Normalisation of Material Crack Resistance Curves by the T Stress

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ABSTRACT: *The effect of geometry constraint on ductile fracture is qualitatively known in the literature. Lower constraint will increase the crack resistance curve, and vice versa. The traditional use of fracture mechanics specimens with high geometry constraint often leads to very conservative results when the crack resistance curves are used for failure assessment analyses of low constraint geometries. In this paper crack resistance curves are studied as a function of the T-stress. It is demonstrated that ductile crack resistance curves can be normalised by the T stress. The work is based on J-R curves obtained by FE analyses using different ductile damage models, and experimental verification by testing of three different geometries of an aluminium alloy (7108). This finding implies that the T stress is also controlling the ductile fracture. A materials resistance curve can be separated into a reference material resistance curve, which is transferable, and a geometry factor, which is a function of the T stress. The results indicate that the materials crack resistance curve can be found for all different geometries and loading conditions if the T stress is known. Many solutions for the T-stress for different geometries exist in the literature. The results open for a simple and more accurate method to establish the material resistance curves for different geometries that may lead to more accurate failure assessment analyses and more realistic acceptance criteria for cracks.*

INTRODUCTION

The transferability of fracture toughness is based on the similarity of the near crack tip stress and deformation fields. The similarity is most commonly described using one parameter that describes the strength of a singular crack tip field. It is now clear that the single parameter fracture toughness only provides a single parameter characterisation of the crack tip stress field for a very limited range of highly constrained loading configuration and deformation levels.

In recent years, there has been considerable effort to quantify dependence of fracture toughness on geometry using so-called constraint parameters. The reason for the second parameter is to provide further information that J on its own is unable to convey, concerning how the structural and loading configuration affects the constraint condition at the crack-tip.

Among the proposed parameters for description of constraint are the elastic T stress, first studied by Larson and Carlsson [1] and later more thoroughly studied by Rice [2], and the Q parameter proposed by O`Dowd and Shih [3].

Under well-contained yielding T and Q are uniquely related, but unlike the T stress, the Q parameter can be evaluated in fully yielded bodies. However, Betegon and Hancock [4] have shown that even beyond strict small scale yielding, T still provides a good estimate of the constraint. That is, geometries with the same level of T stress have similar near tip stress distributions, when distances are normalised by J/σ_0. Thus, T may be used as a parameter to characterise constraint beyond the elastic and small scale yielding regimes [5].

When ductile stable crack growth occurs, fracture toughness at initiation or at a certain amount of crack growth is not enough for assessment of the criticality of a structure. The whole R curve is necessary for fracture assessment.

Much work has been performed with the aim of finding how the critical J depends on constraint parameters like the T-stress and the Q-parameter. However, for J-R curves little effort has been made to see if it is possible to find a constraint parameter that can be used to normalise the whole J-R curve for different geometries.

The foundation of J as a characterising parameter is much less sound for growing cracks in ductile materials. Despite of the discussions about the validity of J-R curves, J-R curves measured and evaluated by standard procedures [6] are probably the most often used measure of fracture toughness for evaluation of the structural integrity of constructions when ductile tearing is considered. Due to the geometry dependence of the curves the limits of validity that are set forth in the standards are severe. The standard requires that the permitted crack extension does not exceed one tenth of the remaining ligament, and high constraint specimens like deeply cracked single edge notch bend (SENB) and compact tension (CT) specimens are usually used to establish the materials J-R curves. As mentioned above, the constraint for such testing is high, and when these curves are used for fracture assessment of a low constraint structure, predictions become very conservative. A reduction of this conservatism would be of major importance, as expensive repairs might be avoided and inspections and dimensions might be reduced.

In this paper we will show that J-R curves can be normalised by the T-stress. This opens for much more accurate failure assessments.

CONSTRAINT CORRECTED J-R CURVES

Most of the studies on constraint correction with the Q parameter and T-stress have been performed for brittle fracture. Because it has been observed that both testing and numerical studies of ductile crack growth give quite parallel J-R curves for different constraint, the J-R curves as a function of T-stress have been studied. J-R curves from modified boundary layer (MBL) model analyses using Roussileir continuum damage model, Figure 1, the so-called computational cell model, Figure 2 and Figure 3 and the complete Gurson model, Figure 4, have been studied.

In Figure 1a J-R curves taken from Burstow and Howard [7] are replotted, and normalised by the T-stress in accordance with Eq. 1, Figure 1b. In Figure 2 and Figure 3 J-R curves from Ruggieri and Dodds [8] are presented and normalised in the same way. To verify the results J-R curves by FE simulations based on the complete Gurson model [9] were obtained. The results from these calculations are presented in Figure 4. For all the J-R curves obtained by numerical simulations (Figure 1 - Figure 4), a good normalisation of the J-R curves could be performed. This means that constraint corrected J-R curves, $J^c(\Delta a)$, could be found by multiplying a material dependent reference J-R curve, $J^{ref}(\Delta a)$, with a function of the T-stress, g(T), see Eq 1. It further indicates that if the geometry function is known for one material, a constraint corrected J-R curve can be established if the T-stress is known.

$$J^c(\Delta a) = J^{ref}(\Delta a)\, g(T) \qquad (1)$$

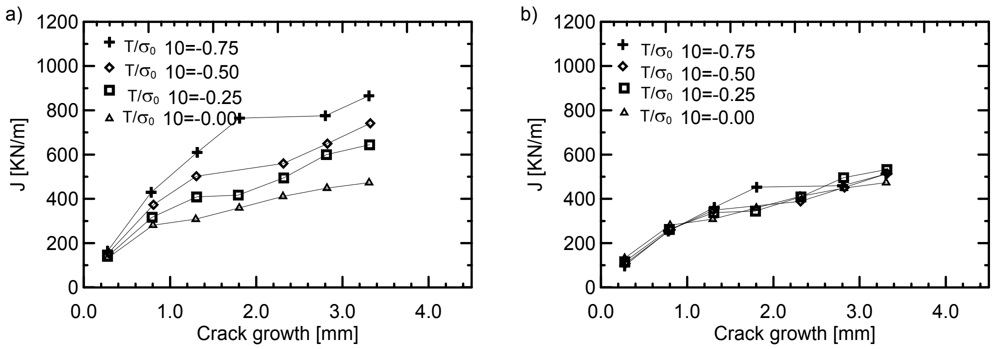

Figure 1: **a)** J-R curves at different T-stress[7]. **b)** J-R curves normalised by the T-stress.

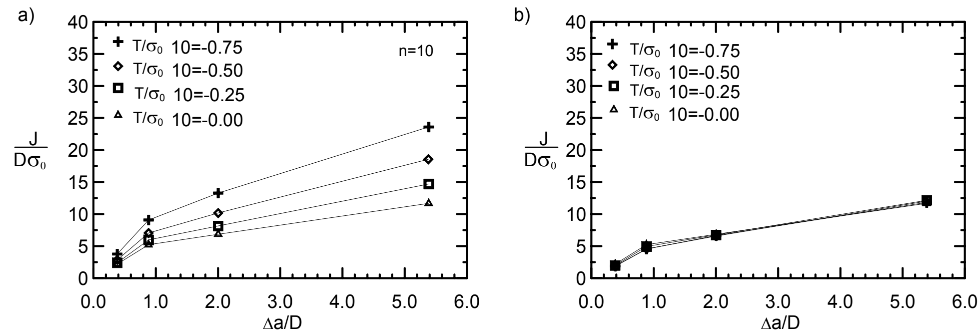

Figure 2: **a)** J-R curves at different T-stress[8]. **b)** J-R curves normalised by the T-stress.

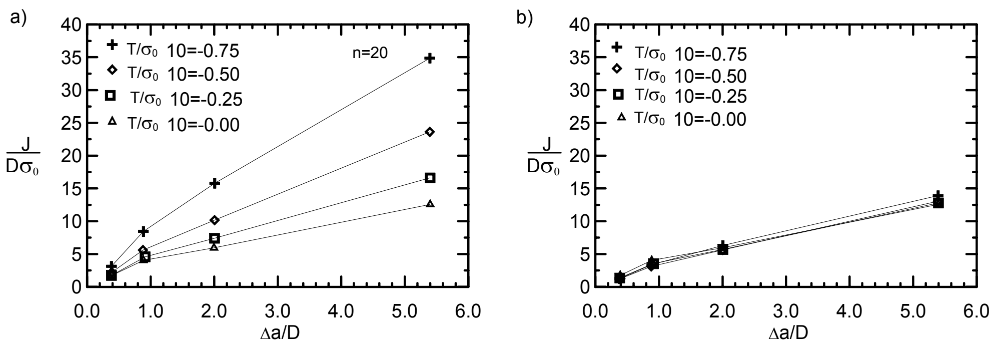

Figure 3: **a)** J-R curves at different T-stress[8]. **b)** J-R curves normalised by the T-stress.

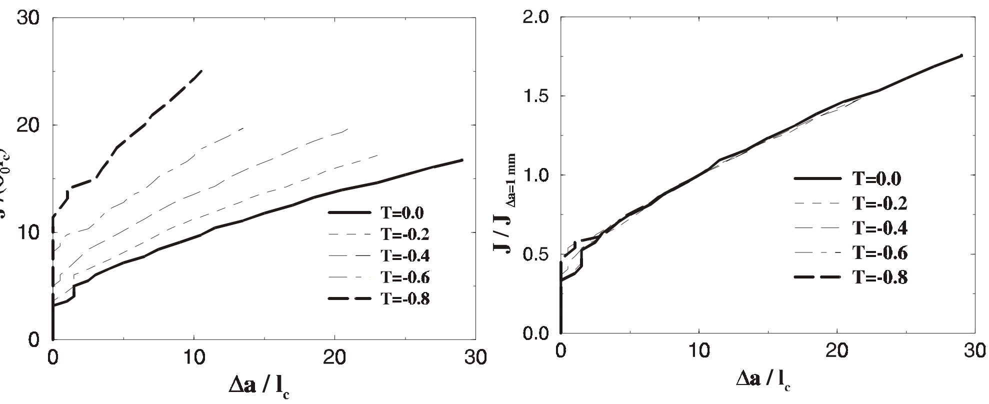

Figure 4: **a)** J-R curves at different T stresses. **b)** J-R curves normalised by the T-stress.

There is one fundamental difference between the numerical simulations based on the MBL model and testing of an actual geometry. The T-stress will not be constant during loading in a component or in a test specimen like it is in a MBL model. The same procedure for constraint correction was therefore performed on experimental data for a 5 mm thick aluminium plate of alloy 7108. Three different specimens were tested, one center cracked tension specimen (CCT) with a/W=0.5, and two different CT specimens with a/W equal 0.5 and 0.3. The J-R curves are plotted in Figure 5a. All the curves are based on multiple specimen testing. In Figure 5b the normalised curves are plotted. Also these curves could be normalised by the T-stress. The T-stress solutions for the actual geometries have been taken from the Sherry, France and Goldthorpe compendium of T-stress solutions [10], where T-stress solutions for different geometries are collected. During loading of a specimen the T-stress will increase, but when stable ductile crack growth initiate the load-displacement curve will flatten out. After initiation of ductile crack growth the T-stress is almost constant. The conditions in the MBL model with constant T-stress and the conditions in the test specimens after initiation of ductile crack growth are therefore comparable.

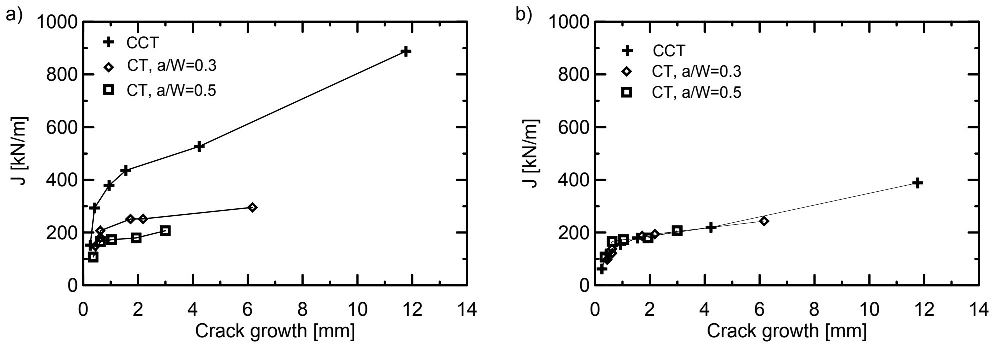

Figure 5: **a)** J-R curves for three different specimens (Aluminium 7108). **b)** J-R curves normalised by the T-stress.

In Figure 6a, J for different geometries (different T) are plotted for different amount of crack growth. The data were taken from Hancock et al [11]. Ainsworth and O`Dowd [5] have suggested an equation for the failure locus and used the data from [11] to show that the equation could be used for both ductile and brittle fracture. The failure loci are drawn in Figure 6a, where the material constants in Ainsworth and O`Dowd s failure loci are fitted individually for the three different failure loci. In Figure 6b Eq. 1 has been used to fit the data points with the same material constants for the whole J-R curve (the three failure loci). A quite good fit is obtained except for the lowest $T/\sigma y$ values, Hancock et al commented the low J for $\Delta a = 0$ and $T/\sigma y = -1.2$: "This may arise from the rather subjective nature of crack extension measurement over small distances in geometries with very low constraint and from the choice of a linear curve fitting procedure." The results from Hancock et al [11], Figure 6a, are often referred to as results that indicate that crack initiation is not dependent of constraint. However, with the uncertainty of the $\Delta a = 0$ values with low constraint this interpretation is questionable. All the J-R curves in Figure 1 - Figure 6 do, however, indicate that quite good normalisation of the whole J-R curve could be obtained with the assumption that the ratio between two J-R curves with different constraint is constant and independent of ductile crack growth, Eq. 1.

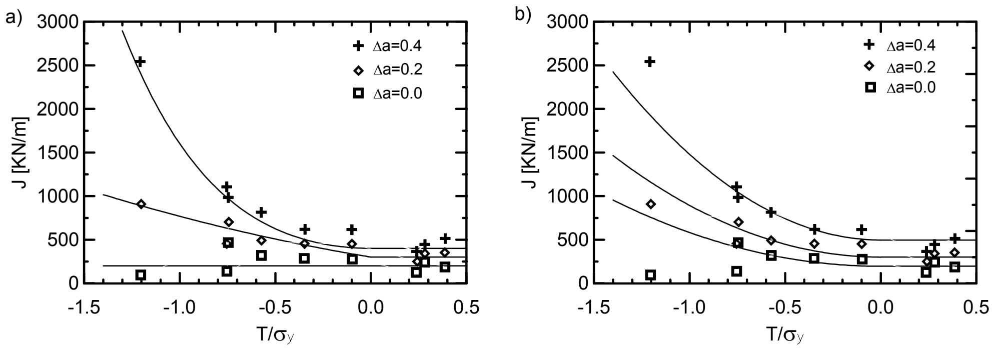

Figure 6: **a)** Experimental test data [10], failure loci [5]. **b)** Normalised by the T-stress with Eq. 1.

These findings pave the way for a simple and more accurate engineering method for failure assessments. It is, however, necessary to perform more work in order to establish the equations for the geometry factors for using in a real component. This may be done with a combination of numerical work and experimental verification for different materials to find a lower bound failure locus for a group of materials. When the geometry function is established, J-R curves can be found for all different geometries and loading conditions if the T-stress is known. A number of solutions for the T-stress for different geometries are established in the literature, many of these solutions are found in [10].

The method can reduce the conservatism in engineering critical assessment (ECA) significantly. For low constraint geometries like cracks in plates loaded in tension and circumferentialy cracks in pipes loaded in tension or bending the reduction in conservatism will be substantial. In Figure 5a the J-R curve for the low constraint CCT specimen is about 250% higher than the standard CT specimen with a/W=0.5.

CONCLUSIONS

It has been shown that the ductile crack resistance curves can be normalised by the T stress. This finding implies that the T stress is also controlling the ductile fracture. A materials resistance curve can be separated into a reference material resistance curve and a geometry factor, which is a function of the T stress. The results indicate that the materials crack resistance curve can be found for all different geometries and loading conditions if the T stress is known.

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