Crack Growth in a Pipe Grade PVC Material under Static and Cyclic Loading Conditions

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Summary: The creep crack growth (CCG) and the fatigue crack growth (FCG) behavior of a commercial pipe grade PVC material was studied based on a linear elastic fracture mechanics (LEFM) methodology. The FCG tests were performed under sinusoidal load control at a frequency of 5 Hz and at R-ratios (F_{min}/F_{max}) of 0.1, 0.3 and 0.5; the test temperatures were 23 °C and 60 °C. The creep crack growth behavior (corresponding to R = 1) was studied at a test temperature of 60 °C. The results of the FCG tests revealed that fatigue crack propagation is primarily controlled by the cyclic component of the crack tip stress field rather than by the mean stress level. Comparing FCG and CCG data in terms of K_{Imax} and K_I, respectively, also confirmed the deteriorating effect of the fatigue loading on the crack growth resistance. Fracture surface investigations for both fatigue and static loading were performed to gain insight into the micromechanisms of crack advance.

Introduction

Today plastics pipes for water and gas distribution networks are designed to have a lifespan of at least 50 years. The verification of the long-term performance of these materials requires appropriate test methods. The traditional way to evaluate the long-term behavior is the use of internal pressure tests. To evaluate new pipe material grades, especially in terms of performance ranking, the time for pressurized pipes testing is generally considered to be too long. Other newer test approaches like linear elastic fracture mechanics (LEFM) concepts allow the study of failure behavior in a significantly shorter timespan. In the past the crack propagation behavior of various pipe grades, especially polyethylene (PE) and poly-vinylchloride (PVC) types, was investigated using crack growth tests under both static (creep crack growth (CCG)) and cyclic loading conditions (fatigue crack growth (FCG)).[1-16]

Compared to static loading, fatigue loading enhances the tendency of quasi-brittle failure and at given levels of crack tip stress intensity it leads to accelerated crack growth. Despite the

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basic difference in loading conditions, investigations with PE showed that there are similar characteristics between creep crack growth and fatigue crack growth. Even though, hardly any information could be found in literature dealing with the correlation between the kinetics of crack propagation under static and cyclic loads using LEFM concepts. While there are some data for PE presented by van der Grinten and Schreur[9] and Pinter et al.[10], no such attempt was found so far for PVC. Hence, it is the main objective of the present work to investigate the effects of R-ratio (minimum load to maximum load, F_{min}/F_{max}, in a fatigue cycle) on FCG behavior at various temperatures and to compare the FCG results with the kinetics of CCG behavior. To gain more insight into the micromechanisms of crack propagation, fracture surfaces generated under various loading conditions were investigated via scanning electron microscopy (SEM).

General Background

According to the concepts of LEFM, the applied stress intensity factor, K_I, describes the local crack tip stress and strain field and governs crack propagation assuming a sharp crack, linear elastic material behavior and small scale plasticity.[17] The index I stands for opening mode or pure tensile loading conditions. Generally, K_I can be expressed as:

$$K_I = \sigma \cdot \sqrt{a} \cdot Y \qquad (1)$$

where σ is the applied stress, a is the crack length and Y is a non-dimentional correction function accounting for crack and component geometry as well as the type of loading.

Using these concepts CCG rates, da/dt (where t is the time), may then be plotted as a function of K_I and FCG rates, da/dN (where N is the number of cycles), as a function of the stress intensity factor range at the crack tip, $\Delta K_I = K_{Imax} - K_{Imin}$.[11, 18] For many plastics an extended linear section is revealed on a double logarithmic scale over a certain range of crack growth rate, indicating a power law relationship of the form

$$\frac{da}{dt} = A \cdot K_I^m \qquad \text{for CCG} \qquad (2)$$

$$\frac{da}{dN} = A' \cdot \Delta K_I^{m'} \qquad \text{for FCG} \qquad (3)$$

where A, A' and m, m' are constants, which depend on the material als well as on test variables such as temperature, environment, frequency and stress ratio. Investigations in a wide range of da/dt (da/dN) show that deviations from the power law may be observed as illustrated in Figure 1. That is, crack growth rates in region I rapidly decrease to vanishingly small values as K_I (ΔK_I) approaches the threshold value, K_{Ith} (ΔK_{Ith}), and they markedly increase in region III as K_I (K_{Imax}) approaches the material's fracture toughness, K_{Ic}, and crack propagation becomes unstable.

Experimental

Specimen Preperation

The investigations in this work were carried out with a commercial, lead-stabilized PVC pipe grade material used for pressurized water pipelines. Pipes with an outer diameter of 225 mm and a wall thickness of 10.8 mm were taken from normal production (Pipelife, A), slit and warmed in an oven at 180 °C for 40 min before they were stretched open and pressed between metal plates to produce flat sheets. Compact tension (CT) specimens with a specimen width, W, of 40 mm (see Figure 1) were machined from these plaques. All specimens were kept at a controlled temperature of 23 °C and a relative humidity of 50 % for at least 14 days before testing. Precracks were introduced into the test specimens prior to the fracture mechanical experiments by pressing a fresh razor blade with a nominal thickness of 0.1 mm into the V-notch tip at room temperature.

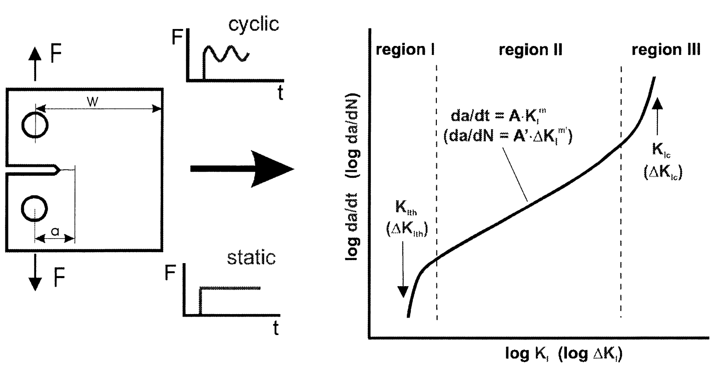


Figure 1. Specimen and loading configuration and schematic illustration of the crack growth behavior of polymers under static and fatigue loads, respectively (F = force, W = specimen width, t = time).

Test Performance

The CCG experiments were performed in a test apparatus, designed and constructed at the Institute of Materials Science and Testing of Plastics (University of Leoben, A).[19, 20] FCG testing was conducted with a servohydraulic closed-loop testing machine (MTS Systems GmbH, Berlin, D) under sinusoidal load control at a frequency of 5 Hz and at R-ratios (F_{min}/F_{max}) of 0.1, 0.3 and 0.5. Both, CCG and FCG tests were performed in air at temperatures of 23 °C (only FCG) and 60 °C. Crack length values were monitored with the aid of travelling microscope units equipped with linear variable transducers (LVTD) for displacement measurements.

Fractographic investigations of specific surface details were carried out using a scanning electron microscope (SEM; Zeiss, Oberkochen, D). Prior to the investigations all specimens were sputter coated with a 15 to 20 nm thick layer of gold. The operating voltage was 5 kV.

Results and Discussion

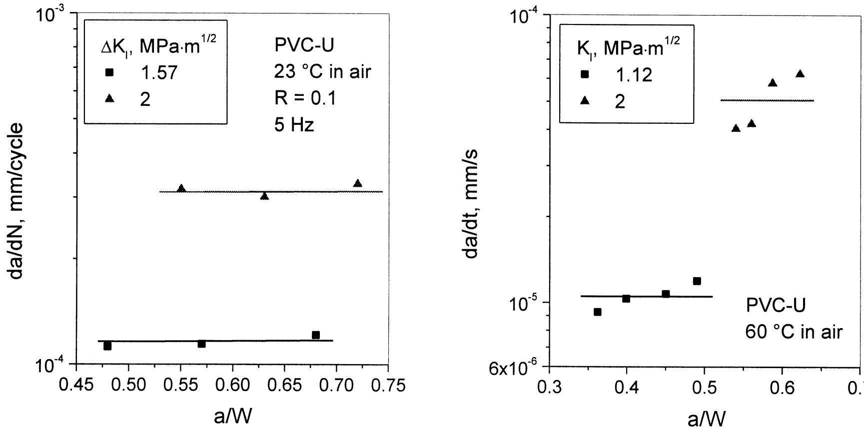
Crack Growth Behavior

To verify the applicability of LEFM, the results of constant ΔK_I and constant K_I experiments, respectively, are presented in Figure 2 in form of da/dN and da/dt, respectively, versus the normalized crack lengh, a/W. The data depicted via fatigue testing show remarkably constant crack growth rates with very little scatter over the entire a/W range, thus providing good support for the applicability of LEFM to the material investigated. Compared to the FCG data, the CCG results exhibit a wider scatter band. This behavior is a result of the more difficult measurement of crack lengths under static loads.

Crack profiles under both, static and cyclic loading are illustrated in Figure 3 (the crack propagation direction is from the left to the right side.). In both cases a white zone, indicative of plastic deformation, can be seen around the crack at the specimen surface. While in the case of fatigue no branching of this zone can be detected until rather large values of ΔK_I (or K_{Imax}), branching is the predominant phenomenon in the case of static loads indicating shear lips at the side surface of test specimen (compare also Figure 9b later).

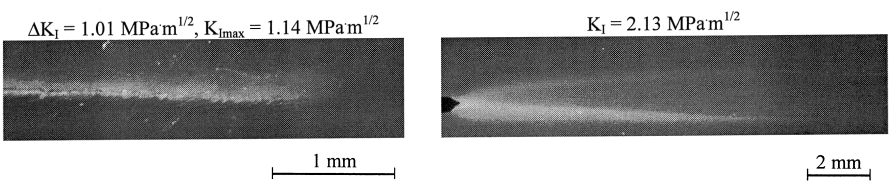
To illustrate the scatter band and the reproducibility of the tests, an overview of all cyclic and static experiments including different initial values of ΔK_{I0} and K_{I0}, respectively, is given in

Figure 4 by presenting the crack growth rates as a function of the applied stress intensity factor range and stress intensity factor, respectively. In general, it can be deduced from the results presented that LEFM concepts represent a useful tool for characterizing the crack propagation behavior of PVC-U under static and cyclic loading conditions.



(a) (b)

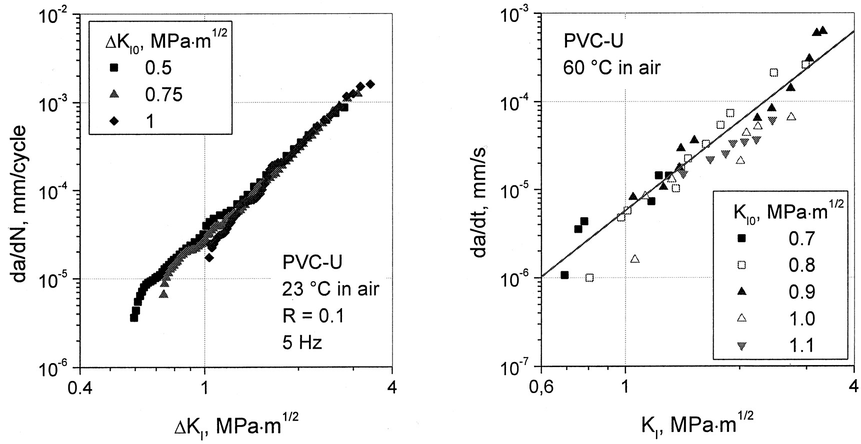
Figure 2. FCG rates (a) and CCG rates (b) in PVC-U under constant ΔK_I and constant K_I conditions, respectively.



(a) (b)

Figure 3. Crack profiles of PVC-U under cyclic (a) and static loading conditions (b).

In Figure 5 the fatigue behavior of the PVC-U investigated is illustrated for two different temperatures and an R-ratio of 0.1. As expected, the FCG curve is shifted towards lower ΔK_I values with increasing test temperature. The reduced fatigue resistance at higher temperatures is generally explained with more favorable conditions for chain disentanglement and chain slippage.[16, 18]



(a) (b)

Figure 4. Influence of different initial values of ΔK_{I0} and K_{I0} on the FCG behavior (a) and the CCG behavior (b) of PVC-U.

FCG data for the two test temperatures illustrating the effects of variations in R-ratio at a given frequency are shown as a function of applied stress intensity factor range in Figure 6. Although there is a slight increase of da/dN with increasing R-ratio, in terms of ΔK_I the effect of mean stress may be considered insignificant. Similar results for a different grade of PVC-U were found previously by Kim et al.[14] Apparently, FCG rates in PVC-U are primarily

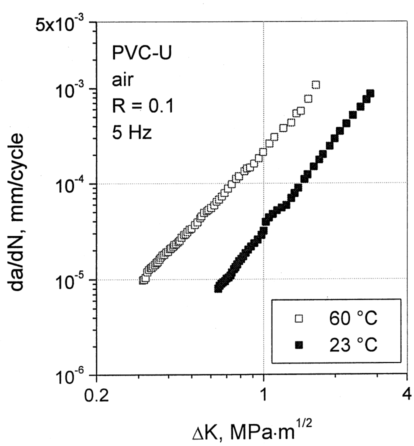


Figure 5. Influence of test temperature on FCG behavior in PVC-U.

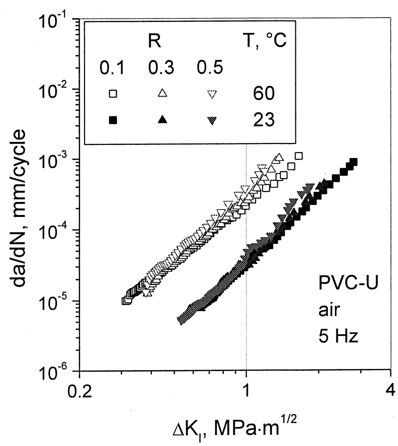


Figure 6. FCG rates of PVC-U for various R-ratios and temperatures as a function of ΔK_I.

controlled by the cyclic component of the crack tip stress field described by ΔK_I rather than an additional creep crack growth component which would imply a more significant effect of the mean stress level on FCG resistance.

Nevertheless, FCG data should also be studied in terms of K_{Imax}, since it has been suggested that it is the latter parameter controlling the size of the plastic zone in front of the crack tip.[21] In addition, FCG plots based on K_{Imax} also allow for a direct comparison with CCG data, if the frequency-time correspondence is properly accounted for (i.e., to transfer da/dN data of 5 Hz experiments to da/dt data the former values are divided by 5). Hence, the FCG data are shown in Figure 7 in terms of da/dt versus K_{Imax} for both test temperatures (23 °C and 60 °C). For 60 °C in Figure 7b, the CCG data corresponding to an R-ratio of 1 are also included for comparison. Figure 7 also illustrates the importance of the cyclic component on crack growth behavior in PVC-U, as the crack speed da/dt at given values of K_{Imax} clearly increases with decreasing R-ratio over the entire range investigated. On the other hand, once the R-ratio increases to a value of 0.5 or more, the crack speeds da/dt of FCG and CCG values approach one another (see Figure 7b).

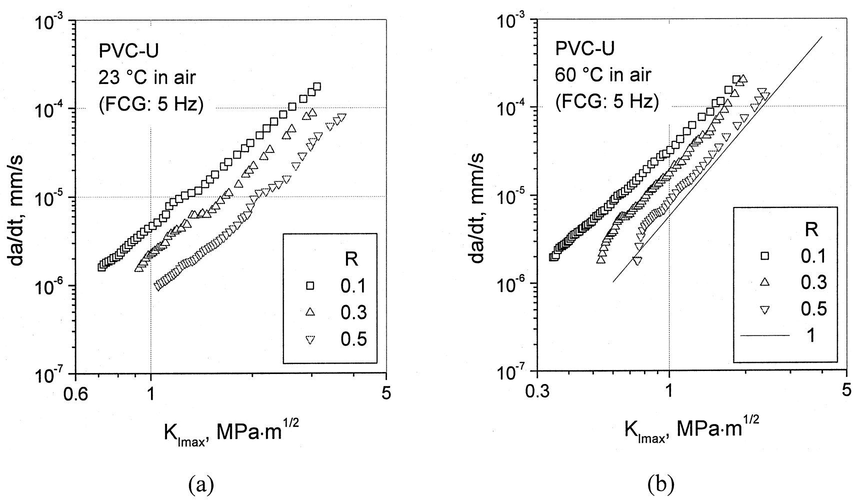


Figure 7. FCG rates of PVC-U for various R-ratios at temperatures of 23 °C (a) and 60 °C (b) as a function of K_{Imax} and comparison with CCG data (R = 1).

Fracture Surface Morphology

Crack profiles of fatigue testet specimens are presented for various R-ratios and a constant K_{Imax} value of 1 MPa·m$^{1/2}$ at 60 °C in Figure 8. An increase in R-ratio results in a rougher appearance of the crack profile on the specimen side surface. On the other hand, the fracture surfaces of all specimens macroscopically appeared rather flat and brittle, independent of the R-ratio. Moreover, comparing the fracture surfaces of specimens tested under fatigue and creep conditions (see Figure 9), both loading modes lead to similar fracture surface characteristics. However, while no shear lips developed under cyclic loading conditions, statically loaded specimens exhibit pronounced shear lips in the side surface regions, especially at higher stress intensity factor levels (cf. Figure 3b). Apart from the shear lip development restricted to a limited region close to the side surface in CCG tests, craze formation and breakdown are the predominant mechanisms responsible for crack propagation in the temperature range investigated.

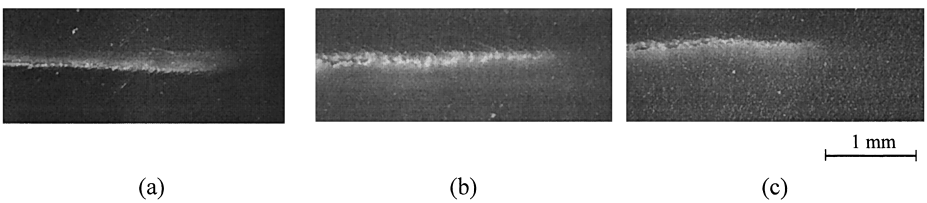


Figure 8. Crack profiles of PVC-U at 60 °C and a constant K_{Imax} value of 1 MPa·m$^{1/2}$; (a) R = 0.1, (b) R = 0.3, (c) R = 0.5.

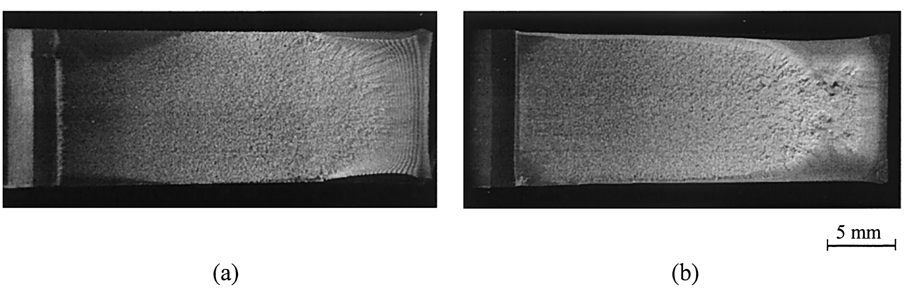


Figure 9. Comparison of the fracture surfaces of PVC-U at 60 °C; (a) fatigue: R = 0.1, (b) static: R = 1.

Fracture surface details of PVC-U tested at 60 °C under cyclic loads with different R-ratios in the range from 0.1 to 0.5 and under static loads are compared in Figure 10 for two K_{Imax}

values (cyclic loads) and K_I values (static loads), respectively. For cyclic loads (see Figures 10a to 10f), the fracture surface appearance reveals more stretched out and plastically deformed features with increasing K_{Imax} values, which corresponds to the concomitant increase in crack tip craze zone dimensions. While no significant differences can be observed with regard to different R- ratios in the range from 0.1 to 0.5, the fracture surfaces of

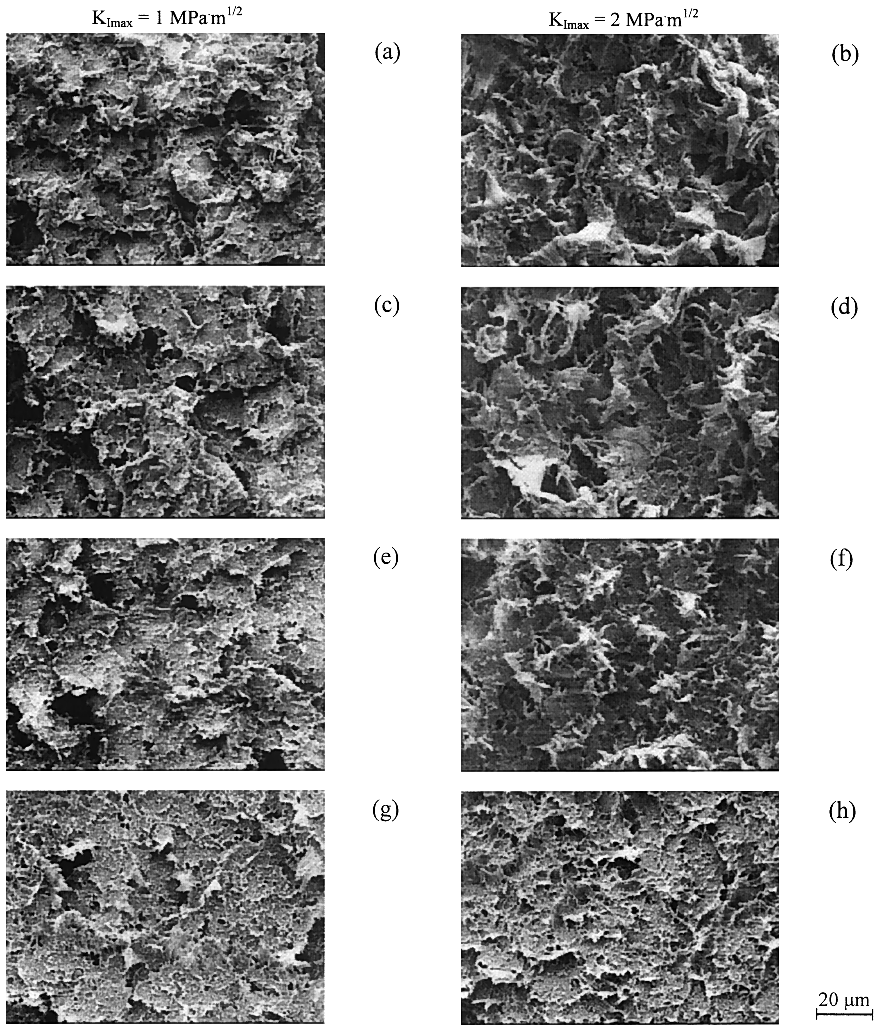


Figure 10. Comparison of the fracture surfaces of PVC-U at 60 °C and constant K_{Imax} resp. K_I values of 1 MPa m$^{1/2}$ and 2 MPa m$^{1/2}$; (a, b) fatigue: R = 0.1, (c, d) fatigue: R = 0.3, (e, f) fatigue: R = 0.5, (g, h) static: R = 1.

specimens from static experiments (corresponding to an R-ratio of 1) appear distinctively different (see Figures 10g and 10h). In contrast to the observations on cyclic fracture surfaces, hardly any difference in fracture surface features depending on the K_I value could be found for statically loaded specimens. These differences indicate that the failure micromechanisms in FCG and CCG tests may also be distinctively different. Further research work is needed to evaluate the causes for these differences.

Conclusions

LEFM provides a proper framework and may be applied for the characterization of the crack growth resistance of PVC-U under both static and cyclic loading conditions. The commercial PVC-U grade investigated exhibits a reduced fatigue resistance at higher temperatures, at least when comparing the behavior at 23 °C and 60 °C. On the other hand, based on a ΔK_I comparison, the effect of mean stress level (i.e., R-ratio variations from 0.1 to 0.5) may be considered insignificant at both test temperatures, indicating that FCG rates are primarily controlled by the cyclic component of the crack tip stress field rather than an additional creep crack growth component associated with higher mean stress levels. This conclusion is confirmed by a comparsion of FCG data and CCG data in terms of da/dt versus K_{Imax} and K_I, respectively. On the basis of crack speeds, da/dt, the overall crack growth kinetics of FCG tests at an R-ratio of 0.5 approaches the crack growth behavior under static loading conditions. It should be recognized, however, that different micromechanisms of failure are involved for both loading conditions.

Fracture surface investigations of statically loaded specimens revealed pronounced shear lips in the plane stress regime in side surface near regions. In contrast, no shear lip formation could be detected on fracture surfaces of fatigue tested specimens. While the stress intensity level in terms of K_{Imax} in FCG tests was found to have a pronounced influence in fracture surface appearance, no significant fracture surface differences could be observed for FCG specimens testet at different R-ratios in the range from 0.1 to 0.5 for given values of K_{Imax}. Apparently, at least for fatigue loading conditions, crack tip plastic zone formation seems to be controlled rather by K_{Imax} than by ΔK_I, while crack growth rates and thus plastic zone breakdown depends on ΔK_I rather than K_{Imax}. In comparison, hardly any effects of K_I on the fracture surface appearance could be verified for CCG specimens. Moreover, distinctively different fracture surfaces were observed for static loading conditions, confirming the above conclusion on different micromechanisms of crack advance for static and cyclic loading.

Acknowledgements

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