Determination of Fracture Mechanics Characteristic Values in the Toughness Transition Range

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ABSTRACT

The behaviour of a cracked component under a given loading situation depends on material toughness. For ferritic steels, the material toughness is variing with temperature. At low temperature dominantly brittle fracture behaviour is observed, at high temperature the failure mode is dominantly ductile fracture. The transition between these two extremes is floating.
In the lower shelf of toughness, K_{Ic} is the characterising value for crack initiation and immediate instable crack extension (cleavage). With increasing temperature the plastic zone at the crack tip rises and yields to a nonlinear load-displacement (F-COD)-behaviour prior to cleavage fracture, so that K_{Ic} is no longer valid. Between crack initiation and cleavage there is an increasing amount of stable crack growth. The characterising parameter is the J-Integral, which is proportional to the deformation energy. In the upper shelf of toughness stable crack growth occurs after crack initiation.
For the transition region and the upper shelf of toughness, several „material characteristics“ are proposed to characterize the materials behaviour and will be highlighted in the paper.
Experimental results from specimens of two different materials show, that the physical initiation value J_i can be used in the whole range of materials toughness to determine crack initiation for standard specimens, shallow crack specimens and components.

NOMENCLATURE

K_{Ic}	Initiation of unstable crack growth (cleavage fracture)	Only linear elastic behaviour up to fracture
K_{IJ}	Initiation of slow stable crack growth, formally calculated from J_i (J-value at initiation of stable crack growth)	Elastic plastic behaviour (Transition, upper shelf of toughness)
K_{Jc}	Instability, formally calculated from J_c (value at cleavage fracture)	Lower shelf and transition, not upper shelf of toughness

INTRODUCTION

Ferritic steels have a distinct lower shelf – transition – upper shelf behaviour. This also applies to fracture mechanics properties. In the lower shelf the plastic deformation properties of the material under the stress state in the area of the crack tips are very limited. A plastic zone develops under these conditions in the very vicinity of the crack tip area (stretched zone). However, it can be neglected in comparison to the specimen dimensions. Following the mostly linear-elastic load- crack opening displacement behaviour spontaneous instability (cleavage fracture) occurs in the specimen as soon as a limit loadability is reached (stress level over a “critical volume”). In this case (lower shelf) crack initiation causes immediate instability (cleavage).
With increasing temperature, Fig. 1, a continuous increase in the crack initiation values can be determined. It is obvious that a stress distribution in the area of the actual crack tip can be obtained causing initiation of a limited stable crack growth also governed by a limited redistribution of stresses leading to spontaneous fracture which also is possible as cleavage fracture. Also it is obvious that plastic yielding in the transition regime is influenced by external parameters such as specimen thickness, specimen size or crack length, i.e. the multiaxiality of the stress state ahead of the crack tip and in the ligament. This means that a change from ductile crack growth to instantaneous failure is also influenced by these parameters.
On reaching a certain temperature level (beginning upper shelf) the maximum ductility of the material is reached and the initiation values will no longer increase even if further temperature increase takes place. This temperature range is the upper shelf level of the initiation. It is highly probable that distinct ductile crack growth occurs in this temperature range.

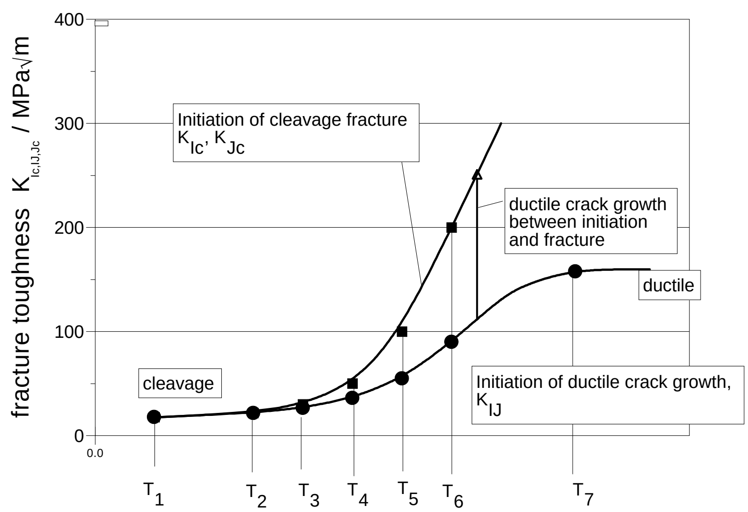

Fig.1: Increasing difference between initiation values K_{Ic}, K_{IJ} and instability values K_{Jc} with increasing test temperature

EXPERIMENTAL TESTING PROGRAM

Experimental tests with various C(T) specimens (C(T) 25 – C(T) 235) and SE(B) specimens (B=25 mm, a/W ~ 0.55) and shallow crack SE(B) specimens (B=25 mm, a/W < 0.1) from two different steels were carried out in the whole temperature range from brittle to ductile material behaviour. The steels were a multi-layer weld material 10 MnMoNi 5 5 with a upper shelf toughness of >200 J at room temperature and a modified material 17 MoV 8 4 subjected to a special heat treatment with the purpose to put it in a state of reduced toughness with high transition temperature.

FRACTURE MECHANICS CHARACTERISTICS VALUES FOR LINEAR-ELASTIC BEHAVIOUR

If brittle fracture occurs without previous relevant plastic deformation the interpretation of the test results is generally acknowledged. The fracture load of the specimen is used to determine the K_{Ic} value, if certain clearly defined requirements (e.g. ASTM E 399/1, 2/) are adhered to leading to size insensitivity of the material characteristics. The most important criteria is the demand on the linearity of the load deformation characterisitic of the specimen up to cleavage.

FRACTURE MECHANICS CHARACTERISTICS FOR DISTINCT ELASTIC-PLASTIC BEHAVIOUR

In the case of an obvious ductile behaviour of the specimen, from the load-displacement record the crack resistance curve is determined. From this crack resistance curve crack initiation characteristics can be deviated according to the standard criteria.
The procedure for determining the crack initiation characteristics for ductile initiation is described in various standards, e.g. /3 to 5/. It has to be differentiated between qualifying "characteristics" e.g. J_{Ic} according to ASTM E 1820 /6/, formerly ASTM E 813 /3/, $J_{0.2}$ and $J_{0.2bl}$ according to ESIS /4, 5/) and quantifying transferable material characteristics which can be used in fracture mechanics safety analyses. Such quantitative transferable material characteristic is a value J_i according to /4/ (determined by the potential drop technique or from the stretched zone /7/).
A "characteristic" for the failure (fracture) is not possible, since the fracture of the specimen under these conditions depends on the type of the test performance, the chosen specimen geometry and on its size /8/. To determine a valid crack resistance curve according to standard the specimen must not break but a required minimum value of stable ductile crack growth must occur prior to unloading the specimen.

FRACTURE MECHANICS CHARACTERISTICS IN THE TRANSITION REGIME

In the transition regime the failure behaviour of specimens made of ferritic steels depends on temperature, specimen size and multiaxiality of the stress state. Because of this they show more or less large plastic deformation and limited stable crack propagation before fracture. The temperature range shall be considered as transition regime in which specimens have so much plastic deformation that the requirements of the standard ASTM E 399 /1/ in view of the linearity of the load-deformation behaviour cannot be kept and simultaneously, the requirements of the standards for upper shelf behaviour in view of the required stable crack growth values as a result of specimen fracture cannot be maintained.
The relevant testing recommendations for the transition regime (eg ESIS P2-92 /5/, ASTM E 1921-97 /9/) take account of the actual state at fracture of the specimen in the transition area but not of the crack initiation. The "characteristic" at fracture of the specimen (instability by cleavage) is denoted as J_c.
One of the validity criteria of /9/ is that prior to the cleavage event the stable crack growth was smaller than 0.05 ($W-a_0$). Consequently, a value of about 1 mm stable crack growth prior to instability is allowed in a usual C(T)25-specimens. This means that the specimen has developed a crack resistance curve up to a considerable stable crack growth before instability. Consequently, these instability values represent no characteristic values because the J_R-curve is strongly affected by the stress state.
According to ASTM E 1921-97 the instability value (J) is converted in K-values using the relation

$$K_I = \sqrt{J \cdot E}$$

which is valid for linear-elastic behaviour. Subsequently, it will be converted in K_{Jc}-values using a thickness correction depending on the crack front length. This thickness correction is also applied to K_{Ic}-values according to ASTM E 399 and may lead to two distinct different characteristic values depending on the standard used both of which have to be regarded as valid.
The difference between the thickness corrected instability values (K_{Jc}) and the crack initiation values K_{Ic} and K_{IJ} increases more and more with rising testing temperature, Fig.1. Therefore, $K_{Jc'}$-values are not applicable for the initiation exclusion in the safety analysis.

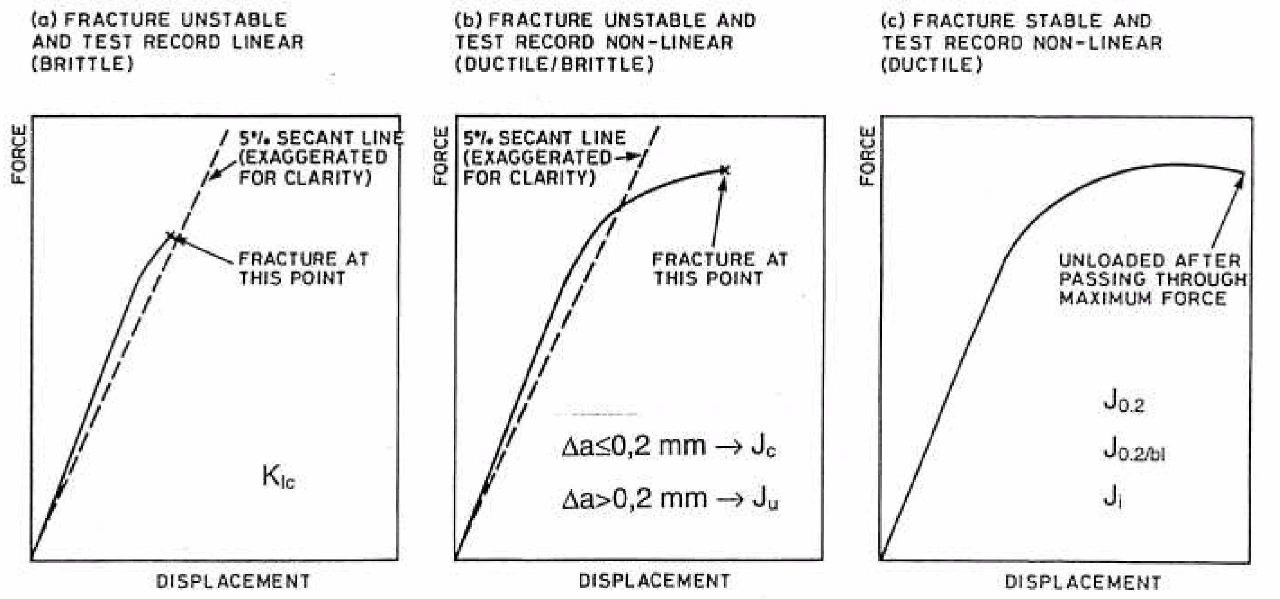

Fig.2: Criteria for fracture toughness values in lower shelf, transition and upper shelf acc. to ESIS P2

The instability values are distinguished in J_c and J_u. according to ESIS /5/. According to ESIS J_c is designated if the stable crack growth prior to spontaneous cleavage is <0.2 mm and J_u if spontaneous cleavage occurs with prior stable crack growth ≥0.2 mm. Thickness correction is not recommended according to ESIS test recommendation.
According to BS 7448 /10/ an additional J-value is introduced on reaching a distinct load maximum as J_m-value.

FRACTURE MECHANICS CHARACTERISTICS FOR THE SAFETY ASSESSMENT OF COMPONENTS

In the testing standard ASTM E 1921-97 a procedure is outlined to determine a reference temperature and a fracture toughness curve using small fracture mechanics specimens. The reference temperature T_0 according to ASTM E 1921-97 is determined by testing of at least 6 specimens. In determining the reference temperature T_0 failure probabilities may be indicated following the statistical analysis of the data. Usually in combination with the Master Curve (50 % probability of failure) the 5%- and the 2%- fractiles are determined.
In applying to existing data sets it has to be taken into account that available test data are usually distributed over the temperature. According to ASTM E 1921-97 a procedure is not available for the assessment of such data distributions. For such cases a method has been developed in /11/ in which the reference temperature T_0 can also be taken from data sets with temperature distributed data using the Maximum Likelihood method.

This is a favourable method in so far as the reference temperature is introduced by fracture mechanics values. The disadvantage is that it is based on not directly transferable "characteristic values" (instability values, thickness corrected).

REQUIREMENTS ON FRACTURE MECHANICS CHARACTERISTICS FOR SAFETY ANALYSES

In consequence of the phenomenological delineation of the failure of precracked ferritic specimens fracture mechanics characteristic values have to delineate the temperature dependent continuous course in the total relevant temperature regime. This is of very importance if a transient, i.e. temperature depending load has to be considered in the fracture mechanics assessment of RPV. Depending on the material condition, in that case the total temperature range from upper shelf to lower shelf may have to be taken into account.

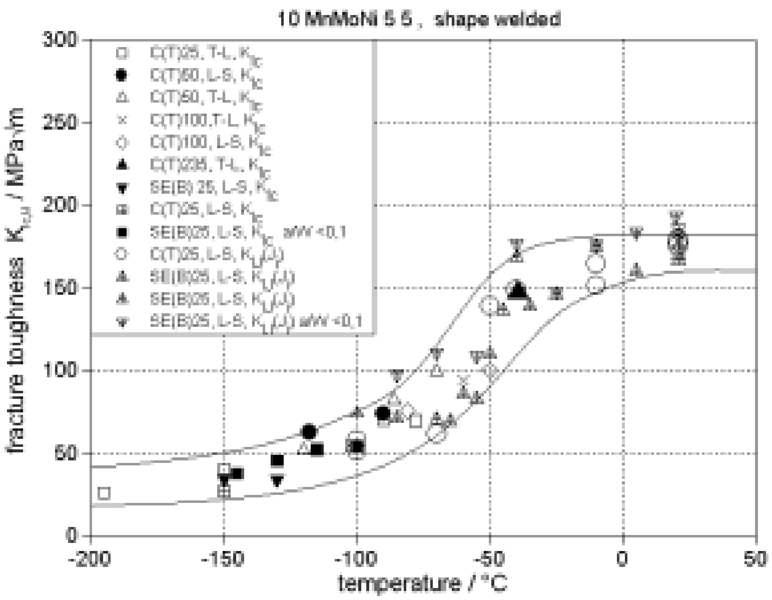

Fig. 3: Initiation values K_{Ic} and K_{IJ} form J_i for standard and shallow crack specimens

Only initiation values can be used for such analyses in the sense of the required exclusion of fracture initiation, cf. Fig. 1. This is exemplarily shown in the representation of various "characteristic values" for a multi-layer weld material 10 MnMoNi 55. Figure 3 shows the initiation values (K_{Ic} and K_{IJ} from J_i) of this material determined on specimens of different geometry and size. The initiation values show the required continuous course over the temperature even for standard and shallow crack specimens. However if the thickness corrected instability values K_{Jc} are used in the transition range (only valid values according to ASTM E 1921), it is not possible to assess the safety margins on the basis of these values in direction to higher temperatures in contrary to the initiation values Fig. 4. While the crack initiation values K_{IJ} from J_i is not affected by the a/W-ratio, the K_{Jc}-values from standard and shallow crack specimens differ more and more with increasing test temperature. The reason for this behaviour is the increase of stable crack growth prior to cleavage due to the lower multiaxiality of the stress state in the ligament of shallow crack specimens than in standard specimens. Therefore shallow crack specimens yield higher J-values than standard specimens at the same crack growth. The Master Curve fit was carried out for the data sets of standard specimens and shallow crack specimens using the Maximum Likelihood method. The Master Curve T_0-temperatures from shallow crack specimen results and standard specimen results show a temperature shift of $\Delta T_0 = 35$ K.

However it should be noted that the fixed shape of the Master Curve doesn't fit well the course of the measured instability values K_{Jc} of the shallow crack specimens.

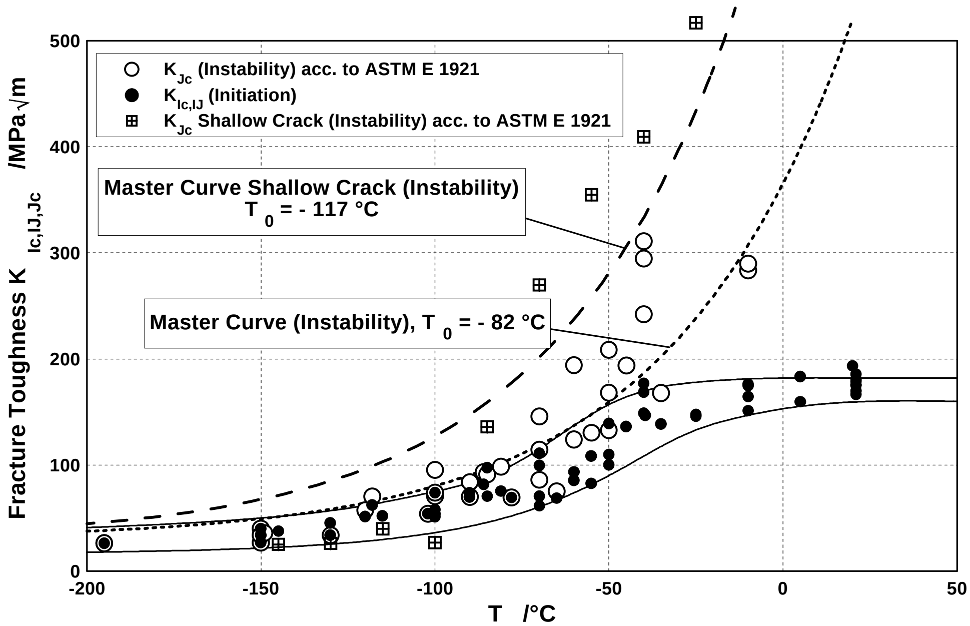

Fig. 4: Initiation values (K_{Ic} and K_{IJ}) and instability values (K_{Jc}) from standard and shallow crack specimen

EXAMPLE OF USING FRACTURE MECHANICS CHARACTERISTIC VALUES FOR THE ASSESSMENT OF TRANSIENT LOADED LARGE SCALE TESTS

Within the scope of research projects MPA Stuttgart carried out eight pressurised thermal shock tests on pre-cracked cylindrical specimens with dimensions of ($D_a$xs = 800 x 200 mm^2). The test cylinders have been loaded by internal pressure and thermal transients in all tests. Various crack geometries, material toughness and transients have been investigated.

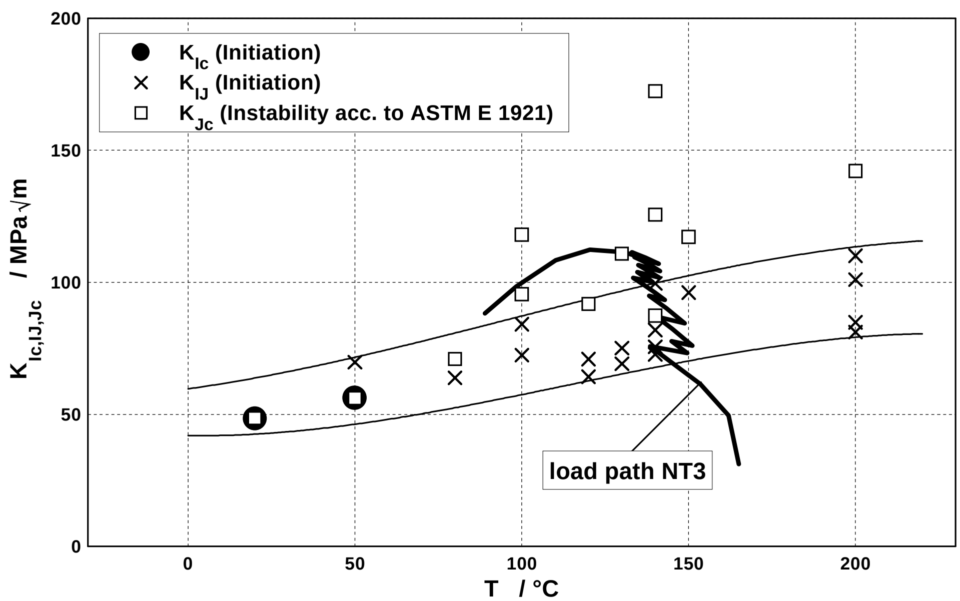

Fig. 5: Load path NT3 compared to Initiation values (K_{Ic} and K_{IJ}) and instability values (K_{Jc})

Test NT3 /12/ is of special interest in this discussion. The specimen NT3 was made of modified material 17 MoV 8 4 subjected to a special heat treatment with the purpose to put it in a state of reduced toughness with high transition temperature. The boundary condition for the transient load was so that crack initiation

should occur in the upper transition regime. The ratio of the original crack depth to wall thickness a/t was about 0.1.
The load path of specimen NT3 is represented in Fig. 5 together with the fracture toughness values K_{Ic} and K_{IJ} and the appertaining instability values K_{Jc}, according to ASTM E 1921-97 /9/. The loading of the NT3-specimen resulted in the initiation of a "brittle" crack event shown on the fracture surface as dominantly transcrystalline cleavage fracture surfaces. Following a limited crack "jump" a crack arrest took place with subsequently repeated re-initiation and crack arrest /12/ for several times. The first crack initiation event is of significance to this discussion. Crack initiation takes place in the lower scatter band area of the measured initiation values K_{Ic} and K_{IJ} and so can be predicted correctly by means of these material characteristics, Fig. 5. The test cylinder neither reached the Master Curve (instability values K_{Jc} (thickness corrected according to /9/)) of the standard specimens nor that of the shallow crack specimens, Fig 6.

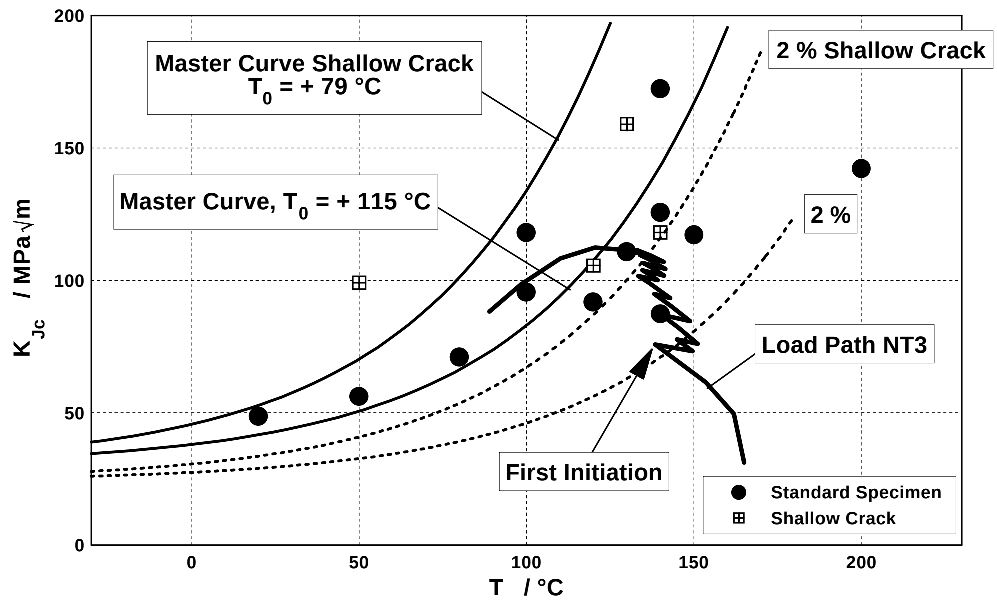

Fig. 6: Load path NT3 compared to Master Curves for deep and shallow crack specimens

Only the 2 % probability of instability curve from the standard specimens meets the first crack initiation event of specimen NT3, Fig. 6.
A correction of the Master Curve taking into account crack front length only can not be sufficient. Additionally the influence of the multiaxiality of the stress state on instability has to be taken into account.

SUMMARY

The safety analysis of nuclear pressure boundary components has to prove that a postulated crack does not cause crack growth leading to failure of the component. Therefore, the exclusion of crack initiation needs to be proven first of all. Fracture mechanics assessment methods and the material characteristic values used as a basis are of considerable importance.
In order to quantify better or reduce partly large conservativities, the characteristic material values for the lower shelf and the transition area of the fracture toughness (K_{Ic}-curves) are under discussion internationally.
The above discussion demonstrated that various methods to determine fracture mechanics characteristic values and the corresponding fracture toughness curves clearly result in parameters with various material-mechanical importance.
The result of the investigation with standard and shallow crack specimens on the transferability of material characteristics proved that only crack initiation characteristic values can be transferred directly to components. Instability characteristic values do not comply with the transferability conditions required for

the material characteristic values because of the effect of the stress state in the ligament on J-Integral and crack growth. Therefore it is not practicable to deviate limit curves by applying correction functions on the basis of these instability values. This is demonstrated on the example of a large scale test specimen (to simulate pressurised thermal shock conditions). The crack initiation characteristic values should be preferred as a basis for the initiation exclusion, since it is material-mechanical proven.

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