IMPACT-INDUCED TWINNING IN CALCITE AS REVEALED BY MEMIN EXPERIMENTS WITH MARBLE

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Introduction: Shock effects in calcite, one of the most abundant minerals in the Earth's continental crust, are currently lacking and make the unequivocal proof of craters formed in limestone or marble difficult. In the framework of MEMIN we conducted a series of experiments with marble targets in order to better understand crater formation in this lithology and to search for characteristic microstructures indicative for shock loading.

Methods: Here we present a MEMIN impact crater experiment with marble conducted with a two-stage light gas gun at the Fraunhofer Ernst-Mach-Institute for High-Speed Dynamics in Freiburg (EMI), Germany. The light-gas gun with an 8.5 mm caliber launch tube was employed to accelerate a Campo del Cielo iron meteorite of 2.5 mm diameter to an impact speed of ~5 km s^{-1}. The ambient pressure in the target chamber was reduced to 0.001 bar during the experiments. A 25 cm cube of Carrara Marble with a grain size of 80–100 µm, an average porosity of $\leq$ 1%, and a composition of ~98 vol% calcite plus traces of quartz, mica and dolomite was selected as target material. The crater subsurface was systematically scanned with an electron microscope [1] and microstructures were mapped in detailed. Foils for TEM inspection were prepared from in situ crater floor material and from a depth of 300 µm below the crater floor.

Results: The marble crater has a volume of 3.9 cm³, a diameter of 56.6 ± 4.2 mm and a depth of 6.0 ± 0.4 mm, resulting in a d/D ratio of 0.11. The crater is unusually shallow and small. The cratering efficiency is low compared to other lithologies such as quartzite or sandstone. Apart from intra-granular cracks and tensile fractures the main deformation features in the marble crater subsurface are twin lamellae and open cleavage. Polarized light microscopy images of the uppermost crater subsurface show heavily deformed grains. In plane polarized light calcite grains show a brownish color; in cross polarized light they show a lack of extinction and reduced interference colors. The intensity of these features decreases with depth down to ~1.5 projectile diameters, below which they are no longer observed. In thin section, SEM and TEM microscopy these features were recognized as micro-twins. Micro-twins occur mostly in three orientations in single grains. The average twin density, measured in TEM-foils at constant magnification, exceeds 1000 twins per millimeter and locally reaches values of 30000 twins per millimeter. At dilatant intersections of crosscutting twin lamellae, Rose-channels [2] of rhombohedral shape develop. Their sizes depend on the width of the intersecting twins and vary between 10 nm and one micrometer. Intersecting twin planes also cause local excursions in strain and are responsible for the formation of local dislocation tangles and the initiation of slip on twin planes. Backscattered scanning electron imagery shows that gliding on narrow-spaced twin planes produces open cleavage planes and leads to the bending of crystal lattice domains and buckling instabilities.

Discussion: Mechanical twinning is the most abundant type of deformation in calcite and occurs predominantly as so-called e-twins, e.g. [3]. Their critical resolved shear stress range between 9 MPa and 12 MPa [4]. The peculiar optical behavior of shocked calcite is explained with the presence of extremely high micro-twin densities, partly high dislocation densities and the micro- cleavage planes. The spacing of twins is in the order of the wavelength of visible light, in some regions remarkably below the wavelength of light. The twin structure works as a diffraction grating. The lack of extinction under crossed polarized light is due to the dispersion in several directions, in particular if three twin orientations are present. The brown staining suggests massive light absorption.

Numerous tectonic studies revealed a systematic relationship between twin density in calcite and the applied shear stress, e.g. [5]. Numerical modeling of our experiment suggests that calcite grains of the TEM foils experienced peak shear stresses between 800 and 1000 MPa, above the Hugoniot elastic limit of calcite. The relationship between micro-twin density and shear stress matches with calcite twin piezometers [5] derived for tectonic deformation and suggests that calcite twin piezometry is applicable to the shock stage. We will now test if shock-microtwinning in calcite and the associated peculiar optical behavior of calcite can be applied as useful shock indicators to natural craters.

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