A Study of the Process Zone at the Crack Tip (Behaviour of the Voids at the Crack Tip of an Aluminum Alloy Specimen)

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The plastic zone created at a crack tip is observed microscopically by using a scanning electron microscope. CT specimens of 2017-T 4 and 7075-T 6 aluminum alloy are loaded onto or into the J_{IC} level and the crack tip regions are observed, so that the size of the process zone (PZ) and the fracture mechanism in it are estimated. The results are as follows: (1) In the process zone, the number of nucleated voids and their diameters decreased along the propagation direction of the crack. The size of PZ is about 100-130 μm for 2017-T 4 and 50-150 μm for 7075-T 6. (2) The diameter of the void which is nucleated at the inclusion in the process zone, increased with the increase in J value and became saturated just before separation; that is, at the nucleation of the dimple. (3) The coalescence of voids seems to occur in two ways. (4) For ductile fracture, as in 2017-T 4 and 7075-T 6, the crack tip is always blunted both on the blunting line and the R -curve.

Key Words: Ductile Fracture, Fracture Mechanism, Process Zone, Fractography, Inclusion, Void, Nucleation, Growth, Coalescence(of Voids), Dimple

1. Introduction

By means of LEFM, the secret of a fracture is confined in the plastic zone, which is the black box in LEFM. In LEFM the plastic zone should be small compared with the K field, where LEFM is valid. Outside the small scale yielded zone and inside the K field, σ_{ij} , ε_{ij} can be expressed by K as shown in Fig. 1(a). By the development of EPFM, the secret is driven into the process zone or the damaged zone, and when the process zone is small compared with the plastic zone, outside the process zone and inside the HRR field, σ_{ij} , ε_{ij} can be expressed by J , the same as LEFM (Fig. 1(b)). So, now, the key for solving the secret of the fracture mechanism exists in the process zone. In this paper, we would like to report some experimental results which were obtained in our laboratory. By detailed observation inside the process zone, using fractography, the behaviour of the voids at

the crack tip of an Al-alloy specimen was clarified.

The experiments using Al-alloy, 2017-T 4 and 7075-T 6 are described. In 2, the behaviour of the voids at the tip of a crack are observed by using fractography, and the existence and the size of the process zone are studied. In 3, the fracture process, including nucleation, growth and the coalescence of voids are investigated. In 4, the mechanism of the crack propagation and the condition of the coalescence of a crack and voids are discussed.

2. Experiments

2.1 Materials

Two kinds of Al-alloy, 2017-T 4 and 7075-T 6 are used. Figure 2 shows the CT specimen. The direction of the specimen is in the L-T direction. After machining to the determined dimensions, the machining strains are excluded by the heat-treatment, as shown in Table 1. The mechanical characteristics and the chemical composition of the materials are shown in Table 2.

2.2 Experimental apparatus

The testing machine is a 490 kN computer controlled hydraulic loading machine of the MTS Co..

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Table 2

(a) Mechanical properties

Material	σ_{ys} (MPa)	σ_B (MPa)	σ_{fs} (MPa)	E (GPa)
2017-T4	322.4	463.5	384.2	71.8
7075-T6	375.3	463.5	419.4	71.8

(b) Chemical compositions (wt.%)

Material	Si	Fe	Cu	Ti	Mn	Cr	Zn	Mg
2017-T4	0.61	0.32	4.18	----	0.70	0.03	0.19	0.54
7075-T6	0.15	0.21	1.50	0.07	----	0.21	5.50	2.60

Fig. 3 Observation of void at crack tip

tact with other dimples.

(3) Their boundaries look like mountains capped with white snow, according to the photograph of the scanning electron microscope.

These voids will be called "precursory or preceding voids". They are observed in the central part of the fractured surface at the crack tip, whose width is $600\ \mu\text{m}$, and where the length along the propagating direction is $300\ \mu\text{m}$. The diameter and the distance from the tip of the crack are measured, as shown in Fig. 3, and the distribution of the diameters is examined, assuming the shape of the dimple to be a circle.

Fig. 4 Observation of dimple at D.Z.

2.4.2 Observation of the dimples on the ductile fracture surface

It is thought that the process of dimple fracture is recorded in dimples on the ductile fractured surface, from which information about the fracture mechanism can be obtained. Also, the diameters of the dimples show the diameters of the voids after the coalescence and, at the same time, represent the distance between the inclusions which nucleate the voids.

For all test pieces, in which the cracks propagate when $J > J_{IC}$, the diameters of the dimples and the distances from the preceding edge of the crack are observed, as shown in Fig. 4. Also, it is ascertained that these dimples belong to the dimple fractured surface; and the ratio of the dimpled surface to the whole area is evaluated.

2.4.3 Observation of the inclusions

The diameters of the inclusions in the precursory

voids, which are the diameter of the inclusions that nucleate the voids, are measured.

3. Experimental Results

3.1 J_{IC} test

Both the fatigue precrack and the markings are produced as $\Delta K = 35 \text{ kgf/mm}^{3/2}$ and the stress ratio $R = 0.1$. The displacement speed is 2 mm/min in the loading test. J_{IC} is obtained as the intersection of the blunting line and the limit line of SZW in the case of Al-alloys 2017 and 7075.

The fracture toughness J_{IC} and the critical stre-

ched zone width SZW_c are

(1) 2017-T4: $J_{IC} = 38.9 \text{ (kN/m)}$, $SZW_c = 29.5 \text{ (}\mu\text{m)}$

(2) 7075-T6: $J_{IC} = 11.5 \text{ (kN/m)}$, $SZW_c = 6.7 \text{ (}\mu\text{m)}$ respectively.

3.2 Results of observation

3.2.1 Inclusions

The mean values of the diameter of the inclusions, which is found in the precursory voids, are $5.6 \mu\text{m}$ for 2017 and $4.9 \mu\text{m}$ for 7075, respectively.

3.2.2 Dimples on the ductile fracture surface

Figures 5 and 6 are the electron microscopic photographs of the dimpled surface. In the case of

Fig. 5 Dimple fracture surface

Fig. 6 Dimple fracture surface

2017, a dimple grows like a circle from an inclusion. On the other hand, in the case of 7075, there are smaller dimples inside a dimple, which means that the fracture state is more complicated. These fracture states depend on the coalescence condition.

Figure 7 shows the distribution of the mean diameter and its unbiased variance to the distance from the pre-crack tip/DZW (Dimple Zone Width). As the distribution of the diameters of the dimple shows a normal distribution (Fig. 8), the mean values are the representative values, and the unbiased variance gives a 68.3% existence range. From Fig. 7, the diameters of the dimples are seen to be constant, independent of the distance from the pre-crack tip. These results show that the state at the crack tip during crack propagation seems to be always constant, which means that

the precursory voids always grow under the same conditions.

It follows that the mean value of the diameters of the total number of dimples give the value of the precursory voids after separation. This value is independent of both the J -value and the state of crack propagation, and so the diameters of voids after separation, $\bar{D}_0$, is the characteristics of the materials. These values $\bar{D}_0$, are $12.8\mu\text{m}$ in 2017 and $12.1\mu\text{m}$ in 7075 Al-alloy, respectively. The occupied area by these dimples are 61.6% in 2017 and 50.8% in 7075, and the fractured surface is composed mainly by these dimples.

Fig. 7 Behaviour of dimples

(a)

(b)

Fig. 8 Distribution of the diameters of the dimples

3.2.3 Precursory voids

Figure 9 is a photograph taken by the electron microscope showing the central part of the fractured surface near the stationary crack. As is shown, many precursory voids can be seen in the fatigue fractured surface. Figure 10 is a photograph taken by the electron microscope showing the precursory voids, and the void nucleates from the inclusion as its centre. Figures 11 and 12 show the distribution of the mean diameters to the distance from the pre-crack tip. As the distribution of the precursory voids at each position is normal, so the mean diameter is the representative value. As shown in the figure, the diameters decrease remarkably along the direction of crack

propagation in 2017, and a little in 7075.

Figures 13 and 14 show the number of nucleated precursory voids of 2017 in the case of $J < J_{IC}$ and $J > J_{IC}$, respectively. The number of the precursory voids in the process zone decreases along the crack propagation. When $J < J_{IC}$, the field of nucleation is narrow, and the field becomes wider with the increase of J ; but for $J > J_{IC}$, it becomes constant. The same is also observed in the case of 7075.

4. Discussion

4.1 Process zone

As shown in 3.2.3, the precursory voids in the process zone, their diameter and the number decrease

Fig. 9 Positions of measured dimples

Fig. 10 Precursory voids

Fig. 11 Value of measured voids

Fig. 12 Value of measured voids

Fig. 13 Distribution of growing voids

Fig. 14 Distribution of growing voids

Fig. 15 Damaged region

Fig. 16 Damaged region

along the propagation direction of the crack. So the product of the mean area of voids and the number of voids is adopted as a parameter, which shows the damaged zone. Assuming the process zone is the damaged zone, the 0 value of the ordinates (number $\times$ area) shows the boundary of the process zone.

From Fig. 15 to 18, in the case of $J < J_{IC}$, both the length and the area of the damaged zone increase according to the increase of J . In the case of $J > J_{IC}$, the damaged state is almost constant and coincides with the state of the blunted crack near J_{IC} . From these results, the lengths of the process zone are 100–130 μm in 2017 and 50–150 μm in 7075; but in the latter case it is hard to determine the length definitely.

4.2 Mechanism of the crack propagation

Consider the mechanism of the crack propagation inside the process zone. Figure 19 shows the relation between the diameter of the precursory voids and J , where at $J=0$ the diameter of inclusion is substituted as the diameter of the void. From the figures, when $J < J_{IC}$, the diameter of the void increases according to the increase of J ; and when $J > J_{IC}$, it becomes constant, independent of J , and shows the critical value

$\bar{D}_c$. Also, there are differences between $\bar{D}_c$ and $\bar{D}_o$, which is the dimple diameter after separation obtained in 3.2.2. This seems to show that the voids do not grow continuously until the formation of the dimpled surface; rather, just before fracture, it grows and coalesces and becomes $\bar{D}_o$, and the crack propagates. Figure 20 shows the behaviour of voids of 7075 in the process zone.

Now, pay attention to the difference of $\bar{D}_o$ and $\bar{D}_c$. (Table 3) There are differences of ΔD which may depend on the condition of coalescence, but it is necessary to make a detailed examination.

As mentioned above, in the case of crack propagation in a ductile fracture, (1) voids nucleate and grow at the tip of crack; and then (2) the crack and

Table 3 Difference of $\bar{D}_o$ and $\bar{D}_c$

Material	$\bar{D}_o (\mu\text{m})$	$\bar{D}_c (\mu\text{m})$	$\Delta D (\mu\text{m})$
2017-T4	12.8	11.6	1.2
7075-T6	12.1	9.6	2.5

Fig. 17 Damaged region

Fig. 18 Damaged region

Fig. 19 Void growth behaviour

Fig. 20 Void growth behaviour

voids coalesces. Also, as stated in 4.1, the damaged state near J_{IC} on the blunting line coincides with the damaged state when $J > J_{IC}$ on the R -curve. From this, in the case of stable propagation, the crack always accompanies the grown-up process zone at the crack tip, where the grown-up process zone means the process zone full of voids just before fracture.

5. Summary

On the fatigue-fractured surface of the blunting line after blunting, or on the R -curve after dimple fracture, many independent and not coalesced dimples are observed. As there is no nucleation of voids on the fatigue fractured surface, these are the precursory voids which are in the growing state. By the observation of these voids, the following results are obtained.

(1) By measuring the diameters of the voids on the dimple fractured surface, these values are almost constant, independent of both the distance from the crack tip and the J -value. From this, the diameter of the dimple is one of the material's characteristics and its value is $12.8\ \mu\text{m}$ in 2017, and $12.1\ \mu\text{m}$ in 7075 Al-alloy, respectively.

(2) The diameter of the precursory void can substitute for the dimple diameter observed on the fractured surface. By measuring the former, it is shown that they decrease remarkably in 2017, and a

little in 7075, along the direction of the crack propagation; and their nucleation decrease and at last become 0. By combining the area and the number of the nucleated voids, the distribution of the damage is investigated. Assuming that the damaged zone is the process zone, its dimension is $100\text{--}130\ \mu\text{m}$ in the case of 2017, and $50\text{--}150\ \mu\text{m}$ in 7075.

(3) The diameter of the precursory void in the process zone increases with the increase of J , and after $J > J_{IC}$, it becomes almost constant. The difference between this critical value $\overline{D}_c$ and the mean diameter of the dimple $\overline{D}_o$ suggests that the coalescence of void and crack occurs just before crack propagation.

(4) The differences between $\overline{D}_c$ and $\overline{D}_o$ are different in the case of 2017 and 7075, and this is due to the difference of the conditions of coalescence.

(5) The state of the crack tip of the dimple fracture is blunted, just like that of the blunted stationary crack.

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