

Experimental Study of Crackling Noise as Micro-mechanics of Flow

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1. Introduction and Background

It has long been known that typical plastic deformation in metals occurs by means of *dislocation slips*¹. The planes of atoms in a crystal can move past one another once dislocation avalanches are activated (*macro-plasticity*); that is when the applied stress to the bulk is greater than the *yield stress*. Since dislocations are usually pinned by defects inside materials, they can bow out under an application of shear stress that might be much smaller than the yield stress. In this sense, there are dislocation dynamics inside the material (*micro-plasticity*) even though the bulk material is not plastically deformed. This behaviour might lead to micro-structural evolution that generates mechanical noise². At sub-micron scales, dislocation slips are discrete, stochastic processes³; uniaxial loading stress-strain curves are discontinuous and look like ladder steps.

*Crackling noise*⁴ inside crystalline materials is most likely due to the non-linear collective behaviour of pinned dislocations. The complex network of dislocations in the crystal can act non-linearly through long-range, coherent interactions between dislocations.

Crackling noise arises inside the *quadruple pendulum* that is used as the suspension system for the detector of the Advanced LIGO². The maraging steel blades are used for vertical seismic isolation⁶. However, since there is no spring-blade isolation between the upper intermediate mass and the test mass, crackling noise produced in the upper intermediate mass maraging steel blade can propagate vertically, directly into the test mass. This crackling noise profoundly limits the sensitivity of the detector. Characterising, understanding, and hence minimising the crackling noise in the maraging steel blade is the key for more precise measurements.

It has been observed in recent experiment conducted by my mentor's group that the mechanical response of a monocrystalline copper nanopillar (discussed in details later) changes with different applied elastic stress⁵. This behaviour can be predicted by the aforementioned non-linear dislocation network behaviour. My contribution in this project is largely a further confirmation of this behaviour by experimentally investigating the effect of sample size on the mechanical response. Then deeper understandings of the theory and improvements to the model simulation can be made based on the collected experimental data.

2. Objectives

The study will be focusing on monocrystalline (single crystal) metals based on the energy dissipation approach. We choose to use monocrystalline metals because polycrystalline metals are too complicated for any fundamental features of crackling noise to be revealed evidently. The blades used in the detector are maraging steel, which is a bcc polycrystalline metal. However single crystal copper nanopillars are to be used as substitutes for steel in our study because copper also has the fcc structure and is better understood^{5,6}. When a sample is subject to sinusoidal (vibratory) applied stress, the strain response is the key to understanding the dynamic property of the system. For an ideally elastic material the strain response will be sinusoidal, and the phase difference between input and output is exactly 0. However because of the presence of dislocations and other defects, real materials are not ideally elastic. Measuring the *dynamic moduli* will give us insights of the microstructure evolution inside the material.

In the elastic regime, *loss moduli* are expected to be zero if the dislocations inside the crystal do not move². However it was found by my mentor that there were some anomalies in the experiment; the loss moduli were not zero or even constant throughout the static elastic stress sweep². This suggests there be some dislocation dynamics before yielding. Therefore the prime objective for this project is to further investigate this deviation from the perfectly elastic model by measuring the loss moduli under various conditions. In addition, since the mechanical behaviour of nanocrystals largely depends on the size of the crystals themselves, measuring the dynamic moduli over a range of different sizes will give us more insight on the underlying mechanism.

More data need to be collected in order to confirm this anomalous behaviour according my mentor's experiment. After that the effect of sample size on the mechanical response is to be investigated. Our hypothesis is that if the system is larger, the non-linear deviation will be smaller due to the loss of coherency^{2,5}. Measurements of dynamic moduli are to be conducted for a range of nanopillars with different size. If this size effect were confirmed, the non-linear picture would be verified.

3. Approach

Monocrystalline copper nanopillars are used as samples for the reason described in the previous section. They can be fabricated using the conventional *Focus Ion Beam* method by shining a beam of gallium+ ions onto the monocrystalline copper substrate¹. The beam will mill the material away. The desired size of the nanopillar can be achieved by adjusting the power and size of the beam.

Then the copper nanopillar is set into oscillatory uniaxial compressions by using *Hysitron*, a nanoindenter machine mounted with a flat punch. The oscillatory stress is

applied in stages i.e. the mean value of stress is increased after each stage, and the strain response is recorded for each of the stages. Then from the load displacement data acquired, the dynamic moduli can be evaluated.

The strain response is usually embedded in a large amount of noise and hence the dynamic moduli have large errors and we cannot firmly conclude the deviations from the ideal elastic behaviour are present. However the resolution of the machine cannot be improved by us. The main challenge is that we have to verify that the anomalous behaviour is intrinsic to the mechanical response of the material not due to the machine or any other immanent systematic errors.

In order to surmount this challenge, we need to perform conventional *compression tests* to serve as system benchmark; highly reliable values of Young's moduli are measured and used as reference. The elastic part of each of the dynamic moduli measured from the *dynamic mechanical analysis test (DMA test)* should agree well with the reference value. Any data points where the deviation from the reference value is significant will be excluded from the analysis. SEM images are taken before and after the tests.

4. Schedule

Week 1: Learn and develop fabricate skills. Prepare batches of monocrystalline copper nanopillars (diameter 500nm) using the focused ion beam (FIB) technique for further tests.

Week 2: Learn nano-mechanical test, simple compression test, and dynamic mechanical analysis (DMA) test. Perform compression tests for the 500 nm copper nanopillars, and compare the results with those from my mentor's previous experiment.

Week 3: Perform DMA tests for the 500 nm copper nanopillars, and compare the results with those from my mentor's previous experiment.

Week 4: Fabricate 500 nm fused silica nanopillars. Perform DMA tests for calibration.

Week 5: Fabricate batches of monocrystalline copper nanopillars with diameters varying from 200 nm to 1 μm .

Week 6: Perform the compression tests and the DMA tests for all the copper nanopillars.

Week 7: Analyse, organise the data, and evaluate the size effect on the mechanical response.

Week 8: Learn and perform computer simulations.

Week 9: Finalise the results, make conclusions, and prepare for the presentation.

5. Reference

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