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MORPHOLOGY OF METEOROID AND SPACE DEBRIS CRATERS ON LDEF METAL TARGETS

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We measured the depths, average diameters, and circularity indices of over 600 micrometeoroid and space debris craters on various metal surfaces exposed to space on the Long Duration Exposure Facility (LDEF) satellite, as a test of some of the formalisms used to convert the diameters of craters on space-exposed surfaces into penetration depths for the purpose of calculating impactor sizes or masses [1, 2, 3, 4, 5]. The crater depth-diameter ratio (P/D) may depend on projectile diameter, mass, and speed, and on projectile and target density and strength [6, 7, 8, 9]. We find the average P/D of craters formed in aluminum targets by normal impacts to be 0.56-0.60, significantly higher than the canonical value of 0.50. P/D does not change with crater size, with target Brinell hardness for values between 40 and 90, or with average impact velocity above 5 km/s. P/D varies roughly as target density to the 0.1 power. Less than 10% of the craters examined had major-to-minor axis ratios higher than 1.5, consistent with the production of shallow, elongated craters exclusively by oblique impacts. The natural width of the P/D distribution of non-oblique craters probably stems from variation in projectile shapes.

Target Materials and Orientation Surfaces examined in this work included panels of 1.6 mm thick 6061-T6 aluminum from the space-facing end of LDEF, plus smaller surfaces ("flanges") facing each row of the LDEF cylinder. Two of these faced 8° off the apex (leading) and antapex (trailing) directions respectively. Other surfaces came from the Chemistry of Micrometeoroids Experiment (CME) which exposed sheets of >99.99% Au and >99.9% Al facing different directions, allowing investigation of the effects of target density and Brinell hardness.

Crater Measurements and Sample Populations Craters were measured to an accuracy of 3% with an optical microscope coupled to a CCD camera and video printer. For each measurement, the microscope was focused on the flat target surface surrounding the crater, and diameters were measured along the crater's longest and shortest dimensions. The "diameter" we refer to is the average of the two measurements, and the circularity index is the long:short axis ratio.

Crater depths were measured by moving the motor-driven vertical focusing mechanism downward until the lowest point in the crater floor was in focus. The height difference between this point and the original surface plane was recorded as the crater depth. Most of these measurements were performed using an objective lens with a 3 μm depth of focus, yielding depths accurate to better than 5% for most craters.

Effects of Oblique Impacts P/D for the 552 craters on the two best-examined space-end panels is 0.528±0.104. This sample included relatively shallow, elongated craters, probably produced by impacts at angles greater than 70° from normal [10]. Very elongated craters formed a very small part of the sample. Less than 10% of impacts on zenith-pointing surfaces in LEO occur at such oblique angles [11], so the scarcity of elongated craters in our sample is understandable.

To address P/D independent of oblique impacts, we selected against them by excluding craters with circularity index > 1.05. The remaining group of circular craters had P/D = 0.574±0.069 (N=241), significantly larger than the value of 0.5 usually adopted for normal incidence craters in aluminum [1]. We also selected nearly-circular craters when comparing surfaces with different orientations (which experience impacts from different distributions of angles) to minimize the effect of varying proportions of oblique impacts on the P/D distributions.

We also chose craters with circularity index ≤ 1.05 when comparing the depth-diameter ratios of crater populations with very different average diameter, even on surfaces with identical orientation. Our definition of average diameter allows rare, highly elongated craters (formed by uncharacteristically small projectiles) to be included in any given size-selected crater population. At projectile sizes above 200 μm, the steepening impactor size distribution slope [12, 13]. means that, for a given resulting crater size, the proportion of rare oblique impacts of smaller particles becomes higher in comparison to the reduced flux of large particles at more normal incidence. Choosing circular craters decreases the importance of this effect in the P/D data.

Effects of Projectile Velocity To investigate velocity effects, we examined the apex (highest

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impact speed) and antapex (lowest speed) flanges. Mean encounter speeds for natural meteoroids are 21.1 and 13.4 km/s for the leading and trailing edges respectively [14]. Mean impact velocities for man-made debris are 7.8 and 1.8 km/s for the leading and trailing edges respectively [15]. Because the relative numbers of artificial versus natural impactors is not known, a mean velocity for all the cratering events is difficult to define. P/D is 0.589±0.063 (N=16) for the apex, and 0.581±0.034 (N=12) for the antapex. The z-ratio of 1.22 suggests that the two populations are statistically similar, indicating that relative crater shape is invariant above some velocity threshold value. In support of this conclusion, craters recently produced at 1 to 7 km/s at the JSC Experimental Impact Laboratory, employing aluminum targets and glass projectiles, seem to approach a constant P/D value near 0.55 at speeds above 5 km/s.

Effects of Crater Size We obtained P/D data for the 30 smallest (~80 μm diam.) and the 30 largest (~700 μm diam.) circular craters measured in this study. P/D is 0.556±0.070 for the smallest craters, and 0.560±0.042 for the largest craters. The z ratio of 0.27 shows that there is no significant difference between the distributions.

Effects of Target Hardness Brinell hardness (H) can be used to describe the penetration behavior of metals [1, 10]. To isolate its effects, we compared surfaces of 6061-T6 and 1100 aluminum surfaces, differing only in Brinell hardness, exposed to identical bombardment conditions. P/D is 0.586±0.076 (N=25) for 6061-T6 alloy (H=90), and 0.585±0.078 (N=28) for the 1100 alloy (H=40). There is no statistical difference between the distributions.

Effects of Target Density The surfaces available for this study included pure Au. The Brinell hardness of Au is 30, similar to that of the 1100 Al. Since the latter's P/D distribution was identical to that of the 6061-T6 aluminum with the same orientation, comparison of crater shapes from the gold targets with those from the identically-exposed 6061-T6 flange should reflect the effects of target density only. P/D is 0.581±0.033 (N=15) for aluminum (2.7 g/cc), and 0.476±0.050 (N=20) for gold (19.3 g/cc). This difference is significant (z=7.4), but P/D varies only as roughly the 0.1 power of target density.

Effects of Projectile Properties The range of P/D for circular craters probably results from variable projectile density and shape. If the range of P/D were attributed to projectile density alone, the dominant range of the P/D distribution should correspond to the dominant range of impactor densities. A study of ~100 stratospheric micrometeorites found that most had densities of 1.0 to 5 g/cc [16] which would imply that P/D varies as density to the 0.2 power. An 8 g/cc (Fe-Ni) projectile can be associated with the deepest LDEF craters with P/D = 0.8 On the other hand, the scarcity of shallow craters (P/D < 0.4) rules out large numbers of projectiles densities <1 g/cc. A multi-peaked P/D distribution has been reported for craters on glassy lunar spherules [17] possibly indicating a meteoroid population with distinct density components. We find no analogous structure in our data.

Alternatively, the natural width of the P/D distribution for circular craters may depend on projectile shape. We refer to rod penetrator studies [18, 19, 20] to constrain projectile shape. Typically, the rod length to diameter ratio (*l/d*) controls relative penetration depth. For *l/d* = 0.5, penetration depth (at 5 km/s) is typically only 20% shallower than for *l/d*=1. The shallowest circular craters observed on LDEF may correspond to flat disks of *l/d* < 0.3, while the deepest craters would correspond to projectiles of *l/d* > 2. Because projectiles need not be substantially elongated or flattened to affect crater shape, we attribute the range in P/D to projectile shape.

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