CONSTRAINT EFFECTS AND MODELING UNDER GENERAL LOADING CONDITIONS

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ABSTRACT

The constraint effect has been studied extensively during the past years in order to improve the transferability of fracture toughness values. Combining experimental works and numerical analyses, some success has been achieved in determining validity criteria for geometry independent toughness values and in analyses of variability of material toughness under different states of constraint.

Issue important in practical design of structures with respect to constraint is whether the material's toughness response is invariant for constraint under different general loading states. This question has been recently emphasized, when it has been found that metallic materials when failing with a ductile mechanism produce lower fracture toughness values in mixed-mode loading than in mode I. Thus, in order to answer the questions concerning the transferability of these fracture resistance values, the resemblance and deviations in the constraint effect need to be described. This way consistent scaling methods can be attained for fracture mechanical design of structures.

Current work addresses the constraint response under mixed-mode loading by combining numerical analyses, experimental results and micromechanical considerations of the fracture event. Numerical analyses are used in determining the levels of constraint as dependent on the mode mixity. The constraint is characterized with the near crack tip region stresses, the Q-parameter and by a scaling correction. The experimental toughness results of specimens of different size are compared to the numerical results. The interpretation on the correspondence of numerical and experimental results and analysis methods is performed on the basis of micromechanical concepts of the fracture behavior of the materials.

The numerical results concerning the analysis of the near crack tip regions indicate the loss of constraint associated to a general loading state as a decrease of the hydrostatic stress state. Thus, the finite strain constraint analyses indicate that the extreme of mixed-mode loading, a pure shear state, can be attributed to a type of a plane stress state. When compared to the micromechanical analyses, on the other hand, it is found that the interpretation will be material dependent, since depending on the degree of material ductility the micromechanisms of fracture the constraint response can differ. Combining the numerical and experimental constraint analyses lead to a situation, where for ductile materials the shear end of the loading spectra is a low constraint state, but because of the changes in fracture micromechanisms it is also a state of lowest fracture toughness. This is inferred as a change in the definition of constraint depending on the degree of mode-mixity of loading. A concept is proposed for grading the constraint response of ductile materials under general loading conditions.

INTRODUCTION

Mixed-mode fracture mechanics has traditionally focused on assessing the differences between initiation toughnesses in mode I and a general combination of other modes of in-plane shear (mode II) and out-of-plane shear (mode III). Several criteria have been presented for this purpose, commonly focusing on fracture behavior of materials failing with a weakest link type of a brittle fracture mechanism. The usual result has been that the fracture toughness under general modes of loading is higher than in mode I, and as such the topic has gained little actual interest until lately.

Recent results concerning the fracture behavior of ductile materials under mixed-mode loading have emphasized the significance of mixed-mode loading states, since the experimental works conducted in this regime have found the mode I fracture toughness to be an unconservative estimate for other types of loading. Thus, the fracture toughness values of standardized tests in mode I are not directly transferable to ductile fracture assessment of e.g. steels due to the associated differences. The implications are relevant especially for practical design purposes, where asymmetric loading conditions and in welded components material mismatch cause the load state to be of general type.

Results pertaining the decrease of fracture toughness in ductile materials under mixed-mode loading have been recently presented e.g. by Laukkanen [1,2], Dalle Donne [3] and Smith et al. [4]. Laukkanen presented results concerning fracture resistance curves of ferritic and austenitic steels, and found decreases of order of fifty percent for initiation toughness J-integral. DalleDonne found similar magnitudes for StE550 steel and Al2024-T3 aluminum alloy. Smith et al. presented results for A508 steel at room temperature, and by using a multiple specimen technique illustrated the decrease to be even 80% (again for J-integral) in a membrane loaded testing arrangement. All in all, the results illustrate a contradicting trend opposite the previous conceptions concerning mixed-mode fracture toughness of materials. For overall assessment of mixed-mode loading conditions, this means that the fracture toughness treatment becomes more complex and must be linked to the overall persisting fracture conditions.

Concerning constraint effects, fewer works have been presented in comparison to the vast amount of mixed-mode fracture research done for overall toughness determination. Works focusing on direct numerical determination of constraint parameters and stress-strain fields have been numerous, such as the works of Hallbäck [5] for determining the T-stress and assessing fracture criteria, Budden [6] in describing the deformation fields and Ghosal and Narasimhan [7] and Laukkanen [1] in presenting results for local approach type of analyses for the problem of mixed-mode crack initiation. Typically, the problem in utilizing these works has been that they have illustrated the properties of single criteria or determined e.g. the T-stress variations for a certain specimen under mixed-mode loading, but have been unable to apply or verify the results from an experimental basis. Also, the efforts have been directed in finding solutions, rather than questioning the validity and properties of the underlying theoretical concepts on the basis of actual failure micromechanisms.

The current work presents experimental and numerical results for mixed-mode I-II fracture toughness of F82H ferritic stainless steel, AISI 304 austenitic stainless steel and A533B pressure vessel steel. Numerical results concerning stress-strain states and constraint parameters in the mixed-mode I-II loading regime are presented. The constraint effect is treated on the basis of influences to local near crack tip region continuum fields by considering the interaction of specimen size and the transitions caused by the asymmetric external loading. The results are analyzed with respect to the micromechanisms of fracture and the feasibility of the predictions are discussed.

MATERIALS AND EXPERIMENTAL

The experimental arrangement utilized in determination of the fracture toughness values has been presented in detail elsewhere [8,9], here only a superficial description is given. The mixed-mode asymmetric four-point bend (ASFPB) setup is schematically given in Fig. 1.

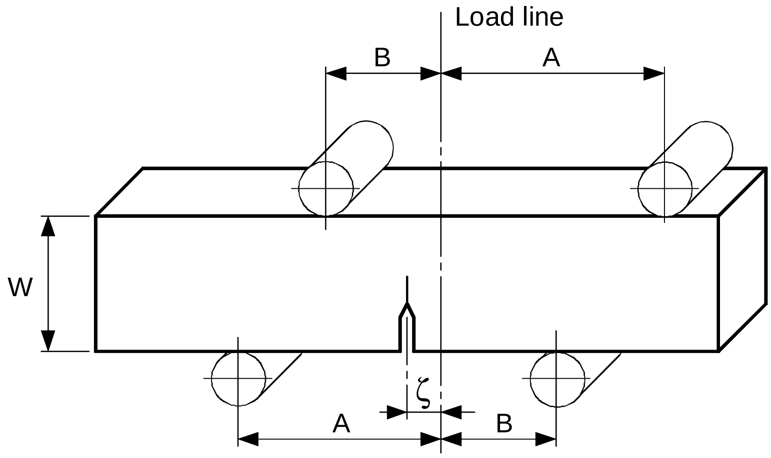

Figure 1: Experimental mixed-mode asymmetric four-point bend configuration.

The mode mixity is controlled by the deflection from the load line, ζ, while the support spans affect the limit load of the configuration. The mode mixity is controlled via an equivalent mode angle , defined by the stress intensity factors (SIFs) for modes I and II as

$$\psi = \tan^{-1}\left(\frac{K_{II}}{K_I}\right). \tag{1}$$

The elastic form was used to control the mode mixity during experiments and finite element analyses (FEAs) have been conducted to provide the calibration between ζ and ψ.

Experimental results are given for four materials: AISI 304 austenitic stainless steel, F82H ferritic stainless steel, A533B pressure vessel steel and CuAl25 copper alloy. The results of AISI 304 and F82H comprise different specimen sizes, which are used in describing the effects of mixed-mode constraint.

NUMERICAL SIMULATIONS

FEAs were carried out in order to determine the local variations of stress and strain as a function of applied mixed-mode loading. Incremental elastic-plastic finite strain formulation of the finite element method was applied to single edge notched bend (SENB) specimen sizes of 10×10×55 mm^3, 10×20×100 mm^3 and 15×30×180 mm^3. An example of one of the crack tip meshes is given in Fig. 2. The results were analyzed for the near crack tip equivalent plastic strain, hydrostatic stress and uniaxial opening stress, in addition to determining the J-integral. Results provided by these variables via further analysis introduced the means to assess the elastic-plastic constraint behavior of the specimens under differing states of mixed-mode loading. The computations were carried out for a model material of intermediate strain hardening, corresponding in average to the properties of the materials used for the experiments with different specimen sizes.

EXPERIMENTAL RESULTS

The experimental results to be presented are the initiation toughness transitions for the four materials within the mixed-mode I-II envelope and the associated values concerning the slope of the fracture resistance curve. Fig. 3 presents the initiation toughness values for the studied materials and Fig. 4 the corresponding values for the slopes of the R-curves. The decrease of both initiation toughness and tearing resistance is illustrated by the presented results, as well as the lower bound nature of the material property values in mode II.

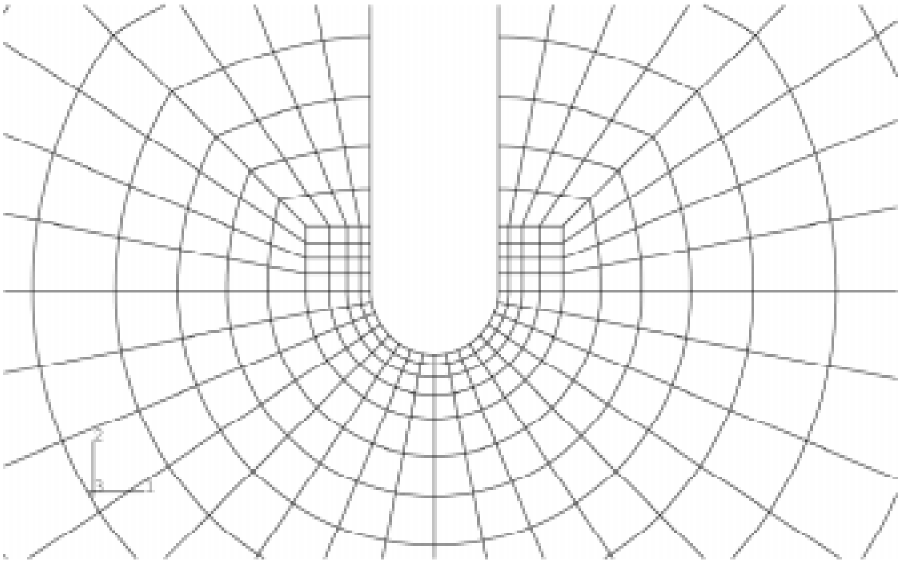

Figure 2: Near crack tip region finite element mesh of 10×10×55 mm^3 specimen.

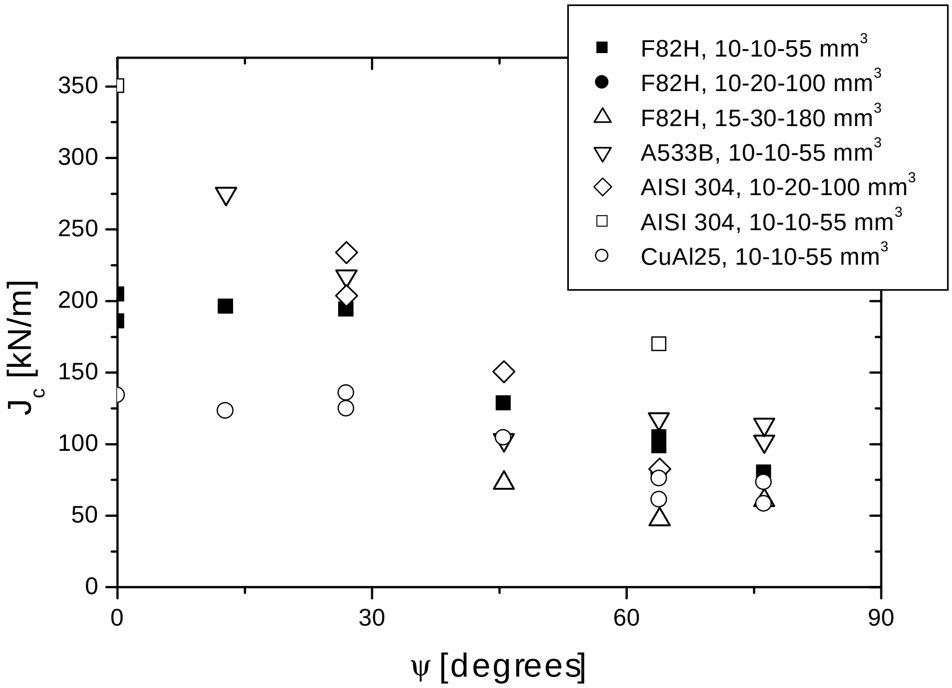

Figure 3: Transition of initiation toughness values in the mixed-mode I-II envelope.

NUMERICAL RESULTS

The prime interest in numerical simulations is in the distribution of constraint characterizing stress variables. Concerning results for deformations essential for ductile type of mixed-mode failure, and also to explain the results interpretation, Fig. 5 presents the variation of equivalent plastic strain in a CVN-size SENB-specimen under mode II loading. Micromechanical interpretations and synthesizes between experimental and numerical results, similar to cases like Fig. 5 below, have been presented in [1,2,8].

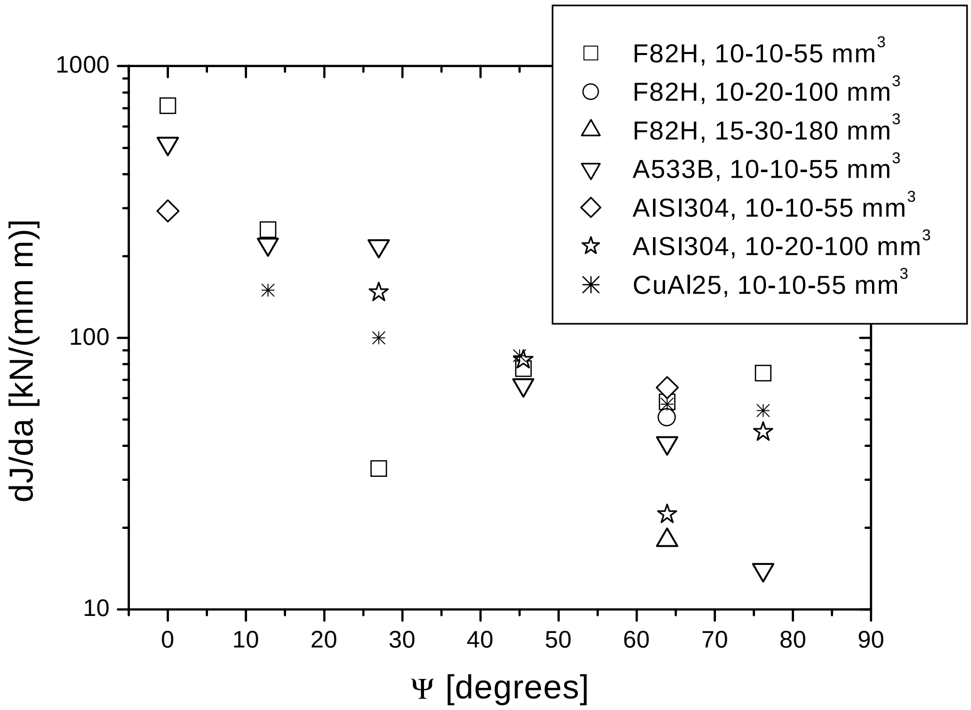

Figure 4: Tearing resistance of fracture resistance curves.

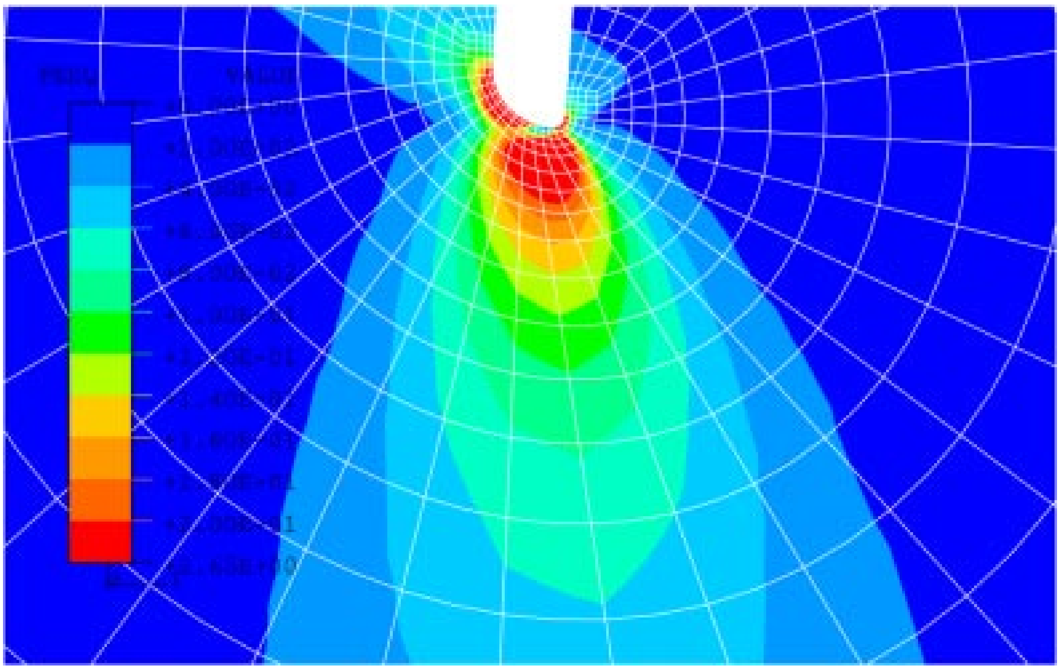

Figure 5: Distribution of equivalent plastic strain in the near tip regions of a CVN-size SENB specimen under mode II loading.

A result emphasized by these studies and similar alike has been that ductile mixed-mode crack initiation has two separate initiation mechanisms. Under mixed-mode I-II loading, these are referred to as mode I type of crack initiation and mode II type of crack initiation. These are illustrated in Fig. 5 by the two peaks of the overall strain distribution, the first mode I high in the bluntening side of the crack tip and the mode II peak in the sharpening side of the finite notch. Infinitesimal modeling of the crack tip can not reproduce such behavior to a great extent, providing justification for the selected blunt crack tip finite strain modeling approach. This way the link to the physical events of crack initiation under mixed-mode I-II loading can be retained as well. Also, for the consideration of stresses near the notch tip, the results are not unique in sense of symmetric or antimetric loading modes, but in practice need to be inferred on the basis of micromechanical considerations.

Definitions of constraint in terms of the Q-parameter are taken from commonly accepted practices, presented e.g. in [10], concerning Q determination and equations applied for this procedure. Since the current work concerns mode I as a reference and assumes initially that some resemblance between the constraint phenomenon in different loading modes exist, the direct use of Q can be considered valid. In Fig. 6 the results concerning the scaling of J-integral under mode I and mixed-mode loading in the different specimen types is presented. The scaling parameter taken here is the mode I J-integral, which is connected to the evolution of J-integral under mixed-mode loading in the same specimen geometry.

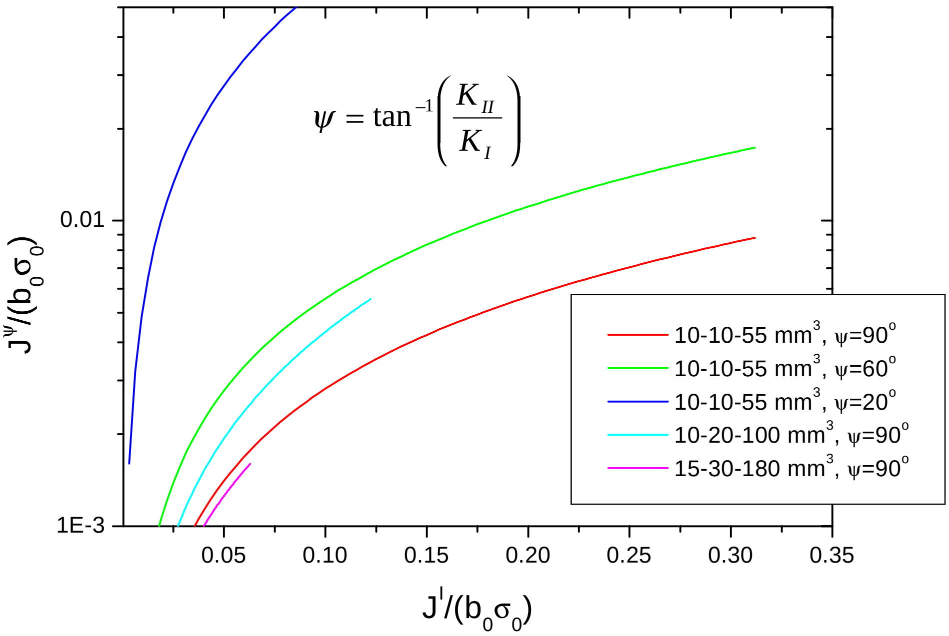

Figure 6: Scaling model results for different specimen sizes under mixed-mode I-II loading (b_0 is the specimen ligament and σ_0 a normalization stress, the proof stress).

The stress based results for constraint characterizing fields under mixed-mode loading states are presented for the Q-parameter in Fig. 7. Because the micromechanisms of fracture (especially for crack initiation) under mixed-mode loading have been introduced to be dependent on mode mixity (see [1,2] and discussion associated to the different strain fields of Fig. 3), the values of the Q-parameter are presented for both of the mixed-mode crack initiation cases, when such deformations exist (on the basis of numerical simulations, this usually tends to occur approximately after $\psi \geq 40^{\circ}$). Fig. 7 clearly illustrates that even the peak hydrostatic stresses in a specimen under prominent mixed-mode loading remain at a very low level, the situation resembling excessively close to plane stress.

DISCUSSION

The experimental results and numerical simulations, especially the work concerning the determination of the Q parameter, illustrate that for a specific material a lower bound presentation of fracture toughness when approaching the limit of mode II appears justified. Thus, for modeling purposes a mixed-mode fracture resistance criteria of the form

$$J^{\psi} \rightarrow J_{IIc} \text{ and } dJ^{\psi}/da \rightarrow dJ^{II}/da \text{ when } \psi \rightarrow \psi_c, \qquad (2)$$

can be considered applicable. The mode angle ψ_c can be approximated by the angle of transition from opening dominated mixed-mode crack growth to shear type crack initiation and propagation. This assumption appears to hold for the materials investigated in the current study, and the argument is supported by fracture micromechanical analyses presented in references [1,2,8]. The lower bound limit can be described as being dependent solely on the plastic dissipation properties of the material in question, primarily the proof stress and the strain hardening exponent. Here, conversely to mode I, the effect of strain hardening exponent to initiation toughness is higher due to the widespread plasticity associated to the entire fracture event.

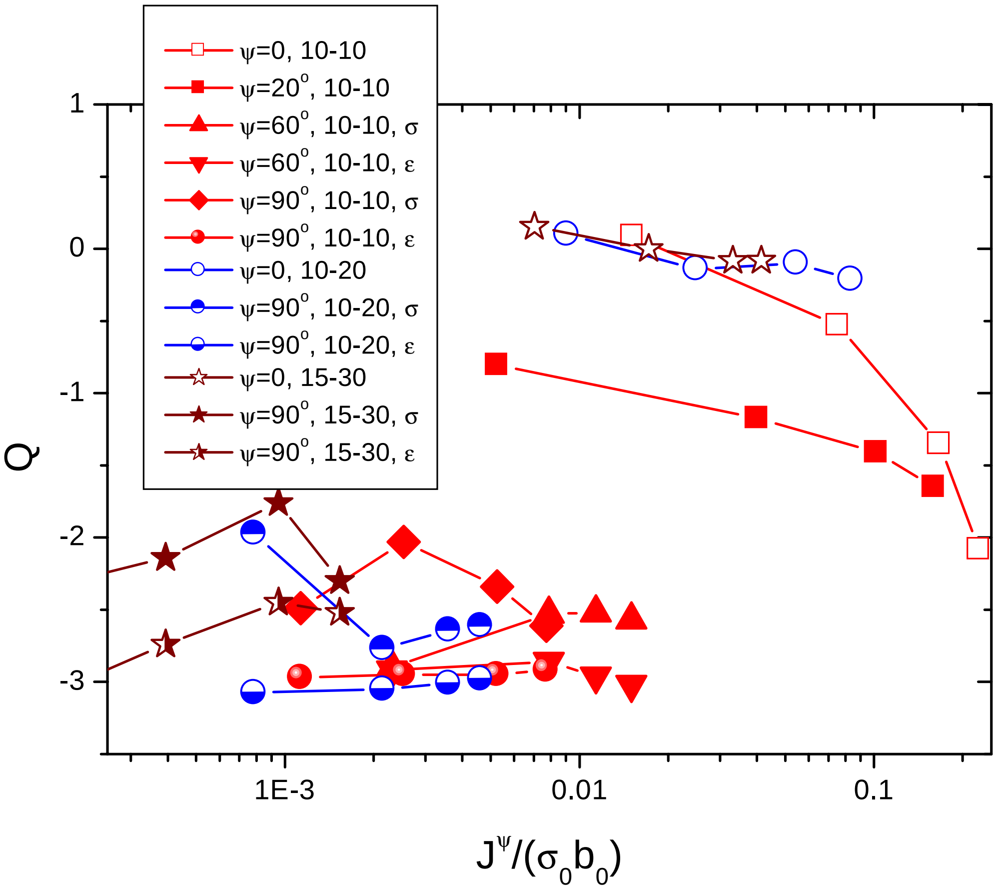

Figure 7: Values of Q-parameter as dependent on state of mixed-mode loading and specimen size.

The numerical determination of constraint conditions, as characterized by the elastic-plastic constraint parameter Q, illustrated that for prominent mode II loading conditions $(\psi \geq 40^{\circ}, \text{approximately})$ the near crack tip regions were in a state similar to that of plane stress, when compared directly to mode I stress fields. The interpretation of the constraint effect on these basis becomes arbitrary, since the constraint can not be interpreted as dependent on stress triaxiality of any kind, due to the low level of hydrostatic tension in the near crack tip regions overall. This accounts also for the so-called bluntening side of the mixed-mode crack tip, which is considered the initial origin of mode I type of mixed-mode crack propagation. The scaling model considerations show, that the relative differences between initiation toughness as given in the experimental part can be explained by the scaling of J-integral under different loading conditions and with the studied specimen sizes. As such, the origin of constraint differs, but it can be connected to the near crack tip stress and strain fields as in mode I. Micromechanical studies [1,2,8] have presented the option, that the constraint shift of toughness is due to strain localization related stress triaxiality effects. The macroscopic version of this supposition is the dependency of limit loads on the three-dimensionality of the stress field. The coalescence stage, which this type of a definition of constraint relates to, can be interpreted as a sequence of local limit failures under mode II type of strain field. The implications of the experimental results near mode II present also that the constraint dependency originates as quite substantial for the initiation stage, which is connected to the given micromechanical interpretation and is understandably different from the crack propagation related constraint effect in mode I.

The scaling approximation for the effect of specimen size can be used both for assessing the constraint effect and considering the transition of initiation fracture toughness within a given geometry in the mixed-mode I-II envelope. Thus, the scaling function for a specific finite element calibration can be presented as

$$\frac{J^{\psi}}{J^{\xi}} = \phi(\Lambda, \psi), \tag{3}$$

where ψ and ξ are two mode mixities such that $\psi \neq \xi$, and ϕ is a function containing the mixed-mode contribution from ψ and a geometry and material property parameter, Λ. The geometry calibration will typically require numerical methods, while the mixed-mode dependency can be either determined via FEA or by using suitable toughness transition criteria, e.g. the maximum equivalent plastic strain criterion or the maximum hydrostatic strain criterion, where in the case of the latter equation (3) would have the form

$$\phi(\psi) = \left[\left(\frac{I_n(\psi)}{I_n(0)}\right)^{1/(n+1)} \bar{\sigma}(\psi)\right]^{n+1}\Bigg|_{\Lambda}, \tag{4}$$

where the parameters of the mixed-mode I-II stress field are given in reference [11].

CONCLUSIONS

Numerical and experimental considerations on mixed-mode fracture toughness and constraint were provided. The results of the work can be concluded as follows:

- Fracture toughness and tearing resistance under mixed-mode I-II loading conditions in ductile metallic materials appears to have a material specific lower bound near mode II.
- The transitions in toughness and the rate of change can be connected to the shift from mode I type of mixed-mode crack initiation to mode II type of shear crack initiation.
- Constraint under mixed-mode loading conditions can not be solely assessed on the basis of common models based on void growth, but methods considering the effects of localized plasticity and its stress state dependency need to be incorporated.
- Scaling methods appear promising in providing both toughness estimates and geometry sensitivity descriptions for mixed-mode loading conditions.

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