INFLUENCE OF IMPACTOR SIZE ON MOMENTUM MULTIPLICATION.

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Introduction: During hypervelocity impact into rock targets a large amount of material (“ejecta”) is ejected backwards. For this reason, the momentum transferred to the target is greater than the impactor momentum. This effect, often called “momentum multiplication”, is generally expressed by a dimensionless quantity: The momentum multiplication factor β. This factor is defined as the ratio of the momentum transferred to the target, Δp_t, and the momentum of the projectile, p_p. Thus, $\beta = \Delta p_t/p_p = (p_p+p_e)/p_p = 1+(p_e/p_p)$, where p_e denotes the ejecta momentum. In the hypervelocity regime, where a large amount of ejecta is generated, β can be significantly greater than 1.

In a recent study it was shown that target porosity leads to reduced β-values [1]. This behavior can be explained by the reduced cratering efficiency in porous targets compared with non-porous targets and, thus, by the smaller amount of ejected mass [1]. Furthermore, a slower and shallower ejection was observed in porous targets [1].

Walker et al. [2] investigated scale size effects for impacts of different projectile materials into aluminum and rock targets. These authors showed that β increases with increasing impactor size. Hypervelocity impact experiments into rock targets using different projectile sizes have shown that increased projectile size leads to a cratering efficiency ($\pi_V = V\rho_t/m_p$, where V denotes the crater volume, ρ_t and m_p denote the target density and the projectile mass, respectively) higher than predicted by strength scaling laws [3]. This effect was attributed to an increased spallation volume if larger projectiles are used. Based on this observation, the goal of the present study was to investigate possible projectile size scale effects and, hence, a potential influence of increased spallation on the momentum multiplication factor β.

Methods: The impact experiments were conducted using a two-stage light-gas gun at Fraunhofer EMI in Freiburg, Germany. In addition to 5 mm aluminum projectiles (see [1]), 2 mm and 7 mm aluminum spheres were used as projectiles. Seeberger sandstone (see [4] for detailed material description) was used as target material. The 20 cm cubic target blocks were attached to a ballistic pendulum. A laser vibrometer was used to measure the pendulum displacement after the impact. Impact craters were digitized using a light scanner and crater volumes were calculated. A special method for the measurement of the transient crater volume [5, 6] was applied using parabola fits to the transient crater. The spallation volume was calculated using the difference between final crater volume and transient crater volume.

Results: In Figure 1 the measured β-values are shown as a function of projectile velocity in scaled form [7]. The results are given in Table 1. Density and uniaxial compressive strength of the target material are ρ_t = 2.04 g/cm^3 and Y_t = 42.3 ± 2.4 MPa, respectively (see [1]). The scaling parameter ν was set to 0.4 [8]. The trend for the 5 mm projectiles taken from [1] is given as a dashed line. The results show that the β-values for the 7 mm projectiles lie above the 5 mm trend line. The β-values for the 2 mm projectiles are below this line but, however, one impact experiment (Exp.# 5649) yielded a β-value which exceeds the 5 mm trend line.

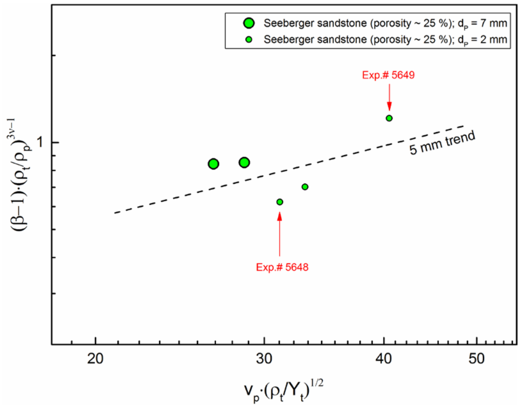

Figure 1. Momentum multiplication factor β as a function of projectile velocity in scaled form for different projectile diameters.

Table 1. Experimental parameters and results (data for 5 mm trend line are given in [1]).

Exp.#	Projectile velocity [m/s]	Projectile diameter [mm]	β	π_V
5648	4487	2	1.67	91.93
5649	5835	2	2.30	163.26
5650	4767	2	1.75	105.00
5651	6111	2	-	153.22
5656	4118	7	1.90	212.18
5657	3824	7	1.89	173.94

Discussion: In Figure 2 the cratering efficiencies π_V are plotted against the strength term π_3 (= $Y_t/\rho_t v_p^2$) [9] where v_p denotes the projectile velocity. Again, the trend for the 5 mm projectiles taken from [1] is given as a dashed line. The 7 mm projectiles lead to cratering efficiencies higher than given by the 5 mm trend line. Cratering efficiencies for the 2 mm projectiles are below this line. These findings are in good agreement with the results given by Poelchau et al. [3].

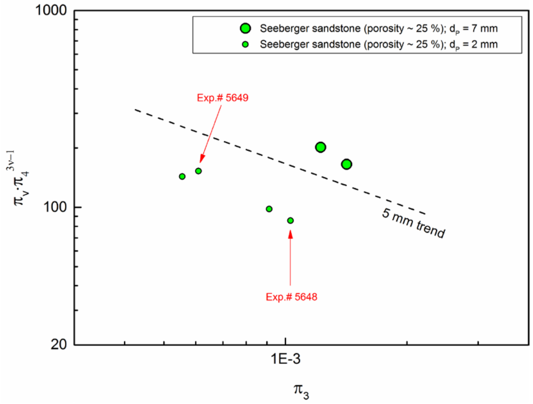

Figure 2. Cratering efficiencies plotted against the strength term π_3.

Calculation of spallation volumes shows that the percentage of spallation volume in final crater volume increases with increasing projectile size. For the 2 mm projectiles, a maximum percentage of 54 % (Exp.# 5649) was measured whereas for the 5 mm and 7 mm projectiles a maximum percentage of 68 % (Exp.# 5553, see [1]) and 74 % (Exp.# 5656) was measured, respectively. In spite of this general trend, spallation shows scattering for constant projectile size. For example, Exp.# 5649 shows an unusually large amount of spallation (54 %) compared with Exp.# 5648 (36 %). Hence, Exp.# 5649 shows the highest cratering efficiency among the 2 mm experiments (Figure 2). This experiment denotes the outlier in Figure 1. Figure 4 shows a comparison between the 3D scans of Exp.# 5648 and Exp.# 5649. The higher percentage of spallation in Exp.# 5649 is caused by the ejection of an additional, large spallation plate. In contrast, however, in Exp.# 5648 a large spallation plate remained attached to the target and led to the low percentage in spallation and the comparatively low β-value shown in Figure 1. Thus, spallation might give a dominant contribution to momentum multiplication.

Holsapple [10] has shown that β is dominated by the slowest but most massive ejecta particles. Hence, in our laboratory experiments where all ejecta particles leave the target after the impact the slow but massive spallation plates can significantly influence the momentum multiplication factor β. For realistic deflection scenarios, the escape velocity has to be taken into account because spallation plates feature comparatively low velocities [e.g., 11].

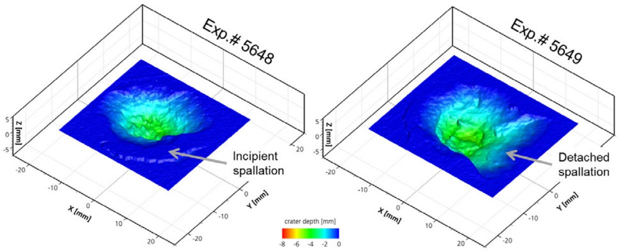

Figure 4. Contour plots of 3D crater scans.

The presence of a regolith layer can significantly influence the crater formation process as shown in laboratory impact experiments [12, 13]. Furthermore, recent impact experiments conducted within the framework of the NEOShield project have shown that beyond a certain thickness of the regolith layer spallation is no longer present in the underlying bedrock [S. Green, pers. comm.].

In addition to the projectile size, the target material properties influence the spallation behavior: Poelchau et al. [3] have shown that non-porous materials like quartzite show a higher percentage of spallation volume in final crater volume than porous materials like sandstone.

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