Size effects in pure and alloyed metals under dynamic loading

The strength of metals and metallic alloys is usually thought to be independent of the system's geometry and dimensions. However, at the micron scale this ceases to be true. Broadly speaking, systems of the size of microns become increasingly stronger the smaller they are: the yield point and the plastic hardening rate, for instance, are known to increase with increasing system's size. This "smaller is stronger" behaviour is known as a "size effect". Size effects are particularly important in the thermal response of thin films on substrates, on indentation problems, on the plasticity at crack tips, and in the mechanical response of nanorods and other microsystems, amongst many other problems.

Size effects are well attested in a wide range of pure metals and alloys via experiments performed under various loading conditions: from torsional loads [1], through bending and compression of nanopillars [2], to nanoindentation[3,5], to the tensile testing of thin films [4,6]. Equally so, various theoretical and numerical models have been proposed to study size effects, from continuum level phenomenological models reliant on strain gradient plasticity[1,6], to crystal plasticity[7], discrete dislocation dynamics[8], and molecular dynamics studies[9]. These studies have served to build a theoretical understanding of the physical mechanisms governing size effects, which are ascribed to dislocations operating at the microscale and their interactions with free surfaces, grain boundaries, and dislocation sources, as well as successful constitutive models of practical relevance.

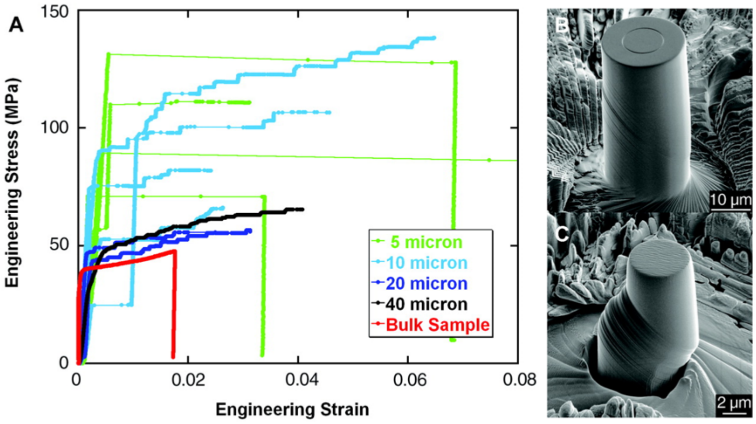

Figure 1 Size effects in the tensile response of pure Ni nanopillars. From Nix et al. Science, 305(5686), 986-989.

Both experiment and theoretical studies of size effects tend to focus on very slow loading rates. That is to say, the loading rate of theory and experiments displaying size effects is typically quasistatic. Under these "low strain rate" conditions (usually below $10^1 s^{-1}$), the number of physical mechanisms responsible for size effects are well understood, particularly for simple metals. However, when the loading rate increases above $10^3 s^{-1}$, many of the physical mechanisms believed to control size effects (e.g., dislocation starvation[10], obstacle-constrained plastic flow[1],…) become inoperative, or can be superseded by alternative mechanisms (e.g., heterogenous or homogeneous nucleation[11], surface sources, inertial effects in dislocation motion[12],…), so that whether or not size effects persist at high strain rates remains an open question that may impact shear band formation and other localisation effects. In particular, a threshold strain rate is postulated to exist (perhaps above $10^6 s^{-1}$), above which the time-dependencies in the plastic response completely overtake geometrical effects. The conditions that may lead to this are far from clear: very little experimental and theoretical work aimed at addressing the presence of size effects under high strain rate loads exists.

The aim of this project is for the student to build comprehensive understanding of the presence (or lack theoreof) of size effects at strain rates above $10^3 s^{-1}$, and to clarify the many issues surrounding them under such loading. The student will use discrete dislocation dynamics (both quasistatic and elastodynamic[11]) and molecular dynamics, and develop computational and analytical tools aimed at unravelling size effects under high strain rates.

This project will be held at the School of Metallurgy and Materials at the University of Birmingham. The candidate will have or be expected to obtain at least a 2:1 class degree in Materials Science, Physics, Applied Mathematics, Engineering, or other relevant discipline. A background or interest in computer programming and applied mathematics would be advantageous. This project is open only to Home Students (UK applicants).

For further information, please contact Dr. Beñat Gurrutxaga-Lerma at bg374@cam.ac.uk. Application deadline is 31st October. To apply please send a two-page CV and covering letter to bg374@cam.ac.uk

[1] Fleck, N. A., et al. "Strain gradient plasticity: theory and experiment." *Acta Metallurgica et materialia* 42.2 (1994): 475-487.

[2] Stölken, J. S[illegible], and A. G. Evans. "A microbend test method for measuring the plasticity length scale." *Acta Materialia* 46.14 (1998): 5109-5115.

[3] Stelmashenko, N. A., et al. "Microindentations on W and Mo oriented single crystals: an STM study." *Acta Metallurgica et Materialia* 41.10 (1993): 2855-2865.

[4] Venkatraman, R., and J. C. Bravman. "Separation of film thickness and grain boundary strengthening effects in Al thin films on Si." *Journal of materials research* 7.8 (1992): 2040-2048.

[5] Volkert, Cynthia Ann, and Erica T. Lilleodden. "Size effects in the deformation of sub-micron Au columns." *Philosophical Magazine* 86.33-35 (2006): 5567-5579.

[6] Haque, M. A., and M. T. A. Saif. "Strain gradient effect in nanoscale thin films." *Acta Materialia* 51.11 (2003): 3053-3061.

[7] Bittencourt, E., Needleman, A., Gurtin, M. E., & Van der Giessen, E. (2003). A comparison of nonlocal continuum and discrete dislocation plasticity predictions. *Journal of the Mechanics and Physics of Solids*, *51*(2), 281-310.

[8] Nicola, L., E. Van der Giessen, and A. Needleman. "Discrete dislocation analysis of size effects in thin films." *Journal of Applied Physics*93.10 (2003): 5920-5928.

[9] Schiøtz, J., F. D. Di Tolla, and K. W. Jacobsen. "Softening of nanocrystalline metals at very small grain sizes." *Nature* 391.6667 (1998): 561

[10] Greer, J. R., W. C. Oliver, and W. D. Nix. "Size dependence of mechanical properties of gold at the micron scale in the absence of strain gradients." *Acta Materialia* 53.6 (2005): 1821-1830.

[11] Tschopp, M. A., and D. L. McDowell. "Influence of single crystal orientation on homogeneous dislocation nucleation under uniaxial loading." *Journal of the Mechanics and Physics of Solids* 56.5 (2008): 1806-1830.

[12] Gurrutxaga-Lerma, B., et al. "A dynamic discrete dislocation plasticity method for the simulation of plastic relaxation under shock loading." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*469.2156 (2013): 20130141.