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Modeling Incipient Spallation in Commercially Pure Tantalum

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We model commercially pure tantalum incipient spallation data from normal plate impact gas gun experiments. VISAR traces of the free surface velocity, porosity profiles from recovered samples, and void density profiles from three shots at 200, 220, and 254 m/s impact velocity are included. The three quantities measured are compared with versions calculated in the 1D hydrocode, FIDO. The damage modeling includes a stress based nucleation model, an early time cavitation wave void growth model, and a late time macroscopic porosity growth model. The fitting is reasonably successful. Possible improvements are discussed.

1. INTRODUCTION

Recent gas gun experiments done on tantalum [1–2] studies have stimulated further gas gun work emphasizing damage morphology of recovered specimens. [3] These results are an opportunity for micromechanical spallation modeling, that requires such information. Some preliminary work of this sort using a macroscopic porosity growth model appears in [4] and in [5]. Here, we extend this modeling to include, in addition, a stress based nucleation model and a cavitation wave void growth model. The modeling is applied to data from three gas gun experiments done on commercially pure tantalum at impact velocities of about 200, 220, and 254 m/s. Incipient spallation, i.e. incomplete spallation, occurred in all three cases. Using a single parameter set, the modeling successfully tracks the changes due to impact pressure.

Further information about the experiments is available in Ref[6].

2. EOS AND PLASTICITY MODEL

The pressure - volume equation of state is modeled using a conventional Mie-Grueneisen equation of state based on the following Hugoniot equation [7] relating U_s , the shock velocity and U_p , the particle velocity:

$$U_s = (0.3293 \text{ cm}/\mu\text{s}) + 1.703 U_p. \quad (1)$$

The shear modulus value used is 0.690 Mbar [8].

The deviatoric matrix plasticity model, used for both forward and backward plasticity, which was not degraded by damage, was the following:

$\dot{\psi} = \dot{\psi}_o (\tau - \tau_{y,i})^2$ where $\dot{\psi}$ is the effective plastic strain rate, τ is the von Mises effective deviatoric stress, and $\tau_{y,i}$ is the yield stress, $i=f$ and $i=b$ indicating the forward and backward yield stress, respectively. Values used for $\tau_{y,f}$ and $\tau_{y,b}$ were 0.9 and 0.2 Gpa, respectively. Steinberg [9] also found different forward and backward yield strengths useful in modeling the shock release behavior of tantalum.

The linear version of Johnson's back stress model [9–11] was used to provide the smooth release, or Bauschinger effect, of the top region of the release portion of the shock wave. Without this model, the calculated release becomes a steep drop that departs greatly from the data. The formula for the evolution of β , the backstress, is the following:

$$\dot{\beta} = (2/3)k_7 k_8 (\tau - \beta), \quad (2)$$

where values used for k_7 and k_8 are 7×10^{-6} and 0.5×10^6 , respectively. τ retains its sign. The units of β are Mbar. The formula for the plastic strain rate generated by β is: $\dot{\psi}_{back} = (8gk_8 / k_6^2)(\tau - \beta)$, where the value used for k_6 is 800 and g is the shear modulus.

3. VOID NUCLEATION MODEL

In the stress based void nucleation model, it is assumed that a void nucleates instantly when its (negative) nucleation pressure is reached. The model is parameterized by a density, $n(p)$ that is a function of the threshold nucleation pressure magnitude, p .

Hence the total void density, ρ , nucleated by $|P|$, the maximum magnitude of negative pressure, is

$$\rho(|P|) = \gamma(|P| - P_o) = \int_{P_o}^{|P|} n(|P|) d|P|, \quad (3)$$

where P_o is the nucleation threshold. The middle expression gives the actual form used for ρ which is linear in the pressure with the proportionality constant, γ . This implies that n is a Heaviside function beginning at P_o . This form was suggested by comparing the measured final void density with the maximum negative pressure attained in some preliminary 1-D code calculations.

4. CAVITATION WAVE MODEL FOR EARLY VOID GROWTH

If void nucleation happens suddenly at great negative pressure, as in tantalum, it seems reasonable that some sort of wave expansion process should govern early void growth, instead of a model assuming stress equilibrium and an incompressible matrix. A model for such a process can be obtained from earlier modeling by Hunter and Crozier[12] on warhead penetration in which a pressurized spherical hole expands in a ductile matrix. The boundary value problem there was changed by us to be a negative pressure at infinity instead of a pressure in the hole. It was found that the resulting solution changed very little from Hunter and Crozier's solution [12]. The solution is a similarity or asymptotic solution in which the void expansion velocity is constant.

Fig. 1 shows a schematic of this process in which a spherical cavity expands inside a plastic wave front, which expands inside an elastic wave front. The expansion velocity of the cavity depends on the magnitude of remote negative pressure. When the pressure magnitude is small compared to the bulk modulus, which is certainly the case for spallation

Figure 1. Cavitation wave void expansion process

tensions in tantalum, the equation for void expansion velocity assumes the following simple form:

$$P = P_c + \alpha V^2, \quad (4)$$

where P_c is the static cavitation pressure and α is a constant whose value is very close to the mass density. P_c is given by

$$P_c = (2/3)y\{1 + \ln[(2/3)g(1+\nu)/(1-\nu)y]\}, \quad (5)$$

where y is the yield stress, g is the shear modulus, and ν is Poisson's ratio.

Since voids are spawned at different times, a statistical treatment is necessary to relate the void population to the macroscopic porosity. This treatment relies on the total void number and an average void radius, r_{ave} . The total porosity, ϕ , is given by:

$$\phi = (4/3)\pi\rho(r_{ave})^3. \quad (6)$$

It is possible to average the product $n(|P|)$ r_{ave} , instead of averaging the factors, as was done above, but this leads to more state variables to be carried in the calculation. The simpler form (6) above appears to be adequate.

The average radius is given

$$\text{by: } r_{ave} = \left\{ r_o \rho + \int_{P_o}^{|P|} [t - t(|P|)] V(|P|) n(|P|) d|P| \right\} / \rho$$

(7) where r_o is a nucleation radius, t is the current

time, $t\{IPI\}$ is the time of nucleation, and $V(IPI)$ is the void surface velocity given by Eq. (4). This equation describes the average radius of an ensemble of expanding spherical voids. A void is taken to keep its nucleation velocity. In the modeling, this is true because the growth is a wave expansion process that will continue until the waves meet a boundary. Hence, as the voids are nucleated, r_0 grows and more and more voids contribute their expanding spheres to the integral in Eq. (7) above.

At some point, the waves will reach some boundary and, then, the behavior must change. At this point, we transition to a more conventional porosity growth model based on a spherical cell, stress equilibrium, and an incompressible matrix. This is the same model used earlier [4-5], but with an initial seed porosity, instead of void nucleation. The transition point will be taken to be when a factor, β , times the average void nearest neighbor distance in a computational cell becomes equal to the elastic wave speed times the time since the beginning of void nucleation. Schematically, this can be written as follows:

$$\langle \text{ave nn void distance} \rangle \beta = c_{\text{plastic wave}} (t - t_{\text{start}}) \quad (8)$$

The cavitation wave void growth mechanism should be an early time mechanism that produces only a small amount of porosity before the transition. This transition law accomplishes this criteria.

5. MACROSCOPIC POROSITY GROWTH LAW

The formula for late time porosity growth, used in earlier work, is the following:

$$\dot{\phi} = 15 \dot{\epsilon}_0 \phi (1 - \phi) \left[\left(-\frac{3}{2} P + y \ln \phi \right) / \left[\sigma_0 n (1 - \phi)^{1/n} \right] \right]^n \quad (9)$$

where the material parameters ϵ_0 , σ_0 , n , and y describe the strain rate plasticity of the matrix around the expanding void through the power law:

$$\dot{\epsilon} = \dot{\epsilon}_0 [(\tau - y) / \sigma_0]^n \quad (10)$$

Here, τ is the effective deviatoric stress, and $d\epsilon/dt$ is the plastic strain rate. The parameter values used

in this equation differ from those of the matrix plastic constitutive law because the region surrounding the void is hot and expanding at a much higher strain rate than the matrix background.

In earlier work, [4-5], the above formula was used with a seed porosity. With this usage, the term $y \ln \phi$ above constitutes a pressure barrier to void growth which can mock up a void nucleation stress. The disadvantage to this modeling is that the y value so used helps determine subsequent void growth, i. e. y is used both for void nucleation and void growth. The nucleation model described above removes this problem, i.e. the y parameter in Eq. (9) above only describes void growth: the modeling is more flexible.

A simple inertia model was used in conjunction with the porosity growth law. It involves calculating void growth at the beginning of each time step with this plasticity model and with a model involving inertia only plus a rigid plastic yield stress. The slower of the two growth rates is taken. This "switching model" is described in Ref[13]. In these calculations, the inertia law dominated only a small fraction of the time, about 6%. Hence, the calculated void growth is mostly plastic.

6. RESULTS

A discussion of the fitting parameter values used and zoning and time step values will first be given, followed by a presentation of calculated and experimental data.

The fitted parameter values used in the void nucleation model and cavitation wave model are given in Table 1.

Table 1

Void Nucleation and Cavitation Growth Parameters

Parameter	Meaning	Value
P_c	Cavitation pressure	-4 GPa
P_0	Nucleation threshold pressure	-4 GPa
r_0	Void nucleation radius	1 μm
α	Void velocity coefficient	16 g/cm^3

$C_{\text{plas wave}}$	Release wave velocity	0.34 cm/ μ s
γ	Factor in void number density	2×10^8 /Gpa*cm ³
β	Factor in cavitation wave transition criteria.	2

The values of P_c and P_o were set to be the same for lack of information. The value was important in fitting the spall dip in the data. It is interesting that the value -4Gpa is close to the calculated static cavitation pressure. The r_o value is a guess. $C_{\text{plas wave}}$ is calculated from the theory of Hunt and Crozier[12]. The value for β is a reasonable guess. The fitting results are sensitive only to the value of $P_c = P_o$, which serves to set the depth of the "spall dip" just after the main pressure plateau. The value of r_o is not critical because subsequent model growth of r_{ave} is additive to r_o .

It is worthwhile mentioning that the transition from the cavitation wave to the macroscopic void growth mechanism occurred at a porosity of, roughly, 4×10^{-4} , which is consistent with the cavitation mechanism being an early, small porosity mechanism.

The parameter values, based on the strain rate plasticity surrounding the growing voids, used in the macroscopic porosity growth law are given in Table 2

Table 2
Porosity Growth Parameter Values

Parameter	Meaning	Value
γ	Flow stress	0.33 GPa
σ_o	Scales stress	0.4 GPa
ϵ_o	Scales strain rate	1/ μ s
n	Exponent	1

The value of 0.33 Gpa for γ is lower than that seen in Hopkinson bar experiments at room temperature, but is not unreasonable for the high temperatures expected around a growing void.

Figure 2. Free surface particle velocity, shot 254 m/s

The 1D zones for the 200m/s and 220m/s shot calculations were 0.0017 cm wide, which provided for about 120 and 260 zones in the flyer and sample, respectively. The time step used was 0.001 usec.

Figure 3. Final porosity, shot 254 m/s

The zones for the 254 m/s shot were 0.00084 cm wide, with about 250 and 500 zones in the flyer and sample, respectively. There was little change in the results when the number of zones was halved for the 254 m/s shot.

The calculated and measured free surface particle velocities for the gas gun shot at 254 m/s impact velocity are shown in Fig. 2. The agreement is satisfactory. The agreement can be made very good, in fact, by adjusting the parameter fitting values away from the common set used for all three experiments. Since, no experimental absolute timing measurements were done, the curves have been shifted in time for best overlap.

The calculated and measured final porosity profiles are seen in Fig. 3. They have been shifted in space for best overlap. The agreement is also reasonable. It turns out that the final calculated porosity is very sensitive to the modeling, so agreement of this sort is quite good.

The calculated and measured final void number densities are shown in Fig. 4. The overall height was matched by adjusting γ . The calculation is somewhat broader than the data, but the data could be

Figure 4. Final void number density.

truncated.

The calculated and measured free surface particle velocities for the shot at 220 m/s is shown in Fig. 5. The fit is reasonable. The calculated and measured

Figure 5. Free surface particle velocity, Shot 220 m/s

final porosities are shown in Fig 6. The agreement is fair. No analysis for final void number density is yet available for the 220m/s and 200m/s shots. The peak calculated number density was about 170,000/cc.

The calculated and measured free surface particle velocities for the shot at 200 m/s is shown in Fig. 7. The fit is reasonable. The calculated and measured final porosities are shown in Fig. 8. The agreement is good. The peak calculated final void number density is about 100,000/cc.

The calculated porosities all involve growth during subsequent pressure rings, after the first, main negative pressure excursion. This late porosity growth amounts to, usually, about 20% of the final porosity, and, so, is not major porosity, and, so, is not very significant. However, if it is absent in reality, the final calculated porosities would fit the data better. The modeling allowed void contraction under positive pressure, so some of the late void growth was reversed from this cause.

The strength of the Hugoniot elastic limit is not modeled especially well for the shot at 254 m/s impact velocity. The data show a greater HEL strength for this shot than the others. This could be due to texturing effects, as pointed out by Furnish et

Figure 6. Final porosity for shot 220 m/s

al [2](aps shock 1995), which are common in tantalum.

The shape of the main release or pullback, after the main shock peak, is modeled fairly well. As, remarked earlier, a Baushinger effect model or reverse plasticity model is necessary to accomplish

this.

Figure 7. Free surface particle velocity, shot 200 m/s.

7. CONCLUSIONS

The three data sets are fitted reasonably well with a single damage model parameter set. The general trend in incipient damage at lower and lower impact velocities is captured. It is found that modeling both final damage (porosities and void number densities) and VISAR traces constrains modeling much more than modeling only the VISAR trace. The void nucleation model and early cavitation void growth model work smoothly and allow the modeler to separate the nucleation modeling from the late void growth modeling. During the fitting process, this part of the model needed much less change than the macroscopic, late time void growth model.

The above is encouraging, but certain problems remain. One is the late time ringing behavior, which is captured somewhat here, but not really modeled well. In the case of the 254m/s shot, void interaction and coalescence modeling will surely be needed as a remedy, such behavior is seen in the micrographs of recovered samples.[4].

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Figure 8. Final porosity, shot 200 m/s

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