Utilizing Impact Experiments and 3D Scanning to Investigate Crater Scaling on M-Type Asteroids

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Abstract

The upcoming Psyche mission, part of the NASA Discovery program, will investigate the largest known M-type asteroid, 16 Psyche. Previous research has suggested that 16 Psyche may be an exposed planetary metallic core. With cratering being a fundamental process in modifying the surfaces of all solid planets and satellites, one of the main objectives of the mission is to characterize 16 Psyche's impact crater morphology. Consequently, in order to understand the cratering histories on M-type asteroids, it is essential to investigate how impact variables affect crater formation and crater scaling. We conducted experiments at the NASA Ames Vertical Gun Range that formed hypervelocity impact craters in copper and aluminum blocks with different impact angles, impact speeds, projectile sizes, and projectile materials. In the experiments, impact angles ranged from 15° to 90°, impact speeds ranged from 1.91 km s-1 to 5.69 km s-1, projectiles were either 6.35 mm or 12.7 mm in diameter, and the projectile materials were aluminum, Pyrex, quartz, basalt, and serpentine. Afterwards, 3D scanning was applied to investigate the morphometry of the resultant experimental craters. We analyzed the scans to measure diameter, cratering efficiency, length, width, and depth variations within the craters. Additionally, the crater scans will be analyzed for their morphology, including their planform, slopes, and other asymmetries. From there, we will use pi scaling to develop crater scaling relationships that enable the results of this analysis to be used to interpret crater size and morphology on metallic asteroids. These results can help in interpreting craters on 16 Psyche and on other M-type asteroids. In turn, these observations will also help generate a richer understanding of the formation and evolution of our solar system.

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THE PURPOSE

Cratering is a key process in modifying the surfaces of all solid planets and satellites [1]. The upcoming Psyche mission will investigate the largest M-type asteroid 16 Psyche that may be an exposed planetary metallic core. One of the five main objectives of this mission involves the characterization of Psyche's impact crater morphology. Hypervelocity impact craters formed in laboratories, in this case NASA Ames Research Center, provide insight into the formation and structure of meteorite impact craters [2]. Experiments conducted at the NASA Ames Vertical Gun Range shot projectiles into metal targets under different conditions, including impact angle, impact speed, target material, and projectile material. A new method has been applied here in order to study the morphology and dimensions of the resultant craters.

Figure 1: M-Type Asteroid 16 Psyche

Image Credit: Peter Rubin / ASU

THE METHODS

The crater experiments being analyzed were performed into ETP copper and 6061 aluminum blocks. In order to find the accuracy and precision of the 3D models generated by the scanner, models and measurements were made of copper and aluminum blocks. Craters were then scanned using the Artec Spider 3D scanner. The scans were edited, processed, and converted into OBJ files for analysis with SolidWorks. Six scans and multiple meshes were made of each original experimental impact crater in order to find the reliability of the method and maximize the accuracy of subsequent calculations.

THE RESULTS

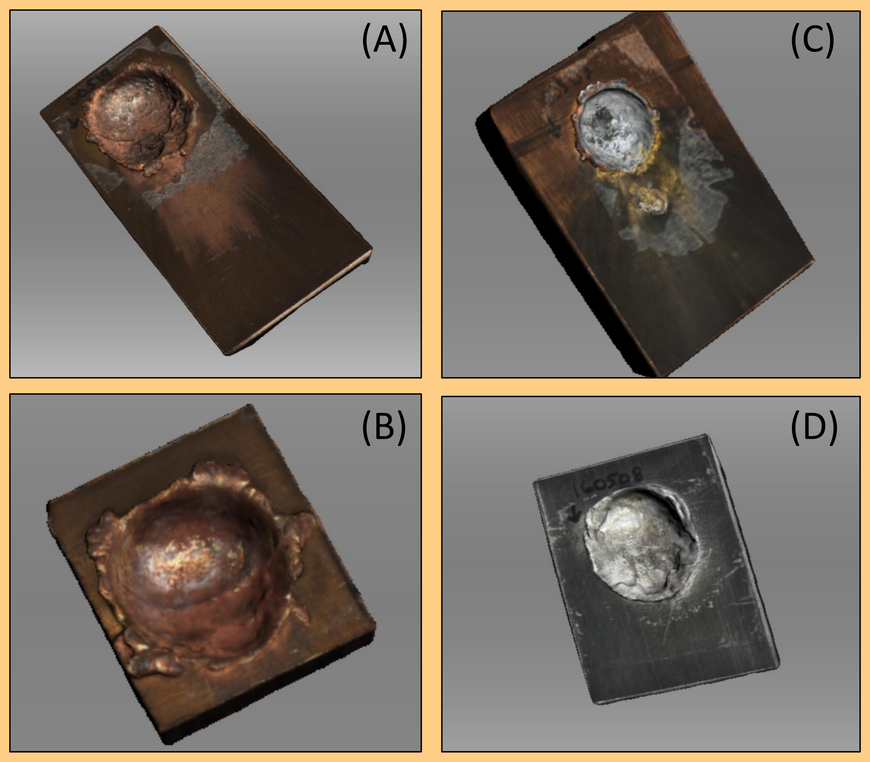

Figure 2: Example 3D meshes of experimental craters. (A) ETP copper target; Agate projectile. (B) ETP copper target; Serpentine projectile. (C) ETP copper target; Aluminum projectile. (D) 6061 aluminum target; Quartz projectile. These will be used to study with a new degree of accuracy and precision the characteristics of hypervelocity impact craters in metal, such as their volume, diameter, and shape.

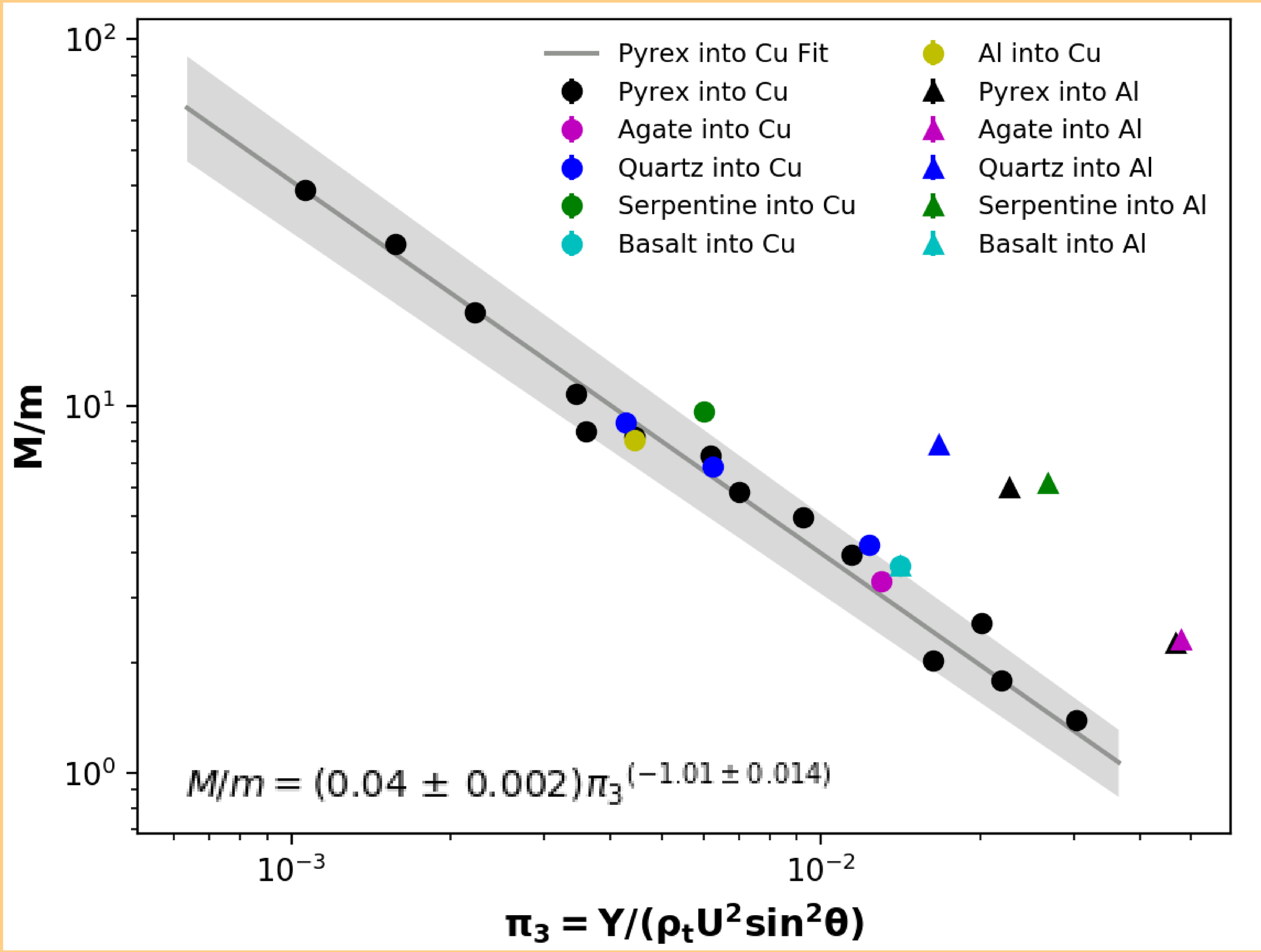

Figure 3: Plot with crater efficiency data from all experiments, separated by projectile and target material. M/m is the cratering efficiency, which is the ratio of the mass of the material displaced by the impact, found via analysis of the 3D scans, to the mass of the impactor. Π_3 is the ratio of target material strength to the initial dynamic pressure [3]. Here we assumed that for oblique impacts cratering efficiency depends only on the vertical component of the impact velocity, *U* [4] The trend line and equation show the power-law fit to the data for experiments in which Pyrex projectiles impacted copper targets. Gray shading indicates the 95% confidence interval for the fit. Experiments into copper, regardless of projectile type, appear to fall within the 95% confidence interval of the trend, indicating that projectile material likely has only a minimal effect on cratering efficiency, with the possible exception of serpentine. Target material appears to have a much greater effect on cratering efficiency, with the experiments into aluminum showing much large craters for a given value of Π_3. All uncertainties for measurements are smaller than size of the data points.

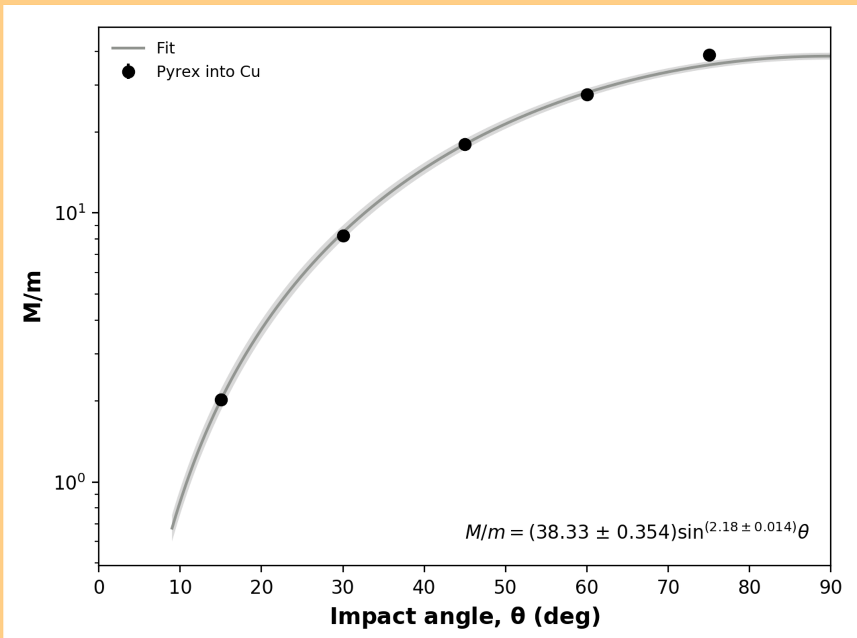

Figure 4: Plot examining the relationship between impact angle (*θ*) and cratering efficiency for experiments done with the same projectile, target, and impact speed. As the impact angle approaches 90°, crater sizes increase. The data can be explained by a ~sin²(*θ*) dependence on impact angle, consistent with the hypothesis of [4].

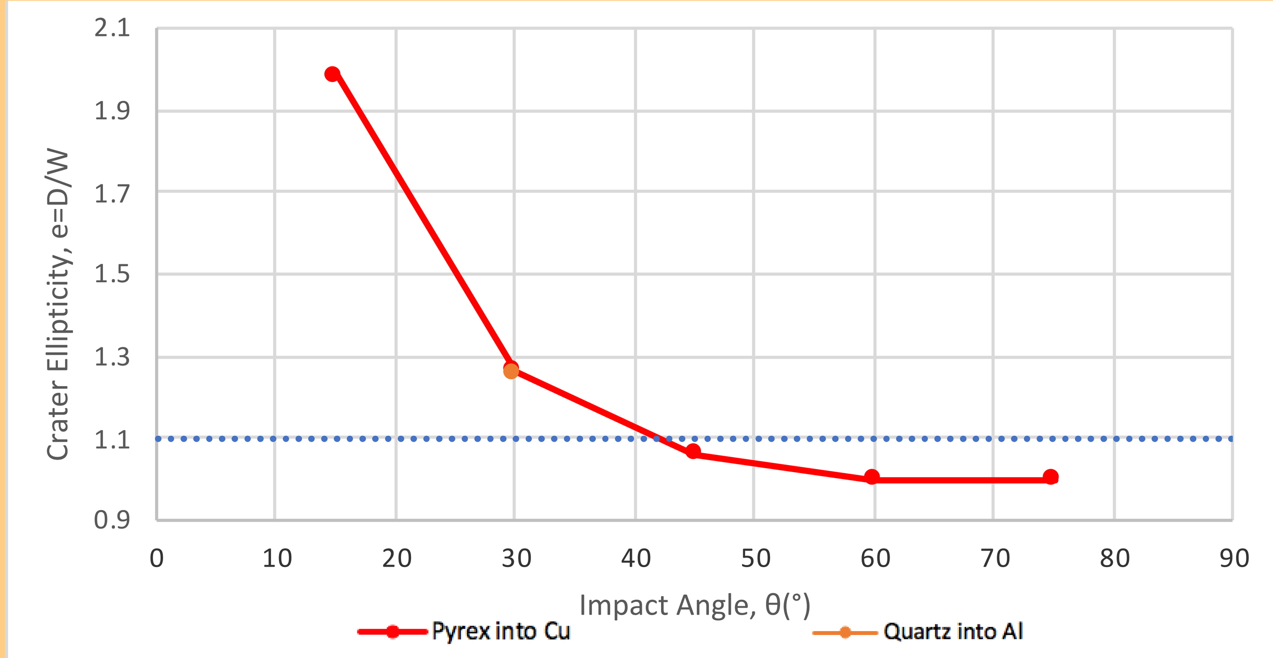

Figure 5: Plot shows the relationship between impact angle and crater ellipticity. The crater ellipticity is defined in Bottke et al. [5] as e=D/W where D is the crater diameter as measured in the direction of the projectile trajectory and W is the width of the crater as measured in the direction directly perpendicular to the projectile trajectory. We define craters as elliptical if $e > 1.1$, consistent with the threshold used in previous studies [e.g., 6]. As impacts become more oblique, craters become more elliptical. The results show that the elliptical crater threshold (θ_e) is θ_e = 40°-45° for this combination of target and projectile. Although these results are from impacts into copper, an experiment at a similar impact speed into aluminum target had an ellipticity comparable to that of the experiment at the same impact angle in the copper target, thereby suggesting that the results from copper target also apply to other metals.

CONCLUSIONS

This method of crater analysis involving 3D scanning promises new and more accurate knowledge on the extent to which different variables affect impact cratering. These experiments suggest that larger craters are formed in targets composed of aluminum compared to copper. However, the material of the projectile appears to have little effect on the cratering efficiency in a given target. Furthermore, in oblique impacts, the experiments suggest crater volume follows a $\sin^2(\theta)$ relationship. Moreover, in metal targets, the ellipticity of a crater appears to decrease with impact angle. When considering acoustic impedance, the results into copper targets, rather than aluminum, are more accurate in understanding the formation of impact craters on 16 Psyche. Through these results, by looking at the shape of craters on Psyche, predictions can be made about the impact angle. Furthermore, the results suggest the type of asteroid hitting Psyche is likely to not affect the subsequent crater size. Further analysis will examine from the crater models how other variables describing crater shape, including offset, profile symmetry, and d/D change under different conditions. Future research by conducting experiments with iron targets will help further understand cratering in M-type asteroids.

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