Fatigue Crack Initiation and Propagation in Lotus-Type Porous Copper

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We studied fatigue crack initiation and propagation in lotus-type porous copper with cylindrical pores aligned in one direction. For fatigue loadings in the direction parallel to the longitudinal axis of pores, stress field in the matrix is homogeneous. Therefore, slip bands are formed all over the specimen surface. On the other hand, for the perpendicular loadings, slip bands are formed only around pores in which stress highly concentrates. Since the localized slip bands form fatigue crack, fatigue fracture occurs even when the total plastic strain range is small. Stress field in the matrix of lotus copper affects the direction of crack propagation. For the parallel loadings, a crack propagates along a straight line as well as nonporous copper. On the other hand, for the perpendicular loading, a crack propagates along a path in which stress highly concentrates. Since stress highly concentrates around anomalously large pores, fatigue cracks are preferentially formed around the large pores and cracks propagate by crossing the large pores. [doi:10.2320/matertrans.MRA2007623]

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1. Introduction

Porous metals show potential for use in various applications because of their unique features such as lightweight, permeability of fluid, and sound absorption.1,2) Therefore, the extensive researches have been carried out and various porous metals such as closed-cell and open-cell aluminum foam have been developed.3) The pore structure of porous metals strongly affects their mechanical strength. For conventional porous metals such as aluminum foams, porosity is higher than 70%, and the pores with irregular shape are randomly distributed in the matrix. Therefore, the mechanical strength of conventional porous metals is low.1–5) On the other hand, the pore structure of lotus-type porous metals (lotus metals) is different from those of conventional porous metals. The porosity of lotus metals is lower than 70%, which is lower than that of conventional porous metals (upper 70%). Additionally, pores of lotus metals are cylindrical, and are oriented in one direction. Since the magnitude of stress concentration around the cylindrical pores depends on loading directions, the mechanical strengths of lotus metals show anisotropy.6–13) For a loading along the longitudinal axis of pores, the specific strength is almost constant because stress hardly concentrates around pores. Thus, the mechanical strength of lotus metals is superior to those of conventional porous metals. Therefore, lotus metals are expected to be used as lightweight structural materials. When used as structural materials, the fatigue properties should be clarified. For closed-cell or open-cell aluminum foams, the fatigue properties were investigated.14–19) However, the fatigue properties of lotus metals have not been clarified in detail compared with those of aluminum foams; Seki et al. clarified the effect of porosity, anisotropic pore structure, and pore size distribution on the fatigue strength of lotus copper.13) In order to discuss the fatigue fracture mechanism of lotus metals, it is necessary to clarify the fatigue crack initiation and propagation.

In this paper, employing lotus copper as a model of lotus metals, we studied fatigue crack initiation and propagation in lotus metals. For nonporous and lotus copper with various porosities, plastic strain range against the cycles of fatigue loading was determined from the stress-strain hysteresis curves in order to discuss the slip band formation and crack initiation around the pores. Furthermore, fatigue cracks were observed in various cycles of fatigue test, and the crack-propagation path was investigated using lotus copper specimens with a notch.

2. Experimental Procedure

2.1 Specimen

Pure copper with purity of 99.99% was melted by induction heating in a high-pressure chamber filled with the mixture of hydrogen and argon gas. The partial pressure of hydrogen or argon was controlled in the range from 0 to 1.0 MPa to obtain lotus copper with various porosities. The copper was melted and was held at 1523 K for 1.2 ks for hydrogen to be dissolved in the melt uniformly. Then, the melt was poured into a mold. The lateral side of the mold was made of a stainless steel sheet with a thickness of 0.1 mm, and the bottom was made of a water-cooled copper. Thus, the melt was unidirectionally solidified from the bottom to upward and pores grew along the solidification direction, and lotus copper ingot was obtained (the details of this fabrication procedure are described in Ref. 6, 9). One nonporous copper ingot and three lotus copper ingots were prepared; porosity and average pore diameter of each porous ingot are shown in Table 1. The average pore diameters of the ingots were measured by an image analyzer (Winroof, Mitani Corp.). The porosity p of a porous specimen was determined from the

Table 1 Porosity and average pore diameter of prepared ingots, and the shape of specimens prepared from each ingot.

<table>
<thead>
<tr>
<th>Porosity (%)</th>
<th>Average pore diameter (μm)</th>
<th>Specimen shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>61</td>
<td>dog bone, plate</td>
</tr>
<tr>
<td>23</td>
<td>108</td>
<td>dog bone, plate</td>
</tr>
<tr>
<td>40</td>
<td>130</td>
<td>dog bone</td>
</tr>
<tr>
<td>40</td>
<td>130</td>
<td>plate</td>
</tr>
</tbody>
</table>

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apparent density of the porous specimen and the density of nonporous copper. Figure 1 shows the pore structure of prepared lotus copper ingots. Most pores in lotus copper are cylindrical and oriented in one direction. It is to be noted fiber texture exists in the matrix of lotus copper (nonporous copper) and the preferential growth direction of crystals in the texture is the $<100>$ direction. The average grain sizes of lotus copper with porosity $p$ of 40% and nonporous copper on the cross section perpendicular to the longitudinal axis of the column crystals are 0.69 mm and 1.3 mm, respectively. The grain size of lotus copper ingots is smaller than that of nonporous copper ingots.

Dog-bone type specimens with a gauge diameter of 4 mm and gauge length of 6 mm were prepared from the nonporous and lotus copper ingots (Table 1). The longitudinal directions of the specimens are parallel or perpendicular to the longitudinal axis of pores (solidification direction). The surfaces of all dog-bone type specimens were polished with emery papers and then were buffed with slurry containing diamond particles of 1 μm. After the polishing, the specimens were annealed in vacuum at 873 K for 3.6 ks to eliminate the hardening by the machining. In order to observe position of initial crack and direction of crack propagation, two kinds of plate-shaped specimens were prepared. Plate-shape specimens with a gage length of 20 mm, gage width of 6.7 mm, and gage thickness of 2 mm were cut out from the prepared ingots (Table 1) with a spark erosion cutting machine (LN1W, Sodick Corp.). Plate-shape specimens with a gage length of 12 mm, gage width of 4 mm, gage thickness of 2 mm were also cut out from the prepared ingots. For the latter plate-shape specimens, a notch with a depth of 500 μm were cut with low-speed diamond wheel cutting machine (Isomet 11-1180, Buehler Ltd.). The surfaces of two kinds of the specimens were polished with emery papers and then were buffed with colloidal silica particles of 0.04 μm.

**2.2 Fatigue test**

For all the prepared specimens, constant stress amplitude fatigue tests were conducted with a servo-valve-controlled electro-hydraulic testing machine (V-1912, Saginomiya Corp.) in air at room temperature. For the dog-bone type specimens, cyclic tension-compression stress of $R = -1$ was applied to nonporous and lotus copper specimens, where $R$ is the ratio of the minimum stress to the maximum stress. The stress amplitude $\sigma_a$ applied to a specimen was calculated from an applied load and cross-sectional area including pores. Strain on the gauge of a specimen was measured by a clip gauge during fatigue tests. The frequency of the cyclic stress was 5 Hz. Figure 2 shows the waveform of cyclic stress applied to specimens in the initial stage of a fatigue loading. The stress amplitude increases until about 12 cycles, and then, the stress amplitude becomes saturated.

For the plate-shape specimens with and without notches,
cyclic tension stress of $R = 0$ was applied in order to prevent the plastic buckling of the specimen. It is to be noted that a positive mean stress such as $R = 0$ does not affect fatigue behavior as crack initiation and propagation, although the mean stress affects relationship between stress amplitude and number of cycles to failure. \(^{21}\) The maximum cyclic tensile stress of 60 MPa or 26 MPa was applied to both the plate-shape specimens in the direction parallel or perpendicular to the longitudinal axis of the pores, respectively (The stress is chosen from S-N curve of lotus copper \(^{13}\) in order for specimens without a notch to fracture at 1000 cycles.). The frequency of the cyclic stress was 0.25 Hz. For the plate-shape specimens without a notch, the formation of slip bands and crack initiation were observed with a scanning electron microscope by interrupting a fatigue test in various stages of fatigue. For the plate-shape specimens with a notch, the fractured specimens after fatigue tests were observed with an optical microscope in order to investigate the crack-propagation path.

3. Experimental Results

Figure 3 shows the stress-strain hysteresis loops of lotus copper with porosity of 23% for cyclic loadings in the directions (a) parallel and (b) perpendicular to the longitudinal axis of the pores. For both parallel and perpendicular directions, the plastic strain ranges increase with increasing cycles of loadings, and Young’s modulus for a tensile loading decreases with increasing cycles of loadings.

Figure 4 shows the plastic strain range as a function of number of cycles to failure for lotus copper with porosity of 23%, where cyclic stress was applied in the directions (a) parallel and (b) perpendicular to the longitudinal axis of pores.
with increasing stress amplitude in both directions. In the initial stage of fatigue, the plastic strain ranges increase, and then, they decrease; a peak of the plastic strain range appears around $10^4$ cycles in plastic strain range-cycle curves. This is because a plastic strain range increases with increasing applied stress amplitude in the initial stage of a loading (Fig. 2), and then, the plastic strain range decreases by the cyclic hardening of the specimen. After the peak, the plastic strain range becomes saturated. In the final stage of fatigue, plastic strain range increases with increasing cycle of loadings. These trends of the plastic strain range for lotus copper with porosity 23% are consistent with those with porosity of 40%.

Figure 5 shows the saturated plastic strain ranges as a function of the number of cycles to failure $N_f$ for nonporous and lotus copper with porosity of 40%, where cyclic stress was applied in the directions parallel and perpendicular to the longitudinal axis of pores (solidification direction). The plastic strain range of lotus copper is smaller than that of nonporous copper for the same $N_f$. For nonporous copper, the plastic strain range in the direction perpendicular to the solidification direction is almost consistent with that in the parallel direction. On the other hand, for lotus copper the plastic strain range in the perpendicular direction is smaller than that in the parallel direction.

Figure 6 shows the SEM micrographs of lotus copper when cyclic loadings of (a) 0 (before loading) and (b) 112 cycles were applied in the directions parallel and perpendicular to the longitudinal axis of pores; Figs (c) are the higher magnification of Figs (b). For the parallel loading, many slip bands are formed all over the surface of the specimen, including inner wall of pores. The slip band forms initial cracks (grooves whose depth direction is parallel to slip bands) as indicated by the arrow in the figure. On the other hand, for the perpendicular loading slip bands and initial cracks are formed only around pores.

Figure 7 shows fatigue cracks which are formed around pores of lotus copper with porosity of 40% for loadings of (a) 0 (before loading), (b) 212, (c) 412 and (d) 812 cycles in the direction perpendicular to the longitudinal axis of the pores. The number of fatigue cracks increases with increasing loading cycles. The average diameter of pores with initial crack is 235 µm, while the average diameter of all the pores in a specimen is 130 µm, which was measured by the image analyzer. This indicates that fatigue cracks are preferentially formed around anomalously large pores.

Figure 8 shows crack-propagation paths in nonporous and
lotus copper with a notch: (a) nonporous copper and (b)–(d) lotus copper with homogeneous pore structure (porosity is 23%), and (e) lotus copper with anomalously large pores (porosity is 23%). When cyclic loadings are applied to nonporous copper [(a)], a crack propagates in the direction perpendicular to the loading direction. When cyclic loadings are applied to lotus copper in the direction parallel to the longitudinal axis of pores [(b)], a crack propagates in the direction perpendicular to the loading direction regardless the existence of pores. For loadings perpendicular to the...
When a notch-depth direction is perpendicular to the loading in the direction perpendicular to the longitudinal axis, stress field in nonporous copper is homogeneous as well as that in nonporous copper. For a loading parallel to the longitudinal axis of pores is also homogeneous. Therefore, fatigue fracture occurs at the same cycle for both the loadings. This means that the total amount of plastic deformation for the perpendicular loading is smaller than that for the parallel loading although fatigue fracture occurs at the same cycle for both the loadings. This difference in the amount of plastic deformation is caused by the difference in stress field in a specimen. For the parallel loadings, the stress field in the matrix is homogeneous. Therefore, slip bands are formed all over the surface of a specimen as shown in the upper figure of Fig. 6(b), i.e., plastic deformation homogeneously occurs in the matrix. On the other hand, for cyclic loadings in the direction perpendicular to the longitudinal axis of the pores, stress field in the matrix is inhomogeneous; stress highly concentrates around pores. Therefore, slip bands are formed only around pores as shown in the lower figure of Fig. 6(b). Plastic deformation is localized around pores although plastic deformation does not occur in the other regions. Therefore, cracks are formed and fatigue fracture occurs even when the total amount of the plastic strain is small.

When cyclic loadings are applied to lotus copper with anomalously large pores, fatigue cracks are formed around the large pores as shown in Fig. 7. A region in which high stress concentrates is wide around the large pores because the region is proportional to the pore size. Therefore, initial crack easily forms around large pores. Additionally, the probability that the stress field caused by the large pore overlaps with the stress field caused by other pores is high, which results in the preferential formation of fatigue cracks around pores.

4.2 Crack propagation

When cyclic loadings are applied to lotus copper in the direction parallel to the longitudinal axis of pores, a crack propagates along a straight line as well as a crack in nonporous copper. This is because stress field in lotus copper for a loading parallel to the longitudinal axis of pores is homogeneous as well as that in nonporous copper. For a loading in the direction perpendicular to the longitudinal axis of pores, the stress field in the matrix is inhomogeneous. When a notch-depth direction is perpendicular to the longitudinal axis of pores, a crack propagates between pores in which stress highly concentrates, and therefore, the crack-propagation path is not straight. When anomalously large pores exist, a crack propagates by crossing the large pores, because high stress concentration occurs around the large pores owing to the overlap of stress field. When a notch-depth direction is parallel to the longitudinal axis of pores, stress field is homogeneous along the longitudinal axis of pores. Therefore, a crack propagates in a straight line along the homogeneous stress field.

5. Conclusions

We studied crack initiation and propagation in lotus-type porous copper for fatigue loadings using specimens with and without a notch, and obtained the following conclusions.
(i) Fatigue loadings in the direction parallel to the longitudinal axis of pores, stress field in the matrix is homogeneous. Therefore, slip bands are formed all over the specimen surface. On the other hand, for the perpendicular loadings, stress field in the matrix is inhomogeneous. Therefore, slip bands are formed only around pores in which stress highly concentrates. The localized slip bands form fatigue cracks, which leads to fatigue fracture. Therefore, fatigue fracture occurs even when plastic strain range is small.
(ii) Stress field in the matrix of lotus copper affects the direction of crack propagation. For the parallel loadings, a crack propagates along a straight line as well as that for nonporous copper, because the stress field in the matrix is homogeneous. On the other hand, for the perpendicular loading a crack propagates along a path in which stress highly concentrates. When the notch-depth direction is perpendicular to the longitudinal axis of pores, a crack propagates between pores in which stress highly concentrates. When the notch-depth direction is parallel to the longitudinal axis of pores, a crack propagates along stress field which is homogeneous in the parallel direction.
(iii) Stress highly concentrates around anomalously large pores. Because of the high stress concentration, a fatigue crack is preferentially formed around the large pores, and a crack propagates by crossing the large pores.

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