Impact Cratering and Spall Failure of Gabбро

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Both hypervelocity impact and dynamic spall experiments were carried out on a series of well-indurated samples of gabбро to examine the relation between spall strength and maximum spall ejecta thickness. The impact experiments carried out with 0.04- to 0.2-g, 5- to 6-km/s projectiles produced crater-like to crater-rim crater craters of various diameters and demonstrated crater efficiencies of 0.01 g sq cm, an order of magnitude greater than in metal and some two to three times that of previous experiments on less strong igneous rocks. Most of the crater volume (some 60 to 80%) is due to spall failure. Distribution of cumulative fragment mass, as a function of mass of fragments with masses greater than 0.1 g, yields values of B = [log N/log M] of ~0.5 to ~0.6, where N is the cumulative number of fragments and M is the mass of fragments. These values are in agreement with slightly higher than those obtained for less strong rocks and indicate that a large fraction of the ejecta resides in a few large fragments. These large fragments are state-like with mean values of 3/4 and 3/4 of 0.8 and 0.2, respectively (A = long, B = intermediate, and C = short fragment axes). The small fragment-dimensioned fragments (mass < 0.1 g and B > 0.1 mm) represent material which has been subjected to shear failure. The dynamic tensile strength of San Marcos gabбро was determined at strain rates of 10⁶ to 10⁷ sec⁻¹ to be 127 ± 9 MPa. This is 3 to 10 times greater than inferred from quasi-static (strain rate 10⁻⁹ sec⁻¹) loading experiments. Utilizing these parameters in a continuum fracture model predicts a tensile strength of ɛ = 0.1 to 0.3, where ɛ is strain rate. It is suggested that the high spall strength of basic igneous rocks gives rise to enhanced cratering efficiencies due to spall in the ~10⁻⁷ cm center diameter strength-dominated regime. Although the impact spall mechanism can enhance cratering efficiencies it is unclear that resulting spall fragments achieve sufficient velocities such that fragments of basic rocks can escape from the surfaces of planets such as the Moon or Mars.

1. INTRODUCTION

The size and shape of impact and explosion craters having characteristic dimensions of less than ~10² m are strongly dependent on the dynamic strength of the rock target medium and the impactor properties and speeds. The size and velocity distribution of fragments in the resulting ejecta cloud also depends on these same dynamic strength characteristics of the target (Grady and Kipp, 1980; Melosh, 1984). Moreover, the recent discovery of lightly shocked meteorites, which apparently represent impact ejecta from the Moon's (and possibly Mars') surface (Wasson and Wetherill, 1979; Stolper et al., 1979; Wood and Ashwal, 1980), has focused considerable interest on the spall phenomenon as it occurs on planetary surfaces (Melosh, 1983). Also, the possible destruction of growing protoplanets by impacting planetesimals is determined by the ability of the planet to withstand dynamic stresses associated with impact.

Attempts to generalize the description of fracturing and comminution processes and to obtain predictive capability for practical applications of breakeage have been recently summarized by Grady and Kipp (1980), Shockey et al. (1974), and Curran et al. (1977). They have described dynamic tensile failure by producing numerical models which consider both the statistical and microscopic aspects of nucleation and growth of cracks under the influence of varying..
strain rates. These models yield results which are in qualitative agreement with a given set of data for a rock type.

Previously, Grady and Hollenbach (1979), Grady and Kipp (1980), and Cohn and Ahrens (1981) obtained dynamic tensile strength data on igneous rocks and oil shale. In the present study we have carried out several cratering experiments in a well-characterized gabbro in the energy range 10⁷ to 10⁹ erg, and performed measurements of the dynamic tensile strength in the same material at strain rates of 10⁷ to 10³ sec⁻¹. We have applied the dynamic fracture data to the cratering results by employing Melosh's (1984) theory, as well as describing the distribution of compressive and shear failure fragments using the formulation of Grady and Kipp (1980).

2. SAMPLE: SAN MARCOS GABBRIO

San Marcos gabbro (Escondido, Calif.) is a basic intrusive igneous rock (Table I). The present samples contain relatively large plagioclase grains (1 to 3 mm) and amphibole (1 to 2 mm) intergrown with pyroxene and biotite (Hansen, 1948; Miller, 1937). On a microscopic level, the sample is essentially crack-free with cracks and fractures of less than 1 mm being absent. However, incipient microcracks are present along grain boundaries. The density of sample material used was 2.867 g/cm³ and the compressional wave velocity, C₀ = 6.36 ± 0.10 km/sec, was determined at 10 MHz.

3. CRYRING EXPERIMENTS

(a) Experimental Details

Cubic blocks, ~20 cm on a side, were cut from samples and a polished surface was imparted. The target blocks were embedded in cylindrical concrete blocks approximately 30 cm in diameter and 30 cm in height. Inverted aluminum cans, 30 cm in diameter and lined with Styrofoam, were suspended about 20 cm above the top surface of the gabbro in order to catch high-speed ejecta. The target assembly was then inserted in the target chamber of the NASA Ames Vertical Gun Facility. Prior to each experiment, the chamber was evacuated and the target was impacted with spherical, Pyrex glass, stainless-steel, and lead projectiles 3.3 mm in diameter (Table I).

(b) Results

Figures 1a-c illustrate the effect of impact of a lead projectile (Shot 3). The resulting crater is highly irregular in outline and its morphology is characterized by relatively large flat spill surfaces. Clearly visible are radial cracks which also reflect the shape of a larger recovered ejecta fragment (Fig. 1b). The fragments also show incipient cracks which follow a concentric pattern. Reflecting the irregular crater shape, the ejecta fragments differ in size and shape; however, all the spill fragments are plate-like and mostly are easily fit back into the crater (Fig. 1c). Some 60 to 80% of the crater volume is taken up by these large spill fragments which remained intact whereas the remaining volume of the crater consisted of completely fragmented small fragments in the 2- to 3-cm to submillimeter size range. The impact of the stainless-steel projectile (Shot 1) resulted in similar crater...
and ejecta fragment characteristics. In Fig.
2, the cross section through a crater (Shot
2) shows the relatively large flat shallow
spall surfaces and the generally rough and
irregular outline of the crater. Also visible
is the central trough which is observed in all
targets. This trough is similar to that ob-
erved by Moore et al. (1963) and Hörz
(1969) in which the central portion of the
rock falls in compression and shear and is
evacuated when the resulting small frag-
ments are ejected. Based on the distribu-
tion and shape of ejecta fragments we con-
clude that whereas the trough contained
highly fragmented small ejecta, the upper
large portion of the crater contained rela-
tively few large fragments.

The variance from simple energy scaling
can be seen in the crater dimensions given
in Table II. Although the energy of the Py-
rex impactor is comparable to that of the
lead and stainless-steel impactors the re-
sulting crater was considerably smaller.
However, even taking this into account the
present crater volumes are a factor of 3
larger than those obtained in a variety of
rocks by Moore et al. (1963) and in granodi-
orite by Hörz (1969).

All ejecta fragments for Shots 1 and 3
were collected and the fragment size and
fragment shape distribution, the latter only
for large fragments, are shown in Figs. 3
and 4. We plot the fragment mass, m, of
the larger ejecta fragments (mass > 0.1 g) ver-
sus cumulative number of fragments, N,
according to

$$\log(N) = a + b \log(m). \quad (1)$$

The slope, b, of the lines fit to these data
provides a measure of the degree of com-
motion of the target ejecta. Smaller val-
ues of b indicate distributions which are
dominated by smaller fragments whereas in
the present case the distributions with pre-
dominantly large fragments result in larger
values of b. The slopes for our distribution
lie at about -0.5 to -0.6, a value generally
in agreement or slightly higher than those
reported in the literature for collisional in-
teractions and impact ejecta. For collisional
interactions Hartmann (1969) obtained b
values which varied from -0.6 to -1.2. Fu-
jwara et al. (1977) found b values of -0.4
to -0.7 for all the fragments produced upon
destruction of basalt targets. Lange and
Ahrens (1981) obtained values ranging from
-1.0 to -1.8 for destruction of ice and ice
alike targets. Impact ejecta from basalt
targets from which spall fragments were
specifically omitted yield comparable val-
ues for b of -1.3 (Gault et al., 1963).

We measured the long (A), intermediate
(B), and short (C) axes for all the larger
fragments from Shots 1 and 3. Figure 4

<table>
<thead>
<tr>
<th>Shot no.</th>
<th>Projectile material</th>
<th>Target mass (g)</th>
<th>Projectile mass (g)</th>
<th>Projectile velocity (km/sec)</th>
<th>Impact energy (10^6 ergs)</th>
<th>Diameter (mm)</th>
<th>Crater depth (mm)</th>
<th>Volume (cm^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless steel</td>
<td>20.270</td>
<td>0.143</td>
<td>5.2</td>
<td>1.9</td>
<td>118</td>
<td>13</td>
<td>40.5</td>
</tr>
<tr>
<td>2</td>
<td>Pyrex</td>
<td>-</td>
<td>0.964</td>
<td>6.3</td>
<td>0.87</td>
<td>28 +</td>
<td>56</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Lead</td>
<td>18.300</td>
<td>0.195</td>
<td>4.6</td>
<td>2.1</td>
<td>113</td>
<td>13</td>
<td>43.8</td>
</tr>
</tbody>
</table>

*a Mean value for four measurements.
*b Mean value of three measurements.
+c Derived from mass of fine grained sand (mean grain size ~0.1 mm, mean density 1.44 g/cm^3) used to fill crater volume.
+d Only measurements on two thin sections, cut diametrically through crater, were carried out.
Fig. 1. Experimental impact crater in San Marcos gabbro resulting from impact of a lead projectile (mass = 0.2 g, impact velocity, 4.6 km/sec). (a) Crater, (b) recovered large fragments, (c) reconstructed spall fragments.

Fig. 2. Photomicrograph of a cross section of the experimental crater in San Marcos gabbro. Impact of a Pyrex sphere (mass = 0.04 g, impact velocity = 6.3 km/sec). The light mineral grains are predominantly plagioclase and amphibole. The dark grains are pyroxene and hornblende.
Fig. 3. Mass distribution (>0.1 g) of fragments from cratering experiments 1 and 3 in San Marcos gabbro. Parameters fit to Eq. (1) for Shot 1 are \( a = 1.04 \) and \( b = -0.67 \) and those for Shot 3 are \( a = 0.97 \) and \( b = -0.49 \).

shows the observed ratios \( R/A \) versus \( C/A \) which allow characterization of fragment shape (Lange and Ahrens, 1961). Values of \( R/A \) and \( C/A \) approaching unity and zero, respectively, are for ideal plate-like fragments. As evident from the figure, most of the fragments have \( R/A \) values greater than 0.6 and \( C/A \) values less than 0.25 with means of 0.77 ± 0.13 and 0.73 ± 0.11, and 0.21 ± 0.07 and 0.16 ± 0.06 for Shots 1 and 3, respectively. The above values indicate that the larger ejecta fragments are plate-like and presumably are spall fragments. The smaller fragments (<0.2 g) from Shots 1 and 3 were sieved-analyzed to obtain a fragment size distribution in order to determine a principal fragment dimension (Fig. 5). The fragment size distributions for both shots were similar and demonstrate that most of the fragments are less than 0.1 to 0.12 mm in size.

In summary, the present impact experiments on San Marcos gabbro resulted in craters which are characterized by spallation of a few large plate-like fragments, both the fragment mass distributions and the fragment shape distributions lead to this conclusion. Completely fragmented shear- and compression-fault material is probably derived from the central section of the crater and is dominated by fragment sizes of less than 0.1 to 0.12 mm size. The principal

Fig. 4. Fragment shape distribution for fragments (mass > 0.1 g) of cratering experiments 1 and 3 in San Marcos gabbro. \( A \) is the long, \( P \) the intermediate, and \( C \) the short axis of each fragment, respectively.

Fig. 5. Cumulative number, \( N \), versus nominal diameter, \( d \), of smaller fraction (mass < 0.1 g) of fragments from cratering Experiments 1 and 3 in San Marcos gabbro obtained in sieving analysis. Sphericity shape has been assumed.
pal crater-forming process is tensile failure (spallation), which, as discussed in Section 6, results from release wave interaction near the impacted surface of each target block. Thus, classification of these experiments and derivation of possible scaling laws require knowledge of the dynamic tensile strength of the rock on an appropriate time scale.

4. DYNAMIC TENSILE STRENGTH MEASUREMENTS
(a) Experimental details

The dynamic tensile strength of San Marcos gabbro was determined using techniques similar to those of Cohn and Ahrens (1981). The impact of a Plexiglas flyer plate onto a cylindrical sample (20 mm diameter, 6 mm thick) generates compressional waves which upon reflection from the free surfaces of a flyer and sample become rarefaction waves. Appropriate dimensions of the flyer and sample allow interaction of these two rarefaction waves and a state of tensile stress in one-dimensional strain to be obtained in the middle of a sample. Varying impact velocities result in different-ampitude tensile stresses. Upon sample recovery the stress levels required to produce incipient and complete tensile failure of samples may be determined (Lange and Ahrens, 1982). The experimental parameters of the experiments (Table III) are such that the strain rates varied from $10^4$ to $10^5$ sec$^{-1}$ which is comparable to the strain rates associated with the impact experiments of the previous section. The impacted samples were recovered intact. Radial cross sections were polished and thin sections were examined under an optical microscope to obtain crack statistics.

(b) Results

The length and condition of small cracks observed in thin sections of the shock-loaded samples are given in Table III. Figure 6 gives examples of observed cracks and explains the terminology used to describe the cracks. In samples which experienced only low or moderate tensile stresses, cracks propagated only along the grain boundaries. With increasing stress level an increasing number of cracks were observed to propagate through grains, generally following a direction parallel or subparallel to the impacted surface of the sample. Several cases of coalescence of cracks which started out either parallel to each other from one side of the sample or which met within the sample but originated in opposite directions were observed. Branching of cracks was not observed. In most of the samples cracks were closed and only samples from the highest stress levels (about 170 MPa) had open cracks. In order to identify those cracks which cause tensile failure, the following criteria were employed: (1) We identified only cracks greater than 0.5 mm long, (2) only cracks running parallel or near-parallel to the impact surfaces were counted, and (3) only cracks close to the midplane of each sample, i.e., the region of maximum tensile stress, were counted. Figure 7 shows the number of cracks selected according to the above criteria as a function of tensile stress from all samples. As can be seen, for peak tensile stress of $\sim$150 MPa the onset of large continuous spall cracks (greater than 1–2 mm long) was taken to indicate stresses in excess of the dynamic tensile strength. The mean value of tensile stress for these samples was $147 \pm 9$ MPa. This result agrees with earlier results for an anorthositic gabbro but is distinctly greater than the values of 70 to 110 MPa measured for quartzite rocks (Cohn and Ahrens, 1981).

5. CONTINUUM FRACTURE MODEL FOR GABBRO

In order to extrapolate the present results for dynamic tensile strength to other strain rates, we attempted to generalize our findings in terms of the continuum fracturing model of Grady and Kipp (1980). We estimated the value of the principal fragment size, $L_{cr}$, for the totally fragmented target
<table>
<thead>
<tr>
<th>Impact velocity (m/s)</th>
<th>Peak stress (MPa)</th>
<th>Sample no.</th>
<th>Description of Crack</th>
<th>Crack type</th>
<th>Crack length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.9</td>
<td>88.5</td>
<td>SNG 1</td>
<td>No visible cracks</td>
<td></td>
<td>0.5-1</td>
</tr>
<tr>
<td>38.1</td>
<td>84.4</td>
<td>SNG 5</td>
<td>No visible cracks</td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>34.4</td>
<td>97.8</td>
<td>SNG 2</td>
<td>Inception, not well-developed</td>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td>37.0</td>
<td>101.5</td>
<td>SNG 7</td>
<td>No visible cracks</td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td>40.2</td>
<td>104.2</td>
<td>SNG 10</td>
<td>Inception, partially-developed cracks</td>
<td></td>
<td>4.4</td>
</tr>
<tr>
<td>51.0</td>
<td>145.0</td>
<td>SGO 22</td>
<td>Several arrested cracks, history of propagation, fairly well-developed cracks</td>
<td></td>
<td>5.2</td>
</tr>
<tr>
<td>53.7</td>
<td>152.7</td>
<td>SGO 23</td>
<td>Inception cracks, few fairly well-developed fibril cracks, some of any size, arrested</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54.1</td>
<td>153.8</td>
<td>SGO 2</td>
<td>Inception, pre-crack / arrested system of cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>58.2</td>
<td>165.5</td>
<td>SGO 9</td>
<td>Inception cracks, poorly-developed crack</td>
<td></td>
<td></td>
</tr>
<tr>
<td>59.8</td>
<td>170.0</td>
<td>SGO 24</td>
<td>Inception cracks, fairly well-developed system of cracks, continuous, relatively long, uncracked</td>
<td></td>
<td></td>
</tr>
<tr>
<td>61.0</td>
<td>178.6</td>
<td>SGO 26</td>
<td>Inception cracks, fairly well-developed system of cracks, continuous, relatively long, uncracked</td>
<td></td>
<td></td>
</tr>
<tr>
<td>82.1</td>
<td>179.6</td>
<td>SGO 4</td>
<td>Inception cracks, well-developed, arresting cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>67.1</td>
<td>190.8</td>
<td>SGO 25</td>
<td>Inception cracks, well-developed, arresting cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70.1</td>
<td>219.9</td>
<td>SGO 21</td>
<td>Inception cracks, well-developed, arresting cracks, system of continuous cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>71.9</td>
<td>204.4</td>
<td>SGO 11</td>
<td>Inception cracks, well-developed, arresting cracks, system of continuous cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>77.5</td>
<td>220.3</td>
<td>SGO 5</td>
<td>Inception cracks, well-developed, arresting cracks, system of continuous cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80.8</td>
<td>229.7</td>
<td>SGO 12</td>
<td>Inception cracks, well-developed, arresting cracks, system of continuous cracks</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE III

EXPERIMENTAL PARAMETERS FOR TEMPLE STRENGTH EXPERIMENTS ON S. T. M. CARBON REACTANTS. RESULTS OF MICROSCOPIC ANALYSIS.

Notes: 1. The impact velocity is the velocity at which the specimen was struck. 2. The peak stress is the maximum stress reached during the test. 3. The sample number is the identifier for each test specimen. 4. The description of the crack includes the type of crack (inception, partially-developed, etc.) and the length of the crack. 5. The crack length is measured in millimeters.
portion of our sample; the time, $T_m$, at which maximum stress is reached in the sample; and the time, $T_s$, at which tensile failure conditions are satisfied (Table IV). In the Grady–Kipp model, the values of $k$ and $m$ are the two parameters of the Weibull crack distribution and

$$n = ke^m$$  \hspace{1cm} (2)

where $n$ is the number of flaws per volume which can be activated at or below tensile strain level $e$. The values of $k$ and $m$ which relate principal fragment size to strain rate and tensile strength are

$$L_m = 6C_p(m + 2)\alpha^{-\frac{1}{2}}e^{\frac{m}{4}}$$  \hspace{1cm} (3)

and

$$\sigma_m = K(m + 3)(m + 4)\alpha^{\frac{3}{2}}e^{\frac{m}{2}}$$  \hspace{1cm} (4)

where

$$\alpha = \frac{8\pi C_p\lambda}{(m + 1)(m + 2)(m + 3)}$$  \hspace{1cm} (5)
Here, $K = C_0 \rho$, the effective modulus for one-dimensional strain where $C_0$ is the $p$-wave velocity and $\rho$ is the density of the sample. Also, $C_0$ is the growth velocity for activated cracks. The model of Table IV provides theoretical values of $\sigma_{m}, l_{m}, n_{m}$, and $n$. The values of $m = 9.1$ and $k = 10^6$ are comparable to those found for ice and ice--silicate mixtures (Lange and Ahrens, 1982) and lie above values of $m$ and $k$ obtained by Grady and Kipp for oil shale. The value of $C_{m} = 2.56 \text{ksi/sec}$, lies at the upper end of the plausible range of $C_{m}$:

$$C_{m} \leq C_0 \leq 10 C_{m}$$  \hspace{1cm} (6)

The values of $k$ and $m$ are used to predict the poison (tensile strength as a function of strain rate in Fig. 8.

### CRATER SPALL FRACATURES

Comparisons of cratering efficiencies observed in the present experiments (Fig. 9) with those observed for a variety of decimeter-sized craters in various rocks by Moore et al. (1963) and Börjesson (1969) demonstrate that the present large spall craters (Fig. 9) are large by a factor of 2 to 3 than those of previous cratering studies. In metals, the cratering efficiency can be described in terms of

$$\pi = \frac{V}{pM}$$  \hspace{1cm} (7)

<p>| TABLE IV |
| CONTINUOUS FRACURING MODEL PARAMETERS FOR SAN MARCO GABBRO AND COMPARISON WITH NUMERICAL RESULTS |</p>
<table>
<thead>
<tr>
<th>( x )</th>
<th>( m )</th>
<th>( k )</th>
<th>( C_0 )</th>
<th>( \sigma_{m} )</th>
<th>( l_{m} )</th>
<th>( n_{m} )</th>
<th>( \sigma_{m} )</th>
<th>( \sigma_{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.1</td>
<td>$10^6$</td>
<td>2.56</td>
<td>10</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>5 x 10</td>
<td>9.1</td>
<td>$10^6$</td>
<td>2.56</td>
<td>44</td>
<td>9</td>
<td>44.2</td>
<td>44</td>
<td>9</td>
</tr>
</tbody>
</table>

* Observed force, strength values for Wehrlentorf granite in "crushed" tests (Lange and Ahrens, 1982).
* $\sigma_{m}$ is the mean and $\sigma_{m}$ is the standard deviation from a set analysis of repeatedly fired 0.1-in. diameter craters on San Marco gabbro (1982). Sample.
* $\sigma_{m}$ is the total duration of study, 1966. Note that to the sample, $\sigma_{m}$ for the sample from this time.
where $V$, $\rho$, and $M$ are the volume of the crater, the density of the target, and the mass of projectile, respectively (Holsapple and Schmitt, 1982). For a series of impacts of metals onto metal, the density scaling parameter

$$\pi_1 = \frac{\Delta \rho}{\rho}$$

and strength parameter

$$\pi_s = \frac{Y}{fU}$$

were fit to the relation for different impacts given by

$$\pi_s(\pi_1^{1.73}, \pi_t^{0.70})^{0.07} = 0.48 \pm 0.08.$$  (10)

Here, $\delta$ and $U$ are projectile density and velocity and $Y$ is effective material strength. Upon applying Eqs. (9) and (10) to calculate for the craters produced by polyethylene impacts into Vacaville basalt (Moore et al., 1963), impact of aluminum onto granite (Hohler, 1964) and the present experiments yield values of $Y$ in the range of 3–6 MPa. These values are on the order of $10^{-2}$ times the elastic modulus of these competent rocks. We infer that rather than yielding the effective shear or compressive failure strength the assumption underlying the strength scaling [Eqs. (9) and (10)] does not really apply. Thus in the present cratering experiments and all previous cratering experiments in competent rock, most of the crater volume is the result of spall failure. The present measurements of spall strength of gabbro ($\sim 147$ MPa) suggest that this is high relative to that of quartzite rocks (Fig. 8). Recent measurements of the fracture energy of olivine (Swain and Atkinson, 1978) indicate that its surface energy is comparable to that of quartz ($\sim 1$ J/m$^2$). Moreover, microcline has an even greater surface energy ($\sim 3$–5 J/m$^2$). (Atkinson and Avde, 1980). No simple reason can now be given for the greater spall strength of gabbro and basalt those those of quartz-bearing rocks. Hence, there is no straightforward correlation between spall strength or spallation of a certain material and its value for the surface energy. As was noted earlier (Grady and Kipp, 1980), the amount of energy needed to create the combined surface area of all fragments in a fragmentation experiment does not agree with the energy imparted in the target body due to the impact. Taking the dynamic tensile strength of $147$ MPa, the theoretical maximum spall thickness, $z_s$, can be calculated from a wave interaction treatment of Melosh (1984). Using his hydrodynamic approxi-
mation of spall thickness as a function of radius, \( r \), which is given as

\[
z_0 = \frac{d}{\sqrt{2\mu\alpha(1-n)d^2}}
\]  

(11)

where \( d \) is the equivalent projectile diameter and \( d \) is the assumed explosive equivalent depth of impact. Here \( d \) is assumed to be given as

\[
d = 2a(8\mu p)^{1/2}
\]  

(12)

The elastic shock pressure \( P \) is assumed to decay according to the approximation

\[
P = \frac{\mu_0 U_0}{\sqrt{1 + \frac{1}{n}}} (1/r)^{(n+1)/2}
\]

where \( n = 1.87 \) (which is observed near explosions). The value of \( n \) chosen by Melekh is close to the value found for the decay of peak pressure from impacts in the range 7.5 to 15 km/sec by Ahrens and O'Keefe (1977). Notably the spall surfaces predicted by Eq. (11) are convex upward which is opposite to what is observed (Fig. 9). Using the measured value of the parameters in Eq. (11) yields predicted spall thicknesses of \(-1.5\) cm (Fig. 10). These values are comparable to the maximum value observed. The average spall thickness is \(-1.0\) cm at a diameter of 4 cm for the two experiments for which intact spalls were recovered (Fig. 10). An interesting prediction of Eq. (11) is thinner spalls for weaker tensile strength materials. The available data for spall strength (Fig. 8) and the resulting cratering efficiency (Fig. 11) agree at least qualitatively with this prediction.

7. CONCLUSIONS

Application of the Grady-Kipp (1980) fracturing model to the present data for fragment size and dynamic tensile strength yields a prediction dependency of tensile strength on strain rate. Hypervelocity impact experiments producing decimeter- to centimeter-sized craters in gabbro yield crater morphologies which appear to be dominated by spalling or tensile fracture. Melosh's (1984) theory of near-surface spalling is used to predict a value of maximum spall thickness of \(1.5\) cm which compares favorably with observed spall thicknesses of \(-1.0\) cm observed in the present experiments. The enhanced cratering efficiency due to spalling is such that the cratering efficiency is increased from the 2 to \(2 \times 10^{-5}\) g/erg for siliceous rocks to \(6 \times 10^{-6}\) g/erg for the present basic, high-tensile strength rocks. This effect of spallation-induced cratering appears, at least the present experiments, to enhance the proposed (Melosh, 1984) impact-induced projection of lightly shocked ejecta from the surfaces of Moon and Mars. The velocity of such spalls needs to be studied.

Fig. 10. Cross sections of spall fractures produced in Shot 3 and theoretical spall surface calculated from Eq. (11).

Fig. 11. Relation of projectile energy to experimental crater volumes for various rocks. Present results are for Shots 1 and 3.
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