IMPACT EXPERIMENTS IN Fe-Ni INGOTS AND IRON METEORITES: IMPLICATIONS FOR THE NASA PSYCHE MISSION.

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Introduction: The NASA Psyche mission will visit the 226-km diameter main belt asteroid (16) Psyche, which may be an iron-rich object. This mission provides the first opportunity to visit a metal-rich object at close range, while previous space missions to small bodies have investigated either rocky or icy targets. The unique and poorly understood nature of Psyche offers a challenge to the mission as we do not have experience on what type of surface morphology and composition to expect. It is commonly accepted that the main evolutionary process for asteroid surfaces is impact cratering. While a considerable body of literature exists for hypervelocity collisions on rocky/icy objects, less work is available for metallic targets. Here we present a suite of impact experiments performed at the NASA Ames Vertical Gun Range (AVGR) facility on metallic targets, including several types of iron meteorites and man-made ingots that mimic the Fe-Ni composition of iron meteorites. Our experiments were designed to better understand crater formation (e.g., size, depth, etc.) in Fe-Ni alloys typical of iron meteorites, over a wide range of impact conditions.

Experimental set-up: Our intent is to explore the effects of key parameters on crater morphology, including target composition and temperature, impactor size and velocity, and to a limited extent impact angle. We performed 42 impact experiments divided in three runs. We present the experimental set up in the following sections.

Target temperature. The mechanical properties of metals can have a strong temperature dependence. In particular, body-centered cubic metals at low temperatures exhibit a brittle behavior, while at high temperatures are ductile. In addition, material strength can also vary as a function of temperature [1] or alloy composition [2]. To investigate if these parameters affect crater morphology formed by projectiles shot in a laboratory setting, we performed experiments at room temperature and with the targets cooled with liquid nitrogen (~ -140° C), thus encompassing the brittle-ductile transition in Fe-Ni alloys estimated to occur near or below -70° C [1].

Target materials: ingots. Two sets of experiments were undertaken. In the first we used man-made Fe-Ni ingots to allow us to perform a large number of experiments using relatively expendable materials. Two bulk Fe-Ni compositions were chosen Fe(94%)-Ni(6%) and Fe(90%)-Ni(10%), indicated by I94 and I90, respectively. These compositions were chosen to reflect the bulk Ni content of most iron meteorites, which range from ~5 to ~11 wt%.

Target materials: meteorites. In a second set of experiments we impacted onto three different iron meteorites, i.e., Coahuila, Gibeon, and Santiago Papasquiero [3]. These three irons were chosen in part because of their availability, and also for their distinct iron microstructures.

Projectile speed and size. We used spherical quartz projectiles in most of our experiments, with the exception of three impacts with Al projectiles. The projectile diameters were 3.175, 4.762, and 6.350 mm. The bulk density of the projectiles was 2.2 and 2.8 g/cm3, respectively. The impact speeds were between 2.9 and 5.9 km/s. The latter is approximately the maximum speed that can be achieved at the AVGR for our projectile sizes.

Impact geometry. In run #1, the ingots were freely suspended with two wires (to measure target recoil) and the impacts usually took place at 75° from the surface. In runs #2 and #3, impacts were perpendicular to the samples (head-on), except for two tests at 30°.

Results: We present here preliminary results regarding crater morphology and cratering efficiency.

A consistent finding in our experiments is that craters exhibit sharp rims that retain a competent structure, as opposed to cratering in rocks. This difference is caused by the significantly higher material strength and fracturing behavior of metals compared with rocky materials. Also, crater floors are characterized by the presence of concentric segments, resembling somewhat the structure of a rose's petals (fig. 1).

We next compared the morphological results of our experiments with cratering analytical scaling relationships. Here we use the so-called pi-group relationships as formulated in [4]. An important input parameter in these equations is the target "cratering strength", Y. For ingots I90 we find Y ~480 and 630 MPa for room and cooled temperature targets, respectively. A similar result is found for ingots I94, Y ~580 and 630 MPa for room and low temperature targets, respectively. Compared to a basalt strength of 20 MPa [5], our ingots are about 20-30 times stronger. We find target temperature produces notable effects on crater scaling, with cooled targets having higher strengths. These results are similar to those for the iron meteorites. In particular, for Gibeon, Santiago Papasquiero, and Coahuila the strength varies from *Y* ~500 to 650 MPa, ~520 to 620 MPa, and ~560 to 800 MPa, respectively. Notice that the higher inferred strength for Coahuila with respect to Gibeon and Santiago Papasquiero corresponds to the lowest Ni content among the three meteorites. This seems in accordance with our I90 and I94 experiments, although more data is needed to fully assess the role of Ni concentration on cratering efficiency. Laboratory data on Fe-Ni alloys [2] indicate tensile/yield strength in the range 200-400 MPa at room temperature for Fe content between 100% and 90%. Also, the temperature dependence of the measured strength [2] is in line with our results.

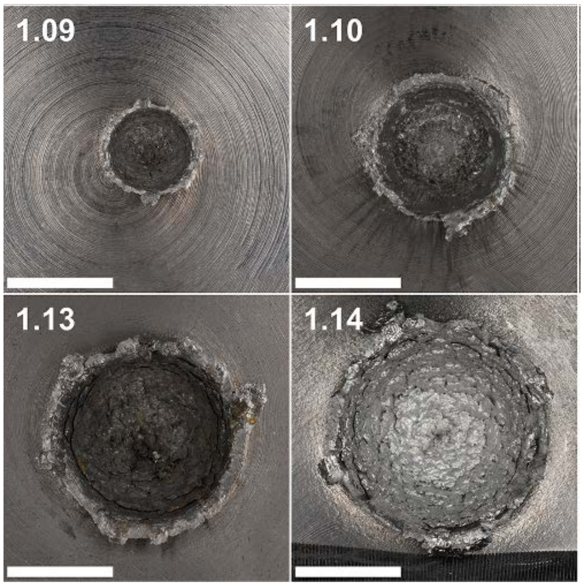

Figure 1. Examples of craters produced in I90 ingots (numbers indicate experiment ID). Scale bars is 1 cm. Experiment 1.14 was performed with an Al projectile, hence the brightness of the crater floor.

We also used two high-energy impacts in meteorites to constrain the catastrophic disruption energy. While in these experiments we did not shatter the iron meteorite targets, we came very close to it based on the extensive damage observed. Thus, our experiments provide a useful lower limit for the specific energy for catastrophic disruption, Q_D* ~10^8 erg/g. As a reference, rocks have Q_D* ~$1.5\text{x}10^7$ at a size scale similar to our targets [6]. In an unpublished series of experiments by Davis and Ryan (1997) they shattered ~2x2x2 cm Gibeon cubes and derived Q_D* ~$6.5\text{x}10^8$ erg/g (pers. comm.).

Finally, we also looked at the depth/diameter (*dd*) ratio. Impact experiments in rocks and sand have shown that typically *dd* ~0.2 [7]. In our experiments we find a mean *dd* ~0.3 (only considering head-on impacts), suggesting that craters into metallic targets are deeper than in rocky targets.

Implications for origin and evolution of iron meteoroids: The relative strength of iron meteorites and iron-rich meteoroids in the asteroid belt can be deduced from their cosmic ray exposure (CRE) histories. CRE ages describe the length of time a body spends between its final reduction in size by impact, which places its entire interior within a few meters of the radiation environment, and delivery to Earth. Ordinary chondrites and other relatively stronger meteorites have CRE ages between ~10 Myr and many tens of Myr [8]. Iron meteorites, however, have CRE ages between 0.1-1 Gyr. To survive such long time spans, however, it is also likely that iron meteoroids are better able to survive small impacts than stony meteoroids. Based on our experiments, we estimate that the lifetime of meter-sized iron objects is roughly 10□ longer than for rocky objects, in keeping with CRE ages.

Implications for Psyche: Ground-based shape models of Psyche suggest the presence of large cavities, which have been interpreted as putative craters [9]. We ran a collision model using a nominal cratering strength of ~50 MPa and computed that the putative craters correspond to a very old surface (~4.5 Ga). The corollary is also that the presence of several large craters is not compatible with an intact metal strength, as their formation would require a time span longer than the age of the Solar System for the assumed impact history.

Conclusions: We used our experiments to derive a "cratering strength" for Fe-Ni ingots and iron meteorites ranging from ~480-630 MPa, and assess the specific energy for catastrophic disruption of iron meteorites to be ~10^8 erg/g. Overall, our results suggest that our Fe-Ni ingots are good starting points for crater scaling and morphological analyses of Psyche's surface. These results provide useful constraints for interpreting Psyche's cratering. In particular, Psyche's observations of the size and number of large craters will be useful to constrain its past collisional evolution with implication for a putative episode of mantle stripping early in Psyche history.

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