Notch Effect in Brittle-Ductile Transition Behaviour

L. Tóth

Bay Zoltán Institute of Logistics and Production Systems, Miskolc, Hungary

ABSTRACT: *The reliability and life-time of engineering structures are determined by the external and internal local stress, strain concentrators. The internal stress, strain concentrators are caused by microstructure inhomogenities of materials, the external ones by notches. It is obvious that it is not possible to design a construction without considering the effects of stress, strain concentrators. The behaviour of local areas at notches is determined by the notch geometry, loading conditions and the local material responses. From the engineering point of view the so called "notch effect" is very important both in brittle-transition behaviour and in fatigue failure of structural elements because 90% of the failures are initiated by the stress-strain concentrators. Considering the statistical data that each countries loses the app. 4% of the GDP by failures, so the „notch effect in engineering practice" is a very important issues from the economical point of wives as well. This paper attempt to join the concepts of the linear fracture mechanics and the notch mechanics by defining the notch-stress, notch-strain and notch-energy intensity factors.*

INTRODUCTION

The notched specimens under tensile test may have different fracture surfaces. From **macroscopic** point of view they are either totally ductile or brittle or they have a brittle-ductile character. It is clear that the ratio of ductile and brittle areas depends on factors influenced by the notch geometry, testing conditions (temperature and loading rate) and material behaviour. These fracture surfaces are schematically illustrated in Figure 1. From ***microscopic*** point of view we can find a ductile fracture surface at the notch vicinity even at the most dangerous loading conditions (i.e. at high loading rate, and at low temperatures). This ductile fracture surface can also be realised at the notches with a possible highest notch acquity (i.e. in the case of crack). Obviously these areas could have only a magnitude of grain size. Considering only the ***macroscopic*** approach the following question can arise: *How can be the brittle-ductile behaviour of materials of notched elements characterised and* *how can the effect of loading conditions (temperature and loading rate) and the notch geometry be taken into account?*

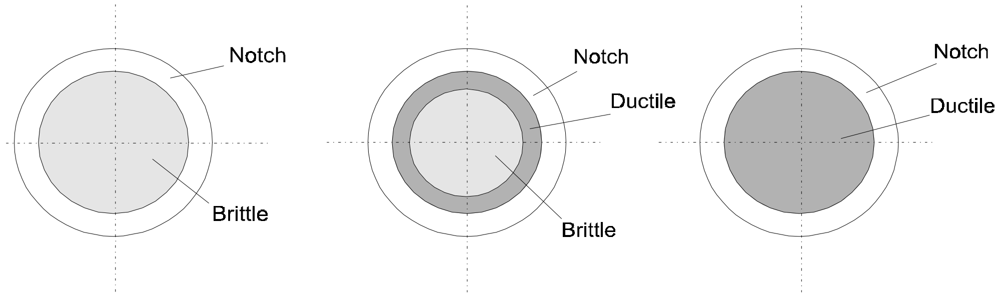

Figure 1. The possible fracture surfaces of notched specimens tested in tensile

NOTCH STRESS- NOTCH STRAIN AND NOTCH ENERGY INTENSITY FACTOR

It is obvious that the ductile, brittle or ductile-brittle transition behaviour of materials depends on the local circumstances at the notch-influenced areas. This local circumstances will be created by the external (loading rate, temperature and notch geometry) and internal parameters of materials which is the most simple selforganised system. It means that if a high value of energy can be stored at the notch vicinity before fracture than the material behaves brittle during fracture because the crack will start with a higher rate. If the measure of energy concentration is not enough high than the crack will start with a smaller rate and the fracture surface will have either totally ductile or ductile-brittle character. They may schematically be characterised by the local stress, strains or absorbed energy distribution as is shown in Figure 2.

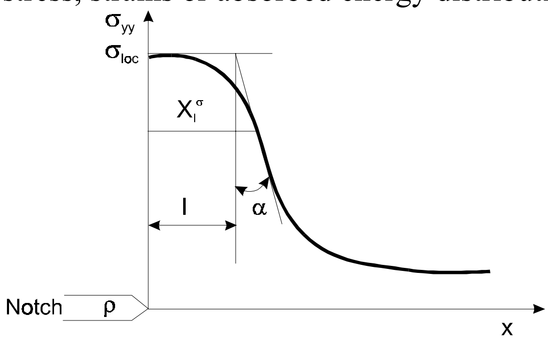

Figure 2. The stress distribution at the notch influenced area (scheme)

Figure 2. shows that the ***local circumstances*** at the notch vicinity can be characterised by three parameters, i.e. by the local maximum stress ($\sigma_{\mathbf{loc}}$), by the length of the plateau of the maximum stress (**l**) and by the gradient of stress

(α). Both of the two last parameters may be summarised by a single length parameter denoted by $\mathbf{X_I^\sigma}$ (where the index I denote the loading mode, i.e. the loading is perpendicular to the fracture surface). Using these parameters the **measure of stress concentration** in the notch-influenced area of the material can be characterised by the ***notch stress intensity factor*** in the form of

$$\mathbf{K_I^\sigma} = \sigma_{\mathbf{loc}} \sqrt{\pi \mathbf{X_I^\sigma}} \tag{1}$$

The **measure of strain concentration** in the notch influenced area of the material can be characterised by the ***notch strain intensity factor*** ($\mathbf{K_I^\varepsilon}$) and the **measure of absorbed energy concentration** by the ***notch energy intensity factor*** ($\mathbf{K_I^w}$) i.e.

$$\mathbf{K_I^\varepsilon} = \varepsilon_{\mathbf{loc}} \sqrt{\pi\, \mathbf{X_I^\varepsilon}} \tag{2}$$

$$\mathbf{K_I^w} = \mathbf{w_{loc}} \sqrt{\pi\, \mathbf{X_I^w}} \tag{3}$$

where $\varepsilon_{\mathbf{loc}}$ and $\mathbf{w_{loc}}$ are the local strain or energy concentrations on the surface, the $\mathbf{X_I^\varepsilon}$ and $\mathbf{X_I^w}$ are the characteristic distances respectively. The local stress ($\sigma_{\mathbf{loc}}$), strain ($\varepsilon_{\mathbf{loc}}$) or energy ($\mathbf{w_{loc}}$) is proportional to the effective stress, strain or energy concentration factor.

Taking a notched cylindrical specimen having a crack (i.e. notch radii is app. equal to zero) and loaded by a given value tensile force the value of $\mathbf{K_I^\sigma}$ (in an elastic media) is equal to infinity, because the local stress is also infinity (the stress field has an $\mathbf{1/\sqrt{r}}$ type singularity, where $\mathbf{r}$ is the length measured from the crack front). If only the notch radii increases in the above mentioned and loaded specimen then the notch stress intensity factor decreases. Because the local stress concentration factor **($\mathbf{K_t}$)** at the notch vicinity in elastic media is proportional to the $\mathbf{1/\sqrt{\rho}}$**,** where ρ is the notch radii, it can be predicted that a linear relationship exists between $1/\mathbf{K_I^\sigma}$ and $\sqrt{\rho}$as is illustrated by the straight line starts at the origin in Figure 3. It means that the reciprocate value of the **measure of stress or strain concentration** in the notch influenced area of the material is proportional to the value of $\sqrt{\rho}$. Considering the fracture surface it could be either brittle, or transition or totally ductile. It is obvious that the fracture parameters are different. We can also say that if the measure of stress concentration is enough high in the notch influenced area of the material than the material is totally brittle. This situation can be characterised by the ***plane fracture toughness*** ($\mathbf{K_{Ic}}$) which has no geometry dependence, i.e. it has no influenced by size and geometry of specimen. If the fracture surface is not totally brittle, or it is totally ductile than the fracture parameter is some kind of

fracture toughness (**K_c** or **σ_c**) which has geometry dependence (i.e. its value depends on the size and geometry of specimen and the notch).

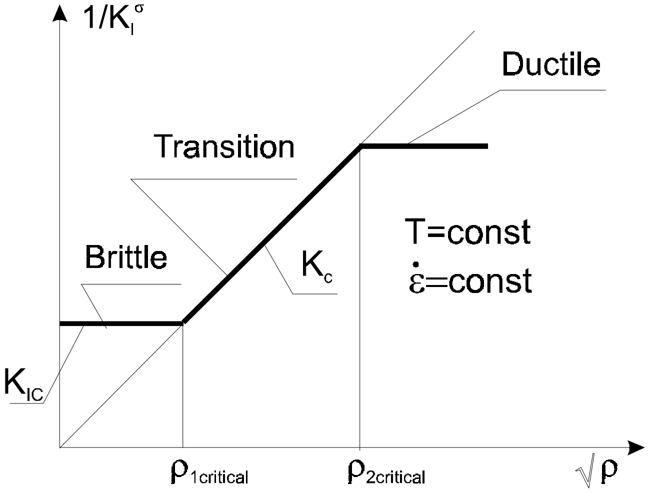

Figure 3. Relationship between **measure of stress concentration** in the notch influenced area of the material i.e. between the notch stress intensity factor and fracture parameters

This is perfectly in agreement with the experimental observations, i.e. there exists a small notch radius by which the brittle fracture of materials can be reached. This notch radius is denoted by $\boldsymbol{\rho_{1crit}}$. In this case the fracture parameter is the plane fracture toughness which is constant.

The suggested model can be validated by the experimental data, which can be found in the literature. The most persuading data will be detailed in the next paragraph in which the grain size effect on brittle-ductile behaviour of mild steel will be discussed. Some results of the ASTM activities also exactly supports the validity of the above-mentioned model. In the Fig. 4. the fracture toughness parameters of H-11 modified stainless steel is presented measured on 1 inch wide edge notched specimens with different notch radius [1]. Considering the Figures 3-4 the following conclusions can be drawn:

- the fracture parameter vs. sqr(notch radius) has a linear character which straight line has the cross-section with the origo
- the fracture parameter is constant up to a given notch radius (which has been denoted by $\boldsymbol{\rho_{1crit}}$) and it has no geometry dependence, i.e. its value does not depend on the specimen geometry.

These statements are in fully agreed with the proposed model, and it can be validated by many experimental results [1-6]. It need to be pointed out that taking any energy parameter (like the J_{Ic}) its reciprocal value v.s. sgr(notch radii) has a linear character.

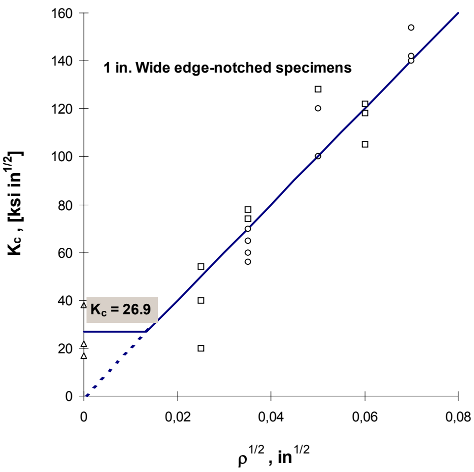

Fig. 4. The fracture parameter of H-11 modified stainless steel measured on 1 inch ***wide single notched specimens.***

If only the notch radius increases, the fracture has brittle-ductile transition character and upon reaching an upper limit of notch radius for instance ρ_{2crit} the fracture is totally ductile. At these ranges the values of fracture parameter depends on the ratio of the ductile-brittle surfaces measured on fracture surface i.e. the brittle tendency of materials can be characterised by the slope of the straight line as it is shown in Figure 5.

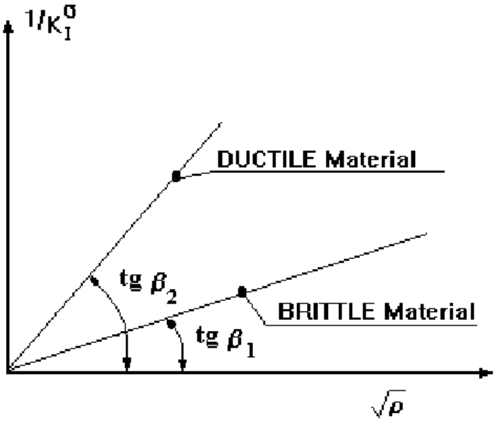

Figure 5. The brittle - ductile transition sensitivity of materials characterised by the slope (tan β_i) of 1/ $\mathbf{K_I}^{\sigma}$ vs. $\sqrt{\rho}$

If the value of slope (tan β_1) is small then the material is brittle, because the total brittle fracture can occur on a specimen with larger notch radius. In contrast, if the slope is high (tan β_2) then the material is generally ductile, because the brittle fracture can only be found for a very small notch radius i.e. on a specimen with high notch acuity. The brittle-ductile transition sensitivity of materials i.e. the slope (tan β_i) of 1/ $\mathbf{K_I}^{\sigma}$ vs. $\sqrt{\rho}$ curve depends on

- type of materials,
- testing temperature and

- loading rate.

The last two will be analysed in the next paragraphs.

EFFECT OF THE TEMPERATURE

If the test temperature decreases, then the material becomes more and more brittle, it means that the value of (tan β_1) decreases as is demonstrated in Fig. 5. It can also be formulated, that by decreasing the test temperature the notch sensitivity increases, i.e. notches are more dangerous at low temperatures. The mentioned details of course are in good agreement with experiences.

THE LOADING RATE EFFECT

The loading rate effect on brittle-ductile transition sensitivity of a given material is illustrated in Fig. 6. The quasi-static loading condition is characterised by continuous line. With increasing loading rate the material becomes more and more brittle and its yield stress increases, i.e. the perfectly brittle fracture can be found on a specimen with higher value of the notch radius, consequently tan β_4 < tan β_3 .

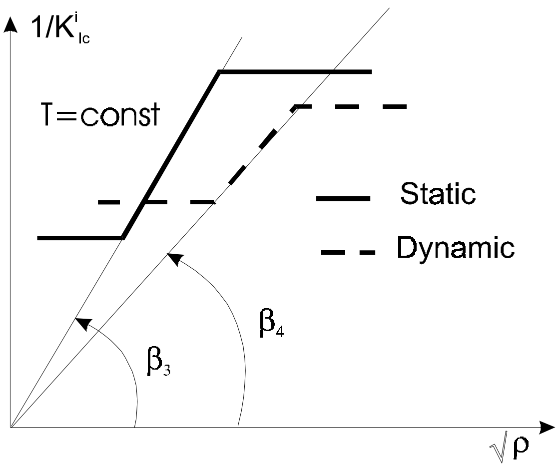

Fig. 6. The loading rate effect characterisation on brittle -ductile transition sensitivity of a selected material by the slope (tan β_i) and 1/ $\mathbf{K_I}$ vs. $\sqrt{\rho}$ curve

THE LOADING RATE AND TEMPERATURE EFFECTS

The same tendency can be observed if the testing temperature decreases. These are summarised in Fig. 7.

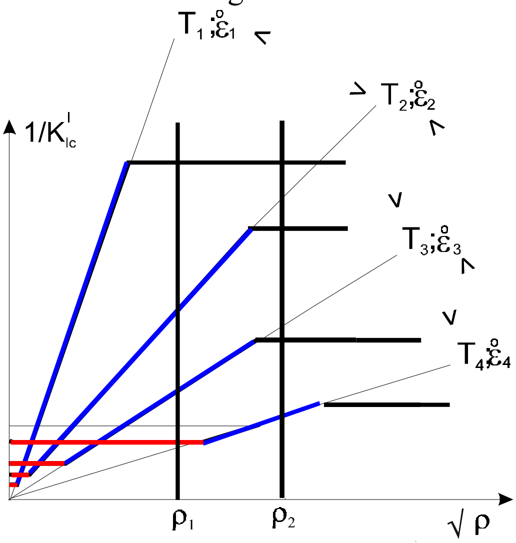

Fig. 7. The loading rate and temperature effect characterisation on brittle-ductile transition sensitivity of a selected material by the slope of 1/ $\mathbf{K_{ic}}^{\mathbf{i}}$ vs. √ρ curve

NOTCH RADIUS EFFECT ON THE SENSITIVITY INDEX

It is also well known, and experimentally verified fact, that with increasing notch radius the brittle-ductile transition temperature also increases (the other experimental conditions are the same). This fact directly follows from the proposed concept. Following Fig. 7. if the test is performed on a specimen with a notch radius of $\boldsymbol{\rho_1}$, then at $\mathbf{T_1}$ temperature the fracture is ductile. At a lower temperature $\mathbf{T_2}$ the fracture has a ductile-brittle transition character. If the temperature is lower i.e. $\mathbf{T_4}$, then the tested material is totally brittle. This fact is illustrated in Fig. 8. If the notch radius is higher i.e. $\boldsymbol{\rho_2} > \rho_1$, then in accordance with Fig. 7. the brittle-ductile transition has a lower value.

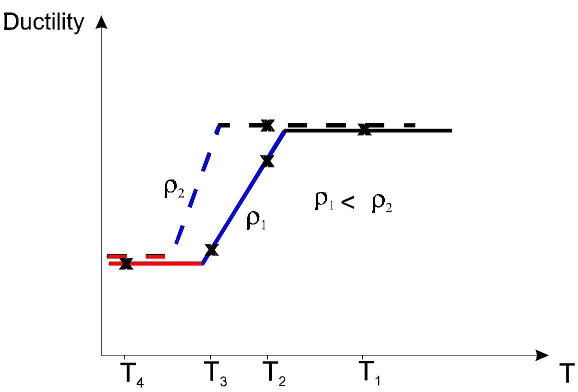

Fig. 8. Notch radius effect on brittle-ductile transition

SUMMARY

1. The elastic-plastic deformation state of the notch influenced area (the measure of stress, strain or energy concentration in the materials as the most simple selforganised system) can be characterised by **local parameters** by notch stress, strain or energy intensity factors.
2. The local parameters, the notch stress, strain and energy intensity factors are expressed by:

$$\mathbf{K_I^{\sigma}=\sigma_{glob}\,K^{\sigma}\sqrt{X_{\sigma}}=\sigma_{loc}\,\sqrt{X_{\sigma}}};\quad \mathbf{K_I^{\varepsilon}=\varepsilon_{glob}\,K^{\varepsilon}\sqrt{X_{\varepsilon}}=\varepsilon_{loc}\,\sqrt{X_{\varepsilon}}};\quad \mathbf{K_I^{w}=W_{glob}\,K^{w}\sqrt{X_{w}}=W_{loc}\,\sqrt{X_{w}}}$$

where the global stress, strain or deformation energy fields are characterised by, $\boldsymbol{\sigma_{glob}}$ $\boldsymbol{\varepsilon_{glob}}$ and $\mathbf{W_{glob}}$; the local fields at the notch tip are expressed by the local, $\mathbf{K}^{\sigma}$, $\mathbf{K}^{\varepsilon}$ and K^{w} concentration factors and the distribution of these fields by characteristic distances, $\mathbf{X_{\sigma}}$, $\mathbf{X_{\varepsilon}}$ or $\mathbf{X_{w}}$ respectively.

3. The relationships between the notch intensity factors $(\mathbf{K_I^i})$ and the notch radius (ρ) in $1/\mathbf{K_I^i}$ vs. $\sqrt{\rho}$ co-ordinate system are linear for stress and strain ($i=\sigma$ or ε) and the brittle-ductile transition sensitivity of materials can be characterised by the slope of $1/\mathbf{K_I^i}$ vs. $\sqrt{\rho}$ curve (i= stress or strain).

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