FRACTURE MECHANICS ASSESSMENT OF COMPONENTS

E. Roos, K. Kussmaul *

The presentation introduces methods to determine fracture mechanics characteristics from small scale specimens which can be used to predict crack initiation for large structures even under complex loading conditions, for example mechanical and thermal loading. The fracture mechanics concepts were verified for crack initiation and crack arrest. Taking the multi-axial stress state into consideration also the amount of stable crack growth could be determined in case of thermal shock loading. It could be confirmed that the fracture mechanics concept of the Code, based on the reference temperature RT_{NDT} describes the material behaviour conservatively and can be applied to unirradiated as well as irradiated material states.

INTRODUCTION

In the safety assessment of the RPV the incredibility for initiation of a brittle fracture has to be demonstrated throughout the entire life-time for all service loading conditions including postulated accidents when considering a semi-elliptical surface flaw. Since this assumption is most challenging, the fracture mechanics understanding of material behaviour and the necessary concepts and tools will be discussed in this paper.

LINEAR-ELASTIC FRACTURE MECHANICS PARAMETERS

The linear-elastic fracture mechanics parameter is the fracture toughness K_{Ic}. The K_{Ic} value is characteristic for the initiation of a brittle fracture. The procedure to determine K_{Ic} values is given in the Test Standards ASTM E 399, BS 5447 and ISO/DSI Draft 12 737. The K_{Ic} values determined by that procedure are supposed to be size independent.

* Staatliche Materialprüfungsanstalt, University of Stuttgart

ELASTIC-PLASTIC FRACTURE MECHANICS PARAMETERS

The parameter mainly used is the J-integral. From the crack resistance curve (J over crack growth) crack initiation values can be derived according to the following Standards and drafts: ASTM E 813 (J_{Ic}), ESIS P1/P2 (J_i, $J_{0,2}$, $J_{0,2/bl}$). At the MPA Stuttgart, since several years, a procedure is applied additionally to evaluate crack initiation value J_i based on the determination of the "stretched zone" Δa_i (1), Figure 1. This is the region at the crack tip of large plastic deformation ("blunting") before the event of stable crack extension. For the quantitative determination of the crack initiation value J_i, that point of the J_R-curve is selected for which Δa equals Δa_i. The crack resistance curve itself is not a material law, Figure 1.

DYNAMIC FRACTURE TOUGHNESS

The lower bound fracture toughness curve (K_{IR} and K_{Ia}) as presented in the ASME and KTA Code are based on crack arrest K_{Ia} and dynamic initiation values K_{Id}, respectively. For the determination of dynamic fracture mechanics values there exist only the standards ASTM E 399, App. 7, BS 6729 and in the elastic-plastic regime BS 7448, Part 3. The dynamic fracture toughness data can be used for an additional lower bound consideration supporting the static data, since at the crack tip high strain rates can occur even under low load rates (2).

CRACK ARREST TOUGHNESS

The procedure to determine crack arrest toughness values for ferritic materials is described in ASTM E 1221. The K_{Ia}-value is the stress intensity at the crack tip after the crack has arrested. To obtain valid K_{Ia}-values linear-elastic material behaviour and plane strain conditions are required as for static crack initiation values. Usually K_{Ia} values cannot be determined at temperatures $T > T_{NDT} + 60$ K due to plastic deformation before unstable crack extension (3).

FRACTURE MECHANICS DATA IN COMPARISON WITH THE CODE

The individual material toughness of different melts is implemented by means of their reference temperature RT_{NDT} which is according to the Code (ASME, KTA) the reference temperature on the basis of

$T_{Cv} = T\ (Cv = 68\ J) - 33\ K$	(energy criterion)
$T_{le} = T\ (le = 0.9\ mm) - 33\ K$	(lateral expansion criterion)
T_{NDT}	(nil ductility transition temperature)

It could clearly be shown that all experimental K_{Ic}-data are conservatively be covered by the Code curve (K_{Ic}-curve) in the relevant temperature range, however, the different materials exhibit quite different margins to the K_{Ic}-Code curve. Specific recognition deserves the fact that in the brittle/ductile transition region the initiation value of the small CT 25 specimen determined as J_i from the J_R-curve and converted into K_{IJ}

corresponds almost exactly with the K_{Ic}-values determined with large specimens (CT 235 and CT 500) at the same temperature. This confirms the J_i value as size independent physical material parameter. In the linear-elastic regime the Code curve K_{IR} also covers the experimental data for dynamic crack initiation, Figure 2.

TRANSFERABILITY OF FRACTURE MECHANICS CONCEPTS AND MATERIALPARAMETERS TO COMPONENTS

The transferability of fracture mechanics characteristics is verified when data from small specimens describe the behaviour of large structures.

TRANSFERABILITY TO MECHANICALLY LOADED STRUCTURES

In the frame of the research program FKS crack resistance curves were evaluated on large scale specimens (4), (5). The K_{IJ}-values derived from J_i of specimens with different size and geometry CTB ≥ 100 mm, SECT, DECT and CCT as well as TPB specimens (100 mm ≤ B ≤ 600 mm and 2 W = 200 mm) are within the band of initiation values obtained from small scale specimens. This demonstrates that the effective crack initiation value J_i is not depending on specimen size and geometry, whereas the crack resistance curves show with increasing stable crack growth Δa increasing differences, Figure 3. The general application of ductile fracture mechanics characteristics, however, is limited to the initiation value J_i which does not include any stable crack extension. The reason for the different behaviour after initiation is obviously the significantly different stress state (6). For the quantification of the three dimensional stress state in the ligament of a structure the coefficient of multi-axiality

$$q = \frac{\tau_r}{\sigma_m} = \sqrt{\frac{-9J_2'}{J_1^2}}$$

can be used (τ_r reduced stress acc. to Hencky (7), σ_m mean stress, J_2' second invariant of the stress deviator, J_1 first invariant of the stress tensor). The quantification of the stable crack growth is also possible by analyzing the coefficient of multiaxiality across the ligament of a specimen or a component.

TRANSFERABILITY TO THERMALLY TRANSIENT LOADED STRUCTURES

The transferability of fracture mechanics concepts and material characteristics to structures which are subjected to thermal transient load was proved at the MPA Stuttgart by means of thick walled hollow cylinders (i. D. = 200 mm, t = 200 mm) under mechanical and thermal shock loading with circumferential crack (a/t = 0,17). The material used was a MoV steel with a Charpy energy of 30 J, therefore, the reference temperature RT_{NDT} could not be determined. For this reason a transition temperature was evaluated from the instrumented Charpy impact test taking crack arrest load P 4 = 4 kN FATT 50 into account. The transition temperature T_{ref} was selected as the lower temperature of both. The specimen was made of the MoV steel at the inner part and weld metal (S 3 NiMo 1) with high USE at the outer part. After fabrication, the specimen was post weld heat treated. The load path K_I for the specimen during the cooling phase is shown in Figure 4 together with the fracture toughness curves K_{Ic} and K_{IR} and the K_{IJ}-data of the base and weld metal. The first crack initiation occurred predominantly in a ductile mode which is in accordance with the experimentally established K_{IJ}-curve and the first intersection of the load path with this curve. In continuation of the cooling process the load path intersects the K_{Ic}-curve which caused a spontaneous crack jump of 20 mm. The crack was then arrested still in the base material with low toughness. The fracture surface of this crack jump shows 100 % brittle fracture. After further cooling a second crack initiation with a crack jump of 41 mm in the weld metal occurred. In this case both the region of crack initiation and the crack growth showed ductile appearance. Acoustic emission signals showed clearly the spontaneous event of the first crack growth and signals over a period of time indicating ductile crack growth.

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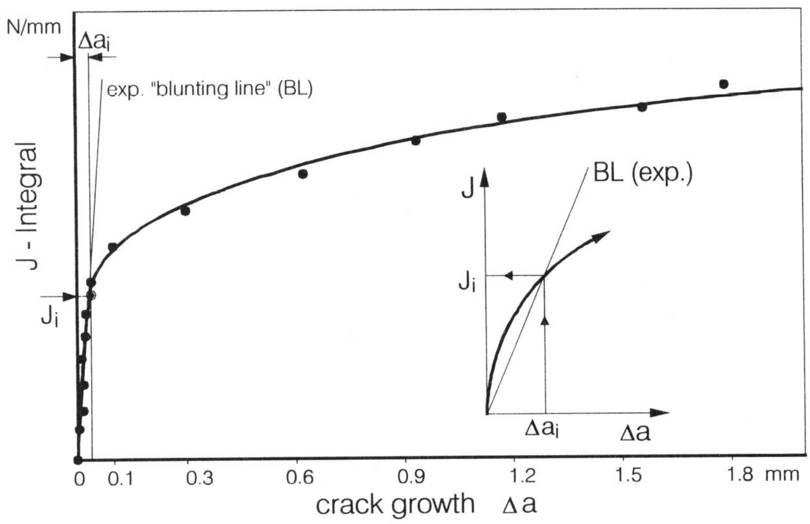

Figure 1: Determination of the crack initiation value from the crack resistance curve on the basis of the "stretched zone" Δa_i

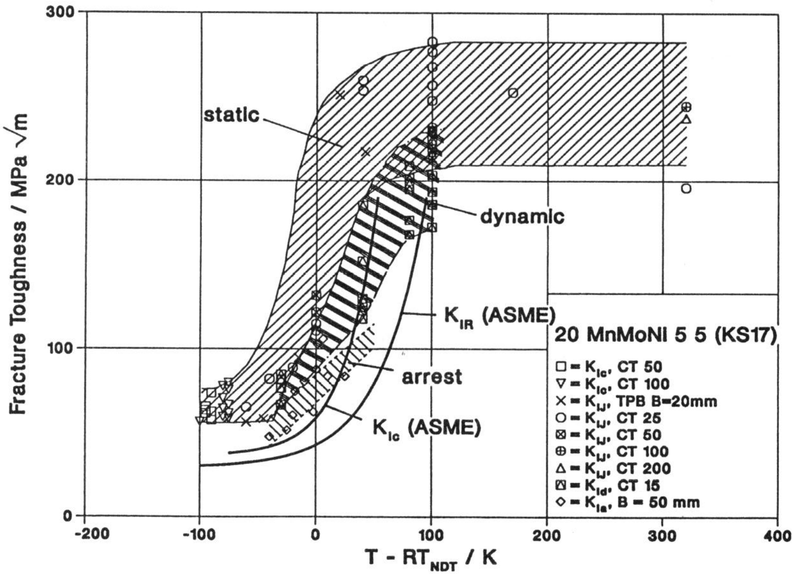

Figure 2: Static and dynamic crack initiation values and crack arrest data of fine grained steel KS 17 with upper shelf energy of 200 J

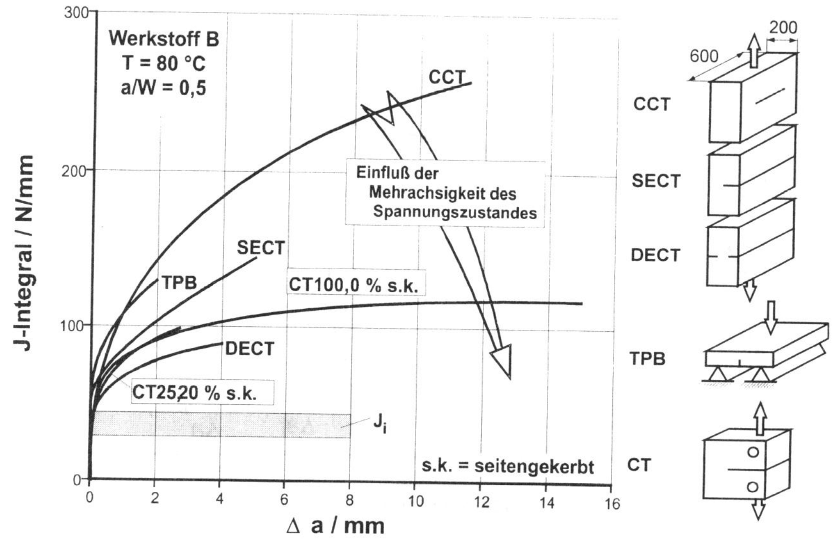

Figure 3: Crack resistance curves of large scale specimens of different geometry with fatigue crack

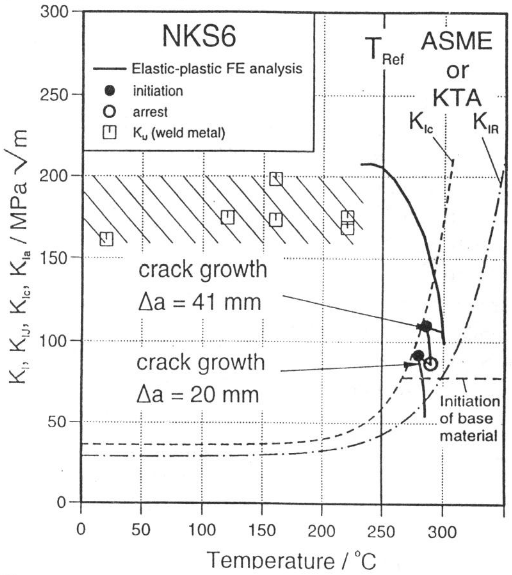

Figure 4: Load path and fracture mechanics data of thermal shock experiment NKS 6