STUDY ON THE RELATIONSHIP BETWEEN CORROSION DAMAGE AND RESIDUAL STRENGTH OF AL 7075-T6 ALLOY

GUO Yingnan, WU Ling, Sun Qin

School of Aeronautics, Northwestern Polytechnical University
Xi'an, Shaanxi, P.R.China, 710072

Keywords: *Corrosion Tensile behavior Gurson's model void volume fraction*

Abstract

It has been found in experiment that the local-scale pit corrosion of aluminum alloy 7075-T6 can lead to dramatic loss of its macroscopic tensile ductility. Based on the Gurson's void model, the present paper aims to investigate quantitatively the changing characteristics of the plastic property and ultimate strength for the aluminum alloy with skin-deep pit corrosion. The tensile behaviors of the corroded 7075-T6 specimens with the different degrees of pit corrosion and weight loss are estimated by micromechanical analysis in this paper, and also the yielding strengths of the specimens are evaluated by the Gurson's criterion. The predicted properties of the corroded specimens are in accordance with the experimental results very well.

1 Introduction

Residual strength assessment of aged aluminum aircraft structures requires a thorough consideration of the material's mechanical performance degradation due to corrosion. Corrosion induced structural degradation is presently taken into account by limiting the effects of corrosion to a decrease in the thickness of the structural member as well as an increase of the probability for the onset of fatigue cracks. But long-standing investigations performed by the many researchers, have provided sufficient evidence that corrosion of the aircraft aluminum alloys is not limited to the reduction of the material's thickness. It has been demonstrated that the corrosion of the alloy exposure to specific corrosive environments, including outdoor, is mainly in form of pits, and induces a moderate reduction in yield and ultimate tensile stress and a dramatic reduction in tensile ductility.

It is of vital importance to estimate the residual strength of damaged structures, because it is essential to seek rational standards for the structural integrity of aging structures. The aim of the present study is to assess the influence of pits on the plastic properties of aluminum plates under tensile loads in the framework of micromechanics.

Micromechanical approach has been introduced to describe the process of fracture in a way that is as close to the actual phenomena in a material as possible. Such an approach is based on the models that account for and quantify the process of microscopic damages, in order to predict macroscopic failure. In present study, we apply micromechanical model based on a particular yield criterion of a porous solid, proposed by Gurson[1] and later modified by Tvergaard and Needleman[2]. The most frequently used damage parameter is void volume fraction f, which is equal to the weight loss rate of corroded specimens. The evolution of void volume fraction during the process of ductile fracture is given in a modified form, and the parameters were determined on the tensile test result of non-corroded specimens.

2 Mechanical model

It is assumed that the shape of pit in the corroded aluminum alloy is one half of a prolate spheroid [3], and the pits distributed at random throughout the material. Subsequently, the corroded material with many pits can be regarded as damaged material with voids, and its properties approximate to the properties of porous material.

2.1 Yield criterion

Gurson [1] presented his damage model in 1977 based on weakening of the material due to damage caused by void nucleation and growth. Tvergaard and Needleman [2] later improved this model. The relationships defining the damage model are expressed in terms of the void volume fraction f, which is defined as the ratio of the volume of voids to the total volume of the material. For metals containing a dilute concentration of voids, the yield criterion is proposed as follow,

$$\Phi = (\frac{\Sigma_e}{\sigma_e})^2 + 2fq_1\cosh(\frac{3q_2\Sigma_m}{2\sigma_e}) - (1+q_3f^2) = 0 \tag{1}$$

where, σ_e is the yield stress of matrix material, Σ_e is the equivalent Von. Misses stress, and $\Sigma_m = \frac{1}{3}tr(\mathbf{\Sigma})$ is the hydrostatic pressure. Tvergaard and Needleman proposed the constants q_1, q_2 and $q_3 = (q_1)^2$ as coefficients in the equation. The original Gurson model can be seen by taking $q_1 = q_2 = q_3 = 1$.

It is supposed that the matrix material obeys the law of isotropic hardening, and the relationship between the matrix material's yield stress σ_e and its equivalent plastic strain ε_e^p is ruled by the initial hardening modulus h:

$$h = \frac{d\sigma_e}{d\varepsilon_e^p} = \frac{EE_t}{E-E_t} \tag{2}$$

where, E is the initial elastic modulus, and E_t is the initial tangent modulus on the hardening curve.

The plastic work rate for a porous material has to be equal to that of the ductile matrix only:

$$\Sigma_{ij}\dot{E}_{ij}^p = \sigma_e\dot{\varepsilon}_e^p(1-f) \tag{3}$$

where, E_{ij}^p represents the plastic strain of the porous material. Furthermore, it is easy to get the evolution law of the matrix material's yield stress σ_e from Equation 2 and 3.

$$\dot{\sigma}_e = \frac{h\Sigma_{ij}\dot{E}_{ij}^p}{(1-f)\sigma_e} \tag{4}$$

2.2 The evolution of void volume fraction

The void volume fraction f of damaged material will increase during the process of ductile fracture. Tvergaard and Needleman suggest that void coalescence occurs at f approximately equals to 0.15, and that fracture is likely to happen at $f \approx 0.25$. Tvergaard and Needleman propose that the evolution of the void volume fraction is to be caused by both growth of existing voids and nucleation of new voids:

$$\dot{f} = (\dot{f})_{growth} + (\dot{f})_{nucleation} \tag{5}$$

With

$$(\dot{f})_{growth} = (1-f)\dot{E}_{kk}^p \tag{6}$$

where $\dot{E}_{kk}^p$ is the trace of the plastic volume strain rate.

The plastic-strain controlled mechanism can be employed to model void nucleation at small particles (less than 1 μm in size), which can be assumed to be uniformly distributed in the matrix. Thus void nucleation in the current model was considered to depend exclusively on the equivalent plastic strain in the matrix,

$$(\dot{f})_{nucleation} = A\dot{E}_e^p \tag{7}$$

The void nucleation intensity A is a function of the equivalent plastic strain $\dot{E}_e^p$ in the matrix material, and was assumed to follow a normal distribution as suggested by Chu and Needleman [4],

$$A = \frac{f_n}{hS\sqrt{2\pi}}\exp[-\frac{1}{2}(\frac{\varepsilon_e^p - \varepsilon_N}{S})^2] \tag{8}$$

where, f_n ε_N and S are the volume fraction of void-nucleating particles, the mean strain for void nucleation and the corresponding standard deviation respectively.

According to the mechanical analysis of McClintock[5], Rice and Tracey[6], Yang described the relationship between the evolution of void volume fraction and plastic deformation as follow[7],

$$\dot{f} = A\dot{E}_e^p \exp\left(\frac{3\Sigma_m}{2\sigma_e}\right) \tag{9}$$

where, A is a constant associated with $f_F - \varepsilon_c^p$ relation, ε_c^p is failure logarithmic plastic strain of tensile specimen, and f_F is the void volume fraction at final separation of the material.

It is easy to see from the comparison between Equation 2 and Equation 6, that Equation 6 is simpler than Equation 2 and has less parameter to be determined. But it doesn't consider the effect of existing f on the evolution in Equation 6. In order to reflect the effect of existing f in evolution process, Equation 6 is modified:

$$\dot{f} = A(f)\dot{E}_e^p \exp\left(\frac{3\Sigma_m}{2\sigma_e}\right)$$

and $$A(f) = \alpha f^{\beta} + A_0 \tag{10}$$

where, the parameters α , β and A_0 are determined by the testing results of non-corroded specimens.

3 Experimental investigation

3.1 Specimen

Experiments have been carried out on dogbone specimens, Fig. 1. Specimen configurations are given in Fig. 1. The composition of the material can be found in Table 1.

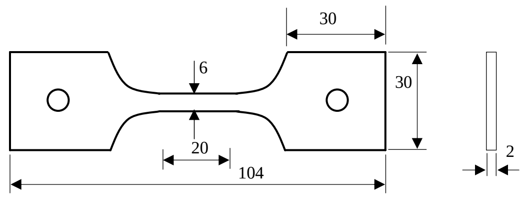
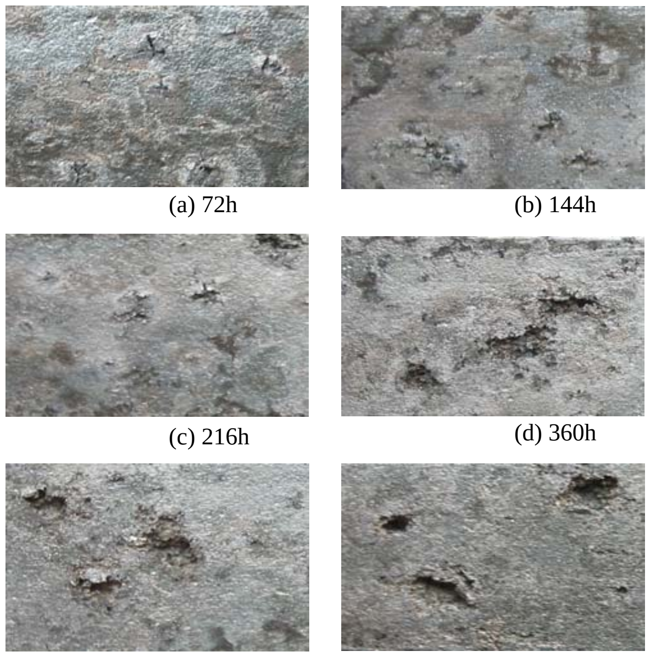


Fig.1 Test specimen configuration

3.2 Corrosion Experiment

To determine the relationship between corrosion damage and residual strength of Al 7075-T6 alloy, salt spray (fog) tests were conducted according to the ASTM G85-94 specification. The salt solution was prepared by dissolving 5 parts by mass of Sodium Chloride (NaCl) into 95 parts of distilled water. Acetic acid (0.1~0.3% CH_3COOH) was utilized to adjust the pH of the solution to 3.1~3.3. The temperature in the zone of the specimens exposed inside the salt spray chamber was maintained at 35±1℃. The spray volume was controlled in the range of 1.0~2.0mL/(80cm^2•h).



(a) 72h (b) 144h

(c) 216h (d) 360h

(e) 432h (f) 792h

Fig2. The typical surface figures of corroded specimens

Tab.1 Chemical composition (in wt%) of 7075 aluminum alloy

ALLOY	Cu	Mg	Mn	Si	Fe	Cr	Zn	Ti	others
7075-T6	1.2-2.0	2.1-2.9	max0.30	max0.40	max0.50	0.18-0.28	5.1-6.1	max0.20	Max0.05

The specimens were corroded by salt spray exposition for 72, 144, 216, 360, 432 and 792 hours respectively.

From the macro view, the corrosion of the alloy is not uniform, and results in roughness of specimen surface. As show in Fig.2, corrosion in 7075-T6 alloy is mainly in the form of pit.

3.3 Results

In order to determine the void volume fraction f, the loss mass was measured. The dependency of the obtained mass loss on the salt spray duration is displayed in Fig. 3.

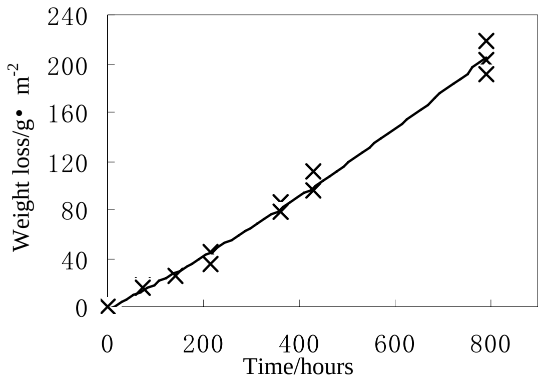


Fig.3 The weight loss varies with time

3.4 Mechanical testing

The pre-corroded specimens were subjected to tensile tests. The performed tests aim to find out the effect to the mechanical properties by the corrosion experiment. The tensile properties: yield stress Rp, ultimate stress Rm were evaluated. As shown in Fig.4, both of the yield stress and ultimate stress are all degraded during salt spray corrosion.

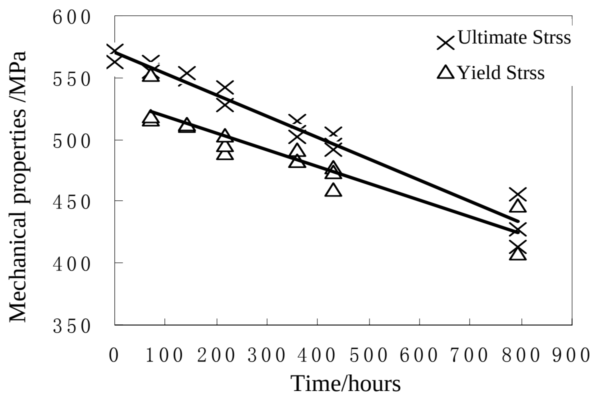


Fig.4 The decline of the samples' mechanical properties with corrosion time

4 Determination of the model parameters

In order to apply the proposed mechanical model to simulate the ductile fracture of corroded specimens, various model parameters must first be determined. The parameters can be determined by fitting to experimental results for tensile specimens. Aluminum 7075-T6 alloy was selected for this process, and some of the specimens had been exposed to acid salt spray environment [8] for varied period of time before tensile test. The process of determination is described below.

The first set of parameters is q_1 and q_2 in the yield criterion. The original Tvergaard q-values ($q_1 = 1.5$ and $q_2 = 1$) were recovered for the perfectly plastic case. In order to describe the yield surface of corroded material, in this study, q_1 and q_2 were determined by the numerical analysis of the residual yield strength of corroded specimens. The weight loss rates of corroded specimens served as the initial void volume fractions of the material, and were taken into Equation 1 together with the tested residual yield strength of corroded specimens. From the numerical analysis, we get

$$q_1 = 4, \quad q_2 = 1.0, \quad q_3 = q_1^2 = 16 \qquad (11)$$

The void volume fraction f_F at final separation of the material must be set secondly. From the tensile test results of corroded specimens, it is easy to find that the corroded specimens' tensile ductility decreased rapidly with the increase of their weight loss rates. When the weight loss rate of specimen reaches 0.047, the specimen will lead a brittle fracture and there was no ductility to be found. It is assumed that the corroded specimen's void volume fraction equals its weight loss rate, and the void volume fraction of material only evolves with plastic strain, that means the material attains a plastic limit-load if f reaches the limit 0.047. So in this study, $f_F = 0.047$ was used as the void-volume fraction at final failure.

Void evolution parameters (α, β and A_0) are the last parameters required. Based on experimental results of non-corroded tensile specimen, the parameters are determined by regression analysis.

$$\alpha = 51.28\,,\quad \beta = 1.85\,,\quad A_0 = 0.11 \qquad (12)$$

5 Numerical results and model predictions

The numerical simulations require an initial void volume fraction as input for the proposed model. Fig.5 presents a series of numerical predictions with different initial void volume fractions. This shows that different initial void volume fractions result in very different predictions for the load-displacement behavior. It is apparent from Fig.5 the ductility of the material is strongly dependent on the initial void volume fraction, which accords well with the micromechanical theory and test results.

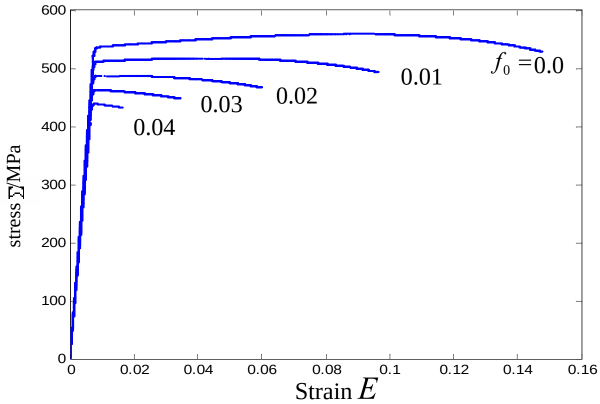
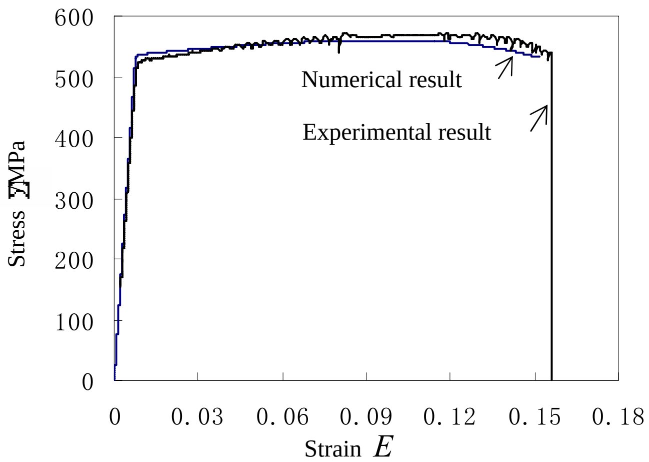
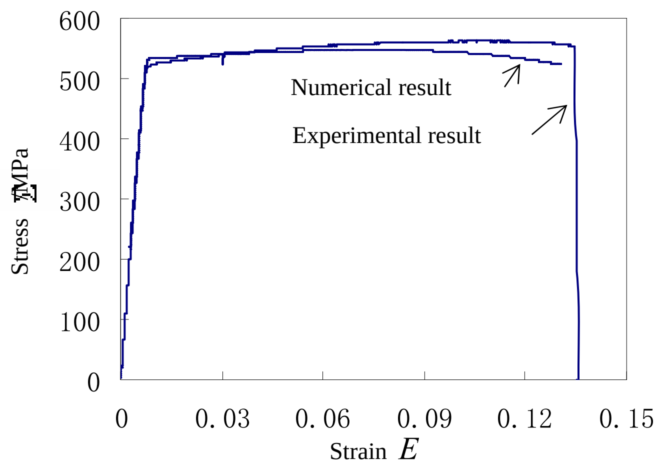


Fig.5 The numerical simulation of stress-strain curves for 7075-T6 aluminum alloy with different initial void volume fraction

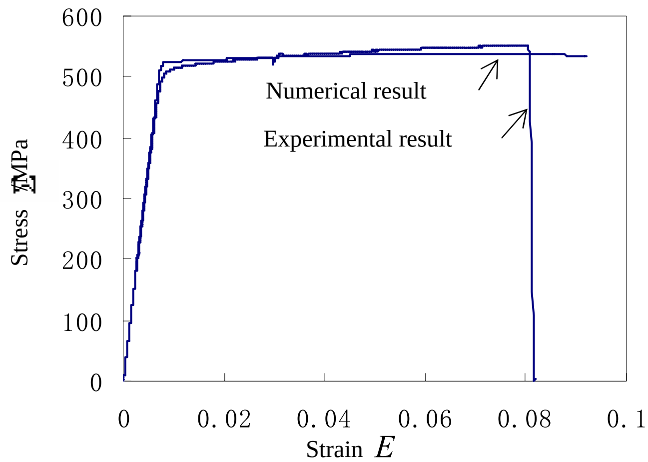
As discussed early, namely the weight loss rate, can be identified as initial void volume fraction of the corroded specimen. The residual properties of the corroded aluminum 7075-T6 alloy specimens have been predicted with the current model. The comparisons between the numerical simulations and tensile results are showing in Fig. 6. And (a) ~ (g) in Fig. 6 are stress-strain curves of the corroded specimens with different corrosion time. The model gave a good fit to the experimental data, and the numerical simulation also predicted an accurate maximum load and maximum plastic strain.



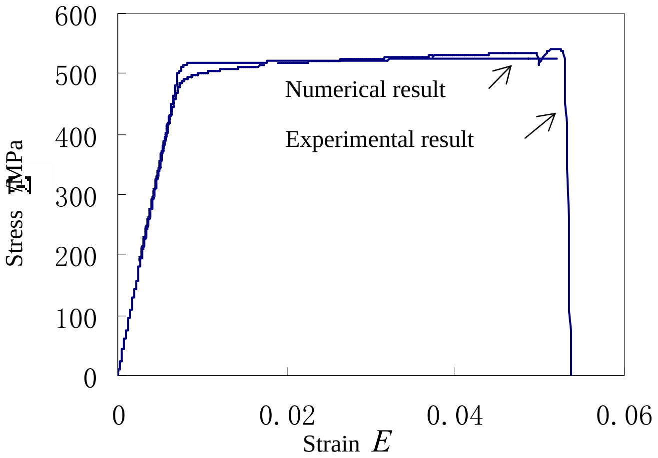
(a) Corrosion time t=0 hours



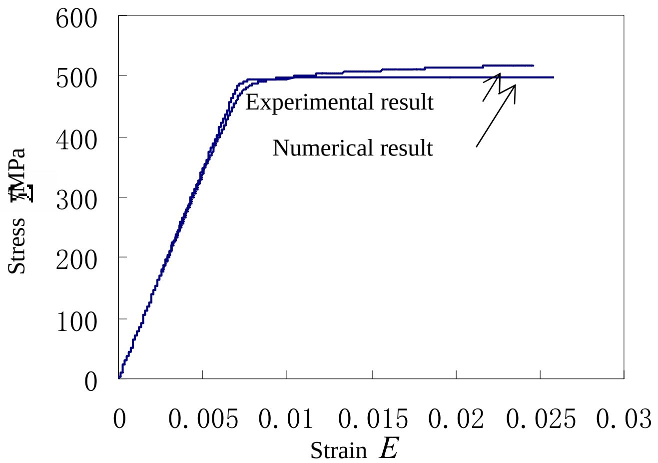
(b) Corrosion time t=72 hours



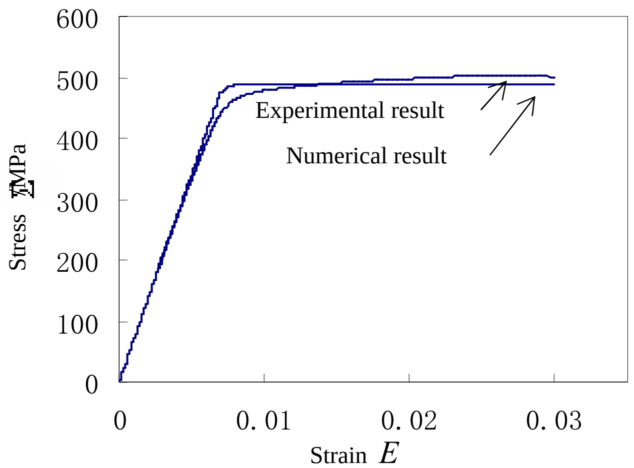
(c) Corrosion time t=144 hours



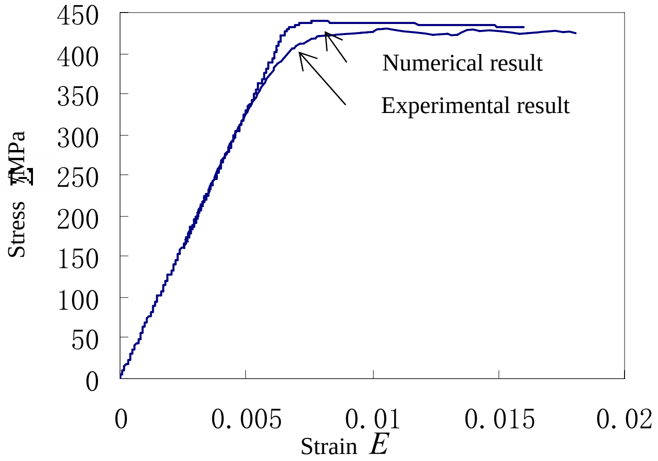
(d) Corrosion time t=216 hours



(e) Corrosion time t=360 hours



(f) Corrosion time t=432 hours



(g) Corrosion time t=792 hours

Fig.6 Comparison between the numerical results and experimental results of the macroscopic stress–strain curves for corroded aluminum 7075-T6 alloy specimens, (a) ~ (g) represent the results of the corroded specimens with different corrosion times respectively.

6 Conclusions

This study has demonstrated a micromechanical model to predict the plastic properties of high strength aluminum alloy with corrosion pits. The concept of voids in micromechanics is employed in this study, to describe the pits on corroded specimens. So the pit corroded material can be regarded as the material with voids, and the initial voids volume fraction of the damage material takes the value of weight loss rate of the corroded material. Then, the residual properties of the corroded material can be calculated in the framework of the micromechanics. The proposed model was able to account for both maximum load and ductility of corroded material. As an application, the proposed method is used to predict the residual properties of aluminum 7075-T6 alloy, which has been pre-corroded in the salt spray environment for different periods of time. The model predictions were in good agreement with experimental data irrespective of pit geometry and size. As a result, its potential as a tool for analyzing load-carrying capacity of corroded structures is evident.

References

[1] Gurson A. L., Continuum Theory of Ductile Rupture by Void Nucleation and Growth: Part I: Yield Criteria and Flow Rules for Porous Ductile Media, Transaction of ASME, 1977(2):2~15.

[2] Tvergaard V., Influence of Voids on Shear Band Instabilities under Plane Strain Conditions, Int. J. Fracture, 1981, Vol.17:389~407.

[3] Harlow G. & Wei R. P., A Probability Model for the Growth of Corrosion Pits in Aluminum Alloys Inducted by Constituent Particles, Engineering Fracture Mechanics 1998, Vol.59(3):305~325.

[4] Chu C. C., Needleman A., Void Nucleation Effects in Biaxially Stretched Sheets, J. Eng. Nater. Tech, 1980, Vol.102:249~256.

[5] McClintock F. A., A Criterion for Ductile Fracture by the Growth of Holes, J. Appl. Mech., 1968, Vol.35:363~371.

[6] Rice J.R., Tracey D. M., On the Ductile Enlargement of Voids in Triaxial Stress Fields, J. Mech Phys. Solids, 1969(17):201.

[7] Yang Wei, Macro and micro fracture mechanics, National defense industry press, September, 1995. (in Chinese)

[8] ASTM G85-94, Standard Practice for Modified Salt Spray(Fog), Testing[S],1994.

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