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Evaluation of the creep cavitation behavior in Grade 91 steels

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ABSTRACT

Even in properly processed Grade 91 steel, the long term performance and creep rupture strength of base metal is below that predicted from a simple extrapolation of short term data. One of the mechanisms responsible for this reduction in strength is the development of creep voids. Importantly, nucleation, growth and inter linkage of voids under long term creep conditions also results in a significant loss of creep ductility. Thus, elongations to rupture of around 5% in 100,000 h are now considered normal for creep tests on many tempered martensitic steels. Similarly, creep damage development in the heat affected zones of welds results in low ductility cracking at times below the minimum expected life of base metal. In all cases, the relatively brittle behavior is directly a consequence of creep void development. Indeed, the results of component root cause analysis have shown that crack development in Grade 91 steel in-service components is also a result of the formation of creep voids. The present paper examines background on the nucleation and development of creep voids in 9%Cr type martensitic steels, presents information regarding methods which allow proper characterization of the creep voids and discusses factors affecting creep fracture behavior in tempered martensitic steels. It is apparent that the maximum zone of cavitation observed in Grade 91 steel welds occurred in a region in the heat affected zone which is ~750 μm in width. This region corresponds to the band where the peak temperature during welding is in the range of ~1150–920 °C.The cavity density in this band was over about 700 voids/mm^2 at an estimated creep life fraction of ~99%.

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1. Introduction

Tempered martensitic 9%Cr steels are favored in a range of boiler applications because when properly processed they exhibit a favorable combination of properties including; high thermal conductivity, low thermal expansion coefficient, low susceptibility to thermal fatigue, good corrosion and oxidation resistance, and relatively good creep resistance [1,2]. These properties derive from the presence of a homogeneous tempered martensitic microstructure where the matrix contains a substructure with a high dislocation density and a fine dispersion of second phase precipitates.

The complex nature of the long term creep behavior is emphasized by consideration of data compilations considering creep ductility. Published information for Grade 91 steel showing the variation of the reduction of area at fracture after creep testing at 600 °C (1112 °F) is presented in Fig. 1 [3,4]. It is apparent that while most steels show reduction of area above 70%, some results for lives of 10,000 h or less, exhibited reduction of area at failure of around only 1%. Post test examination has shown that the high ductility failures occur after significant strain accumulation and necking. Post test metallographic assessment of the creep brittle fractures showed that high densities of creep voids were present. Detailed examination has revealed that the nucleation of creep cavities was linked to the local microstructure and composition [5–8]. In particular, even relatively small (as measured in weight percent) amounts of sulfur (S), copper (Cu), tin (Sn), antimony (Sb), lead (Pb) and arsenic (As) have been shown to make tempered martensitic steels more susceptible to void nucleation. Detailed reviews considering the effects of composition, steel making and processing on the high temperature performance of Grade 91 steel have been published [9,10].

A unified understanding of damage evolution in Grade 91 steel must be grounded by the use of valid methods of assessment applied to well designed and executed experiments. While there is an appreciation that creep damage is often concentrated in the heat affected zone (HAZ) there are different explanations for this susceptibility. It is important to note that there have not been many

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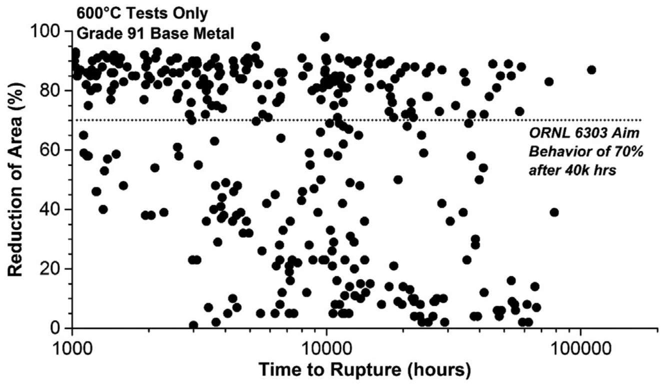

Fig. 1. An example of the variation in creep performance for Grade 91 parent material as a function of reduction of area versus time to rupture and as reported in Ref. [3]. This data is compared to the stated objective in the design of Grade 91 steel to achieve 70% reduction of area in 40,000 h in Ref. [4].

comprehensive studies where the evolution of creep damage in well pedigreed Grade 91 steel and in welded components is recorded. Perhaps more alarmingly, there have been few studies which provide a full justification of the method or means used to assess damage in either base metal or weldments. A comprehensive approach should include details of specimen preparation, the equipment used and the procedures for creep void counting using either conventional or state-of-the-art tools.

As shown in Fig. 2 [11] there is a general trend for the number density of creep voids present in martensitic steels to increase with creep life fraction, t/t_r. The shape of this curve is related to the value of λ, where λ is a function of tertiary creep strain. In higher ductility tests, λ will be generally be a higher value, and the tests show more accelerating or 'tertiary' type creep. In most tempered martensitic steels, void nucleation is linked to the presence of 'hard' particles such as inclusions within the steel. The mechanism of cavity growth is linked to local creep strain, with the growth or dilation rate of individual voids considered to be constrained by deformation of the local matrix. Under these conditions the following relationship provides a reasonable description of the development of creep damage.

In this expression the life fraction is related to the number fraction of voids as:

$$\frac{t}{t_r} = \left[1 - \left(1 - \frac{N}{N_f}\right)^{\lambda}\right]$$

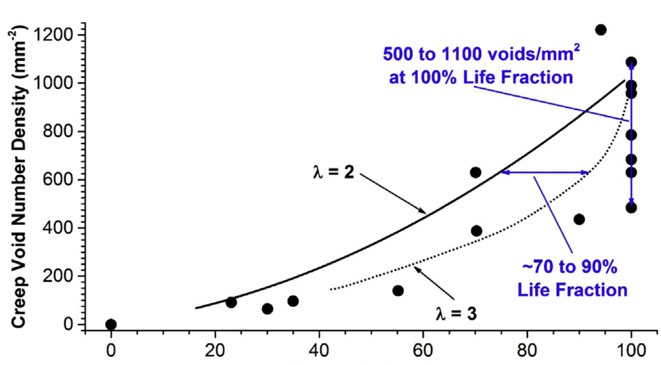

Fig. 2. Compilation of data showing how the number density of creep voids present increased with creep life fraction for CSEF base metal.

where t is the creep exposure time for given conditions, t_r is the creep rupture life for the same conditions, N is the number of voids per mm^2, N_f is the number of voids per mm^2 at fracture and λ is a function of tertiary creep strain. Thus, a higher value of λ is calculated for steels and conditions which exhibit greater tertiary creep.

The values of the parameters in this equation have a significant influence on the form of the relationship between the number of voids and creep life. The way in which the value of key parameters relates to damage rate is illustrated in Fig. 2. Both of the lines drawn in this Figure have been based on the same number of voids at fracture, namely an N_f of 1200 voids mm^{-2}. However, the calculations of the relationship between number of creep voids and life fraction have been made for different values of λ. As λ increases from 2 to 3, the curve defining the rate of change in void density becomes noticeably steeper; this is particularly true as the life fraction increases. Thus, it is interesting to note that for a void density of ~600 voids/mm^2, the calculated life fraction range is 70–90%, Fig. 2. This range approximately bounds the experimental data. Similarly, at 100% of life fraction, the void density values vary from 600 to >1200 voids/mm^2. It is clear that an accurate assessment of component integrity can only be performed based on knowledge of how steel composition and microstructure change N_f and λ.

Some of the variation in reported creep void densities from the experimental studies is undoubtedly a consequence of differences in the experimental methods used. Thus, when post test examination is performed, samples maybe investigated on different planes, using different methods of preparation and variations in the methods and magnifications used to reveal creep voids. Thus, for example, in most cases when using high magnifications for the examination more creep voids will be resolved. Furthermore, even when sophisticated equipment, such as a laser microscope, was used to track the development of damage in the HAZ of Grade 91 steel welds [12], no detailed procedure regarding the experimental methods was presented. It is apparent then that the variability in methods used for characterization adds to the uncertainty present from the wide variations in creep testing methods and control. These uncertainties makes definitive comparison of results from different sources very difficult. Moreover, the uncertainty introduced by the lack of experimental definition, makes it much more difficult to isolate the influence of specific metallurgical features from scatter which results from preparation effects or inconsistencies in counting methods.

Recent research at EPRI has generated information regarding the factors affecting damage development in selected creep strength enhanced ferritic (CSEF) steels. One specific research project provided interrupted creep tested samples as the basis for development of NDE techniques to evaluate damage in Grade 91 steel weldments. A key issue in this work was to establish a reliable procedure for precise creep cavitation counting and characterization of damage in martensitic steel Grade 91 weldments. The present paper describes the development of this procedure, including the use of advanced metallographic techniques for sample preparation and recording damage a consistent and well-engineered method for post-processing of the data using image analysis software. The cavity characterization method is illustrated with reference to a number of critical observations regarding creep damage development in Grade 91 steel weldments.

2. Material and creep testing

EPRI have been involved in on-going research activities to establish the factors affecting creep and fracture behavior of CSEF steels for many years. This research has involved planning and execution of comprehensive projects on damage development in

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