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Prediction of fracture toughness based on experiments with sub-size specimens in the brittle and ductile regimes

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HIGHLIGHTS

- Prediction of fracture toughness on standard-size specimens.
- Valid fracture toughness based on sub-size specimens.
- Triaxiality dependent cohesive zone model.
- Approach works independent on fracture appearance (brittle, ductile).

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ABSTRACT

For determination of fracture toughness in the brittle regime or ductile fracture in the upper shelf region, special standard specifications are in use e.g. ASTM E399 or ASTM E1820. Due to the rigorous size requirements for specimen testing, it is necessary to use big specimens. To circumvent this problem an approach based on finite element (FE) simulations using the cohesive zone model (CZM) is used. The parameters of the cohesive zone model have been determined using sub-size specimens. With the identified parameters, simulations of standard-size specimens have been performed to successfully predict fracture toughness of standard-size specimens in the brittle and ductile regimes. The objective is to establish small size testing technology for the determination of fracture toughness.

1. Introduction

The determination of fracture toughness requires specimens which are big enough to fulfill the size-requirements according to the standards. The geometrical size effect plays a major role in that case [1]. For brittle fracture toughness K_{Ic} the ASTM E399 [2] has to be taken into account and for ductile fracture toughness K_{JIc} the ASTM E1820 [3]. In the case of ASTM E399 the plane strain fracture toughness can be determined directly from force vs. deflection or crack opening displacement (COD) records, where in contrast the ASTM E1820 can only determine the fracture toughness indirect using the J-integral and the crack resistance (J-R) curve. Due to limited material availability e.g. in irradiated conditions, it is mandatory to use sub-size specimen geometries. This paper deals with an approach which is able to circumvent the geometrical size effect by using the cohesive zone model [4]. The parameters to describe the fracture process with the cohesive zone model are identified on sub-size specimens. Fig. 1 shows the sub-size specimens (top) in comparison to a standard-size fracture mechanics bend specimen (bottom) which are necessary for parameter identification of the cohesive zone model (CZM). In the past the approach has already been used for ductile fracture [5]. Now focus is on the brittle fracture behavior of the ferritic-martensitic steel T91. Some additional work on the ductile behavior will also be shown in summary.

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Nomenclature

a_0/W	pre-crack ratio
B	thickness
B_N	netto thickness
F	force
h	triaxiality $h = \sigma_H/\sigma_v$
J	J-integral
J_Q	preliminary J-integral at 0.2 mm offset line
K_{Ic}	fracture toughness based on ASTM E399
K_{JIc}	fracture toughness based on ASTM E1820 and J_Q
K_{JQ}	preliminary fracture toughness based on ASTM E1820 and J_Q
K_Q	preliminary fracture toughness based on ASTM E399
L	length
R_n	notch root radius
W	height
Γ_c	cohesive energy
δ_1	shape parameter 1 for the cohesive zone model
δ_2	shape parameter 2 for the cohesive zone model
δ_c	critical separation
σ_c	cohesive stress
σ_H	hydrostatic pressure $\sigma_H = 1/3\ (\sigma_{11} + \sigma_{22} + \sigma_{33})$
σ_v	equivalent von Mises stress

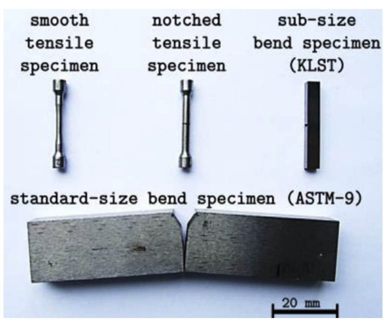

Fig. 1. Specimen geometries.

2. Approach and material

First of all tensile tests on smooth specimens have to be performed to identify the flow curve of the material. This data set is necessary to be able to describe the mechanical behavior for FE simulations. In that case the occurrence of necking has to be taken into account and the stresses have to be corrected due to the Bridgman correction [6] to result in an uniaxial true stress vs. true strain curve.

The approach is based on the idea that the finite element method in combination with the cohesive zone model is able to deal with the geometrical size effect. The main idea of the cohesive zone model is shown in Fig. 2 (left). The finite element model with continuum elements is extended by using cohesive elements [4]. The cohesive elements are embedded in between the continuum elements where the crack will appear. These cohesive elements follow a so called traction separation law (TSL). The TSL needs two parameters, namely cohesive stress σ_c and cohesive energy Γ_c (or critical separation δ_c). We used the TSL developed by Scheider [4] with two additional shape parameters δ_1 and δ_2, see Fig. 2 (right). These shape parameters open the flexibility to change the shape of the TSL. He implemented this TSL as user element into the finite element program ABAQUS with the possibility to consider triaxiality dependent cohesive zone parameters.

Fig. 3 shows the already mentioned approach which is used. To be able to describe the fracture process using the cohesive zone model, the parameters for the traction separation law of the CZM have to be identified. Following the approach there are two experimental tests for parameter identification necessary, which are highlighted in green, see Fig. 3.

The first experimental test is on sharp U-notched tensile specimens with notch root radius R_n of 0.1 mm and specimen length L of 27 mm. The true strain at fracture is identified by observing the notch root diameter reduction with a CCD camera system. Based on that information a FE simulation of this specimen geometry up to the experimentally determined true strain is analyzed to get information about the local stress distribution in axial direction in the specimen at the onset of fracture. Cornec et al. [7] call this method a hybrid technique to identify the cohesive stress. To consider stress triaxiality h a notch root sensitivity study was figured out to get the local maximum stress vs. triaxiality information at fracture.

The second parameter (cohesive energy) is identified by parameter fitting. The simulation result of fracture mechanics three point bending test using the cohesive zone model with the TSL developed by Scheider [4] is adjusted by changing the cohesive energy until experimental results can be described. Due to the big scatter in low temperature testing, the experimental 50% failure probability for deflection and J-integral are considered for fitting procedure. For ductile behavior the J-R and the deflection curves are used. The geometry of sub-size bending specimen is $27 \times 3 \times 4$ ($L \times B \times W$) mm^3.

After cohesive zone parameter identification is finished, the simulation of a standard-size specimen can be performed to successfully predict the J-R curve of this geometry and finally the

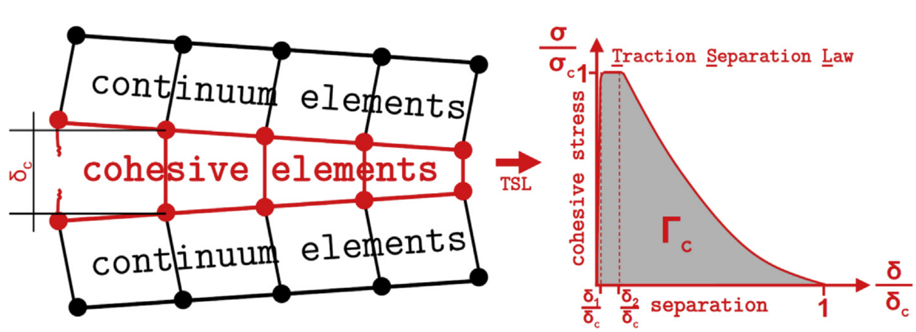

Fig. 2. Cohesive elements embedded in the damage free continuum (left), Traction Separation Law (right).