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Author(s): W. Rich Thissell, MST-8
Anna Zurek, MST-8
Duncan Macdougall, MST-8
Davis Tonks, X-7
Frank Addessio, T-3

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LINKING DAMAGE MODELS TO QUANTIFIED EXPERIMENTAL MESO-SCOPIC DAMAGE MEASUREMENTS

W. Rich Thissell[*], Anna K. Zurek[*], Duncan A. S. Macdougall[*], Davis L. Tonks[**], and Frank Addessio[***]

[*] *Structure-Property Relations, MS: G755,* [**] *Constitutive Modeling, MS: B216,* [**]*Fluid Mechanics, MS: P952, Los Alamos National Laboratory, Los Alamos NM 87545*
thissell@lanl.gov

ABSTRACT: This paper describes the techniques that we employ and are developing in capturing, measuring, and describing the evolution of dynamic damage accumulation in metals, from the first nucleation event up to final failure surface formation. These measurements are used in damage model development, verification, and validation. Ta and Cu quantification examples are given.

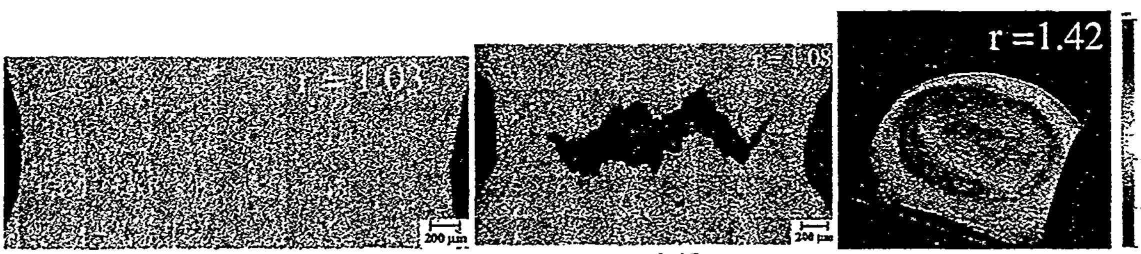
INTRODUCTION: Predicting and understanding ductile failure is perhaps the most vexing problem in structural materials today. Many difficulties combine to make this a complex problem, both computationally and experimentally. The microstructural phenomena involved in ductile failure resistance include the nucleation, growth, and coalescence of voids and/or micro-cracks. The size and spatial proximity of these features are intrinsically meso-scopic in length scale, *i.e.*, ranging from µm to cm. Damage nucleation is intrinsically statistical in nature and highly dependent upon microstructure and material cleanliness. Growth is deterministic, but also complicated by a dependence on the ratio of hydrostatic to deviatoric stress, strain-rate, and inertia. Coalescence is also rather deterministic, but it also shares a dependence on the spatial proximity of features that are remnants of the statistical nucleation step. The volume averaged flow stress decreases precipitously during ductile damage accumulation, thus capturing intermediate states of damage is difficult or practically impossible in traditional load frames because of elastic unloading of the frame. Furthermore, identifying, measuring and describing microstructural damage features is not straightforward and time-consuming.

A characteristic all dynamic damage models share is their need to be calibrated and validated with experimental measurements of incipient fracture tests. Measurements such as position-time and force-time, the most readily available, are necessary but insufficient for determining a unique set of model parameters. All the above mentioned damage models contain one or more internal state variables such as porosity, void size or size distribution, and number density that may evolve during a loading excursion. Proper model calibration and validation requires measurements of all of the model's internal state variables. Extrapolation to strain rates, stress-states, and accumulated strain outside of the calibration condition often cause large deviations between model predictions and experimental measurements.

MECHANICAL TEST METHODS: We perform incipient failure tests using both a gas gun and a tensile Hopkinson split pressure bar (THSPB) to probe a wide range of strain rates and stress states. An 80-mm gas gun, equipped with soft recovery, performs momentum trapped flyer plate impact experiments and probes $\dot{\varepsilon} \approx 10^5$ and $-P/2\tau \geq 7$, where P is the hydrostatic pressure and τ is the flow stress. A VISAR provides free surface velocity measurements. Typical impact velocity precision is > 99%. The pulse duration can be controlled from 0.4-4 µs. The THSPB also uses momentum trapping, and combined with cylindrical uniaxial stress and notched specimens, probes $10^2 \leq \dot{\varepsilon} \leq 10^4$ and $1/6 \leq -P/2\tau \leq 1.5$, with a pulse duration variable from 20-400 µs. The striker impact velocity precision is > 99.5 %. Three strain gage signals (incident, reflected, and transmitted stress waves in the bars) and high-speed photographs of the evolving waist are recorded. The recovered minimum and maximum waist diameter are also recorded; the ratio of which is a measure of the expression of the evolved texture in the sample, as shown in Figure 1.

INCIPIENT DAMAGE MEASUREMENTS: The recovered specimens are sectioned in a plane parallel to the principal strain direction, polished, and lightly etched. Image analysis of the entire damaged area combined with optical profilometry provides volumetric measurements of all the features that intersect the section plane. This reduces the necessary size of the sampled region to be statistically representative of the bulk compared to just image analysis alone of a section plane. The three-dimensional sampling also provides information on coalescence phenomena such as clustering and plastic instability development between voids.

The flyer plate experiments are one-dimensional, so averaging in bins oriented normal to the principal stress direction is relatively straightforward. The THSPB tests are inherently two-dimensional, with distributions in stress-state and total accumulated deviatoric strain in both the radial and longitudinal directions. Statistical damage data reduction is thus intrinsically more difficult in the THSPB test than in the flyer plate test. Typical measurements made on voids or other features include centroid location, major, minor, and average diameter, angle between the major diameter and the vertical image axis, depth, roundness, and aspect ratio. The raw two-dimensional image analysis data is used to calculate porosity spatial distributions along contours of an approximately equivalent relevant parameter. This parameter may be distance along the principal strain direction in the flyer plate experiment, which maps to a particular time duration at the hydrostatic tensile stress plateau. For the THSPB test, the relevant parameter is the total accumulated deviatoric strain and/or the ratio of mean to deviatoric stress.



$\varepsilon_{eng} = 0.38$ (a) $\varepsilon_{eng} = 0.45$ (b) $\varepsilon_{eng} = 0.57$ (c)

Figure 1: The relationship between tensile plasticity, texture evolution, and damage accumulation in a half-hard 10100 Cu plate, tested at a strain rate of about 3000 1/s, using the Hancock-Mackensize "E" notch geometry (Hancock and Mackenzie [1976]). The evolved aspect ratio of the neck, r, is an indication of the texture evolution in the material.

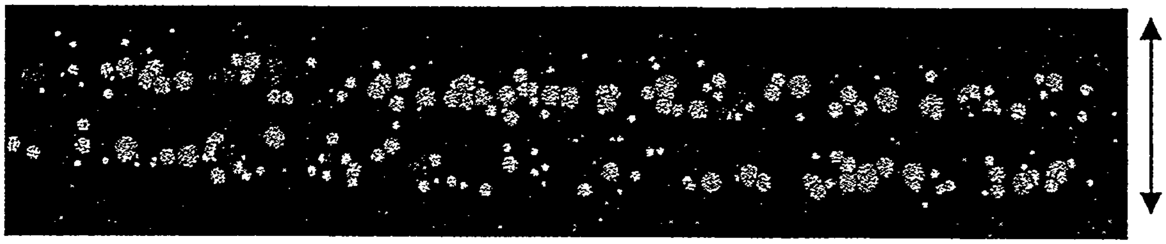


Figure 2: ACIS model of two sections of a symmetric flyer plate impact of Ta. The camera is about 20° above the section plane, with the projection of the principal strain direction shown by the arrow. The spacing of the section planes is arbitrarily assigned to be 1 mm. Green represents isolated voids, blue clustered voids, and red represent linking ranges.

STATISTICAL REDUCTION: The raw feature information is analyzed to determine cluster membership, defined as when the ratio of the minimum edge to edge distance is less then one tenth the smaller feature diameter. Identification of plastic instabilities yields linking range membership. A three-dimensional solid model of the data can also be visualized, as shown in Figure 2 for two section planes in a Ta flyer plate experiment. Statistical reduction of the data involves sorting from smallest to largest and fitting to appropriate cumulative distribution functions. These functions are corrected to transform the observations that are distorted by the sectional sampling method to favor large features at the expense of small ones, to volumetric approximations. The volumetric distribution functions are used to determine a mean volumetric size value, which is then used to determine the mean sampling depth that is used to determine volumetric size distributions and number densities.

COMPARISON WITH MODEL PREDICTIONS: A rigorous test of a model's predictive accuracy is to compare both its internal state variable predictions and overall mechanical behavior with experimental measurements distinct from the calibration conditions. We applied this technique to a void growth model, applied to flyer plate experiments in Ta, and found that the standard error of the porosity distribution prediction from the experimental measurement increased from 0.81 to 3.7 as the impact velocity decreased 20 % from the calibration condition (Thissell et al. [1999]).

CONCLUSIONS: Much more work needs to be performed before damage models become accurate predictor's of dynamic failure resistance. Unique model parameter determination requires experimental microstructural measurements of incipient failure experiments, of all of a model's internal state variables as well as external manifestations of model mechanical behavior such as free surface velocity and/or transmitted and reflected stress wave profiles.

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