Ductile Fracture of Aluminum Alloys*

(Observation of the Fracture Process by FRASTA and FEM Simulation)

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The microscopic process of ductile fracture in the process zone is studied in this paper. First, the FRASTA (fracture surface topographic analysis) technique is used, and the ductile fracture processes of two kinds of aluminum alloys, 7075-T6 and 2017-T4, are observed. The nucleation, growth and coalescence of voids are observed in detail. The finite element analyses based on Gurson's model are then carried out. The element vanishing method is used with the finite deformation theory. Using the void volume percent as the fracture criterion, the nucleation and growth of voids and coalescence with the crack are simulated. It is shown that these phenomena occur in the process zone, and the numerical results agree qualitatively with the experimental ones.

Key Words: Fracture, Process Zone, Gurson's Model, FRASTA, FEM analysis, Element Vanishing Method, Void

1. Introduction

The nucleation, growth and coalescence of voids which nucleate in the process zone play a central role in the ductile fracture process. A large deformation occurs locally near the crack tip. It is necessary to use the finite deformation theory in the analysis of the crack tip region.

It is said that the conventional J_2 -flow theory is inadequate to simulate this phenomenon, and several new equations have been proposed : (1) Gurson's model of voided materials⁽¹⁾, (2) J_2 corner theory by Christofferson and Hutchinson⁽²⁾, and (3) slip line theory by Pierce et al.⁽³⁾. Numerical analyses have been carried out by Needleman and Tvergaard⁽⁴⁾, Needleman⁽⁵⁾, Tvergaard^{(6),(7)}, Aoki et al.^{(8),(9)}, Tohgo et al.^{(10),(11)}, Kitagawa et al.^{(12),(13)} using each model.

The authors have analyzed the interaction problems between a crack and voids near the crack tip

using Gurson's model and the J_2 -corner theory^{(14)~(16)}.

In this study, Gurson's model modified by Tvergaard is used in the finite element analysis, and the ductile fracture process of two kinds of aluminum alloys is simulated. In the following, the FRASTA technique is used to observe the fracture process and several parameters used in Gurson's model are determined based on this observation. Finally, these values are used in FEM analyses, and the crack growth analyses are carried out using the element vanishing method.

2. Fracture Process Observation by FRASTA

In this study, two kinds of aluminum alloys, 7075-T6 and 2017-T4 are used in the experiment. The material properties are shown in Table 1. In the case of 7075-T6, it is seen that the crack propagation area is covered with dimples before brittle fracture occurs. The 2017-T4 is a ductile material. The fracture surface of the CT specimen is observed by FRASTA. FRASTA is the method which reproduces the fracture process using three-dimensional matching analysis⁽¹⁷⁾. A set of photos (upper and lower ductile fracture surfaces of specimen) are made by using SEM and a

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three-dimensional configuration is drawn as shown in Fig. 1. Using these fracture surfaces and by cutting a specific section along the Y-Z plane and sliding them gradually, Figures 2(a)~(d) are obtained. These figures are results of the 7075-T6 specimen. The black part of these figures corresponds to the overlapped part of the upper and lower surfaces, and the white part corresponds to the separate part. These figures show the ductile fracture process of void nucleation, growth and coalescence with the crack tip. Figure 2(a) is the state before crack growth, that is, $J=0$. Figures 2(b)~(d) show the state when the crack opening distances between the fracture surfaces are $5\mu\text{m}$, $10\mu\text{m}$ and $20\mu\text{m}$, respectively. The results of the 2017-T4 specimen are shown in Figs. 3(a)~(d).

Table 1 Material properties

Material	σ_{ys} (MPa)	σ_s (MPa)	σ_{rs} (MPa)	E (GPa)	J_{1c} (kJ/m)
2017-T4	272	529	401	71.8	22.9
7075-T6	421	529	475	71.8	16.1

Fig. 1 Ductile fracture surface with three-dimensional configuration (7075-T6)

Crack tip by fatigue

Fig. 2 Sections along the Y-Z plane. (7075-T6)

surface of the 7075-T6 and the 2017-T4 specimens, respectively. Figure 4(a) corresponds to the state before loading and the white part of the upper side shows a fatigue precrack. Figures 4(b) and (c) show the state when the crack opening distances between fracture surfaces are $10\mu\text{m}$ and $16\mu\text{m}$, respectively. The expanse of the white part shows the growth of voids and crack tip. Figure 4(b) is the state when the stretching zone is formed, and the void growth and coalescence begin ahead of the crack tip. In Fig. 4(c), it is seen that the voids coalesce with neighboring voids and become bigger and then coa-

Fig. 3 Sections along the Y-Z plane. (2017-T4)

lesce with the crack tip. Figures 5(a)~(c) are the results of 2017-T4. These figures show that voids nucleate within $100\mu\text{m}$ from the crack tip and grow rapidly with deformation and coalesce with the crack tip without coalescing with the neighboring void. Voids again grow rapidly ahead of the new crack tip.

3. Parameter Determination for Numerical Analysis

Gurson⁽¹⁾ proposed a yield function of a voided material using a void volume fraction f as follows :

$$\Phi = \frac{\sigma_e^2}{\bar{\sigma}^2} + 2fq_1 \cosh\left(\frac{\sigma_{KK}}{2\bar{\sigma}}\right) - (1 + (q_1 f)^2) = 0, \quad (1)$$

where σ_e is Mises effective stress and $\bar{\sigma}$ is the average strength of the matrix material. Parameter q_1 is introduced by Tvergaard⁽¹⁸⁾ and f is the void volume fraction.

The rate of increase of the void volume fraction is taken to be⁽¹⁹⁾ :

$$(\dot{f}) = (\dot{f})_{\text{growth}} + (\dot{f})_{\text{nucleation}}, \quad (2)$$

where the first term is due to the growth of existing voids and the second one is due to the nucleation of voids. Each term is expressed by the following equations :

$$(\dot{f})_{\text{growth}} = (1-f) \dot{\epsilon}_{KK}^p, \quad (3)$$

$$(\dot{f})_{\text{nucleation}} = B \left(\dot{\bar{\epsilon}} + \frac{\dot{\bar{\sigma}}_{KK}}{3} \right) + D \dot{\bar{\epsilon}}$$

$$D = \frac{1}{h_m} \frac{f_N}{S_N \sqrt{2\pi}} \exp \left\{ -\frac{1}{2} \left(\frac{\bar{\epsilon}^p - \epsilon_N}{S_N} \right)^2 \right\}, \quad B=0, \quad (4)$$

where in equation (4), h_m is the hardening ratio, f_N is the volume fraction of the nucleation particle, S_N is the standard deviation, $\bar{\epsilon}^p$ is the equivalent plastic strain of the matrix and ϵ_N is the mean strain for nucleation. Equation (4) means that the void nucleation is controlled by the amount of plastic strain. Although the stress controlled model is also proposed, only the strain controlled nucleation model is used in this study.

Tvergaard and Needleman⁽¹⁹⁾ proposed using the function f^* instead of f in equation (1) as follows :

$$f^*(f) = \begin{cases} f, & (f \leq f_c) \\ f_c + \frac{f_u^* - f_c}{f_F - f_c} (f - f_c), & (f \geq f_c) \end{cases} \quad (5)$$

This function is used to represent the more rapid loss of stress carrying capacity associated with void coalescence at failure. In this equation, f_c is the critical value when the stress carrying capacity begins to decrease, and it is completely lost for $f = f_F$. Figure 6 shows the relationship of the void diameter and the J value of 7075-T6 obtained by Okayasu et al⁽²⁰⁾. Hollow circles show the diameters of voids before coalescence, and hollow squares show the diameters of dimples observed on the ductile fracture surface.

Fig. 4 Interior fracture surfaces along the X-Y plane.
(7075-T6)

Fig. 5 Interior fracture surfaces along the X-Y plane.
(2017-T4)

Fig. 6 The relationship between void diameter and J value

The diameter of voids converges to D_c , a little less than D_o , the diameter of dimples. This is due to the large plastic deformation associated with the void coalescence. When voids grow (diameter of a void is D_c and the void volume fraction is f_c), localization occurs between voids and the coalescence of two voids may be completed (diameter of a dimple is D_o and the void volume fraction is f_F). The values of f_c and f_F are determined by measuring the number of dimples in a unit area and using the values of D_o and D_c . The results are shown in Table 2. The f_N values are also shown in the same tables. The f_N values are determined by measuring the number of segregated particles using SEM photos. The f_c , f_F and f_N values of the 2017-T4 are nearly twice those of the 7075-T6, which corresponds to the fact that 2017-T4 is a ductile material while 7075-T6 is a brittle one.

Then, other parameters which appear in equa-

Table 2 The values of f_N , f_C and f_F

	f_N	f_C	f_F
7 0 7 5 - T 6	0. 0 0 9	0. 0 7 5	0. 1 1 8
2 0 1 7 - T 4	0. 0 2 1	0. 1 7 0	0. 2 0 6

tions (4) and (5) are determined. The f_u^* in Eq. (5) is the void volume fraction when the voided material loses the stress carrying capacity. Tvergaard⁽⁷⁾ determined this value as $1/q_1=0.67$, which is also used in this study. Value ε_N in equation (4) is obtained by Broek as 0.3 for aluminum⁽²¹⁾. The S_N in Eq. (4) is the standard deviation of the strain at the void nucleation which is measured statistically. This value should be determined by precise experiment, which is not conducted in this study. Then S_N value is changed from 0.05 to 0.3 and the effect of the S_N value is studied. As a result, the effect of the change of the S_N value does not appear significantly. In the following analyses, the S_N is assumed to be 0.1 which is used by Tvergaard in his analysis.

The stress-strain relationship is approximated by the following Ramberg-Osgood type equation:

$$\frac{\sigma}{\sigma_{ys}} = \alpha \left(\frac{\varepsilon}{\varepsilon_{ys}} \right)^N, \quad (6)$$

where σ_{rs} is the yield stress and $\varepsilon_{rs} = \sigma_{rs}/E$ is the yield strain. Values of $\alpha=1.768$, $N=0.109$ for 7075-T6, and $\alpha=3.173$, $N=0.248$ for 2017-T4 are used.

4. Crack Growth Analysis by FEM

The CT specimen, as shown in Fig. 7, is analyzed by the finite element method based on the finite deformation theory. Two kinds of finite element models at the crack tip region are made as shown in Figs. 8(a) and (b). They correspond to two kinds of materials, 7075-T6 and 2017-T4. They are made based on the results of FRASTA. Two or three voids are located at the crack tip regions which are considered to be smaller than the process zone sizes.

Crack growth analysis is carried out using the element vanishing method proposed by Tvergaard⁽²²⁾. The critical void volume fraction f_F is used as a fracture criterion. The cross triangle element is used in the FEM analysis. The mesh of 7075-T6 and 2017-T4 consists of 2152 and 2148 elements, respectively.

Figures 9(a)~(c) show the results of 7075-T6, where the amount of deformation is denoted by the ratio of J to J_{IC} . Figure 9(a), $J/J_{IC}=0.555$, shows the state just after a microvoid nucleation between the crack tip and the large voids. At the same time, the crack tip propagates for two elements toward the large void. Figure 9(b) shows the state when mi-

Fig. 7 CT specimen

(a) for 7075-T6

(b) for 2017-T4 near the crack tip

Fig. 8 Initial finite element mesh

crovoids coalesced with a large void, and Fig. 9(c) is the state when the coalescence of the large void with a crack tip occurred. Generally, it is said that the large voids nucleate from the large inclusions at the initial stage of deformation and micro-voids nucleate from the small inclusions according to the increase of the deformation, and small voids connect the large voids and the crack tip. In this analysis, situated voids

can be considered to be the large voids which nucleate at the initial stage of deformation, and the nucleated void between the crack tip and the large void during the analysis seemed to be micro-voids. It means that these analyses simulate the process of ductile fracture qualitatively well.

Figures 10 (a) and (b) show the localized regions corresponding to Figs. 9(a) and (c). The localized area is the region in which the condition of the instability deformation proposed by Rudnicki and Rice⁽²³⁾ is satisfied. In Fig. 10 (a), the region between the crack and the nearby void is covered by the localized area and the microvoids nucleate in this region. Figure 10(b) shows that the localized region extends from two large voids as if they pull each other.

In this analysis, the calculation was terminated at this stage. If the deformation proceeds, it is supposed that these localized regions come into contact with

each other and new microvoids nucleate in these regions and coalescence occurs between two large voids. Figure 11 shows the distribution of equivalent plastic strain in the matrix corresponding to Fig. 9(c). It is seen clearly that two large voids affect each other.

Figures 12(a)~(c) show the results of 2017-T4, in which three voids are situated near the crack tip. Figure 12(a) is the state just after crack propagation begins, and the nucleation of the microvoids occurs at two places: the first between the crack tip and the first void, and the second between the second and third voids. In Fig. 12(b), the crack coalesces with the first

Fig. 9 Deformed mesh near the crack tip (7075-T6)

Fig. 10 Distribution of localization (7075-T6)

Fig. 11 Distribution of equivalent plastic strain (7075-T6)

Fig. 12 Deformed mesh near the crack tip (2017-T4)

void, and at the same time, the second and third voids coalesce with each other. In Fig. 12(c), all voids coalesce with the crack tip.

In both materials, it is seen that microvoids nucleate between the large voids, and microvoids coalesce with the large void, and ductile fracture proceeds. Therefore, these results clearly represent a feature of ductile fracture.

The amount of crack growth is $30\mu\text{m}$ in 7075-T6, and $70\mu\text{m}$ in 2017-T4. When J is equal to J_{1c} in the experiment, the value of Δa is $10\mu\text{m}$ in 7075-T6 and $50\mu\text{m}$ in 2017-T4, respectively. The calculated Δa values are larger than those of the experiment. It is thought that a stable crack growth is simulated in Fig. 9(c) and Fig. 12(c). However, in both cases, J values are smaller than J_{1c} values in the calculations. This reason is because (1) the shape of voids are assumed to be a circular cylinder, and (2) several

initial voids exist before deformation in this model although large voids ahead of the crack tip actually do not exist before deformation. Because of these two reasons, the crack growth might occur before the J value reaches the J_{1c} value. In the future, the latter reason will be considered and more realistic analysis will be carried out.

5. Conclusions

The mechanism of ductile fracture is studied by using two kinds of AL-alloys, 7075-T6 and 2017-T4.

(1) The microscopic ductile fracture process can be observed by using the FRASTA technique.

(2) The parameters included in the constitutive equation of Gurson material are determined by using the results of the experiments.

(3) Analyses of crack propagation due to FEM are carried out by using the element vanishing method. The characteristic features of ductile fracture, the crack propagation due to void nucleation, and the growth and coalescence of microvoids between the crack and large voids, are obtained.

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