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FROM FREE-SURFACE VELOCITY HISTORIES

AUTHOR(S): D. J. Cagliostro, R. H. Warnes, N. L. Johnson, and R. K. Fujita

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SPALL MEASUREMENTS IN SHOCK-LOADED HEMISPHERICAL SHELLS FROM FREE-SURFACE VELOCITY HISTORIES*

D. J. CAGLIOSTRO, R. H. WARNES, N. L. JOHNSON, and R. K. FUJITA

Los Alamos National Laboratory, P. O. Box 1663, Los Alamos, NM 87545

Copper and tantalum hemishells are externally loaded by a hemishell of PBX 9501 detonated at its pole. Free-surface velocity histories of the metal hemishells are measured at the pole and at 50° from the pole with a Fabry-Perot interferometer. These histories are used to determine spall strengths and depths by simple wave-interaction analyses and are compared with hydro-code (CAVEAT) predictions using simple and void-growth spall models.

1. INTRODUCTION

There has been much interest in the dynamic fracture, or spall, of metals in planar geometries.[1] Here, however, we address spall in 2-D axisymmetric converging geometries, which occur in the design of shaped charges where both normal and oblique shock waves travel through a thin-walled shell.

2. EXPERIMENTS AND MEASUREMENTS

The HE (Fig. 1) is machined from a 101.6-mm-diam cylinder to fit tightly around the hemishell. The SE-1 detonator and 12.7-mm-diam PBX 9407 booster initiate a detonation wave that sweeps around the shell transmitting a shock wave through its wall, normal at the pole and oblique away from it. When the shock reaches the shell's free surface, the reflected tension wave interacts with the Taylor-wave-induced negative pressure gradient producing tensile stresses that spall the shell.

These interactions and the spall itself are inferred from the free-surface velocity measurements. A laser beam is reflected from the desired spot on the hemishell to the interferometer, which produces a circular fringe pattern that is focused onto the slit plane of an electronic streak camera. To ensure sufficient reflected light for a satisfactory camera record, the copper is electroplated with 2000 angstroms of gold and the tantalum is polished with #400 emery cloth and cleaned with acetone. Details on recording and analyzing the data are given by Warnes.[2]

The copper hemishells are machined from OFHC 50.8-mm-thick plate stock, and the tantalum hemishells are forged from 3.18-mm-thick, annealed, 99.8%-pure sheet stock. The copper grains are 10 to 100 µm with a mean size of about 80 µm and are slightly elongated along the circumference. The tantalum grains are 40 to 150 µm with a mean size of about 80 µm and

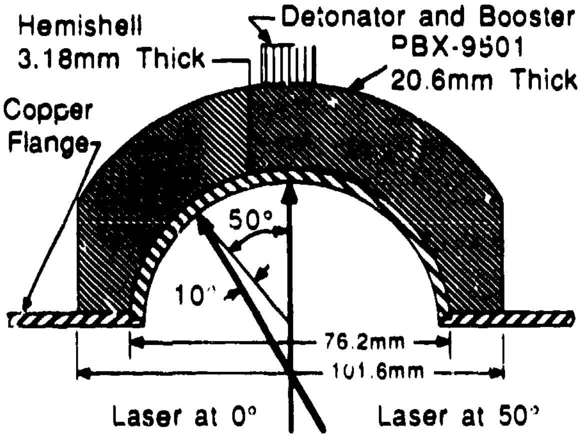

Fig. 1. Apparatus and instrumentation

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are also slightly elongated along the circumference.

The velocity histories for the copper and tantalum hemishells are shown in Fig. 2. In general, at the pole the surface accelerates to a jump-off velocity when the transmitted shock arrives and then decelerates because the Taylor wave attenuates the transmitted shock. This pull back in velocity is limited by the material's tensile strength. After pull back the velocity remains relatively constant, indicating spallation, until the rest of the shell catches up with the spalled layer, and then it increases. At 50°, jump-off occurs later and is lower because the detonation wave travels farther and impacts the shell obliquely. Catch-up occurs much sooner indicating a smaller spall gap. The two repeated tantalum experiments are very similar except for an unexplained 0.2-μs time shift. Record durations at the pole are limited by surface reflectivity and at 50° by explosive gases blocking the reflected light.

From the jump-off and pull-back velocities (Table 1) and Ref. 3. spall strength $\sigma = \rho_0 C_L \Delta U/2$ where ρ_0 is the material density, C_L the elastic wave velocity, and ΔU the pull-back velocity with $\rho_0 = 8.924$ and 16.656 g/cm^3 and $C_L = 4.76$ and 4.16 mm/μs for copper and tantalum, respectively.

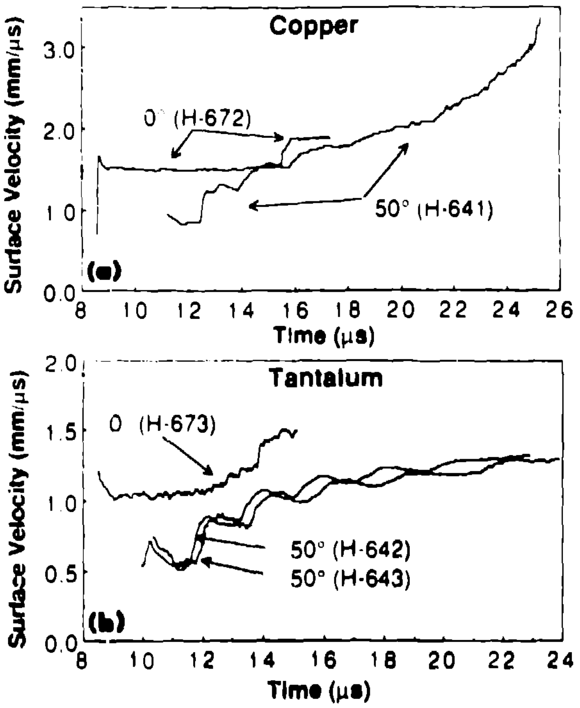

Fig. 2. Free-surface velocity histories for (a) copper and (b) tantalum hemishells

Our spall measurements (Table 1) for copper are higher than the 6.2-25 kbar reported by Meyers and Aimone[1] for copper impacted in a gas gun and are higher than the 10.3 kbar measurements by Speight and Taylor[3] for copper impacted by an aluminum flier that produced a free-surface velocity of 0.22 mm/μs (0.953 mm/μs in our experiments). On the other hand, our measurements are much lower than the 150 kbar ultimate yield strength measurements by McQueen and Marsh in explosively driven copper-copper plate impact experiments. For tantalum our measurements agree with Speight and Taylor's[3] that showed a spall strength

Table 1. Experiments and Measurements

Shot	Material	Polar Angle (Degrees)	Jump-Off Velocity (mm/μs)	Pull-Back Velocity, ΔU (mm/μs)	Pull Back Time, Δt (μs)	Spall Strength (kbar)	Spall Depth, X_s (mm)	Spall Time, t_s (μs)
H-672	Copper	0	1.68	0.16	0.33	35	0.81	0.21
H-641	Copper	50	0.95	0.13	0.61	27	1.50	0.35
H-673	Tantalum	0	1.20	0.20	0.55	71	1.12	0.31
H-642	Tantalum	50	0.747	0.20	1.00	71	2.13	0.56
H-643	Tantalum	50	0.720	0.22	1.05	76	2.24	0.58

greater than 65 kbar. The variation in the copper spall strength may indicate a dependence on initial shock pressure or strain rate or both.

We have estimated spall depth, or distance from the free surface, X_s using the jump-off velocity U_j, the pull-back velocity ΔU, and the duration of pull back Δt. Refer to Fig. 3; the following two equations for X_s can be written in terms of Δt and the unknown spall time from jump-off t_s: (1) $X_s = U_t t_s$ and (2) $X_s = U_{sp}(\Delta t - t_s)$. Solving these for X_s, we get: $X_s = U_t U_{sp} \Delta t/(U_t + U_{sp})$. Substituting X_s in (1) yields t_s (Table 1).

3. NUMERICAL SIMULATIONS

CAVEAT[5] is primarily a computer code for shock physics problems with large distortion and internal slip. It has second-order spatial accuracy with van Leer limiting and uses the Godunov method with an approximate Riemann solver; this results in a highly accurate description of shocks in multi-dimensions and multi-materials. It was used in the two-dimensional, Lagrangian mode with a spherical mesh with an axis of symmetry (90 elements in the azimuthal direction and 20 and 40 elements across the thickness of the hemishell and HE).

The HE is modeled using a programmed burn with a JWL equation of state with unmodified parameters[6] and is detonated at the surface between the detonator and HE (Fig. 1). The metals are modeled with a HOM equation of state with unmodified parameters.[7] Spall within the metal was modeled in two ways: (1) a minimum spall strength model in which if the pressure falls below the spall strength, the material fails and cannot sustain any tension thereafter and (2) a dynamic fracture model[8] that includes a porosity as a state variable and solves a rate equation for void growth and collapse during spallation and compression. The spall strength for the first spall model was adjusted to best fit the experiments; the dynamic fracture model was used unmodified.

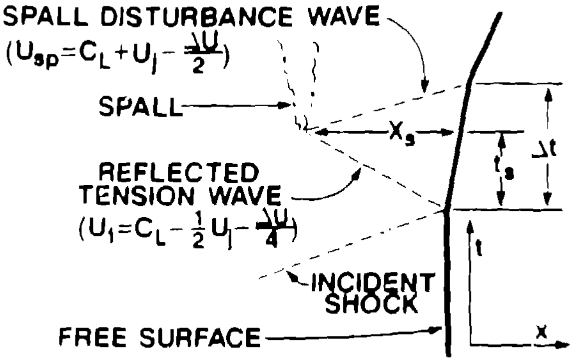

Fig. 3. Incident, reflected, and spall-disturbance waves at free surface

Only the calculations of the copper hemishell have been examined. Figure 4 illustrates the relative performance of the two spall models. The HE model was satisfactory at

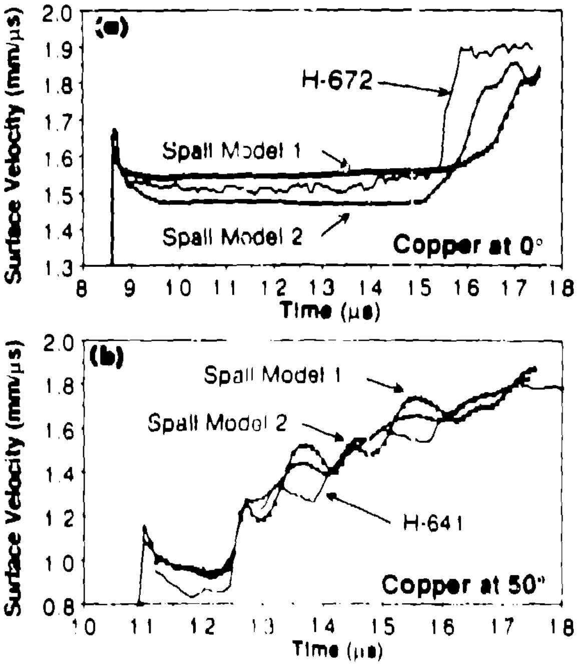

Fig. 4. Experiment and calculations for copper (a) at 0° with spall strength for model 1 = 30 kbar, and (b) at 50° with spall strength for model 1 = 50 kbar.

the pole, but the jump-off velocity at 50° was too high by about 50%, which indicates that the JWL equation of state needs to be modified. The larger jump-off velocity probably causes some of the discrepancy between the calculations and experiments.

Overall, the minimum spall-strength model was found to have three difficulties: (1) two different values of spall strength were necessary to describe the velocity history at 0° and 50° because of the different wave structure at the two locations; (2) a spall strength much larger than those measured was necessary to compensate for the inability of the model to exhibit tension after failure; and (3) the pole velocity was very sensitive to the spall parameter and therefore, to slight changes in the HE model, detonation area, and mesh size. The dynamic fracture model exhibited none of these difficulties. The predicted spall thickness at the pole of 0.80 mm agrees well with the experimental results. At 50°, because the spall plane is not normal to the surface, the spall thickness predicted by CAVEAT ranges from 0.8–1.16 mm. This suggests that the analysis of the experiment is sensitive to the deepest spallation point in the shell.

4. SUMMARY AND CONCLUSIONS

From measured inside-surface velocities in explosively loaded copper and tantalum hemishells, spall strengths and depths are determined (Table 1). The dynamic fracture model for spall was found to be superior to the commonly used minimum spall fracture model.

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REFERENCES

1. M. A. Meyers and C. T. Aimone, Dynamic fracture (Spalling) of metals, in: Progress in Materials Science, Vol. 28, (Pergamon Press Ltd., Great Britain, 1983) pp. 1-96.
2. R. H. Warnes, "Fabry-Perot Interferometry," Los Alamos National Laboratory Report LA-UR-86-4377 (1986).
3. C. S. Speight and P. F. Taylor, Dynamic fracture criteria from free surface velocity measurements, in: Metallurgical applications of shock-wave and high-strain-rate phenomena, eds. L. E. Muir, K. P. Staudhammer, and M. A. Meyers (Marcell Dekker, Ina, NY, 1986) pp. 805–820.
4. R. G. McQueen and S. P. Marsh, Applied Phys., 33, No. 2 (1962) 654.
5. F. L. Addessio, et al., "CAVEAT, A Computer Code for Fluid Dynamics Problems with Large Distortion and Internal Slip," Report LA-10613-MS, Los Alamos National Laboratory (1986).
6. B. M. Dobratz and P. C. Crawford, "Los Alamos Explosives Handbook," UCRL 52997, Los Alamos National Laboratory, 8 (1985) p. 23.
7. C. Mader and M. Shaw, "Users Manual for SIN," Report LA-7264-M, Los Alamos National Laboratory (1978).
8. J. N. Johnson, J. Appl. Phys., 52 (1981) pp. 2812-2825.