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Author(s): R. F. Davidson, M. L. Walsh

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CONSTITUTIVE MODELING FOR HYPERVELOCITY CRATERING

R. F. Davidson and M. L. Walsh

Los Alamos National Laboratory, Los Alamos, New Mexico 87545

The Hypervelocity Microparticle Impact program conducted cratering experiments on copper and aluminum targets at impact velocities up to 30 km/s (1). These data are presented with minor corrections in a form that will be useful to a variety of investigators. Hydrocode analysis of the data was performed to gain understanding of the "plateau" features in the data. Analyses using conventional strength models were not satisfactory due to the very high strain rates of these experiments (strain rates on the order of 10^{10} /s). Calculations using the PTW strength model rate dependence (2) gave very accurate reproduction of the experimental results, and allowed computational examination of the "data plateaus." These results show that the "data plateaus" may be due to strain-rate effects and experimental variation in the data.

BACKGROUND

The Van de Graaff facility at Los Alamos was used to conduct the Hypervelocity Microparticle Impact (HMI) experiments on a variety of materials(1). Careful examination of these data for aluminum and copper targets led to the discovery that the data values contained slight errors. A reanalysis of the original data was conducted paying careful attention to determining the variation in the data.

There are two interesting data features that were investigated using computations. The strain rates were extremely high (on the order of 10^{10} /s), and the data exhibited an unexplained erratic velocity dependence, sometimes called "data plateaus" (1). Computations on aluminum targets were conducted to test the hypothesis that material strain-rate effects combined with data variation could explain the "data plateaus." The high strain-rate dependence of the PTW model was used to accurately depict the strain-rate effect on the flow stress.

EXPERIMENTAL OVERVIEW AND DATA REANALYSIS

In the Van de Graaff facility, iron microparticles were charged and then accelerated down the beam line. Those particles that met the desired characteristics of velocity and mass were

"selected" to be directed onto the target. Tests were conducted for a variety of target materials with impact velocities up to 30 km/s and particle masses of about 0.1 to 1000 fg ($1 \text{ fg} = 10^{-15} \text{ g}$). Because the craters were very small (on the order of a few μm), the dimensions were measured using electron photomicrographs. To date, only crater diameters have been measured, and that is why D^3 (crater diameter cubed) was chosen as the best available estimate of the crater volume.

The data from the reanalysis are given in Figs. 1 and 2 and in Table 1. The primary independent variable D^3/M (crater diameter cubed divided by impactor particle mass) was chosen as an estimate of the crater volume related to the particle mass - thus allowing comparison to data over a wide range of impactor sizes (masses). Additional data is given in the tables so that other independent variables may be examined for these test data.

Each test had a number of particle impactors and a number of craters in the target. It was not possible to determine which particle made which crater. In fact, the number of particles associated with each test was not the same as the number of craters found in the targets (see Table 1). This was due to difficulties in the particle selection apparatus that could have allowed "leakers" onto the target or caused a "selected" particle to be deflected off the target. Because the particles could not be correlated to specific craters it was not possible to determine the standard deviation of D^3/M exactly.

TABLE 1. Aluminum and Copper Data from Reanalysis

Run ^a	Material ^b	Part. Num ^c	Cr. Num ^d	V (m/s) ^e	SD V ^f	M (kg) ^g	SD M ^f	D (m) ^h	SD D ^f	D ³ /M (m ³ /kg) ⁱ	SD D ³ /M (ρ=0.7) ^f
9023310	Aluminum	22	24	6752	138	2.136e-15	166.e-18	2.837e-06	156e-09	0.01069	0.00132
9023309	Aluminum	19	28	8797	125	616.4e-18	55.2e-18	2.185e-06	114e-09	0.01692	0.00193
9023308	Aluminum	10	13	10658	171	2.885e-15	153.e-18	4.182e-06	113e-09	0.02535	0.00147
9023307	Aluminum	17	19	12521	149	1.028e-15	81.3e-18	2.901e-06	95.e-09	0.02374	0.00168
9023306	Aluminum	10	11	14240	287	580.5e-18	90.3e-18	2.527e-06	195e-09	0.02781	0.00459
9023305	Aluminum	18	40	16217	137	276.5e-18	36.7e-18	2.015e-06	182e-09	0.02957	0.00598
9023201	Aluminum	23	29	17787	253	290.4e-18	14.8e-18	2.484e-06	66.e-09	0.05279	0.00301
9023301	Aluminum	22	31	19841	309	100.0e-18	15.5e-18	1.703e-06	118e-09	0.04938	0.00737
9023302	Aluminum	17	21	21429	335	108.3e-18	30.8e-18	1.772e-06	231e-09	0.05137	0.01436
9023304	Aluminum	7	11	23663	233	87.46e-18	26.3e-18	1.820e-06	189e-09	0.06893	0.01634
9023401	Aluminum	19	38	26017	746	86.06e-18	37.4e-18	1.859e-06	318e-09	0.07471	0.02797
9022103	Copper	29	27	5770	214	1.509e-15	130.e-18	2.583e-06	95.0e-09	0.01142	0.00091
9022104	Copper	23	22	8046	194	240.9e-18	31.4e-18	1.507e-06	87.9e-09	0.01421	0.00178
9022105	Copper	21	22	10390	218	375.2e-18	107.e-18	2.020e-06	210.e-09	0.02197	0.00511
9022107	Copper	20	15	12167	357	1.990e-15	506.e-18	3.982e-06	365.e-09	0.03173	0.00653
9022110	Copper	19	8	14241	374	877.0e-18	124.e-18	3.384e-06	171.e-09	0.04418	0.00504
9022203	Copper	30	26	16032	254	535.2e-18	25.5e-18	2.749e-06	101.e-09	0.03881	0.00325
9022201	Copper	24	22	17884	311	364.6e-18	22.8e-18	2.521e-06	125.e-09	0.04396	0.00503
9022504	Copper	16	23	19630	777	245.6e-18	46.5e-18	2.377e-06	130.e-09	0.05465	0.00759
9022209	Copper	20	25	21810	369	117.3e-18	8.22e-18	1.843e-06	52.9e-09	0.05333	0.00332
9022501	Copper	25	24	23043	561	91.66e-18	13.5e-18	1.673e-06	98.9e-09	0.05112	0.00658

^aRun number designates a specific test and target.

^bTarget plate material.

^cNumber of impactor particles that met the particle selection criteria for this Run.

^dNumber of craters found on the target for this Run.

^eAverage ("selected") particle velocity.

^fSD = standard deviation.

^gAverage ("selected") particle mass.

^hAverage crater diameter.

ⁱD³/M is an estimate of (two times) the crater volume normalized to the particle mass.

To approximate the error in D³/M, the correlation coefficient (ρ) between crater diameter (D) and particle mass (M) was estimated. The correlation coefficient varies from 0 (independent or not correlated) to 1 (exactly correlated). A value of ρ = 0.7 was used, which means that the crater diameter was assumed to be strongly, but not exactly correlated with the particle mass. Thus, as the particle mass increases, the crater diameter tends to increase as well. In Figs. 1 and 2, the error estimate for D³/M is plus or minus one standard deviation with ρ = 0.7. The tabulated statistics for D (crater diameter), V (particle velocity), and M (particle mass) are straightforward. Details of the data reanalysis are

documented in an informal report that is available from the authors.

COMPUTATIONAL OVERVIEW

All the computations were made with the 1994 EPIC hydro-code (3). A mesh study was conducted which showed the mesh to be accurate and sufficiently large. The same mesh was scaled for different projectile (particle) sizes. Care was taken so that the computed craters were all measured in a consistent manner. Details of the calculations are documented in an informal report that is available from the authors.

FIGURE 1. Iron Microparticle Impacts onto Aluminum Targets - HMI Data.

FIGURE 2. Iron Microparticle Impacts onto Copper Targets - HMI Data.

FIGURE 3. Iron Microparticle Impacts onto Aluminum Targets Showing the Data Plateaus and a Linear Fit to the Data.

The computations considered only the aluminum targets. Figure 3 shows the "data plateaus" at 11-16 and 18-22 km/s. Figure 3 also shows that a simple linear fit to the data does not touch all the data error bars.

Figure 4 shows the problem of using a strain-rate hardening law based on data at rates lower than occurred during these tests. The Johnson-Cook (JC) strength model for 1100 aluminum includes rate dependent flow stress behavior up to $10^4/s$, and predicts a crater volume that is much too large. The HMI tests had strain-rates that were typically $10^{10}/s$. To match the HMI data at 6 km/s, the JC flow stress was multiplied by 5 (5). However, the simple multiplication did not match the crater volume data at higher velocities (See "JC w/ $Y_0 \times 5$ " in Fig. 4).

By examining over-driven shock data, Preston, et. al (2) found a strong increasing rate dependence for copper and aluminum at strain-rates of 10^5 to $10^{10}/s$. This increasing rate dependence is included in the PTW (Preston, Tonks, Wallace) strength model. This same increasing rate dependence was added to the JC model. The modified JC model was called the "JC/HSR-PTW" model to indicate that the high strain-rate (HSR) dependence of the JC model was modified to look similar to the rate dependence in the PTW model. This model came reasonably close to matching the HMI data (Fig. 4). The computations tend to bound the data on the low side - computed crater diameters were consistently (slightly) smaller than the test data. The "numerical erosion technique" used in the EPIC calculations is known to produce craters that are too small in diameter (4). Therefore, the JC/HSR-PTW model results give excellent comparison to the test data.

The different particle sizes in the tests introduced some additional strain-rate differences. By making computations using both a small projectile and a large projectile typical of the particle size range in the tests, the difference in crater volume due to particle size could be investigated. These two sets of computations (small projectile - high strain-rate and large projectile - low strain-rate) were adjusted to be centered on the linear fit to the data. The spread between the high-rate and low-rate curves shows the scatter due to particle size differences (Fig. 5). Since the two curves intersect all the data within one standard deviation, this plot shows that rate

FIGURE 4. Iron Microparticle Impacts onto Aluminum Targets. HMI Data and Computational Results for 3160 fg Particles.

FIGURE 5. Iron Microparticle Impacts onto Aluminum Targets. HMI Data and Computed Variation Due to Strain-rate Effects.

dependence effects alone are sufficient to model the HMI experimental data. In other words, the "data plateaus" can be explained by the expected error in the data (one standard deviation) and the strain-rate dependence of the target material.

CONCLUSIONS

The corrected HMI data are presented in Figs. 1 and 2 and Table 1. The data are presented so that a variety of independent variables can be examined.

The strain-rate dependence of the PTW model was found to accurately describe the behavior of the HMI data at these extremely high strain-rates. The aluminum "data plateaus" can be explained by strain-rate effects and the expected error in the data, as shown in Fig. 5. Careful investigation would probably support similar conclusions regarding the copper data.

The "data plateaus" have commonly been attributed to phase change effects (5). This work does not refute this or other explanations for the "data plateaus," but simply shows that strain-rate effects and the expected error in the data are sufficient to explain the "data plateaus."

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