Witness to strain: Subdomain boundary length and the apparent subdomain boundary density in large strained olivine grains

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ABSTRACT
Electron backscatter diffraction (EBSD) investigation of strain mainly uses polycrystalline samples to study fabric development. We extend the use of EBSD for the analysis of large single mineral grains by measuring the apparent surficial subdomain boundary density per unit area, reported here as unit segment length (USL). We apply this USL technique to examine and quantify the plastic deformation recorded by naturally shocked olivine in the low to moderately shocked ureilite meteorite Northwest Africa 2221 and the highly shocked martian dunitic cumulate meteorite Northwest Africa 2737, by assessing the types of subdomain boundaries and the increase of subdomain misorientation with increasing shock metamorphism. We further compare USL results for the shocked olivine in the meteorites with those for the terrestrial deformation of Hawaiian olivine. USL of olivine increases with shock level, and USL from shocked olivine is significantly greater than that of terrestrially deformed olivine. USL is a promising tool for the quantification of plastic deformation in large single crystals from shock as well as terrestrial deformation. The results derived from USL measurements along with local EBSD maps are complementary with quantitative 2D X-ray diffraction analysis of crystal deformation and disruption, leading to a more comprehensive understanding of characteristic shock deformation recorded by large single crystals.

Keywords: EBSD, crystal deformation, subdomain walls, shock metamorphism

INTRODUCTION
Hyper-velocity impacts cause shock metamorphism and deformation in rock. Impact events release enormous kinetic energy nearly instantaneously, which can vaporize and melt rocks, as well as produce heat and do mechanical work on rocks that remain in the solid phase (Melosh 1989; Fritz et al. 2017). For individual mineral grains in a target rock, the impact may be recorded as crystal damage and deformation during the pressure pulse, and in post-shock plastic deformation, producing highly strained crystals (French 1998).

The effects of shock in single crystals are largely recognized microscopically by petrographic textures in minerals, such as undulatory extinction, mosaicism, or recrystallization (Stöffler et al. 1991, 2018; French 1998; Fritz et al. 2017). Optically, non-strained crystals show complete extinction at a single orientation (also called straight extinction for minerals with higher symmetry, e.g., orthorhombic, hexagonal, and tetragonal system; minerals in lower symmetry systems undergo extinction at a single point with an angle to N-S/E-W, e.g., inclined extinction) under cross polarized light (XPL). A mosaic spread of crystal subdomain orientations is observed optically in XPL as undulatory extinction (a wave of extinction sweeping through the grain) or mosaicism (patchy extinction) when observed in thin section. Single crystals may also exhibit the development of planar fractures, planar deformation features and patchy amorphization (Stöffler et al. 1991, 2018; French 1998; Fritz et al. 2017).

Subdomain misorientation produced by shock deformation has also been reported by X-ray diffraction. Strain of single crystals as a mosaic spread of subdomain orientations is observed by X-ray diffraction as streaking of diffraction spots in two-dimensional XRD patterns. This phenomenon is collectively described as strain-related mosaicity (SRM), with increased diffraction streak length correlated with greater shock level (Hörz and Quaide 1973; Flemming 2007; Izawa et al. 2011; Jenkins et al. 2019; Rupert et al. 2020; Li et al. 2020, 2021a).

These techniques are sensitive to degree of shock metamorphism, even allowing its quantification, but do not distinguish between shock-related strain in crystals and strain from geological processes. It is necessary to make the observations at the mesoscale to study shock effects on subdomains and their boundaries in crystals to investigate possible differences between strain mechanisms and establish the linkage to the petrographic observations and XRD.

In a distorted crystal, the excess free energy induced during shock metamorphism mobilizes dislocations by glide motion and produces strain in crystal structures (Cordier 2002). For unstrained crystals, statistically distributed dislocations are balanced and would not contribute to grain surface curvature. For strained crystals, non-uniformly distributed dislocations are displaced forming subdomain boundaries and further misorienting subdomains, as a manifestation of accumulation of strain energy. The displacement mechanism is believed to be controlled by the glide motion at lower homologous temperatures (e.g., $T < 0.4$ T of melting point), and at higher temperatures,