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# Dependence of ductile crack formation in tensile tests on stress triaxiality, stress and strain ratios

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**Abstract**

An experimental and numerical study on ductile crack formation in tensile tests was conducted. Five different specimens including flat specimens, smooth round bars, notched bars (two types) and flat-grooved plates were investigated. Von Mises equivalent strain to crack formation, stress triaxiality, and stress and strain ratios at critical locations, were obtained. Accuracy of the Bridgman formulas for stresses in necked round bars, and McClintock's model for flat-grooved plates, were studied. A relationship between the stress triaxiality and equivalent strain to crack formation was determined in a high stress triaxiality range for Al 2024-T351. More importantly, it was found that equivalent strain and stress triaxiality are the two most important factors governing crack formation, while stress and strain ratios cause secondary effects. It appears possible to make a good prediction of crack formation with equivalent strain and stress triaxiality.


*Keywords:* Stress triaxiality; Equivalent strain; Stress and strain ratio; Experiment; Numerical simulation; Ductile crack formation

## 1. Introduction

In many practical problems, equivalent strain to crack formation at the critical location in tensile specimens is taken as a measure of ductility [1–5]. In this paper, ductility is defined as the ability of a material to accept large amounts of deformation without crack formation. Different types of tensile test pieces are often used, such as flat and round specimens. However, equivalent strain to crack formation is dependent of the stress state, which is related to the shape of specimens, and clearly it is not the same in tensile specimens with different geometries. Consequently, different specimens do not necessarily have the same equivalent strain to crack formation. Clausing [1] observed from a series of tests on uniaxially loaded wide, flat, double face-grooved plates that tensile ductility of structural steels was substantially reduced when the strain state was changed from axisymmetric (round specimens) to plane strain (flat-grooved

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plates). The degree of difference was found dependent on the hardness of the steels. The interpretation of the difference was qualitative and limited to the degree of physical constraint. However, for engineers the outputs of structural analysis are the components of stress and strain tensors. Clearly, a qualitative explanation is not sufficient.

In tensile tests on specimens with different cross-sections, the stress triaxiality, and stress and strain ratios are likely to be different, especially for flat plates and round bars. McClintock [3] and Rice and Tracey [6], by studying growth of long cylindrical voids and spherical voids, respectively, have shown that fracture strain of ductile metals is strongly dependent on hydrostatic stress. Atkins [5,7] also pointed out that ductile crack formation should depend on hydrostatic stress. Quantitative studies of the effect of stress triaxiality on crack formation for metals performed in the past were conducted mainly using pre-notched round tensile bars. For example, Hancock and Mackenzie [2] carried out a series of tensile tests on pre-notched steel specimens. It was found that ductility depended markedly on the triaxiality of stress states. In their study, stress triaxiality was calculated using the Bridgman's [8] formula. Recently, Mirza et al. [9] performed an experimental and numerical study on three different materials (pure iron, mild steel and aluminum alloy BS1474) over a wide range of strain rates ($10^{-3}$–$10^{4}$ $s^{-1}$). Equivalent strain to crack formation for all the three materials was found to be strongly dependent of the level of stress triaxiality. The dependence was different for different materials.

In comparison, although some of the empirical fracture criteria proposed are related to stress and strain ratios (e.g. [10,11]), to the best of the author's knowledge, the dependence of ductile crack formation on stress and strain ratios has not been well understood.

Detailed study on ductile crack formation in tensile specimens with different cross-sections for the same material will certainly contribute to a more complete picture. In this study, tensile tests on flat specimens, flat-grooved plates, and smooth and pre-notched round bars, were conducted. All the specimens were cut from a same block of Al 2024-T351. Those tests give not only different stress triaxialities, but also different stress and strain ratios. Certainly, they provide a good way to study the effects of stress triaxiality, and stress and strain ratios, on crack formation.

## 2. Theoretical consideration

### *2.1. Flat specimen*

For ductile metals, necking in a thin sheet under uniaxial tension usually occurs before fracture. Obviously, necking is an important mechanism in thin sheets under tension for fracture prediction. The analysis for necking under plane stress was conducted by many authors such as Hill [12], and McClintock and Zheng [13]. For a thin sheet in uniaxial stress subjected to an axial load, $P$, necking occurs when $P$ reaches a maximum. The necking is spread over a length of the order of the width $w$ shown in Fig. 1 while the rest of the specimen remains prismatic. This is called diffuse necking. The maximum load, at which necking begins, occurs when the slope of the equivalent stress–strain curve satisfies the condition

$$\frac{d\bar{\sigma}}{d\bar{\varepsilon}} = \bar{\sigma} \tag{1}$$

For a power-law material, which has the relation,

$$\bar{\sigma} = \sigma_0 \bar{\varepsilon}^n \tag{2}$$

where, $\bar{\sigma}$ and $\bar{\varepsilon}$ are equivalent stress and strain, respectively; and $\sigma_0$ and $n$ are two material constants for power law materials. The corresponding equivalent strain at the onset of necking is