Creep Cavitation in the Neighborhood of Stress Concentrations

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ABSTRACT

The results of several experiments into the formation and distribution of creep cavitation in the neighborhood of stress concentrations is reported. Of particular interest is the use of an image analyzing computer to construct quantitative maps of cavity sizes and distributions. Comparisons are drawn in one case with the results of a finite element simulation, and some degree of overall agreement is noted.

1. Introduction

For elevated temperature components in which the loads are relatively static over long periods of time, creep rupture is usually the dominant failure mode of concern to designers. At stress levels of engineering interest, it is generally accepted that creep rupture is brought about by the formation of tiny voids, or cavities, along the grain boundaries. The process by which such cavities form and grow has been the subject of considerable recent research [1]-[3], but the complexities of the process make it still not well understood.

A problem of particular practical importance is that of understanding the process by which cavities develop in the neighborhood of a stress concentration. Stress concentrations are typically characterized by complex multiaxial stress fields which, under creep conditions, may be time-varying as well. The presence of such stress fields results in fairly complicated spatial distributions of cavitation, and may lead to such interesting and poorly understood effects as the notch strengthening phenomenon.

We report here on two sets of experiments, both of a somewhat preliminary nature, which are concerned with measuring the distribution of creep cavitation in the neighborhood of a stress concentration. A novel feature of these experiments is the use of an automatic image analyzing computer to measure the extent and the distribution of the cavitation. In addition, a numerical simulation of one of these experiments was conducted and the results compared to experimental observations.

2. Experiments and Analysis

Two sets of experiments were conducted: one with specimens fabricated from the ferritic steel 2 1/4 Cr-1 Mo and the other with specimens of AISI type 304 stainless steel. In both cases the specimens contained either internal cutouts or external notches so as to give rise to stress concentrations. All specimens were loaded under constant or piecewise constant load conditions in standard creep machines.

2.1 2 1/4 Cr-1 Mo Tests and Analysis

Two specimens were fabricated from a commercial heat of 2 1/4 Cr-1 Mo and were heat-treated so as to achieve a ferrite-pearlite microstructure with an average grain size of 40.4 μm . The specimen geometry was that of a standard plane stress specimen containing a central circular hole with a diameter one-quarter of the specimen width. Both specimens were tested under piecewise constant load conditions at 565°C. One of the tests, which was continued to failure, was discussed in greater detail in [4]. The other was loaded at a remote nominal section stress of 42 MPa for 3000 hours followed by 1324 hours of 87.4 MPa. The test was then terminated prior to failure, and the specimen carefully polished and etched for metallographic examination. Optical microscopy revealed fairly abundant intergranular cavitation near the edge of the hole covering an area about 30° to either side of the axis of minimum cross-sectional area. Figure 1 shows a photograph of this region of the specimen, with the tensile axis being oriented vertically. Sparsely distributed cavitation was also observed outside this region.

The specimen was also scanned by the QuantimetTM image analyzing computer at the National Bureau of Standards. This device is capable of sequentially examining a large number of microscopic fields on the specimen and measuring the grey level content of each field. Under the proper conditions, this will be equivalent to the area fraction of cavities contained within the field because the cavities stand out in dark contrast against a polished metal

surface. This information can then be used to build up a quantitative picture of cavity distribution throughout a specimen. When used in conjunction with optical microscopy, the QuantimetTM is capable of resolving cavities having a minimum diameter of about one micron.

The principal drawback to the use of image analyzing computers in this application is that certain types of inclusions also appear as dark objects against the light polished background, and hence will be included when computing the grey level content. This proved to be a particular problem with the 2 1/4 Cr-1 Mo specimen because of the relatively large proportion of sulfide particles distributed along the grain boundaries.

Figure 2 shows the results of the computer scan of the 2 1/4 Cr-1 Mo specimen as displayed on a CRT terminal. The scale at the left of the figure gives the measured grey level fraction in units of 0.1%, with the specimen tensile axis being oriented vertically. The area of each field examined was 0.12 mm². It may be seen that there exists a fairly homogeneous distribution of fields containing grey level fractions of between 0.1% and 0.5%. This may be attributed to the presence of sulfide inclusions and results in a sort of background noise which effectively serves to mask the presence of the smaller creep cavities.

Another difficulty experienced here was the fact that the bulk of the observed cavitation lay in close proximity to the edge of the central hole. Hence most of the fields scanned in this area overlapped a portion of the hole and yielded artificially high values of grey level fraction. In Figure 3 such fields were included as part of the central hole, and thus little of the cavitation existing near the edge of the hole is apparent here.

The problems just discussed, along with the sparsity of the cavitation existing outside the immediate neighborhood of the hole, make the interpretation of Figure 2 a somewhat ambiguous process. As noted, the sulfide particles tend to mask the presence of the smaller cavities, and hence only the fields containing larger cavities (or larger numbers of cavities) stand out. Interestingly enough, these appear not to be distributed along the axis of minimum cross-sectional area, but rather at angles to this axis.

In order to aid in understanding the experimental results, a numerical simulation of the test was conducted using finite element techniques. The analysis is discussed in some detail in [4], but one of its noteworthy features is the use of an advanced, time-dependent constitutive model due to Robinson [5]. The finite element analysis yielded the time-dependent stress and deformation fields in the specimen. These were used in conjunction with some empirical cavitation data for 2 1/4 Cr-1 Mo obtained from density change measurements due to Matera and coworkers [6], and which was generalized to non-constant stress histories by Piatti et al. [7]. The result was the predicted cavity volume fraction distribution for the specimen, a quantity which can be directly related to the cavity area fraction. Figure 3 shows the distribution calculated using a maximum principal normal stress multiaxial criterion, with the data normalized to unity. A similar calculation using a von Mises effective stress multiaxial criterion led to results which did not differ greatly from those shown in Figure 3.

Not surprisingly, Figure 3 indicates that the region of greatest cavitation is predicted to lie in the area of highest stress concentration at the edge of the hole. However the predicted cavitation level drops off rather sharply with angular distance along the circumference of the hole, and is about a third of the maximum value at 30° from the horizontal axis. This is in rough agreement with what may be seen in Figure 1, except that here the cavitation appears to be fairly uniformly distributed along the circumference to about 30° to

either side of the horizontal axis. Moreover, Figure 3 shows that the contours seem to develop a banded structure at an angle to the horizontal with increasing distance from the horizontal axis. This again is in rough agreement with the experimental results shown in Figure 2.

2.2 Type 304 Stainless Steel Tests

A number of experiments were also conducted on specimens fabricated from AISI type 304 stainless steel. All specimens were given a solution annealing heat treatment (1050°C for 30 minutes) prior to testing under constant load conditions at 600°C. These specimens contained external notches of varying geometry. Both axisymmetric, round-bar specimens and plane stress specimens were tested. In order to produce the greatest amount of cavitation, the specimens contained double sets or rows of notches. The specimens were then tested to failure. Failure always occurred at one of the sets of notches, leaving the other set of notches at the point of impending failure and usually containing a well-defined pattern of cavitation.

The results from two representative tests are shown in Figures 4-7, which show the region of the unfailed notches. Both specimens shown here were axisymmetric, round-bar specimens containing double sets of notches in the shape of shallow circular arcs. The specimens were sectioned axially after testing and then polished for examination. The specimen shown in Figures 4-5 was tested at a nominal stress across the minimum cross-sectional area of 310 MPa, and failure occurred in eleven hours. Figure 4 shows that the bulk of the cavitation occurred near the plane of minimum cross-sectional area.

Figure 5 shows the results of the imaging analyzing computer scan for this specimen, the area of each field scanned being 0.5 mm^2 . Because type 304 stainless steel contains far fewer inclusions than 2 1/4 Cr-1 Mo steel, the data shown in Figure 5 can be attributed almost exclusively to creep cavitation. It is to be noted in this regard that a comparison of Figures 4 and 5 indicates a close correspondence between the image analyzing computer scan and what can be observed optically.

Figures 6 and 7 show the results of a similar test carried out at the somewhat lower nominal stress of 264 MPa across the minimum cross-sectional area. Failure occurred after 90 hours. The cavitation pattern observed here was both quantitatively and qualitatively different from that seen on the previously described test, being in general more widespread and less severe. Of particular interest is the spatial distribution of cavities observed in this test. This took the form of a double V or chevron, with cavitation spreading out from the base of each notch and meeting in the center to form the apex of the V. The distribution here is in marked contrast to that shown in Figures 4 and 5 where the cavitation is essentially confined to the plane of minimum cross-sectional area.

At the moment, the reasons for the difference in spatial distribution of cavities between the two tests is not known, beyond the obvious observation that the test shown in Figures 4 and 5 was conducted at a higher stress level than that shown in Figures 6 and 7. Numerical simulation such as was carried out for the 2 1/4 Cr-1 Mo test would be helpful in answering this question, but a lack of the appropriate material constants required by Robinson's constitutive model for type 304 stainless steel, as well as several difficulties to be mentioned subsequently, have thus far precluded this.

3. Discussion

We have reported here on the results of several experiments, one with accompanying analysis, into the distribution of creep cavitation in the neighborhood of stress concentrations. One of the interesting features of these experiments is the use of an image analyzing computer to define and quantify the cavitation distribution. This is felt to represent the first use in this application of image analyzing computers, which yield information which is quite difficult to obtain by other techniques.

Efforts are now under way at extending the work reported here with type 304 stainless steel specimens. Of obvious importance in interpreting the results is a knowledge of the time-dependent stress and strain fields within the specimen, which can be in practice obtained only by numerical techniques such as the finite element method. Accordingly, efforts are also under way to modify our finite element code to analyze the tests of type 304 stainless steel specimens. Besides obtaining an appropriate set of constants for the constitutive model, other, more difficult, problems must be addressed such as nonlinear kinematics for large deformations and rotations and the effect of cavitation upon the constitutive behavior of the material.

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Fig. 1 - Intergranular cavitation near side of hole in 2 1/4 Cr-1 Mo specimen.

Fig. 2 - Image analyzing computer scan of 2 1/4 Cr-1 Mo specimen.

Fig. 3 - Predicted normalized cavity volume fraction distribution for 2 1/4 Cr-1 Mo specimen.

Fig. 5 - Image analyzing computer scan of type 304 stainless steel specimen ($\sigma=310$ MPa).

Fig. 4 - Optical view of type 304 stainless steel specimen ($\sigma=310$ MPa).

Fig. 6 - Optical view of type 304 stainless steel specimen ($\sigma=264$ MPa).

Fig. 7 - Image analyzing computer scan of type 304 stainless steel specimen ($\sigma=264$ MPa).