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# Slow-crack propagations through bimaterial interfaces studied by scanning electron microscopy

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The scanning electron microscope (SEM) is used for the study of slow crack propagation through a bimaterial interface. This work is concerned with the variation of crack velocity, the variation of crack tip opening angle (CTOA) and the stress intensity factor ($K$) at the crack tip, and the investigation of crack arrest phenomena at the bimaterial interface. It was observed that the crack accelerates to a maximum velocity as the crack tip approaches the interface and then decreases rapidly to a minimum value at the interface. The interface acts as a "decelerator" to crack propagation. The position and the value of the maximum velocity depends on the mechanical properties of two phases and specimen configuration. The crack propagates at a constant CTOA until it arrests at the interface. During the crack-arrest time the CTOA increases rapidly to a limiting value. Then the crack passes across the interface and propagates in the next phase with almost the same CTOA as the initial crack in phase I. The stress intensity factor, $K$, increases to a maximum value near the bimaterial interface.

## 1. Introduction

The study of crack propagation in composite materials and the investigation of phenomena which are observed when the crack tip touches the interface of a bimaterial specimen are of great interest.

Zak and Williams [1] studied the stress singularity at the crack tip, Cook and Erdogan [2] encountered the same problem using the Mellin transform. Bogy [3], also using the Mellin transform, solved the problem of the crack tip singularity of a stable crack, terminating at any angle to a plane bimaterial interface. The problem of the order of singularity at a multi-wedge corner of a composite plate has studied by Theocaris [4], who also [5] evaluated the order of the singularity of the crack tip when it touches the interface at any angle, by the method of reflected caustics.

All these papers treat the interface as ideal, assuming that the materials are perfectly bonded along a surface of zero thickness. In addition, the analysis of the stress system is a static one and, in principle, does not allow any prediction about the dynamic behaviour of a fast- or slow-running crack, crossing a real interface. Other studies consider the interface as a third intermediate phase with its own mechanical properties, acting as a material discontinuity [6].

The problem of dynamic interaction between a propagating crack and a real interface has been also studied [7, 8] by means of dynamic photoelasticity, focusing on the variation of the stress intensity factor in the different material phases. The problem of transient phenomena when a crack crosses the boundary of two different phases has been studied in a global and extensive way by the method of caustics (Theocaris and co-workers [9, 10]), which gave results about the crack velocity and the variation of the stress intensity factor at the crack tip. The senior author of these references has also faced the problem of a slow stable brittle crack growth in poly-methyl-methacrylate), using the optical method of caustics [11].

In the present work an investigation was undertaken for a slow crack propagation in ductile bimaterial specimens. The study concerns the variation of the crack velocity, the CTOA and the stress intensity factor during crack propagation and the crack arrest phenomena when the crack tip touches the interface. The paper describes the experimental procedure and the observed results.

## 2. Preparation of specimens and experimental procedure

The materials for all specimens were prepared from a pure cold-setting epoxy pre-polymer Shell Epicote 828 polymerized by the addition of 8% triethylenetetramine (TET) hardener per weight of the epoxy prepolymer. The plasticizer, added from 0 to 90% of the epoxy prepolymer in steps of 10% was a polysulphide polymer Thiokol LP3.

The specimens used in the tests were bimaterial epoxy-polymer specimens with a length of 60 mm, a width of 6 mm and a thickness of 3 mm. Every specimen was composed of two phases (Fig. 1) with width $w = 3$ mm and at the free boundary of phase I an initial transverse slit of length $a_0 = 0.5$ mm was introduced in advance by cutting phase I with a thin razor blade.

The two faces were bonded together without any further adhesive layer by casting the material of phase II along the interface of the already prepared phase I. After consolidation of phase II, the bimaterial plate was treated thermally for one week with a maximum temperature of 110° C and a temperature gradient up

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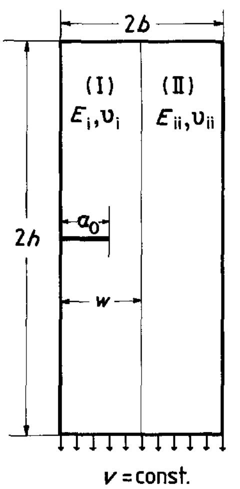

*Figure 1* Geometry of the cracked specimen.

and down of 3° C $h^{-1}$. The reason for this treatment was to ensure total polymerization and an interface with minimum shrinkage stresses, much lower than the singular components of stresses.

All specimens were polished and coated with an aluminium coating to prevent charging effects on their surface from the high voltage of the electron beam. The microscope was the S4-10 scanning electron microscope made by Cambridge Scientific Instruments and the Stereoscan tensile specimen stage of the same company. SEM parameters were: beam voltage 20 kV, beam current 200 mA, filament current 3.5 A, jaw velocity varying 0.001 to 1.0 mm $\text{min}^{-1}$ and maximum load capacity 2226 N.

The specimens were put in the tensile specimen stage of the microscope and submitted to a constant strain rate $\dot{\varepsilon} = 1.3 \times 10^{-3}\,\text{sec}^{-1}$. In each step of crack-propagation the crack tip zones were photographed, using a magnification factor equal to 1000. We determined the factors which influence the mode of crack propagation, the crack arrest phenomena at the interface, the variation of the stress intensity factor, the variation of CTOA and the crack propagation velocity at the vicinity of the interface.

## 3. Experimental results and discussion

In order to study the crack propagation and the transient phenomena developed at the time when the crack is reaching the interface, all our experiments were concentrated at the vicinity of the interface and on the side of phase I. This phase I, whose free longitudinal boundary contained an initial crack of length $a_0 = 0.5$ mm, was always prepared from an epoxy resin containing 90% plasticizer and presenting an elastic modulus $E = 0.30\,\text{GN}\,\text{m}^{-2}$ and Poisson ratio $\nu = 0.495$. This plasticized polymer was selected to allow a slow propagation of the crack at a strain-rate $\dot{\varepsilon} = 1.3 \times 10^{-3}\,\text{sec}^{-1}$, which facilitated the observation of the progress of the crack. Phase II was always more brittle than phase I, with an elastic modulus within the values 0.30 to 1.82 GN $\text{m}^{-2}$. Figs. 2a and b and 3 a and b contain a series of photographs of the propagating tips where the shape of the crack approaching the interface is apparent for different values of the ratio $E_I/E_{II}$. Fig. 2a corresponds to a ratio $E_I/E_{II} = 1.0$, while Figs. 2b, 3a and 3b correspond to ratios $E_I/E_{II} = 0.94$, 0.60, 0.33, respectively.

In all cases, the crack approaches the interface with a constant value for the crack tip opening angle (CTOA) (Figs. 2a(1), 2b(1), 3a(1), 3b(1)). At the moment when the crack tip reaches the interface, the crack arrests and the CTOA increases (Figs. 2a(2), 2b(2), 3a(2), 3b(2)). At this stage, the crack remains stable, while the CTOA increases until it reaches a limit value (Figs. 2a(3), 2b(3), 3a(3), 3b(3)). The next step is the crack propagating through the interface, creating a new crack in phase II (Figs. 2a(4), 2b(4), 3a(4), 3b(4)). In this second phase we see that the CTOA is about equal to the corresponding values of the initial CTOA of phase I.

The above observations are valid for all types of biphase specimens studied independently of the respective values of the mechanical properties of their phases. Of course the parameters characterizing this transient phenomenon, namely the velocity of crack propagation, the CTOA variation during the crack propagation and finally the $K$ variation, are changing from specimen to specimen and they depend, among others, on the mechanical properties of the phases, as well as on the properties of the interfacial band.

### 3.1. The velocities of crack propagation

We have carried out experiments using combinations of epoxy polymers yielding values for the ratio $E_I/E_{II}$ from 1.00 to 0.16 for a constant value $E_I = 0.30\,\text{GN}\,\text{m}^{-2}$ for the elastic modulus of phase I. We related $E_I/E_{II}$ to the variation of crack velocity and the influence of the properties of phase II. The instantaneous crack velocity was evaluated by dividing an almost constant length of 100 $\mu$m of crack expansion by the corresponding time interval.

Fig. 4 presents the curves of crack velocity against the distance between the crack tip and the interface. These curves correspond to six different values of the $E_I/E_{II}$ ratio, between 0.16 and 1.00. For comparison, the crack velocity in a plain specimen with the same elastic modulus as phase I is given.

All these curves have the same form. The curves, starting from zero, are increasing continuously and smoothly as the crack extends, reaching their maximum values before reaching the interface. They then decrease rapidly to a minimum value as they reach the interface. This minimum value can be zero corresponding to crack arrest.

Note that the maximum values for the crack velocities are further from the interface as phase II becomes harder, i.e. as the ratio $E_I/E_{II}$ becomes smaller. So, if the distance between the initial crack tip and the interface is $a = 2.75$ mm the maximum for $E_I/E_{II} = 0.16$ is located at $a = 2.37$ mm, while for $E_I/E_{II} = 1.0$ the maximum is at the position $a = 2.69$ mm.

In addition, we note that the maximum values of crack velocities are proportional to the ratio $E_I/E_{II}$. For $E_I/E_{II} = 0.16$ the maximum value of the crack velocity is $1.8 \times 10^{-5}\,\text{m}\,\text{sec}^{-1}$, while the maximum value of the crack velocity for $E_I/E_{II} = 1.0$ is $5.28 \times 10^{-5}\,\text{m}\,\text{sec}^{-1}$. On the other hand, the variation

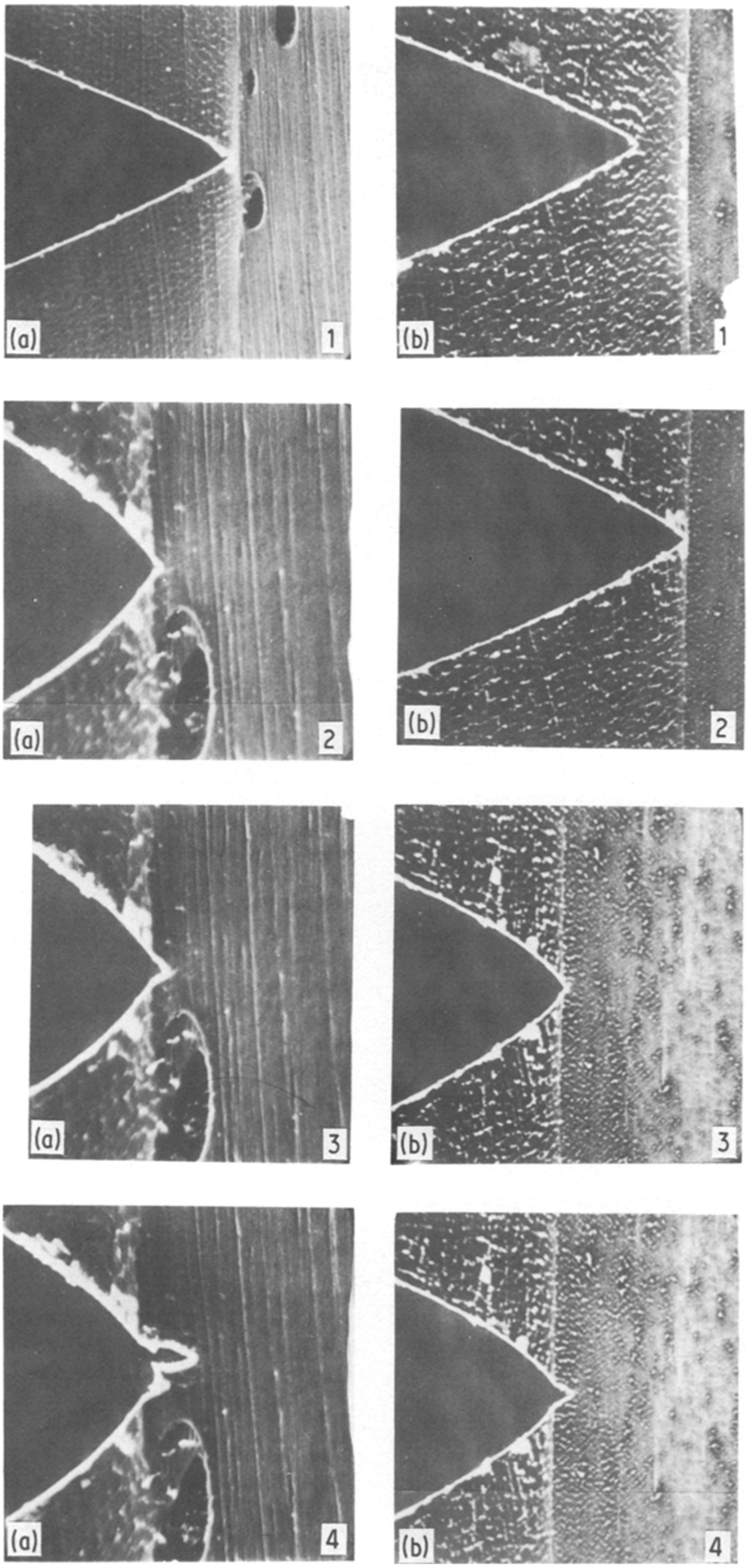

*Figure 2* Series of photographs showing crack propagation in a bimaterial specimen. (a) $E_I/E_{II} = 1.00$; (b) $E_I/E_{II} = 0.94$.

of the crack velocity for a specimen with the same value of the elastic modulus continues to increase as the crack length increases.

We examine now the values of the maximum crack velocities for different values of the ratio $E_I/E_{II}$ and for different values of the ratio $w/a_0$, where $w$ is the width of phase I and $a_0$ is the length of the initial crack. We observe that, for a given ratio $w/a_0$, the values of the maximum crack velocities increase in a similar way as the ratio $E_I/E_{II}$ increases (Fig. 5). This means that, for

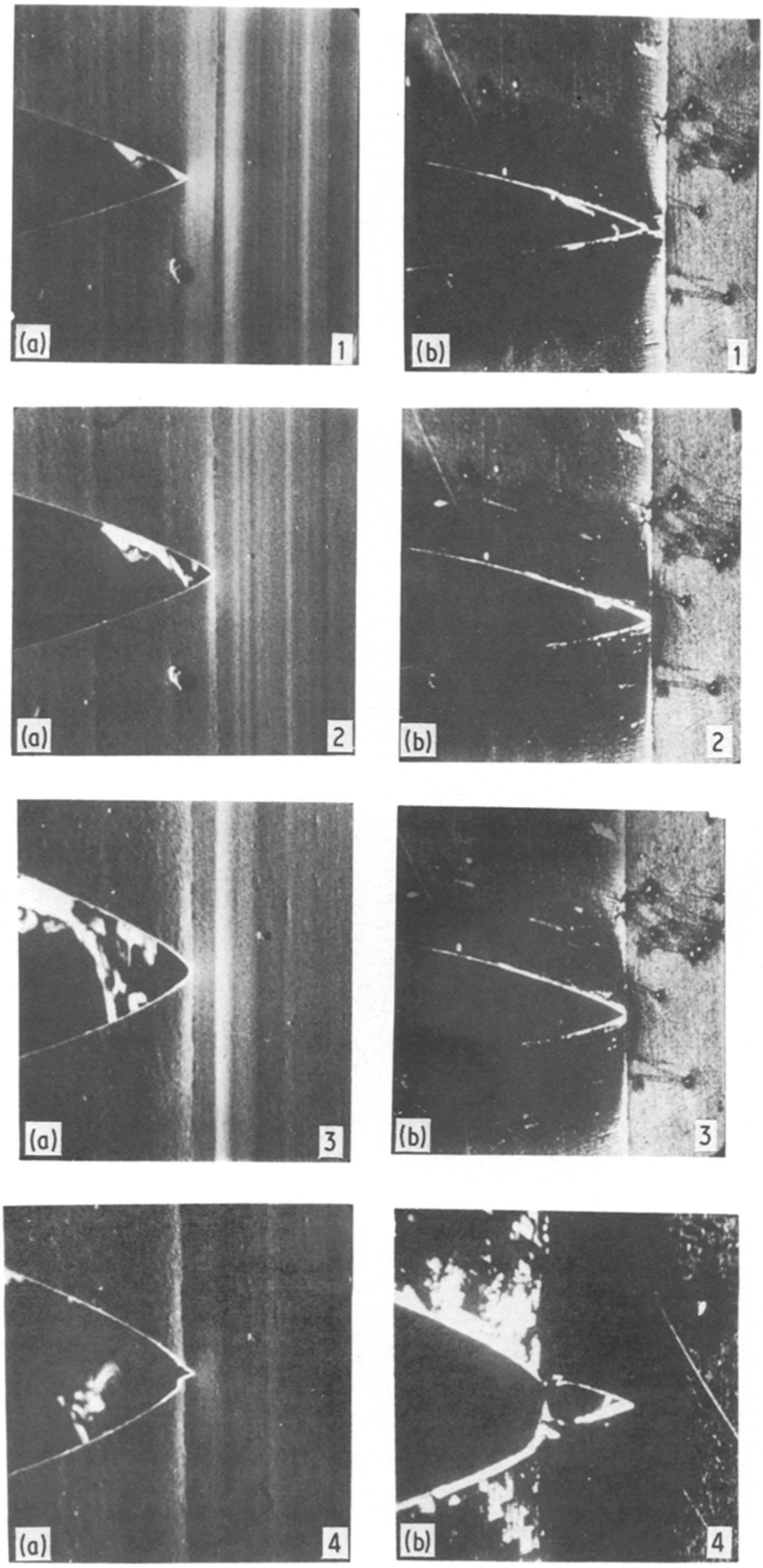

*Figure 3* Series of photographs showing crack propagation in a bimaterial specimen. (a) $E_I/E_{II} = 0.60$; (b) $E_I/E_{II} = 0.33$.

the same specimen configuration the maximum velocity increases as the phase II becomes softer.

### 3.2. Crack tip opening angle (CTOA)

The variation of CTOA during the propagation of the crack is presented in Fig. 6. This quantity was measured directly in photographs of the crack tip area at various steps of crack propagation (see Figs. 2 and 3). At the beginning of the test the CTOA is roughly zero. Under increasing load, CTOA increases con-

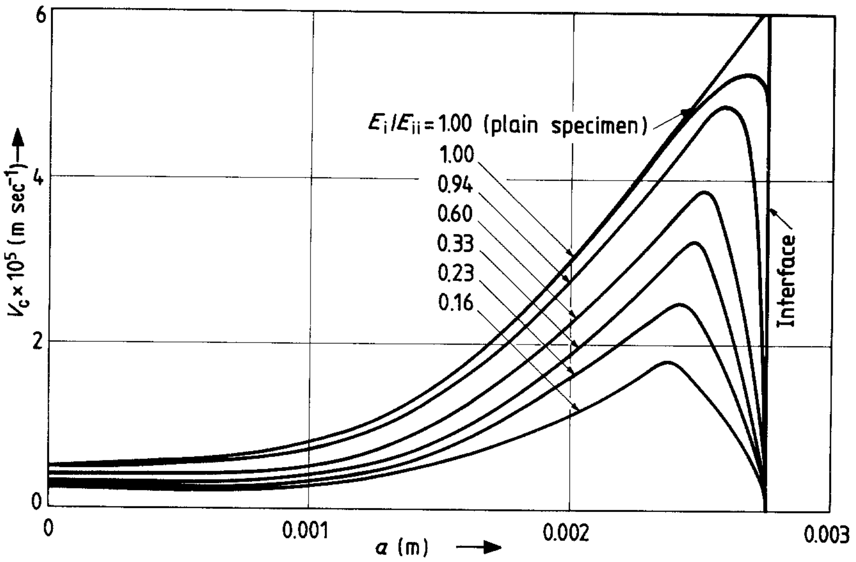

*Figure 4* Variation of crack velocity with $w/a_0$ ratio.

tinuously until an upper critical limit for the angle is reached. Then, the crack propagates at a constant value of CTOA. At the moment the crack tip reaches the interface, crack propagation stops, the crack arrests, and the CTOA increases until another critical value is attained. At this point a new crack is initiated in phase II, with almost the same value for the CTOA as that of the initial crack in phase I.

The curves presented in Fig. 6 are plotted for the values 0.94 and 0.33 of the $E_I/E_{II}$ ratio, respectively. For these cases the initial values of CTOA were 52° and 42°, respectively, while the final limiting values were approaching 180° during the crack arrest (see also Figs. 2 and 3).

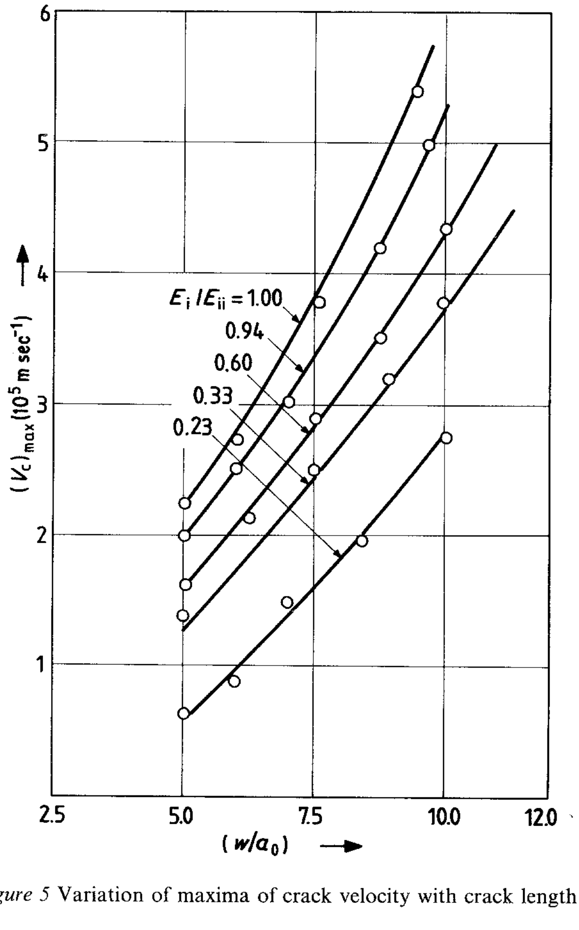

*Figure 5* Variation of maxima of crack velocity with crack length.

### 3.3. Stress intensity factor ($K$)

In order to calculate the variation of $K$ during crack propagation, the well-known simple relation was used to calculate K:

$$K = Y\sigma a^{1/2} \qquad (1)$$

where $Y$ is a correction factor depending on the dimensions of the specimen and on the ratio $a/L$, ($a$ is the crack length and $L$ is the width of the specimen) and $\sigma$ is the applied stress [12] measured in our experiments directly by the load machine.

If we define $K_0$ for the initiation of cracking with values $Y_0$, $\sigma_0$ and $a_0$ and $K_I$ when the crack is propagating with values $Y_I$, $\sigma_I$ and $a_I$, then the ratio $K_I/K_0$ is given by:

$$\frac{K_I}{K_0} = \frac{Y_I}{Y_0}\frac{\sigma_I}{\sigma_0}\left(\frac{a_I}{a_0}\right)^{1/2} \qquad (2)$$

The variation of the ratio $K_I/K_0$ during the crack propagation is presented in Fig. 7. The two curves correspond to ratios $E_I/E_{II} = 0.25$ and 0.94, respectively.

We observe from this figure that, for both cases, $K$ is increasing smoothly from an initial value to a limiting one when the crack is reaching the interface. This limiting value is eight times greater than the initial one, when the ratio $E_I/E_{II} = 0.94$ and ten times when the ratio $E_I/E_{II} = 0.23$. Taking into account that phase I has the same elastic modulus in both cases studied we may conclude that the limiting value for $K$ is increasing as phase II is becoming more brittle.

## 4. Conclusions

1. During the slow crack propagation in ductile biphase plates, the crack velocity increases smoothly to a maximum value developed near the interface zone, and then it decreases rapidly to a minimum value when the crack reaches the interface. This behaviour means that the interface acts like a decelerator of the crack propagation velocity.

2. For a given elastic modulus of phase I, the position of the maximum velocity, as well as its value lie closer to the interface as phase II becomes more ductile than phase I.

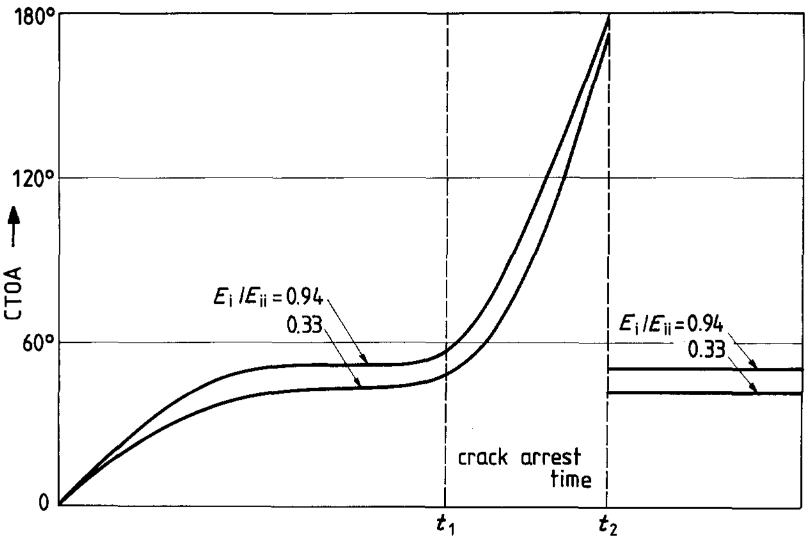

*Figure 6* Variation of CTOA during crack propagation in bimaterial specimens.

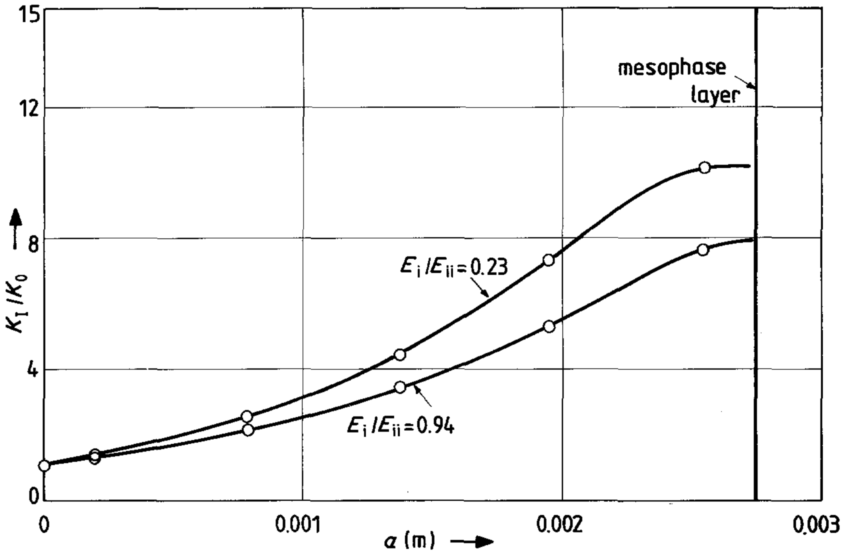

*Figure 7* Variation of SIF with crack length.

3. For a given width of phase I, the maximum value of the crack-propagation velocity becomes higher as the initial crack length is smaller.

4. The crack propagation takes place with constant limiting CTOA until the interface is reached, whereas during the crack arrest time it increases rather rapidly to another limiting value.

5. The new crack which is created in phase II has almost the same CTOA as that of the initial crack in phase I.

6. The SIF increases during crack propagation and the increasing rate is inversely proportional to the ratio $E_I/E_{II}$ of the elastic moduli.

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