Abstract

Description of creep fatigue crack initiation behaviour of power plant steels

For power plants which are used in the medium and peak load regime the dominant loading situation of high temperature components is creep fatigue. Thus, the life assessment requires data about crack initiation and crack growth under creep fatigue conditions. These characteristics can not be easily substituted by pure fatigue crack or creep crack data. Therefore, a comprehensive test programme was carried out to investigate experimentally the creep fatigue crack behaviour of a bainitic turbine rotor steel (30CrMoNiV4-11) and a martensitic pipe steel (X10CrMoVNb9-1). The test materials were taken from industrial products. All tests on 1%CrMoNiV-steel were carried out at 550 °C, all tests on steel 9%CrMoVNb at 600 °C. Side grooved compact tension (CT) specimens with 25 and 50 mm thickness as well as double edge notch tensile (DENT) specimens with 15 and 60 mm thickness have been tested in order to observe possible influences of geometry and thus to check the transferability of specimens test results to the behaviour of components. Long term tests up to 8 000 h under cyclic tension load with $R = F_{min}/F_{max} = 0.1$ were performed with hold times at maximum load from 0.1 up to 10 h to come near to service conditions. These loading frequencies are also chosen to build up the range of interaction between trans- and intergranular crack growth.

Long term tests of power plant steels under creep and creep fatigue loadings are serving as a basis to transfer experimentally results to component behaviour, concerning the time dependent material behaviour in the high temperature regime like decreasing creep strength and ductility and increasing notch susceptibility. An analytical description of crack initiation and crack growth under creep fatigue conditions is of technical and economical interest. To achieve this relevant data describing crack behaviour under creep and pure fatigue are needed. A large database of creep crack data is already available for steel 30CrMoNiV4-11 from several German research projects of IfW Darmstadt and MPA Stuttgart. On steel X10CrMoVNb9-1 several additional tests have been performed. The fatigue crack behaviour at notched specimens was determined on both steels at a frequency of f = 0.05 Hz.

A short summary of experimentally results of creep fatigue test will be given below:

- With increasing hold time, i.e. decreasing frequency, the number of cycles to crack initiation N_A decreases. These tests are predominantly influenced by creep processes, data are plotted in the form $K_{I\,max} = f(t_A)$. The parameter $K_{I\,max}$ used here is the value for the maximum load of the cycle.

- The high frequency tests present shorter crack initiation times due to the influence of fatigue. For the same value K_{IA} , the ratio of the creep fatigue crack initiation time $t_{A(KE)}$ to the creep crack initiation time $t_{A(K)}$ delivers a factor

$$D_s = \frac{t_{A(KE)}}{t_{A(K)}}$$

which expresses the influence of creep damage on the creep fatigue crack initiation.

- It can be assumed, that there is no further reduction of the creep fatigue crack initiation time as compared to the creep crack initiation time for frequencies below about 10^{-5} Hz.

- For large specimens, a retarded creep crack initiation time t_A is visible, which is a consequence of differences in stress state at the crack tip and of the lateral constraint.

For the prediction of crack initiation under creep fatigue conditions a modified two-criteria-method is proposed. The original method was developed for creep crack initiation. A nominal stress σ_{n0} considers the stress situation in the ligament of a specimen or a component, i.e. in the farfield of the creep crack. The fictitious elastic parameter K_{I0} characterizes the crack tip situation. The stress intensity factor

$$K_I = \frac{F}{B \cdot \sqrt{W}} \cdot f(a/W)$$

is valid for linear elastic behaviour only, but it can be approximately used for a limited plastic zone near the crack tip. These loading parameters are normalised in a two-criteria-diagram by the respective time and temperature dependent values, which indicate the material resistance against crack initiation. The normalised parameters are the stress ratio $R_\sigma = \sigma_{n0}/R_{mt,\vartheta}$ for the farfield and the stress intensity ratio $R_K = K_{I0}/K_{IA}$ for the crack tip. The value $R_{mt,\vartheta}$ is the creep rupture strength of the material and the parameter K_{IA} characterizes the creep crack initiation of the material. This parameter has to be determined from specimens with high ratio K_I/σ_n, preferably CT25-specimens. The two-criteria-diagram distinguishes three fields of damage mode separated by lines of constant ratio R_σ/R_K. Above $R_\sigma/R_K = 2$ ligament damage is expected, below $R_\sigma/R_K = 0.5$ crack tip damage is expected and between these lines a mixed damage mode is observed. Crack initiation is only expected above a boundary line. The two criteria method described has been developed as a way of practice to transfer creep crack initiation data from specimens with different sizes to larger components with similar farfield and crack tip situation and the applicability of the method was proven by the results of more than 100 small and large scale specimens with artificial and natural defects.

In the modified two-criteria-diagram for creep fatigue crack initiation, only loading situations with damage mechanisms, dominated by creep deformation processes, are predictable conservatively, caused by the reference to results of creep tests on smooth and spark eroded specimens. Therefore the portion of fatigue damage, must be restricted. This can be done by a commitment of an upper frequency for the application of Two-Criteria-Diagram. For the tested frequency range from 10^{-1} Hz down to $2{\cdot}10^{-5}$ Hz in the above mentioned experiments, the transition between frequency and time dependent fracture behaviour was estimated to about 10^{-3} Hz. This estimation is based on microscopical investigations of the fracture mode (trans- vs. intergranular), observations of crack growth rate da/dN vs. frequency and hold time respectively as well as comparisons of crack initiation results between creep fatigue tests and pure cyclic / pure static tests. Below $f \approx 10^{-5}$ Hz differences between creep fatigue and pure creep results are rather neglectaible, the application of the Two-Criteria-Diagram for static (creep) loading is suggested. For creep fatigue loading, instead of K_{I0} as parameter to describe crack tip behaviour in the component $K_{I\,max}$ should be used as the stress intensity calculated for maximum load F_{max} during the service cycle. $K_{I\,max}$ is also calculated in the fictitious, linear elastic manner, as described above.

An additional farfield / ligament damage, caused by fatigue loading, is not expected. Therefore, a validity extension of Two-Criteria-Diagram has to modify the crack tip ratio R_K, not the stress- (ligament-) ratio R_σ. This crack tip ratio should consider the creep damage and the (limited and tolerable) fatigue damage in the specimen / component, too. Consequently for creep fatigue crack initiation below 10^{-3} Hz it is proposed to characterize the material's resistance in the two-criteria-diagram by a new time dependent parameter $K_{IAC}(t_{A(K)})$, which is reduced against the parameter $K_{IA}(t_{A(KE)})$ according to a reduction of the crack initiation time from $t_{A(K)}$ to $t_{A(KE)} = 0.6 \cdot t_{A(K)}$. All other details concerning the two-criteria-method remain unchanged.

An example of assessment of natural defects in large specimens of a cast steel via the two-criteria-method is given in the text. For this case study, a large specimen machined from a pilot casting of steel 1%CrMoV with a weight of 5 t and a wall thickness comparable to steam turbine casings and valve bodies with clear ultrasonic findings of open and partly healed hot tears was chosen. These findings of the magnetic particle as well as ultrasonic inspection indicates that the defects are located perpendicular to specimen axis as a corner crack and an internal crack respectively.

This specimen was tested under creep fatigue loading at 530 °C and a load ratio R = 0.1 with a hold time of 60 min at maximum load ($f = 2.8{\cdot}10^{-4}$ Hz). The stress was calculated to

σ_n = 156 Nmm^{-2}. After 3,495 h test was interrupted for non-destructive inspection and finished after 10,351 h at a remnant strain ε_r = 1.19 % .

After unloading the specimen was cooled and broken open in a brittle fracture mode in order to permit identification of the initial defect and extend of cracking in the scanning electron microscope. The supposed corner crack was identified not as a single defect but as two small defects, splitted by a partly healed hot tear (Defect A, B). Defect C was described correctly by non-destructive testing with respect to type and size.

According to the assessment of crack initiation by Two-Criteria-Diagram it was necessary to calculate the different ratios, namely R_σ and R_K, which both depend on time. The required material data $R_{mt,\vartheta}$ and K_{IAC} were based on smooth and spark eroded specimen of the same cast. The findings are plotted in Two-Criteria-Diagram, the line indicates a damage path for the three investigated defects. When this path is crossing the borderline crack / no crack, a crack with 0.2 mm depth is initiated.

Crack initiation is expected at t_i > 1000 h. That correlates well with experimental results. After 3,495 h, no defect extension is visible by means of ultrasonic inspection. After test was finished at 10,351 h, crack growth was visible at fracture surface and measured by means of SEM with $\Delta a \approx 0.4$ mm for all defects. The diagram gives also a conservative estimation of initiation time. Concluding from the position of data points in Two-Criteria-diagram, ligament damage is expected for the smaller ones (defects B, C) and mixed-mode damage for defect A with $K_{I\,max}$ = 350 $Nmm^{-3/2}$. That is validated by experimental results too.

The validity of the proposed assumptions in the modified two-criteria-diagram must be carefully checked conducting long term investigations on small and large specimens with loading conditions close to practice. Especially the "conservative" behaviour of the large scale specimens has to be considered with respect to the application to full scale components. In addition it requests an Engineering judgement for different R-values and loading situations near or below a threshold of cyclic crack extension to exploit the hidden conservatism.