# RELEVANCE OF FRACTURE MECHANICAL MATERIAL PROPERTIES FOR STRUCTURAL INTEGRITY ASSESSMENT

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Fracture mechanics parameters are widely used to determine materials resistance to fracture. Presently there exists a number of both standardized as well as nonstandardized parameters. Their main goal is to be able to describe the material fracture resistance with one single factor. All the different parameters are assumed to describe the integral effect of critical stress and strain fields ahead of a sharp crack, i.e. they are supposed to represent a material characteristic. By definition, they should all be geometry independent for a constant stress state. A large number of investigators, however, have found a distinct effect of specimen size and geometry on the test results. In this work the relevance of different standard and non-standard parameters is examined with respect to structural integrity assessment.

## INTRODUCTION

Structures and materials can behave in a ductile or brittle manner. Fracture mechanics assessment methodologies are usually directed towards determining the macroscopic behavior of the structure, whereas materials testing is directed towards determining the microscopic behavior of the material. The behavior of materials is not always equivalent to the behavior of structures and this has led to different definitions of brittle and ductile. The meaning of different definitions describing the behavior of structures and materials are presented in Table 1.

Based upon fracture mechanics theory, the different fracture mechanics parameters have a specific relationship and they all describe the "loading" of the material. In the case of a critical event like fracture they, in principle, take a material specific critical value (fracture toughness). Normally the fracture toughness is, however, determined according to certain testing standards. Even though the testing standards basically describe the loading of the material correctly, their definitions of the critical event is more obscure. The relevance and the correct application of "fracture toughness" data will thus depend upon the testing standard.

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TABLE 1- Meaning of different definitions describing the behavior of structures and materials.

| Definition | Material | Structure/Specimen |
|---|---|---|
| Brittle | Material fails by a brittle micromechanism like cleavage fracture. Specimen behavior may be elastic or elastic plastic. | Structure fails without significant plastic deformation. Materials failure micromechanism may be brittle or ductile. |
| Elastic plastic | Not used. | Structure fails with some amount of plastic deformation. Materials failure micromechanism may be brittle or ductile. |
| Ductile | Material fails by a ductile micromechanism like microvoid coalescence. Specimen behavior may be elastic or elastic plastic. | Structure fails by plastic collapse. Materials failure micromechanism likely to be ductile. |

Unfortunately, present testing standards do not give any statement regarding the significance of, nor recommendations for the correct application of, fracture toughness data for structural integrity assessments and yet this is a crucial point for a successful assessment. Standardization bodies have been reluctant to produce what they call application documents. Their single interest has been the test performance. The problem would not be of importance if there would only exist one fracture mechanism for the material or if all fracture mechanisms would respond to the fracture mechanical loading identically. Unfortunately this is not the case.

The two main fracture mechanisms are brittle fracture and ductile fracture and their response to the fracture mechanical loading is completely different. The fracture toughness definitions in the standards correspond to the mechanical behaviour of the test specimen, not the fracture mechanism. Therefore, different parameters, describing different fracture mechanisms have different interpretations for structural integrity assessments, i.e. they have a different significance. Factors affecting the significance and use of fracture thoughness data are e.g. the fracture mechanism, definition of critical event and the applied testing standard.

## MICROMECHANISMS OF FRACTURE

The term macromechanism of fracture relates to the behavior of the structure, whereas the micromechanisms relate to the behavior of the material, as presented in Table 1.

The two main micromechanisms encountered in fracture resistance testing are ductile fracture and cleavage fracture. A third micromechanism i.e. grain boundary fracture is also possible, but it appears to be of lesser relevance. This is fortunate, because the fracture mechanical modelling of grain boundary fracture is still incomplete. Modelling of grain boundary fracture is a challenging task for the near future.

There is a widely recognized view that ductile fracture proceeds by a continuous mechanism of microvoid nucleation and coalescence (see e.g. McClintock (1)). Therefore it is impossible to detect the first physical initiation point. The initiation point is instead usually taken as a point at which there already has been some small amount of detectable ductile tearing.

Microvoid coalescence is a critical strain-controlled type of mechanisms. As such, it is strongly governed by the maximum strain state along the crack front. In order for the crack to propagate macroscopically, microvoid coalescence must occur along the whole crack front. The measured fracture resistance to ductile fracture is thus governed by the mean toughness properties of the material. This means that for a material that is homogeneous on a macro-scale, the parameters related to ductile fracture ($J_{IC}$, $J_i$, $\delta_i$) should show only a small amount of scatter. Also, as long as the J-integral and crack-tip opening displacement correctly describe the strains in front of the crack, the parameters should also be specimen size and geometry independent.

Brittle cleavage fracture differs completely in mechanism from ductile fracture. It is assumed that cleavage fracture is initiated by a, weakest link type, critical stress-induced mechanism, governed by locally situated cleavage initiators or "weak spots" (see e.g. Curry and Knott (2) and Beremin (3)). As such, cleavage fracture will be affected, besides by changes in the stress distribution, also by the probability of finding a critical cleavage initiator. This weakest link type statistical nature of cleavage fracture unfortunately denotes that fracture toughness in the case of cleavage fracture is not a simple material property. Firstly, cleavage fracture initiation toughness exhibits a large amount of scatter (Wallin (4)), and secondly, it shows a characteristic statistical size effect associated to the length of the crack front (4). Because of this statistical size effect one must always correct the experimental toughness values to correspond to the relevant crack front length. Some test results indicate that the statistical size effect may disappear at very low temperatures (Wallin (5), but since the findings are still somewhat equivocal, it is safer to assume the existence of a size effect also in the case of lower shelf toughness.

## RELATIONSHIP BETWEEN STANDARD PARAMETERS K, J AND δ

There exists a theoretical relationship between the different fracture mechanical parameters. Basically this relationship applies also for parameters determined according to test standards. However, the test standards (even for the same parameter) often apply slightly different equations for the calculation of the parameter. Thus differences up to 10 % (expressed in the form of K) are possible, when the parameter is determined with different standards. Likewise, the relationship between e.g. J and δ will (in addition to the stress state) be dependent upon what standards are applied. Furthermore, the relationship may also be affected by the specimen type used. In the case of plane strain loading the ESIS Procedure for Determining the Fracture Behaviour of Materials, ESIS P2-91, indicates roughly the relation

$$J \approx 2 \cdot \sigma_Y \cdot \delta_e + 1.8 \cdot \sigma_Y \cdot \delta_p \qquad (1)$$

where $\delta_e$ and $\delta_p$ are the elastic and plastic part of the crack tip opening displacement ($\delta$). The relationship described by eq (1) is somewhat affected also by the load level of the specimen. It's accuracy is estimated to be better than 20 % both for compact and single edge notch specimens. Other standards or combination of standards produce slightly different relationships. Thus, it is of some importance to register with the data also the applied testing standard.

## SIGNIFICANCE OF DIFFERENT FRACTURE PARAMETERS

The testing standards define several different fracture parameters that correspond to different "critical" events occuring during the test. The significance of the parameters is not necessarily the same from the viewpoint of structural integrity assessment.

### $K_{Ic}$, $K_c$

Fracture resistance for LEFM applications is ordinarily expressed in the form of a critical stress intensity factor $K_{Ic}$, denoted "fracture toughness". The validity of the stress intensity factor to describe the stress field in front of a crack is well documented and also the stress intensity factor equations used in the different testing standard are accurate. As such the stress intensity factor is well suited for determination of fracture resistance for LEFM applications.

The fracture toughness $K_{Ic}$ is classically supposed to be a material characteristic, but in reality this is not the case. Ordinary $K_{Ic}$-tests according to ASTM E 399 and related standards applies LEFM-formulas and allows the use of the 95 % secant procedure. The secant procedure is based on the assumption that the deviation from linearity in the load-displacement curve is practically only due to stable (ductile) crack growth. Thus a $K_{Ic}$ value corresponding to the 95 % secant is assumed to be related to a toughness value corresponding to a 2 % stable crack growth in the ligament (Landes (6)). The size criterions in the standard are actually included to ensure that the specimens load-displacement response will be unaffected by plasticity effects. Parameters violating the $K_{Ic}$ size criterions (e.g. $K_c$) usually describe mainly specimen plasticity effects and as such they should not be used. The problem with $K_{Ic}$ is that it does not distinguish between ductile fracture and brittle cleavage fracture. This originates from the development phase of the standard, where only materials failing by a ductile mechanism where used for the testing.

In the case of ductile fracture the $K_{Ic}$ will correspond to a 2 % crack growth in the ligament. This causes that a larger specimen will correspond to more ductile crack growth in mm. Because ductile fracture always has an increasing R-curve ($dK/da > 0$), a large specimen will yield a higher $K_{Ic}$ than a small specimen, even for valid tests. On the other hand, the validity criteria in the testing standards are such that a $K_{Ic}$ value for ductile fracture is obtainable only for materials whose R-curve is very flat (6). Thus the size effect in the case of $K_{Ic}$ corresponding to ductile fracture is relatively small and therefore it can be regarded nearly as a material characteristic. If it is possible to determine the true ductile initiation value $K_i$ it is more preferable than $K_{Ic}$ provided that it otherwise fulfills the validity criteria for $K_{Ic}$.

For ferritic steels $K_{Ic}$ corresponds usually to brittle cleavage fracture. In this case $K_{Ic}$ is a measure of a true critical event and as such it is a preferable parameter for LEFM fracture resistance determination. However, because the probability of cleavage fracture initiation may be specimen thickness/crack width dependent, one should always correct the fracture toughness to correspond to the relevant crack width. The need for statistical modelling of cleavage fracture initiation has been acknowledged during the last few years. A number of models, for describing the behavior of fracture toughness in the cleavage fracture temperature region, have been presented (4). Most of them are based on the assumption of cleavage fracture initiation to behave like weakest link statistics i.e. one single critical event is sufficient to cause macroscopic failure. Even though the models may differ quite a lot in their basic assumptions of the microscopic fracture mechanism, macroscopically they still yield similar results.

Most models evidence that the results can, in the case of brittle fracture, be thickness corrected with equations like (4)

$$K_{B_2} = (K_{B_1} - K_{min}) \cdot (B_1/B_2)^{1/4} + K_{min} \tag{2}$$

where $K_{min}$ is a lower bound fracture toughness. The exact value of $K_{min}$ is not known, but for steels a value of 20 MPa$\sqrt{m}$ has been successfully used for representing experimental test data (4).

The above equation has been validated for a large number of both low and high strength structural steels and for specimen thicknesses ranging from 10 mm to 200 mm (4).

Most of the models also indicate that the scatter of brittle fracture toughness results can be described with the equation (4)

$$P_f = 1 - \exp(-\left(\frac{K-K_{min}}{K_0-K_{min}}\right)^4) \tag{3}$$

where $P_f$ is the cumulative failure probability at a load level K and $K_0$ is a specimen thickness and temperature dependent normalization parameter which is related to the mean approximately by $K_0 \approx 1.1 \cdot \overline{K}_{Ic}$.

With the help of equations 2 and 3 it is possible to apply cleavage fracture $K_{Ic}$ results in the assessment of component integrity by fracture mechanics.

At very low temperatures corresponding to the lower shelf of toughness, it is possible that the cleavage fracture mechanism may change from initiation control to propagation control. In such a case there will not exist a statistical size effect and also the scatter distribution will be slightly different (5). Equation 3 yields a sufficiently good desription of the scatter even on the lower shelf and what is more, it yields a conservative estimate for $K_{min}$ (5). The criterion for when the size effect may disappear is not yet determined. Therefore it is safer to assume the size effect also for data corresponding to the lower shelf.

$J_c$, $\delta_c$, $J_u$, $\delta_u$

EPFM parameters describing brittle cleavage fracture initiation are $J_c$, $J_u$, $\delta_c$ and $\delta_u$. Of the two definitions the one corresponding to cleavage fracture initiation after more than 0.2 mm ductile tearing is less reliable (Thaulow et. al. (7)) even though it relates to a catastrophic type of failure event, for which the occurrence is not directly dependent on the load bearing capacity of the structural part. The one thing that deteriorates the relevance of $J_u$ and $\delta_u$ is the ductile tearing preceding cleavage fracture, because this ductile tearing in itself affects the brittle fracture probability (4). This effect has not until recently been clarified quantitatively.

Recently, a method to account for the effect of ductile tearing on cleavage fracture probability has been developed (4). The methodology is originally developed for the J-integral and it results in a correction function for the ductile crack growth (4) as well as a minimum specimen ligament size requirement (4). The ligament size requirement gives the maximum measuring capacity of the specimen regarding cleavage fracture. If the ligament is smaller than given by the size requirement a corrected value of the fracture toughness should be used in the crack growth correction expression. The methodology has been shown to yield promising results, but it still needs some further validation and possible refining. Just recently, the size requirements have been further refined by detailed FEM-calculations (Anderson and Dodds (8)). The fact remains that the most problematic region for fracture resistance determination is the transition region and much more detailed 3-D FEM-calculations are required.

If only a conservative estimate of the brittle fracture resistance is required, one can neglect the ductile tearing and (if the toughness violates the size requirements) assume the toughness to be equal to the one, given by the size requirements. For ferritic steels a comparatively safe estimate is obtained applying $J_{max} = B,(W-a)\,|_{min} \cdot \sigma_{flow}/100$, or $\delta_{max} = B,(W-a)\,|_{min}/150$. Test results imply that even these requirements can be further relaxed by a factor of 2 (Wallin (9)).

As a whole, the EPFM parameters describing brittle cleavage fracture are well suited for the determination of fracture resistance and have thus a high significance.

There are cases where one is forced to apply EPFM material parameters with LEFM integrity assessment procedures. In such cases it is relatively safe to estimate the critical stress intensity factor for cleavage fracture from $J_C$ by the equation

$$K_{JC} = \sqrt{E' \cdot J_C} \tag{4}$$

provided that the fracture resistance is corrected to correspond to the relevant crack front length with equation 2.

The validity of equation 4 has been comparatively well verified, both directly by comparing small specimen EPFM data with large specimen LEFM data (9), as well as indirectly by showing that a Charpy-V - $K_{IC}$ correlation (Wallin (10)) is also valid for $K_{JC}$.

Equation (4) also basically makes it unnecessary to use full thickness specimens in the fracture toughness tests, in the case of brittle fracture. The standard arguments why full thickness specimens are required are based on constraint effects. It has, however, been shown, both experimentally (9) and numerically (Braam and Prij (11)) that the main reason for thickness effects on cleavage fracture toughness is the statistical size effect. It seems that thickness based constraint effects become important only in cases when the thickness B is clearly less than $B<100 \cdot J/\sigma_{flow}$ or $B<150 \cdot \delta$.

$\underline{J_{0.2/BL}, \delta_{0.2/BL}, J_m, \delta_m}$

The parameters used in connection with ductile fracture are either representing ductile fracture initiation or the specimen load maximum.

It is commonly recognized that load maximum fracture toughness is a geometry dependent toughness value. It has, however, been argued that under specified conditions it is possible to use $J_m$ or $\delta_m$ values to obtain a safe flaw size evaluation (Towers and Garwood (12)). A special requirement is that the test must be performed with a full thickness specimen ie. specimen thickness must be equal to the structural thickness.

The maximum load occurs when the load rise caused by the increasing strain hardening is balanced by the reducing ligament area because of crack growth and/or necking of the bend specimen (7). Thus the load maximum toughness is a measure of the specimens tearing instability. Of the two causes for ligament reduction necking is normally not important in the case of fracture toughness testing. Necking becomes possible only at load levels well beyond any validity criteria for fracture toughness. The load maximum toughness can actually be used to determine the materials tearing characteristics, but it demands that a full tearing instability analysis of the test specimen is performed (7),(Anderson et al (13)).

If the measured load maximum fracture toughness is so high that the size requirements are not fulfilled, the result should not be considered as descriptive of the material. Instead one should use the minimum value given by the respective size requirement. This ensures that unconservative results will not be used in the tearing instability analysis. If the size requirement is fulfilled, the reduction of ligament area will basically be due to crack growth only. Also, when the size requirement is fulfilled the J-$\Delta$a-curve will be nearly specimen size independent. In such a case the value of $J_m$ and $\delta_m$ will be determined directly by the ligament size and not by the specimens thickness (7,13).

One reason for allowing the use of load maximum toughness is that if the specimen is ductile up to load maximum, it is assumed to guarantee that the structure will not fail by cleavage fracture. Unfortunately this cannot always be guaranteed. A surface crack in the structure may well have a longer crack front than the test specimen thickness. Only if also the statistical size effect is accounted for, load maximum toughness may be used as a conservative value against cleavage fracture. Often the use of load maximum toughness is also justified by the argument that the ductile fracture initiation toughness is unduly conservative, but if the initiation value proves to be high enough from a failure assessment point of view, it is better to apply the initiation toughness rather than $J_m$ or $\delta_m$.

There exists a variety of engineering definitions for the ductile initiation toughness, one of which is $J_{0.2/BL}$. This variety is not, however, a very relevant problem as long as it can be shown that the structure will not fail by brittle fracture. All the different definitions of ductile initiation toughness will produce safe estimates with regard to ductile failure instability of the structure and therefore they can well be applied for failure assessment. A tearing instability analysis based on the tearing resistance (J-$\Delta$a) curve is, however, much more unreliable (7).

The EPFM tearing instability analysis is not yet comprehensively validated (7) and this reflects also upon the experimental determination of the materials tearing resistance. Besides from analytical problems concerning crack growth corrections and J, CTOD equations (7), also the experimental error sources can be considerable. It seems indisputable that the J-$\Delta$a curve testing still needs further development and improvement before the tearing resistance curve can be considered as a fully reliable material characteristic.

Indirect Estimates of Fracture Tougness

In case of steel $K_{Ic}$ usually describes the materials resistance against brittle cleavage type fracture. In some cases like radiation embrittlement surveillance testing, the direct determination of $K_{Ic}$ is relatively expensive as well as difficult. Therefore there have been attempts to determine the value of $K_{Ic}$ indirectly from simpler tests through the application of correlations (10).

The most common simple test for studying the fracture characteristics of steels is probably the Charpy-V impact test. Therefore, most of the empirical fracture toughness correlations that have been developed are between Charpy-V energy and fracture toughness $K_{Ic}$. Numerous different correlations have been determined for a variety of materials, over the past years.

Finding an empirical correlation that would be universally applicable has proven to be quite difficult. Even though both tests describe the materials fracture behavior, they have differences. The most important differences between Charpy-V and $K_{Ic}$ tests are presented in Table 2 (10).

TABLE 2- Differences between CVN and $K_{Ic}$ tests.

| DIFFERENCE | CVN | $K_{Ic}$ |
|---|---|---|
| Specimen size | 10·10·55 mm | $B > 2.5\cdot(K_{Ic}/\sigma_y)^2$ |
| Loading rate | dynamic | static |
| Flaw geometry | short blunt notch | deep crack |
| Event described in test | fracture initiation + propagation | fracture initiation |

Due to the differences in the tests the empirical correlations are usually very case dependent. It is also difficult to decide which correlation to use in a given case.

Based on Table 2 it is clear that one cannot reliably correlate the impact energy directly with the fracture toughness. One must first clarify which parameters are realistic to correlate. To achieve this the basic features of each test must be examined separately to see which features are the same.

Based on such a theoretical treatment, it has been shown that the toughness transition temperature $TK_{28J}$ and $TK_{100MPa\sqrt{m}}$ are suitable for correlation (10), providing that the fracture toughness values are size corrected to correspond to a constant thickness. An energy level of 28 J is preferred rather than the commonly applied level of 41 J, because the higher energy level is more affected by the materials ductile tearing resistance. The correlation has the form

$$TK_{100MPa\sqrt{m}} = TK_{28J} - 18\ °C \quad \text{(for } B = 25 \text{ mm)} \tag{5}$$

and its standard deviation is $\sigma = 15$ °C.

Remarkable with the correlation is that the yield strength of the material does not seem to have a statistically significant effect. The effect has been estimated to be of the size 1 °C / 100 MPa. Thus the correlation is equally applicable for both low and high strength steels.

It has been found experimaentally that the shape of the fracture toughness transition curve for ferritic steels is only slightly material and yield strength dependent (9). The resulting equation for the temperature dependence of $K_0$ (see eq. 3), corresponding to 25 mm thickness, can be written as (10)

$$K_o = 31 + 77 \cdot \exp\,[0.019 \cdot (T - T_0)]\ . \tag{6}$$

By combining equations 2, 3, 5 and 6, it is possible to describe the whole fracture toughness transition curve, corresponding to brittle fracture, as a function of temperature, specimen thickness and fracture probability. Thus if the Charpy-V transition temperature ($TK_{28J}$), specimen thickness and desired fracture probability is known, the whole fracture toughness transition curve corresponding to cleavage fracture can be approximated.

## SUMMARY AND CONCLUSIONS

The relevance of different standard and non-standard fracture mechanical material properties for structural integrity assessment have been examined by accounting for the implications from the fracture micromechanisms.

Preferable parameters to use are the parameters describing a true critical event like ductile or brittle fracture initiation. Even then one must also consider the relevant fracture micromechanism in order to assess the macroscopic behavior of the structure accurately.

Table 3 contains a summary of the conclusions regarding relevance and different size and geometry effects of common fracture toughness parameters.

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TABLE 3- Relevance and different size and geometry effects of common fracture toughness parameters.

| TYPE | PARAMETER | SCATTER | SIZE EFFECT | CRACK LENGTH EFFECT | RELEVANCE |
|---|---|---|---|---|---|
| LEFM | $K_{IC}$ | medium small | small | small | good |
| | $K_Q$ | small | unpredictable | medium | poor |
| | $K_m$ | small | unpredictable | medium | poor |
| | $K_i$ | small | unpredictable | medium | good ⇒ poor |
| | $K_{Ia}$ | medium | small | medium | good |
| EPFM | $J_{IC}$ | medium | small | small | good preferable |
| | $J_i$ | medium | small | small | good |
| | $CTOD_i/\delta_i$ | medium | small | small | good |
| | $J_C$ | large predictable | large predictable | small | good preferable |
| | $CTOD_C/\delta_C$ | large predictable | large predictable | small | good preferable |
| | $J_m$ | small | large unpredictable | large | negligible |
| | $CTOD_m/\delta_m$ | small | large unpredictable | large | negligible |
| | $J_u$ | large | large | medium | medium |
| | $CTOD_u/\delta_u$ | large | large | medium | medium |

## REFERENCES


(1) McClintock, F.A., J. of App. Mech. Vol. 35, No. 7, 1968, pp. 363-371.

(2) Curry, D.A. and Knott, J.F., Metal Sci., Vol. 13, 1979, pp. 341-345.

(3) Beremin, F.M., Met. Trans., Vol. 14A, 1983, pp. 2277-2287.

(4) Wallin, K., "Defect Assessment in Components - Fundamentals and

Applications", ESIS/EGF9, J. G. Blauel & K.-H. Schwalbe, Eds., Mechanical Engineering Publications, London, 1991, pp. 415-445.

(5) Wallin, K., "Macroscopic Nature of Brittle Fracture", 3rd European Conference on Advanced Materials and Processes EUROMAT 93. Paris, June 8-10, 1993, 15 p.

(6) Landes, J.D., Int. J. Frac., Vol. 17, No. 4, 1981, pp. R47-R51.

(7) Thaulow, C., Debel, C., Søvik, O., Wallin, K., Holmgren, M., Olofsson, O. and Anderson, H., "Recommendations on Fracture Mechanics Testing", NT TECHNICAL REPORT 109. Nordtest 1989, 32 p. + 184 p. app.

(8) Anderson, T. and Dodds, S., J. Testing and Eval., JTEVA, Vol. 19, No. 2, 1991, pp. 123-134.

(9) Wallin, K., Proceeding of the Joint IAEA/CSNI Specialist's Meeting on Fracture Mechanics Verification by Large Scale Testing", NUREG/CP-0131, Oak Ridge Ntional Laboratory, 1993, pp. 465-494.

(10) Wallin, K., "Innovative Approaches to Irradiation Damage and Fracture Analysis", PVP-Vol.170, D.L. Marriott, T.R. Mager & W.H. Bamford, Eds., The American Society of Mechanical Engineers, 1989, pp.93-100.

(11) Braam, H. and Prij, J., Transactions of the 9th International Conference on Structural Mechanics in Reactor Technology, 17-21 August 1987, Lausanne, Ed. F.H. Wittman, vol. G, pp. 33-38.

(12) Towers, O.L. and Garwood, S.J., The Welding Institute Research Bulletin, Vol. 20, No.10, 1979, pp. 292-299.

(13) Anderson, T.L., Gordon, J.R. and Garwood, S.J., "Fracture Mechanics: Nineteenth Symposium", ASTM STP 969. T.A. Cruse, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 291-317.