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THE EFFECT OF MATERIAL PROPERTIES ON THRESHOLD PENETRATION

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ABSTRACT

One criterion often selected to assess the hypervelocity impact resistance of space materials is that of the threshold condition for penetration. Such a criterion is applicable in determining the performance of many space-vehicle components, such as manned modules, pressurized containers, fuel tanks, etc. Accordingly, thin plates of a variety of metals were subjected to the impact of small aluminum spheres from relatively low speeds to velocities as high as 8.5 kilometers per second. The metals tested ranged in density from a magnesium-lithium alloy to a beryllium-copper alloy and were selected to have diverse mechanical and physical properties. Threshold penetration conditions were determined and details of the mode of failure, such as lip formation, spalling, and cracking, were examined. No single material property was found which could explain the relative performance of the test metals. Examination of the test data resulted in a possible explanation for the failure of the stainless-steel sensors on the Explorer XVI satellite to record expected meteoroid impacts. author

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INTRODUCTION

Meteoroid damage experiments were conducted on Explorer XVI to yield engineering data to aid logical design of structures for future space vehicles. Pressurized beryllium-copper cells recorded some penetrations during the flight, but gold-wire-grid detectors covered by stainless steel recorded no penetrations. These tests are described in references 1 through 4.

In applying results from the former tests to the design of structures made of materials other than beryllium-copper, which is not often used in space vehicles because of its high density, it is necessary to determine the relative performance of the desired materials. Thus a parametric study of thin-sheet penetration is being conducted at the Ames Research Center and the present paper summarizes the results so far obtained.

NOTATION

t target thickness, mm

d projectile diameter, mm

v projectile velocity, km/sec

ρ target density, gm/cm^3

ϵ target ductility

p penetration depth into semi-infinite target, mm

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DESCRIPTION OF TESTS

Since only relative performance of the target materials was sought, the projectile properties were standardized; 1.59-millimeter-diameter balls of 2017-T4 aluminum alloy were used as projectiles in all tests and were sabot-launched from existing 22-caliber light-gas guns at Ames Research Center. The time and space coordinates of the models in flight were recorded by six spark shadowgraph stations. The velocity in the tests ranged from 0.5 to 8.5 kilometers per second. (See ref. 5 for a more detailed description of the test methods.)

Target materials were selected to provide a wide variation of physical and mechanical properties and yet retain useful structural characteristics. Table I lists the properties of materials that were included.

THRESHOLD PENETRATION DEFINED

When penetration of thin sheets is discussed, it is useful to define a failure criterion. We define "threshold penetration" as that point at which a given specimen is sufficiently damaged that it will no longer sustain a pressure differential of a few atmospheres without leaking. It is also useful to know the threshold spallation point, where the rear face of the target just begins to spall, that is, lose material. Spallation may or may not occur at impact velocities below the penetration threshold.

Because of slight differences in material properties from sample to sample, the threshold penetration point defined above has an inherent velocity spread of approximately ±0.15 kilometer per second. At velocities below this scatter range, then, projectiles would not penetrate; whereas at velocities above it the projectiles would leave a hole.

TEST RESULTS

The very wide range of target-material properties was selected to pin down the factors controlling relative performance. The effects of ductility and density were found to be most important.

The differences in failure modes resulting from differing ductility are well illustrated by test series with aluminum and beryllium-copper. Shown in figure 1 are photographs of sectioned targets of both alloys. It is apparent that the penetration process at the threshold point is quite different in these two materials. The hardness of both materials is equal, 74-76 Rockwell "B" scale, but the ductility of the 2024-T4 aluminum was 15-20 percent as compared to 35-60 percent for annealed Berylco 25. The aluminum target was penetrated when large irregular chunks of the metal began to yield from the target directly behind the crater. In the more ductile beryllium-copper alloy, the crater form changed from near hemispherical to a distended crater which was finally perforated at the threshold point. Evident also in figure 1 are the different spalling characteristics of the two materials. In the aluminum alloy, spalled material was ejected from the rear face of the target prior to perforation; but potential spall products of the beryllium-copper tended to be retained in a curled lip on the rear surface. Spallation is not present in all cases prior to perforation. Thinner targets, for example, when struck by slower projectiles were perforated without being spalled. A plot of threshold penetration points of 2024-T4 aluminum alloy and annealed Berylco 25 is shown in figure 2. Here, target thickness, t, is plotted versus projectile velocity, v. The dotted lines are the curves for the approximate point of onset of spallation for the two materials.

To study the effect of ductility further, the roles of aluminum and beryllium-copper are reversed; hardened Berylco 25, 36 Rockwell "C" scale, with reduced ductility, 3-10 percent, and 1100-0 aluminum alloy with ductility of 45 percent were impacted. In each case the more ductile material of a given density resisted penetration slightly better than the less ductile metal, as shown in figure 3. It should be noted that the more ductile materials, 1100-0 aluminum and annealed Berylco 25, exhibited the same type of crater distending and spall retention. Furthermore, the less ductile 2024-T4 aluminum and hardened Berylco 25 showed the same characteristic disrupting of material behind the crater and ejection of spall products from the rear target faces. This effect is illustrated in figure 4.

The threshold penetration of other metals was determined for the same range of velocities. These were: LA141-A magnesium-lithium alloy; 304 stainless steel; and Armco 17-4PH stainless steel, condition A. The threshold penetration point of these and the previously discussed materials is plotted in figure 5.

The Armco 17-4PH stainless steel exhibited a different perforation phenomenon than any of the other materials tested in that a cone-shaped nugget was punched out of the base of the crater (fig. 6). It is felt that annealing and increasing the ductility of the Armco 17-4PH stainless steel would produce cratering characteristics similar to other materials of like ductility, the condition A state being prone to the type of brittle failure noted.

The thinner targets of 304 stainless steel had threshold penetration points similar to Armco 17-4PH stainless steel, but thicker targets of 304 stainless steel resisted penetration better than Armco 17-4PH stainless steel and Berylco 25. The thinner sheets of 304 stainless steel did not spall but the thicker sheets had spall retention similar to the more ductile samples tested. These features might change if the projectile size were changed.

None of the specimens of magnesium-lithium alloy LA141-A spalled prior to perforation. Photographs of the cross section of each of the various target materials at their respective threshold penetration points are presented in figure 7.

In addition to comparing the thickness of materials perforated, it is significant to compare penetration on a mass per unit area basis. The plot of figure 8 does just this.

Here one may see that although much thicker light-alloy bumpers would be needed, they still are to be favored from the standpoint of weight reduction.

DISCUSSION

It has been customary to predict that a thin target will be perforated by a projectile if its thickness is 1.5 times the penetration which the projectile would make in a semi-infinite slab of the same material.[6] Two commonly used penetration formulas in this "rule of thumb" are the Ames penetration formula[7] and that due to Herrmann and Jones.[8]

In the range of velocities tested the threshold perforation data for 2024-T4 aluminum and 1100-0 aluminum determined by this test series are divided by the penetration depth determined by each of the above-mentioned equations and are plotted versus the impact velocity in figure 9. Although all of the data points are plotted, those below 4 kilometers per second are outside the region in which the Ames penetration equation is usually considered valid. If one designs a structure using 2024-T4 on the basis of the Herrmann and Jones equation, calculating the expected semi-infinite target penetration and multiplying by the factor 1.5, the resulting structure will be too thin. If the Ames penetration formula is used, the resulting structure will be approximately 25 percent too thick. The trend of the curves suggests that at higher speeds these margins are likely to change.

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If we consider the micrometeorite sensors used in Explorer XVI described in the Introduction, we are now in a position to discuss their relative performance. The present impact tests indicate that perforation may be achieved without spallation. The pressure cells may have been penetrated sufficiently to leak, and thereby record a hit, but the same impact into stainless steel may not have caused enough spallation to activate the grid-type sensor. Also on the basis of these tests, 304 stainless steel exhibited greater penetration resistance at the higher velocities than did Berylco 25. Therefore, one might expect to record penetrations in the Berylco 25 pressure cells much more readily than in the 304 stainless-steel-covered wire grids.

Although a threshold penetration equation is not available at this time, one can note several factors which affect the thickness penetrated. If all other factors are constant, the threshold penetration thickness varies linearly with velocity, within the velocity spread of these threshold penetration point measurements. Figure 10 is a plot of t/d versus v.

If the data are adjusted to constant velocity and ductility, the penetration varies inversely with density to the one-half power. A plot of t/d versus $(1/\rho)^{1/2}(v)$ appears in figure 11.

Furthermore, if the velocity and density are constant, the thickness perforated varies inversely with the ductility to the 1/18 power. Figure 12 is a plot of t/p versus $(1/\epsilon)^{1/18}(1/\rho)^{1/2}(v)$. The improved correlation is apparent.

CONCLUDING REMARKS

The correlation just described should not be considered a general threshold penetration formula, but is intended to stimulate further experimentation. Certainly, future experiments would:

1. Include a wider range of target materials,
2. Extend to higher impact velocities, and
3. Provide a variation of projectile parameters.

One might anticipate from the appearance of the target material properties in this limited correlation study that comparable projectile material properties would enter in a similar manner Also, a projectile-scaling relationship similar to that reported by Denardo[9] would certainly be expected to manifest itself as a size effect.

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TABLE I.- MATERIAL PROPERTIES

	Specification	Density, gr/cc	Minimum yield, dynes/cm^2	Minimum tensile, dynes/cm^2	Elongation in 2 in., percent	Elastic modulus, dynes/cm^2	Hardness
Magnesium-lithium	LA141A	1.35	9.66×10^8	13.12×10^8	10-20	4.135×10^{11}	58 Brinell
Aluminum	2024-T4	2.768	32.42	46.9	19	7.32	120 Brinell 75 R/B
Aluminum	1100-0	2.71	3.45	8.98	45	6.9	23 Brinell
Stainless steel	Armco 17-4PH	7.78	76.0	103.5	6-15	19.65	35 R/C
Stainless steel	304	8.02	24.15	58.6	50	19.3	150-175 Brinell 80 R/B
Beryllium-copper	Berylco 25	8.25	19.33 96.6	41.4 114.0	35-60 3-10	12.75	75 R/B 36 R/C
Aluminum	2017-T4	2.79			22		105 Brinell

FIGURE CAPTIONS

Figure 1.- Ductility effects on failure mode.

Figure 2.- Threshold penetration and spallation of 2024-T4 aluminum and Berylco 25 - annealed.

Figure 3.- Effect of ductility on threshold penetration of aluminum Berylco 25.

Figure 4.- Ductility effects on threshold penetration.

Figure 5.- Threshold penetration of various metals.

Figure 6.- Armco 17-4PH stainless steel.

Figure 7.- Threshold penetration.

Figure 8.- Weight comparison of various metals at threshold penetration.

Figure 9.- Threshold penetration compared to existing semi-infinite target penetration equations.

Figure 10.- Variation of t/d with velocity at threshold penetration.

Figure 11.- Variation of t/d with velocity and density correction at threshold penetration.

Figure 12.- Variation of t/d with velocity and density, ductility correction at threshold penetration.