SHOCK EFFECTS OBSERVED AND QUANTIFIED IN SINGLE CRYSTALS

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Introduction: Shock metamorphism is distinct from slower strain rate types of deformation that occur during geological processes on Earth [1-2]. During impact events, shock waves immediately unload kinetic energy, generating enormous overpressure over a very brief time, quickly compressing and decompressing the solid target rock. The rapid local volume change induces a large amount of strain energy in crystals, and they are distorted and misoriented producing permanent plastic deformation textures [1-2]. In silicates, the plastic deformation of shocked crystals is observed petrographically as an increase of mosaicism with increased shock pressure [2], representing the subdivision of single crystals into smaller mosaic blocks. In 2D X-ray diffraction the mosaic spread of subgrain misorientation is shown as streaks along the Debye rings [3]. More recent research [4-9] has shown that this shock mosaicism or strain-related mosaicity (SRM) in 2D XRD may be quantified, revealing a positive trend of streak length increasing with increase of shock pressure. This petrographic or 2D XRD work, however, does not clearly differentiate mineral strain due to shock metamorphism from terrestrial strain, and also does not identify the finer scale mechanisms of how shocked crystals accommodate shock loading to become a set of misoriented subdomains. We use 2D electron backscatter diffraction (EBSD) orientation maps to examine the shock mosaicism by segregation of the misoriented subdomain in large single crystals, leading to a useful quantification of the apparent subdomain boundary density. We hypothesize that the increase of shock mosaicism or XRD streaks length results from the increased density of misoriented subdomains due to dislocation creep in the distorted crystal lattice by shock deformation. We demonstrate that it is possible to visualize the increased subdomain boundaries and further calculate their apparent density from the 2D EBSD map. This subdomain boundary density in shocked crystals may be a useful index of shock metamororphism, and also provide a means of investigating deformation mechanisms specific to shock events.

Methods: To study the misorientation of shocked subdomains, we apply unit segment length (USL) analysis in combination with traditional EBSD misorientation analysis and misorientation index, to large olivine single crystals in a range of differently shocked ultramafic achondrite meteorites. The USL analysis is designed for single crystal analysis using an EBSD orientation map to calculate the apparent boundary trace density [10]. Misorientation index [11] measures the fabric strength in polycrystalline samples, but using a modified method, it can be applied to test the randomization of highly misoriented subdomains in shocked single crystals in meteorites. The sample selection includes low shock Elephant Moraine 96042, moderate shock Northwest Africa 2221, anomalous moderate to high shock Larkman Nunatak 04315, high shock Northwest Africa 2737, and anomalous high shock Allan Hills A81101 [8 -10].The results are compared with terrestrially deformed olivine crystals derived from the mantle in kimberlite and a Hawaiian xenolith as well as olivine in a Hawaiian basaltic flow showing deformation texture [12].

Results and Discussion: Shocked olivine shows greater density of subdomain boundaries with higher shock level, reflected by the increased values from USL measurements, compared with olivine in terrestrial samples. In LAR 04315, we further observed increased randonmization of subdomains reflected by M-index. At the crystal scale, shock deformation appears to produce pervasive plastic deformation as mosaicism, accommodated by an increased apparent density of low degree misorientation subdomain boundaries, measured here as USL. A possible mechanism is highly localized dislocation migration by gliding or climbing in the crystal lattice, driven by the strain energy induced during shock events. Post-shock thermal events could allow further migration of the dislocations forming the highly misoriented but strain-free subdomains as observed in LAR 04315 [8]. With the increase of misorientation angles between domain boundaries from the dislocation creep regime, it would eventually undergo dynamic recrystallization forming new strain-free olivine crystallite as observed in ALHA81101 [8]. Our study provides a quantitative and direct approach to examine and explain the destructive shock effects in meteorites. Furthermore, this work establishes a link between the two analytical techniques for measuring strain: EBSD observations and 2D XRD patterns, in that the increase in subdomain density in strained single crystals as observed by EBSD is consistent with the increase in mosaic streak length along the Debye rings as observed by 2D XRD.

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