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ON MODELING THE EFFECT OF PORE SHAPES ON DUCTILE FRACTURE

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An initial effort has been made to simulate the effect of pore shape on the ductility of porous metals. The simulation is performed utilizing a computer model in which distributions of pores are modeled in two dimensions by pseudo-random arrays of either circular or elongated holes. As expected, the simulations predict that tensile ductility decreases as the area fraction of holes increase and that specimens containing elongated holes are less ductile. However, somewhat unexpected is the prediction that the hole/pore shape effect becomes more pronounced with increasing area fraction of holes/pores. The results can be readily understood in terms of the local strain distributions near holes, the dependence of inter-hole spacings on the area fraction of holes, and strain-based hole-linking criteria.

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ABSTRACT

An initial effort has been made to simulate the effect of pore shape on the ductility of porous metals. The simulation is performed utilizing a computer model in which distributions of pores are modeled in two dimensions by pseudo-random arrays of either circular or elongated holes. As expected, the simulations predict that tensile ductility decreases as the area fraction of holes increase and that specimens containing elongated holes are less ductile. However, somewhat unexpected is the prediction that the hole/pore shape effect becomes more pronounced with increasing area fraction of holes/pores. The results can be readily understood in terms of the local strain distributions near holes, the dependence of inter-hole spacings on the area fraction of holes, and strain-based hole-linking criteria.

INTRODUCTION

The effect of porosity on the ductility of porous metals is well known; see ref. 1 for a review. In particular, it has been established experimentally that metals containing rounded porosity are more ductile than those containing irregularly-shaped pores at the same volume fraction of porosity [2]. Pore-shape effects have been analyzed on a qualitative basis in terms of plastic strain distribution differences between rounded and angular porosity [2], and on a quantitative basis with regard to the effect of pore geometry on tensile strength, but not ductility[3]. That latter analysis is also restricted by its reliance on regular arrays of holes[4], while the former offers no quantitative insight. Thus, comparatively little is known of the mechanism(s) responsible for pore-shape effects on fracture, especially with reference to the implications of such mechanisms. The purpose of this study is to model the effect of pore shapes on the ductile fracture of porous metals. Particular attention in this initial effort will be given to the influence of the spatial distribution of the pores, the strain-hardening behavior of the matrix, and the role of the volume fraction of porosity on pore-shape effects.

The present study utilizes a computer model which simulates three-dimensional pore distributions by two-dimensional arrays of through-thickness equisized holes in sheet specimens wherein deformation occurs primarily under plane-stress conditions [4-7]. Fig. 1 shows an example of such a hole array. Two-dimensional modeling of the fracture of porous or voided metals using arrays of holes has been performed several times in the past, although usually on the basis of regular arrays [3-16]. As may be recognized in Fig. 1, a principal advantage of the modeling approach is the ability to simulate the random nature of the spatial distribution(s) of pores in powder-processed materials. Such a simulation is clearly a very simplified version of the realistic case in which pores of various shapes and sizes exist in three-dimensional space and wherein failure of the specimen is associated with flow localization (but probably not cracking which causes linking between pores. Difficulties in determining three-dimensional strain distributions and pore-linking criteria among random distributions of pores preclude a rigorous three-dimensional simulation. However, the methodology and significant trends predicted by the present two-dimensional analysis are consistent with both plane-stress and plane-strain experiments [4-7] and should be valid for a three-dimensional porous metal.

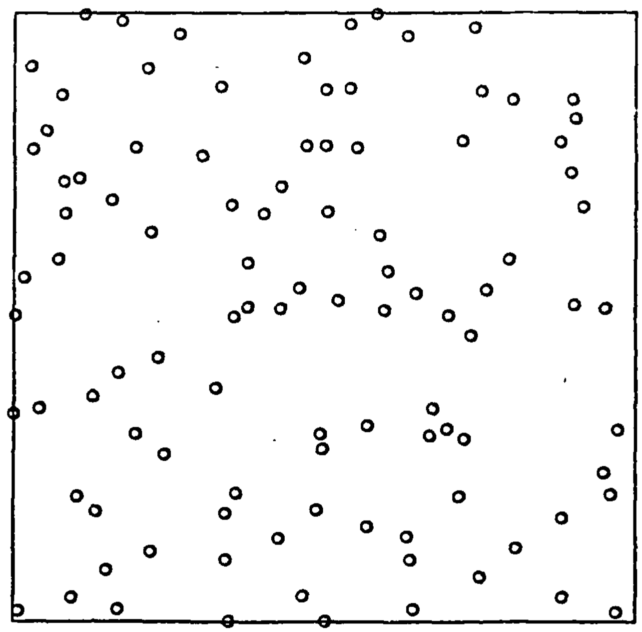

Figure 1. An example of an "inhibited" random hole array containing .02 area fraction of 2.916mm diameter circular holes, with an interhol spacing of 1.0mm.

RESULTS AND DISCUSSION

A. Basis for the Analysis

The present analysis is based on the utilization of a computer simulation [6,7] which predicts the ductility behavior of specimens that possess "inhibited" random arrays of through-thickness holes. The term "inhibited" refers to the fact that the hole array is subject to a minimum interhole spacing within which adjacent holes cannot exist. In the present study, the simulation is extended to contrast the behavior of specimens containing elongated vs. circular holes. Fig. 2 shows the two hole geometries used in the simulations; the elongated hole has a length to width ratio of 4/1. The major axes of the elongated holes are maintained perpendicular to the tensile direction, since the strain localization effect of the elongated holes is maximized under this condition. The dimensions of the circular and elongated holes were selected such that the areas of the holes are a constant value. In the computer simulation, the strain fields of the elongated holes are obtained from empirical relations based on experiments utilizing pairs of circular holes in either 1100 Al or alpha brass which have been linked by a free surface prior to deformation.[6,17] The specimens containing arrays of holes are simulated to deform under plane-stress conditions and contain inhibited random arrays of through-thickness holes with area fractions which range from 0.01 to 0.10 and whose minimum allowable interhole spacing is 1.0 mm. The specimen size and shape (a square of 137.61 mm x 137.61 mm) was chosen in order to have a minimum number of 50 holes at the lowest value of area fraction (0.01); at higher area fractions, the number of holes obviously increases to, for example, 500 holes at an area fraction of 0.10. Both specimen size and shape are kept constant since these can have significant effects on the ductility behavior of the specimens.[7] Under the test conditions in this study, the holes have cross-section areas of 3.7875 mm^2 with the circular holes having radii of 1.098 mm and the elongated holes having tip radii of 0.5 mm.

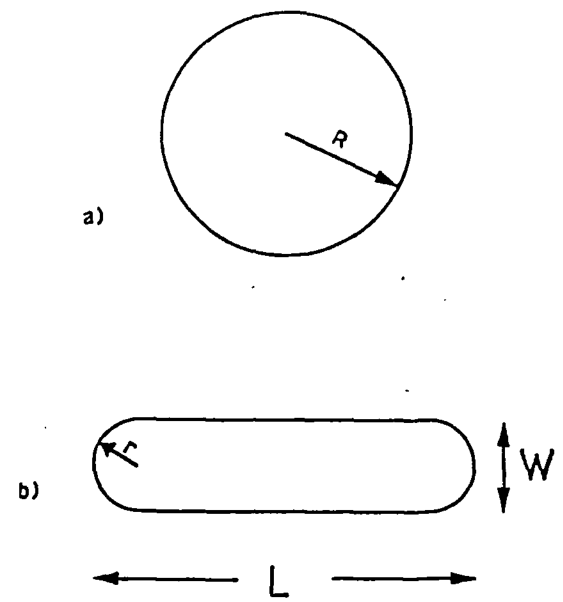

Figure 2. Hole geometries used in this study: (a) circular (R=1.098mm) and (b) elongated (r=0.5mm and the length to width ratio of 4 to 1).

For each set of conditions, a minimum of ten computer runs was performed in order to obtain statistically reliable predictions. The influence of the strain-hardening capabilities of the material is examined by simulating specimens whose stress-strain behavior correspond to 1100 aluminum (n=0.27) and 70-30 brass (n=0.46), where n is the strain-hardening exponent and is related to the true stress σ and true strain ε of the material by $n = d\ln\sigma/d\ln\varepsilon$. The ability of a material with a high n-value to avoid flow localization between pores and to delay strain-induced pore linking has been previously established [4,5].

A complete description of the simulation procedure can be found in ref. 6. It is significant that previous work [6,7] has shown that the computer simulation is in good agreement with experimental data with only the use of empirically represented experimental data and without the use of additional parameters to force fit the data.

B. Simulation Results

The effect of hole shape on the ductility is shown in Fig's. 3 and 4 for '1100 aluminum' and '70-30 brass', respectively. An examination of Fig's. 3 and 4 indicates the following trends:

1) The ductility of the specimens decreases as the area fraction of holes increases for both circular and elongated holes. This result is in accordance to previous work on the ductile fracture of porous materials, see ref. 1, for example.

2) The predicted ductility of the 'brass' specimens is greater than that of the '1100 Al.' This is consistent with increased ductility being associated with metals of high strain-hardening capacity.

3) As expected, the ductility of the specimens depends on hole shape in that the ductility of specimens with elongated holes is less than the ductility of specimens with circular holes. This is consistent with the ductility behavior of PM iron containing rounded vs. angular porosity. [2] However, the present study indicates that the hole-shape effect depends on the area fraction of holes. Specifically, at low area fractions of holes such as 0.01 to 0.02, the hole-shape effect is small, while at high area fractions of holes (~0.10) the decrease in ductility due to the elongated hole shape is large. This effect occurs in both the 'Al' and the 'brass' specimens.

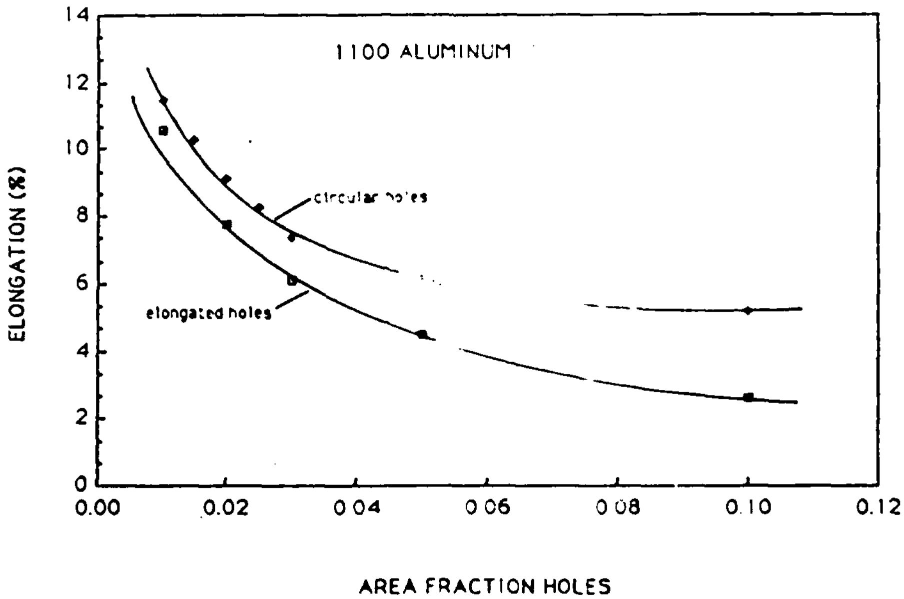

Figure 3. The predicted dependence of elongation to failure on area fraction for both circular and elongated holes for a material whose strain hardening corresponds to annealed 1100 Al.

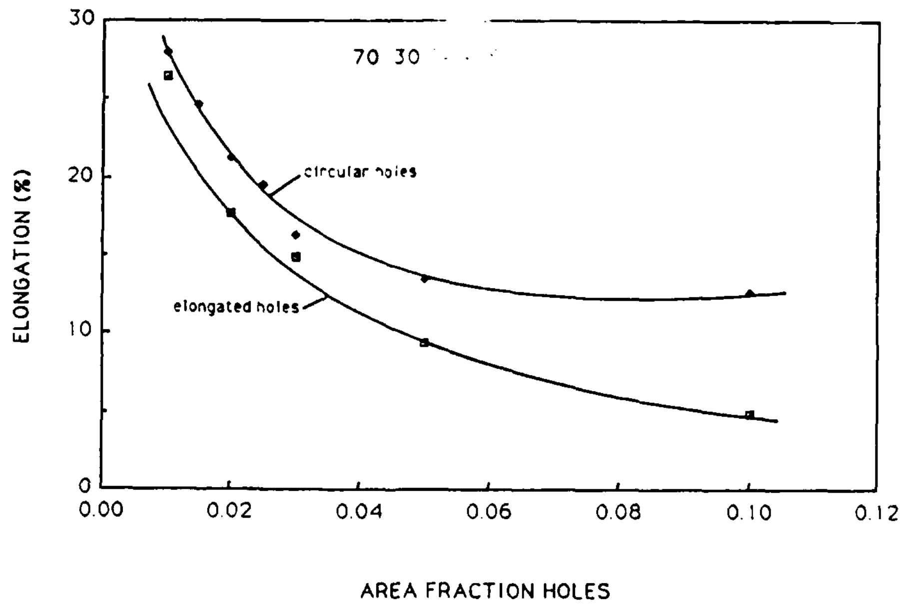

Figure 4. The predicted dependence of elongation to failure on area fraction for both circular and elongated holes for a material whose strain hardening corresponds to annealed alpha brass.

In summary, the computer simulation predicts a decrease in ductility due to presence of elongated holes or angular pores. However, the loss of ductility effect depends on the area fraction of holes and is most pronounced at large area fractions.

C. Discussion of Results

The above results can be understood in terms of a strain-induced hole/pore linking process. Under plane-stress conditions, the ligaments between neighboring holes fail at a critical thickness strain.[18] The effect of the hole (or pore) shape is to change the concentration of strain in the vicinity of the hole at a given macroscopic, applied strain. The magnitude of the strain-concentration depends on (1) the distance from the hole, (2) the shape of the hole, (3) the applied macroscopic strain level, (4) the strain hardening of the matrix, and (5) the location of neighboring hole. In the latter case, overlap of adjacent strain fields elevates the strains between the holes even in the absence of interaction effects.

In view of Fig. 5 and the concept of a critical local strain to cause hole linking,* the observed behavior may be understood as follows:

(1) "The ductility decreases as the area fraction of holes increases for both circular and elongated holes". The critical strain for hole linking is achieved at smaller macroscopic strains when adjacent holes are spaced closely together; this is a result of the increased overlap of strain fields at small hole spacings. Thus, hole/pore linking occurs more readily at high hole/pore contents due to decreased interhole/pore spacings.

(2) "The predicted ductility of the brass specimens is greater than that of the 1100 Al". This indicates that strain-induced pore linking is easier in materials with low strain hardening capacity. The cause for this behavior is evident in a comparison of the magnitude of the local strains which develop near holes in the 'Al' compared to the 'brass' at the same macroscopic strain level. For example, comparing Fig. 5a to Fig. 5b indicates that at a macroscopic strain of 0.10, the local strains near the holes in the 'Al' are nearly four times greater than those in the 'brass'. Thus very high local strain levels are created near the holes in the "low-hardening" Al, while the high n-value of brass diffuses the strain effectively. As a result, hole linking by either crack initiation or flow localization, is expected to occur at smaller macroscopic strain levels in the 'Al', decreasing its ductility to less than that of the 'brass'.

(3) "Ductility of specimens with elongated holes is less than that of specimens with circular holes". Fig. 5 shows that elongated holes act to increase dramatically the level of local strain adjacent to a hole. Thus, the critical local strain to initiate a crack or cause flow localization is achieved at a smaller applied macroscopic strain if the holes are elongated. This results in accelerated hole linking and therefore decreased ductility.

(4) "The hole-shape effect depends on the area fraction of holes"... being largest at high area fractions of holes. Although somewhat surprising, this prediction is quite reasonable in view of Fig. 5, <u>if</u> pore linking occurs by a localized flow instability process and not pore-induced crack initiation. Fig. 5 indicates that at distances greater than ~1 hole radius, the local strains are nearly equal for both circular and elongated holes. For large interhole spacings, the element of ligament material midway between holes cannot recognize whether the holes are elongated or circular. If hole linking occurs by a shear instability of the ligament when the "midway" element achieves a critical strain, as is experimentally observed for pairs of holes,[18] then there will be very little accelerated hole linking due to elongated holes at large interhole spacings. This is the case at small area fractions of holes. For example, at an area fraction of holes of 0.02 with a minimum interhole spacing of 1 mm, the average interhole spacing is 7.78 mm but at 0.10 area fraction, the holes are spaced only 4.34 mm apart on

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* The critical strain value may be considered either to drive a flow localization process between neighboring pores [18] or, in a competing event, the critical local strain to initiate a crack from the pore.

average. Thus overlap of the intense of potion of the local strain fields is much more likely to occur at large area fractions of holes or pores. As a result, pore-shape effects are expected to be more pronounced at large area fractions of pores, provided that pore linking occurs by a flow localization process.

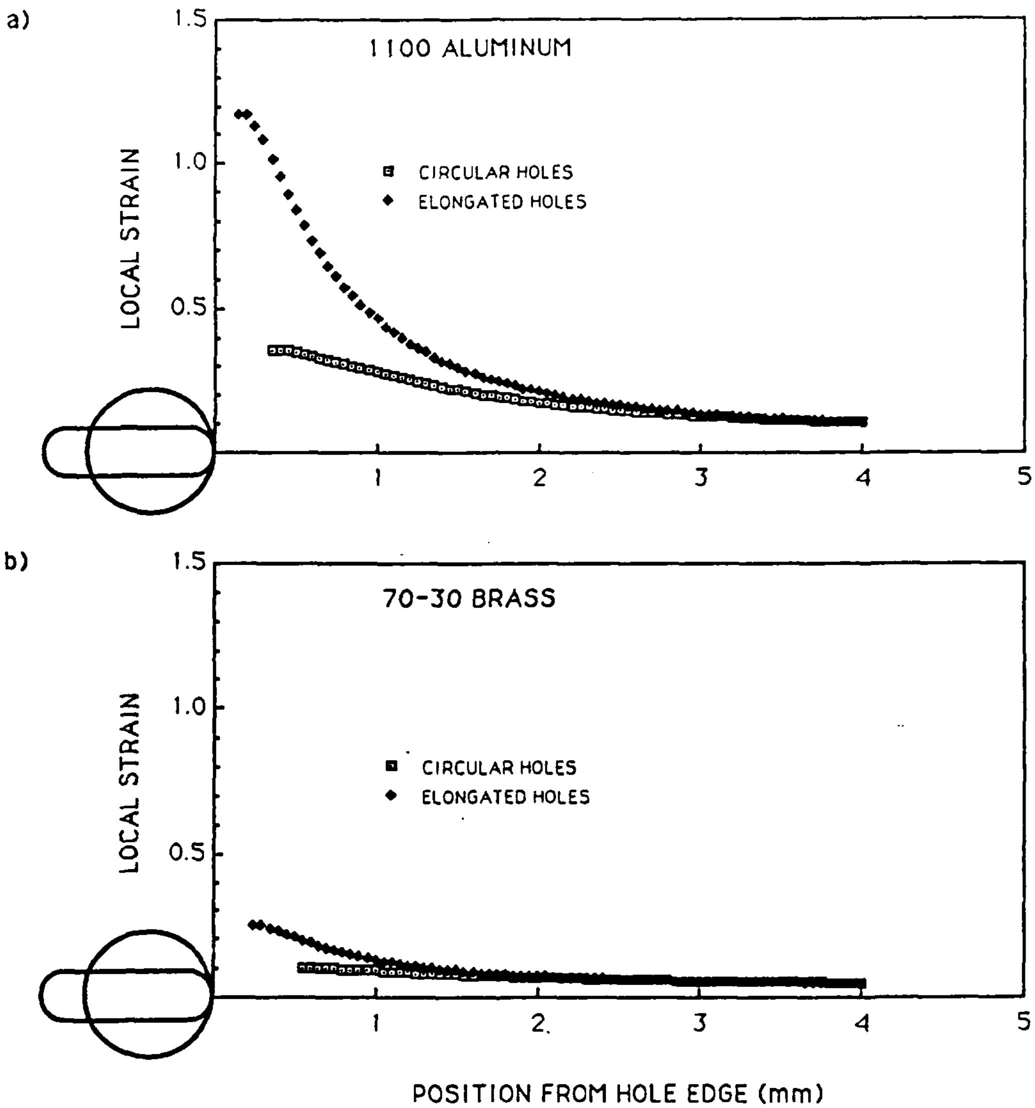

Figure 5. The predicted dependence of the local thickness strain component on position near circular or elongated holes in (a) '1100 Al' and (b) 'brass' and at macroscopic strain of 0.10. The strain profiles are along a line normal to the tensile axis passing through the center of the holes.

SUMMARY

A computer model has been extended to examine the effect of pore shape on the ductile fracture of metals containing porosity. Simulating three-dimensional pore microstructures as circular or elongated (length/width = 4) holes in two dimensions, the model predicts (a) a decrease in ductility with increasing area fraction of holes with low strain-hardening specimens which contain elongated holes being the least ductile, and (b) that the effect of hole shape on ductility is most pronounced at large area fractions of holes. The predicted behavior is consistent with the spatial distributions of local strains near holes/pores and a strain-based hole/pore linking criteria.

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