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BERYLLIUM FRACTURE UNDER SHOCK LOADING

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The spall strength of beryllium, which is one of the most important materials in modern engineering, has been determined in some experiments on shock loading of specimens. For example, Christman and Froula [1] determined the time dependence of the spall strength of beryllium at normal and elevated (260°C) temperatures using metallographic analysis of tested specimens. Stevens et al. [2, 3] have studied the spall strength of beryllium by an interferometer system for recording the free-surface velocity of specimens under loading. The values of spall strength obtained in these studies characterize spallation conditions in specimens. The goal of this work is to determine critical shock loads that lead to macroscopic spall fracture of beryllium specimens at normal and elevated (400°C) temperatures.

Beryllium specimens were disks 90 mm in diameter and 20 mm thick. They were cut from three kinds of pressings denoted by letters A, B, and C. The pressings were fabricated from technical beryllium powder with a particle size of up to 56 μm (A and B by hot pressing in vacuum, and C by sintering of the powder with subsequent extrusion); the ultimate tensile strength of the pressings A, B, and C under static conditions of uniaxial tension were 0.39, 0.36, and 0.58 GPa, respectively. Shock loading of the specimens was performed by an impact of an aluminum plate with cross-sectional dimensions 110×150 mm and thickness of 4 mm. The plate was accelerated to the desired velocity w by means of sliding detonation of a plastic HE layer. Heating of the specimens to 400°C was performed by an electrical heater. The general setup of these experiments is described in [4]. Protective steel rings were used to prevent failure of the specimens by bending loads due to deceleration of a striker of larger size on the specimens.

Experiments were performed by two schemes. In the fist case, a free specimen was loaded without recording of the loading conditions. In the second case, a specimen was placed between an aluminum shield 2 mm thick and a Plexiglas plate 10 mm thick, and manganin pressure gauges were located at the interfaces. Numerical calculations of loading conditions were performed in all the experiments. A one-dimensional numerical program similar to that described in [5] was used to calculate elastoplastic flows.

The material properties necessary for the calculation are given in Table 1, in which ρ is the density, c_0 and λ are the coefficients of the linear relation $D = c_0 + \lambda u$ between the particle and shock-wave velocities, c_l and c_t are the longitudinal and transverse sound velocities, and σ_e is the Hugoniot elastic limit.

The loading conditions of the specimens are given in Table 2. The experimental and calculated stresses in pulses entering the specimen σ_1 and Plexiglas plate σ_2 and also the calculated stresses in tensile pulses σ_3 reflected into the specimen are also listed here.

Figure 1 shows oscilloscope traces of manganin gauge signals in one experiment (material B, $w = 129$ m/sec). The gauges were located at the shield–specimen and specimen–plate interfaces. Pressure calibrations for the upper and lower traces were 0.63 and 0.30 GPa, respectively. The mark frequency of the time sinusoid was 1 MHz. The lower oscilloscope trace records a spalling pulse which is caused by the spall fracture of the specimen and followed the main pulse. Similar spalling pulses were also detected in other experiments.

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TABLE 1

Material	ρ, g/cm^3	c_0, km/sec	λ	c_l	c_t	σ_e, GPa
				km/sec		
Aluminum	2.70	5.25	1.39	6.39	3.15	0.2
Berillium	1.84	8.09	1.73	12.8	8.80	0.2
Plexiglas	1.18	2.59	1.51	—	—	—

TABLE 2

Sample number	T, °C	Material	w, m/sec	Experiment		Calculation		
				σ_1	σ_2	σ_1	σ_2	σ_3
				GPa				
1	~ 0	A	257	—	—	1.99	—	1,60
2			180	—	—	1.40	—	1.05
3			206	—	0.49	1.59	0.46	0.79
4			129	1.11	0.30	1.01	0.28	0.43
5		B	257	—	—	1.99	—	1.60
6			180	—	—	1.40	—	1.05
7			129	0.97	0. 27	1.01	0.28	0.43
8		C	257	—	—	1.99	—	1.60
9			180	—	—	1.40	—	1.05
10			234	—	0.64	1.80	0.56	0.88
11			129	1.05	—	1.01	0.28	0.43
12	400	B	385	—	—	2.98	—	2.48
13			331	—	—	2.56	—	2.11
14			257	—	—	1.99	—	1.60

Some of the results of one calculation (w = 129 m/sec) are shown in Fig. 2, where curves 1 and 2 are the stress profiles at a spall-layer thickness of 6.4 mm and at the specimen-plate interface, provided that the material is intact, and curves 3–5 are the stress profiles at the specimen–plate interface in the case of fracture upon reaching a tensil -stress value of 0.4 GPa or at times of 3.9 and 4.2 μsec.

After experiments the specimens were inspected visually. We consider the results of this inspection. Specimens 1, 5, 8, and 12 (see Table 2) fractured into a large number of fragments. Examination of the fragments showed that before fragmentation the specimens undergone macroscopic spallation, because fragments of the spallation layer and of the remaining part were observed separately.

Some fragments of one specimen thus fractured (material A, w = 257 m/sec) are shown in Fig. 3. Specimens 3, 6, 9, 10, and 13 fractured into a few longitudinal fragments. Visual inspection of the lateral fracture surfaces of the fragments showed small cracks in the assumed spalling zone. Specimens 2 and 4 had longitudinal cracks. Specimens 7, 11, and 14 were macroscopically intact.

The resulting conditions of the macroscopic spallation of the beryllium specimens are shown in Fig. 4, in which the state of the tested specimens is coventionally graded as follows: 1 is complete macroscopic spall fracture, 2 is fracture of specimens into longitudinal fragments and the appearance of small cracks on the lateral surfaces of the fragments in the assumed spalling zone, 3 is a macroscopically intact specimen or the presence in it of longitudinal cracks that do not lead to fragmentation.

Thus, for a characteristic loading time of 1.5 μsec, the conditions of macroscopic spall fracture of beryllium are characterized by calculated tensile stresses of (1.3 ± 0.2) GPa at normal temperature and of (2.3 ± 0.2) GPa at 400°C. As to the spall strength which characterizes the conditions of origin of damage, the following should be noted. Comparison of the experimental results on the formation of spalling pulses at an impact velocity of 129 m/sec (see Fig. 1) with the results of the corresponding calculation of tensile stress

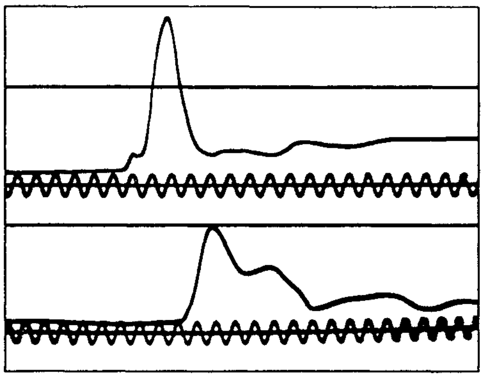

Fig. 1

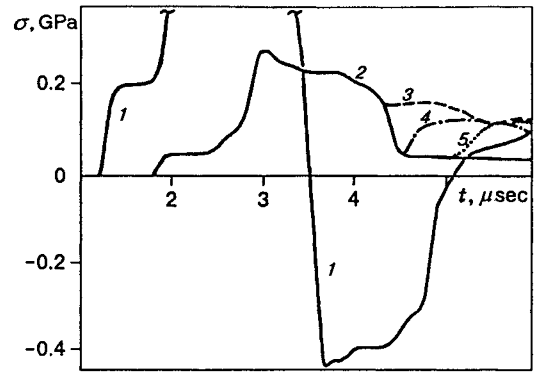

Fig. 2

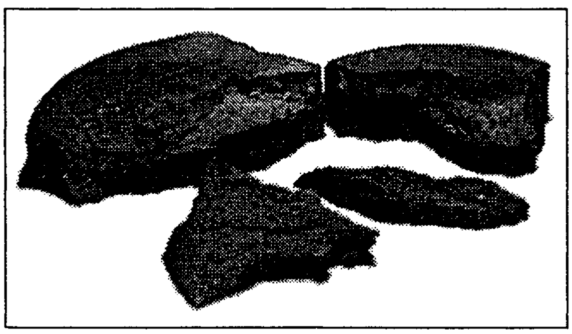

Fig. 3

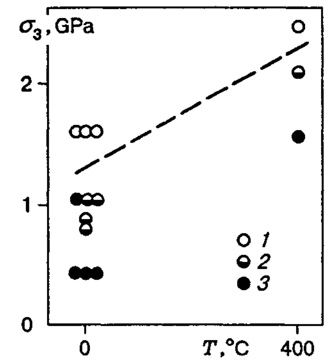

Fig. 4

under such conditions (see Fig. 2) suggests that at normal temperature and for the loading time considered the spall strength of beryllium is about 0.4 GPa.

This value of spall strength agrees well with the results obtained previously. The lowest values of spall strength (0.25–0.33 GPa) were found for high-purity coarse-grained beryllium for characteristic loading times of 0.3–1.0 μsec [1]. The spall strength increased to values of 0.31–0.50 GPa with a temperature rise up to 260°C. Stevens and Pope [2] tested specimens of hot-pressed and textured beryllium. The spall strength was estimated from the results of recording of the free-surface velocity of specimens during loading. For a characteristics loading time of 0.4 μsec, a spall strength of 0.6 GPa was obtained for both the starting and textured material. Bjorkman and Shrader [3] used the same method for hot-pressed beryllium at 230°C and obtained a spall strength of 0.8 GPa for a characteristic loading time of 0.8 μsec. These results indicate that heating up to 230–260°C causes a 25–50% increase in the spall strength of beryllium.

In this work, heating of specimens up to 400°C led to a 75% increase in the calculated tensile stress that corresponds to macroscopic spalling, which agrees well with the tendency revealed previously. The increase in the dynamic strength of beryllium, which is extremely brittle at normal temperature, by heating is obviously due to its increased plasticity. Steinberg and Sharp [6] noted that for beryllium the tensile stress that corresponds to macroscopic spalling exceeds by a factor of greater than three the spall strength that corresponds to the origin of spall fracture, and this is also supported by the results of this work.

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