Direct observation of the liquid-like superplasticity in native alumina under oxygen environment

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The mechanical performance of oxide scales is crucial for the stress corrosion resistance of metals. If cracks in oxide are generated during deformation or oxidation, embittering elements (such as hydrogen or oxygen) can diffuse into metal more easily, leading to greatly enhanced internal corrosion and materials degradation. Therefore, it is often hoped that the native oxide can be superplastic and rapid-self-healing. Recently, researchers discovered that the surface layer (i.e., sub-10 nm region) of polymeric and organic glasses is in liquid state at room temperature because the reduced glass transition temperature (T_g) at the surface. Since aluminum native oxide is amorphous and only 2-5 nanometers thick, it is conjectured that native alumina may possess such properties. However, there is still a lack of experimental evidence, as direct visualization of the mechanical deformation of native alumina in gas environments is challenging.

Via an aberration-corrected environmental TEM, we have performed *in situ* experiments to stretch surface native alumina under oxygen gas environments (i.e., concurrent deformation and oxidation). We discovered that native alumina is liquid-like during deformation[1], and it can remain its integrity without any cracks/spallation (Fig. 1) at moderate strain rate. When the strain rate is higher, fracture in metal will occur, exposing fresh metal surface. We then visualized the initial oxidation of aluminum at the metal-gas interface at atomic resolution (Fig. 2). Unlike traditional thin film growth or nanoglass consolidation processes, we observe seamless coalescence of new oxide islands without forming any glass-glass interface or surface grooves, indicating greatly accelerated glass kinetics at the surface compared to the bulk.

Reference:

1. Yang, Y., Kushima, A., Han, W., Xin, H. L. & Li, J. *Nano Lett.* (2018). doi:10.1021/acs.nanolett.8b00068

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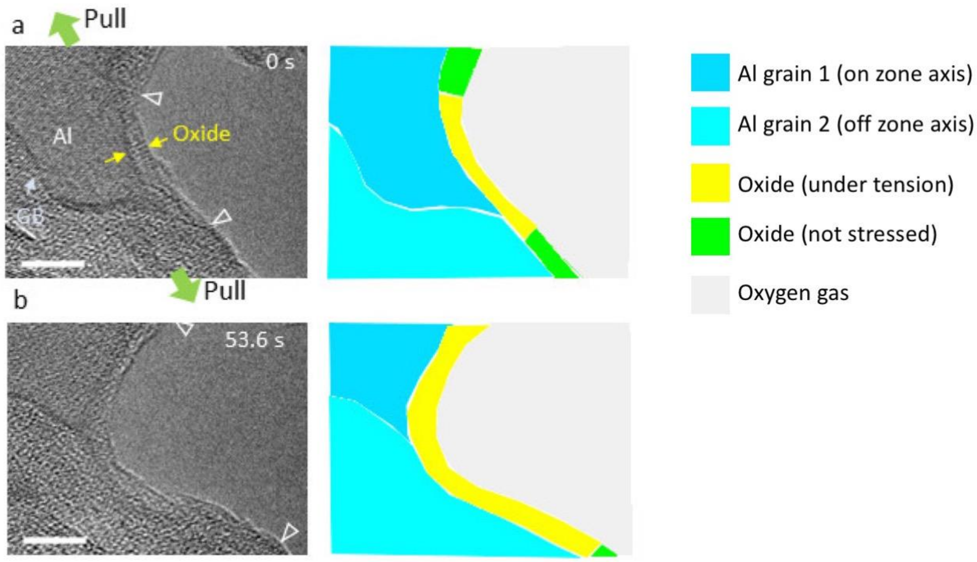

Fig.1. Sequential TEM images showing the super-elongation and self-healing process of aluminum oxide when stretched in O2 environment[1]. Oxide between the two white triangular marks in (a-b) are the segment being stretched (also highlighted as yellow color in the schematic drawings). The green arrow in (**a)** represents the stretching direction. The strain of oxide at (**b)** is about 117%. All scale bars, 5 nm.

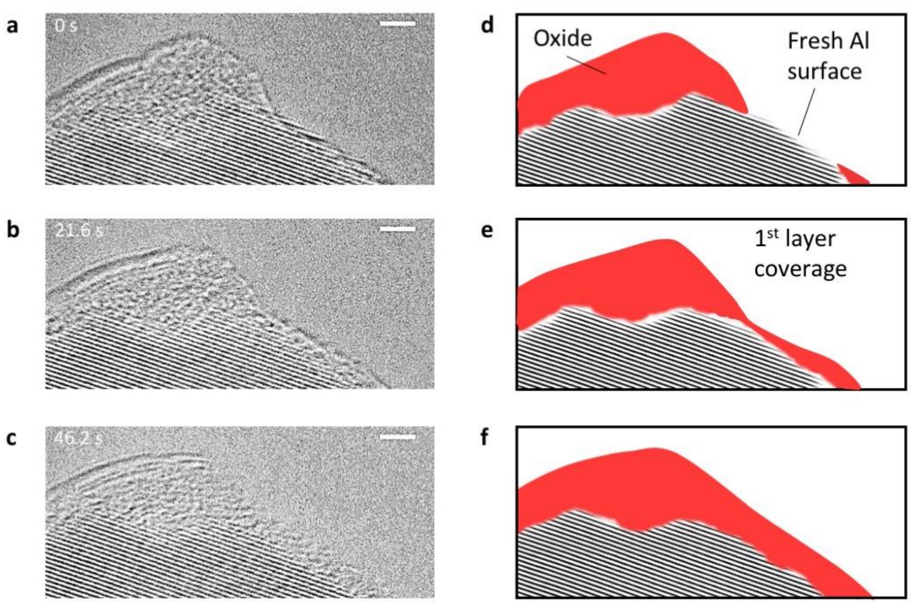

Fig. 2. Initial oxidation of pure aluminum at room temperature[1]. a-c, Sequential HRTEM images of the oxidation process. d-f, processed images of (a-c) to highlight different phase distribution: the aluminum lattice planes, shown by black lines, are filtered images of (a-f) using a set of aluminum (111) diffraction spots; the oxide is shown by red color. All scale bars, 2 nm.