Mansoura Engineering Journal (MEJ), Vol. 18, No.2, June 1993.

INFLUENCE OF ELEVATED TEMERATURE ON STRENGTH AND FRACTURE BEHAVIOR OF AUSTENITIC STEEL

دراسة تأثير درجات الحرارة المرتفعة على سلوك ومقاومة الصلب الأوستنيتي للكسور الميكانيكية تحت تأثير الزحف المعدني والأحمال المترددة

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خلاصة :

نظرا لأهمية الصلب الأوستنيتي في صناعة مكونات الأجزاء الدوارة وعلى الأخص تلك التي تتعرض لدرجات الحرارة المرتفعة والأحمال المترددة وأهمية مدى الطاقة المعدن لمقاومة الكسور الميكانيكية تحت تأثير هذه الأحمال ودرجات الحرارة المرتفعة . فقد اهتم هذا البحث بتطبيق نظريات علم ميكانيكا الكسور في دراسة سلوك الصلب الأوستنيتي عند ارتفاع درجات الحرارة الى مستويات محددة مصاحبة للأحمال المترددة .

وقد تمت الاختبارات المعملية على مرحلتين :

المرحلة الأولى : تحت تأثير الزحف المعدني المصاحب للأحمال المترددة للعينات ذات الشروخ وكذلك الخالية من الشروخ عند درجات الحرارة العادية .

المرحلة الثانية : تحت تأثير الزحف المعدني المصاحب للأحمال المترددة بانتظام مع ارتفاع درجات الحرارة الى نسب تتراوح من ٠٫٦ ٪ الى ٤٢ ٪ من درجة حرارة انصهار الصلب الأوستنيتي وذلك للعينات ذات الشروخ المصنعة على شكل V وكذلك العينات الخالية من الشروخ .

وقد تم تحليل النتائج بعد تطبيق نظريات ميكانيكا الكسور الخاصة بتقدم رؤوس الشروخ (سريانها) الى المستويات الحرجة لتحديد مدى تأثير ذلك على مقاومة المعدن لتقدم الشروخ .

وتشير نتائج هذا البحث الى أهمية هذه النتائج عند تطبيقها في مجالات الصناعات المختلفة التي يتم فيها استخدام الصلب الأوستنيتي تحت تأثير الزحف المعدني والأحمال المترددة مع ارتفاع درجات حرارة التشغيل .

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ABSTRACT

In this invistigation fracture mechanics approaches have been employed to study the fracture behaviour of austenitic steel at normal and elevated temperatures. Test conditions range from ambient to elevated temperature, monotonic to cyclic loading, and creep strain. Work carried out has been classified into two stages. Firstly, creep, creep-fatigue and fatigue fracture on noteched and unnotched specimens at room temperature. Secondly, creep, creep - fatigue and fatigue at high temperature ranging at about 0.06, 0.12, 0.18, 0.24, 0.30, 0.36 and 0.42% of metal melting point for nonheat-treated austenitic steel on unnotched specimen. There after, experiments have been conducted for creep, creep-fatigue and fatigue tests at different elevated temperatures on specimens having V notch. In these cases, smooth specimens loaded under uniaxial conditions have been employed to elucidate the steady state creep, creep-fatigue and fatigue and fracture mechanisms.
A critical analysis of data has revealed the occurence of a kink similar to that observed in the low carbon steel. On the basis of the study, the behaviour of austenitic steel, at high temperature, and the experimental results have been analysed and recommendations for applications are made.

KEY WARDS

creep-fatigue; crack growth rate; stress intensity factor; elevated temperature; notched specimen; material melting point.

INTRODUCTION

In this invistigation, the fracture bahaviour of austenitic steel (AISI 316 SS) which has widely been used in manufacturing numerous components of power generation plants, pressure vessels, nuclear reactors, steam and gas turbiens have been studied in the laboratory to understand the mechanisms of their fracture under different conditions of stresses and elevated temperature. Therefore, fracture mechanisms of specimens tested under tension, low cycle fatigue and fast creep fracture have been studied herein.

Creep is the gradual increases of plastic strain in a material with time at certain load. Particularly at elevated temperaturs some materials are susceptible to this phenomenon and even under a constant load strian can increase continually untill fracture. This form of fracture is particularly related to turbine blades, nuclear reactors, furnaces, rockets, motors, jet engines etc., [1-2].

Fatigue is particularly important in components subjected to repeated and often rapid load fluctuations, e.g. aircraft components, turbine blades, vehicle suspensions, etc.
The useful service life of numerous components are limited mainly by creep, creep-fatigue and fatigure failure, since many of these components are developed flows during fabrication, often in the growth of such pre-existing flows, cracks which control the life or reliability of the components. Growth of such cracks under creep, creep-fatigue and fatigue at elevated temperature can be usefully studied by utilizing the concepts of fracture mechanics [3-5].
Thus, the creep, fatigue and combined creep fatigue crack growth behaviour are examined for austenitic steel [16Cr-11Ni] at room temperature, thereafter at eleveated temperature ranging from about 200 to 800 C°, [6-7].

ANALYTICAL INVESTIGATIONS

The effect of a notch or defect on the creep-fatigue strength at elevated temperature varies considerably with material strength [8]. A fracture mechanics analysis is attempted for the estimation of critical size determining the strength limits of the defected specimen as a function of material strength. This is based on the assumption that the crack propagation stage of small cracks initiated from the defects control the creep-fatigue limits. In case of an elastic crack, the critical length of the crack $2a_{cr}$ under the applied stress is given by [9].

$$\Delta K = f(a) \cdot \Delta \sigma (\pi a_{cr})^{1/2} = \Delta K_{th} \qquad (1)$$

where f(a) a geometrieal factor and ΔK_{th} is the threshold stress intensity factor.

The crack growth rate for the critical notched specimen is affected by increasing yield strength and reduction in ductility. Therefore, as the stress intensity factor increases, the plastic zone also tends to grow and spread ahead of crack tip. In this process the resistance offered due to increasing in yield strength retards the growth of the plastic zone which results in the dip or kink in the crack growth rate. However with further increases in stress intensity factor rate the plastic zone and the stress concentration that builds up lead to increases in the crack growth rate [10-11]. The crack growth rate can be expressed by the Paris equation, [11]:

$$\left| \frac{da}{dN} \right| \propto \left(\frac{\Delta K}{E} \right)^{m} \qquad (2)$$

where ΔK is the stress intensity factor range, and E is the modulus of elasticity for the metal used, m usually lies between 2 and 7 but values close to 4 are generally found.
The rate of crack growth is described in terms of the increase in crack length per load cycle, da/dN. This is related to the amplitude of the stress intensity factors, ΔK, during the cycle.
The presence of notch, crack or defect upon the components performance can be indicated by the creep fatigue strength reduction factor. However, the notch sensitivity factor may be simply expressed by:

$$S_c = \frac{K_r - 1}{K_o - 1} \qquad (3)$$

where K_r creep-fatigue strength reduction factor and K_o stress concentration factor.

From the engineering view point, it is possible to evaluate the notch or defect sensitivity which may depend upon the severity of notch and type of loading. The presence of notch or crack in a specimen subjected to creep or fatigue decreases the specimen creep-fatigue strength at elevated temperature. However, it has been postulated that whilst the specimens were being fatigued or creeped, notch or crack tip propagates to some extent whilst the internal damage or micro crack spreads slowly. Thus, the failure takes place when the notches and internal microcracks propagates and reach some critical lengths and approaches randum loading conditions. For many engineering components to withstand an almost infinite number of stresses reversals in their life time, the stress amplitude are relatively small and usually do not exceed the elastic limit.
The failure of engineering components most commonly occurs at stress levels far below the design stress. This phenomenon, commonly termed fatigue, creep and creep-fatigue, involves the growth of small defects into macro or micro cracks which grow untill fracture toughness for the components material is exceeded and the catastrophic failure occurs.
Based on the above discussions, the representation of crack growth rate in terms of independent veriables was proposed for creep,creep-fatigue interaction and fatigue at high temperatures,respectively,.It is given as follows ,(12):

$$\frac{da}{dt} = B_\alpha . \sigma_\alpha^{m\alpha} . K_r^{n\alpha} \exp[-\{\Delta f_{1\alpha} - \Delta f_{2\alpha} \ln (K_r/G\sqrt{b})\}/RT] \qquad (4)$$

Based on this equation high temperature crack growth rate under creep, fatigue and creep-fatigue interaction can be expressed.

where G is modulus of rigidity, b is Burger's vector R is gas constant, Δf_{1q} is apparent activation energy, Δf_{1q}, Δf_{2q}, m_q, n_q and B_q are constants, dependent on holding time.
The stress intensity factor K_I commonly expressed by

$$K_I = f(a).(\pi . a)^{1/2} . \sigma \quad (5)$$

Thus, the high temperature crack growth rate is obtained from equation (4) for different conditions as follows:

for creep

$$\frac{da}{dt} = 1.81 \times 10^{-4} \sigma_q^{4.14} \exp[-\{3.59 \times 10^5 - 7.25 \times 10^4 \ln(K_I / G\sqrt{b})\}/RT] \quad (6)$$

for creep-fatigue interaction

$$\frac{da}{dt} = 5.28 \times 10^{-4} \sigma_q^{4.12} K_I^{5.41} \exp[-\{2.15 \times 10^5 - 3.51 \times 10^4 \ln (K_I / G \sqrt{b})\}/RT] \quad (7)$$

and for fatigue

$$\frac{da}{dt} = 1.73 \times 10^{-9} K_I^{4.62} \exp[-\{7.12 \times 10^4 - 7.67 \times 10^3 \ln (K_I / G \sqrt{b})\}/RT] \quad (8)$$

The life time for crack propagation in Region II as follows Yokobori, A.T and et al. [12].

$$T [\ln t_f + \theta (T, \sigma_q)] = [\Delta f_{1q} - \Delta f_{2q} \ln (c. \sqrt{a_o} \sigma_q)]/R \quad (9)$$

where a_o is crack length at the start of region II, a_f is the crack length at fracture, and $a_f > a_o$.

EXPERIMENTAL EVIDENCE

Cracks, notches and flows are the common cause of brittle failure of components. Sharp notches act as stress raisers that concentrate stresses in a manner which introduce brittleness. This kind of stress raiser have been observed in many high temperature application. High and normal temperature creep, fatigue and combined creep and fatigue tests were conducted in austenitic steel, to evaluate the behaviour of material of notched bar subjected to different level of temperature. Round bar notched specimen of 10 mm.diameter and 120 mm. length have been employed for experimental verification as shown in Fig.1.

Specimens were made of austenitic steel (AISI 316 SS) with a composition (wt%): C-0.06, N_i-11.95, C_r-16.90, M_o-2.21 M_n-1.6, S_i-0.54, P-0.036 and S-0.02. The specimens were initially subjected to creep alone, followed by fatigue with the creep held almost constant, the specimen remaining elastic but approaching yield. Both creep and fatigue were then increased till yield load had distinctly occured.

Several test of this kind with various ratios of creep and fatigue at seven different temperature levels, representing 0.06, 0.12, 0.18, 0.24, 0.30, 0.36 and 0.42 of melting point of the material, were performed.
Experiments, were performed using a local made mechanical vibrator mechanism (cam system). A special device was employed to compensate for the load suitable for the spcimen used. Spcimens were heated by a radiation furnace. A typical creep-fatigue testing apparatus is shown in Fig.2. Each end of specimen is scrwed into the specimen holders, the thermocouples and extensometers are fixed to the specimen in order to measure temperature and strain.

DISCUSSION

Comparing the results for unnotched specimens with notched specimens indicate that, the sensitivity of a material to notches tends to increase with increasing tensile strength and decreases with increasing plasticity, thus, in design situations, a compromise between these opposing factors must be reached.
Looking at curves shown in Fig.3. indicate that, the presence of crack, flow or any defects decrease the material creep, fatigue resistance. However, in condition of elevated temperature, the notched specimen will develop cracks and failure occurs more rapidly at low stress level. Moreover, when a crack has grown at high temperature, the stress intensity factor K_I is approached and the crack accelerates more rapidly until the critical stress intensity factor K_{IC} is exceeded and final catastrophic failure occurs.
Thus, in order to rule out the possibility of a creep fatigue effect, on notched specimen at different temperature rate, tests were conducted and results are plotted.
The family of curves shown in Fig. 4,5. and 6. show, the significant effect of notch sensitivity at elevated temperature on creep and fatigue fracture behaviour of austenitic specimen. However, when the stress intensity factor increase, the plastic zone also tends to grow and spread a head of the crack tip. Moreover, further increases in the stress intensity factor along with increasing in the temperature results in stress concentration build-up leading to increases in the crack growth rate.
Observation of Fig.7 indicates that, there is a kind of dip in crack propagation rate, where transition from stage I to stage II occurs. Stage I can be described by a smooth curve with a steep slope in all the cases depicted in Fig.7. The crack growth rate da/dN (mm/cycle) increase with increasing stress intensity factor. Thereafter, there is a slight dip in the crack growth rate. The crack growth rate then picks up again. After the onset of stage II, the variation of crack growth rate da/dN with increasing rate of stress intensity factor ΔK is linear.
The fatigue crack growth data on a number of specimen at different temperature level have been analysed and has revealed the occurrence of a kink similar to that observed in the low carbon steel.

The presence of notches, cracks or defects upon the component performance can be indicated by the creep-fatigue life for notched specimens under various stress levels (normalised stress (σ_a/σ_o) for different temperature ratio t/tm as shown in Fig.8. The failure probability is given in terms of stress amplitude, versus time or number of cycles to fracture.

Based on the above discussion it is apparent that, the time dependent deformation called creep or fatigue as with all deformation processes, is largely dependent upon dislocation movement and, therefore, the development of alloys with a high resistance to creep or fatigue at elevated temperature involves producing a material in which movements of dislocations only takes place with difficulty.

Since. creep and fatigue at elevated temperature is an engineering problem specially at temperature of range of 500-700 C, the materials having higher melting point constitute the better. However, there are practical limitations for some high melting point materials such as the difficulty to machine etc.,. Thus, the most suitable metal which can be used extensively at the moment for the situation of creep and fatigue stress at elevated temperature is the austenitic steel. However, to improve the creep-fatigue metal resistance at elevated temperature, the addition of elements whose atomic size and valency are largely different from basic material such as chromium and cobalet, is essential. Moreover, it is clearly imperative that a material which is susceptible to creep-fatigue effects at elevated temperatures should only be subjected to stresses which keep it in the secondary region of straight line strain-time relationship through its service life. This enables the amount of creep extension to be estimated and allowed for in design.

CONCLUSION

Creep and low cycle fatigue tests at elevated temperature were performed at seven different temperatures which are related to the material melting point on austenitic steel specimens with and without notches. Thus it can be conclueded that,

1- The reduction in fatigue life at elevated temperature was mainly due to presence of cracks rather than the creep effect.

2- The sensitivity of a material to notches tends to increase with increase in tensile strength and decrease with increase in plasticity, thus, in design situations, a compromise between these opposing factors must be reached.

3- The resistance offered due to increasing in yield strength retards the growth of the plastic zone which results in the dip or kink in the crack growth rate.

4- The failure of notched specimens occurs at stress levels far below the un-notched specimen design stress level. This phenomenon termed fatigue, creep and creep-fatigue, involves the growth of small defects into macro or micro cracks which grow until fracture toughness for the concerned material is exceeded and the catastrophic failure occurs.
5- The, creep-fatigue resisting alloy is further strengthened by added alloying elements such as chromium and cobalt, but this limits the amount that may be added. Thus, the use of alloying elements which raise the creep-fatigue metal resistance at elevated temperature will be beneficial.

NOMENCLATURE

a_o	crack length at the start
a_{cr}	critical crack length
a_f	crack length at fracture
da/dN	cyclic crack growth rate
$f(a)$	geometrical factor
Ko	stress concentration factor
K_I	stress intensity factor in (mode I)
ΔK	cyclic stress intensity factor
Sf	notch senstifity factor
σ_{app}	applied stress
$\Delta\sigma$	range of stress cycle.

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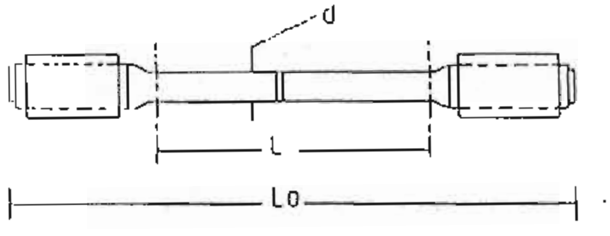

Fig. 1. Round bar notched specimen geometry

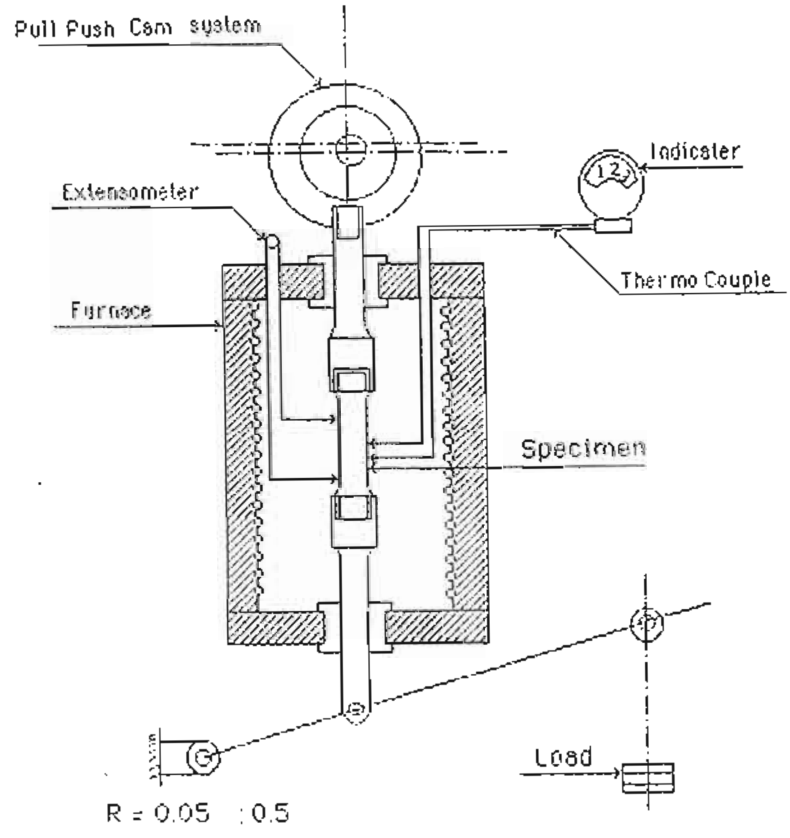

Fig.2. schematic digrame for a typical creep - fatigue testing apparatus

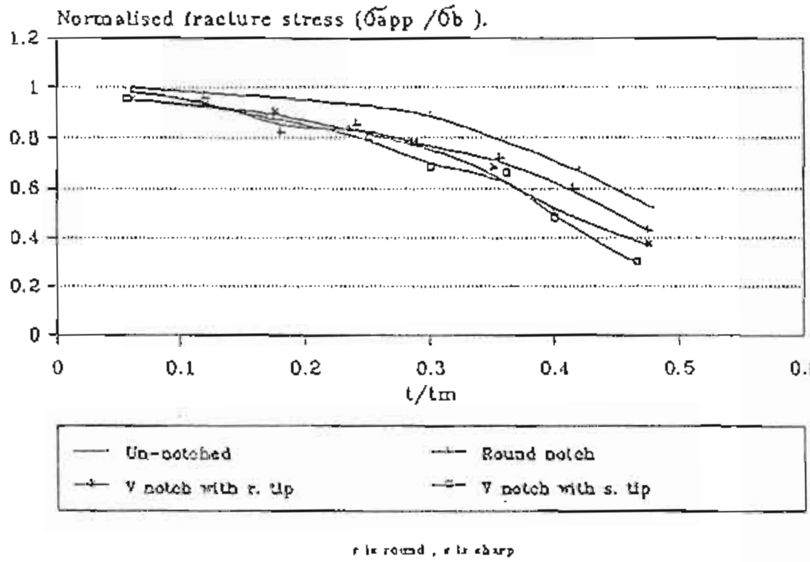

Fig. 3. Variation of fracture stress with temperature to meltingpoint ratio.

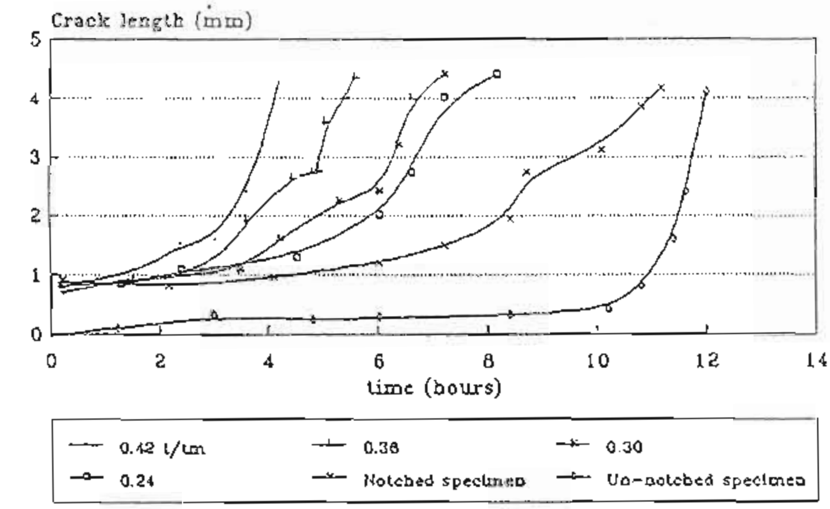

Fig. 4. Creep crack growth as a function of time for notched and unnotched specimen at different temperature ratio.

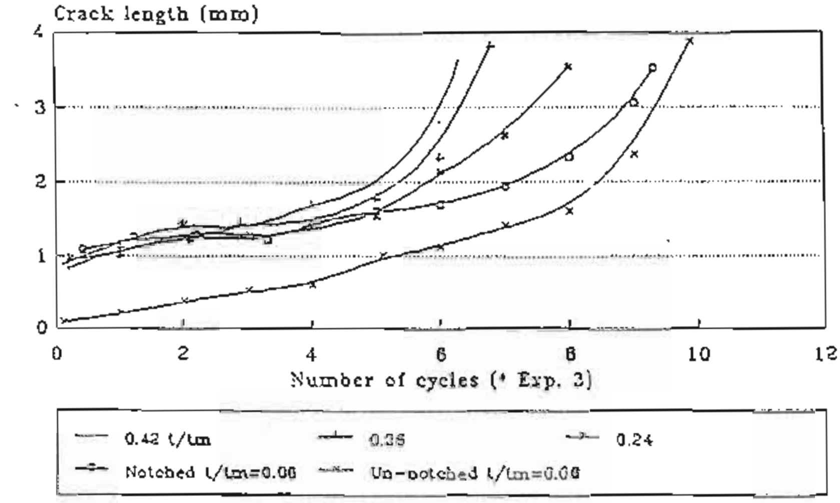

Fig. 5. Fatigue crack length as a function of number of cycles at different temperature ratio.

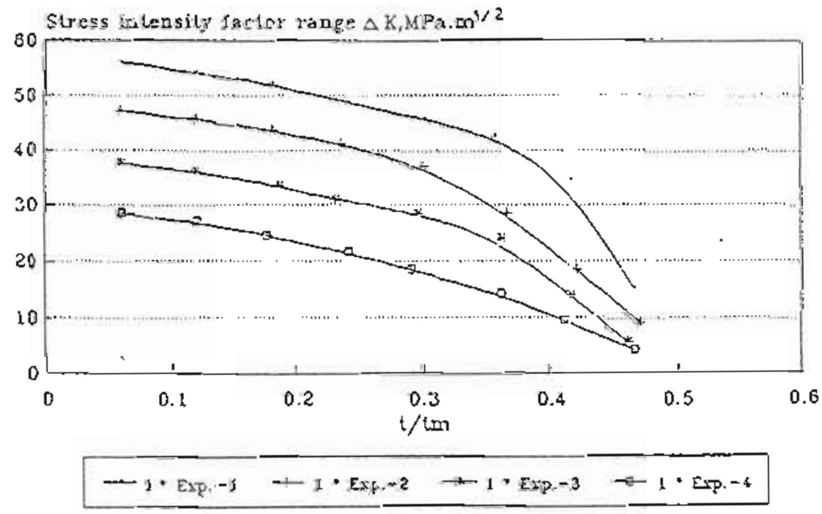

Fig. 6. Change of stress intensity factor with temperature to melting temperature ratio.

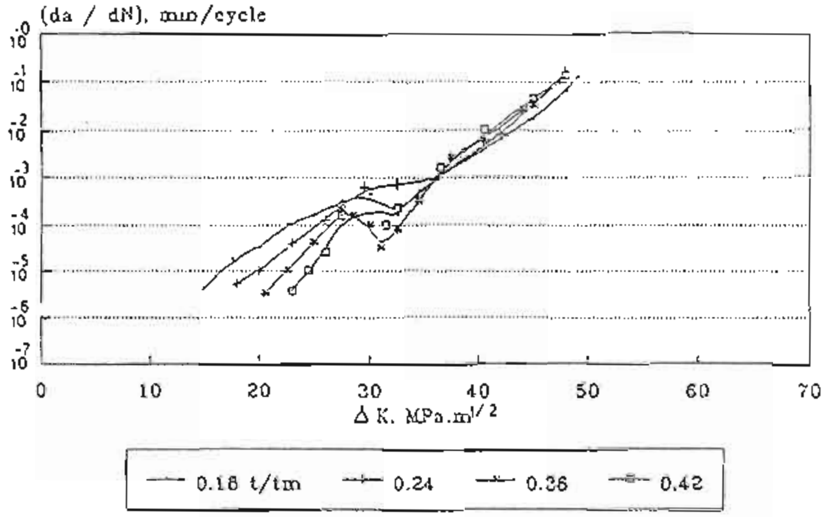

Fig. 7. Creep crack growth as a function of stress intensity factor for different temperature ratio.

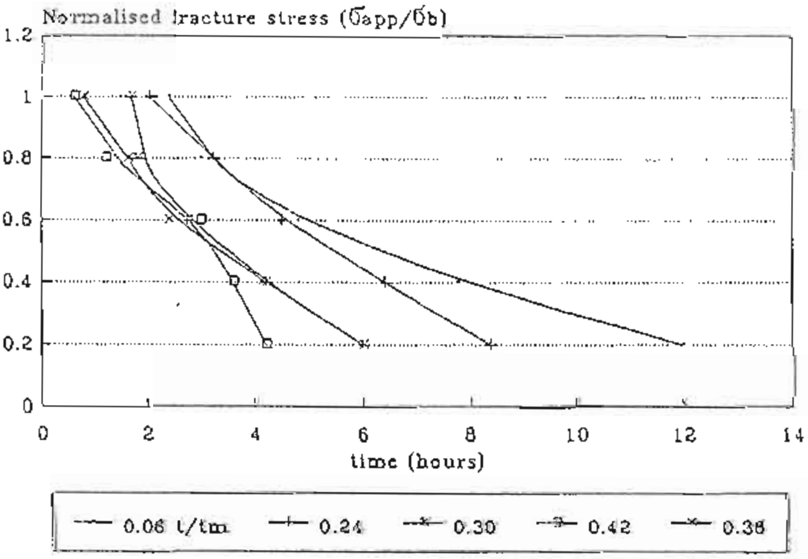

Fig. 8. Creep fatigue stress rupture time curves at various temperature rate.