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Local Temperature Measurement of Joule Heating During In-situ TEM Electroplasticity Test of Ti-6Al

Xiaoqing Li[1,2] and Andrew M. Minor[1,2*]

[1.] Department of Materials Sciences and Engineering, University of California Berkeley, Berkeley, USA.
[2.] National Center for Electron Microscopy at Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.
* Corresponding author: aminor@berkeley.edu

Electroplasticity (EP) is defined by pulsed electrical currents during plastic deformation that results in a flow stress reduction and elongation increase prior to failure [1]. With the development of experimental explorations and theoretical studies with computational simulation, it has been found that the instantaneous thermal expansion stress could contribute to deformation mechanisms, including the accumulation and annihilation of dislocations overcoming Peierls barrier due to thermal effects with [2, 3]. Among many hypotheses, the Joule heating effect (a thermal effect) and the electron wind effect (an athermal effect) caused by the electrical current are the most commonly invoked explanations for instances of EP observed in different materials [4]. Joule heating results in a uniform elevation of temperature throughout the sample after it reaches equilibrium instantly with applied current [5]. Electron wind force is based on momentum transfer from the moving electrons to the atoms or dislocations [6]. However, in order to separate these two effects, direct defect-level observations are lacked to clarify the influence of the various mechanisms. Here we developed a simple and direct temperature tracking technique on nano-scaled sample during in-situ TEM tensile test with applied current to evaluate the Joule heating effect due to EP.

In this work, temperature change was evaluated during the in-situ TEM tensile test on single crystal Ti-Al with applied electrical current carried out on an electrical push-to-pull device (EPTP). The nano-sized single crystal sample was subjected to a uniaxial loading and a controlled voltage input, as shown in **Fig. 1**. The technique is based on the idea of parallel beam selected area diffraction (SAD) but optimized with simultaneous data collection for simultaneous in-situ TEM mechanical tensile testing. With the precise image analysis by contrast subtraction, the elongation of the sample due to thermal expansion was measured, and the equivalent temperature data for the area of interest on the sample was obtained. Also, diffraction data was captured by in-situ frame grabbing and processed to get the lattice expansion in certain direction. In order to take the directional effect into consideration, the geometric extrapolation for the precise lattice expansion measurement of the crystal in the loading direction was performed on the SAD patterns. As an example, the diffraction pattern of a <0001> zone axis was selected, and each diffracted point was indexed. Then, the position of each diffracted point was denoted according to the coordinate of the loading axis. An elliptical geometric estimation of the lattice expansion in the loading direction was presented following by a linear extrapolation of the precise lattice expansion in the loading direction as shown in **Fig. 2**. Lastly, the equivalent temperature increase during the performed test was evaluated with a credibility of ± 10 K and compared with previous works. The data collection and evaluation technique can be easily adapted to any type of in-situ TEM test for temperature tracking and has a significant impact on contribution to the understanding of Joule heating effect due to EP. Moreover, further temperature tracking would be carried out with the in-situ 4D-STEM technique and the quantification of phonon vibrations with electron energy loss spectroscopy (EELS) [7,8].

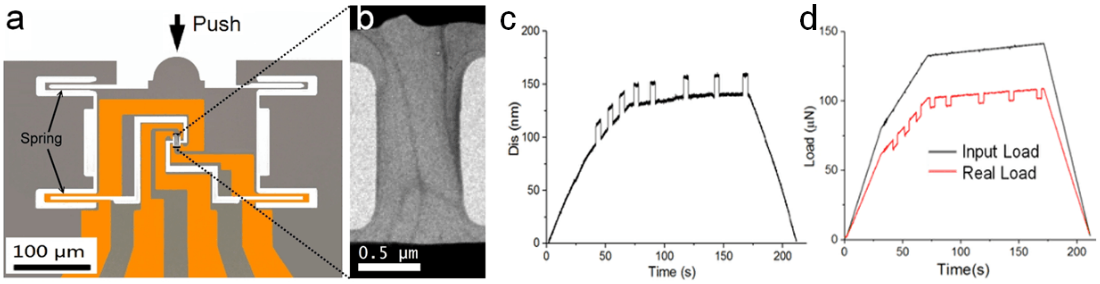

Figure 1: Experimental set up and temperature estimation based on elongation measurement. (**a**) EPTP device, gold patterns are conductive electrodes for electrical current measurements. (**b**) Bright field image of the sample geometry for in-situ mechanical tests. (**c**) Displacement vs. time curve, the displacement jumps were corresponded to the applied electrical current. (**d**) Load vs. time curve, the elongation of the device was subtracted, showing a similar load-drop phenomenon.

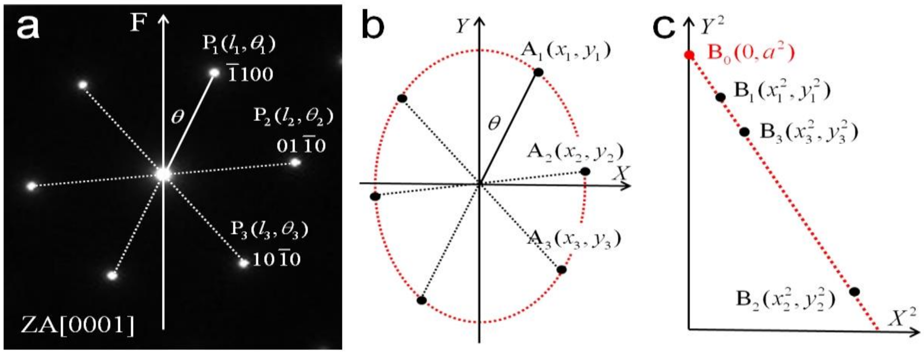

Figure 2: Diffraction pattern and geometric extrapolation for the precise lattice expansion measurement of the crystal in the loading direction by the selected area diffraction. **(a)** Indexed SAD pattern of a <0001> zone axis, and their position was denoted according to the loading axis coordinate. **(b)** Schematic representation of the elliptical estimation of the lattice expansion in the loading direction. **(c)** A linear extrapolation of the precise lattice expansion in the loading direction.

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