How to Make Metal Regolith: Fracture Mechanics in Ejecta from Impacts into Meteoric Iron
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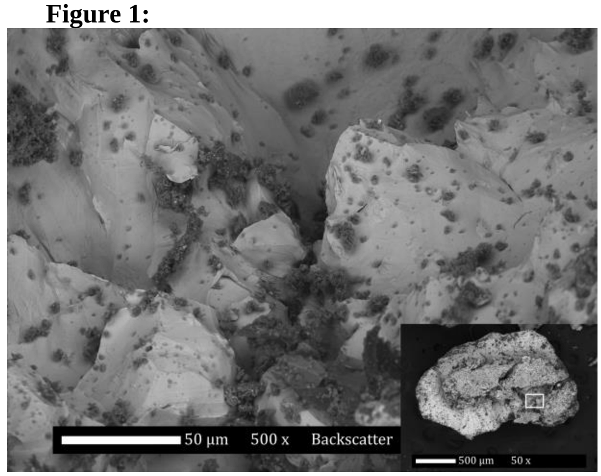
Introduction: The upcoming NASA Psyche Mission may present humanity's first opportunity to explore a potentially metallic asteroid surface [1]. Such a surface will be subject to the same surface processes as other planetary bodies, including impacts and regolith formation. However, the differing mechanical properties between metals (relatively higher bulk strength, ductile plastic deformation) [2][3] and stony minerals (relatively lower bulk strength, brittle fracture) [3] suggest they would respond differently to these surface processes. The big question is: will a regolith on a metallic asteroid be comparable to that on stony asteroids we have previously observed, and how might it differ if not? While a definitive answer must wait until we explore a metallic planetary surface with spacecraft, we can begin to answer this question by studying ejecta fragments from impact experiments into meteoric iron targets. Characterizing their fracture surfaces with Scanning Electron Microscopy (SEM) can reveal the mode(s) of mechanical deformation and failure that occurred during impact, which has direct implications for the morphology and texture of the fragments comprising impact-generated regolith.

Sample & Methods: Marci et al. [4] previously reported a battery of impact experiments into iron meteorite targets using the NASA Ames Research Center Vertical Gun Facility. Previously we reported on initial SEM imaging results from seven of these fragments [5] and here we present a more complete description of the results. For initial analysis we chose fragments from Shot #3.09, a 6.350 mm Al projectile at 5.31 km/s at normal incidence into Santiago Papasquiero, an ungrouped iron meteorite with an interlocking granular microstructure of ~0.1 mm kamacite and taenite grains and interstitial ~0.01 mm tetrataenite [4][6]. Santiago Papasquiero's structure is uncommon among iron meteorites, but similar to interlocking granular structures of igneous rocks. We recorded 292 fragments in total: 1 larger than 5.0 mm in diameter, 74 between 5.0 and 1.0 mm, 210 between 1.0 mm and 0.25 mm, and the rest smaller than 0.25 mm. We imaged the fragments using the FEI XL30 and Helios 5 Scanning Electron Microscopes (SEM) at ASU's Eyring Materials Center. With the fragments mounted on a 1-inch SEM slide, we obtained a mosaic map of the complete all 292 fragments in both secondary and backscatter imaging modes, sorted the fragments by morphological features, then obtained higher resolution images of representative fragments and features within fragments. We further used Energy-Dispersive X-ray Spectroscopy (EDX) point spectra to identify the elemental composition of certain contrast features in the backscatter images.

Results: On some fragments the pre-impact microstructure appears preserved. Grain boundaries appeared intact at low magnification across large areas of multiple grains. However, at higher magnification distortion of the grain boundaries becomes visible, especially on smaller taenite and tetrataenite inclusions. Some individual grains exhibit multiple degrees of deformation e.g. **Figure 1**; the tip is heavily deformed, however where the grain intersects its neighbors, there is almost no deformation visible. Where the pre-impact microstructure is not preserved, there is evidence of partial melt or extreme ductal deformation. There may be little clear evidence of total melt. Some of these partially melted or heavily deformed fragments exhibit backscatter contrast features, e.g. **Figure 2**. EDX spectra of these regions show peaks for Al, likely from the impactor, as well as the constituent Fe, Ni, etc. from the target. A small number of fragments exhibit typical impact textures in stony materials, including fully melted tektites as well as shatter cones and other shock features.

Figure 1:



Discussion: Intact pre-impact microstructure might be interpreted as intergranular fracture, indicating brittle deformation associated with the ultrahigh strain rates of impact shock [3]. However, closer analysis at higher magnification reveals ductile deformation in close proximity and even within the same grains. This apparent discrepancy can be explained by adjacent grains having different composition, orientation, and/or boundary geometry, which can concentrate shock stress to localized points in the microstructure, similar to the mechanics occurring in shock darkening [7].

The mixing of iron and aluminum is surprising; these elements don't typically alloy because they have different solid-state chemistry and crystal structures [3]. A likely explanation is an Al surface coating thinner than the information depth of the electron beam, so that underlying Fe is still detectable. We plan to confirm this by making cross-sections of fragments containing both Fe and Al. In any case, previous work has suggested possible mixing of impactor and target material on metallic asteroid surfaces [8], and these fragments demonstrate individual ejecta fragments can incorporate material from both objects.

Because of the method by which the fragments were collected from the impact chamber, we cannot confirm they are a representative sample of all the ejecta produced during the test. Furthermore, predicting regolith grain size distribution on a metallic asteroid surface from astronomical observations is complicated by the need to interpret how varying mixtures of metallic and nonmetallic grains would alter the surface's thermal and optical properties [9] [10]. With those caveats, the predominance of mm-to-sub-mm particles among our fragments suggests a metallic surface could break down to particles at least this small with extensive impacts.

We will soon have similar characterization results for ejecta fragments from impact tests into Gibeon and Coahuila [4], both of which have Widmanstätten structures more representative of iron meteorites overall. Direct comparison with the Santiago Papasquiero fragments reported here may provide additional insights into metallic regolith formation.

References: [1] Elkins-Tanton et al. 2020, *JGR Planets* 125. [2] Petrovic 2011 *J. Materials Sci.* 36, 1579-1583. [3] Meyers and Chawla 2009, *Mech Behavior Materials*, Cambridge. [4] Marchi et al. 2020, *JGR Planets* 125. [5] Christoph et al. 2021, *LPSC LII*, Abstract #2730. [6] Buchwald 1974, *Handbook of Iron Meteorites* UC Press. [7] Moreau et al. 2018, *Phys Earth Plan Interiors* 282, 25-38. [8] Takir et al. 2017, *The Astronomical Journal* 153, 31-37. [9] de Kleer et al. 2021, *Planetary Sci. J.* 2:149. [10] Landsman et al. 2018, *Icarus* 304, 58.

Figure 2: