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Structural integrity of service exposed primary reformer tube in a petrochemical industry

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ABSTRACT

This paper aims at quantifying creep damage, in terms of Kachanav's continuum damage mechanics (CDM) model and Bogdanoff model of service exposed primary hydrogen reformer tube. Quantification of creep damage was made from scatter in voids which was quantified from light optical microscopy (LOM), SEM (scanning electron microscope) equipped with image analyzing technique and EDX analyser, in terms of two damage parameters A and A*. Scatter in creep deformation behaviour of the material, is probably due to variation in mode of fracture and scatter in voids. Probability of rupture due to void area, shifts towards the higher population of void with increase in true strain. Experimental data for estimating creep damage agrees well with both the simulation based models. The value of damage tolerance parameter λ infers that growth of cavities has been attributed to a purely diffusion controlled mechanism, grain boundary sliding mechanism, or a combination of both.

1. Introduction

Most of the structural materials are developed by optimizing microstructure to deliver a specified short term mechanical performance. During high temperature service, the carefully tailored microstructure may progressively degrade with often unexpected consequences for long term creep performance. An effective life assessment strategy not only requires a robust creep mechanics framework but also a quantitative description of the various microstructural damage mechanisms. Therefore it is essential to quantify the microstructural damage parameters that have a significant influence on the creep behaviour. Nucleation and growth of cavities or voids at grain boundaries or even at precipitate/matrix interface are responsible for creep rupture of the tubes. Quantification of creep damage was made from replicated creep data in terms of two damage parameters A and A*. Quantitative metallography evaluation of void, has already been studied on this material and is reported elsewhere [1].

HK and HP series are centrifugally cast austenitic stainless steels, widely used as for reformer tubes in the petrochemical industry for ammonia, methanol and hydrogen plants., and they operate above 900 °C. The main criteria for their selection is their high creep strength at and above 900 °C [2–4]. But in remaining life estimation studies of these materials, scatter characteristic of service exposed material is not taken into account for damage.

During service exposure in aggressive environment, reformer tubes are subjected to carbonization, oxidation, overheating, stress corrosion cracking, sulfidation and thermal cycling. Traditional stainless steel application for vertical reformer tubes has been gradually replaced or substituted by centrifugally cast HK40 alloys and subsequently by HP modified alloys. Even after these advancements, many reformers fail during service within a period of 3–15 yrs, despite most of these tubes have a specific design life of 10–15 yrs. Literature survey has revealed that they can have a significant remnant life beyond their specified design life [3–8]. Through-wall thermal stresses are known to cause problems like premature failure in HK 40 tubes [3]. Premature failure of reformer tubes are very often observed mainly because of overheating and prolong service ageing leading to embrittlement and early onset of

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creep damage [3–8], although premature ageing can improve ductility and actually reduce thermally induced damage [3]. Overheating because of inadequate feed flow caused by the choking of damage catalyst resulted in failure of reformer tubes made of modified HK40 steel after 4 years of service exposure [6]. The states of damage along reformer tube in service for 10 years [3,6,8] when metallographically analysed, revealed that the damage level was non-uniform. It was significantly higher in the lower part of the tube than that in the upper part due to overheating [3,6,8]. Residual life assessment studies are generally performed at progressive intervals during a well planned shut down, both by non destructive evaluation technique and also by destructive tests like accelerated creep or stress rupture tests above the operating hoop stress level of the tubes.

In the present work accumulation of creep strain data of ~11 years service exposed reformer tube made of HP40 grade of steel in a petrochemical industry has been studied for various stresses at 870 °C. The results are supported with a quantitative metallographic study on the extent of creep cavitations and statistical analysis of void area fraction, carried out on the service exposed reformer tube material at 870 °C/50 MPa and 870 °C/68 MPa respectively. Damage quantification of any component would be constructive if its estimation could be well established within the scatter band of conventional creep strain vs time to rupture plot. The existence of scatter in the replicated creep and creep rupture data leads to substantial amount of uncertainty in the assessment of creep damage. Replicated creep data indicates repeat tests being carried out at identical test conditions i.e., under same stress and temperature. The A parameter is based on the constrained growth and the damage parameter ω in the CDM (continuum damage mechanics) model or (K-model). The microstrucrally determined damage parameter A^* would be compared with the damage prediction by the probabilistic model. Simulation based K-model and Bogdanoff model (B - model) based on Markov process, have been applied for analyzing and estimating creep damage evolution of the material after about 11 yrs service exposure. Quantification of creep damage was made from replicated creep data in terms of two damage parameters A and A^*. A-parameter is equated to the damage parameter, ω from K-model has been related to the measured parameter $A_{1.}$ The **A**-parameter developed by Cane and co-workers [9–11] was used to quantify creep damage. This is equivalent to the continuum damage parameter $\boldsymbol{\omega}$ in the classical Kachanov/Rabotnov model [12,13]. The **A**-parameter approach is based on a concept that as time passes, damage accumulates which changes the proportion of material available to carry load. That is, as and when a grain boundary (GB) in the load bearing cross section is damaged, it starts unloading resulting in an increase in stress on the undamaged part of the cross section. Therefore, an alternative approach for creep damage quantification is the $\mathbf{A^*}$ parameter. In this study, the damage parameter $\mathbf{A^*}$ which is only an extension of the **A**-parameter theory, was considered as the cumulative contribution of damaged grain boundaries and number of creep cavities or voids at the grain boundary triple points (GBTP). Quantitative metallography study was required to obtain microstructural information. A^* is more sensitive to damage prediction than **A** because it picks up localized damage in the form of voids which actually forms in the tertiary region of creep life. Nevertheless, $\mathbf{A^*}$ takes into account a greater compensation of the experimental scatter in creep data than **A**. Creep damage accumulation and its associated scatter was simulated using Markov process and Monte Carlo technique [14].

In particular, developing a suitable methodology for characterizing creep damage evolution through quantitative metallography evaluation of creep cavitations is aimed at, which is so far, not been well established in this material.

2. Experimental procedure

The tube material used in this study is made of HP40 grade of steel which is about 11 years service exposed and operating at 870 °C, though the designed operating temperature of the tube specified by the plant is 920 °C. The service temperature of the bottom portion of the tube was at times ~10 °C greater than the top portion of the tube as reported from plant history due to overheating. The tubing material is equivalent to 25Cr35Ni1Nb0.2-Ti0.01Mo. Room and high temperature (850 °C, 870 °C and 890 °C) tensile tests of the material were carried out as per ASTM-8M standard, which enables one to fix the operating stress level during creep tests so that rupture occurs reasonably within a stipulated time frame. Conventional creep tests of the tubes at 870 °C were conducted as per ASTM E 139/83 specification in single point ATS Creep Testing Machines (2T capacity), equipped with a three zone split furnace and maintaining zonal temperature within ±2 °C with a high precision controller. Strain measurements were made as per ASTM E 139/83 standard procedure, with LVDT (Linear Variable Displacement Transformer) attachment in the bottom pull rod, outside the furnace but connected to both the extensometers fixed at the top as well as bottom portion of the specimen gauge length, well within the furnace of the ATS creep testing machine. Standard round bar cylindrical solid specimens having a gauge diameter of 5.0 mm and a gauge length of 28.47 mm were chosen along the length of the tube both for tensile as well as creep tests [1]. Creep specimens were loaded namely at 50 MPa, 56 MPa, 62 MPa and 68 MPa/870 °C i.e. in the stress range (50–68 MPa) at 870 °C. In other words, conventional creeps tests were carried out on a set of four specimens at each stress and at 870 °C in the stress range (50–68 MPa), i.e. at four stress levels to examine the statistical creep behaviour.

Scatter in voids was quantified from light optical microscopy (LOM), SEM (scanning electron microscope) equipped with image analyzing technique and EDX analyser. Identification of various elements was carried out with EDX. A detailed analysis of this technique and its interpretation is given elsewhere [1]. Fractographic features were recorded and studied for all the crept samples in the SEM. One half of the creep ruptured pieces were cut longitudinally along the mid plane, mirror polished through conventional metallographic technique to reveal creep cavity. Fractography was carried out on the other half of the fractured specimens. Quantification of damage in terms of voids, was made both at perpendicular as well as parallel directions to the loading axis of the gage length of the specimens,. These observations were made on a plane which corresponds to the mid section of the specimen diameter at different distances from the ruptured surface. Ten optical images at diametric locations were recorded digitally at 400X. Only after appropriate grey-thresholding, these optical images had been analysed with a view to obtaining the void area as a function of true strain after creep rupture.

It is well established that true stain is a function of the diameter (D) of the specimen at the specific transverse plane and is represented by Ref. [1]:

$$\varepsilon = 2Ln\left(\frac{D_0}{D}\right) \tag{1}$$

where D is the measured diameter and D_0 is the original diameter of the specimen. For the purpose of maintaining uniformity, void area was normalized with respect to true strain which has been measured from crept and ruptured specimens as shown in Fig. 5.