A strain based criterion for creep crack initiation

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Abstract

Commonly, for components under creep loading, the maximum tolerable inelastic strain is limited to 1 %. The strains are calculated for components which are free from defects, using appropriate material models. Within the fabrication process internal defects such as crack or cavities cannot be avoided, especially for large thick-walled components. For these internal defects fracture mechanic concepts must be applied for safety assessment.

Existing fracture mechanics concepts such as the Two-Criteria-Diagram or the Time-Dependent-Failure-Assessment-Diagram do not include the effect of the material's ductility which has a clear effect on crack initiation process. Under creep load, the strains within the crack tip region dominate local material separation. Therefore a concept is introduced, which formulates a deformation exhaustion rule. With this procedure a better material utilisation is achieved.

In a next step, crack initiation is calculated using an internal damage variable, which can be used as a life time parameter. Within this approach, the influence of a multiaxial state of stress on the damage evolution must be implemented. This procedure simplifies crack initiation assessment, replacing fracture mechanic methods by the evaluation of the damage variable.

Keywords Creep, crack initiation, failure criterion, creep strain

1. Introduction

For components under creep loading, the maximum tolerable accumulated inelastic strain must be limited, [1]. This limitation in strain is well-founded on evaluations of the remaining life-span with reference on microstructural damage, [2]. If an inelastic strain of 1 % is accumulated, monitoring arrangements must be established. This does not account for internal defects or cracks. For a safe operation of the component, the assessment must include the description of crack initiation and crack growth. If now the period to crack initiation is longer, than the period to accumulate the limit strain, the assessment procedure could be simplified. This can be described by the relation of the time to crack initiation t_A to the time, say for 1 % inelastic strain, $t_{1\%}$:

$$t_A \geq t_{1\%} \quad (1)$$

The aim of this work was to identify crack sizes for which **Eq. (1)** is met. Therefore the time to crack initiation t_A must be identified, which requires an appropriate assessment concept. Commonly used concepts, such as the Two-Criteria-Diagram, [3], (TKD, see **Figure 1**) or the Time-Dependent-Failure-Assessment-Diagram, [4], [5], are based on stress relations. The TKD differs between three damage modes. Within the crack-tip-damage region the specimens or components have large cracks with a low mean stress. Within the ligament-damage region there are small cracks with a high mean stress and a high accumulated strain within the far-field region of the specimen. In between there is the mixed-mode damage region. Ligament damage is defined by accumulation of 1 % strain in the farfield of the specimen, [3], [4]. The analysed specimens within this work are aimed to have an $R_\sigma = 0.75 \div 1$ and $R_K \approx 0,5$ and lie on the edge of the ligament-damage field.

Over the past decade, there have been analysed various steels used in power plant operation generating a wide database for describing the material's behaviour and crack initiation, [5], [6], [7], [8], [9]. Modern high chromium steels however, exhibit a high creep ductility influencing strongly the crack initiation behaviour. The ductility in this case is represented comfortably by the material's creep rupture strain. The more deformation within the region of the crack tip is attainable, the later the crack initiation will start. Therefore it is sensible to set up a strain based criterion to describe crack initiation. With this, the influence of ductility is directly implemented. To gain a concept which is valid for either high or low ductility, materials differing in their ductility must be analysed to validate the concept. Describing crack initiation applying a stress formulated concept - such as the commonly used assessment procedures- will be too conservative. The influence of ductility on crack initiation have been analysed theoretically or have been approximated, [10], [11], [12], [13]. Concerning the TKD, a modification based on the creep rupture strain has been proposed in [13]. This was done mainly for the crack-tip-damage region. For the ligament-damage mode a dependency of ductility could not yet be established.

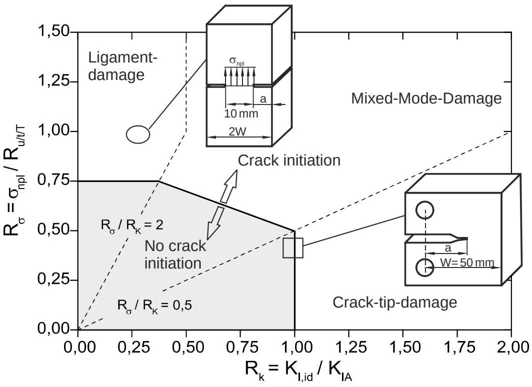
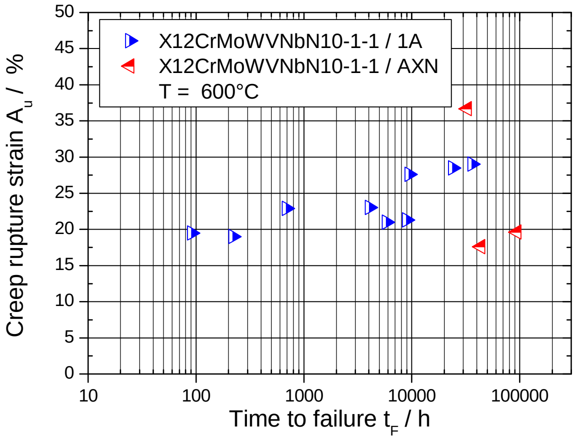


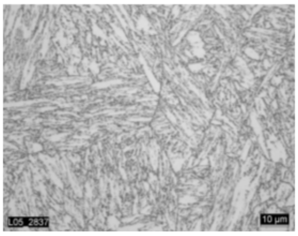
Figure 1. Creep rupture strains of a 10Cr-steel at T = 600 °C, different heats

The specimens investigated will have Double-Egde-Notched-Tension (DENT) in different sizes or compact-tension (CT) geometry. The loading times for the numerically treated specimens are up to operational relevant times of 200.000 h. The aim is the determination of initial crack sizes as a function of the creep rupture strain for different specimen sizes which account for Eq. 1. Below this limit of initial crack size a_{limit}, a fracture mechanics assessment is not necessary. The creep data used to set up the material law is available up to 140.000 h for uniaxial creep tests. The fracture mechanics experiments are available up to 20.000 h.

2. Investigated materials

To account for the influence of the material's ductility, one 10Cr-steel and two 1Cr-steels have been considered. The creep rupture strain of the 10Cr-steel is shown in **Figure 2**.





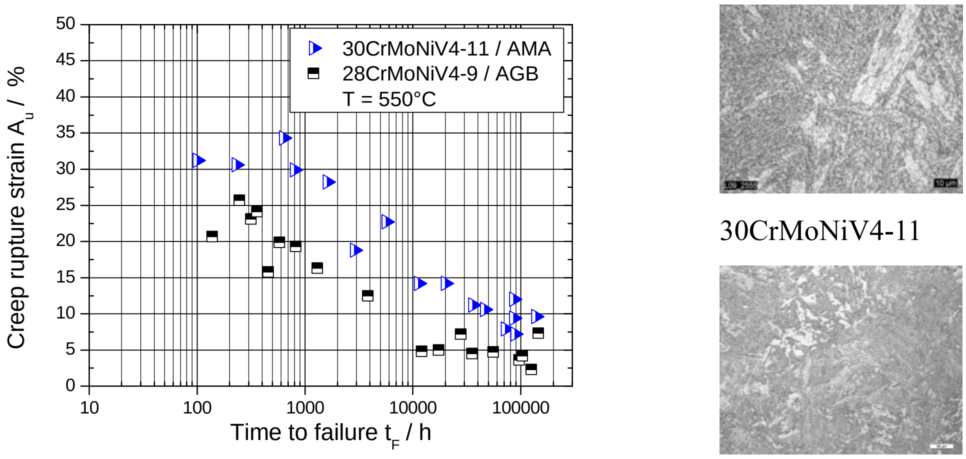
X12CrMoWVNbN10-1-1

Figure 2. Creep rupture strains of a 10Cr-steel at T = 600 °C, different heats

There are two heats shown, which differ only with respect to the initial heat treatment. Due to the loading times up to 100.000 h the material properties are not supposed to differ. As shown, the creep rupture strain is about 20%-25% and can be approximated by a constant.

The creep rupture strain of the two 1Cr-steels is shown in **Figure 3**. It can clearly be seen, that the rupture strain is decreasing with increasing loading time. Both steels differ in the initial heat treatment.

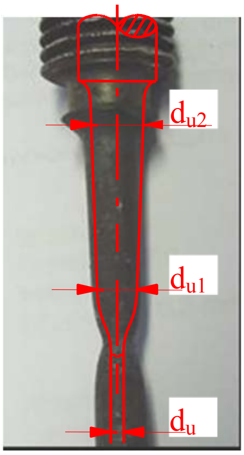
The creep rupture strain itself, however, is not an appropriate measured variable, due to the influence of the reduction of area gained in creep tests on materials with high ductility. Concerning thick-walled components, no transverse strain is observed. To meet this problem a reference strain was introduced, which does not include the influence of the reduction of area on the creep rupture strain value, see **Figure 4**. Two different formulations have been analysed. One is based on the volume of the creep test specimen. This method was preferred for the implementation of the failure criterion. The second method is based on the strains at the onset of the tertiary creep stage.



30CrMoNiV4-11

28CrMoNiV4-9

Figure 3. Creep rupture strains of 1Cr-steels at T = 550 °C



$$\varepsilon_{r,1} = \left(\frac{2 \cdot d_0}{(d_{u1} + d_{u2})} \right)^2 - 1 \tag{2}$$

$$\varepsilon_{r,2} = \varepsilon_{2/3} + \dot{\varepsilon}_{min} (t_u - t_{2/3}) \tag{3}$$

with: t_u – time to failure,

$\varepsilon_{2/3}$ – Strain at onset of tertiary creep

$t_{2/3}$ – Timepoint at onset of tertiary creep

Figure 4. Definition of a reference strain

The reference strain according to **Eq. (2)** is used as material parameter within the failure criterion, which relates a characteristic strain within the specimens to the reference strain. The reference strain is referred as ε_r. The reference strain can be plotted over the creep rupture strain, see **Figure 5**. This yields the correlation of the creep rupture strain and the calculated initial limit crack length a_{limit}.

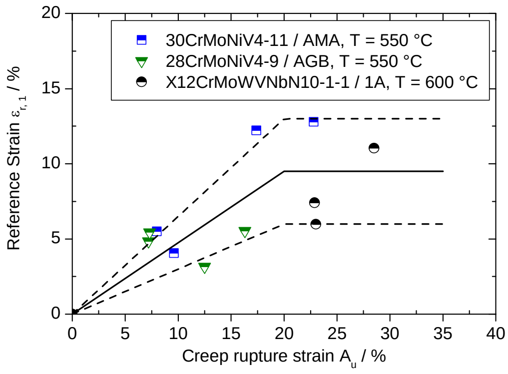


Figure 5. Correlation between reference strain and creep rupture strain

3. Investigation of small cracks

To analyse the dependence of the pre-loading crack size a_{limit} on the material's ductility, 3D models of specimens with DENT geometry have been used. The crack was modelled with a crack tip radius of 0.1 mm, which is valid for the experiments. The crack tip was meshed with a fine mesh to represent the stress and strain gradients correctly. For the description of the material's behaviour a modified Graham-Walles formulation have been implemented, [14]. The calculations were conducted with the Finite-Element-Code ABAQUS ©.

The numerical analysis of specimens with loading times up to 200.000 h requires a failure criterion to correlate with crack initiation. Within the creep regime and with respect to the dependence on ductility, a strain based formulation of the failure criterion is appropriate. Since the creep deformation and the creep damage is dependent on the multiaxiality of the stress state, this must also be considered, [15], [16], [17], [18]. With higher multiaxiality, the deformability is reduced. To account for that effect, the concept of Cocks&Ashby is applied, [19].

To correlate the calculated strains with the material dependent reference strain, a characteristic point within the crack tip region to evaluate the strains and the multiaxiality must be chosen. The calculated strains were evaluated at the point of maximum triaxiality near the modelled crack tip. Due to the high constraints, crack initiation begins at this point by formation, growth and coalescence of creep cavities. In addition a definition of crack initiation in the experiment must be set up. Crack initiation is defined for a crack growth of Δa = 0.1 mm.

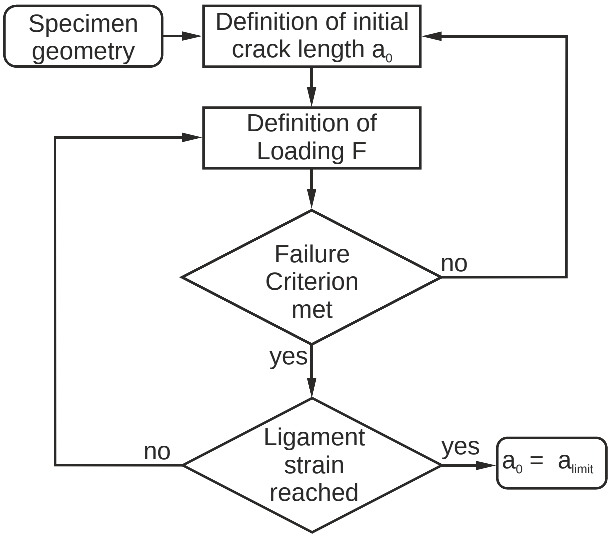
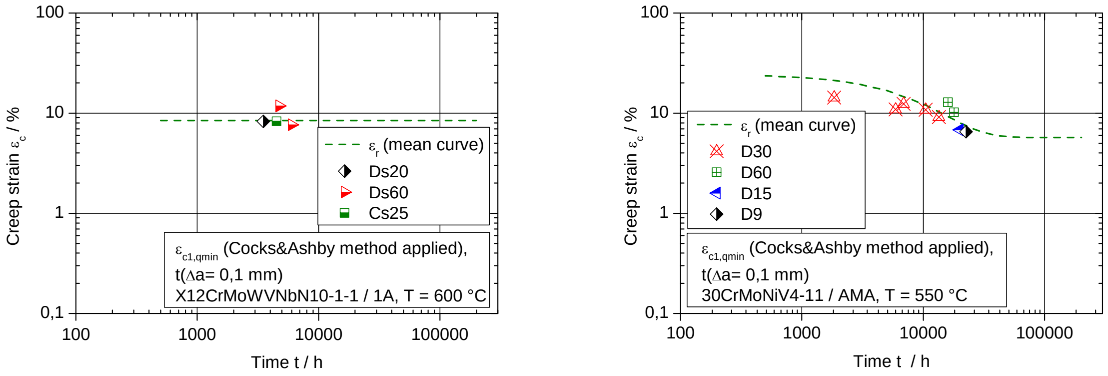


Figure 6. Schematic overview of calculation of a_{limit}

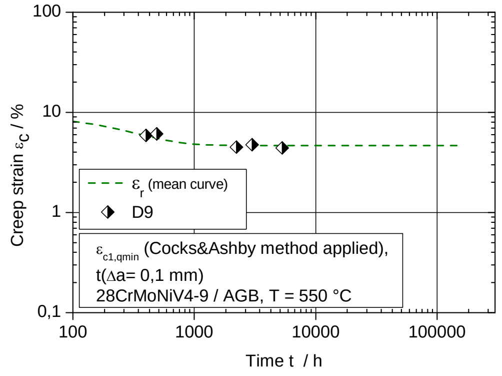
This value was chosen on the one hand to avoid the need of modelling crack propagation in the FE-calculations and on the other to be able to detect crack initiation within the experiments. In **Figure 6** the calculation procedure is schematically shown. The optimisation of the results with respect to the initial crack length and the accumulated strain within the ligament are done iteratively.

The concept for describing crack initiation was first validated by applying on already run experiments. In **Figure 7** are the results shown for the analysed 10Cr and 1Cr-steels. The results of the FE-calculations are in good agreement with the defined reference strain for all materials and different ductility. The failure criterion now can be applied to find out, if there is a limit crack size below a fracture mechanics assessment is not necessary. The limit of initial crack size a_{limit} will be determined in correlation to the creep rupture strain corresponding to loading times of 100.000 h and more, which cannot be done experimentally. The creep rupture strain for the 10Cr-steel is assumed to be constant between 100.000 h and 200.000 h. For the 1Cr-steels the low creep rupture strain at 100.000 h is extrapolated as constant up to 200.000 h.



a) X12CrMoWVNbN10-1-1

b) 30CrMoNiV4-11



c) 28CrMoNiV4-9

Figure 7. Validation of the strain based failure criterion for 10Cr and 1Cr-steels

The limit of initial crack size a_{limit} sought, is defined dependent on the accumulated inelastic strain within the ligament of the specimen. It is that size of surface type crack for the DENT specimen, when simultaneously the failure criterion in the crack-tip region is met and the selected creep strain is reached. To quantify the influence of specimen geometry and size, these have been varied. The results of the calculations are shown in **Figure 8**. It can be seen, that there is small scatter of the data with respect to geometry and size of the specimens at a constant creep rupture strain. In general it can be stated, that with increasing size (especially breadth) the limit of initial crack size increases, too. An increasing ductility also leads to a higher limit of initial crack size. Also different levels of ligament strain have been analysed. This is derived for the operation of different components. A strain level of 1 % within the net section stress area is valid for thick-walled components and is founded on [1]. For turbine runners, this strain would lead to component failure due to the component tolerances. In this case a strain level in the ligament of the components of 0.2 % is discussed.

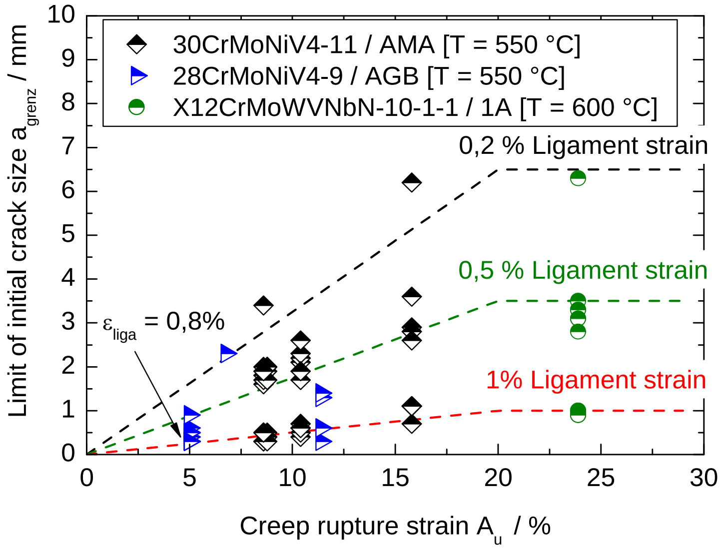


Figure 8.

With a decreasing ligament strain, the net section stress is reduced, which results in a reduced crack tip loading for constant crack length. As it is shown in Figure 8, the limit in initial crack size therefor increases. It is clear, that with growing of a_{limit}, the wall thickness must have a minimum larger than a_{limit}.

For the creep-brittle 1Cr-steel 28CrMoNiV4-9 a ligament strain of 1 % could not be attained even for crack sizes of 0.3 mm. Instead of modelling initial crack sizes below 0.3 mm a ligament strain of 0.8 % was accepted, too.

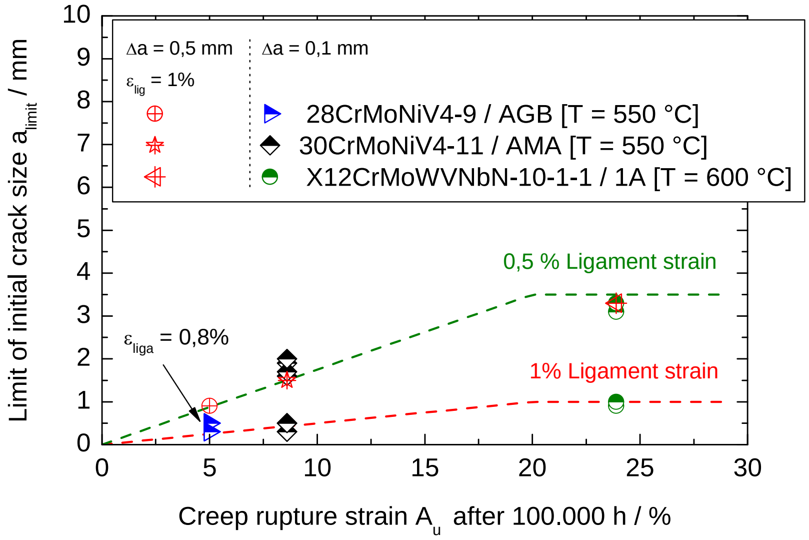


Figure 9.

Considering the relation between the reference strain and the creep rupture strain (see Figure 5) it correlates well with the observed dependence of the initial crack size and the creep rupture strain, i.e. above 20 % of creep rupture strain a_{limit} and ε_r remain constant.

This analysis was conducted defining crack initiation at a crack growth of 0.1 mm. In general a crack propagation of 0.5 mm is assumed. So the above applied strain based failure criterion is met at earlier loading times, i.e. it is more conservative, if a crack growth of 0.5 mm is tolerable. Otherwise, for a fixed loading time and net section stress, a larger initial crack size is tolerable if at crack initiation a defined ligament strain is reached. This was investigated for a fixed loading time of 100.000 h, shown in **Figure 9**. It can clearly be seen, that the initial crack sizes increase if crack initiation occurs for a crack growth of 0.5 mm at the same ligament strain.

Since no crack propagation was modelled in the numerical analysis, the crack growth was approximated using:

$$\frac{da}{dt} = m \cdot (C^*)^k \tag{4}$$

With the C*-parameter, see [14], [22]. The parameters C and m are dependent on the material and are listed in Table **1**.

Table 1. Crack propagation parameters

	X12CrMoWVNbN10-1-1 T = 600 °C	30CrMoNiV4-11 T = 550 °C
m	0,25	0,25
k	0,18	1,05

Within the small crack propagation of 0.4 mm a constant crack growth rate can be assumed. The total time span of 100.000 h is then the sum of the time to reach the strain based failure criterion with a crack propagation of 0.1 mm and the crack growth to $\Delta a = 0.5$ mm.

4. Summary

Modern steels for high temperature operation, e.g. in power plants, are showing high deformability. Classical methods, determining failure formulated on the stress field, are highly conservative. Improving the assessment aiming at a better material usage requires a concept which includes the actual deformability. Additionally, for high ductile materials, crack initiation does not readily start before a certain strain within the net section stress region is accumulated, defining monitoring measures or the replacement of the component. To be able to determine this crack size dependent on the material´s ductility a more accurate failure criterion is needed.

A strain based concept has been introduced and applied on three 10Cr- and 1Cr-steels with different ductility. It correlates a characteristic strain within the crack tip region of the specimen and a material dependent reference strain. Determining the stress and strain field within the crack tip at a certain loading time requires Finite-Element modelling and calculations to crack initiation. With a crack initiation criterion with a crack growth of 0.5 mm modelling of the crack propagation is essential. To avoid this effort, crack initiation was attained for a smaller crack growth of 0.1 mm. The concept was validated on fracture mechanics specimens with loading times up to 20.000 h.

It could be shown that the initial crack sizes of interest, i.e. such sizes which does not show crack initiation before a certain strain is reached within the ligament section, is dependent on the materials ductility. For a ligament strain of 1 % the limit of initial crack size is up to 1 mm for creep rupture strains of 20 % and more. Reducing the ligament strain is leading to an increase of the limit of initial crack size.

5. Discussion and conclusions

Within the creep regime, local failure can be described through the available deformability of the material. With regard to crack initiation it would lead to a less conservative concept, than using stress based formulations, since the deformability does markedly have impact. The formulation of failure set up could be validated on fracture mechanics experiments, providing a limit of initial crack size for practical operation times. This limit characterises crack sizes for which crack initiation does not occur before a certain strain within the ligament (in the net section stress region) is reached. If now the operation period of the component is defined by these creep strains within the net section stress area, pre-loaded cracks would not tend to initiate. For this cracks and internal defects, a fracture mechanics assessment is not necessary. So, the results of this work can be used to simplify the assessment of components, depending on the ductility, i.e. the creep rupture strain at a given loading period. In addition for materials with a high ductility a more precise failure assessment could be provided.

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Literature

1. TRD508, Technische Regeln für Dampfkessel, Zusätzliche Prüfung an Bauteilen, berechnet mit zeitabhängigen Festigkeitskennwerten. Carl Heymanns Verlag (Taschenbuchausgabe 2007, Stand 2002)
2. VGB-Richtlinie-TW 507: Richtreihen zur Bewertung der Gefügeausbildung und Zeitstandschädigung warmfester Stähe für Hochdruckleitungen und Kesselbauteile. 2. Auflage (2005)
3. Ewald, J.: A Two Criteria Diagram for Creep Crack Initiation. In : Int. Conf. on Creep Tokyo, Japan, p.p. 173/8 (1986)
4. R5 Issue 3, An Assessment Procedure for the High Temperature Response of Structures. British Energy Generation Ltd. Procedure (2003)
5. R6 Revision 4, Assessment of the Integrity of Structures Containing Defects. Britisch Energy Generation Ltd. Procedure (2011)
6. Ewald, J., Maile, K., Tscheuschner, R.: Creep Crack Growth Assessment by Means of a Crack Tip/ Far Field Concept. Nuclear Engineering and Design 117, 185/95 (1989)
7. Berger, C., Granacher, J., Roos, E., Maile, K.: Kriechrissverhalten ausgewählter Kraftwerksstähle in erweitertem praxisnahem Parameterbereich. Schlussbericht zum AVIF-Forschungsvorhaben Nr. A78, Institut für Werkstoffkunde der TU Darmstadt und Staatliche Materialprüfungsanstalt, Universität Stuttgart (1999)
8. Berger, C., Granacher, J., Roos, E., Maile, K.: Rissverahlten typischer warmfester Kraftwerksbaustähle im Kriechermüdungsbereich. Schlussbericht zum AiF-Forschubsvorhaben Nr. 10395 I/II, Institut für Werkstoffkunde der TU Darmstadt und Staatliche Materialprüfungsanstalt, Universität Stuttgart (1999)
9. Berger, C., Scholz, A., Roos, E., Maile, K., Müller, F., Schellenberg, G.: Einfluss inerter Atmosphäre auf das Rissverhalten warmfester Stähle im Kriech- und Kriechermüdungsbereich. Abschlussbericht zum AiF-Forschungsvorhaben Nr. 11722 N, Institut für Werkstoffkunde der TU Darmstadt und Staatliche Materialpfürungsanstalt (2002)

10. Kloos, K. H., Kußmaul, K., Granacher, J., Maile, K., Tscheuschner, R., Eckert, W.: Kriechrisseinleitung und Kriechrisswachstum warmfester Kraftwerksbaustähle unter Berücksichtigung des Größeneinflusses. Abschlussbericht des AiF-Vorhabens Nr. 6038, Institut für Werkstoffkund der TH Darmstadt und Staatliche Materialprüfungsanstalt, Universität Stuttgart (1988)
11. Berger, C., Scholz, A., Roos, E., Maile, K., Müller, F., Stadtmüller, W.: Hochtemperaturverhalten der neuen 600 °C-Stähle für Wellen und Gehäuse von Dampfturbinen. Abschlussbericht zum AVIF-Forschungsvorhaben A127, Institut für Werkstoffkunde der TU Darmstadt und Staatliche Materialprüfungsanstalt, Universität Stuttgart (2002)
12. Ewald, J., Wellinger, K.: Stützwirkung bei höherer Temperatur, Zeitstandversuche an Biegeproben. Technisch wissenschaftlicher Bericht, Staatliche Materialprüfungsanstalt, Universität Stuttgart (1972)
13. Gooch, D. J., Haigh, J. R., King, B. L.: Relationship between Engineering and Metallurgical Factors in Creep Crack Growth. In : Metal Science. (1977) pp. 545-550
14. Riedel, H.: Fracture at High Temperatures. Springer-Verlag Berlin, Heidelberg, New York, London, Paris, Tokyo (1986)
15. Ewald, J.: Zwei-Kriterien-Daigramm für Kriechrisseinleitung: Berücksichtigung des Kriech-Verformungsvermögens (für ferritische Werkstoffe). In : Vortrag auf der 26. Vortragsveranstaltung der Arbeitsgemeinschaft für warmfeste Stähle und der Arbeitsgemeinschaft für Hochtemperaturwerkstoffe, Düsseldorf (2003)
16. Roos, E., et.al.: Bewertung von Bauteilen in Abhängigkeit vom Kriechverformungsvermögen. Abschlussbericht zum AVIF-Forschungsvorhaben A252, Materialprüfungsanstalt, Universität Stuttgart und Institut für Werkstoffkunde der TU Darmstadt (2011)
17. Maile, K., Meyer, L. W.: Einfluss der Mehrachsigkeit der Belastung auf die Kriechporenbildung und die zeitliche Schädigungsentwicklung bei typischen Kraftwerksbaustählen. Abschlussbericht des Forschungsvorhabens AVIF A105, MPA Stuttgart, TU Chemnitz (2000)
18. Maile, K., Klenk, A.: Influence of the multiaxial stress state on component failure in the creep range. In : International Conference on Advanced Technology in Experimental Mechanics 2003, JSME-MMD, Nagoya (2003)
19. Hobt, A., Klenk, A., Roos, E., Mao, T., Scholz, A., Berger, C.: Bewertung von Bauteilen mit Fehlstellen in Abhängigkeit vom Kriechverformungsvermögen. In : Abschlussbericht FVV Frühjahrstagung, Bad Neuenahr (2011)
20. Maile, K., et.al.: Kriterien zur Schädigungsbeurteilung von Hochtemperaturbauteilen aus martensitischen 9-11 %-Cr-Stählen. Abschlussbericht des Forschungsvorhabens AVIF A229, MPA Stuttgart, Siempelkamp Prüf und Gutachter Gesellschaft (2008)
21. Cocks, A., Ashby, F.: Intergranular fracture during power-law creep under multiaxial stresses. Metal Sciennce, 395-402 (1980)
22. Vishwanathan, R.: Damage Mechanisms and Life Assessment of High-Temperature Components. ASM INTERNATIONAL, Metals Park Ohio (1989)