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Hypervelocity impact of a steel microsphere on fused silica sheets

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ABSTRACT

We use the commercial finite element software Abaqus to study three-dimensional deformations of glass panels impacted at normal incidence by a 0.5 mm diameter steel sphere moving at about 3 km/s and having kinetic energy of approximately 2.3 J. We quantify effects of the critical erosion strain and the impact speed upon the conchoidal fracture diameters developed on the front- and the back-surfaces of the panel, and on the hole-out diameter. The strength responses of the steel and the glass are modeled as thermoelastoviscoplastic, and their hydrodynamic responses by the Mie–Grüneisen equation of state. An element is assumed to have failed when the erosion strain in it reaches the material-dependent critical value. Failed elements deleted from the analysis domain form cracks in the specimen. Effects of numerical uncertainties on significant failure features are found by repeating simulations with infinitesimal variations in the impact speed. The computed results are compared with experimental findings available in the open literature. For the impact problems studied it is found that (i) the spall front speed and the length of a spalled line are highly sensitive to the impact speed, and (ii) conchoidal fracture diameters on the front and the back surfaces of the target are less sensitive to the impact speed, (iii) values of the critical erosion strain greater than 2.0 do not affect the above listed damage variables.

1. Introduction

The history of hypervelocity impact (HVI) research lucidly reviewed by Fair [1] suggests that the HVI activity started in mid-1950's due to the interest in developing long-range ballistic missiles and launch vehicles to explore the outer space. The HVI research activities have included performing laboratory scale experiments, conducting numerical simulations, and developing material models, damage relations and scaling laws; e.g., see Denardo and Nysmith [2], Moore et al. [3], and Gault and Moore [4]. A typical damage due to HVI evolved in glass and shown in Fig. 1 taken from Ref. [5], is different from that in ductile and even brittle metallic targets. Whereas the front-surface conchoidal fracture diameters, D_s, in brittle aluminum is slightly larger than the crater diameter, D_c, and is about 4 times the projectile diameter, d_p, in glass $D_s \approx 40\, d_p$ and $D_s \approx 4\, D_c$.

The shock pressure produced by HVI is much larger than the low tensile strength of glass. Tensile stresses released on reflections from the free surfaces dominate the material strength over distances several times the diameter of the spherical steel particle. Although the initial impact pressure generated by HVI on glass is not much less than that on Al, the damage is much more extensive.

Flaherty [6] studied crater formation and damage evolution in fused silica glass caused by impact at different velocities and concluded the following.

1. Crater surfaces occupied less than 10% of the total damaged area.
2. The diameter, D_C, of the central zone consisting of chipped out pulverized glass equaled about 4–6 times the projectile diameter.
3. The pit depth, Y_C, at the point of impact equaled 2 to 3 times the projectile diameter.
4. At impact speed >6.9 km/s a spalled region formed.
5. Some craters had smooth profiles while others had subsurface separation without spallation.

Flaherty [6] noted $D_s/d_p \approx 40$ for Al projectiles impacting fused silica glass at 7 km/s, and observed (cf. Fig. 2) concentric rings of

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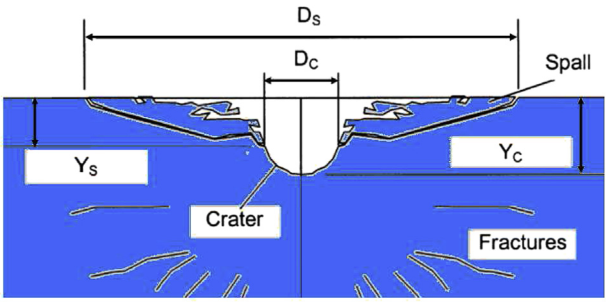

Fig. 1. Schematic sketch of the damage evolved in fused silica glass [5].

surface spallation, conical craters and radial cracks in the glass target. As can be seen from damaged surfaces depicted in Fig. 2, the shattered area and the spall region created around the crater are not symmetric about the point of impact.

Mandeville and Vedder [7], Vedder and Mandeville [8], and Mandeville [9,10] have emphasized that the ratio D_s/D_c rarely exceeds 8 for polystyrene, aluminum, and iron projectiles impacting soda-lime glass in the velocity range of 0.5–15 km/s, and craters formed are nearly hemispherical. Yang et al. [11] conducted HVI experiments on 1.2 cm thick and either 5 cm or 10 cm diameter fused silica glass panes with impact velocity varying between 2.8 and 7.44 km/s. They observed that targets were perforated for 2.5 mm diameter projectiles with impact velocities exceeding 3.95 km/s. In a laboratory, projectiles at velocities greater than ~10 km/s have rarely been propelled.

In a series of papers, Michel et al. [12–14] experimentally and numerically studied the impact of steel spheres on glass targets. For the numerical work, they used the smoothed particle hydrodynamics (SPH) formulation and implemented a material model in LS-DYNA [15] for glass. The computed front and back surface spall and perforation hole diameters were qualitatively similar to those observed in experiments, but their values were 34%, 32%, and 12%, respectively, lower than the average experimental values.

Numerical studies for HVI of brittle materials have employed constitutive models and damage equations developed by Johnson and Holmquist (JH) [16,17], Holmquist et al. [18], and Johnson et al. [19]. The yield strength is usually taken to be a function of the hydrostatic pressure, damage, the residual strength in fractured material, dilation, and the effective plastic strain rate but not of the temperature rise. Recently, thermal and damage softening and the effect of the third invariant of the Cauchy stress tensor have been included in the JH model [20].

Numerous authors have studied HVI problems by using hydrocodes, and we cite here only a few. Alwes [21] used the Lagrangian FE code PAM-EFHYD with automatic mesh rezoning option to numerically analyze axisymmetric deformations of a sandwich structure with 8 mm thick front and back face sheets of glass and 1.25 mm thick PVB core impacted at normal incidence by 2, 3 and 7 mm diameter aluminum projectiles. The glass and the aluminum were modeled as thermally softening elastic–plastic, and the PVB core as bilinear elastic–plastic with kinematic hardening. For studying the impact of glass targets by1 mm diameter Al-2024, Ti, and SS-304 spherical projectile traveling at 5 km/s, Taylor et al. [22] employed the JH model with no strain rate effects and the Mohr-Coulomb strength model, assumed axisymmetric deformations, and used the SPH formulation in AUTODYN. The computed penetration depths for the 1.5 mm diameter nylon and the 2.0 mm diameter Al spheres were smaller by 25% and 20%, respectively, than those measured experimentally. However, computed penetration depths using the JH material model for 1 mm diameter Al, Ti, and SS spheres impacting at 5 km/s exceeded the experimental penetration depth by 7%, 17%, and 16%, respectively. They also simulated the impact of chrome steel and phosphor bronze particles on glass, and found the computed penetration depth to be smaller than the corresponding experimental one by 10–20%.

Davison et al. [5] studied axisymmetric deformations caused by 62 and 124 μm fused silica particles impacting 2.54 mm thick fused silica mirrors at 6.2 and 9.9 km/s, respectively, and used the SPH and the Lagrangian cell methods in AUTODYN-2D. They used the JH material model, the maximum hydrostatic tensile stress equal to 0.13 GPa to delineate the spall failure, a polynomial equation of state (EoS), and the static damping feature in the hydrocode which decreases all velocities by a user defined factor after every time step. They found that the value of the maximum hydrostatic tensile stress at failure significantly affected the spallation. These simulations showed a detached spall in the vicinity of the crater that extended to a large region of the target.

While studying the response of glass targets to HVI by small impactors, Anderson and Holmquist [23,24] analyzed the sensitivity of the computed results to infinitesimal variations in the impact speed. For impact velocities of 2238, 2238.0001, 2238.0002, 2066 and 2066.0001 m/s, they found that for 0.0001 m/s or 5×10^{-6}% increase in the impact velocity, the final depth of the

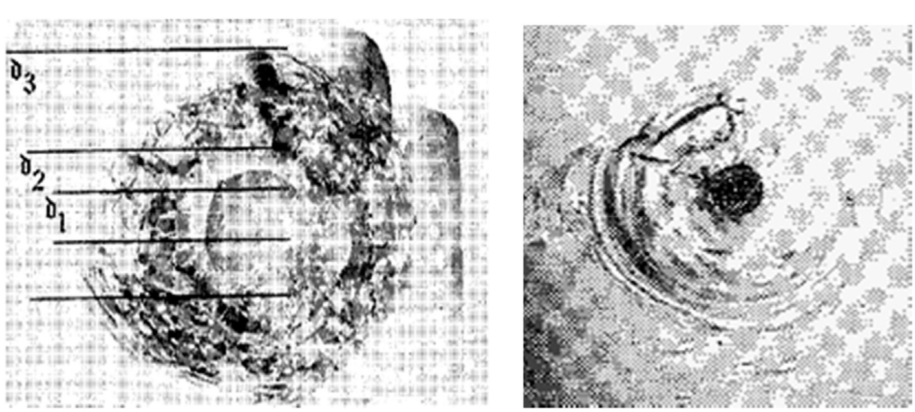

Fig. 2. Damage in fused silica due to the impact of (left) a 396 μm diameter sapphire sphere at 2.4 km/s and (right) a 396 μm diameter Pyrex sphere at 6.9 km/s [6]; d_1 is the dimpled area, d_2 the pulverized zone, and d_3 the rough chip-out zone.