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Impact Force per Crater Area Related to the Tensile Strength

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MANY efforts have been made to relate the extent of impact damage to the properties of the target material. These efforts probably started in 1742 with the resistance-to-penetration theory of Robins.[1] Between 1835 and 1845 the French conducted a series of experiments to measure the velocity of cannon-ball fragments. The fragment velocity was computed by assuming a constant cratering efficiency, i.e., a constant ratio of crater volume to the kinetic energy of the fragment. One of the earliest correlations of cratering data was made by Helié,[2] who observed that the crater volume was approximately proportional to the kinetic energy of the impacting projectile where the constant of proportionality is a function of the target material. Later investigators,[3–7] in general, have agreed with Helié's conclusions.

Cratering involves shock compression of the target material to very high pressure, and the subsequent motion involves high strain and stress. Although the initial phase of the motion resulting from high-velocity impact may be adequately described by hydrodynamic principles, the stresses rapidly decay due to geometrical divergence and dissipation to the point where material strength becomes important. Pressures operative immediately after impact are clearly not representative for the greater part of the cratering process and cannot serve as a valid basis for neglecting the strength of materials. The bulk of the crater formation is caused by a process of energy dissipation and target deformation, during which the only restraining forces are the target properties. The final phase of the motion will involve a certain amount of elastic "springback." Because of this springback, the final crater depth was observed[10] to be 25% less than the maximum depth that occurred during the peak pressure pulse.

It has been observed that the ratio of impact energy to final crater volume‡ (reciprocal of the cratering efficiency) is directly proportional to the following:

Method A: Brinell hardness number§ of the target material which, in turn, is approximately proportional to the yield strength.[6]

Method B: Shear strength of the target material.[7]

The inherent limitations with these approaches to predict the crater damage sustained by a target can be attributed to the following:

Method A: The difficulty in relating other physical properties to the indentation hardness. The Brinell hardness number is *roughly*[8] proportional to the yield stress, at least within the scatter usually associated with empirical correlations. When the yield stress is known, the proportionality constant can be determined accurately, but, due to the approximate proportionality of yield stress to hardness, the crater dimension can be only *roughly* predicted.

Method B: The proportionality constant can be determined only when the shear strength is known, although it has an *approximate* value of 10 for all materials except lead.

The hypervelocity impact force per crater surface area is equal to the ultimate tensile strength,[9]¶ when the measured crater dimensions in aluminum are corrected (25%) for relaxation. Equations for uniformly accelerated rectilinear motion are applicable. The computed ultimate strength for the hemispherical craters is 3.2×10^9 dynes/cm^2 which can be compared to the measured tensile strength** of 2.97×10^9 dynes/cm^2. Nylon, glass, and aluminum projectiles with a mass range of 0.075–0.800 g were used to impact aluminum (6061-T6) targets with velocities in the range of 3.78–5.43 km/sec. Two additional experiments have been made with 0.075-g projectiles with impact velocities of 3.66 and 4.80 km/sec. The computed strength, with the two data points, was unchanged. Thus, the comparison can be made of the computed strength (3.2×10^9 dynes/cm^2), the experimentally determined tensile strength (3.0×10^9 dynes/cm^2), and the handbook value of the tensile strength (3.1×10^9 dynes/cm^2). The concordance is astounding, especially in the light of the assumptions made in computing the area, the averaging of the pressure, and the different material properties that are important during the various stages of crater formation.

In order to further corroborate the force per unit area concept, the data reported by Gehring[10] were used to compare the computed strength with the tensile strength. The 0.10-g steel projectile†† impacted the aluminum (2S-O) target at 5 km/sec and produced a 2.5-cm-diam crater that was 1.2 cm deep. However, the maximum depth of penetration was 1.5 cm as observed by flash x-radiography during the cratering process. The computed strength of 1.05×10^9 dynes/cm^2 can be compared to the tensile strength of 0.9×10^9 dynes/cm^2 or to the compressive‡‡ yield strength[7] of aluminum (alloy not specified) of 1.02×10^9 dynes/cm^2.

Comparison of the ultimate tensile strength with the strength computed from springback corrected data reported by two different laboratories and with different combinations of materials for the projectile and target shows excellent concordance. Thus, the maximum depth of penetration depends upon the force produced by the impact, and the measured (postmortem examination) depth of penetration depends on the amount of elastic recovery or springback.

It is significant that crater damage via hypervelocity impact can be predicted from the tensile strength established by standard metallurgical techniques. Future correlations of impact damage with material properties may be more productive, and better concordance may be achieved between theoret-

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‡ The final crater volume refers to that volume observed after "springback."

§ The ratio of E/V was observed[9] to be 2.1×10^3 joules/cm^3 which can be compared to the value of 2.5×10^3 joules/cm^3 computed from the relationship reported by Gehring.[10] The measured hardness was 93.8 on the Rockwell E scale which can be converted to the approximate Brinell hardness number of 97.

¶ Theoretically, the value of the pressure P is obtained by equating the sum of the pressures over the contact area A to the compressive force F. Then the hemispherical pressure distribution $P = 3F/2\pi r^2$.

** Standard tensile specimens were cut from the material used as targets.

†† This mass refers to the actual or impact mass.

‡‡ Static compressive yield strength or tensile strengths have, in general, about the same value. Yield strengths generally increase with the rate of strain, and the true value of the yield strength would be somewhat larger than the value given.

ical and empirical results when cognizance is taken of the afterflow or springback of target material, e.g, the compressive properties.

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Ultra-Lightweight, Highly Efficient, High-Temperature, Thermal-Insulation System

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MANY years ago, a system of glass vacuum spheres was patented for insulation for room temperature. Today such a system can be modified for high-temperature usage. The modifications consist of replacing ordinary glass by some other ceramic and adding radiation barriers. These barriers consist of many ultra-thin, electrically charged, ceramic flakes housed in the vacuum spheres. The number of rows of spheres is such that over-all heat transfer is at a minimum for a given weight. Minimum gage of the sphere wall is determined by manufacturing limitations. Also, this gage must be large enough to prevent leaks. The density of the ceramic flakes must be kept low in order to minimize conduction and keep radiation blockage.

A typical $(R/t)_{\max}$ of a ceramic sphere is calculated by writing

$$15R/2t = 0.1\, E\, t/R$$

$$(R/t)_{\max} = (0.2\, E/15)^{1/2} \approx 400$$

Thus, for

$R = 0.25$ in., $t \approx 0.0006$ in.

$E =$ Young's modulus $\approx 10^7$

$R =$ sphere radius

$t =$ sphere thickness

More thickness is needed to prevent leakage and allow manufacturing feasibility. Assume the minimum gage to be 0.0015 in. Further, assume four rows of spheres and an average density of ceramic flakes of about 1 lb/ft^3. Then the weight per cubic foot of the total system, using ρ of ceramic of 0.08 lb/in.^{3}, is about 2.5.

If we assume thermal conductivity of sphere material of 0.5 Btu/hr per ft per °F at elevated temperature, the effective k of the total system is estimated to be about 0.05. This value compares with about 0.12 for 4.5 lb/ft^3 dyna-quartz at 2000°F.[1] Various tests are needed to confirm the theoretical efficiency of the vacuum sphere-charged flake insulation system.

One way to manufacture a vacuum sphere filled with electrically charged flakes is to immerse the flakes in a plastic sphere. The ceramic material is cast onto this sphere. Since the casting is porous, the plastic can be sublimed out at a low temperature. Finally, the ceramic is fired to become gas-tight.

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