UNDERSTANDING DAMAGE MECHANISMS IN FERRITIC STEELS

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ABSTRACT

A considerable effort is underway on an international level to better understand the performance of advanced ferritic/martensitic steels under service conditions typical of power boilers. These 9-12% Chromium alloys have been modified by means of Mo, W, V, Nb, N, B, Cu, Cu, and other additions that influence the critical transformation temperatures, corrosion resistance, strength, or long-time stability. Without exception the strength of the steels degrades during service at temperatures above 600°C, so the understanding of damage mechanisms that lead to this degradation is of vital concern in the selection and optimization of the steels for specific boiler components. In the work reported here, a number of damage mechanisms were explored for the advanced 9-12% Cr-Mo steels. The mechanisms included fireside and steamside corrosion of tubes, long-term aging effects, strain-induced dynamic recovery, and microstructural modifications introduced by excursions above the A_1 temperature. In most of the work 9Cr-1Mo-V steel was selected as the reference material but use was made of damage models developed for other advanced steels. Creep-rupture testing was undertaken on material aged for times up to 75,000 hours, exposed to creep stress for times up to 82,000 hours, and service-exposed for times to 143,000 hours. Damage models that were examined included the life-fraction, the Monkman-Grant, the MPC Omega function, and the Dyson Continuum Damage Mechanics model. Because of the importance of weldment behavior to damage models, special efforts were made to develop the capability to predict the critical temperatures as a function of base metal and weld metal compositions. Both experimental and computational methods were used to explore equilibrium and non-equilibrium microconstituents. The rate of evolution of these microconstitutents was found to be an important consideration in the development of "more advanced" damage models but was not needed in the simple damage approximation provided by life fraction and Monkman-Grant.

INTRODUCTION

Advanced ferritic/martensitic steels such as 9Cr-Mo-V, 9Cr-W-V, and 12Cr-W-V are experiencing increased usage for construction of boilers and heat recovery steam generator components. Also, they are being used to replace stainless steels and lower strength Cr-Mo steel in both subcritical and supercritical steam plants. There is concern about the high-temperature performance of the advanced steels for several reasons. First, they exhibit a higher sensitivity to temperature than the 300 series stainless tubing steels that they often replace. Second, they tend to be metallurgically unstable and undergo significant degradation at service temperatures in the creep range. Third, the experience base is limited in regard to duration. Fourth, they will be used for thick-section, high-pressure components that require high levels of integrity. To better understand the potential limitations of these steels, damage models are being developed by a number of investigators. These models vary greatly in complexity from simple concepts such as summation of life-fractions to continuum damage mechanics (CDM) formulations that consider both the metallurgical and mechanical factors that effect component life under constant and variable loadings. In the evaluation of pressure-bearing components, the concerns usually relate to long-time service. The activities described below outline some of the research directed toward resolving some of the issues that are linked to the usage of these steels. Most of the effort involves 9Cr-1Mo-V steel which has experienced service since 1980.

DAMAGE MODELS

Of the many life prediction and damage models that have been proposed over the years, only a few were selected for examination. The models include the Life Fraction, which is time-based and often identified as Robinson's rule (1), the iso-stress method which was used in the 1980s and 1990s (2), the Monkman-Grant method, which makes use of the observed correlation between rupture life and creep rate (3), constitutive creep law models that include tertiary creep (4, 5), the recently developed API-MPC Omega method, which is based on tertiary creep behavior (6) and is often used for fitness-for-service evaluations (7), and Continuum Damage Mechanics models, that incorporate specific damage mechanisms into a creep deformation model (8, 9). Several of these models were reviewed and evaluated recently by Holdsworth and Merckling (10). More details regarding the application of the models to 9Cr-1Mo-V steel are available elsewhere (11,12).

CREEP BEHAVIOR AFTER LONG-TIME EXPOSURE

In the past year, creep tests were undertaken of 9Cr-1Mo-V steel samples exposed to prior creep for times from 40,000 hours to 83,000 hours. In most instances the new testing conditions were 600°C and 100 MPa which would correspond to a life of approximately 60,000 hours for an unexposed sample. The tests condition was maintained for 10,000 hours then new conditions were imposed by changing the temperature, stress, or both. Creep rates for all conditions were observed and the response compared to expectations from different damage models. Results to date indicate that well-established phenomenological models are suitable for representing the long-term performance under creep conditions providing that the thermal aging effects are incorporated into the models either explicitly or implicitly. The rate of evolution of microconstitutents was found to be an important consideration in the development of "more advanced" damage models but was not needed in the simple damage approximation provided by life fraction and Monkman-Grant.

WELDING ISSUES

The performance of weldments in the advanced ferritics/martensitic steels is of a major concern. Issues regarding weldments that were addressed in the past year included the effect of filler metal composition on the critical temperatures, subsequent microstructures, and creep performance. A model was developed for determining the A_1 transformation temperature base on the composition of the base metal or filler metal. Here, 1300 compositions within the chemical specification of 9Cr-1Mo-V were used to estimate the variability of the A_1 temperature using the Thermocalc® program. These values were served as input into a routine for rapid calculation of the A_l. The program was made available to vessel fabricators seeking to optimize fabrication schedules. Creep-rupture testing of weldments was continued to establish the influence of Ni and Mn content of the filler metal. A series of experiments on flux-core arc weldments was completed (13), and test were started to examine the effect of post weld heat treatments near the A_1 temperature.

SUMMARY

In the past year the focus of work on advanced ferritic/martensitic steels has been on a better understanding of factors that contribute to damage accumulation. A number of damage models has been examined with respect to there ability to represent variable loads after long-time creep exposure. The preliminary evaluation of results suggests that phenomenological models are adequate representations of behavior.

Further work on weldments was undertaken and models were developed to provided guidelines for tempering on post-weld heat treatment of weldments that are linked to alloy composition.

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