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GMX-2 SPALLING CALCULATIONS

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LOS ALAMOS SCIENTIFIC LABORATORY
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UNIVERSITY OF CALIFORNIA

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I. INTRODUCTION

During the last few years a considerable amount of experimental spalling data has become available. The one-dimensional numerical hydrodynamic code SIN¹ has been used as an engineering tool for studying and interpreting the experimental data. This report will describe the results of some of these numerical studies.

II. THE EQUATION OF STATE USED IN THE NEGATIVE PRESSURE RANGE

For any spalling calculation, the equation of state of the solid in the region of specific volumes larger than the initial specific volume at STP is the most uncertain feature. We use the $P = 0$ line as the standard curve and the Grüneisen equation of state for state points off the standard curve:

$$P_s = \left[I_s - \frac{C_V}{(3)(23890)(\alpha)} \left(\frac{V_s}{V_o} - 1 \right) \right] \frac{\gamma_s}{V_s},$$

$$T_s = \frac{(I_s)(23890)}{C_V} + T_o \text{ where } T_o = 300^\circ\text{K}.$$

Since on $P = 0$ $I = C_V (T_1 - T_o)$ and $\frac{V_1}{V_o} - 1 = \alpha(T_1 - T_o)$, $I_o = \frac{C_V}{\alpha} \left(\frac{V}{V_o} - 1 \right)$.

The parameters used in the Grüneisen equation are given in the table below.

<u>EQUATION OF STATE PARAMETERS</u>						
<u>Metal</u>	<u>C</u>	<u>S</u>	<u>ρ_o</u>	<u>α</u>	<u>γ</u>	<u>C_V</u>
Al	0.535	1.35	2.785	2.4×10^{-5}	1.70	0.22
Cu	0.3958	1.497	8.903	1.76×10^{-5}	2.00	0.093
Ni	0.4646	1.445	8.860	1.3×10^{-5}	1.89	0.105
Fe	0.378	1.652	7.8561	1.17×10^{-5}	1.68	1.107

Any spall pressures and volumes computed from experimental spall thicknesses are correct for the equation of state used, but are only as realistic as the equation of state happens to be in the range of pressures and volumes of interest. We have investigated two other equations of state for aluminum in the negative pressure region. One equation of state was based on McQueen's assumption that the linear fit to the shock and particle velocity was valid in the negative pressure region. The other equation of state was the Whiteman² fit to the Hugoniot pressure as a function of density. Both equations of state gave tension pressure-distance profiles that closely approximated those we obtained with our equation of state. The spall pressures obtained using the various equations of state agreed to within 5 kbar.

THE NOMENCLATURE

I	total internal energy in mb-cc/gram
V	total volume in cc/gram
V_o	initial volume of condensed component in cc/gram
T	temperature in °K
P	pressure in megabars
C_v	heat capacity of condensed component in calories/gram/degree
C,S	coefficients to a linear fit of shock velocity as a function of particle velocity
α	linear coefficient of expansion
γ	Grüneisen constant

Subscripts

o	initial conditions
s	condensed component

III. SPALL AS A FUNCTION OF INPUT SPALL VOLUME

One of the methods of spalling in SIN consists of testing on the specific volume of each cell. If any cell has a specific volume greater than the input spall volume, the cell pressure is set equal to 1 atmosphere and spall is said to occur. The errors in such a technique become smaller the larger the number of cells one uses to describe the metal.

Using this system for computing spalling, we computed the effect of spalling an aluminum plate with a steeply degrading pressure profile as shown in Fig 1. The spall volume used was 0.4 cc/gm with the initial volume of aluminum being 0.359 cc/gm. The computed free surface velocity for such an aluminum plate spalling at 0.38 and 0.40 cc/gm is shown in Fig 2.

Loree of GMX-4 has made some interesting observations on the system 2" of Baratol, 1" of Al, 1" of Ni. The inch of nickel was a single crystal. The recovered piece of spalled nickel was about 1/2" thick.

We performed a one-dimensional SIN calculation for his experimental arrangement. To spall at 1/2" the computed nickel volume was 0.120 cc/gm ($V_0 = 0.1128$ cc/gm) and the pressure was - 100 kbar for a "tension rate" (ie, pressure gradient) of 79 kbar/cm.

The computed free surface velocity of the nickel as a function of time is shown in Fig 3. The experimental values are in qualitative agreement with the computed curve; however, a detailed quantitative comparison is not possible because time zero is not well known. It is

clear that one observes a decreasing free surface velocity for the first 6 μ sec of run of about the amount computed.

Using Phermex, Venable of GMX-11 has made interesting observations on the system 10 cm of Composition B and 2.54 cm of aluminum. He has found that the initial spall thickness is 0.22 ± 0.02 cm and that 11 ± 1 spalls occur. A radiograph of this phenomenon is shown in Fig 4.

Using various input spall volumes for this system we calculate:

<u>Spall Volume (cc/gm)</u>	<u>Thickness First Spall</u>	<u>No. of Spalls</u>	<u>Spall Pressure (kbar)</u>
0.370	0.136	17	- 9
0.375	0.234	10	-16
0.380	0.392	7	-25

The pressure-distance and particle velocity-distance profiles are shown in Fig 5. On the basis of these calculations we conclude that the spall pressure of aluminum is -16 ± 5 kbar for the tension rate of 75 kbar/cm developed by this system.

Other results obtained by Venable, and the spall volumes and pressures derived therefrom, are summarized in the table below.

<u>Metal</u>	<u>Comp B (cm)</u>	<u>Observed Spall Thickness (cm)</u>	<u>Calculated Spall Volume (cc/cm)</u>	<u>Calculated Spall Pressure (kbar)</u>	<u>Calculated Tension Rate (kbar/cm)</u>
5.0 cm Al	10	0.22 ± 0.02	0.379	-23 ± 5	106
2.5 cm Al	10	0.22 ± 0.02	0.375	-16 ± 5	75
0.6 cm Al	0.635	0.10 ± 0.01	0.398	-50 ± 5	500
2.5 cm Cu	10	0.26 ± 0.03	0.1168	-40 ± 5	154
2.5 cm Ni	10	0.33 ± 0.01	0.1167	-54 ± 5	167

IV. SPALL AS A FUNCTION OF TENSION RATE

We have investigated the possibility of including a description of the spall pressure as a function of tension rate for each material in our one-dimensional hydrodynamic code SIN. With such a technique it may be possible to describe the spalling of multi-component systems.

We use the observations of Whiteman² and Skidmore³ that the spall pressure is a linear function of the square root of the tension rate above some minimum spall pressure, and below some maximum or "ultimate" spall pressure, as shown in Fig 6.

The spall behavior of each material is described by three constants, A, USP, MINP, where

$$P_{\text{spall}} = -A \sqrt{\frac{\Delta P}{\Delta X}}$$

$$P_{\text{spall}} \leq \text{MINP}$$

$$P_{\text{spall}} \geq \text{USP (Ultimate Spall Pressure)}$$

For aluminum A is $0.0714 \text{ (mbar-cm)}^{\frac{1}{2}}$, MINP is - 0.005 mbar, and USP is - 0.050 mbar.

A considerable amount of care must be taken to compute the tension rate $\Delta P/\Delta X$. We have assumed that the tension rate is linear, which is adequate for the problems we have considered.

The spall feature requires for each cell the following procedure:

1. If we are at an interface, we set the X_{spall} equal to the cell location and flag it.

2. If the specific volume of the cell is smaller than the initial specific volume (V_o), we go to the equation of state subroutine to compute the cell pressure.
3. Otherwise, we test to determine if the cell is flagged. If it is flagged, we are at a spall location and set X_{spall} equal to the cell location, the cell pressure equal to P_o (1×10^{-6} mbar), and advance to the next cell. Note that if we were at an interface or a previously spalled cell, the spall condition is assumed to be only that the cell volume is larger than V_o .
4. Otherwise, compute $\frac{\Delta P}{\Delta X}$ for cell n by

$$\frac{\Delta P}{\Delta X} = \left| \frac{P_n - P_o}{X_n - X_{spall}} \right|$$
5. We then calculate P_{spall} as described previously.
6. If $P_n - P_o$ is positive, we do not spall.
7. Compute cell pressure P_n .
8. If the $P_n < P_{spall}$, set P_n equal to P_o and flag the cell.
9. Otherwise, advance to next cell.

We computed the spall characteristics using this technique for the system 10 cm of Composition B and 2.54 cm of Al and obtained a spall behavior similar to the results obtained with the spalling determined by an input spall volume described in Section III. We obtained 8 spalls with the thickness of the first spall being 0.25 cm.

We computed the spall characteristics for 5.08 cm of 9404, 0.508 cm Cu, and 0.508 cm Al, and for 5.08 cm of 9404, 0.508 cm Cu, 0.508 cm Al, and 0.508 cm Cu. We used for the spall constants of copper an A of 0.1035, MINP of - 0.005, and USP of - 0.120. We also computed the spall characteristics for 5.08 cm 9404, 0.508 cm Fe, 0.508 cm Al, and 0.508 cm Fe, ignoring the iron phase change. We used for the spall constants of iron an A of 0.070, MINP of - 0.005, and USP of - 0.150. These constants were estimated using Whiteman's² spalling data. The 9404-plane wave lens interface was treated as a zero velocity piston, which closely resembles the actual experimental situation.

A comparison of the spall thicknesses computed and those obtained from Phermex radiographs of the same systems are shown in Table I. Also, prints of the radiographs are shown in Figs 7 through 13.

Unfortunately, it is necessary to use at least 200 cells per metal layer to obtain sufficient resolution to allow us to compute the tension rate adequately. With each calculation requiring approximately 1000 cells and 10 hrs of computing time, we have not attempted a parameter study of the spall constants. The remarkable agreement shown in Table I between the experimental spall thicknesses and the spall thicknesses computed on a "one-shot" basis makes it likely that one could numerically reproduce the spalling of many multi-component systems with the crude assumptions and techniques we have described. The experimental determination of the spall thickness (which permits the determination of the spall pressure

as a function of tension rate assuming an equation of state) for a number of metals (both single crystal and the more usual forms) would be essential information for others desiring to do engineering spall calculations of this type.

TABLE I

COMPARISON OF CALCULATED AND EXPERIMENTAL SPALLING

9404/Cu/Al System - at 3.24 μ sec after detonation wave strikes first metal surface

<u>Description</u>	<u>Calc Total Thickness of each Component</u>	<u>Experimental Shot No. 390</u>
Cu Layer	0.50	0.54
Al Total Thickness of all pieces	0.59	0.59

9404/Cu/Al System

	<u>Calculated</u>		<u>Experimental</u>	
	<u>6.70 μsec</u>	<u>10.17 μsec</u>	<u>at 6.70 μsec Shot No. 308</u>	<u>at 10.17 μsec Shot No. 392</u>
Cu Layer	0.51	0.51	0.59	0.57
Void	0.03	0.02		
Al Layer	0.05	0.05	0.48	0.59
Multiple Al Layers	0.33	0.45		
Al Layer	0.16	0.16	0.12	0.16
Void	0.12	0.22	0.08	0.10
Al Layer	0.20	0.20	0.15	0.21
Total	1.40	1.61	1.42	1.63

9404/Fe/Al/Fe System

	<u>Calculated at 6.70 μsec</u>	<u>Experimental at 14 μsec Shot No. 338</u>
Fe Layer	0.51	0.50
Al Layer with Back Spalled	0.57	0.50
Void		
Multiple Fe Layers	0.26	0.24
Void		
Fe Layer	0.18	0.17
Void		
Fe Layer	0.10	0.15

TABLE I - continued

Cu/Al/Cu System - at 5.90 μ sec

<u>Description</u>	<u>Calculated</u>	<u>Experimental</u> <u>Shot No. 309</u>
Cu Layer	0.51	0.53
Void	0.03	
Al Layer	0.14	0.14
Void	0.13	0.13
Multiple Al Layers	0.27	0.32
Void	0.02	
Cu Layer	0.54	0.56
Total	1.64	1.68

Cu/Al/Cu System

		<u>Experimental</u>	
		<u>at 9.20 μsec</u>	<u>at 11.61 μsec</u>
	<u>Calculated at 9.20</u>	<u>Shot No. 312</u>	<u>Shot No. 313</u>
Cu Layer	0.519	0.50	0.56
Void	0.046		0.07
Al Layer	0.140	0.11	} 0.49
Multiple Al Layers	0.191	} 0.57	
Al Layer	0.230		
Void	0.125	0.09	0.09
Cu Layer	0.210	0.23	0.24
Void	0.081	} 0.32	} 0.40
Cu Layer	0.038		
Multiple Cu Layers	0.092		
Cu Layer	0.015		
Void	0.050		
Cu Layer	0.212	0.13	0.19
Total	1.949	1.950	

LITERATURE CITED

1. Mader, Charles L., "Stretch SIN - A Code for Computing One-Dimensional Reactive Hydrodynamic Problems", Los Alamos Scientific Laboratory report GMX-2-R-63-1, LADC-5795 (1963).
2. P. Whiteman, "Preliminary Report on the Effect of Stress Rate on the Dynamic Fracture of Steel, Brass, and Aluminum", Atomic Weapons Research Establishment report UNDEX 445 (1962).
3. Private communication.

Figure 1

The pressure-distance (left column) and particle velocity-distance (right column) profiles for a 0.1 cm thick aluminum plate with a steeply degrading pressure profile and a spall volume of 0.4 cc/gm. The third row from the top shows the first spall, the fifth row shows the second spall, and the last row shows the third spall. Times are 0.13, 0.175, 0.18, 0.185, 0.19, and 0.20 μ sec, sequentially, from top to bottom of the two pages.

Figure 2. Free surface velocity of an aluminum plate with a steeply degrading pressure profile and with various spall volumes.

Figure 3. Experimental and theoretical distance of run vs time curves for the system 2" of Baratol, 1" of Al, and 1" of Ni. The zero time for the experimental points was found by using the calculated time for the 0.1 cm experimental point.

Figure 4. A radiograph of a spalled aluminum plate initially 2.5 cm thick and driven with 10 cm of Composition B.

Figure 5

Pressure-distance and particle velocity-distance profiles for 10 cm of Composition B and 2.54 cm of aluminum and a spall volume of 0.375 cc/gm. Pictures 7 and 8 show the first spall and pictures 11 and 12 show the 10 spalls. Times are 12.25, 15.68, 16.30, 16.43, 18.18, and 20.05 μ sec, sequentially, from the top to the bottom of the two pages.

Figure 6. Spall pressure as a function of tension rate.

Figures 7 through 13

The radiographs used to estimate the experimental spall thicknesses. The order of the radiographs is the same as presented in Table I. The shot numbers are 390, 308, 392, 338, 309, 312, and 313.