AN EXPERIMENTAL MODEL OF VOID GROWTH AND COALESCENCE DURING DUCTILE FRACTURE

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ABSTRACT

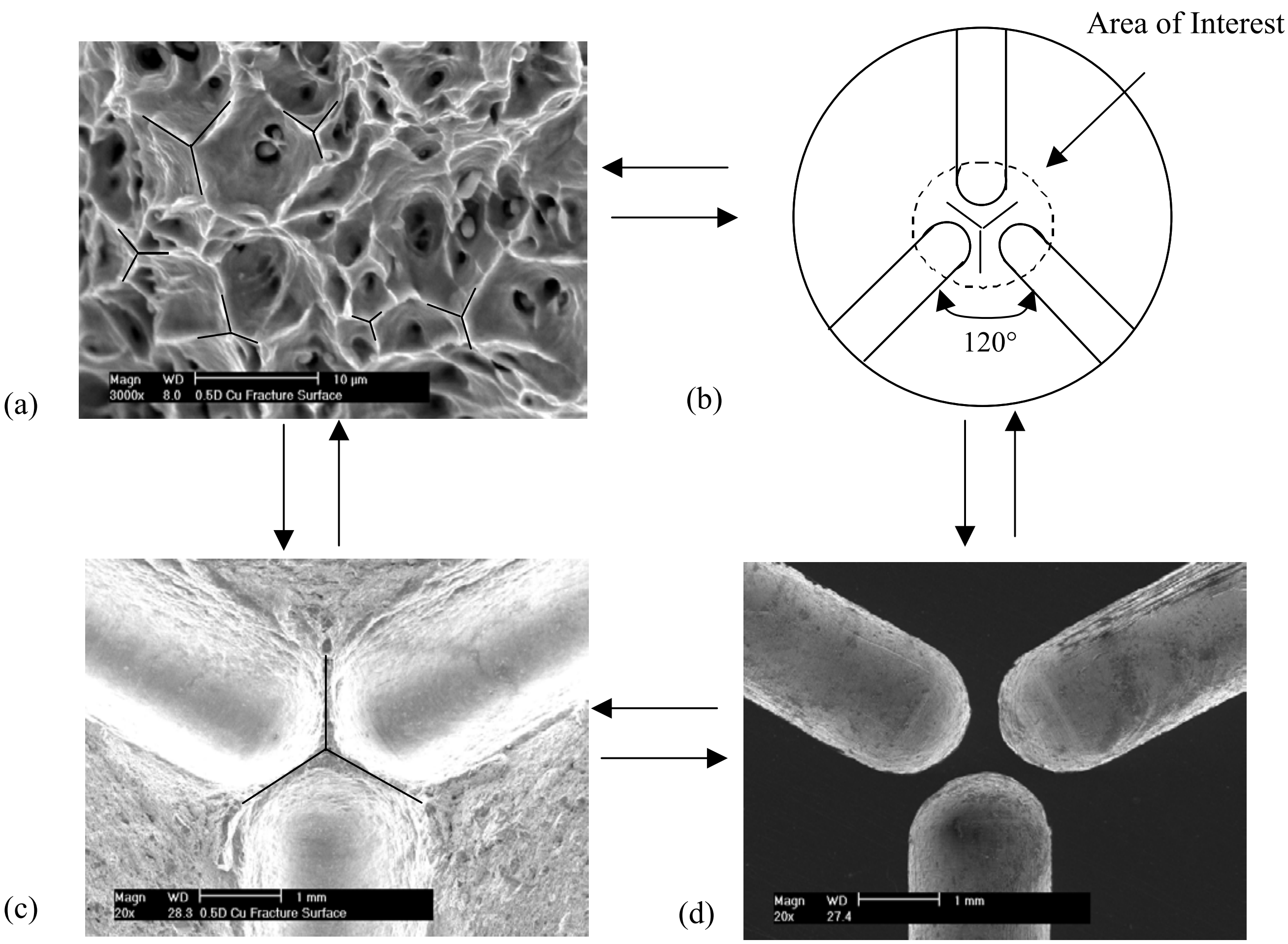
The strain-induced growth and interaction behavior between neighboring voids located within small clusters has been experimentally modeled by determining the thinning behavior of the ligaments between the cavities formed by blind-end holes that have (initially) hemispherical ends and that are contained within uniaxial tensile specimens. The key assumption is the strain-induced thinning and coalescence of the ligaments between the macro-scale cavities is similar to that between neighboring spherical microvoids. Results from Cu specimens containing 2 or 3 blind-end holes indicate strain-induced cavity growth and coalescence behavior that is more rapid for clusters of 3 cavities. For this case, cavity coalescence also results in the characteristic 3-fold symmetry pattern that frequently forms along the ridges on a dimpled ductile fracture surface. When compared to void growth predictions based on the strain-induced growth of isolated voids, these results indicate void interaction effects that are sensitive to cluster geometry such that the three-fold symmetry conditions created by 3 neighboring voids result in accelerated void growth induced by an elevated level of stress triaxiality within the inter-void ligament.

KEYWORDS: Void growth, void coalescence, ductile fracture

INTRODUCTION

Tensile fracture of ductile metals at low temperatures typically occurs by a damage accumulation process that involves microvoid nucleation, growth, and coalescence. For many metals, void nucleation at inclusions occurs at small strains, and fracture is dominated by void growth and coalescence. The strain-induced growth of isolated spherical voids was modeled initially by Rice and Tracey [1], and their predictions have been subsequently supported by computational studies [2,3]. However, for the case of closely spaced voids such as at high void volume fractions near coalescence or among those voids within the clusters, void interactions should result in accelerated void growth, as has been observed experimentally [4,5]. Despite two-dimensional modeling (both experimental and computational) as well as three-dimensional unit-cell models (the study of Thomson et al [6] is especially pertinent to this work), the detailed nature of such interactions among small void clusters, such as inter-void spacing effects or which void cluster geometry promotes strong interactions, is not well understood.

In this study, as shown conceptually in Figure 1, we utilize a novel specimen geometry to model experimentally the growth and coalescence among clusters of three neighboring spherical cavities. Specifically we employ tensile specimens containing three blind-end holes with hemispherical ends and subject the specimens to interrupted deformation in order to measure the ligament thinning behavior between



.Figure 1. (a) Ductile fracture surface illustrating "ridge-crater" shape formed by clusters of three voids. (b) Cross section of tensile specimen geometry employed to model clusters of three voids (c) Fracture surface created by our three-cavity cluster geometry. (d) Micrograph of a strained three-cavity cluster specimen that has been sectioned and polished.

the cavities formed by the hole ends [7]. We believe that the strain-induced thinning behavior of these inter-cavity ligaments is similar to that of the ligament between neighboring spherical voids located a similar relative distance apart. An important experimental advantage of this modeling approach is the ability to measure *directly* that the inter-cavity ligament width (and therefore the "cavity" growth behavior) as a function of strain. Using this modeling approach, we [7] have previously determined the ligament thinning behavior between two adjacent cavities. Geltmacher et al [8] subsequently established that tensile specimens with clusters of *three* blind-end holes failed such that the fracture surface between the cavities had the "ridge-crater" characteristic shape formed by void coalescence during microvoid fracture; however, no cavity growth measurements were performed in that effort. In this communication, we extend these two studies by utilizing copper tensile specimens containing either 2 or 3 co-planar holes with hemispherical ends to examine thinning behavior between these cavities and therefore to assess the "void growth" behavior within such small clusters of voids. The cavities formed by the hole ends form a triangular pattern and are contained on a plane normal to the tensile axis, and thus this cluster geometry differs considerably from those assumed in the three-dimensional computational modeling by Thomson et al [6]. In that study, their three-cavity cluster formed a linear array, as opposed to the triangular array here.

EXPERIMENTAL

The experimental basis for this study is a "blind-end hole" specimen shown in the three-hole configuration in Figure 1. Round bar tensile specimens with 15.5 mm gauge length diameters and 63.4 mm gauge lengths were machined from C11000 copper such that they contained either two or three coplanar holes into the mid section of each specimen. The holes, each with diameter = 1.59 mm, were drilled with a ball end-mill to produce *hemispherical cavity* at the hole end. For the two hole case, the holes were located in the same plane but opposite each other, while the three hole configuration had the hole axes separated by 120° to produce the Y geometry. The test specimens were fabricated with initial inter-cavity ligament widths of 0.79, 1.59, 3.18, 4.77, and 6.36 mm, which correspond to ligament widths of 0.5D, 1D, 2D, 3D, and 4D, respectively, where D is the hole diameter. Typical scatter in initial ligament widths was ± 0.04 D. Note that the inter-cavity ligament width dimension, W, is measured from the base of one hole to the base of another.
The material was C11000 copper, which was vacuum annealed at 375 °C for one hour after machining. The average grain size was 32 μm, which corresponds to greater than 20 grains across the minimum inter-hole ligament. The Cu had a yield stress of 220 MPa and a strain hardening exponent, $n = d\ln\sigma/d\ln\varepsilon$, of $n = 0.28$ for $0.01 \leq \varepsilon \leq 0.45$ as obtained from compression testing.

Inter-cavity ligament thinning was measured by deforming tensile specimens at room temperature at an initial strain rate of 10^{-3} s^{-1}. The specimens were strained in ≈ 0.015 far-field axial strain increments at which point a modified electronic depth indicator with rounded-end probes was used to measure hole depth using a procedure described elsewhere [7]. For the cases of the two-hole specimens, hole depth measurements could be used to determine the ligament width directly. For the three-hole specimens, inter-cavity ligament width was obtained from a straight-forward geometric analysis based on the determination of the distances from the geometric center of the specimen to the ends of two adjacent holes [9]. Five measurements were made of each dimension such that the ligament width was measured to within ±0.04D, where D is the hole diameter.

RESULTS AND DISCUSSION

As a measure of cavity growth, we have determined the inter-cavity ligament width, W, as a function of strain. These results, presented on the basis of the instantaneous ligament width, W, normalized to the initial ligament width, W_o, are shown for the case of three holes in Figure 2. In order to interpret these results, the choice of the strain axis in Figure 2 deserves a comment. The strain basis for Figure 2, $2\ln(d_o/d)_{local}$, relies on measurements of the initial and final specimen diameters, d_0 and d, respectively, in the plane of the holes and measured along a line inclined about 30^0 to the holes in order to avoid displacement effects along the barrels of the hole. We have also measured extensional strain values based on both scribe marks along the top and bottom of the holes and scribe marks along a 25 mm gauge section of the specimen; these extension-strain values coincide with the diameter-based strains until about 0.1 strain at which point specimen necking occurs in the section containing the holes. Thus, we have chosen the value of $2\ln(d_o/d)_{local}$ as the best measure of extensional strain in the vicinity of the cavities, despite the fact that strain-induced hole growth implies the extensional strain is somewhat greater than the $2\ln(d_o/d)_{local}$ -values reported in Figure 2.
Figure 2 shows that the normalized rate of thinning increases as the inter-cavity ligament width decreases, consistent with the fact that closely spaced voids coalesce at small strains during microvoid coalescence.
The special case of clusters of three cavities is also evident in Figure 1a, which highlights the formation of Y patterns along ridges formed by coalescence of groups of *three* microvoids. We believe that these Y patterns form because growth and therefore coalescence is rapid within groups of three voids. It is also likely that, given the small number of voids in such clusters, there is a relatively high probability that clusters of three voids are present so as to promote rapid growth (i.e., clustered roughly on a plane normal to the maximum principal strain axis).

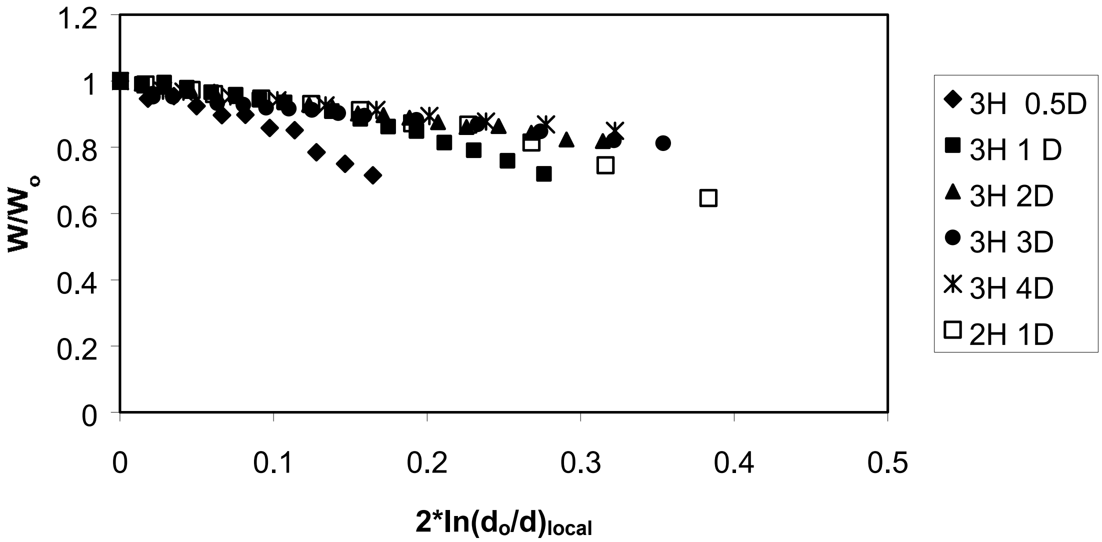


Figure 2. A comparison of normalized inter-cavity ligament thinning as a function of strain for five inter-cavity spacings in the three-cavity specimen. For comparison, the ligament thinning behavior of a two-cavity specimen (with an inter-cavity spacing of 1 cavity diameter) is also shown.

The ligament thinning data in Figure 2 is limited by the failure of the ligament between the cavities. As shown in Figure 1c, the fracture surfaces formed within the cluster of three closely spaced cavities (Figure 1c) mimic the Y ridge patterns formed among clusters of three microvoids in Figure 1a. In Figure 1c, there is sufficient ductility within the inter-cavity ligament at the 0.5D spacing such that the ligaments thin to knife-edges due to purely plastic failure. At larger inter-cavity spacings, an increased level of strain is required for the ligaments to thin to the knife-edge, and instead fracture of the ligament intervenes. In this latter case, there is sufficient constraint between the cavities to induce ligament fracture prior to the strain level necessary for the ligament to thin to a knife-edge.

Both the rapid thinning behavior and the manner of failure suggest that inter-cavity ligament deformation occurs under a level of constraint due to the notch-like geometry of the neighboring cavities. The implication is that the inter-cavity ligaments deform under stress triaxiality ratios higher than that of uniaxial tension. We therefore suggest that it is this locally elevated stress triaxiality that causes the rapid cavity growth and inter-cavity thinning depicted in Figure 2. Compared to the case of the growth of an isolated cavity/void under far-field uniaxial tension, these results suggest that cavity growth within a cluster is accelerated by the presence of a *triaxial* stress state within the ligaments.

As an initial attempt to analyze our results, we adapt the analysis procedure used by others [5,10] to analyze experimental void-growth behavior on the basis of the Rice and Tracey cavity-growth relationship [1]. As a first approximation, we assume spherical growth of cavities under a tensile deformation field at large stress triaxiality ratios that remain relatively constant during deformation. Under these conditions, the following relationship describes the radial growth of the cavities:

$$\ln(R/R_o) = \alpha\varepsilon_{eq}\exp(\beta\frac{\sigma_m}{\sigma_{eq}}) \tag{1}$$

where R_o and R are initial and final cavity radii, ε_{eq} is the equivalent far-field strain, α and β are constants whose values should be $\alpha = 0.283$ and $\beta = 1.5$, according to Rice and Tracey [1]. A more recent analysis [11] indicates $\alpha = 0.427$ for $\sigma_m/\sigma_{eq} > 1$ and for $\sigma_m/\sigma_{eq} < 1$, $\alpha = 0.427\ (\sigma_m/\sigma_{eq})^{0.25}$.

In this study, we use straight-forward geometry to relate our ligament thinning measurements to cavity growth behavior. The following relationship between R/R_o and the normalized inter-cavity ligament width, W/W_o, is readily obtained:

$$\frac{R}{R_o} = 1 + \frac{W_o}{2R_o}\left(1 - \frac{W}{W_o}\right) \qquad (2)$$

where in our case $2R_o$ is the hole/cavity diameter and equals 1.59 mm, while $W_o/2R_o$ is the initial inter-cavity spacing in terms of the diameter D.

Based on Equation 2 and assuming $\varepsilon_{eq} \cong 2\ln(d_o/d)_{local}$, Figure 3 tests the validity of Equation 1 by showing a nearly linear dependence of $\ln(R/R_o)$ on strain for both the two- and three-cavity cases. All of these data support the general form of Equation 1 as a basis for describing cavity growth within small cavity clusters. Small deviations from linear behavior in Figure 3 occur at large strains for the closely spaced cavities in which case linear behavior is observed initially and then followed by non-liner behavior as ligament thinning accelerates. Furthermore, a comparison of the cavity growth behavior in Figure 3 confirms that cavity growth is more rapid in the three-cavity cluster than in the two-cavity case.

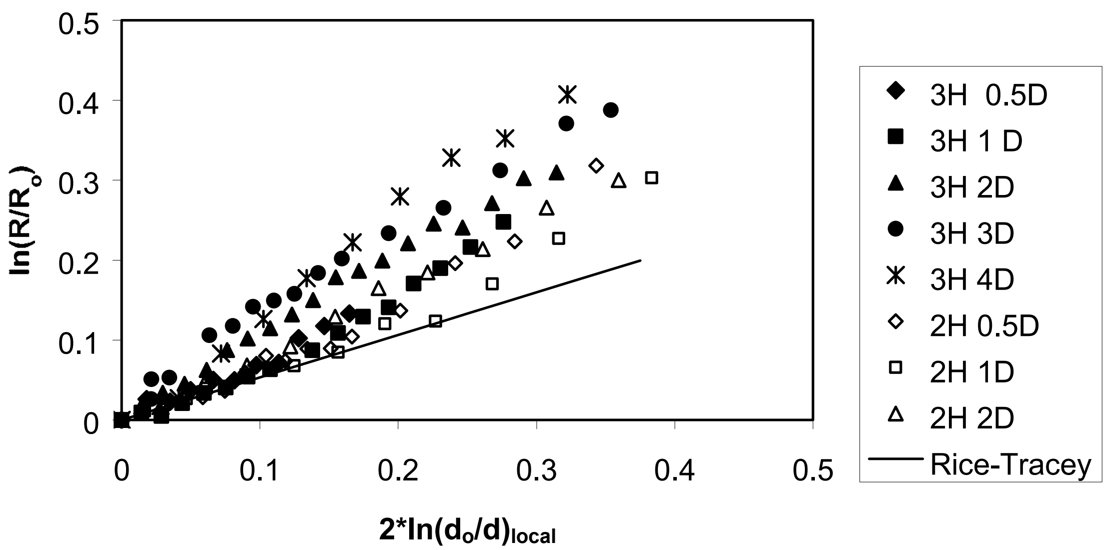


Figure 3. The dependence of cavity growth on strain for clusters of three cavities, designated 3H, and two cavities, designated 2H. Data are for a range of inter-cavity spacings from 0.5D to 4D.

It is also significant that increasing cavity spacing appears to be accompanied by an increase in cavity growth rates. While this effect is small in the case of the two-cavity condition, the cavities spaced far apart in the three-cavity clusters grow significantly faster than those closely spaced (i.e., at 0.5D and 1.0D). Such an effect is also consistent with the presence of elevated levels of stress triaxiality within the ligaments between the clustered cavities. For example, if the cluster of cavities is viewed as an incomplete circumferential notch, then the Bridgeman analysis [12] predicts increased stress triaxiality with increasing inter-cavity spacing.

The combination of the results in Figure 3 and Equation 1 can be used to test our hypothesis that an elevated level of stress triaxiality exists between the cavities and causes their rapid growth. If we assume $\alpha = 0.427$ for $\sigma_m/\sigma_{eq} > 1$ and for $\sigma_m/\sigma_{eq} < 1$, $\alpha = 0.427\,(\sigma_m/\sigma_{eq})^{0.25}$ [11] and $\beta = 1.5$ [1], then the cavity growth data in Figure 3 predict average stress triaxiality ratios within the inter-cavity ligaments that increase somewhat with strain but have values ranging from $\sigma_m/\sigma_{eq} \cong 0.6$ for three cavities spaced initially 0.5D apart to $\sigma_m/\sigma_{eq} \cong 0.8$ for the three cavities spaced 4D apart. Importantly, the predicted stress triaxiality between two cavities is much less: $\sigma_m/\sigma_{eq} \cong 0.4$ to 0.5. While such stress triaxiality levels are significantly higher than the far-field value of $\sigma_m/\sigma_{eq} = 0.33$ characteristic of a uniaxial tension test, the elevated triaxiality values are similar to those imposed within circumferentially notched tensile specimens with very "mild" notch geometries. We are currently performing three-dimensional finite element analysis to examine this issue further [13].

The important implication of the above analysis is that it suggests that void growth within clusters of voids can be predicted on the basis of a straight-forward application of the Rice-Tracey void growth relationship *provided* that the stress triaxiality reflects the local condition within the deforming inter-void ligament. It appears that the clusters of three equal-sized voids with roughly three-fold symmetry and located on a plane normal to the maximum principal stress create elevated levels of stress triaxiality within the inter-cavity ligament (and therefore rapid void growth), *and* such clusters have a high probability of occurring in the optimum configuration/orientation.

SUMMARY

Utilizing copper tensile specimens containing either two or three blind-end holes, we have experimentally modeled the growth behavior of neighboring spherical cavities. Consistent with expectations from fracture surface observations of microvoid coalescence, the results indicate that inter-cavity ligament thinning is more rapid within a cluster of three cavities than between two cavities at the same inter-cavity spacing. Furthermore, the cavity growth within the three-cavity cluster is consistent with the void growth model of Rice and Tracey for a large range of inter-cavity spacings *provided* that the assumed stress triaxiality ratio is increased above that of uniaxial tension. As such, these cavity growth results strongly suggest the void interaction effects during ductile fracture can be understood on the basis of elevated levels of stress triaxiality within the inter-void ligaments.

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