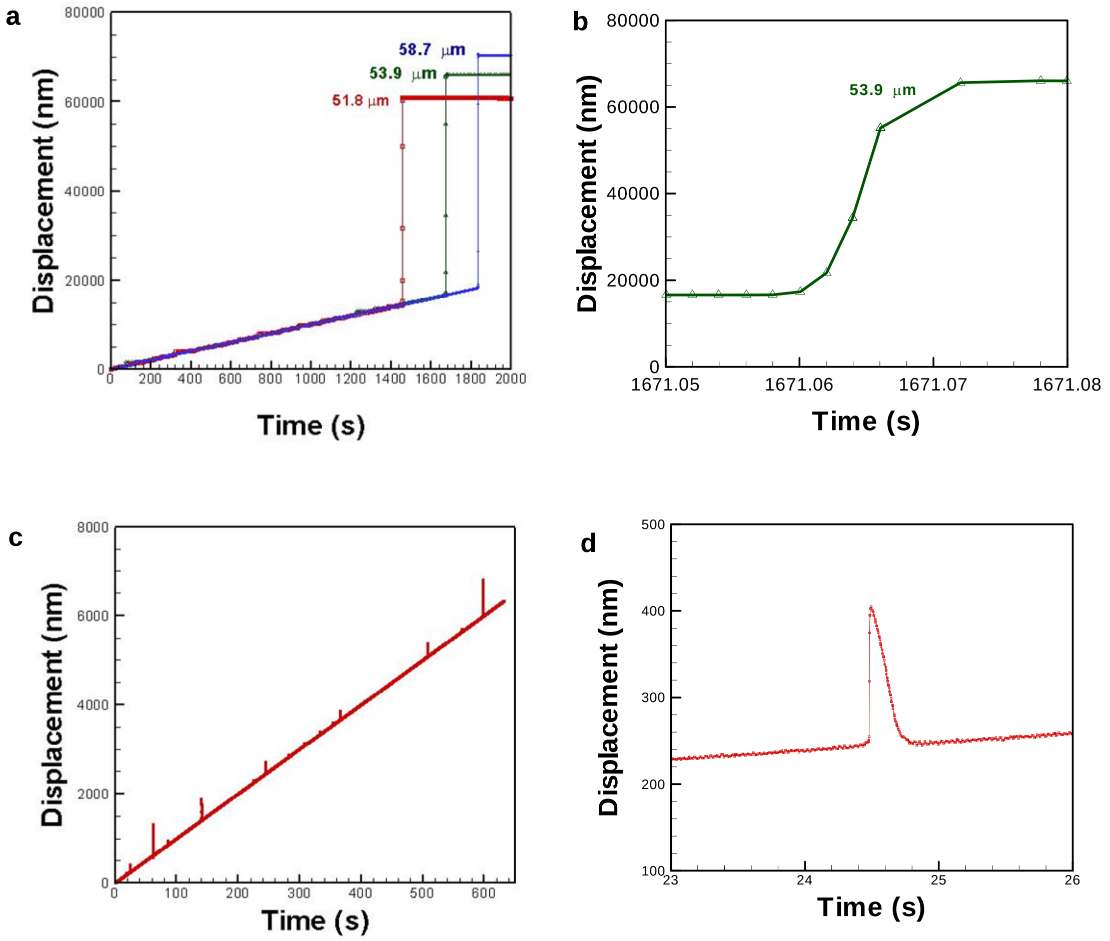

Figure S 2. Displacement vs. time curves of uniaxial compression on 500 nm and 150 nm thick hollow cylinders. (a, b) Displacement vs. time curves (a) and zoom-in of one displacement burst of uniaxial compression on 500 nm thick hollow cylinder. (c, d) Displacement vs. time curves (c) and zoom-in of one displacement burst (d) of uniaxial compression on 150 nm thick hollow cylinder.

References

1. Kim, J.-Y.; Greer, J. R. *Acta Materialia* **2009,** 57, (17), 5245-5253.