Simulation of impact/explosive driven spallation in metals: comparative study of damage and dynamic strength models

V R Ikkurthi, S Chaturvedi
Computational Analysis Division, Bhabha Atomic Research Centre, Visakhapatnam – 530 012, India
E-mail: ramana468@gmail.com

Abstract. Spallation refers to fracture occurring in materials due to tensile loading. This paper presents an overview of our extensive one- and two-dimensional simulations done to study spallation in impact/explosive loaded Copper or Mild Steel targets, using an Arbitrary-Lagrangian-Eulerian hydrocode. Three methods of computing the spall strength and spall thickness have been employed. The computed spall parameters have been compared with Russian spall experiments. In impact loaded targets, due to a square shock wave, only one scab has been observed. In the case of explosive loading, as the rarefaction associated with the incoming shock wave is triangular, there occur many high-tension regions leading to the formation of multiple scabs (typically 2-3 scabs). Effect of flyer velocity and target temperature on spallation has been studied. These trends match with experiments. Edge effects due to finite diameter of the target attenuate the incoming shock wave by lateral release, resulting in more marked damage near the axis than on the periphery. Four damage models and three dynamic strength models have been examined to determine the best-suited model for spallation studies. It is found that the Void Growth (VG) damage model and Zerilli-Armstrong strength model yield spall parameters close to experiments.

1. Introduction
“Spall fracture” is damage that occurs in a body when two rarefaction waves interact and produce enough dynamic tension to fracture it. Spallation is a rate-dependent process in which fracture occurs simultaneously over an area by the nucleation, growth and coalescence of many micro cracks or voids. The schematic of impact and explosive loaded spallation experiments is shown in figure 1. In case of impact loading, two one-dimensional shock waves will be generated. One propagates into the target and the other into the flyer plate. These shock waves reflect as rarefaction waves from the free surfaces of the flyer and target plates respectively. With a thin flyer, these rarefaction waves interact inside the target, producing a state of tension in some region. If this tensile stress level exceeds the dynamic yield strength of the material, fracture takes place, producing a scab (“spall element”) from that section of the target. After fracture has taken place, stress or spall signals are produced that propagate to, and accelerate, the free surface of the target. The velocity and the thickness (“spall thickness”) of this scab depends upon the shape of the pressure profile at the free surface and the yield strength of the target. Here, “spall strength” refers to the relative resistance of the material to spallation.
Many theoretical damage and strength models, both empirical and micro-physical in nature, have been developed to describe and predict high strain phenomena such as spall fracture [1]. These models compute the void volume in the region of fracture to quantify the damage level.

Figure 1. Schematic of (a) Impact, and (b) Explosive loaded spallation experiments.

There are a variety of practical problems involving high-velocity impact, and spallation frequently plays an important role. It is, therefore, of great interest to determine the effect on spallation of parameters like the impact pressure, the duration of the pressure pulse and the initial temperature of the target material. It is also of interest to assess the relative performance of different fracture and dynamic strength models in predicting spall strength and thickness for the flyer and target materials of interest. Finally, edge effects can also critically affect spallation, and their importance must be examined. Using two dimensional simulations, the above problems have been studied in detail and the results are presented in the following sections.

2. Computational Method

An Arbitrary-Lagrangian-Eulerian hydrocode has been used for these simulations. An Aluminum metallic flyer or a cylindrical charge of Composition-B3 (density = 1.717 g/cc) explosive drives a shock into a Copper or Mild Steel (MS) target plate. The schematic of the spallation problem is shown in figure 1. A programmed-burn model is used to compute burn propagation in the explosive. The JWL equation of state (EOS) is used for Composition-B3 and a six-parameter EOS [2] is used for Al/Cu/MS. The microphysical mechanism of ductile damage is nucleation, growth and coalescence of voids in the tension region. As the voids increase, the material softens, i.e., yield strength (Y) and shear modulus (G) decrease. Four damage models [1] and three dynamic strength models have been examined in this study. The damage models compute the void volume fraction (VVF) and also compute Y and G values as functions of VVF. Dynamic strength models compute variation of Y and G with strain, strain rate, pressure, temperature, etc. In our simulations, we monitor the free-surface velocity ($v_{fs}$) of the target and also the spatio-temporal evolution of Y, G and VVF.

We consider three methods of computing the spall strength and spall thickness, based on $v_{fs}$, VVF profiles and degradation of Shear Modulus. The first method, which is routinely used in analyzing experimental data, uses the pullback velocity and the period T of the oscillations in $v_{fs}$, based on the following equations

$$P_{sp} = \frac{1}{2} \rho_0 C_b \Delta W$$

$$t_p = \frac{1}{2} C_b T_p$$

where $\rho_0$ and $C_b$ are density and bulk sound speed at zero pressure. The second method uses a criterion following Eftis [3] that when VVF in a computational cell approaches a critical value (~ 0.3), spallation takes place at that point. The third method is where the shear modulus drops to half its
normal value. Using these methods, we have computed the spall thickness of the scabs generated in impact/explosively-loaded targets and compared with the experiments.

3. Results
Extensive 1-D and 2-D simulations have been performed to study spallation and edge effects. This is an overview of our work on spallation done over many years. Due to limit on the length of the paper, only some results are presented with illustrations or numbers and others are simply listed.

3.1. Multiple spallation
Two-dimensional hydrodynamic simulations have been done to study spallation in explosive-loaded MS target. Here simulations show that multiple scabs emerge from the target. The physical mechanism of multiple spallation is due to two reasons: Very high shock pressures and nonsquare profile of incoming shock wave. This can be explained in detail using the temporal variation of pressure profile along the axis, as shown in figure 2. The rarefaction associated with the incoming shock wave can be assumed triangular and when this incoming rarefaction wave meets the rarefaction wave generated due to interaction of shock front with the free-surface, a tension region is created. As the interaction proceeds the tension strength gradually increases. Spallation or fracture occurs at the point or region where the tension strength exceeds material strength. This creates a free-surface and the new situation is like a comparatively lower strength triangular shock wave interacting with the free-surface. Hence, the whole process repeats and if the initial shock strength is very high two or more spallation regions can occur. This leads to the formation of multiple scabs. The number and size of scabs emerge from the target agree well with the experimental observations.

3.2. Comparison of Damage models
We have done spallation simulations using either of the four damage models [1]: Void growth (VG), Nucleation and Growth (DFRACT), Cochran-Banner (CB), Johnson-Cook (JC). Figure 3 shows the measured and computed free-surface velocity profiles of the spalled element in a copper target, for the parameters of the experiment labelled B-62 [4]. Our simulations show that both VG and DFRAC'T models give results that match fairly well with experiments, with the VG model performing somewhat better.

3.3. Comparison of Strength models
We have repeated spallation simulations using either of the three dynamic strength models: Steinberg-Guinan (SG) [5], Zerilli-Armstrong (ZA) [6], Revised Johnson-Cook (RJC) [7]. Figure 4 shows the

Figure 3. Experimental and computed free-surface velocity profiles for experiment labelled B-62 using VG and JC damage models, with copper target (aluminum flyer).

Figure 4. Experimental and computed free-surface velocity profiles for experiment labelled B-62 using SG, ZA and RJC models, with copper target (aluminium flyer).
experimental and computed free-surface velocity profiles of the spalled element in a Cu target, for the parameters of the experiment labelled B-62 [4]. The results show that ZA model has the best performance for the experiments examined, with SG also doing fairly well. The RJC model generally does not yield a good match.

3.4. Effect of impact pressure and target temperature
We find that $t_s$ monotonically decreases with increase in flyer velocity, for both copper and MS targets. For a copper target (B62), $P_{sp}$ first decreases marginally, but then increases monotonically with the impact pressure. For MS targets (B16), the initial drop is quite large, although it is then followed by a monotonic increase. This can be explained using dislocation mechanics which has been accounted through strength models. With increase in strength of compressive pulse dislocations pile-up and hardens the material resulting in an increase of $P_{sp}$. We see that the spall strength of copper increases only slowly with $T/T_m$, with a maximum increase of only ~20%. These trends agree with experimental observations reported for copper. For MS, the behaviour is more erratic, and no clear trend can be seen.

3.6. Edge effects on Spallation
In situations where the thickness and diameter of the target material are of the same order, the incident shock is attenuated not only by the axial unloading waves but also by lateral release. Due to this extra attenuation, it is only near the axis that the tensile stresses and stored energy are sufficient to produce complete fracture. In case of explosive-loaded metals, heavy damage (3-5 scabs) on the axis has been observed. But, far from axis, due to edge effects, reduced damage (1-2 scabs) has been observed. Hence, the net result is that 2-3 scabs emanate from the target.

4. Conclusion
One- and two-dimensional simulations have been done to study spallation in impact/explosive loaded targets. The computed spall parameters have been compared with Russian spall experiments. In impact loaded targets, due to a square shock wave, only one scab has been observed. In the case of explosive loading, as the rarefaction associated with the incoming shock wave is triangular, multiple scabs (typically 2-3 scabs) emerge. In impact problems, the computed spall thickness decreases with increase in impact pressure. The spall strength is found to be increasing with impact pressure. These trends match with experiments. Edge effects due to finite diameter of the target attenuate the incoming shock wave by lateral release, resulting in more marked damage near the axis than on the periphery. It is found that the Void Growth (VG) and Nucleation and Growth models yield spall parameters close to experiments, with the VG model doing marginally better. In case of strength models, the spall parameters obtained using Zerilli-Armstrong (ZA) and Steinberg-Guinan models show reasonable agreement with experiments. ZA model is a micro-structural model and takes into consideration the crystal structure and hence performing better.

5. References
[1] Ikkurthi V R and Chaturvedi S 2004 International J. Impact Engg. 30 275, and references therein.
[2] Eliezer J S, Ghatak A, Hora H and Teller E 1986 An introduction to equations of state, Theory and applications (Cambridge University Press)
[3] Eftis J 1996 Constitutive modelling of spall fracture High pressure shock compression of solids II ed L.Davison, D.E.Grady, S.Mohsen (Berlin: Springer)
[4] Antoun T H, Seaman L and Curran D R 1998 Dynamic failure of materials, vol.2- Compilation of Russian spall data Tech. Rep. No. DSWA-TR-96-77-V2 DSWA, Alexandria, VA.
[5] Steinberg D J, Cochran S G and Guinan M W 1980 J. Appl. Phys. 51 1498.
[6] Zerilli F J and Armstrong R W 1987 J. Appl. Phys. 61 1816.
[7] Rule W K and Jones S E 1998 International J. Impact Engg. 21 609.