FEMTOSECOND LASER EXPERIMENTS ON ORIENTED OLIVINE SINGLE CRYSTALS: EVIDENCE OF SPACE WEATHERING

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Introduction: Space weathering (SW) is the most important set of processes that irreversibly change the surfaces of the atmosphere-free bodies [1]. Ion irradiation and laser experiments are considered the most powerful techniques to simulate the SW effects. The former are a direct reproduction of solar wind irradiation effects. The latter are assumed to simulate micrometeoroid impacts (e.g., [2-3]). In this work, we present spectroscopic and TEM results of the application of ultra-short laser pulse as a tool to reproduce SW effects on olivine crystals.

Sample and Methods: Laser experiments were performed on oriented slices (300-500 µm thick) of single-crystal olivine ($Fo_{94.5}$). Experiments were carried out under vacuum (10^{-3} mbar) via femtosecond Ti:sapphire laser at the wavelength of 800 nm. On each sample, grids (2.5 x 2.5 mm) of single shots were produced at 3 mJ. Each shot had a pulse duration of 120 fs and a spot diameter of 38 µm. These parameters correspond to a maximum laser intensity of ~10^{15} W cm^{-2}. Spectral features of irradiated and non-irradiated areas were investigated in the NUV-vis-NIR range. FIB-lamellae were prepared from selected craters and were investigated by TEM in order to evaluate the defect microstructures at the nanometer scale.

Results: Single-shot laser irradiation produced spherical to elliptical microcraters on the surfaces of the olivine slices (diameter ~ 80 µm). Craters are covered by glass showing distinct splash-form morphologies at the rim.

Spectra of irradiated areas show a strong reduction in the absolute reflectance (darkening). Spectra of irradiated areas scaled at 550 nm show a strong increase in the reflectance with increasing wavelength (reddening).

Crater cross-sections show a layered structure. In the central zone, we report from top to bottom: a glass layer (~300-500 nm), a polycrystalline layer with palisade-like olivine crystals (~400-300 nm), a polycrystalline layer with very small (~50 nm) polygonal randomly oriented olivine crystals (~350-600 nm), and the olivine substrate with shock effects (>10 µm). Within the substrate numerous planar fractures and *c* dislocations occur. Layers are thicker at the core than at the rim. The polygonal olivine layer is missing at the rim. Two layers of iron nanoparticles ($npFe^0$; d_{110} = 0.206 nm; average diameter 4-7 nm) occur at the interface between the polygonal and the palisade layers and between the palisade and the glass layers. TEM-EDX maps and analyses show a significant Mg-loss in the glass layer. The interface between the polygonal and the palisade olivine is depleted in Fe. $NpFe^0$ contain Ni, particularly at the interface between the palisade and the glass layers.

Discussion: *Experimental approach.* For fs laser pulses, the absorbed energy is transferred from electron to the lattice by electron-phonon-coupling at the end of the laser pulse. The release of a shock wave and thermal energy occurs in a nanosecond to microsecond timescale [4]. Compared to previously used laser pulses with nanosecond duration ([2-3]), ultra-short laser pulses have the main advantages to allow the propagation of a shock wave and to avoid the interaction between the laser light and the ejecta plume, i.e., no additional energy is transferred to the ejecta, and no additional thermal effects are produced.

Contrary to previous experiments, which used mostly powdered samples compressed to pellets [2-3], we performed our experiments on oriented olivine crystals to avoid additional particle-particle interactions and to study the orientation-dependence of shock effects in this anisotropic material.

Origin of the layered structure and $npFe^0$ formation. The propagation of a shock wave in the irradiated material results in the formation of a layered structure similar to the one observed in a lunar microcrater [5]. Due to the splash-form morphology, the topmost glass layer likely formed as a thin sheet of olivine melt, there is no evidence for vapor deposition. The palisade structure of the topmost polycrystalline layer indicates that this layer crystallized from the melt. The underlying polycrystalline layer, due to the polygonal shape of its crystals and the high degree of misorientation, might represent an extremely high shock stage, a transition between a molten layer and the olivine substrate. The in-situ formation of $npFe^0$ is preferred due to the distribution of nanoparticles and the lack of evidence for the vapor deposition of the glass layer (e.g., [3]). The completion of the TEM-EDX analyses and EELS measurements will allow to constrain the mechanism for the in-situ formation of $npFe^0$.

Conclusions and future works: The results of the spectral measurements and the TEM investigation corroborate that the use of an ultra-short laser pulse is a reliable approach to reproduce the effects of the SW and to check and study exactly where and how certain modifications occur. Next steps include to constrain the mechanism for the formation of $npFe^0$ and the characterization of shock-features due to the different crystal orientation (i.e., planar fractures and dislocations).

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