

UNDERSTANDING DAMAGE MECHANISMS IN FERRITIC/MARTENSITIC STEELS

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Introduction

Advanced ferritic/martensitic steels are being used extensively in fossil energy applications. New steels such as 2 1/4Cr-W-V (T23, T24), 3Cr-W-V, 9Cr-Mo-V (T91), 7Cr-W-V, 9Cr-W-V (T92 and T911), and 12Cr-W-V (T122, SAVE 12, and NF12) are examples of tubing being used in boilers and heat recovery steam generators (1). Other products for these new steels include piping, plates, and forgings. 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 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 that consider metallurgical factors as well as mechanical performance factors. Grade 91 steel was chosen as representative of these steels for evaluation of cumulative damage models since laboratory and service exposures of grade 91 exceed 100,000 hours.

Cumulative Damage Model Selection

Of the many cumulative damage models that have been proposed over the years, four were selected for this comparison. The models include the Life Fraction (LF), which is time-based and often identified as Robinson's rule (2), the Monkman-Grant (MG), which makes use of the observed correlation between rupture life and creep rate (3), the API-MPC Omega method (OM), which is based on tertiary creep behavior (4) and is often used for fitness-for-service evaluations (5), and Dyson's Continuing Damage Mechanics (CDM) model, which is representative of models that incorporate specific damage mechanisms (6).

The LF model is, by far, the easiest method to use. One only needs knowledge of the component history and temperature-stress-life relationship derived from uniaxial tests at constant conditions. A damage factor, D_{LF} , ranging from zero to one is calculated by summing the life fraction used at each service condition:

$$D_{LF} = \sum t_i / t_{r_i}$$

Where t_i is the time at any temperature and stress and t_{r_i} is the time to rupture at that temperature and stress. The remaining life fraction is $(1-D)$. The order of summing is not important. The time to rupture for each service condition may be interpolated from isothermal stress-rupture correlations for a specific heat, calculated from a stress-temperature-life parametric fit to the specific heat, or interpolated from parametric curves representing the average strength properties for the steel. A consistent multiaxial stress criterion is necessary but creep rate data are not needed.

The MG model requires that a sample be extracted from the exposed material and subjected to a creep test at a temperature and stress within the range of interest. The observed minimum creep rate (mcr) can then be used to estimate the rupture life, t_r , from a simple correlation for the material:

$$t_r = A \text{ mcr}^p$$

where A and p are experimentally determined materials parameters. Here, it is assumed that A and p do not vary with temperature and stress. A multiaxial stress criterion must be assumed.

The development of the OM model was reviewed by Prager (4) who cites six capabilities of the model that include the prediction of the creep curve, application to specific heats, prediction of remaining life without knowledge of history, generalization to multiaxial stress states, selection of benchmark tests for conditions close to service conditions, and incorporation in finite element analysis. The Omega concept may be expressed in several ways, but to be consistent with the notion of life fraction or damage parameter, D_{OM} :

$$D_{OM} = \dot{\epsilon} \Omega t / (1 + \dot{\epsilon} \Omega t),$$

where $\dot{\epsilon}$ is creep rate based on true stress and true strain, t is service time, and Ω is a “materials creep damage susceptibility parameter.” The Ω parameter represents the combined effect of area

change due to deformation, strain-softening, cavitation, and any other mechanism that could lead to an increased creep rate with increasing time or strain such that:

$$\dot{\epsilon} = \dot{\epsilon}_0 \exp(\Omega \epsilon),$$

where $\dot{\epsilon}_0$ is the initial creep rate. The integration of this equation produces a rupture life. The OM only considers tertiary creep. If primary creep is observed, the initial creep rate will not correspond to $\dot{\epsilon}_0$. It is expected that the API 579 document will provide Ω values for a service exposed material.

The CDM model

A mechanistic approach to damage has been taken by Dyson (6). His model has been developed to include three categories of damage: strain-induced, thermally-induced, and environmentally-induced. In each category, specific damage mechanisms are identified and formulations for the damage parameter, damage rate, and strain rate are identified. In the strain-induced damage category, for example, four subcategories are identified: creep-constrained cavity-nucleation, creep-restrained cavity-growth, dynamic subgrain growth, and multiplication of mobile dislocations. In the thermally-induced category, Dyson introduces particle coarsening and the depletion of solid-solution elements. In the environmentally-induced category, two subcategories have been proposed: fracture of surface corrosion products and internal oxidation. In the model, the creep rate at any instant ($\dot{\epsilon}$) is given by:

$$\dot{\epsilon} = \dot{\epsilon}_0 \sinh(\sigma/\sigma_0),$$

where $\dot{\epsilon}_0$ and σ_0 are composite parameters that contain several microstructural parameters that reflect up to eight more-or-less independent damage mechanisms. Typical materials parameters that are required to use the DM include grain size, a cavitation constant, subgrain radius, dislocation density, particle spacing, a rate constant for particle coarsening, the concentration of solute strengthen elements, a rate constant for particle precipitation, a rate constant for corrosion. Clearly, for alloys such as Grade 91, several damage mechanisms will be active. The parametric constants for the Dyson model have not been formulated for Grade 91 to date, so this model will not be exercised here.

Damage Evaluations for Grade 91

Three damage conditions were selected for evaluation. The first condition was produced by simple laboratory aging. Here, blocks of material that were exposed to temperatures in the range of 482 to 704°C for times in the range of 5,000 to 75,000 hours (7). Specimens from the aged blocks were tested under relatively long time creep conditions and the results evaluated in terms of the predictions of the three of the models mentioned above. The second condition was produced by service exposure in a power boiler. Superheater tubing was removed after 116,000 and 143,000 hours and specimens from the tubing were tested at various stresses and temperatures. The third condition was produced by long-time creep testing that was interrupted for testing at higher temperatures and stresses.

To examine the use of these models, an evaluation was undertaken of the influence of the conditions mentioned above on the rupture life at 600°C and 100 MPa. The material model that formed the basis of the allowable stresses in the ASME Boiler and Pressure Vessel Code sets the average life for 600°C and 100 MPa to be close to 84,000 hours. The first condition examined was a sample aged 10,000 hours at 649°C. Based on the Zener-Hollomon parameter, this condition is comparable to exposure for 100,000 hours at 600°C. The creep life of the aged specimen was estimated as 30,000 hours. The LF damage model would predict no loss in life for aged specimens while results show that 65% of the life was lost just due to thermal aging. The OM damage model estimates life of to be around 33,000 hours. This is a conservative estimate relative to the estimated life based on the trend of ASME Code allowable stress, and suggests that the OM model accounts for some thermal aging effects. The MG, which is based on the measured creep rate of the aged sample and the MG parametric constants averaged for the as-tempered condition, predicted a life of 26,000 hours. Similar to the OM model, this time is roughly comparable to the actual life of the aged specimen. Turning to the specimens service-exposed for 116,000 hours at 560°C and 34 MPa hoop stress, the damage estimated by all three models is negligible. The post-service uniaxial rupture life was 14870 hours for 600°C and 100 MPa. Again, the LF model estimated 84,000 and the OM model estimated 32,700 hours. The MG model, on the other hand, estimated 12,800 hours. The third condition examined involved long-time laboratory creep tests that are in progress. Specimens of two different heats were each exposed to 538°C and 165 MPa for approximately 85,000 hours. For these conditions, the life is expected to be about 425,000 hours using the Code values and 87,500 from the OM model. Both specimens were then tested at 600°C and 100 MPa. Testing times have exceeded 4,000 hours.

The LF model predicts a remaining life of 67,000 hours while the OM model predicts failure in less than 2,000 hours. The MG model predicts 42,000 and 55,000 for the two tests.

It is clear that wide ranges in predicted life can be expected when long-time, high-temperature exposures are evaluated from models that are largely based on short-time test results. Additional testing is underway that involves specimens exposed to long-time creep. Detailed metallurgical characterization is underway to better understand the evolution of the parametric values in the damage equations. As this information develops, the predictions of the Dyson model will be attempted.

References

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