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CHARACTERIZATION OF MATERIAL DUCTILITY BY MICROVOID NUCLEATION PARAMETERS

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ABSTRACT

The ductility and fracture toughness of a material vary with the change of geometry and can not be directly transferred from one geometry to another. For polycrystalline metals, ductile fracture occurs most often as a consequence of nucleation, growth and coalescence of microvoids. It therefore becomes natural to link material fracture behavior to the micro-mechanical parameters, which describe the evolution of microvoids, through a micro-mechanical model. Recently, a complete Gurson model has been proposed by the authors. In the complete Gurson model, both void nucleation and growth characterized by the Gurson model, and void coalescence characterized by Thomason's plastic limit load model are included. With the complete Gurson model, void coalescence is a natural outcome of plasticity development, and ductile fracture is explicitly linked to the void nucleation parameters. A method has been proposed to characterize material's ductility according to nucleation parameters.

1. DEFORMATION AND DUCTILE FRACTURE

Material deformation behavior can be characterized by its true stress and strain curve, which includes both the yield strength and hardening exponent. The true stress strain curve is geometry independent and can be transferred from a standard tensile test to a complicated geometry. The conventional method to characterize ductile fracture is to use macro fracture parameters such as ductility (for un-precracked specimen) or fracture toughness (for cracked specimens). However, unlike the deformation parameters, macro fracture parameters are geometry dependent and can not be directly transferred from one geometry to another. It has been generally understood that the conventional fracture mechanics works only in a limited number of cases. For polycrystalline metals, ductile fracture occurs most often as a consequence of nucleation, growth and coalescence of microvoids. It is therefore natural to link

material fracture behavior to the parameters that describe the evolution of microvoids through a micro-mechanical model.

Several micro-mechanical models have been developed in the past for modeling ductile fracture and one of the best known models is due to Gurson (Gurson 1975). The Gurson model can well predict void growth and material softening resulting form the presence of voids, but it has no intrinsic ability to predict void coalescence. Recently, a complete Gurson model in which the Gurson model is used for describing void nucleation and growth, and Thomason's plastic limit load model is used for characterizing void coalescence has been presented (Zhang 1998). It has been shown that prediction of void coalescence by the complete Gurson model is very accurate compared with FE analysis of cell models (Zhang 1998).

The conventional measure of ductility is fracture strain. With the complete Gurson model, the dependence of ductility on geometry, i.e. notch radius, can be uniquely described by void nucleation parameters. The nucleation parameters can be determined from a series of smooth and notched tensile tests. The nucleation parameters can then be used to characterize material's ductility and to predict ductile fracture.

2. A COMPLETE GURSON MODEL

In the literature, several void growth models have been proposed. The models describe void growth rate as a function of remote applied plastic strain rate and current stress triaxility, neglecting the feedback of microvoids on material's load carrying capacity (Rice and Tracey 1969). In 1975, Gurson presented a model, which can predict the void growth and the softening effect due to voids. The Gurson model has been further modified to take into consideration of the effect of void interaction (Tvergaard 1982,1990) and void shape (Søvik 1996). However, a common feature of the Gurson model and other void growth models is that no intrinsic void coalescence criterion is included. The models can calculate void growth but another failure criterion should be used, such as the critical void volume fraction / void growth ratio or the critical value of the distance between crack tip and the neighboring void. Recent numerical and experimental results have shown that the critical void volume fraction is dependent on the initial value of the void volume fraction and also on the stress triaxility when the initial void volume fraction is large (Zhang 1998).

Thomason has developed a ductile fracture model (Thomason 1990), and argues that plastic localization and void coalescence appears when the plastic limit load of the inter-void matrix material has reached. The plastic limit load, represented by, $s_1^{Localized}$ is very large when the void radius is small compared with the inter-void dimension, and is decreasing when the plasticity develops and the void radius increases. Finally, when the applied microscopically homogenous stress, $s_1^{Homogenous}$, is equal to plastic limit load stress, $s_1^{Localized}$, fracture by void coalescence will occur.

By integrating the Gurson model and the Thomason model together and assuming voids are always spherical or cylindrical, a complete Gurson model which models ductile fracture as the complete process of void nucleation, growth and coalescence is obtained. Detailed description and verification of the complete Gurson model can be found (Zhang 1998, Zhang and Hauge 1998, and Zhang and Niemi 1995). The complete Gurson model is schematically shown in Fig. 1.

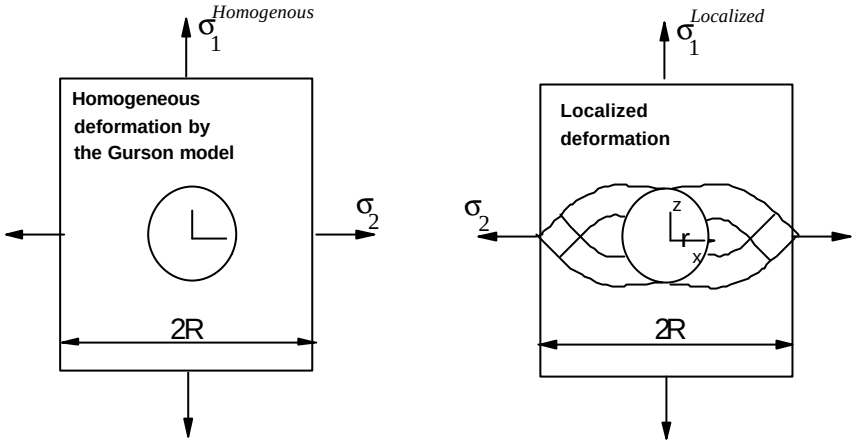


Fig. 1 The complete Gurson model: void nucleation and growth by the Gurson model a) and void coalescence by the Thomason model b). Void is always assumed to be spherical (3D) or cylindrical (2D plane strain) (Zhang 1998).

With the complete Gurson model, void coalescence is not directly a material property but becomes a natural outcome of plasticity development following the void nucleation. Therefore, in the process of ductile fracture, void nucleation is the most critical event, and void growth and coalescence are the response of the nucleated voids to the applied plasticity and stress triaxility. According to the complete Gurson model, ductile fracture is uniquely controlled by materials void nucleation parameters. Void nucleation belongs to material intrinsic properties.

3. VOID NUCLEATION MODELS

Engineering alloys usually contain inclusions, for example, manganese sulfides and aluminium oxides in steels, and second-phase particles, for example, carbides in steels and intermetallic phases in aluminium alloys. Void nucleation in general depends on particle strength, size, shape and the hardening exponent of the matrix material. The nucleation mechanism can be strain controlled, or stress controlled where the hydrostatic tension stress plays a role (Zhang 1998). For strain controlled criterion, the contribution of void nucleation to the increase of void volume fraction, *df*, can be written:

$$df = f_e(\bar{e}^p)d\bar{e}^p \qquad (1)$$

where f_e is the void nucleation intensity and $\bar{e}^p$ is the equivalent plastic strain. For many engineering alloys, the following two simple nucleation models can be used. The

first is a cluster nucleation model characterized by the initial void volume fraction f_0, where all the voids are assumed to nucleate at the beginning of plastic deformation. This model can be applied to materials where large inclusions exist or micro cracks are present in the material. Another nucleation model is called continuous nucleation model, where it is assumed that the amount of nucleated voids per increment of plastic equivalent strain is a constant, which is denoted as *A*. These two models are schematically shown in Fig. 2.

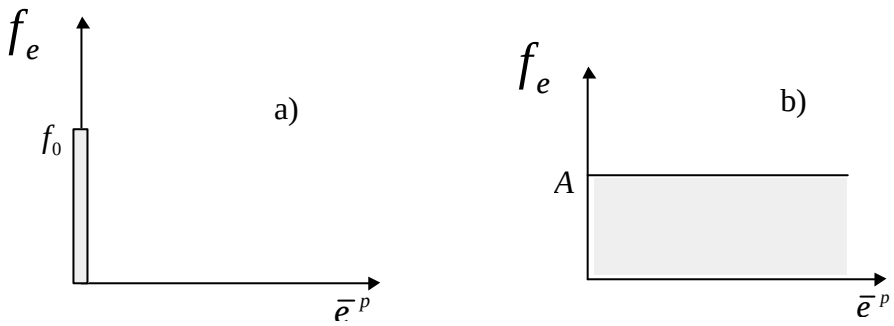


Fig.2 Void nucleation models, the cluster nucleation model characterized by the initial void volume fraction f_0 a), and the continuous nucleation model characterized by a constant *A* b).

The parameters which describe the void nucleation models are in general called micro-mechanical parameters. It should be noted that real nucleation mechanisms are very complicated, and the proposed models are approximate ones. The typical feature of the micro-mechanical parameters is that they can not be directly measured and the directly measured parameters can not be used. Numerical methods must be used for determination of void nucleation parameters. The relation between the ductility of a material, e_f to its nucleation parameters, f_e, can be written:

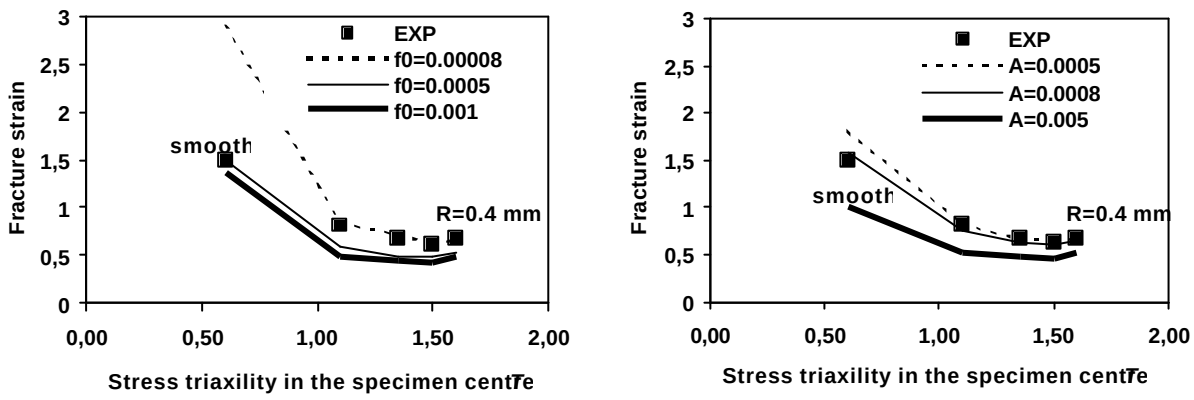
$$e_f = e_f(f_e, G), \tag{2}$$

where *G* represents the geometry of a tensile specimen.

4. DUCTILITY DIAGRAM

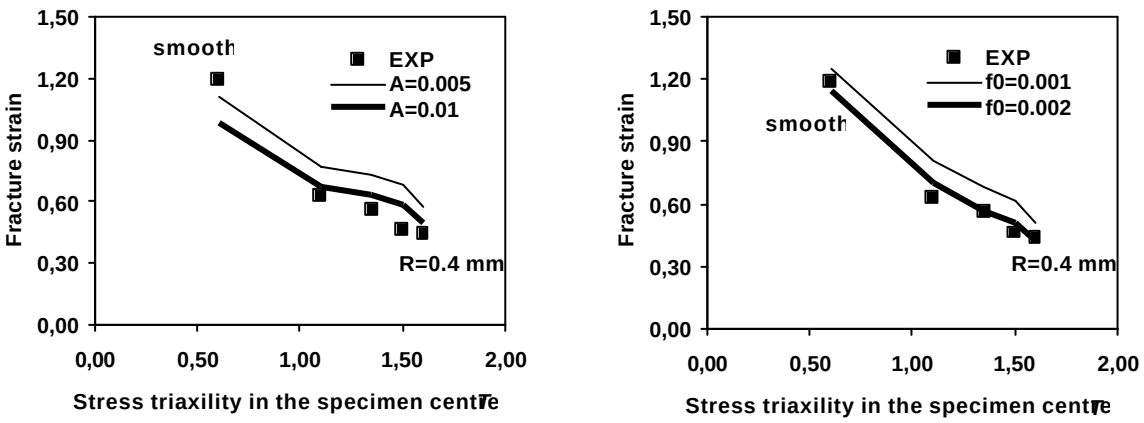
With the complete Gurson model, the ductile fracture is explicitly related to the void nucleation parameters, Eq. (2). For given tensile test results, different void nucleation models and parameters can be tested. The one which fits best with the test results is chosen as the “real” one. A series of tensile tests with smooth and notched specimens are suggested for fitting the void nucleation parameters. When measured fracture strains are plotted with the notch radius or stress triaxility at the centre of specimens, a so-called ductility diagram is obtained. Fig. 3 shows the ductility diagram for a pipeline steel X65 (Taule 1997). The diameter of the tensile specimens is 6 mm. Smooth specimen and specimens with notch radius, R=2.0, 1.2, 0.8 and 0.4 mm were used. In the material, the largest particle diameter is 5.6 μm and the number percentage of these particles is less than 2%. Most of the particles have a diameter about 2.2 μm. The

two nucleation models shown in Fig. 2 have been tested. Fig. 3 shows that the cluster nucleation model does not fit the ductility diagram. The best fitting can be obtained by considering two nucleation mechanisms both for large inclusions and small particles (Taule 1997). As an approximation, the continuous model with A=0.0008 gives a good fit to the test results. The continuous nucleation model can be considered to represent a mixture of both the large and small particles for this material. An Al-4.3%Si aluminium alloy has also been tested. Specimens with 4mm diameter were used. Same notch radius as the steel has been used for the notched specimens. The fitting results of the two nucleation models are shown in Fig. 4. It has been found that the continuous nucleation model, Fig. 4a, does not fit with the material, and the cluster nucleation model, Fig. 4b, with f_0 =0.2% fits very well, Fig. 4b. Metallurgical examination shows that micro-defects acting as microvoids exist in the material prior to testing due to extrusion of the material. The measured initial volume fraction of microvoids is about 0.2% which is close to the initial void volume fraction fitted from Fig. 4b (Ødegård, 1997). On other hand, it can be concluded that the ductility of this material is primarily controlled by the micro-defects.



a) b)

Fig. 3 Ductility diagrams for a X65 pipeline steel, a) cluster nucleation model and b) continuous nucleation model b).



a) b)

Fig. 4 Ductility diagram for an Al-4.3%Si alloy, a) continuous nucleation model; and cluster nucleation model b).

5. DISCUSSIONS AND CONCLUSIONS

In this paper, material ductility has been explicitly linked to the void nucleation parameters, A or f_0. The dependence of ductility on geometry is completely described by the nucleation parameters. The established void nucleation parameter can be used for qualification of material and material selection, and for the prediction of ductile fracture of un-precracked specimens and the fracture toughness of cracked specimens. For practical purpose, the selection of nucleation model can be determined from the fracture strain ratio of smooth specimen to a representative notched specimen. The cluster nucleation model results in high ratio and the continuous nucleation is the opposite.

One of the important aspects in the application of the Gurson model based approach is the determination of micro-mechanical parameters. The complete Gurson model and the proposed ductility diagram provide a method for determining the micro-mechanical parameters. With the complete Gurson model, the “real” void nucleation model can be obtained by using the ductility diagram. It should be mentioned that different void nucleation models can give same prediction at one stress triaxility while the prediction is very different at another stress triaxility, see Fig. 5. It is necessary to test the fitting of void nucleation models and parameters at different stress triaxility, and therefore a ductility diagram should be used.

Different materials follow different nucleation models and will have different nucleation parameters. The nucleation parameters depend on materials microstructure. The ongoing research activities focus on the link between the nucleation parameters and materials microstructure, and eventually to the manufacturing parameters.

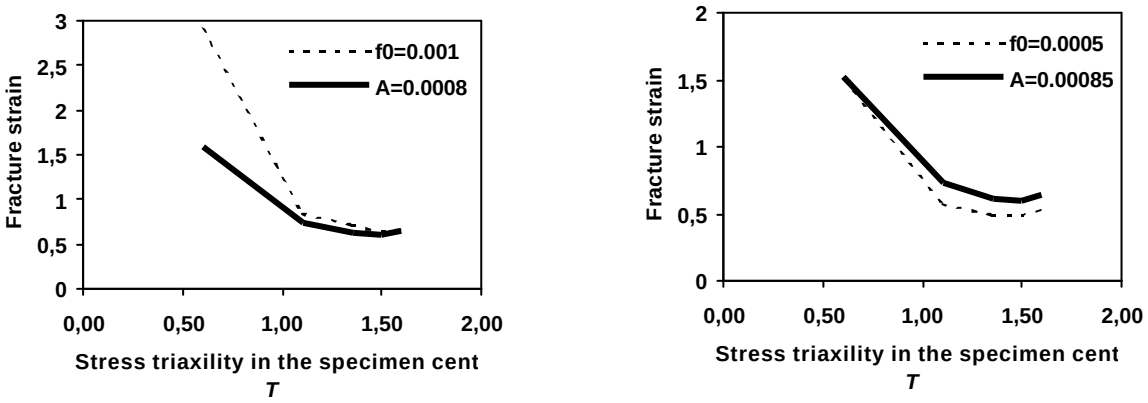


Fig. 5 Different nucleation models predict nearly the same ductility at one stress triaxility case but predict very different ductility at other stress triaxility cases.

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