Creep Crack Assessment of Components at High Temperatures

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During recent years a database on crack initiation and growth under creep and creep fatigue loading was established. In order to make appropriate use of this database for component assessment at high temperatures two-criteria methods for crack initiation have been developed and C* based growth analyses was applied and reviewed, the methods were implemented in a software system which consists of data and calculation modules for analyses and assessments of components with defects operated in the high temperature range.
The paper describes the methods used and their application using the developed software. As an example the assessment of a crack in a pipe bend made of martensitic 12 Cr steel is demonstrated. The assessment results determined by the software "HT-Riss" revealed a fair correlation to the service life which was as long as 185 000 h.

1. Introduction

The remaining lifetime of high temperature components depends in many cases on the material behaviour at cracks caused during production or operation. Depending on the loading conditions creep or fatigue cracks or crack propagation can thereby occur. Due to this reason, it is necessary that besides non-destructive testing methods for the reliable proof of failures, there are also methods available that enable an evaluation of detected failure under operation loading. Particularly the crack initiation and development at imperfections of long-term loaded components deserve a reliable quantitative description.
Within the scope of the AVIF-sponsored research project A 202 [1] an application software "HT-Riss" was developed that permits the determination of the creep(fatigue) crack initiation and the creep(fatigue)crack growth at components inserted at high temperatures using fracture mechanical methods. By means of an example, the application of the software is demonstrated and an overview over the calculation methods of the software is given.

2. Calculation tools and determination of parameters for the description of component loading

The software system "HT-Riss" allows for the calculation of crack initiation by means of the two criteria diagram under static creep loading and under cyclic creep fatigue loading. In addition, "HT-Riss"offers modules for the calculation of crack initiation and crack propagation with the aid of the C*-parameter for creep loading and creep fatigue loading. For the calculation of component loading a module is available for the calculation of stress intensity factors for component geometries like e. g. shaft, tube and cylinder. Besides the calculation modules, the software systems also offers material data for 11 forged steel and cast steel materials with 1%, 10% and 12% of chrome. It also includes creep data for the description of the long-term strength- and deformation behaviour as well as creep crack initiation and creep crack propagation values for tests with running times up to over 30.000 h. The material data are stipulated by verified average value curves and conservative evaluations for the lower and upper scatterband limit within the evaluation and application limits. Fig. 1 shows exemplary the given curves for the determination of crack propagation based on the C*-parameter for a 10% chrome forged steel as well as the experimental data on which the parameter-curves are based.

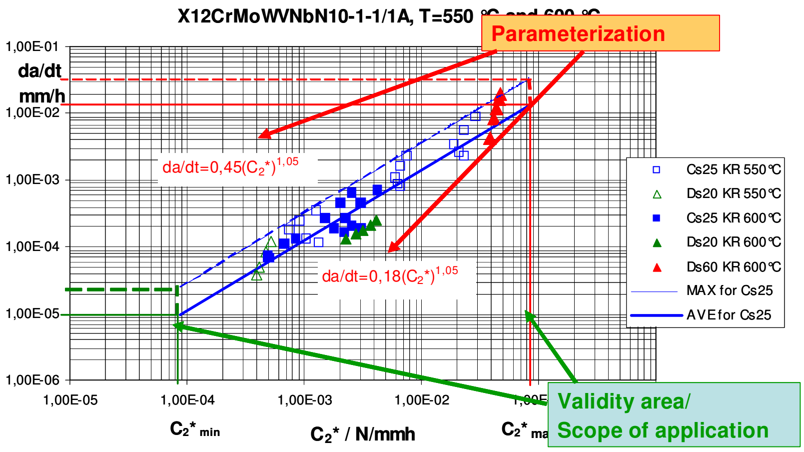

Fig. 1: Material data for X12CrMoWVNbN10-1-1 / 550°C and 600°C, here: creep crack growth depending on the C*-parameter.

The material parameters were determined based on the common operation temperatures (depending on the material 530, 550 or 600°C). For the application on real cases, however, also data/curves for the respective, possibly differing, operation temperatures are required. The necessary shifting/adjustment to higher or lower temperatures of the incipient crack or crack growth curves, based on the stress intensity factor, can be effected using the Arrhenius-equation [2]. The Larson-Miller-approach [3], generally used for creep analyses, is another possible method. In case of an analysis of a material of the above mentioned group, not possessing specific incipient crack and crack growth data, the group curves can be used for the determination of crack initiation time and crack growth.

The determination of fracture mechanical component parameters is especially difficult for the C*-parameter, used for the description of the crack behaviour at high temperatures, and complicates the application of the available tools. The calculation of the stress intensity factor can be performed in approximation using analytical solutions and calculation formulas from regulations and handbooks, e. g. [4,5,6], that are partially recorded in the programme system. The loading parameter C* can be determined as C^*_{ref} from an approximation equation based on the Norton-parameter (see paragraph 3.1.2) [7,8]. In doing so, C* is determined as an approximation of the K_I-value and the Norton-constants A and n for the respective material. Effecting this, one has to count on relatively huge uncertainties as the stress dependence of the creep behaviour and the chronological modification of the stress field around the crack cannot be described. Exact values, especially for C*, can be determined by finite elements analysis. This was done within the scope of the project for different components like shaft, pipe and shell for the typical high temperature steels for operation-like loading and operation temperatures. The parameterised values for the calculated geometries can inserted as approximations. In case of required component specific determination by FE-analyses, complicated geometric calculation models with proportionally increased effort have to be generated.

3. Case of damage on the pipe of the bent tube of a live steam pipe

After an operation time of approx. 185 000 h a leakage was discovered on the straight branch of a bent tube of the power plant Wilhelmshaven. More detailed investigations of the bent tube in the integrated condition, but particularly on the dismounted bent tube showed as cause of the damage a crack initiation on the internal pipe side that resulted from the manufacturing of the bent tube and expanded during the time of operation due to creep loading [9]. Through thickness crack has a length of approx. 207 mm on the internal surface of the pipe in direction of the pipes longitudinal axis (Fig.2). On the outer surface another crack in longitudinal direction of 40 mm of length and a little bit shifted on the perimeter was detected. Evaluation on the metallographic specimen, Fig. 3, lead to the assumption that on the polished surface and at right angle to the internal surface of the pipe two initiation cracks were existing, one with 8.5 mm depth (case 1/crack R1), which during operation time expanded at approx. 18.6 mm in a 45° direction, and another one (case 2 /crack R2) with 7.7 mm initial crack depth and 10.8 mm crack growth. Furthermore, an adjacent crack was detected (case 3/ crack R2a), that developed as a branching out of crack R2. For the crack configuration R2a no crack expansion was stated. After operation the pipe was broken up under liquid nitrogen and the exact crack configurations could be determined and used for the calculation. Geometry, operational loading and crack configuration are summarised in Table 1 and 2. For the following calculation a constant internal pressure load was assumed for the complete operation time.

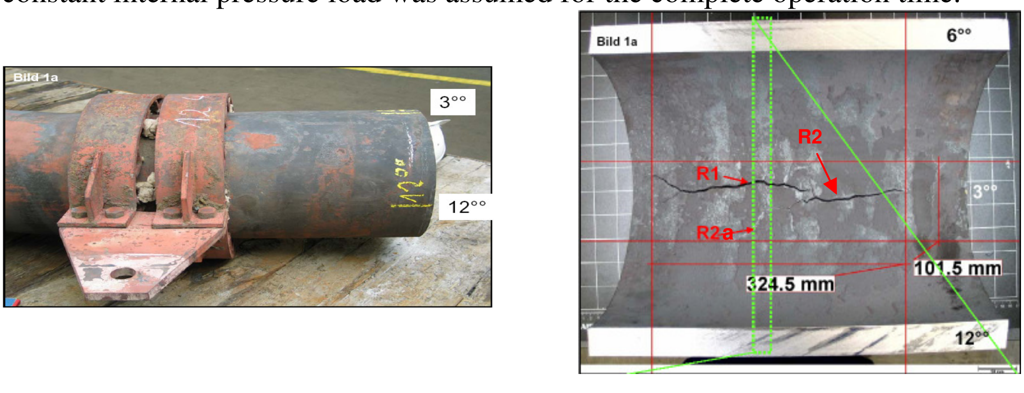

Fig. 2: Damage area of the bent tube, internal side of the pipe [9]

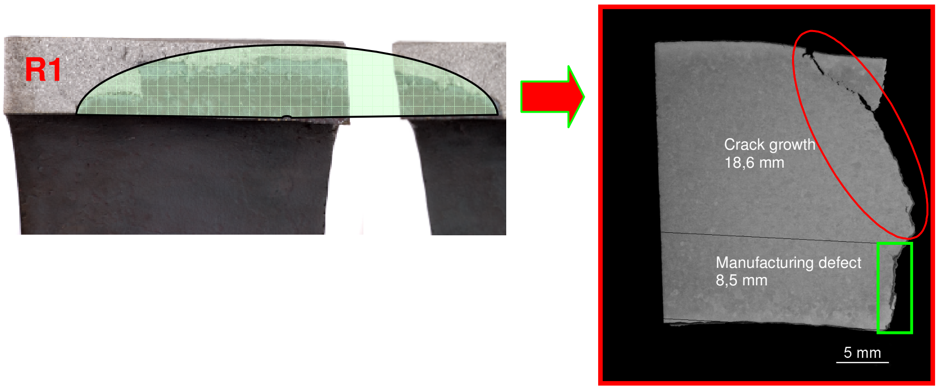

Fig. 3: Crack configuration at the metallographic specimen through the pipe wall, crack R1

Working Data	
Temperature	530°C
Pressure	191 bar
Operation time	185 000 h
Component Data	
Material	12 Cr steel (X20CrMoV12-1)
Inside diameter	260 mm
Wall thickness	29 mm
Bending radius	1500 mm

Table 1: Specifications on the tube

An additional load by pipeline forces was not damage causative according to [9] and was therefore neglected.
By means of the calculation software system ALIAS [10] initially a calculation according to TRD 301[1] was carried out. The required material parameters like heat resistance for the respective temperature and creep strength depending on time and temperature were taken from the material data bank [10]. The calculation results produced life exhaustion of 57 %. The calculated effective stress lies at 100 MPa, which results in a life time of far over 200.000 hours taking the operation temperature of 530 °C.

[1] TRD- German Technical Rules for Steam Boilers

	Initial crack depth	End crack depth	Crack length	Position	Type of defect
Case 1 / Crack R1	8.5 mm*)	Leakage 27.1 mm	inside 206.5 mm, outside 38.9 mm	Through thickness defect	Axial defect
Case 2/ Crack R2	7.7 mm*)	18.4 mm	118 mm	Surface internal	Axial defect
Case 3/ Crack R2a	4.4 mm	4.4 mm	50 mm	Surface internal	Axial defect

*) – caused by stress corrosion before going in duty

Table 2: Configuration of the cracks in the tube

3.1. Calculations for a half-elliptic longitudinal crack (R1)

3.1.1 Determination of crack initiation time

Applying the software "HT-Riss", the crack initiation time was determined by means of the two criteria diagram 2CD [11]. For the given crack configuration the stress intensity required for the determination of the crack initiation time was determined according to A16 [4]. Under the assumption of the appearance of an half-elliptic longitudinal crack on the inner surface of the pipe, a stress intensity factor of 20 $MPam^{0.5}$ results. Since typically the cracks caused by stress corrosion are branched out, like shown in the metallographic investigations (see also Fig. 3), the branching out of the initiation crack is considered in the crack initiation calculation. Therefore, a reduction of the stress intensity factor was stated in [12]. Consequently, resulting in a smaller K_I-value of 14.2 $MPam^{0.5}$. As nominal stress, the effective stress calculated according to TRD was assumed. The crack initiation curve was extrapolated for 530 °C by means of the Arrhenius-equation. The creep data was taken from DIN 17175.

Results

Initial crack:
Stress intensity ratio: 0.117
Net stress ratio: 0.116

At crack initiation:
Stress intensity ratio: 0.85
Net stress ratio: 0.56

Time at crack initiation: **61921 h**

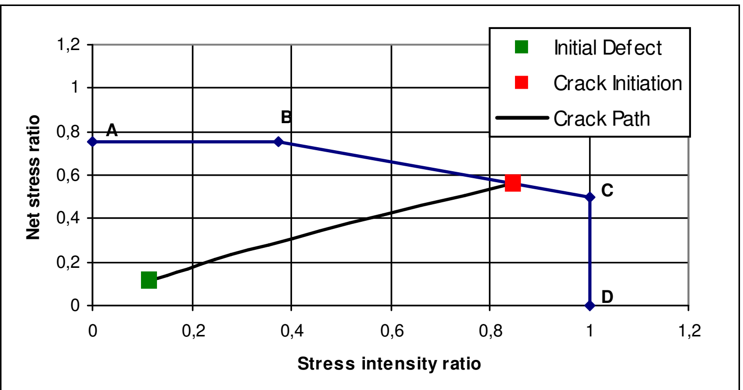

Table 3: Calculation results of the two criteria diagram

The calculation results are summarised in Table 3. Under the assumption of a constant creep loading, a crack initiation time of appox. 62 000 h was calculated. The here determined values are based on materials data for crack initiation with initial technical crack length of 0.5 mm. Thus, in this case the behaviour is described conservatively in the result.

3.1.2 Determination of crack growth

Based on the above calculated crack initiation time, the further crack growth was determined by means of the C*-concept. The therefore required course of the function C*-parameter depending on crack depth was gained by FE-analysis. Therefore, adequate 3D-geometries were produced for a crack configuration with 4 different crack depths of 8.5, 12, 15 and 18 mm (see Fig. 4).

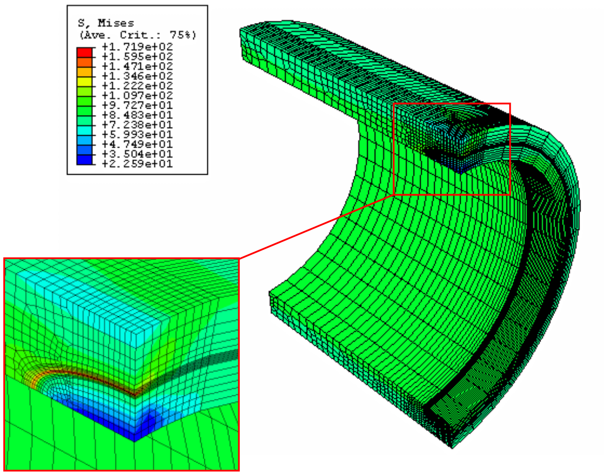

Fig.4. FE-Model of tube with a half-elliptical crack

The C*-parameter (C^*_{FE}) was determined as a stationary value from the chronological sequence of the C*-integral in the programme system ABAQUS.

$$C^* = \int_{\Gamma} (W^* \cdot dy - \sigma \cdot \frac{\partial \dot{u}}{\partial x} ds \cdot) \qquad \text{(Eq.1)}$$

For the FE-calculation a User Creep-Subroutine with a modified Graham-Walles creep formulation [13] was employed. For comparison, the C*-parameter was also calculated by means of a approximation equation

$$C^*_{ref} = A \cdot \sigma_{ref}^{(n-1)} \cdot K_I^2 \qquad \text{(Eq.2)}$$

[7] for 4 different crack lengths and employed for the creep crack propagation calculation. The Norton-constants from [14] were inserted in the approximation equation for the test material. In both cases, the time calculated by means of the 2CD was assumed as initiation time.

The material specific crack propagation data show scattering. Therefore, curves for the average value of the crack propagation and an upper limit value are given in [1]. Fig. 5 shows the determined times up to the diagnosed crack depth of 18.6 mm using upper scatterband and the approximation equation C^*_{ref}. The calculated time and operation time agreed fairly well.
By the calculation with C^*_{FE} the crack growth is underestimated, even on assumption of the upper scatterband-limit. This results in an overestimation of the total time until reaching the diagnosed crack depth. The probable explanation is, that the materials data are plotted in terms of C_2*. If this data are used for a defect description with C^*_{FE}, then (derived from investigation on 1%CrMoV-steels) a correction factor for the magnitude of C^*_{FE} should be used. It has been shown in [1] as well, that higher values of C^*_{FE} are expected in FE calculation with uniaxial load in comparison to multiaxial load.
The calculations described in this paper were performed for the crack developing in longitudinal direction. For the calculation of the stress intensity factor and the C^*_{ref} and C^*_{FE} values a constant ratio of crack depth “a” to crack length “c” was assumed.

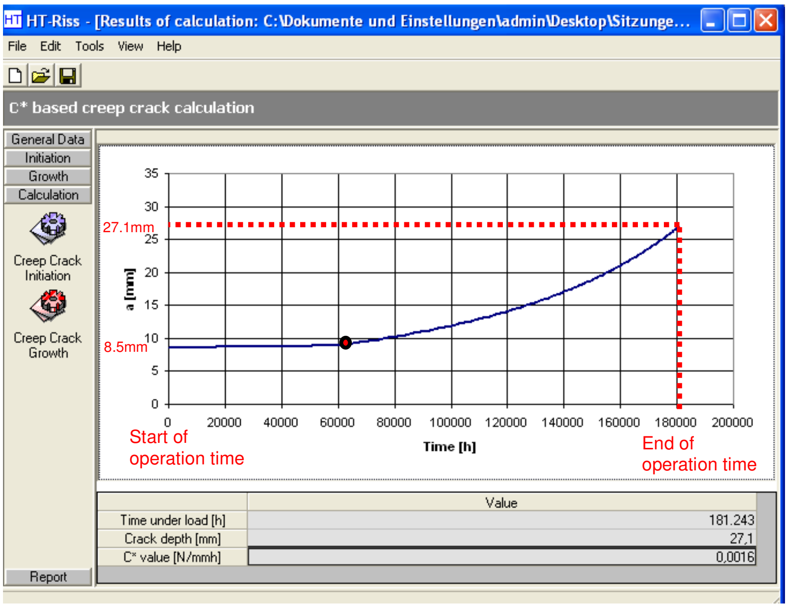

Fig. 5: Calculation result for the half-elliptic crack R1

4. Summary and Conclusions

The calculation possibilities of the software system “HT-Riss” was shown by means of damage case, possessing a metallographic damage analytical diagnosis. For available crack configurations in an operationally used pipe from 12 Cr steel (X20CrMoV12-1), analyses regarding crack initiation and crack growth were being performed. A conservative estimation could be made for an initiation crack with half-elliptical configuration and metallographically determined crack depth. Using the calculation analysis, the metallographically determined damage course

could be retraced and verified taking into account the branching of the crack. The calculated time and operation time agreed fairly well. Exclusively internal pressure loading was considered for the calculation. Starts and showdowns were not considered either, because the power plant operated in base load.
The used software “HT-Riss” presents a simple and effective tool for the fracture mechanical analysis of imperfections and crack in warm-going components. It allows the estimation of crack initiation and crack propagation under creep, fatigue and creep fatigue loading based on the fracture mechanical parameters stress intensity factor K_I and C*-integral using the two criteria diagram and the C*-concept. On the premise of a known crack configuration, the fracture mechanical stress parameters for the component can be determined by approximative solutions or directly quoted. In summary, it can be stated that considering the exactness of available input data and tools and an adequate selection of approximative solutions and crack configurations, useful approximations for crack initiation time and crack propagation can be determined.

5. References

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