MILITARY TECHNICAL COLLEGE

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EXPERIMENTAL STUDY OF CRACK PROPAGATION BY BENDING IN AU4 G1 - T3 AND STEEL 316

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ABSTRACT

The authors have applied fatigue crack bending test of thin sheets for the determination of the crack propagation rate in AU4 G1-T3 aluminium alloy and in type 316 austenitic stainless steel.

In the first stage, the authors have tested the Paris' law and shown its insufficienties, then they have interpreted the results with ELBER'S Theory of crack closure and have measured the crack opening by means of a strain gauge installed near the crack tip.

In addition, the authors have explained the retardation phenomenon due to a single overload in Al. alloy.

INTRODUCTION

In the element of new structures, the problems of crack propagation by fatigue must be previously considered. The laws of crack propagation rate are usually determined for some sepecial cases of tension- compression cyclic load. In this study an experimental method is proposed to test the validity of these previous laws in bending. Paris' law was examined and modified by an exprimental function of stress ratio ($R= F_{min.}/F_{max.}$). Elber's ratio (U) is found to be a function of stress ratio (R) and maximum stress intensity factor (K_{max}). All tests are performed with sinusoidal cyclic load of 8Hz in ambiant conditions of temperature, pressure and humidity. Specimens are chosen to satisfy plane stress condition as 2mm thick sheets. Two alloys which are widely used in aircraft production and nuclear engineering are used in the present work as test materials. In these fatique crack bending experiments, the buckling effect has no influence on cases of negative stress ratio ($R<0$). Further more, the effects of rolling direction of sheets on the crack propagation rate have been examined.

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DESCRIPTION OF EXPERIMENTAL PROCESS

The specimens tested have the dimensions indicated in Fig. 1.

Thickness 2 mm

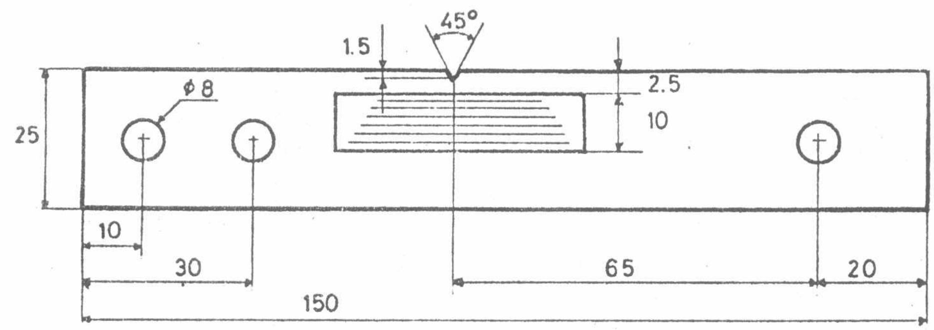

fig.1. Specimen dimension with fatigue gauge (CPAO2).

The chemical composition of aluminium alloy AU4G1-T3 (2024-T3) is :

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	
0.09	0.21	4.4	0.63	1.5	0.01	0.04	0.03	%

and the mechanical characteristics are :

$\sigma_{0.2}$ = 373 MPa , σ_u = 474 MPa , E = 73.1 GPa and ν = 0.33.

The chemical composition of stainless steel type 316 (Z2 CND 17/12) is :

C	Mn	Si	S	P	Ni	Cr	Mo	
0.02	1.39	0.53	0.01	0.03	12.12	17.2	2.17	%

and the mechanical characteristics are :

ν = 0.25 , E = 206.85 GPa , σ_u = 600 - 800 MPa

$\sigma_{0.2}$ = 321 MPa (for specimen type T) and

$\sigma_{0.2}$ = 306 MPa (for specimen type L)

Where, T ... Specimen in which the fatigue crack developed is parallel to rolling direction.

L ... Specimen in which the fatigue crack developed is perpendicular to rolling direction.

The propagation of the crack (initiating from a mechanical notch) is recorded by a fatigue gauge installed over the surface of specimen, fig. 1. The mechanical stand is represented in fig. 2. The details of experimental procedures are explained by [1] .

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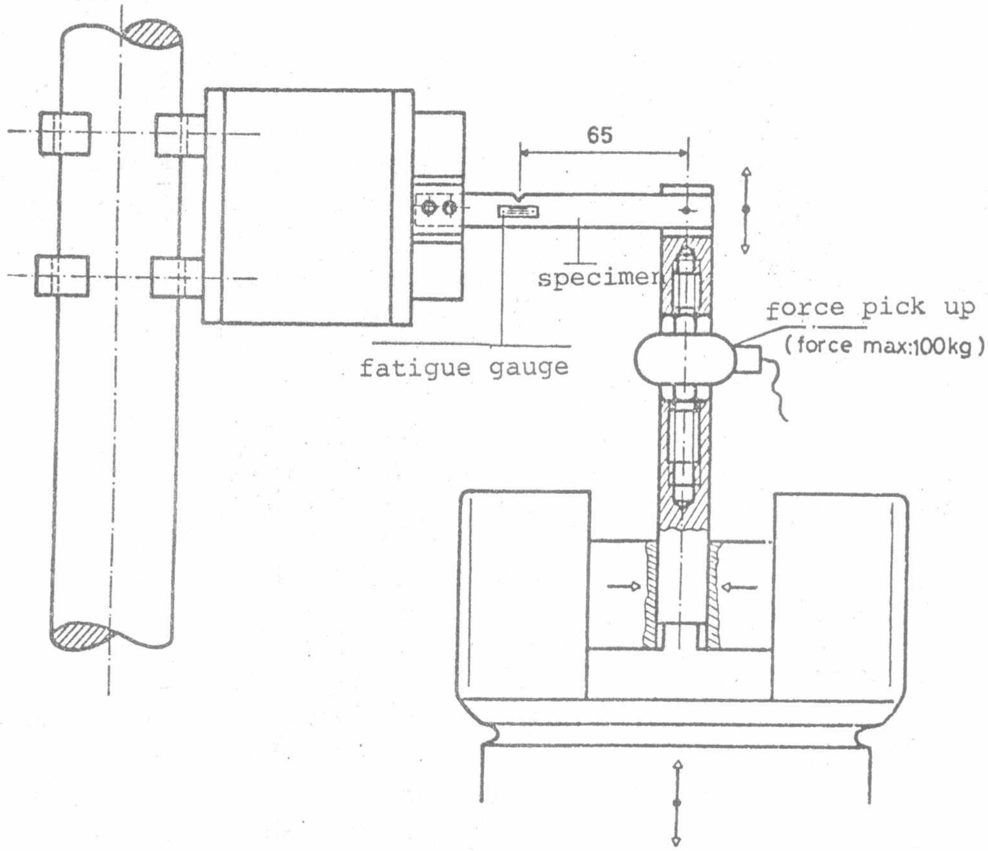

Fig.2. The Mechanical Stand.

ITERPRETATION OF THE RESULTS WITH PARIS' LAW

Pairs' law is a relationship of the form [2] :

$$\frac{da}{dN} = C\ (\Delta k)^m \qquad (1)$$

where "C" and "m" are material constants depending on environoment, temperature, frequency and stress ratio.

a ... is the crack length

$\frac{da}{dN}$ ... is fatigue crack growth per one cyclic load.

and Δk is stress intensity factor range ($\Delta k = k_{max} - k_{min}$)

The formula of the O.N.E.R.A. [3] is used to calculate the stress intensity factor :

$$k = F(\alpha a^3 + \beta a^2 + \gamma a + \delta) \qquad (2)$$

where, F ... is the applied force.

α, β, γ and δ are coefficients obtained by finite element calculation for specimen, figure (1) such ($2.5\ mm \leq a \leq 12.5$) :

$\alpha = 0.0010185$
$\beta = -0.0152775$
$\gamma = 0.2138875$
$\delta = 0.4251875$

The first group of experiments defined by zero stress ratio (R=0). The crack growth rate as function of stress intensity range are plotted in bilogrithmic scale fig.3.

A least squares fit of Paris' equation was performed to these data, the parameters "C" and "m" are given in the following table.

Materials	C	m
AU4G1-T3(L)	3.72×10^{-9}	2.93
Steel 316(T)	1.32×10^{-13}	4.56
Steel 316(L)	7.65×10^{-13}	4.21

It is noticed that the parameters C and m are affected by the direction of sheet rolling.

The second group of experiments defined by non zero stress ratio ($R \neq 0$) the variation of crack growth rate in function of (Δk) are plotted in fig. 4. It is found that the parameter "C" is varying as function of "R". It seems reasonable to expect that a better analysis of crack propagation rates might utilize the influence of stress ratio. The following functional form of the crack propagation equation will be used :

$$\frac{da}{dN} = C \; K_{max}^{m} \; f^{m}(R) \qquad (3)$$

where f(R) ... is the function of influence of stress ratios on crack propagation rate.

Integrating equation (3) between two values of crack lengths "a_1" and "a_2" to get the

$$\frac{1}{C \, F_{max}^{m}} \int_{a_1}^{a_2} \frac{da}{(\alpha a^3 + \beta a^2 + \gamma a + \delta)^m} = \left[N(a_2,R) - N(a_1,R) \right] f^{m}(R)$$

where ... N(a,R) is the number of cycles necessary for the crack length equal "a" in the experiment with stress ratio equal "R". The left hand side of the above equations independent of "R", hence

$$f(R) = \left[\frac{N(a_2,0) - N(a_1,0)}{N(a_2,R) - N(a_1,R)} \right]^{1/m} \qquad (4)$$

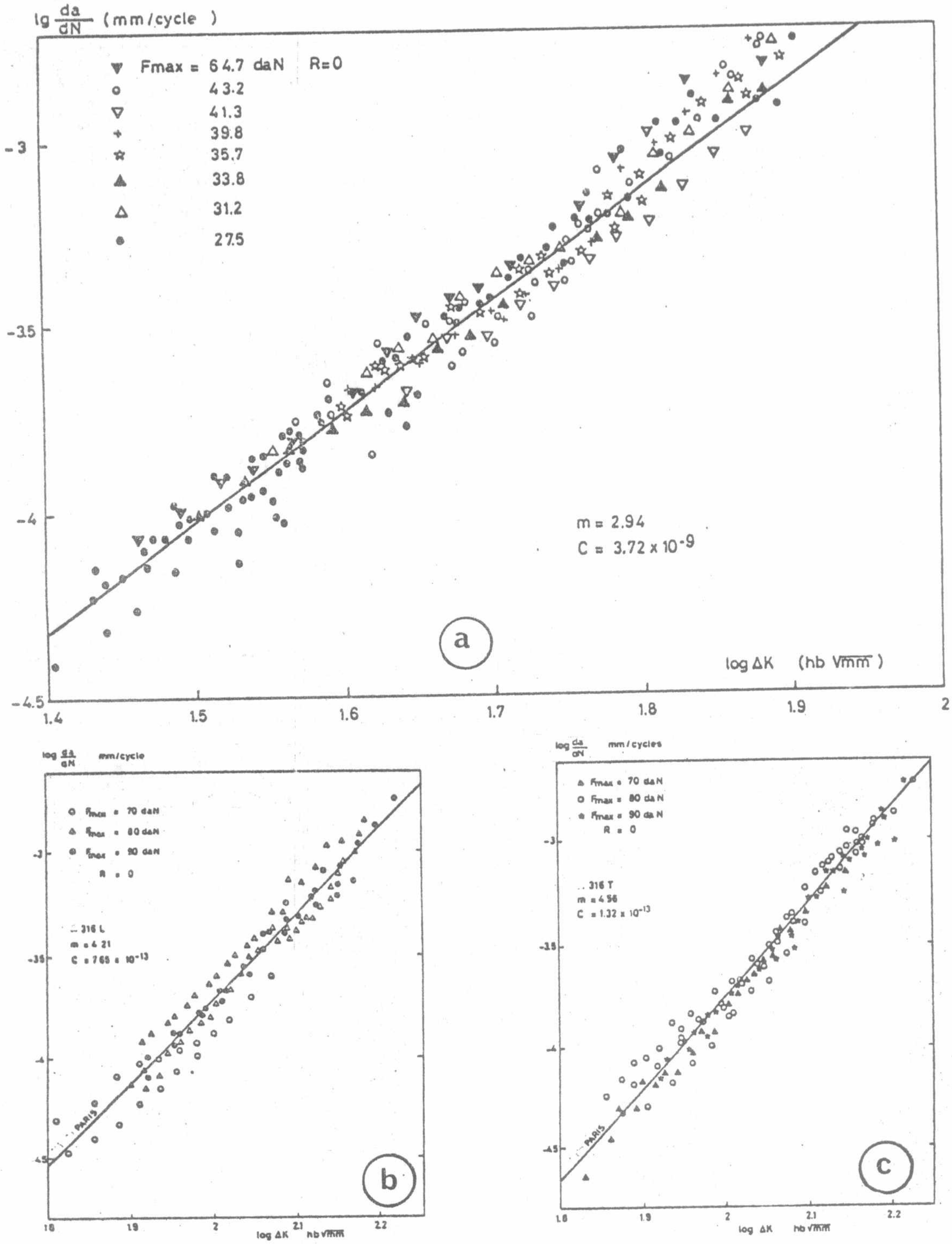

Fig.3. Crack growth rate as function of ΔK for

a- Al-Alloy AU4G1-T3
b- Stain less steel 316 specimen L
c- Stain less steel 316 specimen T

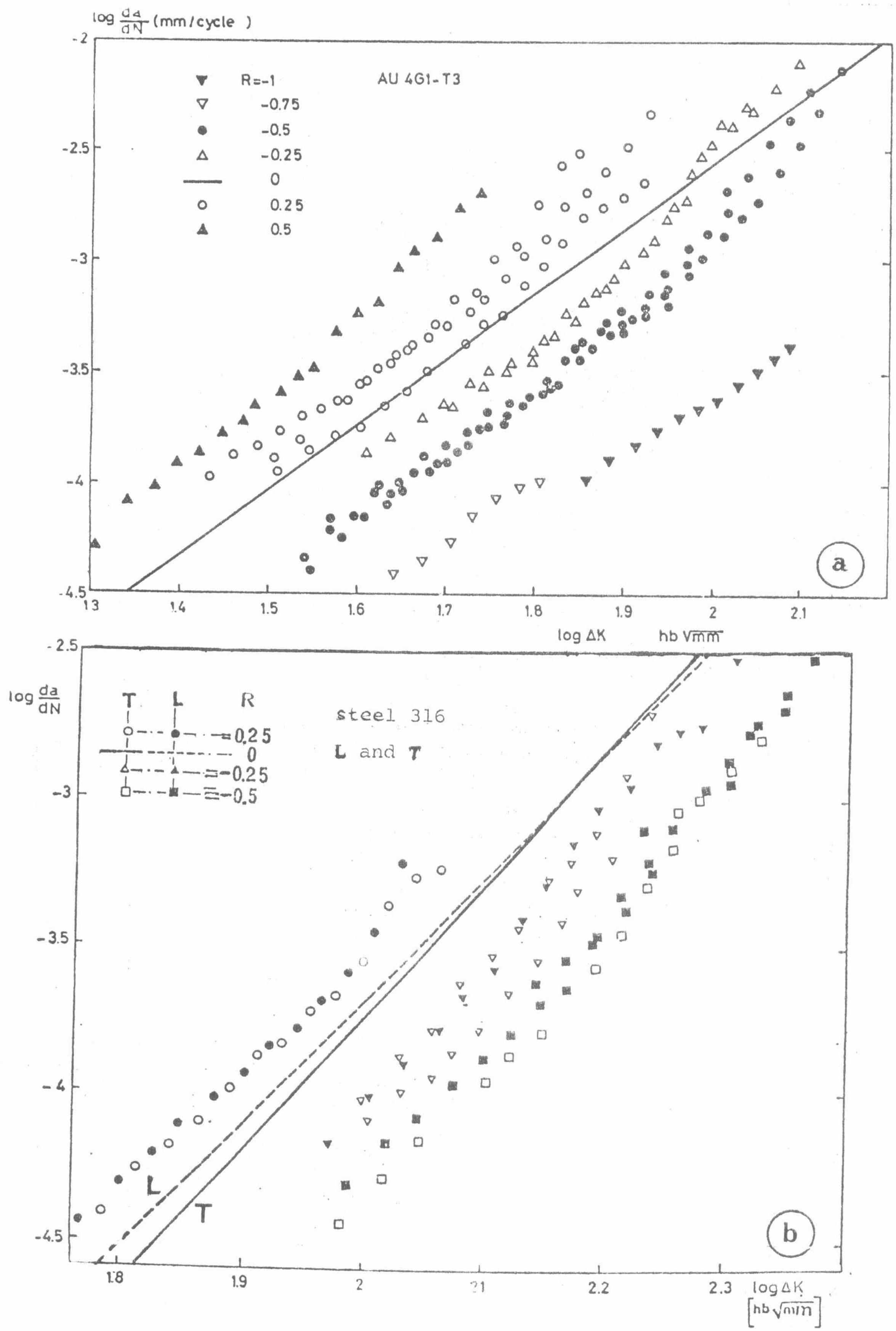

Fig.4. Variation of Crack growth rate in Function of ΔK.
a- AU4G1-T3 b- steel 316

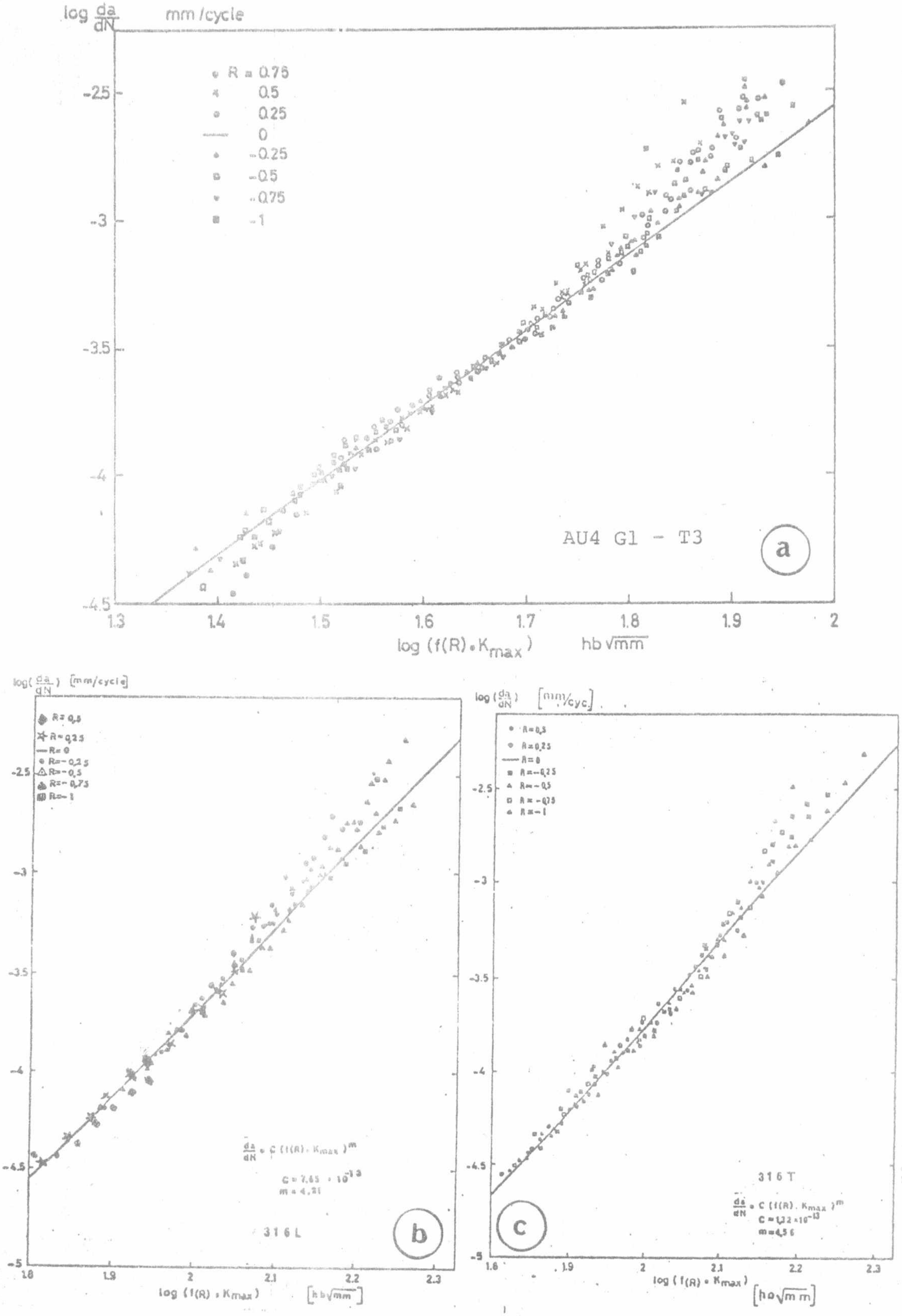

Fig. 5. The variation of $\frac{da}{dN} = f(K_{max}\ f(R)$ for a- AU4G1-T3 Al.Alloy b- Aisi 316 specimen L c- Aisi 316 specimen T.

Fig.5 shows the variation of crack growth rate as a function of $(K_{max} \cdot f(R))$ It should be noted that, Pairs' law corresponds to $f(R) = 1-R$ and Elber's law [4] corresponds to $f(R) = 1-0.2\,R - 0.8R^2$, the two approaches can be compared with the experiemtnal values of f(R) according to equation (4) in fig.6.

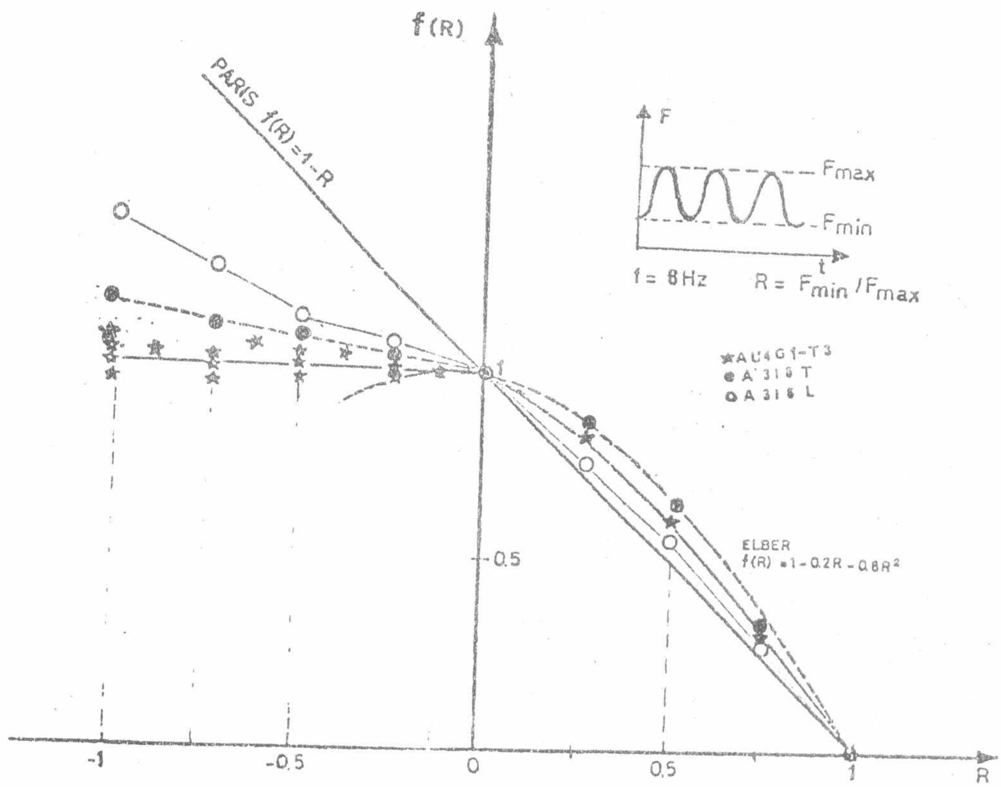

Fig.6. Function of Influence of the Stress Ratio.

Comparing fig.4. with fig.5. it is observed that the assumed function for f(R) have improved the deviations of Paris' law.

INTERPRETATION OF THE RESULTS WITH ELBER'S THEORY

The previous work, usually the assumption has been made implicitly that a crack is closed under compressive stresses and open under tensile stresses. Elber [4] has shown experimentally that a fatigue crack produced under zero-to-tension loading closes during unloading and that large residual compressive stresses exist normal to the surface at zero load. Crack propagation can occur only during that portion of the loading cycle in which the crack is fully open at the crack tip. the effective stress intensity range is defined as [4]

$$\Delta K_{eff} = K_{max} - K_{op} \tag{5}$$

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where K_{op} is the crack opening stress- intensity factor. An effictive stress range ratio (Elber ratio) is then defined as

$$U = \frac{\Delta K_{eff}}{\Delta K} = \frac{K_{max} - K_{op}}{K_{max} - K_{min}} \qquad (6)$$

Based on the above, it seems reasonable to expect that an analysis of crack propagation rates may utilize the effective stress range concept as follows :

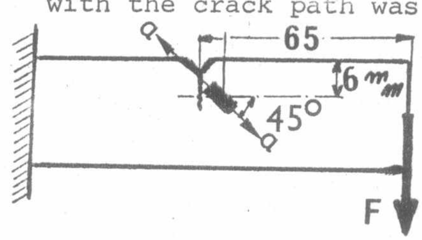
$$\frac{da}{dN} = C'(\Delta K_{eff})^{m'} = C'(U \Delta K)^{m'} \qquad (7)$$

The determination of the crack closure stress must, therefore, be a necessary step in the stress analysis of a cracked structure.

The known methods for measuring the crack closure experimentally are :

a- Crack opening displacement gauge [4]
b- Schmidt gauges [5]
c- Electric potential method [6]
d- Acoustic technique [7]
e- Laser interferometry [8]
f- Crack tip-strain loap [9]
g- Ultrasonic Mothod [7]

In the present work , a strain - gauge of 45° with the crack path was installed over the surface of specimen.



As an example of obtained results as a force - strain diagrams, for AU4G1-T3 Al. alloy, fig.7. indicate that the loading take place in three stages. Initially, the crack remains completely closed producing a linear record which follows that of a specimen containing no crack at all. The crack then begins to open a little at a time producing a non linear record which finally becomes linear again when the crack is completely open. The points on figure 7. then represent the values for the load at complete opening for different crack length (the measurements were done each 0.5 crack length increment) the opening force decreases with increase of the crack length. Fig.8. indicates the variation of ratio $U=f(K_{max})$, for different values of R.

The expression of U developed in the present work is a function of K_{max} and R for AU4G1-T3 Al.alloy as

$$U = (0.424 + 0.204R) + (4.64 + 1.68R)\frac{K_{max}}{1000} \qquad (8)$$

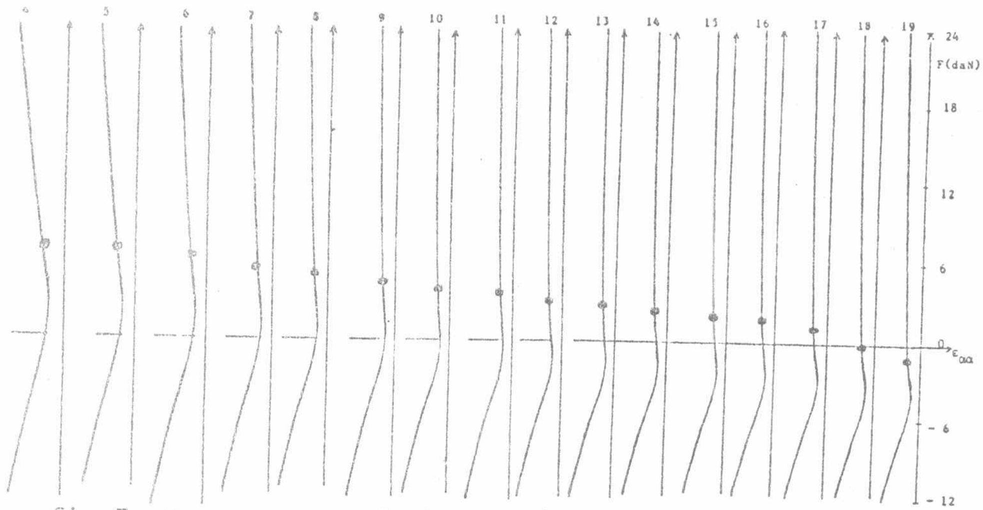


fig.7. Measurement of the opening force of the crack
$R = -0.5$, $F_{max} = 24$ daN

Where K_{max} was measured in hb $\sqrt{mm}$
A series of experiments were performed to establish the constants of Elber Equation, fig. 9. shows that these constant are:

$C' = 66.83.10^{-9}$

$m' = 2.49$

Previously, the constants for Pairs equation fig.4. are :

$C = 3.72.10^{-9}$

$m = 2.94$

Moreover, a series of experiments were performed to establish the crack propagation rate according to Elber Equation for Aisi 316.

Fig. 10 shows the variation of $U=f(K_{max})$ for R=O and different maximum forces such that U=1 when the crack has no closure.

This variation of "U" for Aisi 316 has no generalized form as equation (8) this is because of large cyclic plastic zones at crack tip and anisotropy of material for specimen "L" and "T".

The crack growth rate as a function of effective stress intensity range for Aisi 316 is shown in Fig.11.
Elber constants are

$C' = 1.61.10^{-9}$, $m' = 2.62$

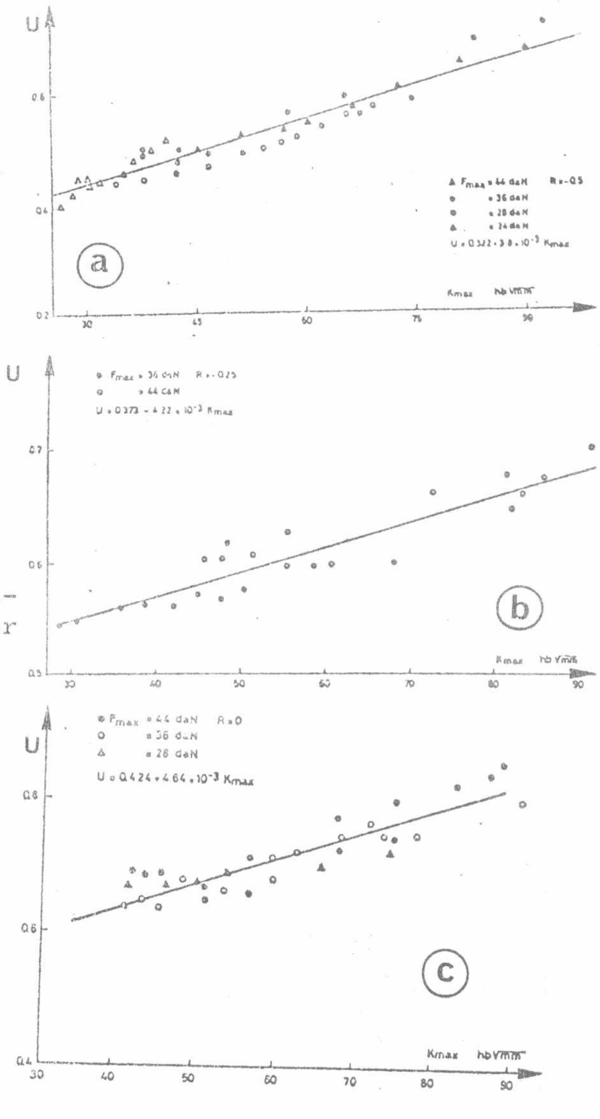


Fig.8.: Variation of U= $f(K_{max})$
for AU4G1-T3 a) R= - 0,5
b) R=-o.25 c) R= O

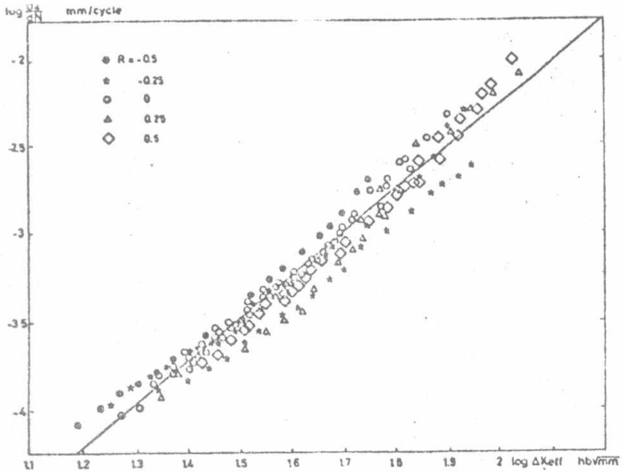


Fig.9. Variation of

$\frac{da}{dN} = f(\Delta K_{eff})$

For AU4G1- T3

Al.Alloy.

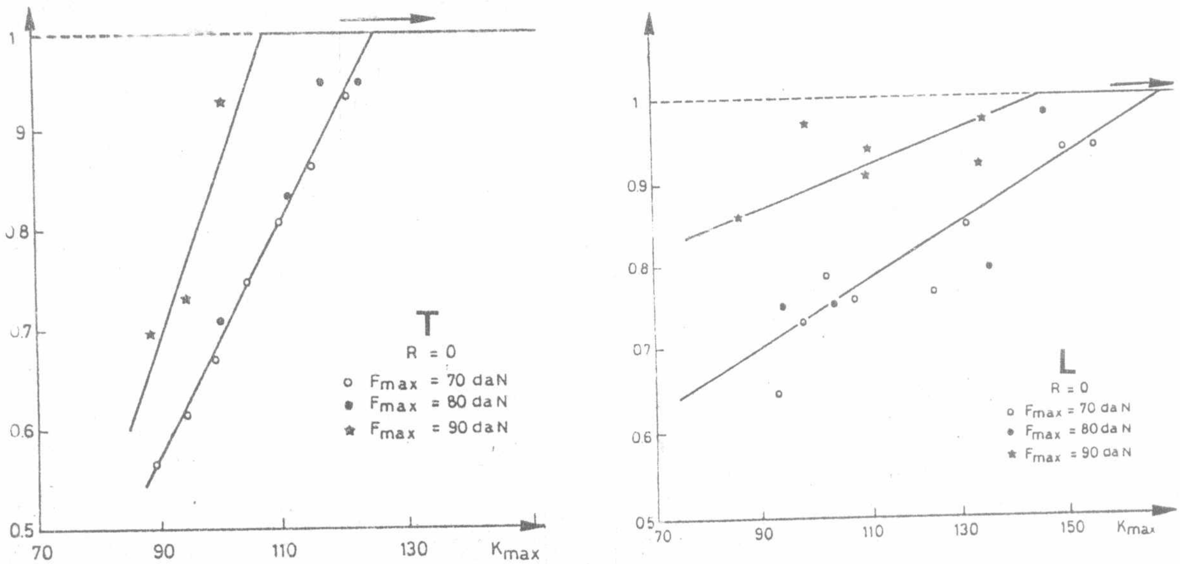


Fig. 10. : Variation of $U = f(K_{max})$ for Aisi 316

a- Specimen T b- Specimen L

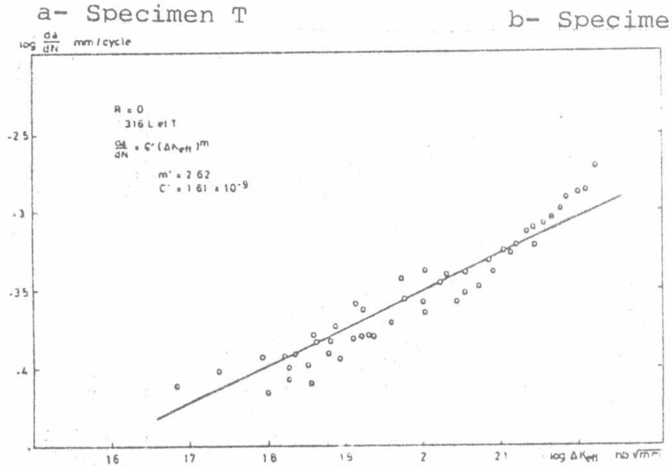


Fig.11. : Variation of $\frac{da}{dN} = f(\Delta K_{eff})$ for Aisi 316.

THE EFFECT OF A SINGLE OVER LOAD

Fig. 12. shows the crack length as a function of number of cycles for different over load ratio

$$R_{oL} = F_{oL} / F_{max}.$$

Several models have been developed to explain the observed crack- growth-retradation behaviour following a single overload cycle. These models consider the single or combined effect of the following mechanisms, developed

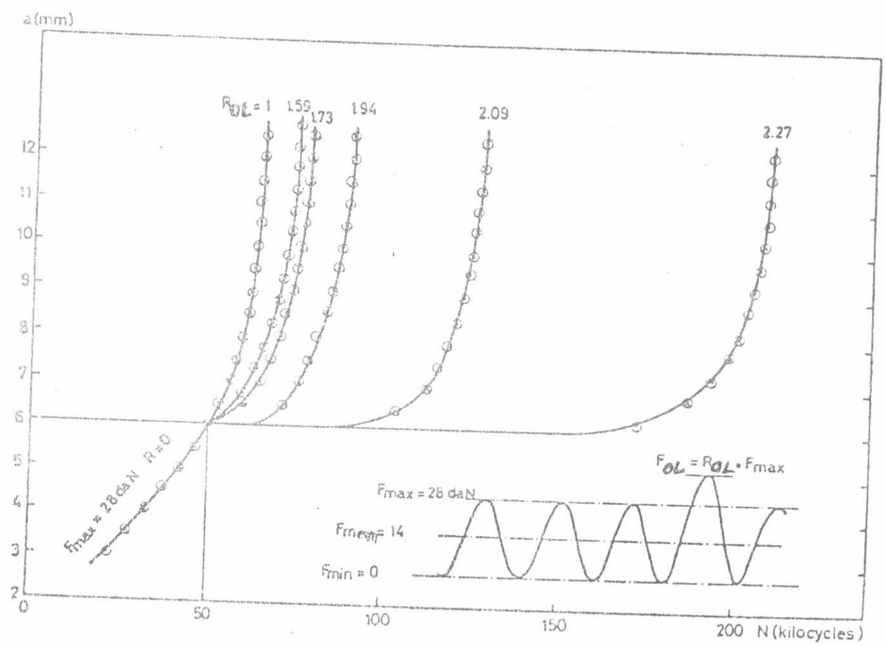


Fig. 12. Tests with a single overload (F_{min} = o)

as a result of overloading [10] :

a- residual compressive stress developed around crack tip (HUDSON, HARDRATH, SCHIJVE)

b- crack closure behined crack front after overloading and unloading (Rice, Elber)

c- plastic zone-interaction or changes in crack tip plastic -zone size (wheeler)

d- change in crack tip geometry or crack blunting (Srawely, Swed law, Roberts)

e- strain hardening from overload (Johnes).

Fig. 13. indicate the measurement of the opening force just before, during and after a single overloading cycles of R_{OL} = 2.26 at crack length a_{OL} = 6 mm, it was noted that there was no crack closure after this overload.

The following table gives the measured values of opening force for different overload ratios "R_{OL}" for the case of R=O and maximum force equal 28 daN. Hence the notation of crack closure was insufficient to explain the influene of loading of variable or Random amplitudes. To explain the

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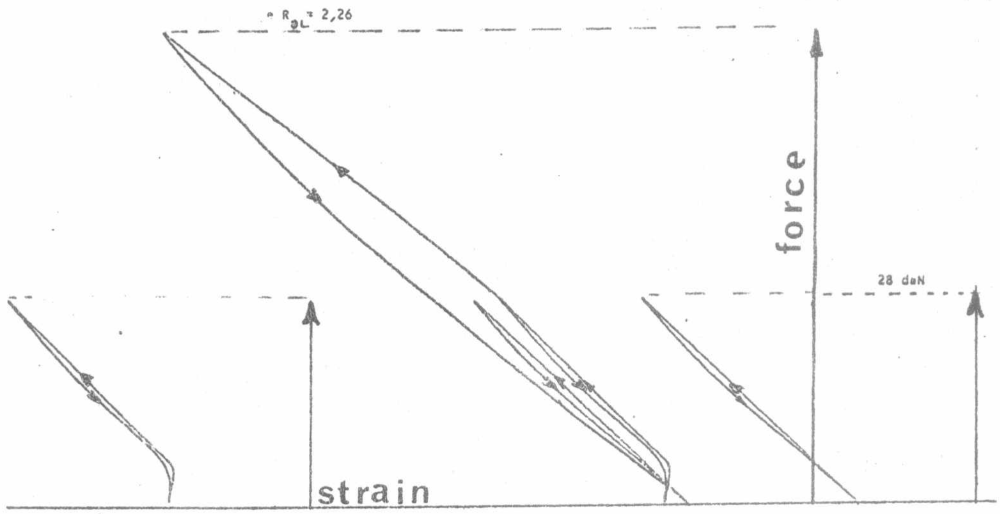
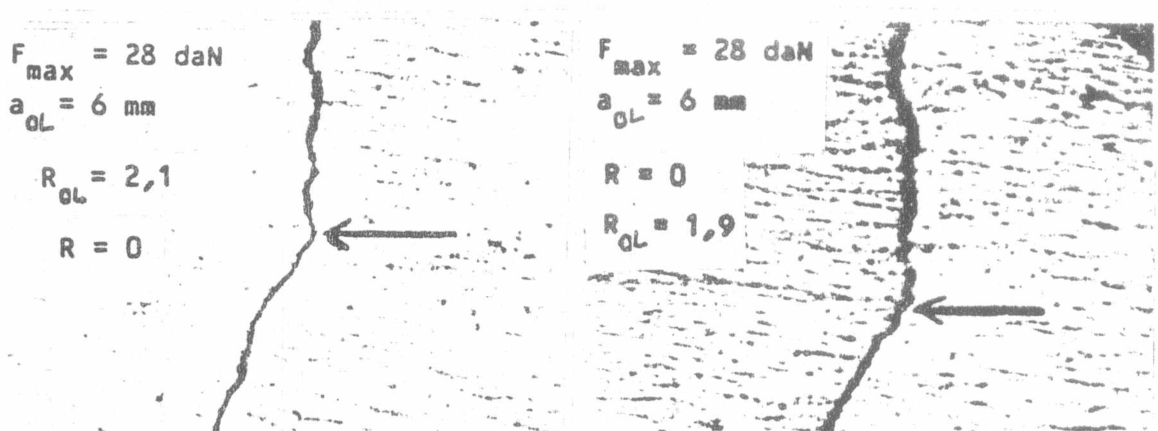


Fig.13. The variation of crack opening force caused by a single over load.

$R_{oL} = \frac{F_{oL}}{F_{max}}$	F_{op} [da N]
1.59	8.2
1.94	6.3
2.o8	5.2
2.26	no closure

retardation due to a single over load, it is necessary to make precise study of the behaviour in tip of the crack. Photo (1) explains the reason for retardation due to a single over-loading.

The cracked path changes its direction after the opplication of a single over load cycle qnd once more the initiation is done in differently new direction followed by propagation.



Photos (1) Mode of propagation of the crack due to application of a single over load.

CONCLUSION

In this work, a proposed technique was presented to study crack growth rate. Although most of researchers had dealt with axial loading the authors have analysed the crack propagation under bending load and consequently the buckling has no effect. The controlling parameters in the governing equations were obtained experimentally. The crack closure was determined experimentally using a strain gauge inclined 45° to the crack path. The experiments have shown that the crack closure depends not only on the stress ratio "R" but also on the maximum stress intensity factor K_{max}. The sheet rolling direction gives anisotropic behaviour on initiation, propagation and closure of the crack. It has shown experimentally, that the crack deviate from its path just after the application of a single over load, and this may explain the phenomenon of retardation. Therefore, it is necessary to make a further research to study the material behaviour in front of the crack tip.

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