Engineering Notes

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Hypervelocity Impact Tests on Space Shuttle Orbiter RCC Thermal Protection Material

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Introduction

THE Space Shuttle Orbiter is expected to be struck by larger meteoroids than previous manned spacecraft because of its greater size and longer cumulative time in space. The damage that these meteoroids will produce in the complex materials of which the Shuttle Orbiter is constructed can be understood only by conducting hypervelocity impact tests, because theories of hypervelocity impact damage have been applied successfully only to homogeneous materials.[1]

The material which will be used on the nose and leading edge of the wing of the Shuttle Orbiter to provide thermal protection during re-entry is made of reinforced carbon carbon (RCC) laminate material with a diffused silicon carbide coating for oxidation protection. This complex composite material has many interfaces between and within the layers of woven material, and certainly falls into the category of materials that must be tested to determine damage characteristics.

Some very brittle materials, like beryllium, crack during hypervelocity impact; the crack runs from the impact site to the edge of the specimen.[2] If the RCC material on the Shuttle Orbiter cracked in that manner, large sections of the material might be lost from the spacecraft during re-entry. It is suspected that, for some cases, the cracking is caused by stress concentrations that are created by the way the material is structurally supported, while in other cases the cracking is simply a result of the material properties and would occur even if the material were floating freely.

The purpose of the present test program was to produce hypervelocity impact damage in specimens similar to that expected from meteoroids, so that the specimens could subsequently be tested in arc-heated facilities to evaluate the degradation in thermal performance. In this report, only the nature and extent of the hypervelocity impact damage is considered. The degradation in thermal performance as a consequence of the damage is not addressed.

Test Procedure

The specimens tested were disks, having a diameter of 72 mm, a thickness of 5.0 ±0.1 mm, a mass of about 34 g, and an overall density of 1.7 g/cm^3. The specimens were mounted in a foam target holder to avoid concentrated stresses that might cause the specimens to crack. This was done to determine if the RCC material had an inherent tendency to crack during hypervelocity impact. The targets were positioned so that the impacts would be normal to the surface of the specimens. The tests were conducted in a test chamber that was evacuated to a pressure of 14 N/m^2.

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Nylon and glass projectiles were both used; the launching was by a small light-gas gun. The nylon projectiles were launched directly from barrels of the same diameter as the projectiles, that is, sabots were not used. Glass projectiles were placed on the front of nylon sabots and launched from a 1.52-mm-diameter launch tube. The sabot and the projectiles separated slightly during flight and the sabot is stopped by a baffle located between the gun and the target. The velocity of the projectile was determined from the distance moved in the time interval between photographs.

Test Results

Eight tests were conducted. The results of the tests are shown in Table 1. The kinetic energy of the projectiles varied from 0.2 to 74 J.

Only the front surface was cratered when the impact energy was 3 J or less. At 3 J, a trace of the black carbon interior was exposed. At lesser energies, only the exterior layers were penetrated. The exterior layers have good resistance to penetration, but they are brittle and spallation occurs around the impact point (see the front surface area damaged in Table 1). Information on how brittle the material is and how much resistance it has to penetration was obtained by comparing the damage with that done to cold-rolled steel under the same impact conditions. The test, using specimen 3-74, provided an excellent comparison. In that test, three identical glass projectiles were launched and accelerated to the same velocity. One projectile struck specimen 3-74, while the other two struck the cold-rolled steel baffle. The area damaged on the RCC material specimen was six times the area damaged on the steel. The depth of penetration was about 480 μm in the RCC material and about 240 μm in the steel.

The impact at 11 J in specimen 3-72 produced an impact crater on the front surface and a spallation crater on the back surface, although there was no hole through the material. Spallation is common in hypervelocity impacts into brittle materials, even in aluminum and steel[1] which are not nearly so brittle as the RCC material.

The specimens were completely penetrated when the impact energy was 34 J or greater. The size of the hole and the area damaged on the front and back surfaces are given in Table 1.

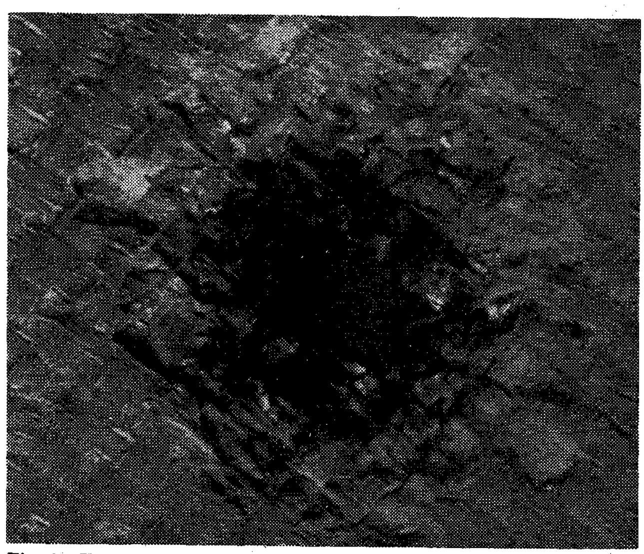

Fig. 1 Front surface of specimen 3-77 after impact by 37-J projectile.

Table 1 Summary of results

Specimen number	Projectile Material	Projectile Shape	Projectile Size, mm	Projectile Mass, mg	Projectile Velocity, km/s	Projectile Energy, J	Impact site from edge, mm	Specimen Area damaged Front, mm^2	Specimen Area damaged Back, mm^2	Specimen Hole size, mm^2
3-76	nylon	cylinder	2.11 diam. 1.52 long	5.1	5.4	74	34	153	213	12.8
3-77	nylon	sphere	1.52 diam.	2.3	5.7	37	29	69	104	3.4
3-73	nylon	cylinder	1.52 diam. 1.17 long	2.4	5.3	34	15	92	121	4.6
3-72	nylon	cylinder	1.00 diam. 0.79 long	0.71	5.5	11	26	35	52	...
3-80	nylon	cylinder	0.76 diam. 0.64 long	0.33	4.3	3	34	18.4	...	...
3-74	glass	sphere	0.27 diam.	0.024	5.4	0.3	32	3.4	...	...
3-70	glass	sphere	0.25 diam.	0.019	...[a]	...[a]	34	2.1	...	...
3-78	nylon	cylinder	0.76 diam. 0.64 long	0.33	1.2	0.2	32	2.2	...	...

[a] No measurement of velocity was obtained for this run. It is estimated from the loading conditions of the gun that the velocity was between 5 km/s and 6 km/s and that the energy was about 0.3 J.

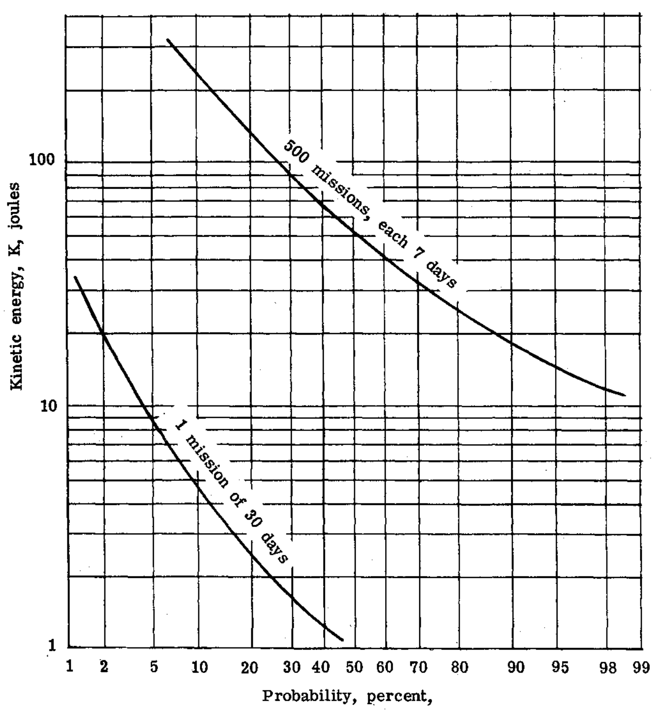

Fig. 2 Kinetic energy of meteoroids expected to strike the leading edge and nose of the Shuttle Orbiter.

Notice that the rear surface was damaged more extensively than the front surface. The shock wave originating at the impact site caused delamination near the back surface when it was reflected from that surface. Much of the delaminated material was lost as detached spall while some remained attached. A photograph of the front surface of a specimen which was completely penetrated is presented in Fig. 1.

A comparison of the penetration resistance of the RCC material with aluminum and steel can be made using the equations in Ref. 1. The energy required to penetrate the RCC material is greater than 11 J but less than 34 J. At 5.5 km/s, nylon projectiles in the 11-34 J range can penetrate 2.0-3.0 mm of aluminum or 1.3-2.0 mm of steel. The RCC material does not have the penetration resistance of the metals on a thickness basis, but on a weight basis, that is, mass per unit area required to stop projectiles, it is superior to steel.

One of the specimens developed cracks during the hypervelocity impact test. The cracks, which are on the back surface and edge of specimen 3-73, did not cause the specimen to fragment or to lose material. Two cracks running from the impact site to the edge of the specimen and other cracks perpendicular to these were produced. No attempt was made to determine the depth of the cracks or the degree to which they effect the strength of the material. The impact site on specimen 3-73 was just 15 mm from the edge of the target. The cracking occurred near the shortest path from the impact site to the edge. None of the other specimens showed any evidence of cracking, even though, in two cases, the impact energy was greater than that for specimen 3-73. In these cases, however, the impact sites were 29 mm or more from the edge of the specimen.

Discussion

The impact energies that can be expected from meteoroids striking the RCC material on the Shuttle Orbiter are shown in Fig. 2. This calculation is based on the NASA meteoroid environment model.[3] The area of the nose and leading edge of the Shuttle Orbiter was taken to be 38 m^2.

The probability of the RCC material being penetrated on a single mission of 30 days duration is only 0.01 (using 34 J as the energy necessary for penetration). However, over 500 missions of 7 days duration are shown in the 1973 Space Shuttle Traffic model,[4] and the probability that a penetration will occur on at least one orbiter increases to about 0.70. More likely than not, during one of the 500 shuttle missions, the RCC material will be struck by a meteoroid with kinetic energy in excess of 50 J. Damage caused by a 1 J impact must be expected to occur about once during each 30-day mission. Of course, many impacts with kinetic energy in excess of 0.2 will occur during each mission.

The probability that cracks will be produced in the RCC material on the Shuttle Orbiter was not calculated, because the dependence of crack formation on projectile properties and impact conditions is not known. Apparently the proximity of the impact site to an edge is an important factor. If this is the case, then the probability of cracks being produced would also depend on the size of the segments covering the nose and leading edge.

References

[1] Frost, V. C., "Protection Against Meteoroids," NASA SP-8042, May 1970.

[2] Humes, D. H., "Influence of the Bumper and Main Wall Material on the Effectiveness of Single Meteoroid Bumpers," NASA TN D-3104, Nov. 1965.

[3] "Meteoroid Environment Model – 1969 (Near Earth to Lunar Surface)," NASA SP-8013, March 1969.

[4] "The October 1973 Space Shuttle Traffic Model," NASA TM X-64751, Rev. 2, Jan. 1974.