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New Insights into Shatter Cone Formation from MEMIN Experiments

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Abstract

We recovered shatter cone fragments from the ejecta of hypervelocity impact experiments, performed in the framework of MEMIN. The fragments geometries were characterized by WLI, and the fractures surfaces themselves by SEM. We estimated low bulk shock pressures of 2 to 5 GPa for the material in which the shatter cones have formed. The microstructural investigation revealed intricate melt films and shear deformation along the shatter cone surface, indicating increasing strain towards the same. Combining our observations with a possible formation model, we interpret shatter cones as the result of symmetric crack branching of rapidly propagating fractures with a resulting mixed mode I/II fracture surface.

1. Introduction

Shatter cones are the only macroscopic shock effect, diagnostic for the recognition and verification of impact structures. Nonetheless, their formation and the physical boundary conditions are still subject of debate [1]. To narrow down the formation conditions of shatter cones, we systematically analyzed hypervelocity experiments conducted in the framework of MEMIN.

2. Shatter Cones in MEMIN

We recovered 24 shatter cone fragments from the mesoscale MEMIN experiments with 20–80 cm sized target cubes of sandstone, quartzite and limestone [2]. Experimentally produced shatter cones were found as fragments of 1.2 to 9.3 mm size in the ejecta and were delivered from the inner crater zone of pervasive grain crushing and compaction [3], which is easily identifiable in most of the MEMIN craters. The width of this area showed a range of 15–38% of the apparent crater diameter, which correlates with a minimum of 2 GPa shock pressure.

We obtained morphometric data from the recovered fragments by means of white-light-interferometry (WLI). In combination with laser scanning data of natural shatter cone samples, we studied apical angles and curvatures and developed a phenomenological model [4].

The SEM analyses of the recovered MEMIN fragments gave the opportunity to study intricate melt films preserved on the fresh shatter cone surfaces. We found both vesicular and polished melt films, decorated by micro-spherules. Subjacent to the melt films are zones of fragmentation and brittle shear, indicating movement away from the shatter cone apex of the rock that surrounds the cone. Smearing and extension of the melt film indicates subsequent movement in opposite direction to the comminuted and brecciated shear zone.

3. Formation Model

The microstructural investigation documents that fracturing, formation of smooth melt films and vesicular melts can be associated to the shock loading and unloading phase. We suggest that deformation along shatter cone surfaces does form as a succession of deformation events: Phase 1: Fragmentation and brittle shearing, along with fracture bifurcation, timed with the passage of the elastic precursor. Phase 2: Continued shearing under enhanced confinement and shock conditions. Frictional melting occurs within a narrow zone along the shatter cone surface. Smooth polished melt films and shock effects develop. Phase 3: Onset of pressure release leads to progressive melt production. Reverse shearing results from a release of stored elastic energy of the rock during unloading. Phase 4: Tensile fracture separation continues during unloading, but reverse shear movement decays. Microstructures that are associated with this final stage include vesicular textures without a preferred orientation/alignment of vesicles.

5. Figures

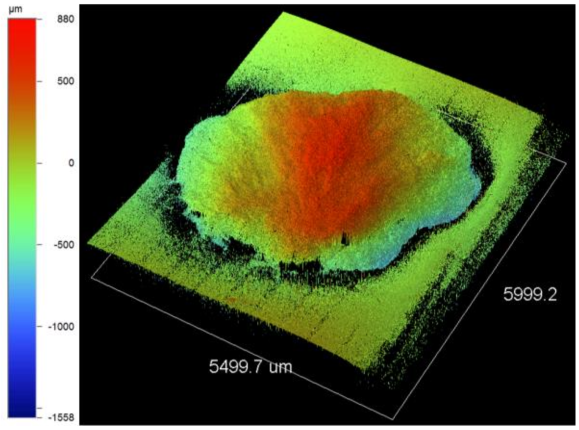

Figure 1: WLI scan of recovered shatter cone fragment from MEMIN experiment A15 (5 mm aluminum projectile shot on a 20 cm sized cube of sandstone at 6.97 km/s).

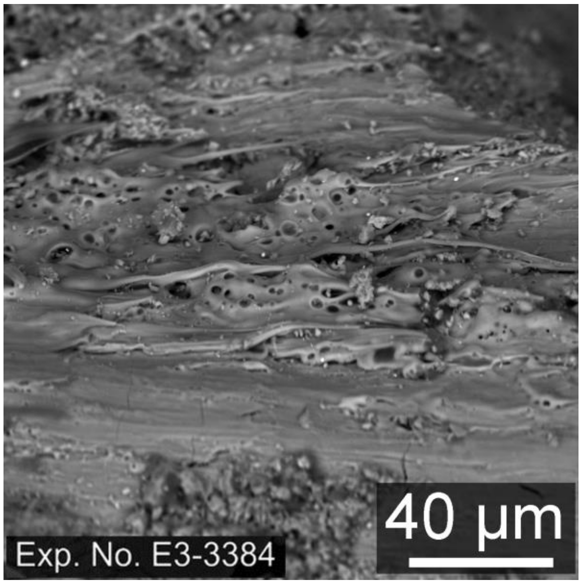

Figure 2: SE images of a shatter cone surface from experiment MEMIN E3 (12 mm Campo del Cielo projectile shot on an 80x80x50 cm sized target block of water saturated sandstone at 4.59 km/s).

6. Conclusion

We envisage shatter cones are build up by numerous cycles of fracture bifurcation early in the cratering process. Crack branching is the result of rapid fracture propagation that may approach the Raleigh wave speed. In experiments, shatter cones can be formed under low bulk shock conditions and still show intricate melt films along the fracture surface. Those melt films are formed by a combination of frictional heating and shock and infer that shatter cone surfaces are mixed mode I/II fracture surfaces.

Acknowledgements

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