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PRELIMINARY REPORT ON A MODEL FOR INCIPIENT SPALL

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PRELIMINARY REPORT ON A MODEL FOR INCIPIENT SPALL

ABSTRACT

A computational model to describe spall is presented. The important features are a spall strength and a damage function that modify material properties in tension. The model can be interpreted as fracture occurring by nucleation, growth, and coalescence of microcracks. The predictions of the model are compared to experiments in copper and the agreement is quite good. Future developments for the model are indicated.

I. INTRODUCTION

Spall occurs when a chip or splinter breaks from one side of a plate that has been impacted on the other side. Spall is normal (Mode I) fracture that occurs under uniaxial strain conditions. For this reason it is perhaps the simplest type of fracture. On the other hand, spall occurs on dynamic time scales, so stress wave interactions are important.

The most straightforward experiment to investigate spall involves a flier plate striking a target plate. Rarefactions from the target and flier free surfaces interact to form a net tension. If the tension is strong enough and lasts long enough at a location, the material fractures there. For our purposes an active gauge that measures the effects of that fracture dynamically will be essential. One such measurement is the velocity of the target free surface as a function of time. We use free surface velocity data for our analysis. Our purpose is to develop a model that can reproduce active gauge records in such general terms that the material properties deduced from these experiments can be used to predict results in other situations. We would achieve even greater success if we could identify the spall properties a priori from other data, but such may not even be possible.

A free surface velocity profile is presented schematically in Fig. 1. Curve 1 is an artistic rendition of typical data and curve 2 would be a computer simulation of that experiment without a fracture model. The arrow represents the time when two-dimensional effects might become important in the signal. The second, or spall, peak (C) is the signature of fracture that has reached the free surface. We wish to describe this part of the record as accurately as the loading portion (A). Obviously, we must also simulate the release section (B) before we can hope to obtain good agreement on the spall peak. A release model used here will be described elsewhere.¹

Let us first mention the general phenomenology of spall fracture. It is observed that there exists intermediate stages between full separation of the spall and no fracture

Fig. 1. Free surface velocity vs time. See text.

at all. Our attention is concentrated on these stages because we infer that any fracture progresses through the same steps. If we hope to obtain a correct description of fracture, we must follow its stress-strain-time history.

An early stage of spall development is called incipient spall at which point fracture damage first becomes noticeable, or significant. Only recently has Banner² suggested a quantitative definition of incipient spall. Incipient spall occurs when the spall peak in Fig. 1 reaches 50% or half of the free surface velocity maximum. Incipient spall is important because the results of many spall studies are summarized in an "incipient spall curve" which is schematically illustrated in Fig. 2. Here, the flier velocity to achieve incipient spall is plotted vs flier thickness. Far above this curve, fracture is complete; and far below, fracture does not occur. Usually, the ratio of target-to-flier thicknesses is maintained fixed. The flier velocity is directly related to the maximum tension achieved and the flier thickness determines the duration of tension in the target. Note that the tension must be larger to achieve incipient spall if the duration is shorter.

We must emphasize that incipient spall curves are not entirely adequate for our purpose. Dynamic records of these same experiments would provide much richer information. For the most part, studies to obtain incipient spall curves were made by soft recovery of the samples, followed by sectioning, polishing, etching, and examination of the fracture damage. Such a technique examines the damaged region after many stress reverberations have occurred. We are interested in the early time (on the order of microseconds) history of the fracture. Postshot examination does, however, reveal the nature of the damage. The following picture of fracture has arisen.³ In the early stages, structural weak points (inclusions, grain boundaries, dislocation pile-up) nucleate into microcracks. In tension these microcracks grow. In the final stages the microcracks (holes) begin to coalesce, finally opening a macroscopic void or fracture. In some materials, which we shall call ductile, the microcracks form nearly spherical holes while in others (brittle), the cracks are penny-shaped.

Our model will be phenomenological in that we will characterize the appearance of microcracks by the degree of damage done to the material. We rely on an effective medium theory to describe a material infested with many small random cracks as an effective medium with properties lying somewhere in between those of a totally fractured and intact solid. Stanford Research Institute³ (SRI) has attempted a detailed model, depicting the distributions of cracks. To do this, independent dynamic variables had to be introduced along with certain equations of motion. The result is a very detailed picture of the fracture at the cost of a very complicated fracture model. The number of parameters needed is too large to be fixed by only the data pictured in Figs. 1 and 2. We attempt a simpler description with the goal of obtaining the dynamic stress history correctly only far from the fracturing region.

Let us now discuss those features of the velocity profile in Fig. 1 that are important in a spall model. As already mentioned, the relative height of the spall peak reflects the amount of damage or fracturing that has occurred. The shape of the peak

Fig. 2. Incipient spall vs flier plate velocity and thickness.

is determined by the rate that damage is done, while the position of the spall plane controls the timing of the second maximum. At the very center of a spall model, then lie the criterion for accumulation of damage, the phenomenological definition of damage and the constitutive model that incorporates damage into material properties.

A significant feature in Fig. 1 is the first minimum in the free surface velocity. Let the pullback velocity, U_{pb} , be defined as the difference between the first maximum and the first minimum. The pullback velocity measures the amount of tension that reached the free surface from the spall plane. The significance lies in the fact that the free surface velocity is not reduced to nearly zero, as a hydrodynamic calculation without fracture would predict. This implies that the material when fracturing does not undergo the amount of tension that it would in the absence of fracture. It turns out that for some materials (copper, aluminum) the pullback velocity depends only slightly (10%) upon flier thickness and velocity. In other words, it is nearly a material constant. Apart from this, the pullback velocity is expected to vary with temperature and material composition and structure. At this stage we report on a model with a nearly constant pullback velocity, even though other materials show variation of the pullback velocity. Modulation of the pullback velocity is a new feature that is currently under development.

Section II presents the physics of this spall model. A successful application of the model is presented in Section III. Finally, future developments are discussed in Section IV. The appendix contains those alterations of the equation-of-state routine required to implement the spall model.

II. DESCRIPTION OF MODEL

The purpose of this model, still under development, is to characterize the essential physics of spall in a one-dimensional Lagrangian hydrodynamics code (KO).⁴ We assume the cracks are small and numerous enough to justify the use of an effective medium theory. The model is intended to be simple, with as few new material parameters as possible. Some attempt is made to attach physical meanings to these phenomenological constants.

It is important to recognize that construction of a spall model supersedes any equation of state (EOS) at negative (tensile) pressures. In this region, the EOS is merely an extrapolation from positive pressures and it is not based on data. We first introduce a spall strength, PM , below which we alter the EOS. This negative or tensile pressure corresponds to the minimum pressure that the material will withstand and remain totally intact. If this were a material constant, the pullback velocity would also remain fixed, provided we ignore work-hardening effects. We are currently investigating how the spall strength might vary in a material. We distinguish between variations of the spall strength (pullback velocity) and variations of the incipient spall threshold.

If the material is further stretched beyond the strain corresponding to PM, it does not respond with increasing tension. We envision that at this point the microcracks, or holes, grow and account for any increase in volume. Indeed, the material begins to weaken. We now consider the material to be a composite – a host material with holes – in other words, porous. We differentiate between the pressure in the host material and the pressure across a gross cross section. The latter is reduced by the appearance of holes occupying some fraction of the area. In other words, we continuously approach the free surface boundary condition of a void by increasing the areal fraction occupied by holes. We assume that the host material remains at the pressure, PM, while the pressure across a gross cross-section begins decreasing. It is only this last pressure that is important in a hydrodynamic sense, because it is the pressure that moves matter.

Now, we must define damage: the quantity that characterizes the appearance of microcracks. We assert that it is the total volume of these holes which is important. Such an assertion can only be proven by actually testing a model founded upon it. However, it can be justified on the basis of percolation ideas. In this instance, percolation suggests the existence of a critical relative volume of holes at which volume the holes link up. The ultimate fracture is due to coalescence of these holes. This indicates, at least, that the ultimate fracture criterion should be based upon the total volume occupied by the cracks. In the case of normal fracture or spall, the damage should be the fracture volume, V_f , per unit area:

$$D = V_f / A, \quad (1)$$

where the damage, D , is a function of space and time. We identify the fracture volume as that volume due to expansion after the spall strength is reached. It is not an independent variable. Finally, damage is irreversible and unrecoverable.

Material properties are altered by the use of a strength function, FNG, which has the following properties:

When

$$D/D_0 = 0, \quad \text{FNG} = 1;$$

and as

$$D/D_0 \rightarrow 1, \quad \text{FNG} \rightarrow 0,$$

where D_0 is some critical level of damage. $\text{FNG} = 1$ corresponds to intact material, while $\text{FNG} = 0$ should represent complete fracture or a free surface boundary condition. The simplest form of FNG during damage accumulation is

$$\text{FNG} = 1 - D/D_0;$$

but some improvement in computer simulation of experimental data is achieved with

$$\text{FNG} = 1 - (D/D_0)^{2/3}. \quad (2)$$

This form can be justified in the following way. Let us limit ourselves to the case of spherical holes. The hole volume can be written as

$$V_f = N \frac{4}{3} \pi \bar{r}^3 \quad (3)$$

where $\bar{r}$ is the average size of the N holes. However, as far as material properties are concerned, it is the cross-sectional area that is important. And, hence, the two third's power arises above. FNG can be interpreted as reducing the effective area over which the pressure in the host material acts. This is consistent with the interpretation of both the spall strength and the damage. On the other hand, its use can be considered a purely phenomenological method of approaching a free surface boundary condition.

The strength function modifies material properties in the following way:

$$P = \text{FNG} * \text{PM} \quad (4a)$$

$$Y = \text{FNG} * Y_0 \quad (4b)$$

$$G = \text{FNG} * G_0 \quad (4c)$$

where P is the effective pressure, Y the yield strength, and G the shear modulus. The subscript zero refers to undamaged values. PM in Eq. (4a) reflects the fact that the host material remains at constant pressure – the spall strength. Work-hardening is turned off wherever $\text{FNG} \neq 1$.

The effect of Eq. (4) is to reduce the total normal stress by FNG . This situation is mechanically unstable; that is, expansion causes a reduction in strength which results in further expansion. We believe the instability to be real, although it has caused some numerical problems. The expansion can be halted by a subsequent stress wave.

The rest of the suggested path in pressure-volume space is illustrated in Fig. 3. In (A), the material follows its normal EOS until PM is reached. Damage is done along (B). Notice the large expansion that a mass zone may undergo. On subsequent recompression, the path is not reversible. We assume that the bulk modulus has been reduced by FNG along (C). In (D), the holes must be recrushed. (E) is the new adiabat, along which subsequent compression would occur. Spall and shocks are the only two mechanisms of changing adiabats in an isentropic hydrodynamics code. (F) is an alternate path for expansion, showing that the spall strength is reduced by the damage that has already been done. We must emphasize that some aspects of (C), (D), (E), (F) have not yet been confirmed by experiment. These parts represent our crude understanding of the physics of crushing a porous material from the point (1). No new parameters are introduced here. An example of the coding that accomplishes such a path is given in the appendix.

Let us summarize the model. We fracture by weakening material properties. Note that there is no need to open a logical void. There are only two substantive material constants: PM and D_0 . PM is the spall strength and D_0 , the critical damage

Fig. 3. Proposed pressure-volume history of a fracturing zone. See text.

for total fracture. The interpretation of the model assumes that fracture occurs by growth and coalescence of microcracks.

III. APPLICATION OF THE MODEL TO OFHC COPPER

This model has been applied to a series of free surface velocity measurements of symmetric-impact plate-slap experiments on copper performed by Banner.⁵ Figure 4 presents the result of measurement and computer simulation for a 3.2-mm flier plate striking a 9.5-mm target at a velocity near incipient spall level, 8.8×10^{-2} mm/ μ s. The dots represent the data; curve 1, a standard KO calculation without fracture; and curve 2, the KO calculation with this spall model. This model fits the spall peak rather well, with $PM = -1.1$ GPa and $D_0 = 0.063$ mm. A standard equation of state⁶ and work-hardening model⁷ for copper have been used, along with a new release model.¹ Variation of the spall strength changes the calculated value of the first velocity minimum. The pullback velocity depends directly on the spall strength. At fixed spall strength, the height of the spall peak varies inversely with D_0 . The shape agrees reasonably well with the form of FNG in Eq. (2). Thus, our model can reproduce an experiment, but now all the parameters are fixed!

Let us consider a set of experiments at fixed target and flier thicknesses, but with varying impact velocities. We have compared our calculation with data of Banner² in Fig. 5. Here, R , the ratio of spall peak amplitude to the initial peak, is plotted vs flier velocity. The curve represents an interpolation of the data and the points represent our calculations. Note that a value of near unity for R represents complete separation. $R = 0$ corresponds to no damage, and Banner associates $R = 0.50$ with an "incipient level." The fracture transition is rather sharp. The agreement is good, the calculation lying within the reproducibility of the data. Having fit one point near $R = 0.5$, no other adjustment is required to fit all these experiments!

Figure 6 presents a comparison of data and calculation for another target thickness near the incipient spall level. Here, the flier is 1.5 mm thick, while the target plate is 3.0 mm (corresponding also to a different target-to-flier ratio than reported above). The impact velocity is 1.12×10^{-1} mm/ μ s. The dots represent the data; curve 1 is a KO calculation without a fracture model, and curve 2 is a KO simulation with this spall model, using the same parameters as above. The agreement is not as spectacular. However, recalling how sharp the transition is in Fig. 5, we are not really far off. A small variation in flier velocity will influence the spall peak. We observe that the data even on the loading portion does not agree well with simulation, suggesting to us some experimental problems. Curve 3 in Fig. 6 is a KO computation of this experiment with the spall strength in the spall model altered to -1.2 GPa. Such a modification is within the variation measured in the experiments in Fig. 5, and we believe it is consistent with data taken at this flier thickness.² Now, agreement of the spall peaks is much better. This, plus other information, indicates to us that some

Fig. 4. Comparison of free surface velocity profile predictions and measurements.

Fig. 5. Ratio of spall peak amplitude to the initial peak vs flier velocity: comparison of data and predictions.

Fig. 6. Comparison of free surface velocity profiles at another flier thickness.

variation of the spall strength will be required. In copper this modulation is a small effect. In some brittle materials the effect is much larger.⁸

We wish to report a surprising result. The value of D_0 that we use by phenomenologically fitting the data for copper corresponds roughly to the size of the spherical holes observed in copper near the point where they will coalesce. D_0 represents the critical damage for complete fracture. The agreement with microscopic data was unexpected. If it can be generalized to other materials, the observation becomes important. If a thorough analysis of the microscopic interpretation of this model can be made, the value of D_0 may lend support to our interpretation and credence to the results of the computer model.

IV. FUTURE DEVELOPMENT

We regard the application in Section III as reasonably successful, justifying further development of the model. These developments and problem areas are pointed out here. As indicated, there is evidence for modulation of the spall strength. The spall strength corresponds to the point at which the host material no longer expands and all subsequent expansion results in growth of microcracks. Such a view is too simplified. Clearly, the holes must be numerous and large enough to account for large expansion. In the SRI model, nucleation and some growth must have occurred; therefore the value of PM depends on stress history. One way to include this effect is to alter the spall strength phenomenologically. At this point, there is no unique prescription. Our first attempt will be

$$PM = A + B * \max(\dot{V}/V),$$

where $\dot{V}/V$ is the local strain rate.

There are other questions about PM. Is the pressure always the correct criterion, or is total stress better? Only by studying many materials will we answer this question, but pressure is probably correct for ductile materials. We believe it probably makes little difference. Another problem is temperature dependence. PM certainly becomes small if the material is melted. We suggest a temperature dependence of the spall strength to be either

$$PM(T) = PM_0 (1 - T/T_m)$$

or

$$PM(E) = PM_0 (1 - E/E_m),$$

(with $PM \leq 0$ always), where T_m and E_m are the melt temperature and energy. These are the simplest possible forms.

In this model nearly all the damage is concentrated in a single mass zone. Examination of samples has shown that the damaged region can have an appreciable width. It is perhaps too much to ask this simple model to predict the spatial distribution

of the damage. It is conceivable that the addition of a modulated spall strength will affect this problem. On the other hand, the spatial distribution of damage is not observable by an active gauge. Any in-situ gauge will be torn apart by the fracture. Only signals far from the spalling region can be observed in a time-resolved manner. In addition, the thickness of the damaged region may be a multi-dimensional effect, influenced by interactions among the microcracks. We have no hope, of course, to simulate multi-dimensional effects with a one-dimensional hydro-code.

We have concluded by admitting the model's faults, but we must again emphasize its overall success. To our knowledge, no other spall model, no matter how complicated, has been as successful in matching dynamic records. The parameters in the model are ideal for affecting the significant portions of dynamic calculations. The evidence in copper suggests that these parameters are nearly material constants. And finally, each constant has a meaningful physical interpretation.

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APPENDIX

The following coding is inserted into a routine which calculates the equation of state. Its effect is to override the EOS under certain circumstances. These definitions have been made:

E	- energy
P	- pressure
TA	- bulk modulus
V	- relative volume
DV	- change in volume
J	- zonal index
K	- regional index
SD	- D/D_0
FNG	- fracture fraction (= FF)
PM	- spall strength
PZ	- crush pressure (= PM)
ESD	- maximum strain rate
CVDAMR	= 2/3

EXAMPLE OF SPALL MODEL CODING

```

51 8382 E(J)-TE-E(J)-(P(J)+.5*(QQ(J)+Q(J)))*DV(J)+E12(J)
52 C
53 C SPALL DAMAGE AND RELOAD MODEL : NTYDAM=4
54 C
55 IF(NTYDAM.NE. 4) GO TO NORM
56 TP= P(J) - FF*TA*DV(J)
57 IF(FNG(J).EQ.1.) ESD(J)=AMAX1(ESD(J),SID(J))
58 PSPALL = PMR(K) + CZDAMR(K)*ESD(J)
59 IF(TP.LT. ((1.-SD(J))*CVDAMR(K))*PSPALL) GO TO DAM
60 IF(FF.EQ. 1.) GO TO NORM
61 DDV = (1.-FF)/(V(J)-DV(J)-TV1)
62 IF(FF*TA.LT. DDV*(-PZDAMR(K))) GO TO LOAD
63 IF(TP.LT. -FF*PZDAMR(K)) GO TO LOAD
64 CRSH CONTINUE
65 FNG(J) = FF - DV(J)*DDV
66 IF(FNG(J).GT. 1.) FNG(J)=1.
67 TP = -FNG(J)*PZDAMR(K)
68 LOAD TP1 = 0.
69 TP1 = ((TU*TA*TB)/TCC + TD*TE)
70 IF(TP1.GT. TP) FNG(J) = 1.
71 IF(FNG(J).EQ. 1.) GO TO NORM
72 P(J) = TP
73 E(J) = TE - .5*(P(J)-TEMP)*DV(J)
74 GO TO OUT
75 DAM CONTINUE
76 IF(DV(J).LT. 0.) GO TO NOD
77 TXJ2 = ABSF(X(J) + X(J-1))/2.
78 SD(J) = SD(J) + CIDAMR(K)*DV(J)*W(J)/(RZ(J)*TXJ2*(HDD))
79 IF(SD(J).GT. 1.) SD(J) = 1.
80 FNG(J) = 1. - SD(J)*CVDAMR(K)
81 NOD CONTINUE
82 TP = FNG(J)*PSPALL
83 P(J) = TP
84 E(J) = TE - .5*(P(J)-TEMP)*DV(J)
85 GO TO OUT
86 NORM CONTINUE
87 TP = ((TU * TA * TB) / TCC + TD * TE )
88 P(J) = TP
89 358 E(J)-E(J)-(P(J)-TEMP)*.5*DV(J)
90 IF(E(J)-EMCUT(NES)).388.388
91 E(J)=0.
92 388 TE=E(J)
93 TP = (( TU * TA * TB ) / TCC + TD * TE )
94 P(J) = TP
95 OUT CONTINUE
96 IF ( ABSF(P(J)) - PCUT ) .398.398

```

CRUSH

RELOAD

DAMAGE

NORMAL EOS

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