SHATTER CONES: A CASCADE OF BIFURCATIONS DURING DYNAMIC FRAGMENTATION

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Introduction: Most models of shatter cone formation require a heterogeneity at the cone apex of high impedance mismatch to the surrounding bulk rock, e.g., [1, 2]. Applying Huygens principle this heterogeneity is the source of spherically expanding waves that interact with the planar shock front or the following release wave after the principle of superposition. While these models are capable to explain the overall conical shape of shatter cones they hamper to explain the diverging and branching striae that characterize the surface of shatter cones and lead to the so-called horsetailing effect. Moreover, the size of the required apical heterogeneities should scale with the width of the shock pulse profile, which, in turn, depends on the impactor diameter. However, the occurrence of shatter cones in MEMIN impact experiments [3, 4] suggests that the shock duration is probably not a critical factor for their formation.

Shatter cones occur in any rock type. Of course, all rocks contain micro-flaws such as dispersed and distributed micro-fractures, but extremely homogeneous micritic limestone that devoid of visible inclusions or voids should contain a lesser amount of relevant heterogeneities that could act as shatter cone sources than, for instance, a coarse-grained granite.

Here we use the delicate arrangement of ridges and grooves of shatter cone surfaces as key for understanding shatter cones formation. Tracing a single ridge from its apex downward along the cone one can observe that each ridge splits into two branches after some distance. These branches themselves bifurcate at constant angle and the new branches do the same. This forms a hierarchical pattern with n cycles of bifurcations so that the number of ridges N grows with 2^n. Bifurcation is the result of rapid fracture propagation [5, 6] and probably starts when the fracture propagation velocity reaches 50% of the Raleigh wave speed. The small ridges of a shatter cone specimen are characterized by a specific curvature and their distance to adjacent grooves remain constant. The ridges represent curved fractures that interpenetrate each other and reach obliquely into the shatter cone interior.

We developed a phenomenological model in which the overall cone geometry results from a several factors: (i) the ridge length between two bifurcation points, (ii) the bifurcation angle, (iii) the curvature of the ridge, and (iv) the distance between adjacent ridges. This simple approach allows us to form linear cones with different apex angle, tube like cones showing the horsetailing effect, or hyperboloids. The exponential increase in the number of fracture stringers with increasing distance from the apex leads to an exponential swelling of the cone radius. This effect is compensated by the curvature of the fractures, and the fractality of ridge arrangements. We propose that the factors (i)-(iv) control the geometry of natural shatter cones. A large heterogeneity at the tip of the apex is not required.

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