Some contribution to process zone fracture mechanics

An analytical study of the ductile fracture in Al Alloy 7075-T6

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Abstract. The mechanism of the ductile fracture is studied theoretically for the Al Alloy 7075-T6 specimens. A model for the interaction of a crack tip with a void nearby is analyzed by using the Modified Gurson's Model. Taking fracture criterion into consideration, the analysis of a crack propagation is carried out and besides the distribution of the equivalent plastic strain, the void volume fraction $f$ and the localization are obtained. Microcracks nucleate on the ligament between crack and void, and grow and coalesce each other, and at last the main crack thus formed coalesces with the void and the coalescence of the crack and void is completed. And these phenomenon occurs in the localized region.

The initiation of the microcrack of 7075 occurs at small $J$ and the microcrack penetration between crack and void occurs at larger $J$, and the propagation does not occur smoothly. These results coincide with the results of the experiments by FRASTA (FRACTure Surface Topographic Analysis) and Fractography.

1 Introduction

It is said that a key for solving the secret of the ductile fracture mechanism exists in the study of the process zone. In the last papers (Miyamoto et al. 1986a, b, 1987a), the problem was attacked from the theoretical aspects and the interaction of a crack tip with a void or voids nearby was analysed using several models. Among the phaenomenological constitutive equations, $J_2$-Flow Theory ($J_2$-F-T), $J_2$-Corner Theory ($J_2$-C-T) and Modified Gurson's Model (MGM) are used for the analyses. The former two are those for the dense materials and the latter is for the voided materials. The best fit one for this problem is selected by the following procedures.

$J_2$-F-T is the standard for the elastic-plastic problem. At first comparison between $J_2$-F-T and $J_2$-C-T is carried out by Miyamoto et al. (1986a). Compared with $J_2$-C-T, in the case of $J_2$-F-T the deformation near the crack tip is too stable. These results coincide with our expectation, because it is said that $J_2$-F-T is not suitable for the analysis of the buckling and the localization. Then $J_2$-F-T is compared with MGM about the thinning of the ligament between the crack and a void. In the case of $J_2$-F-T, when $J$ increases the ligament reduces and at last becomes zero, which means $J_2$-F-T is suitable for the analysis of the hole contact model on the coalescence of the crack and a void. On the other hand, in the case of MGM, the ligament becomes small, but it has a limit and does not become zero, so it is suitable for the analysis of the coalescence due to localized type of ductile fracture. Thus the $J_2$-F-T is not suitable for the analysis of the ductile fracture from the point of both the stability of the deformation and the void coalescence.

Next the comparison is carried out between $J_2$-C-T and MGM. In this case the analytical results are compared with the experiments by fractography. The relation between $J$ value and the diameter of the void $D$ is used for the comparison (Miyamoto et al. 1987b). The experimental results between $J$ and $D$ in 7075-T6 are given as:

$$D = 0.37J + 4.86$$

The analytical results by $J_2$-C-T and MGM are:

$$\bar{D} = 0.91J + 4: \quad J_2\text{-C-T}$$
$$\bar{D} = 0.40J + 4: \quad \text{MGM}$$

(1.1)
respectively, where the second term of the right hand side 4.86 and 4 are the initial diameter of a void when \( J = 0 \). From this, it is clear that MGM is suitable for the analysis of Al Alloy 7075-T6.

By using the MGM, the growth of the localized area between crack and void is calculated (Miyamoto et al. 1986a). As the next step, it is necessary to know how the crack coalesces with a void. In order to carry out this analysis, MGM due to Needleman and Tvergaard (1987) is adopted.

Large deformation finite element analysis is used to study the growth of a cylindrical voids ahead of a blunting crack.

The presence of small-scale voids nucleated at precipitate particles is taken into account by using Modified Gurson's equation to describe the constitutive behaviour of the material.

Assume that at \( f_F = 0.25 \) the stress carrying capacity is completely lost, we are able to study not only the nucleation and the subsequent growth of the microcracks in the ligament between the void and the crack, but also the coalescence of the void and the crack.

The analysis is applied to Al Alloys 7075-T6, for \( \varepsilon_N = 0.3 \) and 0.8.

The behaviours of the crack propagation in 7075 are compared and discussed from the standpoints of the analysis and the experiments.

## 2 Constitutive relations

The material model to be used here accounts for the porosity arising from the cracking or decohesion of second phase particles in a ductile metal. This model is an elastic-plastic version of the model proposed by Gurson (1977).

The function to be used here as the plastic potential is of the form

\[
\phi = \frac{\sigma_e^2}{\sigma_m^2} + 2f^* q_1 \cosh \left\{ \frac{\sigma_{kk}}{2\sigma_m} \right\} - \left\{ 1 + (q_1 f^*)^2 \right\} = 0
\]  

(2.1)

where \( \sigma_e = (3/2 \sigma_{ijj})^{1/2} \) is the macroscopic Mises stress, in terms of the stress deviator \( \sigma_{ij} = \sigma_{ij} - \sigma_{kk} \sigma_{kk}/3 \), and \( \sigma_{kk}/3 \) is the macroscopic mean stress, \( \sigma_m \) the actual microscopic stress in the matrix and \( f^* \) is the current void volume fraction. For \( q_1 = 1 \) and \( f^* = f \) the function (2.1) is identical to the yield condition proposed by Gurson (1977), based on an approximate rigid-plastic analysis for a single spherical void.

The rate of increase of the void volume fraction is taken to be

\[
\dot{f} = (\dot{f}) \text{ growth} + (\dot{f}) \text{ nucleation}
\]

(2.2)

As the matrix material is plastically incompressible, the contribution from the growth of existing voids is

\[
(\dot{f}) \text{ growth} = (1 - f) D_{kk}. \tag{2.3}
\]

The contribution resulting from the nucleation of new voids is taken to be given by

\[
(\dot{f}) \text{ nucleation} = B(\dot{\sigma}_m + \dot{\sigma}_{kk}/3) + D \dot{\varepsilon}_p^p
\]

(2.4)

where the first term is used to model nucleation controlled by the maximum normal stress on the particle-matrix interface, as suggested by Needleman and Rice (1978), and the last term models plastic strain-controlled nucleation, where \( \dot{\varepsilon}_p^p \) is the microscopic plastic equivalent strain of the matrix.

As suggested by Chu and Needleman (1980), void nucleation is taken to follow a normal distribution. Thus plastic strain-controlled nucleation is specified by

\[
D = \frac{f_N}{s_N} \exp \left[ -\frac{1}{2} \left( \frac{\dot{\varepsilon}_p^p - \varepsilon_N}{s_N} \right)^2 \right], \quad B = 0
\]

(2.5)

where \( f_N \) is the volume fraction of void nucleating particles, \( \varepsilon_N \) is the mean strain for nucleation, and \( s_N \) is the corresponding standard deviation.