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Creep-fatigue Lifetime Assessment with Phenomenological and Constitutive Material Laws

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Abstract

Variations in steam temperature due to start-up and shut-down of thick-walled components of power plants induce thermomechanical stresses, which can lead to fatigue and superimposed creep. Subsequently, damage can occur at the heated surface. With respect to component integrity, reliable lifetime assessment methods for critical components are mandatory. Lifetime assessment models have been developed and complex experiments for their verification were conducted. This paper presents a comparison and evaluation of different approaches to reach this target. At first, a phenomenological approach, based on the generalized damage accumulation rule, is introduced. The model takes into account creep rupture damage at stress relaxation as well as fatigue damage. Softening or hardening effects are considered as an enhanced interaction method for the influence of dwell times and internal stresses. Secondly, a more sophisticated viscoplastic constitutive material model of the type Chaboche is introduced. The material parameters were adapted to steels of the types 1CrMoNiV (1Cr), 2CrMoNiWV (2Cr), 12CrMoV (12Cr) and to a forged 10CrMoWVNbN (10Cr) material. The model allows the recalculation of the material behavior under static and cyclic loads, and partly multi-stage loads. The applicability and accuracy of the models is finally demonstrated with the recalculation of a large variety of different uniaxial and multiaxial experiments on notched specimens and cruciform specimens representing local component loading.

Keywords: Creep fatigue; lifetime assessment; phenomenological approach; constitutive model

1. Motivation and challenge of lifetime assessment

Due to the volatility of electrical power demand, power plants are increasingly forced to run at varying utilization levels. Besides typical daily cycles, in recent times, the variable supply from regenerative energy sources causes additional fluctuations. Power plants, which were originally intended to provide the base load, are frequently shut down and powered up. Variations in the steam temperature accompanying the power changes induce thermo-mechanical stresses in thick-walled components, which lead to material fatigue and superimposed creep, and consequently can cause failure. With respect to modern power plants and also for still
running conventional power stations, it is therefore of interest to conduct a reliable lifetime assessment for critical components. The challenge lies, firstly, in the very complex material behavior with hardening and softening effects as well as in creep and relaxation processes.

Secondly, it lies in the great variety of different load cases with respect to strain ranges, strain rates, temperatures and dwell times. A successful attempt to handle these was the classification of typical load cases, allowing the approximation of an arbitrary transient load by a sequence of cold, warm and hot starts (Fig. 1).

2. Phenomenological approach

The model takes into account creep damage at stress relaxation as well as fatigue damage due to cyclic loading. A first step deals with the recalculation of stress strain hysteresis loops by the usage of cycling flow curves. Continuous softening or hardening effects are considered as well as an enhanced method for the influence of dwell times and internal stresses. Further, varying temperatures due to start-up and shut-down processes and cycle counting methods for multi-stage loads lead to an impressive prediction accuracy.

A prevalent rule for creep fatigue life analysis in the long term region is the generalized damage accumulation rule [1-3]

\[ \sum \sum (\Delta t_j / t_{rj}) + \sum (N_k / N_{fok}) = L \]  

which combines the Miner rule for fatigue damage and the life fraction rule for creep damage. The damage summation over all cycles including damage at hold times leads to a creep fatigue damage L.

This rule was modified with physically based features in order to cover mean stress, mean strain and multiaxiality. The reference value of the number of cycles to crack initiation \( N_{io} \)

\[ N_{io} = N_i (\Delta \varepsilon, 2t_h) \cdot \nu \sigma \]  

is taken from standard strain-cycling tests, with tension and compression hold times \( t_h \). In the case of a viscoelastic stress strain path, at low strain amplitudes, where plastic deformation disappears, creep damage dominates due to granular damage and fatigue damage was calculated by a fatigue life curve \( (t_p = 0 \text{ h}) \). In the full elastic-plastic regime at high values of total strain range, creep fatigue damage dominates due to intergranular damage (Fig. 2). Here, fatigue damage is calculated on the basis of a fatigue life curve based on creep fatigue experiments with symmetrical hold times. The calculation method provides a detailed algorithm to determine the parameters, i.e. hold times, of a corresponding standardized experiment with the same failure life curve, or, vice versa, the interpolation rule to obtain the number of cycles from existing experimental data.
The phenomenological approach described is implemented in the software tool SARA, adding sets of necessary material data, i.e. cyclic stress-strain behavior, creep behavior, creep rupture behavior, fatigue life curve and fatigue life curve with the Smith-Watson-Topper parameter (factor $v_\sigma$ in eq. (2)) for some heat resistant steels. The software tool was developed to study the influence of temperature, total strain range, strain rate, and hold time on number of cycles to crack initiation.

In order to determine critical values $L_{crit}$ for the three heat resistant steels above, a significant number of long term creep fatigue experiments were applied to the left hand side of eq. (1). As a result, mean values for the critical creep fatigue damage $D_{crit}$ were determined ($1Cr: 0.5$, $2Cr: 0.67$, $10Cr: 0.80$).

**Fig. 2. Association between failure mode at creep rupture testing (a failure mechanisms at stress relaxation and (b), steel of type 1CrMoNiV.**

3. Constitutive model

A viscoplastic constitutive material model [4, 5] of the type Chaboche extended using the generalized energy equivalence principle was also developed. The evolution equations of isotropic and kinematic hardening are implemented with terms of static and dynamic recovery. An accumulated plastic strain is used in the model, and its evolution is described by a power law according to Norton with four material parameters. A modification of the power law as part of further development was introduced for a higher conformance to a wide stress range. Furthermore, an isotropic damage variable $D$ was incorporated into the model according to the principle of generalized energy equivalence.

The necessity to identify of a high number of material parameters actually represents a key challenge. Therefore, a computer based innovative method was developed in order to establish a route for reproducible identification of approximately 20 parameters by usage of the Neural Network Method.

Beyond the calculation of standardized load cases, the model can be applied to estimate material behavior under any transient thermo-mechanical conditions. It must be pointed out that in general, methods with numerical integration of differential equations tend to be demanding in terms of computational power and calculation time. With a highly sophisticated approach for the extrapolation [6, 7] of inner variables, which had also been developed, it was possible to reduce the calculation time for number of cycles to crack initiation $N_{i**}$ significantly; e.g. for recurring load scenarios by a factor of 10.

4. Discussion

For validation purposes, uniaxial experiments, both on smooth and notched specimens were conducted. Figure 3 provides a comparison of measured ($N_i$) and calculated number of cycles to crack initiation ($N_i^*$). The diagram comprise isothermal creep fatigue experiments on forged 1Cr, 2Cr, 10Cr and 12Cr steels and represents single stage experiments and three-stage experiments according to figure 2. Almost all data are located in a scatter band of factor two.
Additional anisothermal uniaxial & biaxial [8] experiments were conducted representing the service-type loading at the heated surface of heavy components during the transient operation of power plants. The achieved test durations exceed 2,000 h.

Deformation and evolution of damage under creep fatigue loading can be well described and the results allow a reasonable estimation of the lifetime. The simultaneous calculation of deformation and damage is the main advantage in the application of the constitutive material model.

A comparison of the number of cycles to crack initiation of anisothermal & isothermal creep fatigue experiments show a clear trend that 10Cr-steel is more sensitive to superimposed thermal cycling in comparison to 2Cr & 1Cr-steel (Fig. 4). The necessity of conducting anisothermal experiments has been demonstrated on modern 10Cr-steels for uniaxial as well as for biaxial cruciform experiments. Corresponding isothermal experiments were conducted at the maximum cycle temperature. The observed behavior can be explained by higher stresses at lower temperatures. In the case of 1Cr/2Cr and 12Cr steels, degradation at high temperature is more pronounced in comparison to 10Cr steels, which endure higher numbers of cycles under anisothermal conditions.

![Fig. 3. Comparison of number of cycles to crack initiation of fatigue experiments to calculated numbers, phenomenological model $N_i^*(a)$ and constitutive model $N_1^{**}(b)$.](image)

![Fig. 4. Ratio of number of cycles to crack initiation in anisothermal experiments to isothermal experiments for different steel grades; (a) dependence on strain range and (b), dependence on upper application temperature.](image)
5. Summary

At high temperature, power plants components are operating under thermo mechanical loading induced by start-up and shut-down processes. Two versatile, flexible and applicable methods for the demanding question of lifetime-assessment for power plant components were developed and introduced. Based on standardized experiments, model parameters were determined for typical steel grades of type 1CrMoNiV, 2CrMoNiWV, 12CrMoV and 10CrMoWVNbN. The operational capability of the models was proved with complex validation experiments. Service–type creep fatigue experiments on uniaxial, notched and cruciform specimens achieved test durations of 8,000 h until crack initiation, while uniaxial specimens on 1CrMoNiV steel exceed 70,000 h.

A phenomenological model contains a synthesis of stress strain hysteresis loops followed by the calculation of creep and fatigue damage by the life fraction rule and the Miner rule. Modification in terms of creep fatigue interaction as well as mean stress lead to a reliable model. Furthermore, a constitutive material model on the basis of Chaboche with the generalized energy equivalence principle demonstrates the applicability using a newly developed extrapolation method for internal variables. The high number of material parameters can be determined by the Neural Network Method.

In summary, both methods demonstrate their potential addressed to uniaxial and multiaxial loading, partly under thermomechanical or multi-stage loading. In summary, this work reveals important indications about the overall expense and accuracy of the employed methods. Hence, this work contributes to a reduction of the time and expense for the re-engineering of existing and new design of power plant components.

References