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Stress corrosion cracking model in 7075 aluminium alloy

J. OÑORO, A. MORENO, C. RANNINGER
Departamento Ingeniería y Ciencia de Materiales, ETS Ingenieros Industriales. UPM
C/Jose Gutierrez Abascal, 2. 28006 Madrid, Spain

The stress corrosion cracking is a typical fracture process in metals and alloys. Among aluminium alloys, the 7075 alloy, presents a high performance in the mechanical properties but it is susceptible to stress corrosion cracking. This paper presents a semiempiric model of crack growth by stress corrosion cracking for the above alloy. This model only uses macroscopic parameters from fracture mechanic theory and experimental tests which are easy to obtain. The model quantifies the fissure rate related to environmental condition, microstructure and loading level, permitting the evaluation of the crack growth process at different environmental conditions and heat treatments. The model results are compared with the experimental data obtained. The theoretical model reproduces adequately the stress corrosion cracking process for the 7075 alloy.

1. Introduction

The stress corrosion cracking process is a typical failure mode affecting high resistance aluminium alloys of the Al–Zn–Mg–Cu group for built-in mechanical components. Within this wide group, alloy 7075 is the most frequently used for manufacturing light structural components mainly in the aircraft industry.

In spite of its good general behaviour, certain cracking processes identified with stress corrosion have, however, been reported even at low activity environments such as atmospheric dampness [1, 2]. A hack initiation has been reported to take place in the alloy surface at points identified with protective discontinuities where small fissures are generated.

The stress corrosion cracking mechanism results are complicated and difficult to describe when related to aluminium alloys due to the large number of parameters involved.

Once a crack has been initiated at a surface imperfection, its propagation mechanism depends on a series of facts associated with the microstructure, (heat treatment, impurity level, manufacturing process background), stress level and environment. The microstructural condition has been up to now the most widely investigated parameter in developing stress corrosion resistent microstructures while maintaining good mechanical properties [3–6]. In spite of great effort being made in this direction, corrosion cracking processes are still reported as a typical failure mechanism affecting these alloys.

For certain technological application fields, the presence of components with a fixed defect level is actually being accepted, providing that the progression of such defects, after being analysed, can be controlled. In order to carry out such analysis it is essential to have available an experimentally verified description of the defect progression process.

The aim of this work is to present a semiempiric model which describes the stress corrosion process for these alloys. The model quantifies the crack growth rate related to various parameters such as environmental condition, microstructure and loading level. Stress corrosion problem analysis with this model permits the evaluation of the crack growth alloy 7075 at several environmental conditions and heat treatments.

2. Model description

Due to the stress corrosion process complexity, actual models assume the existence of a principal mechanism controlling the crack growth [7]. Generally, the stress level at the defect zone and the process developing environment are empirically related.

The model herein presented, follows the general trends of previous models, but two new approximations are incorporated. Firstly, the complete growing process from the defect initiation to the element failure, is described. Secondly, various macroscopical factors granting generality to the model, are introduced.

The formulation has been developed considering the existence of two different mechanisms, i.e. zone I which fundamentally depends upon the stress level and zone II where propagation is controlled through a physicochemical mechanism involving the material solution and the aggressive medium diffusion through the crack. These two zones are identified with both crack growth processes shown in the stress corrosion cracking growth rate plotted against stress intensity factor curves presented in Fig. 1.

The proposed model in the propagation zone I stress level dependent is

$$V_{\mathrm{I}} = A \exp\left[B(T_0/T)(K_{\mathrm{I}}/K_{\mathrm{IC}})\right]$$

where V_{I} is the zone I propagation velocity, K_{I} the stress intensity factor, K_{IC} the material fracture

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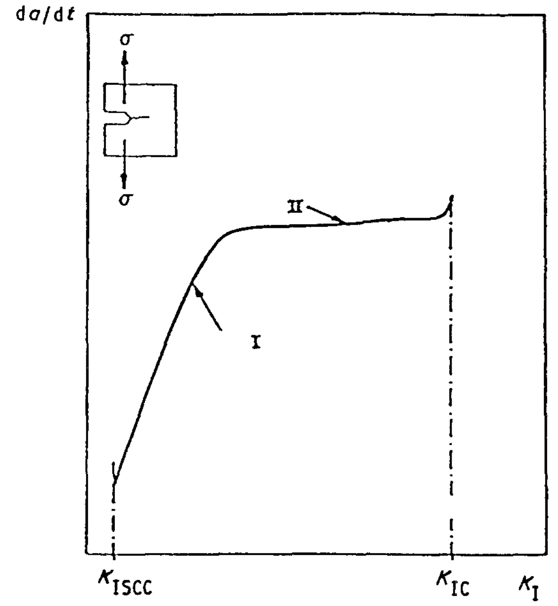

Figure 1 Stress corrosion cracking zones I and II.

TABLE I 7075 alloy compositions in wt %

Al	Zn	Mg	Cu	Cr	Si	Fe	Mn	Ti
90.17	5.5	2.3	1.6	0.21	0.06	0.11	0.03	0.02

toughness, T the absolute temperature and $T_0 = 273\,K$. The values A and B correspond to two macroscopic parameters related to the medium and material represented as follows

$$A = A_1(kT/h)m(1 + H)^2$$

where k is the Boltzmann constant, T the absolute temperature, h Plank's constant, m the environmental relative humidity per cent, H the median Halogen's per cent and A_1 a constant

$$B = B_1(1 + B_2\phi + B_3\phi^2)$$

where ϕ is the hydrogen embrittlement parameter resulting from dividing the toughness of one non-embrittled sample by one embrittled, B_1, B_2 and B_3 are constants.

Formulation for zone II where cracking velocity is independent of stress variations

$$V_{II} = Af(T/T_0)\exp(CQ/RT)$$

where V_{II} is propagation velocity in zone II. The parameters A, T and T_0 have the same significance in the expression for V_I, whereas Q is the activation energy for the cracking process in stress corrosion conditions, R the universal constant and C a constant related to the embrittlement factor whose value is

$$C = C_1(1 + C_2\phi + C_3\phi^2)$$

C_1, C_2 and C_3 are constants and $f(T/T_0)$ is a quadratic function of value

$$f(T/T_0) = D_1 + D_2T/T_0 + D_3(T/T_0)^2$$

where D_1, D_2 and D_3 are constants.

With this double formulation, the approximation of the stress corrosion phenomenon has been achieved for the two zones.

Both formulations can be unified when assuming that the processes are substitutive, i.e. while one process is becoming less significant the other one increases in significance. Thus, the crack growth velocity for the combined process can be expressed as

$$1/V = 1/V_I + 1/V_{II}$$

Thus

$$V = V_IV_{II}/(V_I + V_{II})$$

which becomes the complete formulation once V_I and V_{II} values are substituted so that

$$V = \frac{A\exp(B(T_0/T)K_I/K_{IC})f(T/T_0)\exp(CQ/RT)}{\exp(B(T_0/T)K_I/K_{IC}) + f(T/T_0)\exp(CQ/RT)}$$

This expression states the cracking velocity in stress corrosion conditions involving parameters such as applied stress level (K_I), material characteristics (K_{IC}, Q, ϕ) and medium aggressivity (m, H, T), all other values remaining constant. The modelling involved parameters show a clear significance with the exception perhaps of the embrittlement factor ϕ.

This factor correlates the hydrogen embrittlement susceptibility of a determined microstructure and includes the effect produced by the presence and distribution of impurities, heterogeneities, dislocations, hardened phases and grain size. These microstructural properties also affect the K_{IC} and Q parameters, hence with all three macroscopic variables the complete definition of the the material state can be achieved.

3. Experimental technique

Tests to prove the validity of the model have been carried out with alloy 7075 samples as shown in Table I. With the aim of analysing the stress corrosion process susceptibility for various structures, specimens were heat treated as shown in Table II. In all cases specimens were machined from 25 mm plate to double cantilever beam (DCB) shape with constant displacement as shown in Fig. 2, since with this type of specimen the complete development of Curves V-K_I can be attained, from the initial load state until the crack growth stops.

With the aim of verifying the model validity, tests have been performed under four different conditions:

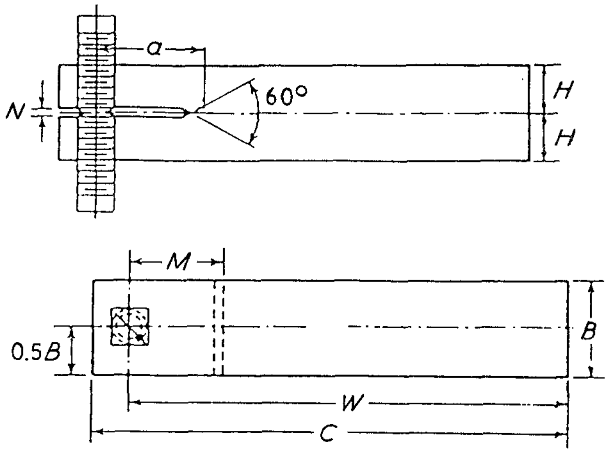

Figure 2 Double cantilever beam (DCB) specimen.

TABLE II Heat treatments applied

T6 = 1 h at 495°C, quenching in water + ageing 24 h at 120°C.

T6RR = T6 + 10 min at 200°C, quenching in water + re-ageing 24 h at 120°C.

T73 = 1 h at 495°C, quenching in water + ageing 1 h at 107°C and 18 h at 168°C.

T7351 = T73 + 2% cold working.

modifying temperature, aggressive medium concentration, and medium states (liquid or moisture).

The four conditions are as follows.

3.5% NaCl acuous solution 20°C
3.5% NaCl acuous solution 80°C
Mist chamber 0% NaCl 30°C
Mist chamber 5% NaCl 30°C

In order to consider the microstructural influence four different heat treatments have been studied, three specimens were tested per heat treatment for each medium to prevent possible result dispersion.

The cracking process was quantified by measuring the length of the crack at both sides of the specimen using a binocular magnifying glass × 20. Assurance that no surface enmasking was produced on the crack growth was evidenced by X-ray. Measurements were carried out every 24 h.

The DCB specimen geometry (shape) enables direct representation in V-K_I diagrams (growth velocity plotted against stress intensity factor). Subsequently, the model was adjusted to the mentioned experimental results. The adjustment consisted in determining the model constant values which permitted a more adequate experimental result representation.

Activation energy values (Q) were obtained by means of plotting Arrhenius curves for each heat treatment analysed here, being the activation energy of the slope of each curve.

4. Result analysis

Some of the results attained adjusted to the proposed model are shown in Figs 3 to 6 (model estimation values are represented by a full line whereas dashed lines indicate experimental results). In these figures, media and different heat treatments have been represented in order to enhance agreement model estimated value – result value in all studied situations.

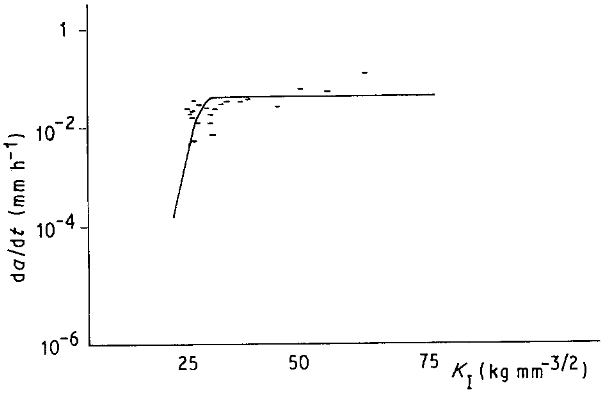

Figure 4 7075 T6RR immerse 3.5% NaCl 293 K.

Figs 3 to 6 show evidence that model values represent accordingly the experimental results. Therefore the proposed model enables the evaluation of the stress corrosion cracking process for alloy 7075, at real conditions providing these conditions are related to the environment and heat treatment conditions employed during testing.

The K_I level associated with real problems can be calculated with a finite element program. The K_IC, Q and ϕ parameters can be obtained from Table III. Although it must be borne in mind that these parameters can present certain dispersion due to heat treatments and to the alloy manufacturing background.

5. Conclusions

1. The theoretical model has proved to reproduce adequately the stress corrosion cracking process for alloy 7075 in all the stages from cracking initiation until the element failure.
2. The performed tests indicate adequate agreement between model and experimental results produced within a wide spectrum of corrosive media and material features.
3. The proposed model only used macroscopic parameters which are easy to obtain.
4. By using macroscopic parameters only, the model can be generalized to other alloys.
5. The global model permits the approximation of the stress corrosion phenomenon in propagation zones I and II.

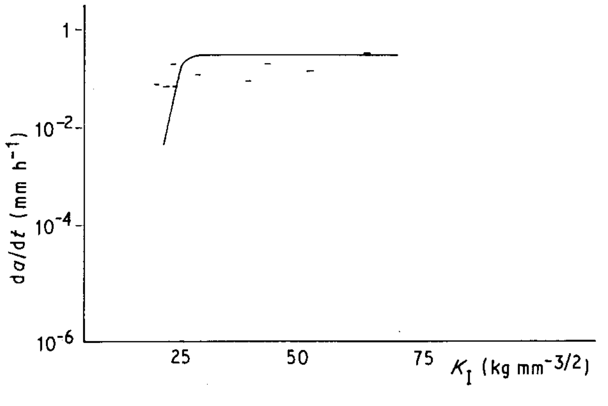

Figure 3 7075 T6. mist 5% NaCl 303 K.

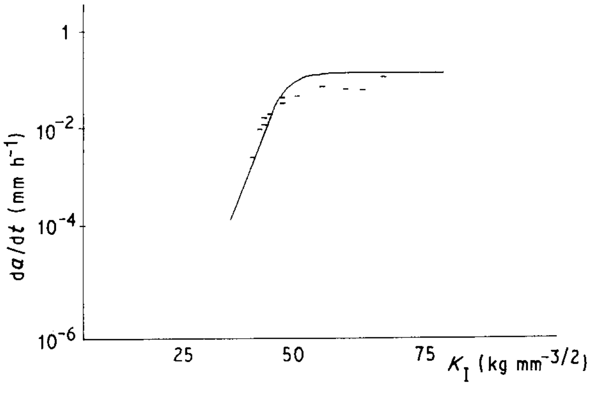

Figure 5 7075 T73 immerse 3.5% NaCl 353 K.

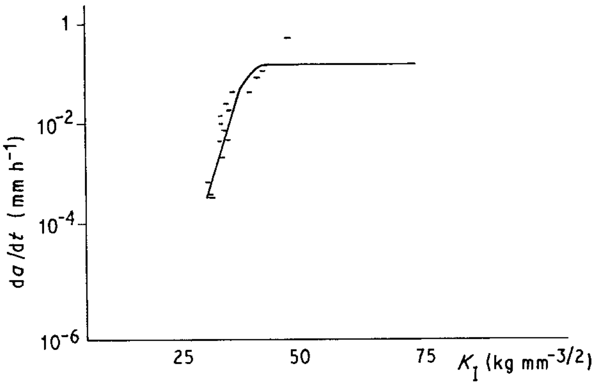

Figure 6 7075 T7531 immerse 3.5% NaCl 353 K.

6. The developed model application in resolving cracked real structures is immediate; it is sufficient to know the environmental conditions, stresses at the bottom of the crack, and the heat treatment in order to evaluate the cracking propagation rate directly. It is also possible to evaluate the component residual life before failure conditions are reached.

TABLE III Parameters value used in the model

Temper	K_{IC} (kg $mm^{3/2}$)	Q (k cal mol^{-1})	ϕ
T6	66	12.7	1.16
T6RR	73	12.2	1.12
T73	77	9.9	1.04
T7351	70	8.9	1.08

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