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SOME OBSERVATIONS ON THE FRACTURE CHARACTERISTICS AND FATIGUE CRACK GROWTH RATES IN A HIGH STRENGTH ALUMINUM ALLOY

بعض الملاحظات على خصائص الكسر وشروخ الكلال
لسبيكة ألومنيوم عالية المقاومة

BY

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خلاصة :

نظرا لأهمية تقدير التكامل الانشائي والتوقع العمري للأجزاء الهندسية فقد نشأ اهتمام متزايد في الاونه الأخيره بتوصيف عملية التشرخ الكلالي ومقاومة الكسر لمختلف المواد الانشائية . والدراسة الحالية موجهة لتعيين كيفية اعتماد خصائص الكسر ونمو الشروخ على المعالجة الحرارية السابق اجراؤها على المادة .

وقد وقع الاختيارعلى سبيكة الألومنيوم عالية المقاومة ٧٠٧٥ لتكون مادة البحث وذلك بعد اجراء المعالجه الحراريه T 6 – المكونة من عمليات المعالجة الذوبانية المتبوعة بعمليتي الاطفاء ثم التشيخ الصناعي – والتي ينتج عنها خصائص جيدة لقوه التحمل والمطولية . وقد تم الاحتفاظ بدرجة حرارة التشيخ ثابته بينما تم تغيير زمن التشيخ بين ساعتين وعشر ساعات، كما استعملت عينات رقيقة ذات الحدش العفرد لتجارب شروخ الكلال وعينات ذات الخدشين الجانبيين لتجارب متانة الكسر .

وتشير نتائج البحث الى أن تغيير زمن التشيخ في المدى المذكور ينتج عنه تغير محسوس في متانة الكسر ومعدل نموالشروح،حيث تؤدى الزيادة في زمن التشيخ الى زيادة معدل نمو الشروخ وخفض متانة الكسر. ويعزى ذلك الى التغيرات الحادثة في المادة نتيجة عملية التشيخ والترسيب مما يؤثرعلى قوة الدفع المحللة عند رأس الشرخ ، وهذه القوة معروفة بتأثرها بعدة عوامل منها اغلاق الشرخ ولدونة المادة وانحراف الشرخ عن مساره المعتاد .

ABSTRACT- Because of the importance of assessing the structural integrity and life expectancy of engineering components, there has been considerable effort in the last thirty years in the characterization of fatigue cracking and fracture resistance for different structural materials. The present study is directed to the determination of the type of dependence of the fracture resistance and the fatigue crack initiation and propagation behavior on previous heat treatment performed on the material.

High strength aluminum alloy, type 7075, has been selected as the test material. A sussessful T6 treatment, consisting of solution treatment followed by quenching and an aging period, results generally in good strength and toughness properties. Aging temperature was kept constant while aging time was varied from two to ten hours. Single-edge notched specimens have been used for fatigue crack propagation test: while double-edge notched specimens have been used for fracture toughness tests.

Test results indicate that variation in the aging time for the alloy results in an appreciable variation in its fracture toughness and the rate of crack growth. Longer aging periods lead to higher crack growth rates and lower fracture toughness. The test results may be explained as being due to variations in the local driving force acting at the crack tip. This force is known to be influenced by several factors such as crack closure, cyclic plasticity, and crack deviation from its regular growth direction.

KEYWORDS
Fatigue crack growth, fracture mechanics, fracture toughness, alumimum alloy, precipitation hardening, crack growth gauge.

NOMENCLATURE

A	a constant in the crack growth equation
a	crack length
a_o	original notch length
b	specimen width
E	modulus of elasticity of material
F	maximum applied load during fracture toughness test
$f(a/b)$	a function which accounts for eraek shape and dimension
J_c	energy release rate at the onset of fracture
K_e	plane stress fracture toughness
ΔK	range of the stress intensity faetor
ℓ_o	particle spacing
m	a constant in the crack growth equation
N	number of loading cycles
t	thickness of test specimen
t_a	aging time
G_c	critical strain energy release rate
ε_f	normal strain at fracture
ε_o	initial normal strain
σ_o	yleld strength of the material
$\Delta\sigma$	stress range
δ_c	critical crack opening displacement
r_{pc}	critical plastic zone size

INTRODUCTION

The last few decades have witnessed tremendous developments in the science of fraeture meehanics whieh is primarily concerned with the behaviour of components containing flaws and microcracks. It has provided the designers with invaluable information regarding the effeets of mechanical, environmental and micro-structural factors on the fracture characteristics of these components. Such information are used towards the attainment of fracture-safe designs and the assessment of the structural integrity of mechanical components. The fracture mechanics approaeh is now in a widespread use particularly for safety-critical structures such as in nuclear and aerospace industries.

While the termination of life of a component may be based on some eritical flaw size for large scale fracture, as ealeulated from the material's fracture toughness, it has long been recognized that the total useful life of a cyclically loaded component is dependent upon the rate of growth of flaws from a subcritical size to a critical size. Therefore, an understanding of the fatigue crack growth characteristics of structural materials under appropriate serviee conditions is also essential for the evaluation of the structure's useful life.

The characteristics of fatigue crack growth is generally dependent on the state of the stress and strain field near the crack tip which is represented by the range of stress intensity factor, ΔK . Such a dependence is generally describable by a sigmoidal curve in a log(da/dN)versus log ΔK coordinate scale, bounded at the extremes by the threshold stress intensity range, ΔK_{th}, and the critical stress intensity range, ΔK_c, as shown in Fig.1. In the intermediate ΔK range, log (da/dN) is almost linearly related to log ΔK, as expressed by the semi-empirical relation proposed by Paris and Erdogan [1]

$$da / dN = A (\Delta K)^m \qquad \ldots (1)$$

Where A and m are termed material constants indicative of the fatigue crack growth in the intermediate range. These constants are generally determined from the best fit to the experimental data as the intereept and the slope of the stralght

line portion of the sigmoidal curve. It must be pointed out that one of the principal limitations of Paris equation, Eq.(1), is that a state of small scale yielding is considered to exist at the crack tip. If extensive local plasticity exists at the crack tip, other alternative analyses have been developed to define the state of the stress and strain at the crack tip. The alternative analyses are based on the J-integral and the crack tip opening displacement concepts [2,3]. In all cases, the initiation of cracking and fracture are characterized by the criterion that the quantities K, J, and δ reach some critical values.

The correlation of the fatigue crack propagation with the stress intensity factor range, as explained above, has been well documented for both mild steels and high strength aluminum alloys [4,5]. The majority of the work done in this direction dealt primarily with variations in the type of materials, applied loads, test specimen, and crack geometry. Studies pertaining to the influence of microstructural parameters on the crack initiation and growth have not been extensive. It was with these points in mind that the present study was initiated. The purpose of the study is the determination of the influence of the precipitation heat treatment performed on the aluminum alloy on the fracture toughness and crack initiation and growth behavior of the alloy.

EXPERIMENTAL PROCEDURE

MATERIAL:

High strength Cu-Mg-Zn-aluminum alloy, type 7075, having a chemical composition as shown in Table 1, has been selected as the test material. This type of material is of the precipitation-hardening type and possesses good strength and ductility properties upon successful T6 treatment and is widely used in aerospace applications. Thin specimens having a nominal thickness of 1.270 mm were first solution treated for one hour at 482°C in a salt bath, quenched in iced water, and then artificially aged at a temperature of 177°C for aging times ranging from two to ten hours. All temperatures were maintained reasonably within the specified limits. The nominal mechanical properties of the alloy are shown in Table 2.

Table 1 Chemical Composition of Aluminum Alloy 7075

Cu	Mg	Zn	Cr	Al
1.5 %	2.5 %	5.5 %	0.3 %	90.2 %

Table 2 Mechanical Properties of Aluminum Alloy 7075

0.2% Yield Strength MPa	Ultimate Tensile Strength MPa	% Elongation in 50 mm G. Length
500	750	11

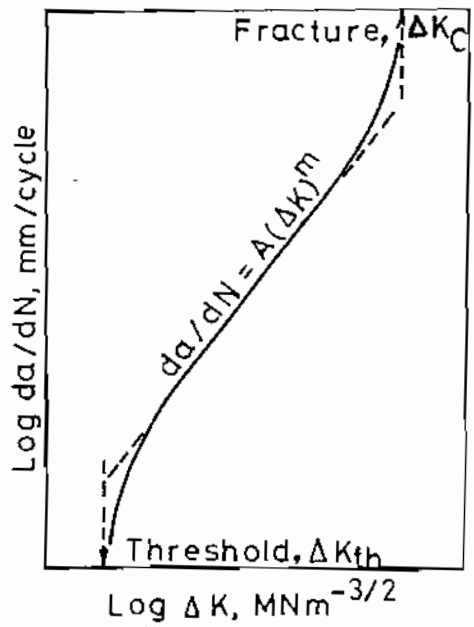

Fig.1 Fatigue Crack Growth Curve

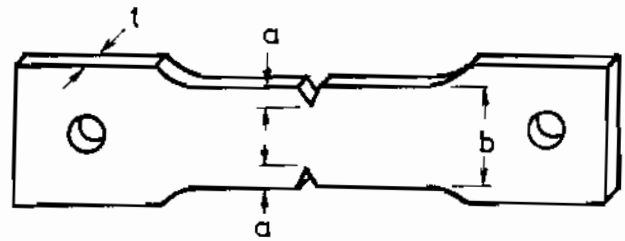

Fig.2 Plane stress fracture toughness specimen

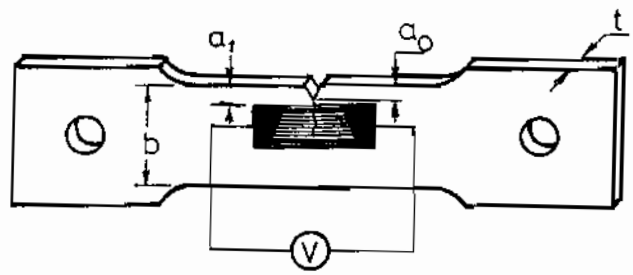

Fig.3. Fatigue Crack Growth Specimen

SPECIMENS:

Plane stress fracture toughness for the alloy were determined using double-edge notched specimens, as shown in Fig.2. On the other hand, single-edge notched specimens, shown in Fig.3, have been used for fatigue crack growth experiments. All tests have been conducted at ambient temperature. Notches have been cut on the milling machine and the notch depths were accurately measured using a travelling microscope. Table 3 shows the dimensions of the specimens tested for fracture toughness and fatigue crack growth. Three specimens have been tested for each aging time in order to obtain meaningful average values for the test parameters.

Table 3 Dimensions of Specimens

Specimen	Ageing Time, hours	a_o, mm	a_f, mm	b, mm	t, mm
1	2	4.445	4.700	25.4	1.143
2	2	4.826	5.080	25.4	1.143
3	2	4.616	4.720	25.4	1.143
4	5	4.554	4.610	25.4	1.143
5	5	4.750	4.941	25.4	1.143
6	5	4.855	5.055	25.4	1.143
7	10	4.572	4.572	25.4	1.143
8	10	4.700	4.800	25.4	1.143
9	10	4.652	4.775	25.4	1.143

(I) Fracture Toughness Tests

Double-edge notched fracture toughness specimens were pulled to a complete separation on a tensile testing machine at a load range of 26.8 kN and a head speed of 6.35 mm/min. The fracture toughness were calculated from the maximum tensile load at which each specimen had failed.

(II) Fatigue Crack Propagation Tests

Fatigue crack growth testing was conducted on the JJ-Lloyd tensile machine Model T22K with cycler. The machine was preset at a mean load of 2 KN and a load range of 11/2 KN. Crack length was determined periodically as a function of the number of loading cycles using fatigue crack propagation gauges mounted on each specimen, as shown in Fig.3. Each guage consisted of a number of five strands which break one after the other as the crack advances through the width of the specimen. This gives rise to a sudden change in the reading of the voltage passing through the electronic guage. The distance travelled by the crack was accurately measured using this method since each guage had a known width which contained twenty equidistant fine strands. The jump in the voltage was also detected on an X-Y recorder. The experiment was stopped immediately after the breakage of the last strand in the guage.

TEST RESULTS

The plane stress fracture toughness were calculated from the fracture load using the formula [6]

$$K_C = (F\sqrt{a}/tb)\,[1.98+0.36(2a/b)-2.12(2a/b)^2+3.42(2a/b)^3] \quad \ldots (2)$$

It must be noted that Equation (2) assumes that the material behaves in a linear manner up to fracture and, therefore, it does not take into account the effect of plasticity. In order to account for plasticity effects, the toughness should be calculated using a modified crack length which includes a plastic zone size, r_p, calculated from the formula [7]:

$$r_p = (1/2\pi)\,(K_c/\sigma_o)^2 \qquad \ldots (3)$$

Other fracture characteristics sueh as the critical energy release rate, G_c, the critical crack opening displacement, δ_c, and the critical plastic zone size, r_p, have been also calculated and tabulated in Table 4 using the formulas:

$$G_c = \frac{K_c^2}{E} \qquad \ldots (4)$$

$$\delta_c = \frac{G_c}{\sigma_o} \qquad \ldots (5)$$

Table 4. Fracture Characteristics Results

Aging Time hrs	Fracture Toughness Kc, MPa $\sqrt{m}$	Critical Energy Release Rate Gc, MPa. mm	Critieal Crack opening Dis-placement δc, mm	Critical Plastic Zone size, r p, mm
1/2	42.45	25.4	0.0508	7.208
2	48.25	32.8	0.0656	9.312
5	37.50	19.8	0.0396	5.625
10	25.10	8.9	0.0178	2.520

Fig.4 illustrates the variation of the fracture characteristics with aging time, while Fig.5 is a log-log plot of the same quantities.

As described above, the process of crack propagation under small seale yielding condition can be correlated with the nominal stress Intensity range, ΔK, with the variation between da/dN and ΔK being sigmoidal in shape over a wide range of growth rates, as shown in Fig.1. The simple power law relationship, Eq. (1), provides a reasonable description of behavior in the intermediate range of growth rates between 10^{-6} and 10^{-3} mm/cycle. Oeviations from such behavior take place at lower ΔK levels approaching the threshold values and at higher growth rates approaching instability and fracture. Since the majority of fatigue lifetime must be spent where the crack is growing most slowly, it generally is the near-threshold and intermediate regions which dominate life of the component.

Plots of the fatigue crack length versus number of cycles for all specimens are shown in Figures 6,7, and 8. These plots were used to determine the rate of crack growth (CGR), da/dN. The excursion in the stress intensity factor, ΔK, which cooresponds with crack lengths, a, were caleulated using the equation [6].

$$\Delta K = (\Delta\sigma)\sqrt{\pi a}\ f\,(a/b) \qquad \ldots (6)$$

where $\Delta\sigma$ is the excursion in the stress,
f (a/b) is a function given, for SEN speclmens, as follows [6], Table 5 :

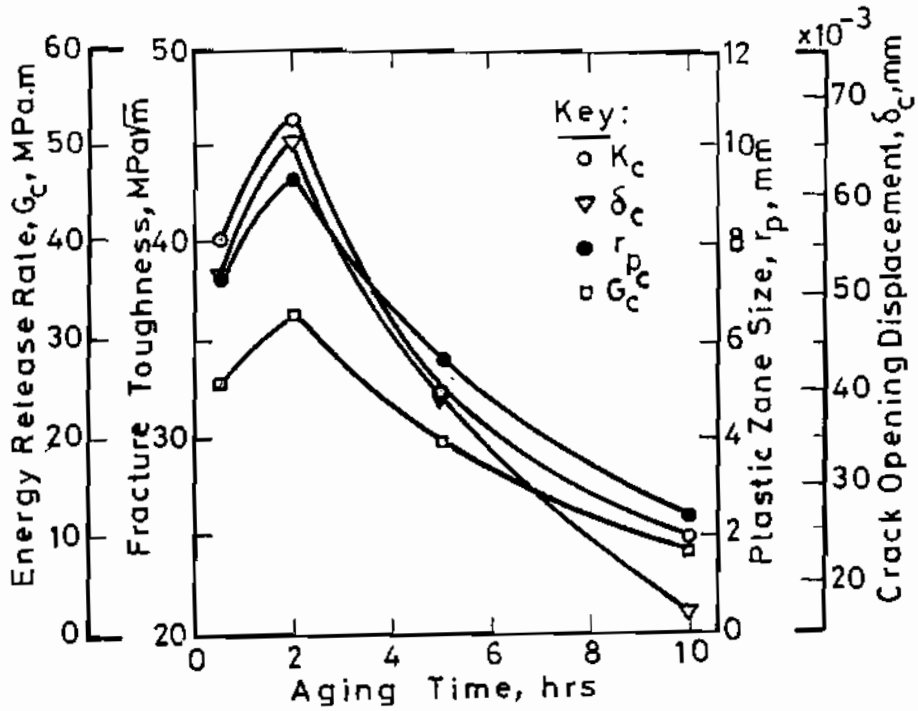

Fig.4 Variation of Fracture Characteristics with Aging Time

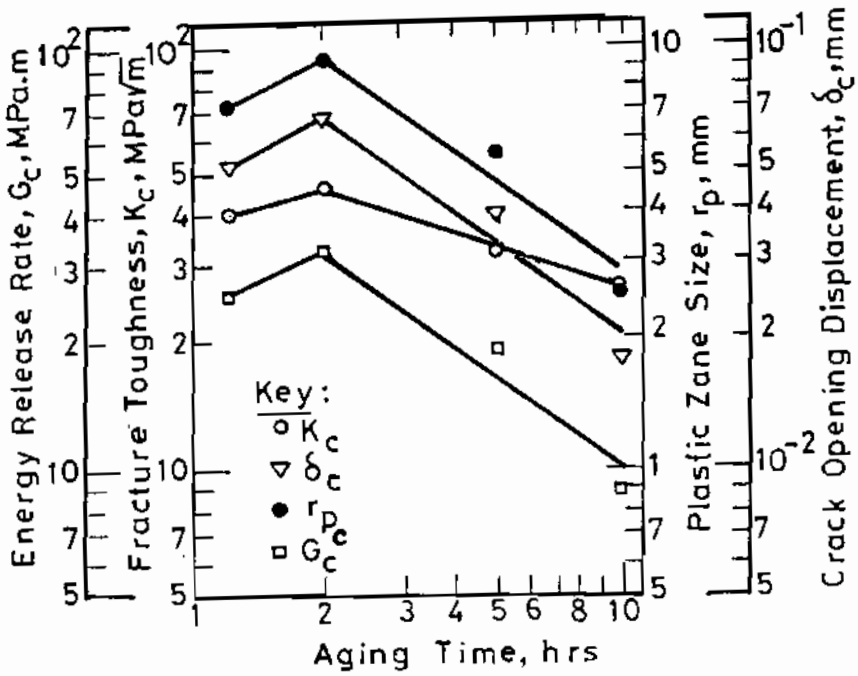

Fig.5 Variation of Fracture characteristics with Aging Time on a Logarithmic Scale

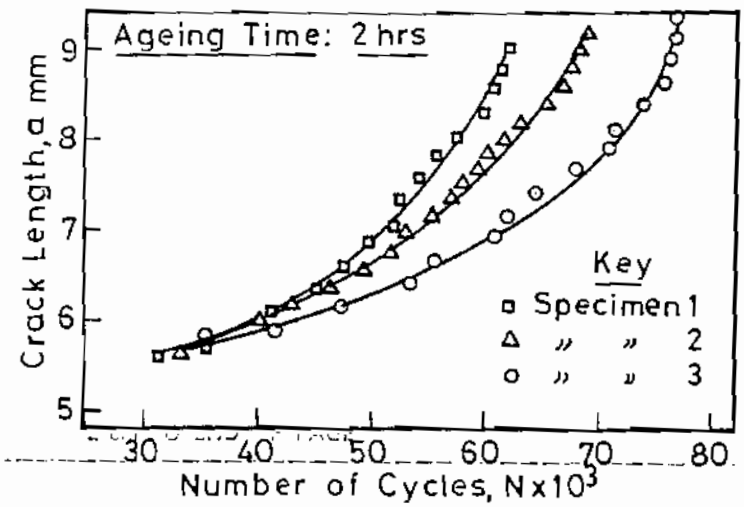

Fig.6 Crack Growth Curve For Aging Time of 2 hours

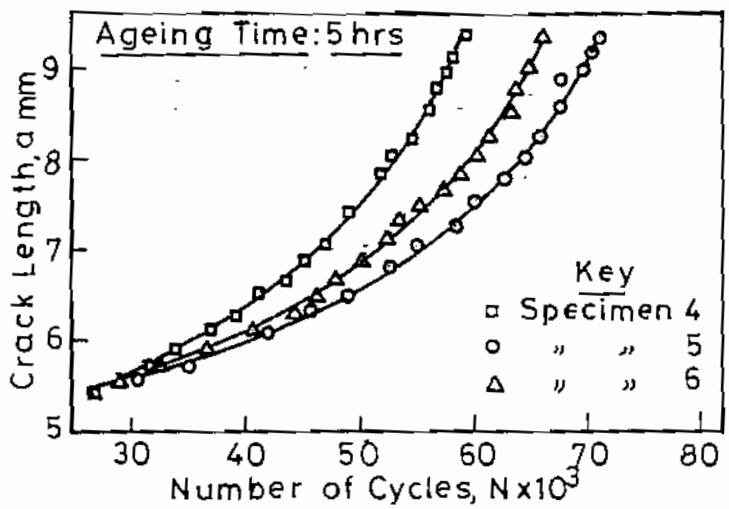

Fig.7 Crack Growth Curve for Aging time of 5 hours

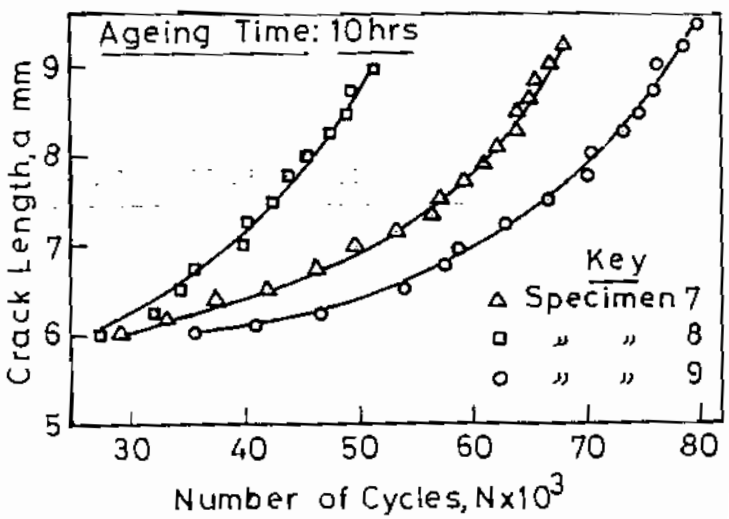

Fig.8 Crack Growth Curve for Aging Time of 10 hours

Table 5 function, f (a/b), for SEN specimens

(a/b)	0.1	0.3	0.6	0.9
f (a/b)	1.14	1.24	1.66	2.44

Crack lengths in Eq. (3) have been corrected for plasticity effects [7] and the stress intensity factors and the fracture toughness were recalculated accordingly.

The resulting values of the crack growth rates, da/dN, which were calculated from Figes. 6,7, and 8, were plotted against the excursion in stress intensity factor, ΔK, on a log-log paper. Figs. 9,10 and 11 show the resulting straight line relationships, the intermediate sections of the segmoidal curves, from which the parameters A and m were calculated. Table 6 and Fig. 12 give a summary of the test results.

Table 6 Summary of Test Results

Ageing Temp., °C	Ageing Time, hr	Average "A"	Average "m"
177	10	2.50×10^{-10}	4.30
177	5	9.85×10^{-10}	4.05
177	2	21.5×10^{-10}	3.60

Fig. 13 illustrates a log-log plot of the parameters A and m with the aging time.

DISCUSSION OF TEST RESULTS

The relationships exhibited in Fig.4 represent the plane stress fracture toughness, K_c, the critical energy release rate, G_c, the critical crack opening displacement, δ_c, and the critical plastic zone size, r_{pc}, as influenced by the aging time, t_a. It is seen that these fracture characteristics increase with increasing the aging time for the under-aged material, i.e. the material with smaller aging time, reaching peak values at an aging time of two hours for the aging temperature of the test. For over-aged material, i.e. the material with longer aging period, the fracture characteristics reduce as the aging time increases.

Exponential regression analysis has been performed on the test results shown in Fig 4 [8]. The fracture characteristics, i.e. the plane stress fracture toughness, K_c, the critical strain energy release rate, G_c, the critical crack opening displacement, δ_c, and the critical plastic zone size, r_{pc}, have been related to the aging time, t_a, through a set of exponential equations in the form.

$$Y_I = A_i e^{B_I t_a} \qquad (7)$$

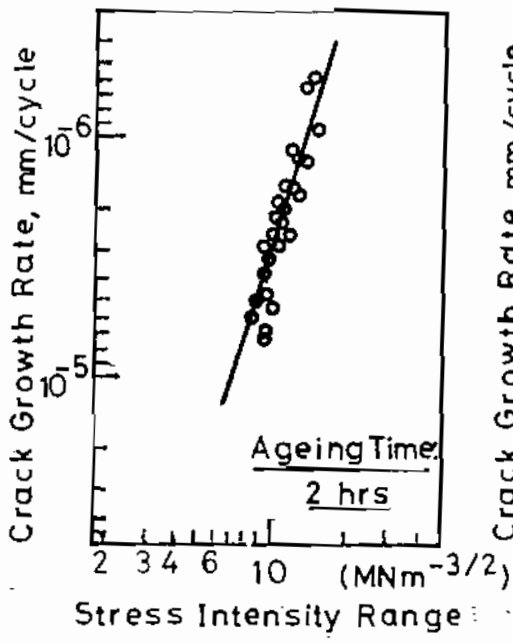

Fig.9 Logarithmic Crack Growth Curve (2 hours Aging)

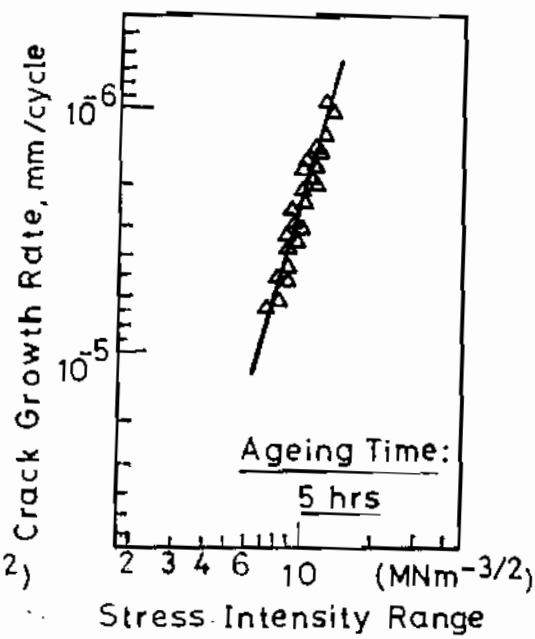

Fig.10 Logarithmic Crack Growth Curve (5 hours Aging)

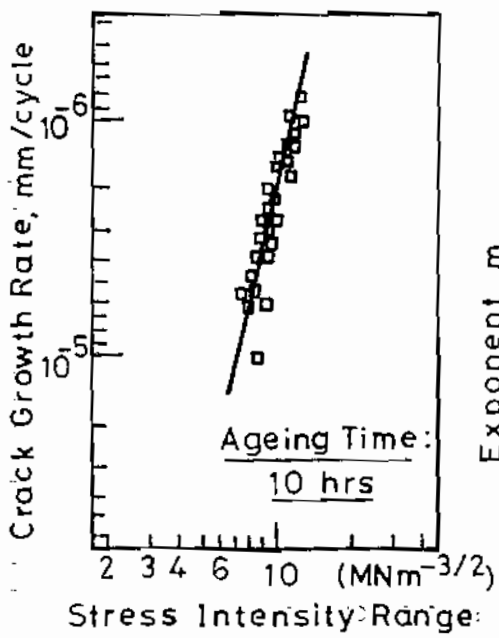

Fig.11 Logarithmic Crack Growth Curve (10 hours Aging)

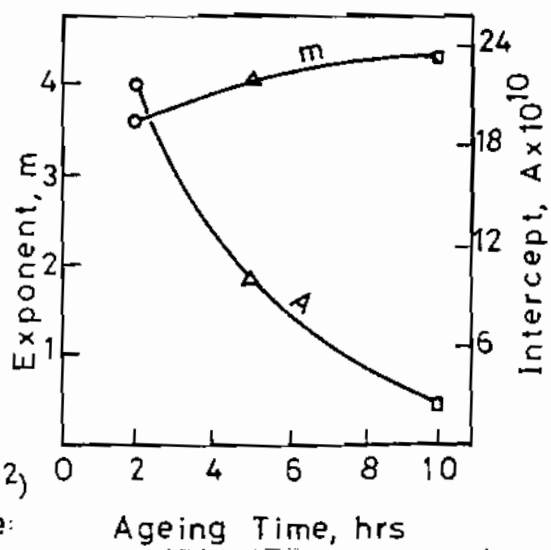

Fig.12 Crack Growth Law Parameters, A & m, with Aging Time

In Eq. (7), Y_i, where i = 1,2,3,4, represent the four fracture characteristics mentioned above, respectively. The coefficients A_i and B_i which have been determined from the regression process are listed in Table 7 .

Table 7 Coefficients of the Exponential Regression Analysis

Regression Coefficients	for Plane Strain Fracture Toughness, K_c	for Critical Strain Energy Release Rate, G_c	for Critical Crack Opening Displacement, δ_c	for Critical Plastic Zone Size, r_{pc}
Coefficient A_1	49.16	34.64	6.81×10^{-2}	9.67
Coeficient B_1	-6.34×10^{-2}	-0.13	-0.13	-0.13
Coeff. of Determination	0.8811	0.8814	0.8814	0.8811
" Correlation	0.9387	0.9388	0.9388	0.9387
Standard Error of Estimation	0.1194	0.2381	0.2381	0.2388

The values of the paramenters A & m, as shown in Fig. 12, reflect the type of crack propagation behavior of 7075-T6 aluminum alloy as a function of aging time. The two parameters, and hence the cracking behavior, are seen to be strongly dependent on the heat treatment performed on the material. The exponent m is shown to have a direct relationship with the ageing time, while the intercept A is having an inverse one. The parameter A for two hours aging time is about ten times its value for ten hours, while the increase in the magnitude of m is about 16%. The resulting conclusion is generally an increase in the crack propagation rate with longer aging periods, which seems to be in agreement with previous studies on other age-hardened materials [9].

The dependence of the parameters A and m of Paris equation, Eq. (1), on the aging time, t_a, may be represented in a mathematical form, based on Fig. 13, as follows:

$$A = A' t_a^{n1} \quad \& \quad m = m' t_a^{n2} \tag{8}$$

where A', m', n1 and n2 are a new set of paremeters to be determined from the experimental data, as illustrated in Table 8 .

Table 8 Experimental Values of Crack Growth Rate Parameters

A'	n1	m'	n2
6.3×10^{-9}	$-\frac{4}{3}$	3.1	$\frac{1}{7}$

It is well known that the rate of crack growth depends on the intensity of the stress and strain fields at the tip of the crack, i.e. the range of stress intensity factor, ΔK. The rate of crack growth is directly proportional to the range of stress intensity factor. In addition, the rate of crack growth is also dependent on the material properties and its resistance to initiation and growth.

Although the stress intensity factor range, ΔK, in the power law, Eq.1, is computed from geometry, crack size, and applied loading, the local driving force experienced at the crack tip may be different from the remote stress field. This may be due to various factors such as cyclic plasticity, crack path deviation, and crack closure; with the latter factor being most influential [10]. Crack closure occurring due to crack surface roughness, crack tip plasticity, and precipitates

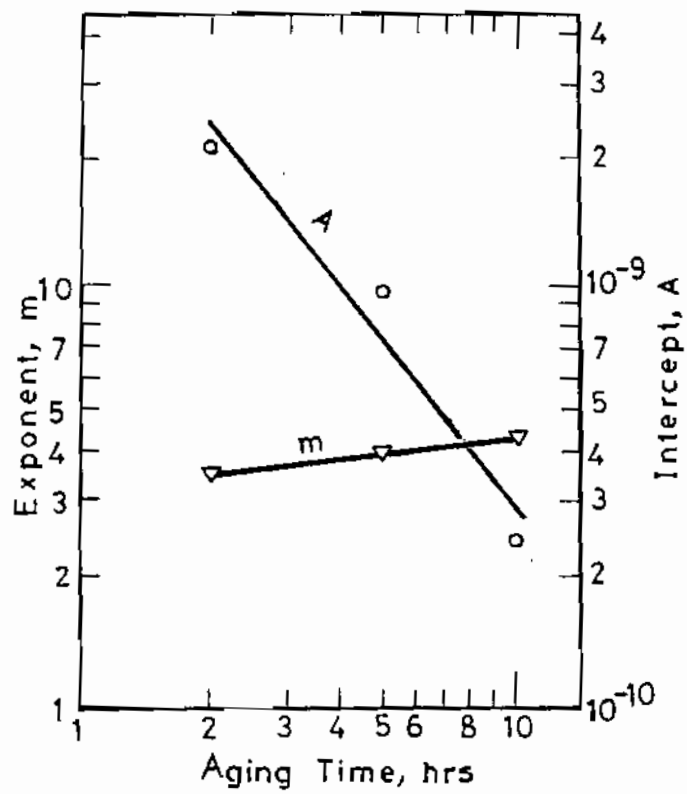

Fig.13 Crack Growth Law Parameters with Aging time on a log Scale

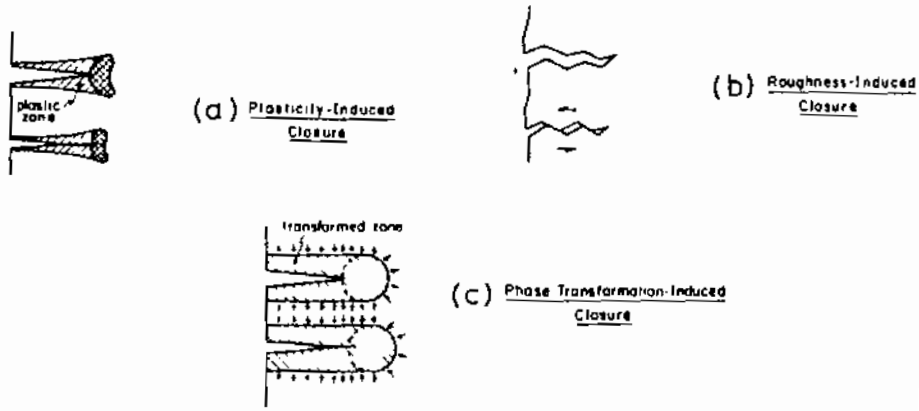

Fig.14 A Schematic Representation of Some Crack Closure Mechanisms.[10]

resulting from phase transformations, as illustrated in Fig.14, lead to an increase in the crack driving force and in crack propagation rate [10].

On the other hand, crack path deviation has been proven to occur on both microstructural and macrostructural scales in aluminum alloys and steel [9,11 ,12] The cause of the deviation of crack growth direction is attributed to the material's microstructure and the applied stress state being uniaxial or multiaxial. It has been shown that in all cases of crack path deviation, the rate of fatigue crack growth tends to decrease or stay constant at the value at the onset of turning [9,11]. Figs. 15 & 16 illustrate the crack path deviation [9, 11, 12].

As to the aluminum alloy tested in this study, it was observed that the fracture characteristics and the fatigue crack growth are affected by the aging time. As the aging time increases, the fracture resistance of the material decreases while the rate of fatigue crack growth increases. Ritchie and Thompson [13] estimated the rate of energy release at the onset of instability, J_{ss}, as being a function of the material's strength, σ_o, the ductility, ε_o, and the interparticle spacing, l_o, as follows:

$$J_{ss} = (\sigma_o^{\,2}/E)\, l_o \exp \left[\frac{0.6(1+\nu)}{(2-\nu)} \frac{\varepsilon_f}{\varepsilon_o} \right] \qquad \ldots (9)$$

From Eq.9 , the critical rate of energy release, and all other fracture characteristics, increase with increasing the ductility, decreasing strength, and increasing the interparticle spacing. In all age-hardening aluminum alloys, the process of diffusion and accumulation of second phase particles increase as the aging time increases. As a result of this process, there will be an increase in the local strain in the material which causes hindering of the motion of dislocation. This will lead to increasing the strength and decreasing the ductility which results in reducing the fracture toughness and other fracture characteristics [14,15].

The explanation for the variation of the rate of fatigue crack growth with aging time may be based on the hardening scheme which occurs in the microstructure [10]. Underaged microstrcutures are hardened primarily by the shearing of small coherent precipitates resulting in planar slip systems which promotes crystallograpghic crack paths. The increased resistance to crack growth will, therefore, be the result of an increase in crack closure in addition to crack tendency to deviate from its principal direction. The result will be slower crack growth rate.

On the other hand, in overaged microstructures, the mode of hardening is one of Orowan bypassing around larger non-shearable precipitates. The resulting wavy slip system whicl consists of a large number of finer slip steps, generates planar fracture surfaces. This leads to less roughness-induced closure resulting in more crack extension per cycle[10,16].

CONCLUSIONS

In this study, an attempt has been made to highlight the fatigue crack growth and fracture characteristics of Cu-Mg-Zn aluminum alloy (7075) and their variation with the aging time.

The following conclusions may be made:

(1) The fracture toughness, K_C, the critical strain energy release rate, G_C, the critical crack opening displacement, δC, and the critical plastic zone size, r_{pC}, all increase with aging time for underaged alloy and then decrease after reaching peak values at a certain aging time. This is explained as being the result of the resistance to the dislocation motion due to the diffusion of the second phase precipitates.

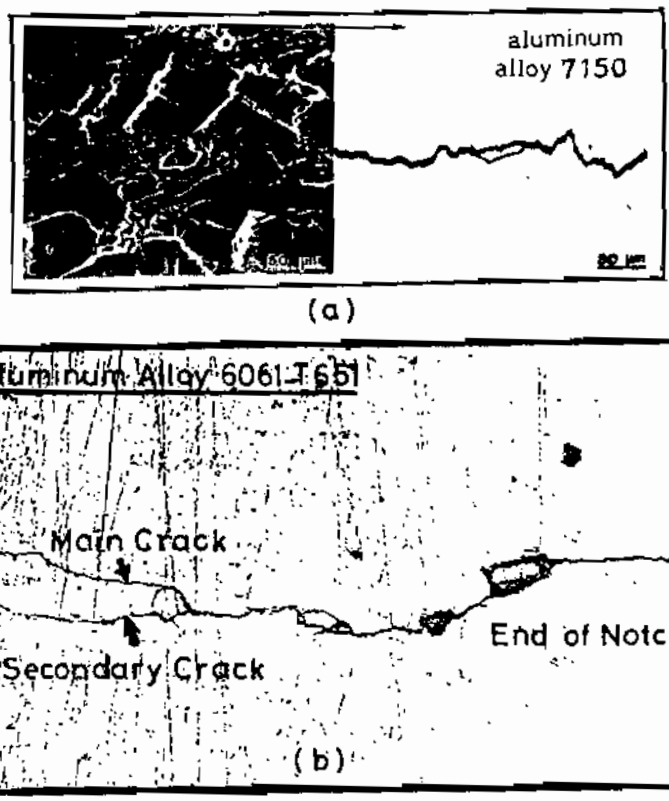

Fig.15 Crack Growth Pattern in Aluminum Alloys [9,11]

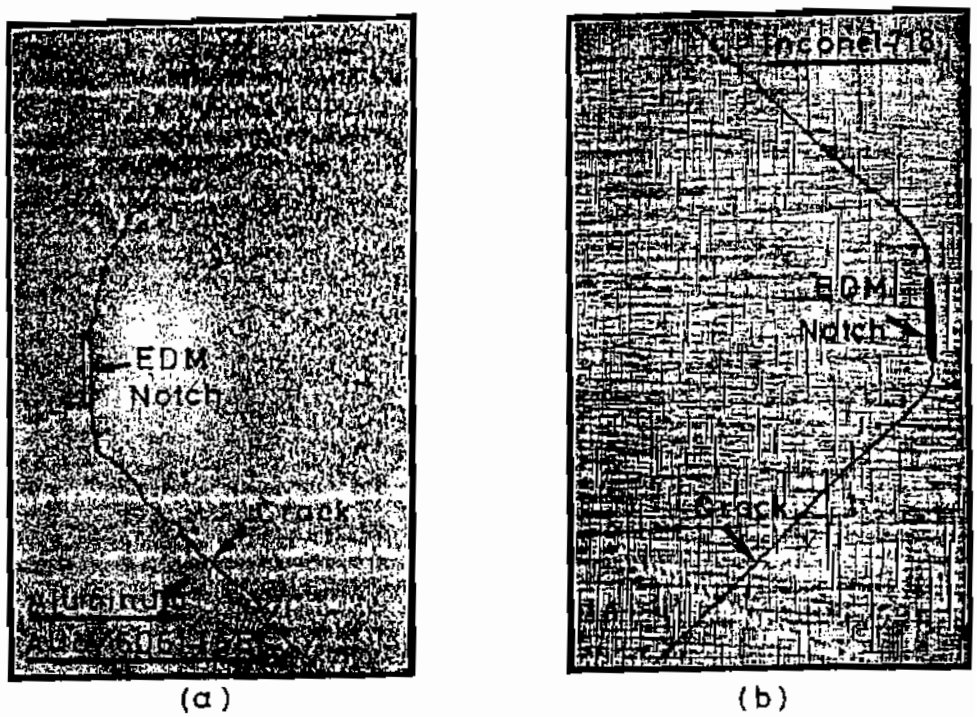

Fig.16 Crack Path Deviation Under Biaxial Stress Fields in an Aluminum Alloy and Inconel 718 [9,11,12]

(2) The rate of fatigue crack growth was observed to be low for underaged alloy and increased with aging time. This is explained as being due to the slip system and the hardening scheme which occurs in the microstructure due to aging.

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