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A new approach for ductile fracture prediction on Al 2024-T351 alloy

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ABSTRACT

The aim of this investigation is to establish a universal, accurate and efficient fracture criterion for ductile metals. First, new experiments including pure torsion, uniaxial tension followed by torsion and non-proportional biaxial compression on the Al 2024-T351 alloy are presented. These experimental results, along with published data on same material by Stoughton and Yoon (2011), are used to establish a phenomenological fracture criterion using the magnitude of stress vector and the first invariant of stress tensor. The results are compared to, and shown better than, the maximum shear stress fracture criterion proposed by Stoughton and Yoon, J_2 fracture criterion and the Xue–Wierzbicki fracture criterion. Moreover, the proposed fracture criterion is used to correlate the ductile fracture data of another aluminium alloy published by Brünig et al. (2008).

1. Introduction

An accurate ductile fracture criterion for ductile metals has been of interest for several decades (McClintock et al., 1966; Rice and Tracey, 1969; Gurson, 1977; LeRoy et al., 1981; Lemaitre, 1985; Johnson and Cook, 1985; Wierzbicki et al., 2005; Li et al., 2011). The fracture of metals is the macroscopic manifestation of the evolution and accumulation of microscopic defects, such as micro-voids and shear bands et al. Efforts have been made to investigate the micro-mechanisms of ductile fracture behavior of different metals. In the last several decades, several micro-mechanically motivated fracture criteria have been proposed to describe the macroscopic fracture due to degradation of the material with the accumulation of internal microscopic defects in order to predict the occurrence of fracture (e.g., McClintock et al., 1966; Rice and Tracey, 1969; LeRoy et al., 1981). It is assumed that micro-void initiation, growth and coalescence are responsible for the fracture of ductile materials. The first microscopic mechanism analysis was proposed by McClintock et al. (1966). By assuming the distribution of cylindrical holes in a continuum material, McClintock analyzed the growth of the cylindrical holes in non-hardening and strain-hardening materials. Based on their analysis, a cumulative damage model was proposed, which was dependent on the transverse principal stresses, equivalent stress and strain hardening exponent of the matrix material. It was shown that besides the maximum principal stress and the equivalent stress, the fracture strain also depended strongly on transverse tensile stress. A pioneering research was carried out by Rice and Tracey (1969) by considering the growth and shape changes of spherical voids in both hardening and non-hardening materials subjected to remote uniaxial tension loading. It was found that the volume change contribution was more significant than the shape change effect; and the fracture strain was expressed by an exponential function of stress triaxiality. However, in the above two models, the existence of micro-void in the continuum was arbitrarily assumed, and the interaction between these microscopic defects was not considered. Their model was further modified by LeRoy et al. (1981) by considering the nucleation of, and interaction between voids. LeRoy et al. modified Rice and Tracey's theory by analyzing the shape changes of micro-voids. They proposed a simple model to simulate the void nucleation, growth and coalescence. In these fracture models, the plastic flow of the material is uncoupled

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with the internal damage evolution and accumulation. The fracture was assumed to occur when the internal damage reached a critical value and resulted in a sudden loss of load carrying capability of the structure. By taking account for the influence of micro-void to the plastic flow, several coupled models were proposed. Gurson (1977) introduced a damage related variable into a porous plasticity constitutive model. In Gurson's porous yield model, the formation of a crack is related to the coalescence of individual voids. A new parameter, the void volume fraction f_v, was introduced to represent the evolution of voids with increasing plastic deformation. It was assumed in the original Gurson-model that fracture occurred when f_v reached a value of unity, which was not realistic in practice. To improve the original Gurson model, Tvergaard (1981), Tvergaard and Needleman (1984) made an important modification to Gurson fracture criterion by introducing two more parameters, q_1 and q_2 to calculate the threshold value of f_v. The evolution of f_v was considered as a function of nucleation of new voids and the growth of existing voids. The void coalescence was also incorporated into their model as acceleration for the growth of void volume fraction. However it became very difficult to determine more than ten parameters in Gurson-type fracture models due to the strong coupling between them. Moreover, the nucleation and growth of voids, which was necessary for the determination of f_v, could only be determined by stochastic methods. Another type of coupled model, known as the Continuous Damage Mechanics (CDM) model, was proposed by Lemaitre (1985) and Chaboche (1988, 2008). Recently, the CDM model was also used by Brünig and Gerke (2011) to simulate the damage evolution in ductile metals undergoing dynamic loading conditions. The CDM model is based on a damage potential function, which defines the partial release of elastic strain energy stored within the matrix material. In the CDM model, the plastic deformation localization is usually neglected, which is not realistic for many loading conditions, such as uniaxial tension. It has been realized that the micro-mechanism of ductile fracture is very complicated and some micro-mechanisms are still ambiguous. For example, when ductile metal is subjected to upsetting compression, an inclined flat fracture surface is usually observed, which is possibly due to the distribution of closest packed sliding planes of the material (Bao, 2003). This mechanism is quite different from the micro-voids nucleation, growth and coalescence assumptions and thus raise questions about fracture criteria based on the micro-voids analysis. There is still no universal understanding that can describe the evolution of the internal damage under all stages of the fracture process. Another drawback for these micro-mechanically motivated fracture criteria is that the material parameters are highly dependent on assumed microscopic values, and are strongly coupled together. The determination of the model constants is very difficult and some values have to be determined by stochastic methods. These shortcomings limit the industrial applications of the micro-mechanically motivated fracture criteria.

The development of micro-mechanically motivated fracture criteria is dependent on the knowledge about microscopic fracture mechanism, and is thus limited by the current experimental techniques. For industrial applications, phenomenological empirical fracture criteria are established to predict the fracture of engineering structure. Although lacking a basis in micro-mechanisms of fracture, the simplicity and accuracy of these empirical fracture criteria for ductile fracture prediction, make them to be more widely accepted in engineering applications. The simplest empirical model may be the equivalent fracture strain criterion and it is still an option in most commercial computational software for ductile fracture prediction. In this fracture criterion, the occurrence of ductile fracture is solely dependent on the equivalent strain. However, it has been shown that equivalent strain itself is not sufficient for indicating the occurrence of ductile fracture (Davidson et al., 1966; Alves and Jones, 1999). Extensive experimental observations show that the hydrostatic pressure, which is related the first invariant of stress tensor, influences significantly the fracture behavior of different metals under tensile loading (French et al., 1973; Kao et al., 1990). An increase in ductility in metals has been observed with the decrease of hydrostatic pressure (Alves and Jones, 1999; Reddy et al., 2000). Recently, in a numerical study, Wu et al. (2009) have demonstrated the enhancement of formability with increase in different hydrostatic pressure. An important parameter, stress triaxiality, which is defined as the ratio of hydrostatic pressure to von Mises equivalent stress, was firstly introduced into the ductile fracture prediction by McClintock et al. (1966), and subsequently used by Rice and Tracey (1969). It was investigated experimentally by Hancock and Mackenzie (1976), Mackenzie et al. (1977). The negative dependence of fracture strain on stress triaxiality was also reported by Hancock and Brown (1983). Different attempts have been made to incorporate the effect of stress triaxiality into various ductile fracture criteria, (e.g., Chaouadi et al., 1994; Schiffmann et al., 2003; Mirone and Corallo, 2010; Oyane, 1972; Malcher et al., in press). The strain rate and temperature dependence in a ductile fracture criterion was first introduced by Johnson and Cook (1985). In the Johnson–Cook fracture model, the strain at fracture is a function of stress triaxiality, strain rate and temperature. Later, the Johnson–Cook fracture model was slightly modified by Clausen et al. (2004) to characterize the fracture phenomenon of aluminium AA5083–H116 alloy under impact loading. The most difficult part for the determination of material constants in these ductile fracture criteria is to acquire accurate and diverse stress, stress triaxiality and equivalent plastic strain values at fracture moment. The most common way to generate different stress triaxiality values is to conduct tensile experiments on smooth and pre-notched round bar specimens. Various positive stress triaxiality values were obtained by varying the notch geometries by Hancock and Mackenzie (1976) and Thomson and Hancock (1984). The stress and strain tensors at fracture, which are used to calculate the stress triaxiality and equivalent fracture strain values, are estimated from the true stress and strain relation by different correction approaches, such as Bridgman correction (Bridgman, 1956) or MLR correction (Mirone, 2004). The main shortcoming for these correction approaches is that only experimental data with high stress triaxiality can be generated. Therefore, the determination of material constants by these values and then application to medium and negative stress triaxiality loading ranges is not accurate. Finite element analyses have been introduced to estimate the local stress and strain values in fracture area during experiments loading to fracture. By using a combination of experimental and finite element approaches, Wierzbicki et al. (2005) designed 15 different experiments including smooth and pre-notched tension, grooved plane strain tension, dog-bone shear and upsetting