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Stress induced creep cavity

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ABSTRACT

Studies monitoring cavity nucleation with strain after creep deformation has limited information with varying applied stresses. In the present communication, a large number of experiments were performed to investigate cavity nucleation at different stresses for a primary reformer tube. It has been found that with the increase in stress, cavity formation increases drastically, which is more prone to nucleate at grain boundary triple junctions rather than grain boundaries where the extent of initial inclusions/other second phase particles was kept unaltered.

1. Introduction

Fracture in ductile polycrystalline alloys occurs through void nucleation, growth and coalescence [1,2]. Typically the voids, which are approximately spherical, nucleate from inclusions/second-phase particles present in the alloy under favourable hydrostatic tensile stress in the presence of plastic strain. The voids then grow under the influence of applied stress. Once the size of the voids grows to a sufficiently large size, they will coalesce either with the nearby crack or with neighbouring voids. Voids not only initiate and grow at inclusions but also nucleate at precipitates, shear band intersections, grain boundary (GB), grain boundary triple points (GBTP), other second-phase particulate matter, etc. [2].

Like most other types of fracture, creep fracture occurs by the nucleation and stable growth of cracks followed by unstable crack growth. Ashby and Dyson [3] have classified four broad categories of mechanism of creep damage: (a) the nucleation and subsequent growth of cavities, and hence fracture by coalescence, (b) failure by the decrease of cross-sectional area with large strain, (c) degradation of the microstructure, by thermal coarsening of particles or by a dislocation substructure induced acceleration of creep and (d) finally, environmental degradation [3,4]. It is generally believed that creep cavities are nucleated at geometrical irregularities or second phase particles, such as carbide particles, on the GB where high stress concentration can develop. Cavity formation occurs either by particle fracture or by separation/decohesion of the particle matrix interface [4].

The size, shape, type, and connectivity of grains in the microstructure also play an important role in controlling void nucleation, their growth and eventually creep fracture. In oxygen free high conductivity copper, Nieh and Nix [5] observed that failure occurred by GB void formation during high-temperature creep tests. Both the GB void size and slip band spacing varied inversely with applied stress [5]. The one-to-one correspondence between GB void size and slip band spacing suggested that void nucleation resulted from the intersection of slip bands with the GB. The creep damage of austenitic stainless steel progresses with the nucleation and growth of cavities or cracks [6]. The cavities or cracks are observed at the GB between precipitates and matrices or the GBTP. The formation and growth of cavities or cracks is dominant after about half of the lifetime. But this material is also used at high temperatures where creep damage is the significant cause for failure. The microstructural inhomogeneities in a polycrystalline alloy may lead to non-uniform local stress distribution; hence the local stresses in the GB phase at the location of large grains can exceed the critical stress for cavity nucleation [7].

Thus far, reported literature pertains to the phenomenology, mechanisms and constitutive relationships for creep and creep rupture. However, information related to creep cavitations at various stresses is limited. Most of the efforts in the study of creep cavitations in steels have been focused on experimental research to examine the effect of microstructure on the formation of cavities. The present work aims at investigating the effect of applied stress on creep cavity formation at constant temperature of a primary reformer tube. These studies have also shown that cavities are formed more easily at GBTP rather than at GB, where other second phase particles and initial inclusions were kept unaltered.

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To test the hypothesis that there is a strong correlation between applied stress and creep cavity nucleation from the GB and GBTP, where initial inclusions and second phase particles were kept constant, a scheme was implemented in centrifugally cast primary reformer tube (HP40 grade) steel for creep tests at various stress levels at 870 °C.

2. Experiments

Eleven years service exposed primary reformer grade HP40 tube (25Cr–35Ni–Nb with C 0.4%) was used in the present investigation. The microstructure of centrifugally cast tubes in the outer wall area is columnar and the inner part is equiaxed. The columnar structure, therefore more dense, and all impurities are separated by the centrifugal forces to the inner wall, as they have a lower density than the liquid melt. Cast austenitic stainless steels of the H-series are commonly used as a reformer tube working at temperatures that can be close to 1000 °C [8]. In the as-cast alloy, mainly $Cr_{23}C_6$ alternating with NbC along the GB and some finely dispersed NbC in the matrix have been found in the material [9]. The austenite dendritic cell size in the columnar region has been found to be significantly lower than that of the equiaxed region [9]. The austenite dendrites are revealed by a network of fine precipitation in alternating white and dark contrast (Fig. 1). Niobium has been used in centrifugally cast tubes as a eutectic carbide forming element to increase creep strength and creep ductility, as well as carburisation, which is mainly used for steam reformer and steam cracker furnace tubes [9].

The creep tests were performed at 870 °C and at four different stress levels (i.e., 50, 56, 62 and 68 MPa) for the top and bottom parts of the primary reformer tube, where the bottom was more degraded due to overheating. Round bar cylindrical solid specimens with a gauge length of 28.47 mm and a gauge diameter of 5.0 mm were used for creep experiments. The fracture surfaces of all the samples were analysed by scanning electron microscopy (SEM) under secondary electron mode and it has been found that the type of fracture was ductile in nature. The other broken pieces were longitudinally sectioned along the mid-plane, polished through conventional metallographic technique to reveal creep cavity. Various techniques, including electron backscatter diffraction (EBSD), X-ray diffraction (XRD), synchrotron microtomography, small angle neutron scattering (SANS), and image analysis, are commonly used to determine the extent of cavity present inside the material. In the present investigation, extensive image processing was carried out on the mirror-finished optical micrographs obtained from the cross-sectional planes along the specimen axis and parallel to the fracture surface, for quantitative information on creep cavity area, in specimens tested at different stresses. Starting from the fracture end of the specimens, a large number of fields (i.e., several optical images) were sequentially viewed under an optical microscope at predetermined diametral locations, and images of the microstructure were digitally recorded with a magnification of 400 ×. Creep cavity appears darker (i.e., grey) against the light background of the austenite matrix under the optical microscope. These optical images were analysed after appropriate grey-thresholding to obtain the creep cavity area as a function of true strain. This method of estimating the extent of creep cavity was employed for all creep tested specimens rupturing at different stress levels. The true strain corresponding to the amount of creep cavity that was quantitatively determined was estimated by measuring the diameter (D) of the specimen at the specific transverse plane with the help of a travelling microscope and making use of the equation: $\varepsilon = 2\,LN\,(D_0/D)$, where D_0 is the original diameter and D is the measured diameter. The cavity population adjacent to the

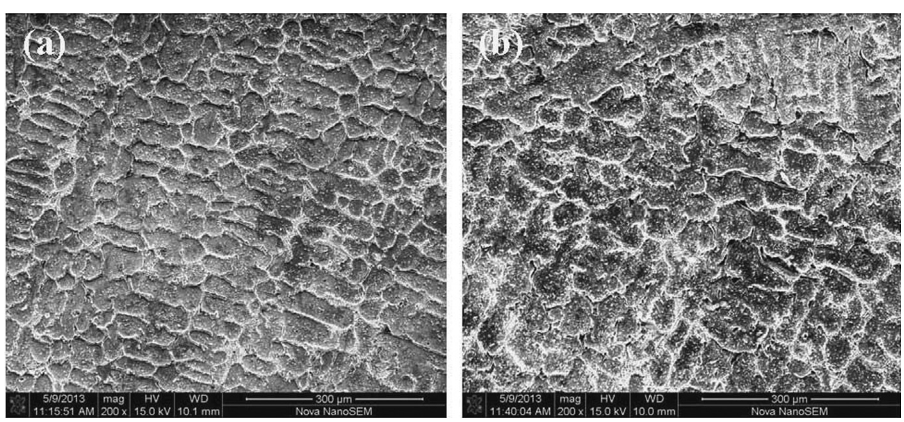

Fig. 1. As received microstructures showing dendritic matrix and carbide precipitation at grain interior, which reach Cr and Nb. (a) Top and (b) bottom tubes.

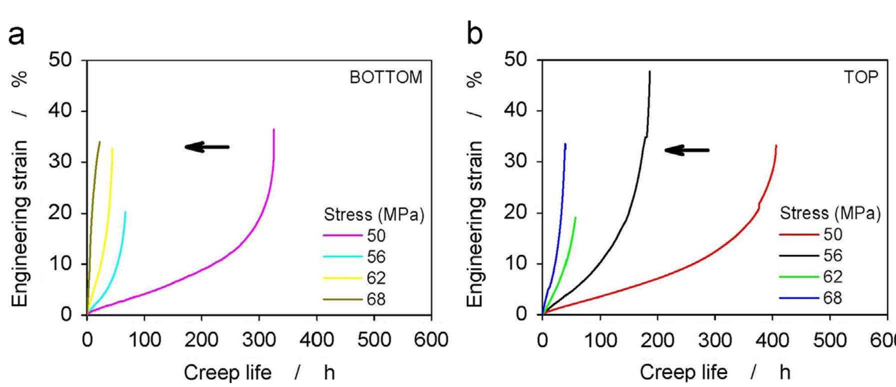

Fig. 2. Experimental creep curves at four different stress levels for the (a) bottom and (b) top tubes.