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Author(s):
D. L. Tonks
W. R. Thissell
C. P.Trujillo
D. S. Schwartz

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COPPER DAMAGE MODELING WITH THE TENSILE HOPKINSON BAR AND GAS GUN

***D. L. Tonks, **W. R. Thissell, +C. Trujillo, ++D. S. Schwartz**

Los Alamos National Laboratory, Los Alamos, NM 87545, *X-7, tonks@lanl.gov; **thissell@cybermesa.com; +MST-8,cptrujillo@lanl.gov; ++NMT-16,dschwartz@lanl.gov

ABSTRACT Ductile damage nucleation in recovered copper tensile Hopkinson bar specimens has been modeled using the 2D EPIC code. The model has also been successfully applied to spallation gas gun data to greatly expand the pressure range.

INTRODUCTION: The split tensile Hopkinson pressure bar permits the creation of damage at fairly high strain rates (10^4/s) with large plastic strains (100%). Careful momentum trapping allows incipient damage states to be arrested and recovered for metallurgical examination. The use of notched samples allows the pressure – flow stress, or triaxiality, to be varied from 1/3 to about 1.2 to study the interplay of pressure and deviatoric stress. In this paper, we will concentrate on modeling the nucleation of ductile damage in pure copper (Hitachi). With the same material, we also study spallation in a gas gun experiment to obtain the nucleation stress under high pressure and small plastic strain. The goal of the modeling is to obtain a unified nucleation model suitable for both.

PROCEDURES, RESULTS, AND DISCUSSION: The ductile damage modeling involves a void nucleation component and a growth component. A preliminary account appears in Ref. 2. In spallation conditions, where the negative pressures are large, void nucleation is determined mostly by stress rather than strain. On the other hand, in some low pressure conditions, like the tensile test, strains are large and dominate nucleation. The nucleation modeling assumes stress based, heterogenous instantaneous nucleation around inclusions with a distribution of nucleation tensile pressure or "strengths, "σ_I. The local pressure at an inclusion, σ_L, taken positive in tension, must exceed σ_I to open up a void. Earlier work has shown that a combination of ambient pressure and strain produces the local stress, σ_L (1). The plastic strain produces a local pressure due to dislocation build-up around a void to which the ambient pressure adds or subtracts to produce the total local tension. We model these two contributions

$$\sigma_L = P + k\sqrt{\psi}\,, \qquad (1)$$

where P is the ambient pressure taken positive in tension and k is the coefficient giving the contribution from the plastic strain ψ. We model the distribution of local strengths by using, $\sigma_{I,threshold}$, the local stress at which nucleation starts, and γ_2 , the "nucleation rate versus stress", so that the void number density produced by a negative local pressure of magnitude σ_L is $\gamma(\sigma_L - \sigma_{I,threshold})$, if $\sigma_{I,threshold} < \sigma_{L1}$. The macroscopic porosity growth

law used [Tonks et al, 1995] is a stress potential whose contour of zero porosity growth is the Gurson surface.

The tensile bar shots Cu11 and Cu15 afford an opportunity to study void nucleation almost independently of void growth since their final porosities are small, 0.0001 and 0.06, respectively. First of all, the gas gun modeling produced a minimum nucleation strength, $\sigma_{I,threshold}$, of 1.425 GPa and "nucleation rate", γ_2, of 0.015/Pa cm^3. Plastic strain was small (0.007) and played a negligible role. In the tensile bar modeling, the nucleation threshold condition was studied by choosing calculated points that correspond to the edge of the damage region in the recovered samples. The calculated values of plastic strain and negative pressure were assembled for these points and used to verify Eq. (1) and to determine the value of k. The gas gun value for $\sigma_{I,threshold}$ was used for σ_L. The nucleation events themselves were too small to be observed in the optical microscope. Fig. 1 shows the field points (the symbols "B") from the calculations for Cu11 that were used and the calculated maximal plastic strain field, together with the experimental porosity map. "Maximal" means those values of P and ψ that simultaneously maximized σ_L in Eq. 1. Fig 2 is a plot of the threshold calculated pressure and plastic strains at the field points for shots Cu11, Cu 12, and Cu15. Cu12 represents a lower bound for damage since it. showed no recovered damage. Also, Eq. 1 is shown plotted in Fig. 2 with σ_L set equal to the 1.425 GPa gas gun value for $\sigma_{I,threshold}$. and with k set to 1.7 GPa. The fit validates the analytical form of Eq. (1) and determines a reasonable value for k, which sets the contribution of plastic strain to nucleation. The value 0.021/cm^3 Pa for the "stress nucleation rate", γ_2, was obtained by dividing a typical experimental void number density for Cu15 by a maximum calculated value for σ_L for Cu15 minus the gas gun value for $\sigma_{I,threshold}$. See Eq(1). The calculations were further validated using the final measured porosity and void number profile for Cu15. Cu11 has too few voids for a void number density. In conclusion, the void nucleation model has been successful with both tensile Hopkinson bar and gas gun data.

An important part of the modeling was to fit the observed final notch contour. This depended almost completely on the matrix plasticity model because of the small final porosities. The MTS model was used with a fit to compression Hopkinson bar data of the same copper. The fit (not shown) to the final Cu15 (E notch) contour was satisfactory and the fit for Cu11 appears in Fig 1. Cu11 involved a smooth specimen so in its calculation the MTS model had the burden of producing the correct necking instability. With this in mind, the contour fit for Cu11, although worse than that for Cu15, is satisfactory.

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REFERENCES:

Goods, S.H. and Brown, L.M., 1979, "The Nucleation of Cavities by Plastic Deformation," Acta Met. **27**, 1

Tonks, D.L., Zurek, A.K. and Thissell, W.R., 2001, "Modeling Incipient Spallation in Commercially Pure Tantalum". in Fundamental Issues and Applications of Shock-Wave and High-Strain-Rate Phenomena, *EXPLOMET 2000*, K.P. Staudhammer et al (ed), pp. 517-512, Elsevier Science Ltd., Amsterdam.

Tonks, D. L., Zurek, A. K., and Thissell, W. R., 1995, "Ductile Damage Modeling Based on Void Coalsecence and Percolation Theories", in Metallurgical and Materials Applications of Shock-Wave High-Strain-Rate Phenomena, L. E. Murr et al (ed), pp. 171-178, Elsevier Science BV, Amsterdam.

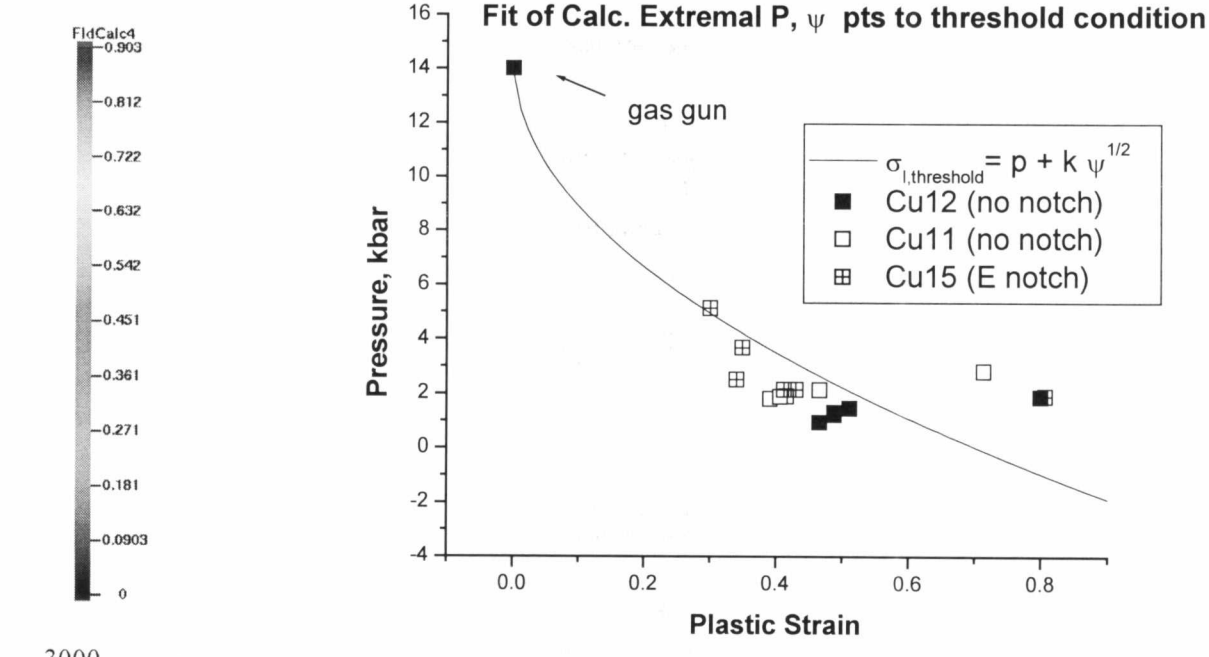

Fig. 2. Fit of Eq. (1) to calculated threshold pressure and plastic strain values selected from edge of damage field.

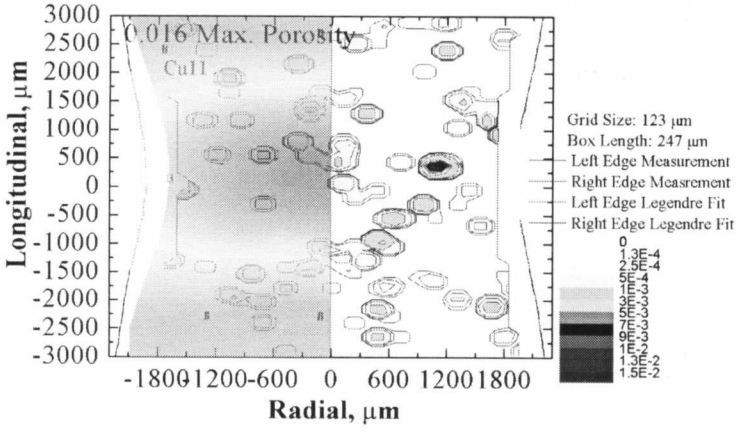

Fig. 1. Calculated maximal plastic strain for Cu11, with the measured porosity field.