QUANTIFICATION OF DAMAGE EVOLUTION FOR A MICROMECHANICAL MODEL OF DUCTILE FRACTURE IN SPALLATION OF COPPER

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Quantification of Damage Evolution for a Micromechanical Model of Ductile Fracture in Spallation of Copper


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Abstract: Detailed quantitative measurements of damage evolution in an incipiently spalled and recovered 10100 OFHC copper sample of 30 μm grain size are described. The free surface velocity is shown. The total porosity of the sample as a function of distance from the spall plane is reported. The observed and true volumetric size distribution of voids and the observed size distribution of clusters of voids are also calculated and presented.

Key words: Ductile Fracture, Spallation, Damage Evolution, Image Analysis, Optical Profilometry, Micromechanical Modeling

1. Introduction

Ductile fracture is and has been a critical issue in fracture mechanics for many years. A quantitative analytical descriptive theory of ductile spallation fracture has yet to be developed due to the mathematical complexity and material dependency of the process. A wide quantitative void exists in the presently employed methodology for the study of dynamic ductile fracture. A fine level of microstructural detail is built into numerical micromechanical models of the kinetics of this process, but the overall experimentally quantifiable parameters are macroscopic, such as impact velocity, shock pressure, and spalled surface velocity. Sample recovery techniques permit post-test microscopy which currently allow for a qualitative validation of the types of micromechanical processes that the model should emulate. The objective of this research is to develop and apply experimental techniques to determine quantitative microstructural descriptors of the ductile fracture process to bridge this quantitative void. The quantitative descriptors will further the development of a micromechanical model of ductile fracture. Micromechanical models of ductile fracture predict damage evolution and failure strengths and energies of materials through modeling plasticity, nucleation, growth, and coalescence of voids (Johnson and Addessio (December 15, 1988), Tonks (1994), Tonks (1995), Tonks (1995), Tonks (1996), Tonks, et al. (1995)).

This paper presents detailed quantification of several micromechanical features that comprise ductile spallation: the void size distribution, aspect ratio distribution and cluster size distribution. The porosity as a function of distance from the spall plane is also presented.

2. Experimental Methodology

2.1. Shock Test

10100 OFHC copper was annealed at 600 °C for 1 hour to produce an equiaxed grain structure with an average grain diameter of 30 μm. A 40 mm bore diameter gas gun was used to perform a plate impact experiment on this material. Separate tests were performed for purposes of soft sample recovery, described in Zurek, et al. (September 1988), and VISAR (velocity interferometry system for any reflector, see Barker and Hollenbach (1972), Hemsing (January 1979)) particle velocity determination; the other experimental parameters were otherwise identical between the tests. The flyer plate was z-cut quartz with a thickness of 1.5 mm whilst the thickness of the target was 1.52 mm. The flyer plate impact velocity was 300.2 m/s. Linear shock wave analysis (Gray (1993)) determined that the peak shock pressure under these conditions is 3.57 GPa with a pulse duration of 0.45 μs. Fig. 1 is the VISAR record of a similar plate impact experiment which had a flyer plate velocity of 238 m/s (2.8 GPa peak shock pressure).

2.2. Quantitative Metallography

The recovered sample was sectioned normal to the propagation of the shock wave and prepared met-
allographically. A light etch was applied using a 1:1:1 solution of NH₄OH:H₂O₂:H₂O. The etch was applied by swabbing the polished surface for a total of 10 and 30 seconds with the solution. Comparative microscopy indicated that the void sizes were not significantly influenced by the difference in etch times, but the etch-revealed linking between voids became more distinct with the longer etch duration. The longer duration etch was used for subsequent analysis.

A composite optical micrograph was taken of the entire specimen cross-section (17 mm) at 100x magnification using a microscope fitted with a video camera and connected to a computer by means of a frame grabber. This composite consisted of 18 individual images captured at 740x480 pixel resolution at 24 bits color. A sample of this composite micrograph is shown in Fig. 2. The composite image was analyzed using Image Pro® software iteratively with extensive interaction with the operator to split identified objects and correctly find the boundaries of the voids. Splitting identified objects involved adding lines to the image across clusters of voids to yield provided sectional area, aspect ratio, average diameter of the section, and the planar cartesian coordinates of the centroid. Optical profilometry was also performed of the entire specimen cross-section using a Wyko RST-Plus® profilometer. This instrument utilizes optical phase shift interferometry to provide non-contact areal depth measurement (Caber (July 1993), Caber, et al. (October 1993)). The purpose of the profilometry measurements was to find the depth of each void such that the true three-dimensional size distribution can be determined, assuming spherical voids. The combined analysis resulted in the number of analyzed voids, N, equal to 592. Fig. 3 shows a schematic representation of a planar section through a volumetric distribution of spheres with an arbitrary size distribution. The true diameter of an observed void is called the equivalent void diameter and it differs from the observed void diameter, or base diameter, when the sampling section does not intersect the centroid of the void. The planar sampling method makes the observed distribution different from the true volumetric distribution because the sampled depth is a function of void diameter, d, the minimum threshold cross-sectional area to be counted, A_min, and the distance from tangency necessary to be observed, h'.

Figure 1. VISAR particle velocity of the back surface of the target

Figure 2. Optical micrograph of part of the analyzed sample section.

Figure 3. Schematic diagram of a planar section through a random volumetric distribution of spheres.

2.3. Damage Analysis

2.3.1. Void Aspect Ratio

Most of our analysis is based on the assumption of spherical voids. Fig. 4 is a plot of the cumulative percentage of observations of aspect ratios. Probability plots are very convenient for discern-
2.3.3. Porosity

The porosity of the sample can be calculated by assuming that the areal fraction in a planar section through a random volumetric distribution of spheres with an arbitrary size distribution is equal to the volumetric fraction. Fig. 6 is a plot of porosity with respect to distance from the spall plane, which is defined as the plane of maximum porosity. This calculation is made across the entire sample in one μm steps and uses the average base diameter measurement. Note that this measurement method provides a great deal of spatial resolution and reveals a complex fine structure. The maximum porosity is about 10%, about 1/3 the maximum experimentally observed (Seaman, et al. (November 1976)) and predicted by void growth models (Johnson (1981), Johnson and Addessio (December 15, 1988)) to result in complete fracture. Fig. 4 visually implies a qualitatively greater porosity than is shown in Fig. 6 because Fig. 4 is a projection of three dimensional objects onto a plane, while Fig. 6 shows the actual porosity as a section through the sampled population of voids.

![Figure 6. Porosity as a function of distance from the spall plane.](image)

2.3.4. Void Size Distribution

The void size distribution was determined across the whole damaged region. Fig. 7 shows experimentally observed cross sectional (base) void diameters and the actual void diameters as a cumulative percentage of observations plot. Three distribution functions were fitted to this data to evaluate the most appropriate statistical descriptor. The log-normal distribution is given by:

\[ f_{\text{log-normal}}(x; \mu, \sigma, \varepsilon) = \frac{1}{2\pi \sigma} e^{-\frac{1}{2} \left[ \ln(x-\varepsilon) - \mu \right]^2} \]

A cumulative log-normal distribution will appear as a straight line or concave downward when the axes are chosen as in Fig. 7. The Weibull distribution is given by:

\[ f_{\text{Weibull}}(x; \eta, \alpha, \kappa) = \frac{\alpha}{\eta} \left( \frac{x - \kappa}{\alpha} \right)^{\eta-1} e^{-\left( \frac{x - \kappa}{\alpha} \right)^\eta} \]

A cumulative Weibull distribution function can appear "s" shaped when the axes are chosen as in Fig. 7. The third distribution function is a linear partition of the log-normal distribution and the Weibull distribution functions:

\[ f_{\text{log-normal}}(x) = \left( 1 - \frac{x}{x_{\text{max}}} \right) f_{\text{log-normal}}(x) + \frac{x}{x_{\text{max}}} f_{\text{Weibull}}(x) \]

where \( x_{\text{max}} \) is the maximum observed \( x \). The cumulative distribution function of equation 5 is straight or concave downward at lower probabilities, like a log-normal, but approaches an upper limit, like a Weibull distribution, again when the axes are chosen as in Fig. 7. The best fits of these dis-

![Figure 7. Observed and volumetric void diameters across the whole damaged region.](image)
Including the one shown which is very similar to the log-normal distribution function.

![Graph showing probability against equivalent void diameter for three distribution functions]

**Figure 8.** Best fits of three distribution functions to the observed and volumetric true void diameters.

Finding the best statistical representation of the observed voids is an important first step. However, the true volumetric distribution of void diameters differs from our observation because our observation method skews the actual distribution of sizes (see Fig. 3). Seaman, et al. (October 1978) solved the problem of finding the true volumetric size distribution of penny shaped cracks starting with base measurements on a polished plane. The following solution method differs substantially from that work, partly because the observed voids' true diameters are known and the voids are approximated by spheres, and partly because our method employs continuous data and functions instead of compartmentalized bins of data.

The effective sampling depth over which void diameters are measured is dependent upon the void diameter. Therefore, small voids are underestimated whilst large voids are overestimated by planar sampling methods. $A_{\text{min}}$ is the minimum area that is counted by the image analysis procedure and was set to 30 $\mu m^2$. A void must be overlapping the section plane by $h'$ in order to be identified as an object. $h'$ is given by:

$$h' = \frac{A_{\text{min}}}{\pi d}$$  \hspace{1cm} (6)

where $d$ is the actual void diameter using the equivalent base void diameter and the profilometry measured void depth from the section plane. Therefore, the sampling depth, $d_{\text{samp}}$, is given by:

$$d_{\text{samp}} = 2\left(\frac{d}{2} - h'\right) = d - \frac{2A_{\text{min}}}{\pi d}$$  \hspace{1cm} (7)

Sir Kendall (Stuart (1987)) discusses the effect of an actual distribution, $f_{\text{act}}$, being modified by the sampling process, resulting in an observed distribution, $f_{\text{obs}}$. Using his proof, the actual volumetric distribution for our sampling method may be found by solving:

$$f_{\text{obs}}(d) = \frac{d_{\text{samp}} \cdot f_{\text{act}}(d)}{\int_{-\infty}^{\infty} d_{\text{samp}} \cdot f_{\text{act}}(d) \, dd} \approx \frac{d_{\text{samp}} \cdot f_{\text{act}}(d)}{\mu_1}$$  \hspace{1cm} (8)

where $\mu_1$ is the first moment or expected value of the distribution function $f_{\text{act}}$. The approximation to this problem was solved assuming that $f_{\text{act}}$ is the same distribution type as $f_{\text{obs}}$ (the resulting goodness indicates that this is a valid assumption) and the results are shown in Fig. 7 and Fig. 8 for comparison with the observed distributions. The wide variance between the Weibull volumetric distribution and the log-normal and linear partition volumetric distribution at smaller void diameters is attributed to the Weibull distribution having a lower bound that makes the approximation in eq. 2.3.4. less appropriate.

The cumulative volumetric distribution functions have a different shape than the observed base (2-D) diameter cumulative distribution functions, but a similar range of sizes. This indicates that calculating porosity based on areal fraction is a reasonable approximation for an arbitrary volumetric size distribution of voids.

Table 1 lists the parameters for the six distribution functions.

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<th>Table 1. Void size statistical parameters</th>
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<td><strong>Observed</strong></td>
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2.3.5. Cluster Sizes

Voids whose edge-to-edge distance was less than 1/10 of each of their equivalent void diameters were assumed to be members of a cluster. The edge-to-edge distance was calculated using the 3-D centroid and equivalent void diameters. 81 clusters were identified consisting of a total of 214 voids. Thus, 36% of the observed voids belonged to clusters. Fig. 7 shows a cumulative length distribution of the clusters and a fit to a log-normal distribution. The cluster length is defined to be the edge-to-edge length of a cluster. The cluster area is a rectangular approximation and is defined to be the cluster length times the average cluster member equivalent void diameter. Fig. 10 is a cumulative distribution plot of cluster areas.

3. Conclusions and further work

The analysis in this paper provides statistical information of the voids contained within the entire incipiently spalled region of a 10100 OFHC Cu sample. A linear partition distribution function between the log-normal and Weibull distribution functions is deemed the most appropriate in describing the observed and volumetric distribution of voids within the damaged region. Further analysis is required to provide statistical information regarding the distribution of damage as a function of distance from the spall plane. Such an analysis will serve as important information for the determination of physically-based void nucleation, growth, and coalescence relations appropriate for this material (see Seaman (July 10-12, 1972) for a relevant discussion of these issues for the case of brittle microcracks).

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