# Creep and Creep-Fatigue Crack Behaviour of 1Cr- and modified 10Cr-steels in air and inert gas

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***ABSTRACT:*** *High temperature components with notches, defects and flaws can produce crack initiation and crack propagation under service conditions. Fracture mechanics procedures are needed to study crack problems and to support an advanced remnant life evaluation. Since a more flexible service mode of steam power plants causes a higher number of start up and shut down events, creep-fatigue crack behaviour is decisive for life assessment and integrity of components. Fracture mechanics experiments normally are carried out under air conditions although in some cases internal defects are not in contact with air. Therefore, it is of interest to which degree environmental conditions, e.g. crack tip oxidation, can influence crack initiation and crack growth behaviour.*
*In order to enlighten these problems for high temperature components, the crack initiation time and crack growth rate were determined in air and inert gas environment on 1% CrMo(Ni)V- and 10% CrMoWVNbN-steels.*
*Crack initiation and crack propagation under creep and creep-fatigue conditions have been described with the usual fracture mechanics parameters* $C^*$, $K_I$ *and* $\Delta K_I$ *and a modified "Two Criteria Approach" was applied. Small differences in crack initiation and crack growth were detected for the different environmental conditions.*

## INTRODUCTION

Documents informing on the material behaviour of crack-like defects/flaws and unavoidable notches are required for the design and surveillance of power plants high temperature components in long-term service. In case of constructive unavoidable notches creep or creep-fatigue cracks may be initiated or propagated by static or cyclic high-temperature loading. In both cases an experimentally safe-guarded and quantitative description is required. The necessary experiments have mostly been performed in air. However, the locations of the stress concentrations on components under potential crack danger are often inside the material or below the surface and are consequently not affected by the environmental medium. Therefore it is of great interest to study the influence of an inert environment, free of oxygen, on the crack behaviour under long-term creep or creep-fatigue loading.

This paper deals with the results obtained from a sequence of an extensive joint research projects [1, 2, 3, 4] carried out at the “Institut of Materials Technologie”, Darmstadt University of Technology, and the “Staatliche Materialpruefungsanstalt”, University of Stuttgart. The crack initiation and crack propagation behaviour under creep and creep-fatigue loading are investigated on the well-established 1% CrMo(Ni)V-steel and on the modern 10% CrMoWVNbN-steel in air and inert gas.

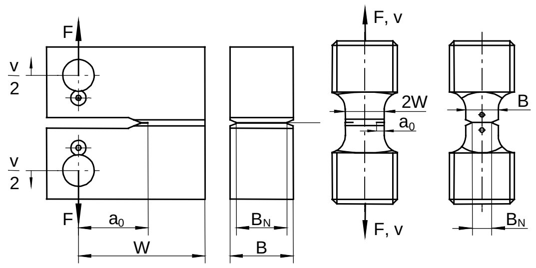
## TEST MATERIAL AND TYPES OF SPECIMENS

Table 1 shows a matrix of test materials and used specimens. The forging steel 30CrMoNiV4-11 and the cast steel G17CrMoV5-11 are taken as reference for the well-established 1% CrMo(Ni)V-power plant steels. The steels X12CrMoWVNbN10-1-1 and GX12CrMoWVNbN10-1-1 are taken as reference for the modern 10% CrMoWVNbN-steels. The materials were investigated in as received condition. Furthermore the 10% CrMoWVNbN-steels were tested after annealing at 633 °C/8 000 h corresponding to 600 °C/100 000 h to simulate long-term ageing.

TABLE 1: Materials, temperatures and specifications of specimens

| Material | T (°C) | Specimen geometries<br>Small scale | <br>Large scale |
|---|---|---|---|
| 30CrMoNiV4-11 | **550** | **Cs25**, D9, D15 | Cs50, CT100, D60 |
| G17CrMoV5-11 | **530**, 550 | **Cs25**, Ds20 | Ds60 |
| X12CrMoWVNbN10-1-1 | 550, <u>**600**</u> | **Cs25**, <u>Ds20</u> | <u>Ds60</u> |
| GX12CrMoWVNbN10-1-1 | 550, <u>**600**</u> | **Cs25**, <u>Ds20</u> | Cs50, <u>Ds60</u> |
| **Bold**: | additional experiment in inert gas (Ar + 3% $H_2$) | | |
| <u>Underlined</u>: | additional experiment on ageded material (8 000 h, 633 °C) | | |

Different specimen types and sizes (Fig. 1) were chosen to determine size and geometry effects on crack initiation and propagation. The crack start notch of most specimens was spark eroded with a notch tip radius of 0.1 mm. A few CT-Specimens have been fatigue precracked to study the influence of different crack starter. All CT- and some DENT-specimens are side grooved (Cs, Ds), in order to ensure uniform crack growth front.




| | Cs25 | Cs50 | Ds20 | Ds60 |
|---|---|---|---|---|
| B (mm) | 25 | 50 | 20 | 60 |
| $B_N$ (mm) | 20 | 40 | 16 | 48 |
| W (mm) | 50 | 100 | 5.25 | 50 |
| $a_0$/W | 0.55 | 0.55 | 0.2 | 0.2 |

**Figure 1:** Dimension of the tested specimens

## TEST PERFORMANCE

The specimens were tested under constant tensile loads (creep crack tests) and under cyclic tensile loads (creep fatigue crack tests). The tests under cyclic tensile loads with R = 0.1 were performed with maximum hold times of 0.3 to 3.0 h. The small scale specimens Cs25 and D(s)20 were tested using the interrupted test technique (multi specimen) and the large scale specimens Cs50 and D(s)60 were tested using the continuous test technique (single specimen), [7]. With regard to typical service temperatures the test temperatures are as follows: 550 °C for the 1% CrMoNiV-forging steel, 530 and 550 °C for the 1% CrMoV-cast steel, 550 and 600 °C for the 10% CrMoWVNbN-steels. The tests in inert gas environment were performed in argon with 3% hydrogen in order to avoid crack surface oxidation.

## TEST RESULTS AND DISCUSSION

### *Crack Initiation Behaviour*

A technical crack initiation length has been defined to determine the crack initiation behaviour, which is independent or dependent of specimen size and geometry. This paper deals with technical crack initiation length, size and geometry dependent, defined as $\Delta a_i = 0.004W$ and $\Delta a_i = 0.01W$, for Cs- and D(s)-specimens, respectively.

For the evaluation of the test results, the linear elastic stress intensity factor $K_I$ [5] as well as the parameter C* [6] were used. $K_I$ is valid for linear elastic behaviour only, but it can be approximately used for a limited near crack tip plastic zone. The parameter C* is valid for stationary creep in the crack tip environment. For the application of the parameter $K_I$ and C* under creep conditions a transition time $t_1 = K_I^2/[C^*(n+1)E']$ was proposed, where

E' = E stand for plane stress and $E' = E/(1-\nu^2)$ for plane strain conditions. For tests with $t \ll t_1$ the parameter $K_I$ is considered as valid, for $t \gg t_1$ the parameter C* should be used. This is also recommended for the creep-fatigue initiation [7]. For the obtained crack initation results, values of the ratio $t/t_1$ were identified between 2 and 100. Therefore the parameter C* should be taken as reference for the characterisation of the crack initiation behaviour. However, a representation as a function of the parameter $K_I$ has to be made in view of the application of the "Two Criteria Approach" [8].

In comparison to the well-established 30CrMoNiV4-11 steel the creep crack initiation values of the 10% CrMoWVNbN-cast steel are higher at 550 °C regarding the $K_{I0}$ - $t_{i\,c}$ - diagram, Fig. 2. Additionally, the graph shows that the crack initiation time for D(s)60-specimens is above the one of the Cs25-specimens. By applying parameter C*, Fig. 3, the creep crack initiation time of the cast steel increases too. The crack initiation results of the large scale specimens (Ds60) are above those of the small scale specimens (Cs25), as found out in case of the $K_{I0}$ - $t_{i\,c}$ - diagram. A specimen size dependence is present in both cases, producing difficulties to transfer the results from small scale specimens to components. The status of the tests performed on cast steel G17CrMoV5-11 does not yet allow a distinct evaluation.

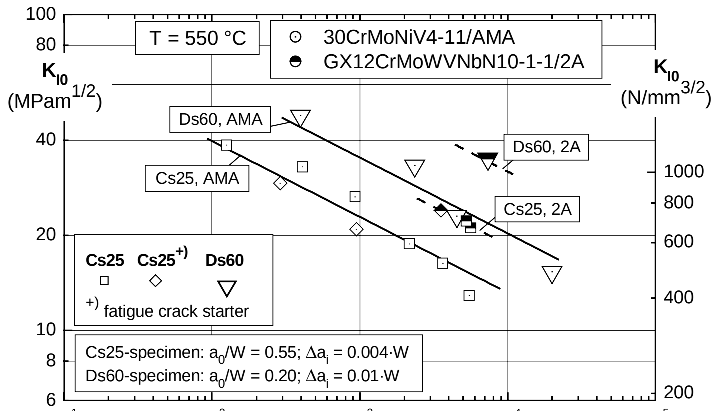



**Figure 2**: Parameter $K_{I0}$ vs. creep crack initiation time $t_{i\,c}$ for Cs25- and Ds60-specimens, steel 30CrMoNiV4-11 and cast GX12CrMoWVNbN10-1-1, T = 550 °C

The creep crack initiation of Ds60-specimens of the 10% CrMoWVNbN-steels in as received and aged conditions is shown in Fig. 4. At high loads the creep crack initiation of the forged steel in as received conditions is distinctly above the one of the corresponding cast steel. With a decrease of load the crack initiation times tend to approach each other. As expected, the crack initiation of the aged steel is faster in both cases. Furthermore, there was no significant difference in the crack initiation behaviour between the Cs25-specimens with eroded crack starter and those fatigue precracked (Fig. 2 and 3). At the present state of the investigations it is not possible to see a clear difference between the results determined in the inert gas environment (argon with 3% hydrogen) and those determined in the air environment. However, it can at least be assumed that the values under inert gas are not below those received in air.

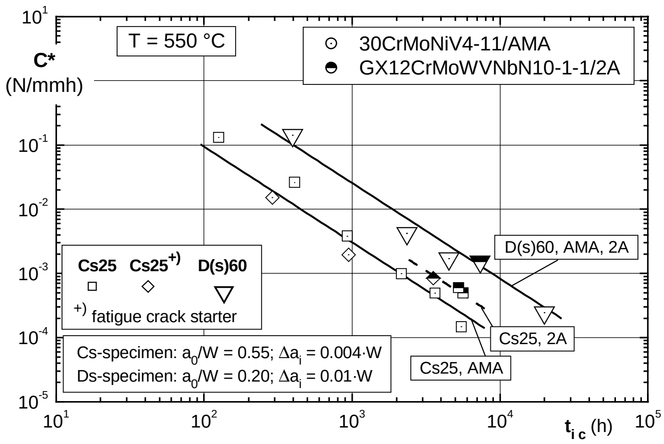



**Figure 3:** Parameter C* vs. creep crack initiation time $t_{i\,c}$ for Cs25- and D(s)60-specimen, steel 30CrMoNiV4-11, cast steel GX12CrMoWVNbN10-1-1, T = 550 °C

The crack initiation under creep fatigue loading for the forging steel X12CrMoWVNbN10-1-1 is shown in Fig. 5 in the $K_{I0}$ - $t_{i\,cf}$ - diagram. Apart from the fact that the results clearly depend on the specimen size and geometry, a reduction in time for crack initiation $t_{i\,cf}$ at decreasing holding times $t_H$ could be found. A clear fatigue predominance can be assumed already at hold times of less than 0.3 h, whereas for 3.0 h the values are similar to those from creep crack tests.

Using the so-called “Two Criteria Approach” [8] it is possible to determine analytically the crack initiation of components under creep conditions. The nominal stress $\sigma_{n\,pl}$ considers the stress situation in the ligament and the fictitious elastic paramter $K_{I\,id}$ characterizes the crack tip situation. These loading parameters are normalized in a Two Creiteria Diagram ("2CD") by the creep rupture strength $R_{u/t/T}$ and the parameter $K_{Ii\,c}$, which characterized the creep crack initiation of the material. The normalized parameters are the stress ratio $R_\sigma = \sigma_{n\,pl}/R_{u/t/T}$ for the far-field and the stress intensity ratio $R_K = K_{I\,id}/K_{Ii\,c}$ for the crack tip. The "2CD" distinguishes three fields of damage modes. 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.

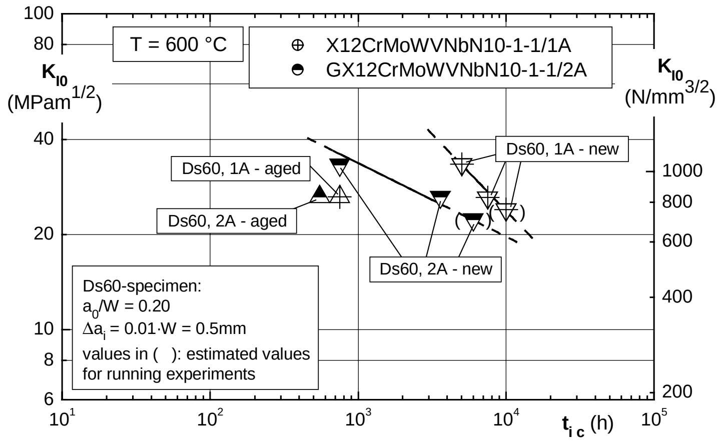



**Figure 4:** Parameter $K_{I0}$ vs. creep crack initiation time $t_{i\,c}$ for Ds60-specimen, steel X12CrMoWVNbN10-1-1 and cast steel GX12CrMoWVNbN10-1-1, T = 600 °C

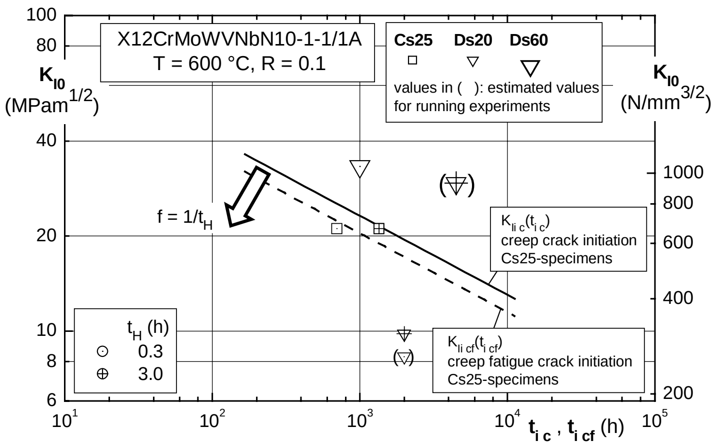



**Figure 5:** Parameter $K_{I0}$ crack initiation time under creep fatigue conditions $t_{i\,cf}$ and under creep conditions $t_{i\,c}$, steel X12CrMoWVNbN10-1-1, T = 600 °C

In order to include the results of creep-fatigue crack initiation, it was suggested to modify the "2CD" for hold times between 0.3 and 3.0 h [7, 9]. This modification takes place via the stress intensity ratio $R_K$ or the material property value $K_{Ii\,c}$ for crack initiation. In this connection the effect of the maximum stress intensity $K_{Ii\,c}$, determined by creep crack tests with Cs25-specimens, is enhanced by reducing the time to crack initiation under creep fatigue loading to 60% of the corresponding time under creep crack loading (Fig. 5). The difference between the creep crack behaviour and the creep-fatigue crack behaviour, determined each by Cs25-specimen tests, is characterised by the solid line ($K_{Ii\,c}$ - $t_{i\,c}$) and dotted line ($K_{Ii\,cf}$ - $t_{i\,cf}$) of the diagram. The modified "2CD" of steel X12CrMoWVNbN10-1-1 is shown in Fig. 6. The validity of the boundary line is confirmed by the results of creep fatigue crack initiation tests.

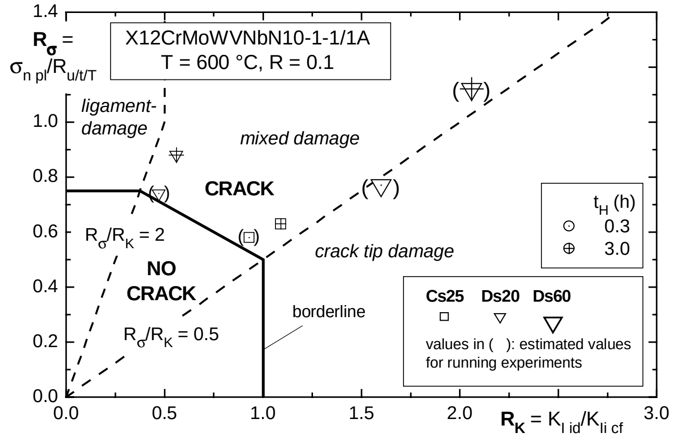



**Figure 6:** Modified Two Criteria Diagram for crack initiation under creep fatigue conditions, steel X12CrMoWVNbN10-1-1, T = 600 °C

***Crack Propagation Behaviour***

The creep fracture mechanics parameter C* has been chosen for the presentation of the creep crack growth rate because of the transition times $t_1$. As an example, the creep crack growth rate of cast steel GX12CrMoWVNbN10-1-1 is plotted in Fig. 7. The scatter band includes the results from specimens varying in geometry and size and tested at T = 550 and 600 °C.

The first crack propagation results obtained from the creep crack tests performed in inert gas show no reduction in the crack growth against those obtained in air under the restriction of relatively high loads. None of the crack surfaces of the specimens tested in inert gas environment, which have been considered up to now, indicate any oxidation symptoms. However, it is possible that steam may have effected the crack behaviour. This shall be investigated in comparison tests in vacuum.

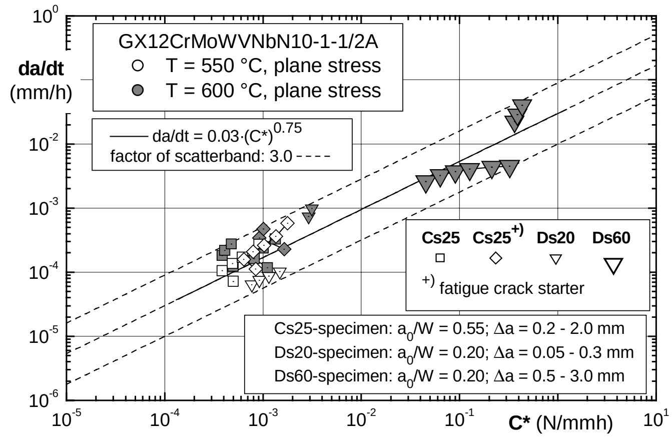



**Figure 7:** Creep crack growth rate versus parameter C*, cast steel GX12CrMoWVNbN10-1-1, T = 550 and 600 °C

## SUMMARY

The crack initiation and crack propagation behaviour of 1% CrMo(Ni)V- and 10% CrMoWVNbN-steels has been investigated under creep and creep fatigue loading. Obtained experimental results enabled production of a data-basis for the assessment of the material behaviour on locations with crack-like stress concentrations which are supplemented by tests performed on aged material and in inert gas environment.

Due to the improved creep properties the modern 10% CrMoWVNbN-steels show an improved crack resistant potential against the well-established 1% CrMo(Ni)V-steels. This could be proved on basis of small scale specimens as well as on basis of component-like large scale specimens. The 10% CrMoWVNbN-forged steel has better properties in view of crack initiation and crack propagation than the comparable cast steel. A corresponding comparison for the 1% CrMo(Ni)V-steel is not yet available. A transition from static loading, i.e. creep crack loading, to cyclic tensile loading, i.e. creep fatigue loading, causes a reduction in the time to crack initiation and an increase in the crack growth at shorter holding times. For both loading types the "2CD" is a tool for the assessment of the crack initiation and the geometry and load depending type of damage.

Further information is available from tests performed on thermally aged materials to assess the behaviour of operation-like loaded material in the

vicinity of defects. The changes in structure due to thermal ageing may cause a distinct reduction in the resistance against crack initiation and crack propagation at least for shorter loading times. The influence of an inert gas atmosphere on the crack behaviour will be investigated by fracture mechanics tests in argon with 3% hydrogen. The first test results obtained show no clear influences on the crack initiation and crack propagation behaviour.

Thanks are due to the “Forschungsvereinigung der Arbeitsgemeinschaft der Eisen und Metall verarbeitenden Industrie e.V.” the “Forschungskuratorium Maschinenbau e.V.”, the “Bundesminister für Wirtschaft”, the “Arbeitsgemeinschaft industrieller Forschungsvereinigungen” and the “VDEh-Gesellschaft zur Förderung der Eisenforschung mbH” for their financial and technical support in these research projects. Numerous discussion with Dr. Ewald on the application of "2CD" were of great importance for the quality of this work.

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