COLLISIONAL PROCESSES OF IRON AND STEEL PROJECTILES ON TARGETS OF DIFFERENT DENSITIES

H. Fechtig, K. Nagel+ and N. Pailer
Max-Planck-Institut für Kernphysik, Heidelberg, FRG
E. Schneider
Ernst-Mach-Institut, Freiburg i.Br., FRG

ABSTRACT: Cratering experiments for μm- and mm-sized iron- and steel-projectiles on various target materials show that crater depths and the ratios of crater diameter to crater depth D/T depend on the densities of the projectile- and target-material and on the ductility of the target material. Cratering experiments into low density material (Saffile ρ = 0.28 g/cm^3) have produced elongated impact "craters". For low target densities the "crater" depth is up to 100 times the projectile diameter, depending on its impact speed. This impact process leads to a complete accretion of the projectile mass within the target.

1. INTRODUCTION

In earlier papers our group has published results of crater diameter to crater depth ratios D/T for lunar microcraters (Nagel et al.1975, 1976 a,b). Similar results have been published already by Brownlee et al. (1973) and Vedder and Mandeville (1974). These results all deal with crater morphology on glass targets. It has first been suggested by Smith et al. (1974) that different D/T values mean projectiles of different densities. Nagel et al. (1976) have performed quantitative measurements showing that iron and silicate particles produce the observed type of microcraters. In a later paper (Nagel and Fechtig 1979) it has been shown that the D/T - values are independent of the impact velocity above a minimum impact velocity of approximately 4 km/s.

All published results have always been based on different projectile materials but always for a constant target material (glass). The intention of this paper is to measure the crater diameters and crater depths on various targets for iron and steel projectiles.

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2. EXPERIMENTS AND MEASUREMENTS

For the performance of these experiments we have used the 2 MV electrostatic dust accelerator of the Max-Planck-Institut für Kernphysik and a light gas gun of the Ernst-Mach-Institut. Operation principles of these accelerators are described elsewhere (Fechtig et al. 1978).

The first part of the experiments performed with the 2 accelerators are shots of iron- and steel-projectiles on a set of different targets. The results are listed in Table 1.

The second part of the experiments have been carried out using extremely low density target material. We have used Saffile Al_2O_3 + SiO_2 with a density of $\rho = 0.28$ g/cm^3. The experimental results of the 11 firings using the light gas gun are listed in Table 2.

3. CRATER DIAMETER TO DEPTH RATIOS FOR DIFFERENT TARGET MATERIALS

The D/T - values of the experiments listed in Table 1 range between 3.4 and 2.7 for the investigated target materials. The corresponding densities and (for the metals) the ductilities are also listed in Table 1. From the data it is evident that for both projectile materials (steel and iron) the density alone does not govern the D/T values.

For metals it is possible to compare the measured crater depths with a depth formula recently published by Pailer and Grün (1979). The formula allows to calculate crater depths or penetration limits in foils. It is based on a formula by Fish and Summers (1965), which has been extended in its applicability down into the μ-size range. The formula reads:

$$T = \frac{1}{\varepsilon^{0.06} \cdot \rho_t^{0.5}} \cdot m_{pr}^{0.40} \cdot V_{pr}^{0.88} \cdot \rho_{pr}^{0.33} \qquad (1)$$

with T = crater depth [cm]
ε = ductility of target material [%]
ρ_t = density of target material [gcm^{-3}]
m_{pr} = mass of projectile [g]
v_{pr} = normal component of impact velocity [kms^{-1}]
ρ_{pr} = density of projectile [gcm^{-3}]

Fig. 1 shows a comparison of the calculated crater depths T according to formula (1) on the ordinate with the measured crater depths T from the experiments. The data compare well between the sub-μ-sized craters and the cm-sized craters (note: these are 5 orders of magnitudes in size difference!). The open symbols are data received from foil penetration experiments as published by Pailer and Grün (1979) for comparison. This result clearly shows that the crater morphology strongly depends on the target density and its ductility.

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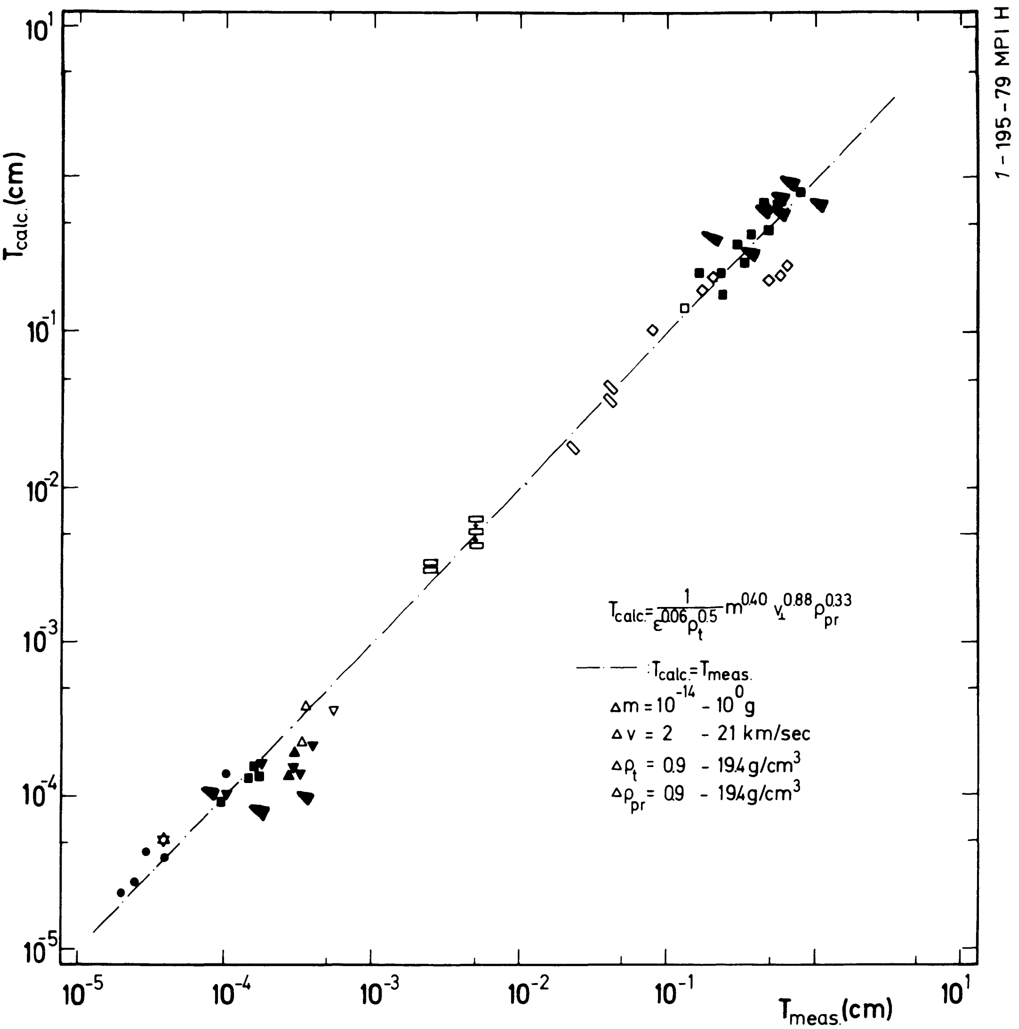

Fig.1 Comparison of calculated depths (ordinate) with measured depths of impact craters. Open symbols: penetration limits (Pailer, N., and Grün, E. (1979)); closed symbols: a) crater depth (Pailer, N., and Grün, E. (1979)) b) ▼ this measurement.

Table 1: Cratering experiments using μm- and mm-sized iron- and steel-projectiles.

projectile			target			crater		
material	diameter d [μm]	velocity v [km/s]	material	density ρ [g/cm³]	ductility ε [%]	diameter D [μm]	depth T [μm]	D/T
Iron	1.2	5.2	Steel	7.9	0.5	2.60	0.80	3.3
"	1.1	5.3	Lead	11.4	0.3	6.50	4.10	1.6
"	0.9	5.2	Copper	8.9	0.4	2.60	1.70	1.5
"	0.6	7.6	Glass	2.6	-	0.74	0.57	1.3
"	0.6	7.5	Feldspar	2.6	-	0.80	0.70	1.1
Steel	$1.5\cdot10^3$	4.1	Corundum (Al_2O_3)	4.0	-	$15.0\cdot10^3$	$4.5\cdot10^3$	3.3
"	$2.0\cdot10^3$	4.7	Glass	2.6	-	$3.0\cdot10^3$	$1.1\cdot10^3$	2.7
"	$1.6\cdot10^3$	4.4	Tungsten	19.3	-	$3.6\cdot10^3$	$1.5\cdot10^3$	2.4
"	$1.6\cdot10^3$	4.0	Steel	7.9	0.5	$5.0\cdot10^3$	$2.5\cdot10^3$	2.0
"	$1.6\cdot10^3$	4.1	Gold	19.3	0.45	$6.7\cdot10^3$	$3.6\cdot10^3$	1.9
"	$2.5\cdot10^3$	3.6	Lead	11.4	0.3	$16.0\cdot10^3$	$10.2\cdot10^3$	1.6
"	$2.0\cdot10^3$	4.3	Copper	8.9	0.4	$8.3\cdot10^3$	$5.5\cdot10^3$	1.5
"	$2.5\cdot10^3$	3.9	Nickel	8.8	0.5	$9.0\cdot10^3$	$5.9\cdot10^3$	1.5
"	$1.5\cdot10^3$	4.2	Titanium	4.5	0.5	$5.5\cdot10^3$	$4.4\cdot10^3$	1.3
"	$1.6\cdot10^3$	4.5	Aluminium	2.7	0.3	$6.0\cdot10^3$	$6.8\cdot10^3$	0.9

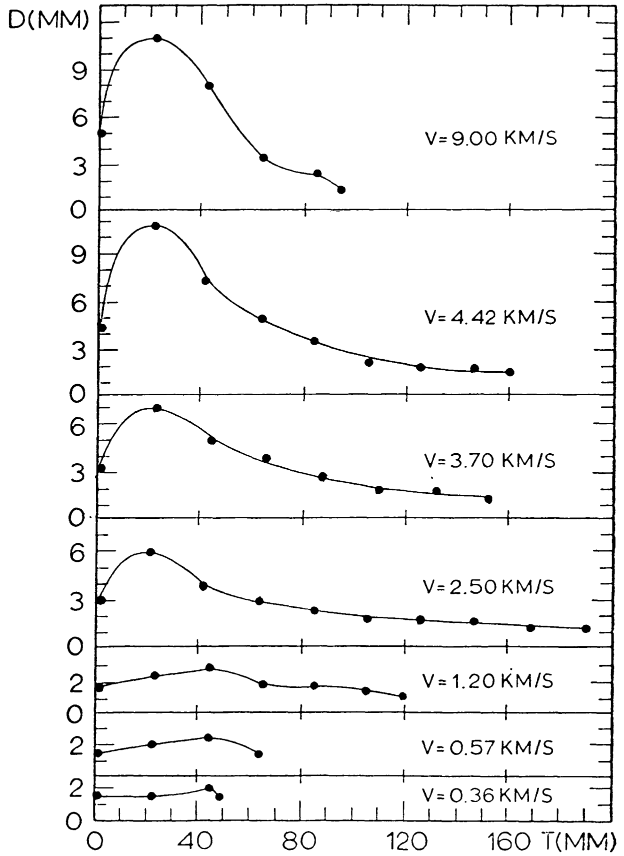

Fig.2 "Crater" widths D vs. "crater" length T in Saffile for various impact velocities.

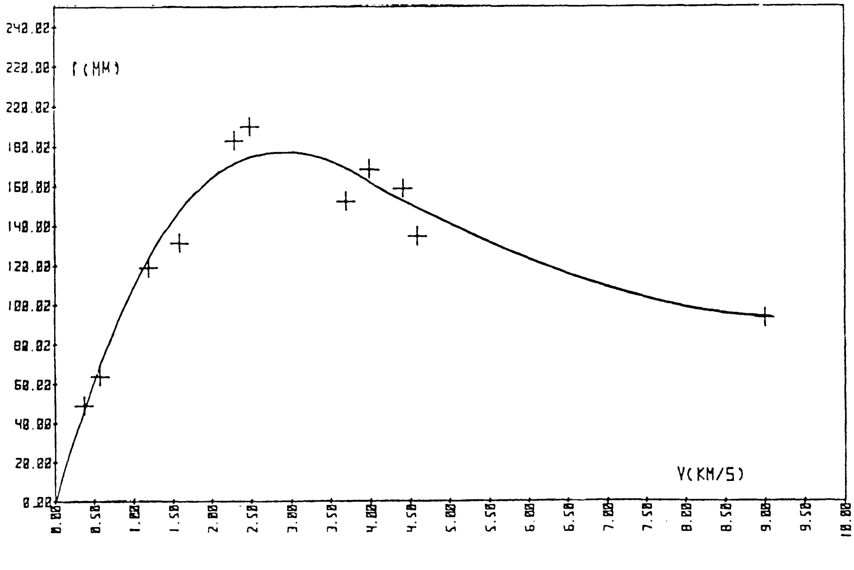

Fig.3 Total "crater" depths T in Saffile as a function of impact velocity V.

4. CRATERING RESULTS IN LOW DENSITY MATERIAL (SAFFILE)

The experiments on Saffile which are listed in Table 2 show "crater" depths which are quite different from those in targets of compact dense material. Craters obtained look more like deceleration channels. In all cases except for v = 9 km/s a considerable part of the projectile was recovered. For low velocities (up to 2.5 km/s the projectile was more or less intact, for medium velocities (2.5 to 5 km/s) about 1/2 of the initial projectile mass was saved.
In Fig. 2 the crater profiles are plotted: crater widths vs. crater lengths. At low velocities (< 2 km/s) the crater channel is slightly wider than the projectile diamter but rather long. Medium velocities give the longest craters with increasing widths. Above 4 km/s the crater width still increases but the crater length decreases. At 9 km/s the crater is rather short, the projectile was completely ablated.
In Fig. 3 the total crater channel length is plotted vs. impact velocity for the 11 experiments. The crater length has a maximum at approximately 3 km/s impact velocity. A similar result (at constant velocity of 6 km/s with variable target densities (0.6 to 0.2 g/cm^3)) has been reported by Cannon and Turner (1967).

The entrance of the crater channel is always comparatively small which leads us to the assumption that almost no crater material is lost during impact. That means, quantitative accretion occurs although it is a high velocity impact process. This fact is of considerable interest in astrophysics. If there is a comparatively small, but fluffy target existent, the target mass grows continuously when impacted by solids in space. This is considered as an interesting extension of the results published by Hartmann (1978) summarizing the conditions and possibilities of planet formation processes.

Table 2: Cratering experiments for 1.5 mm diameter steel spheres on Saffile-targets (ρ=0.28 g/cm^3).

impact velocity v [km/s]	"crater" depth T [mm]
0.37	49
0.57	64
1.20	119
1.60	132
2.30	183
2.50	190
3.70	153
4.00	169
4.42	159
4.60	135
9.00	93

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DISCUSSION

Zook: Glass particles that have been impacted into low-density (0.01 g/cm^3) polyurethane foam at velocities of 7 to 8 km/s give results similar to the highest velocity impact into low-density material that you have shown us here, indicating a universal process. The glass projectiles were apparently completely destroyed but it is presumed that the projectile material was almost completely retained in the foam bounding the crater wall.

Fechtig: These results are referenced. (Cannon and Turner 1967.)