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CRACK ARREST IN DUPLEX SPECIMENS

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Abstract—Dynamic photoelasticity with high-speed photographic recording is employed to study crack arrest and reinitiation in duplex specimens. The starter section of the duplex specimen is fabricated from Homalite 100, a brittle polyester and the arrest section is fabricated from a relatively tough epoxy. The two materials are joined with a tough, high shear-strength adhesive. The crack was observed to arrest abruptly with very short penetration into the adhesive layer. Crack tip decelerations of the order of 4×10^7 g's were estimated. The fracture affected zone of the arrested crack exhibited a diameter of about 0.5 mm. After arrest the stress intensity factor K increases rapidly with time as the kinetic energy in the modified compact tension specimen is converted to strain energy. If K achieves a sufficiently high value, the crack will reinitiate in the adhesive and extend into the arrest section of the duplex specimen. Otherwise, the crack remains at arrest and the K field at the crack tip oscillates.

INTRODUCTION

Theoretical studies of dynamic fracture are relatively recent; however, significant progress has been made[1–5] in describing the elastodynamic stress field at a crack tip during propagation. Experimental studies of dynamic fracture behaviour with dynamic photoelastic measurements have followed and have improved understanding of the stress intensity factor required for crack initiation, propagation and arrest.

Application of dynamic photoelasticity to studies of fracture was made first by Wells and Post[6]. These investigators showed that isochromatic fringe loops representing the stress field near the crack tip could be recorded. Irwin[7] in a discussion of Ref.[6] developed a two-parameter method of analysis for determining the stress intensity factor K from isochromatic fringe loops. More recently Etheridge[8] has developed a three-parameter method with improved accuracy and a somewhat wider range of applicability.

A. S. Kobayashi and his associates[9–12] have used photoelasticity to study fracture dynamics including crack branching and crack arrest in Homalite 100, a brittle polyester. T. Kobayashi and Dally[13] have extended these studies completely characterizing the fracture behavior of this material with a K vs crack velocity $\dot{a}$ relationship over the entire range of stress intensity factor from initiation K_{Ic} to branching K_{Ib}.

Application of dynamic fracture mechanics to engineering design is just now beginning and investigations of methods of measuring the material toughness associated with crack arrest are in progress. Several specimens which include the rectangular double-cantilever-beam (RDCB), the contoured double-cantilever-beam (CDCB) and a modified compact tension (MCT) are being considered in developing test procedures for measuring crack arrest. These specimens may be fabricated from a single piece of material, or they may be fabricated by joining two materials together to form a duplex specimen of say the MCT type. The typical duplex specimen illustrated in Fig. 1 utilizes a low toughness material in the starter section and the test material which exhibits a higher toughness in the arrest section.

There are several advantages of utilizing duplex type specimens in experiments designed to characterize the dynamic fracture characteristics of metals. The specimen with its brittle start section requires lower loads for crack initiation and the initiation can be more closely controlled. Because of the lower loads there are fewer specimen malfunctions due to excessive platic deformation or branching at the crack tip. Also the excess energy available after initiation is lower in the duplex specimen thus oscillation of the K field due to specimen vibration is reduced. Finally, the use of specimen material which is sometimes expensive and/or difficult to procure is minimized by employing relatively small arrest sections in the duplex specimen.

In spite of these advantages, two questions are raised pertaining to crack propagation in a duplex specimen. First, what is the effect of a step change in toughness of the two materials on the behavior of the propagating crack? Second, does the joint between the two materials influence the propagation behavior?

Dynamic photoelastic studies were conducted with duplex specimens fabricated from two different birefringent polymers in order to examine crack propagation in the duplex specimen. This paper describes the experimental procedure and the observed results.

EXPERIMENTAL PROCEDURE

The specimen selected for analysis was a crack-line-loaded (CLL) modified compact tension type which is defined in Fig. 2. The material employed in the starter section was Homalite 100 which is a relatively brittle polyester with a low toughness ($K_{Ic} = 0.44\,\mathrm{MNm}^{-3/2}$). The complete K vs $\dot{a}$ relation for this material was determined by Kobayashi and Dally[13].

The material employed in the arrest section was specially formulated tough epoxy (KTE_2) which contained 100 pph of Epon 828 (Shell Chemical Co.) 35 pph of Jeffamine D-400 and 5 pph

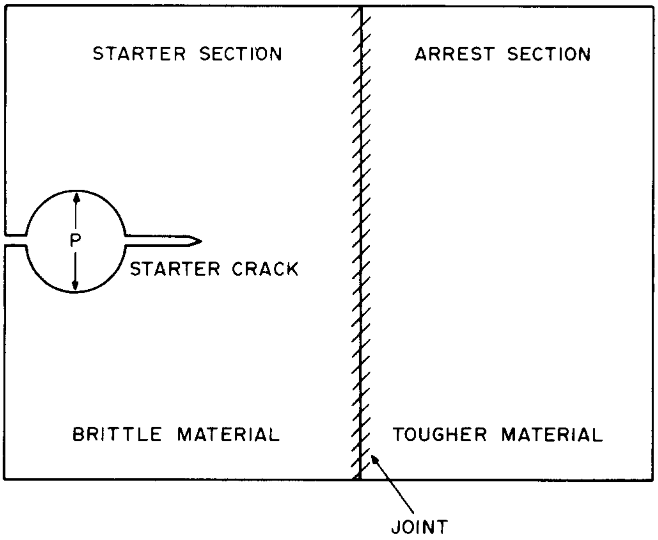

Fig. 1. Typical duplex specimen—transverse wedge loaded MCT type.

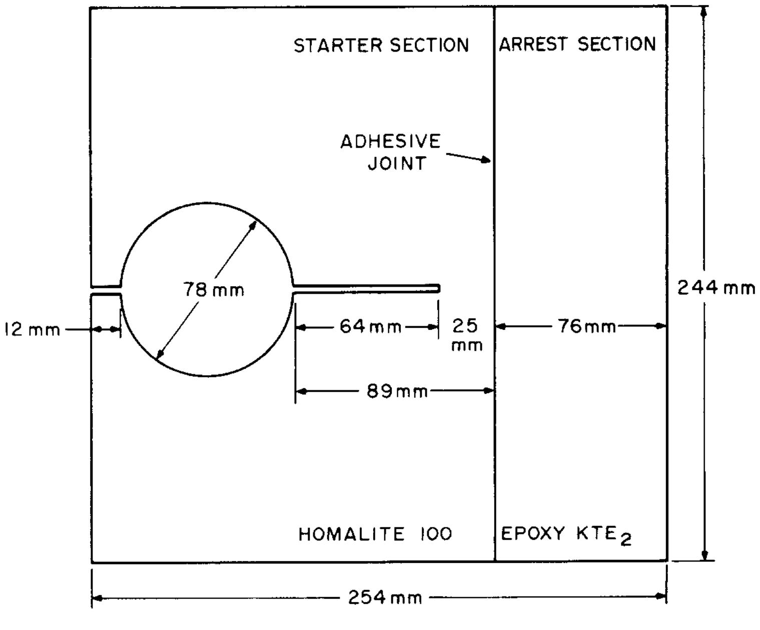

Fig. 2. Geometry of duplex specimen.

accelerator 398 (Jefferson Chemical Co.). This tough epoxy exhibited a $K_{Ic} = 0.90\,\mathrm{MNm}^{-3/2}$ and the complete K vs $\dot{a}$ curve was determined by Irwin *et al.* [14]. The ratio of $(K_{Ic})_A/(K_{Ic})_S$ was about 2.

The starter section and arrest sections were bonded together with a structural epoxy adhesive known as EA9410 and manufactured by Hysol Corp. This two part adhesive system is formulated to give a high shear strength (34.5 MPa) with a room temperature cure. While K_{Ic} of the adhesive has not been determined, it is estimated as $1.4\,\mathrm{MNm}^{-3/2}$. The thickness of the adhesive joint was varied from 0.025 to 0.36 mm. The surfaces of the specimen were faced and then polished to provide for a uniform and smooth transition from the starter section to the arrest section.

The initial crack was saw cut into the specimen and a 78 mm diameter hole was provided for a split D type loading fixture. A wedge moved in the direction perpendicular to the plane of the specimen forced the split D's apart applying load to the crack line. After applying the load necessary to give a prescribed (fixed) displacement, the crack was initiated by drawing a sharp blade across the crack tip.

The propagating crack cuts through a strip of silver conducting paint on the model and initiates a high-speed multiple spark camera[15] to record the dynamic isochromatic fringe loops near the crack tip. A typical set of isochromatic fringe patterns showing crack propagation in a duplex modified CT specimen is shown in Fig. 3. Inspection of these fringe patterns shows the propagation of the crack across the starter section (frames 2–4), the abrupt arrest of the crack at the adhesive joint (frame 5), the build-up of the K field at the arrested crack tip (frames 5–9), reinitiation of the crack in the arrest section (frame 10), and propagation and final arrest (frames 11–16).

These experimental results were reproduced in several tests where the initial K_Q value was sufficiently high to produce reinitiation of the arrested crack at the adhesive joint. In other experiments with lower K_Q values the crack arrested at the adhesive joint and K oscillated but did not become large enough to reinitiate the crack.

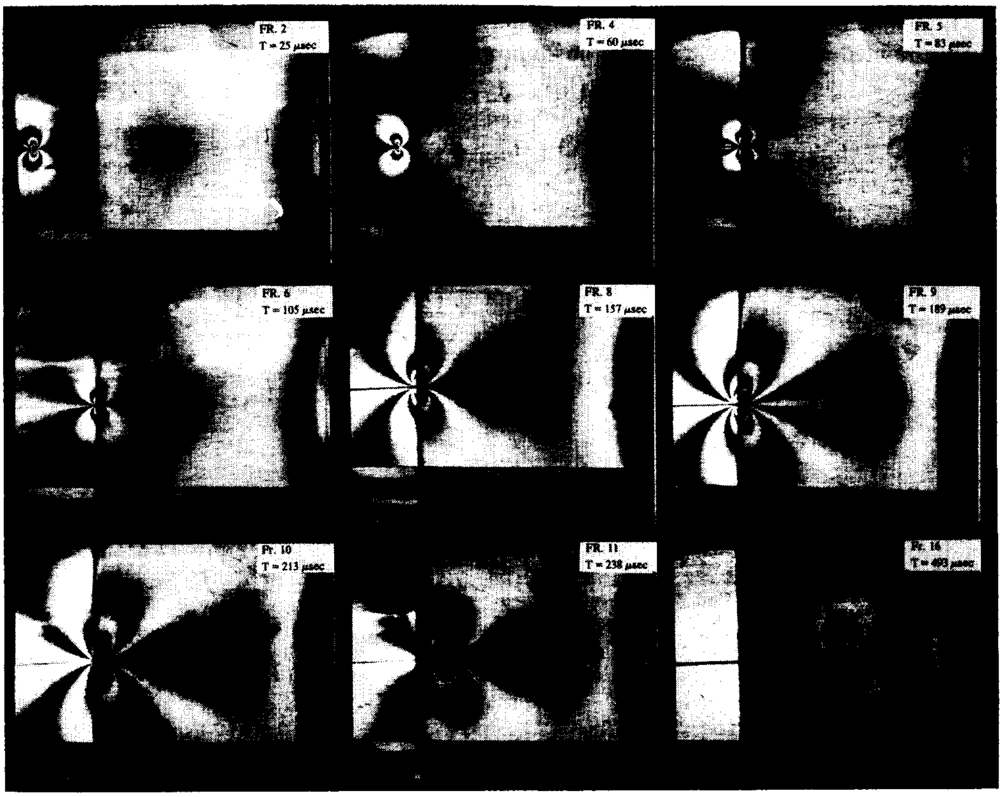

Fig. 3. Dynamic isochromatic fringe patterns showing fracture behavior in crack propagation across the joint in a duplex specimen.

RESULTS FOR CRACK ARREST AND REINIATION

A total of nine different specimens were tested in this series of experiments. The initial load (or displacement) P_Q was varied and the thickness h of the adhesive was changed. A listing of the models tested together with P_Q, K_Q, and h is presented in Table 1.

Table 1. Description of the duplex specimens

Model No.	Load/thickness P_Q/h (N/mm)	K_Q ($\mathrm{MNm}^{-3/2}$)	Adhesive joint thickness	Behavior
187	58.1	1.22	0.406	Arrest
178	70.0	1.47	0.356	Arr/Rein*
177	77.3	1.62	0.356	Arr/Rein
179	54.5	1.15	0.254	Arrest
185	64.6	1.36	0.152	Arrest
191	75.8	1.60	0.102	Arr/Rein
175	73.0	1.53	0.051	Arr/Rein
150	57.4	1.21	0.038	Arr/Rein
151	51.3	1.09	0.025	Arr/Rein

*Arr/Rein... arrest and then reinitiate

In six of these experiments, the crack propagated to the adhesive joint and abruptly arrested. The stress intensity factor increased until the crack reinitiated in the adhesive joint and propagated into the arrest section of the duplex specimen. The results for model No. 178 presented in Fig. 4 show the position of the crack tip as a function of time. It is evident that the crack in the starter section of the duplex specimen propagates at essentially constant velocity, 358 m/sec ($\dot{a}/c_2 = 0.29$) until it is abruptly arrested at the adhesive joint. The crack remains at arrest for a pause period t_p which in this instance was 128 μsec prior to reinitiation. Upon reinitiation in the epoxy material of the arrest section, the velocity is initially 237 m/sec ($\dot{a}/c_2 = 0.21$). As the crack extends sufficiently far into the arrest section, the stress intensity factor K decreases resulting in a progressive loss of velocity until final crack arrest occurs.

The pause time and the velocity in the starter and arrest sections for the six specimens which exhibited crack reinitiation are shown in Table 2.

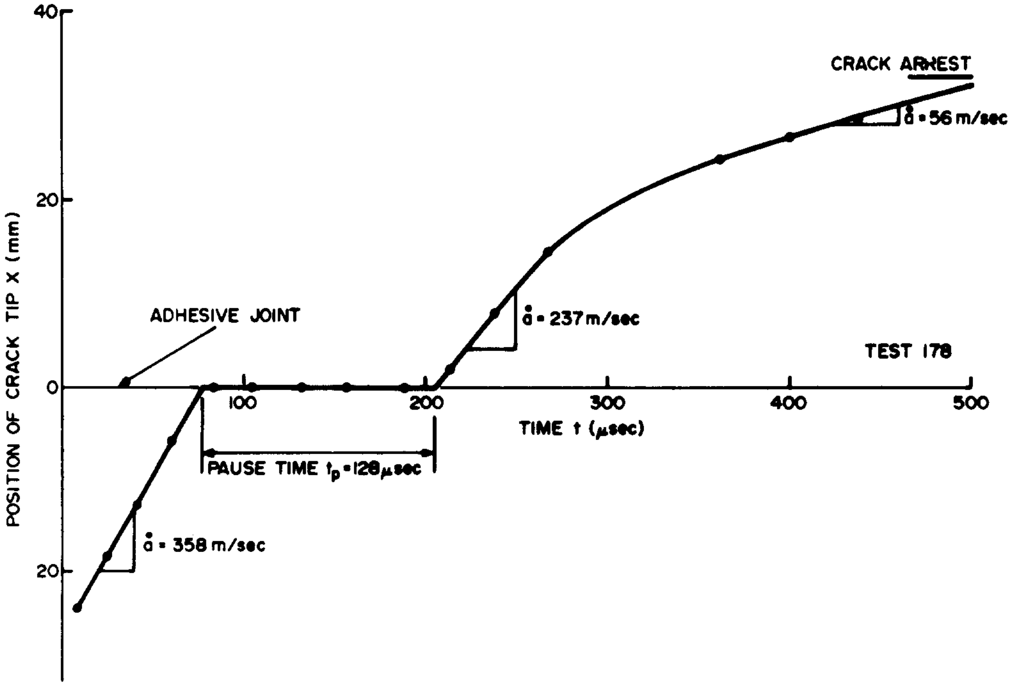

Fig. 4. Position-time function describing crack propagation across the duplex specimen.

Table 2. Results from duplex specimens which exhibited crack arrest and reinitiation

Model No.	Starter $\dot{a}/c_2$†	Arrest $\dot{a}/c_2$‡	Pause time t_p (μsec)	K (MNm$^{-3/2}$) Before arr.	K (MNm$^{-3/2}$) After rein.	$\dot{K} = \Delta K/t_p$ (MNm$^{-3/2}$/sec) × 10^3
178	0.29	0.21	128	0.58	1.24	5.16
177	0.32	0.33	144	0.74	1.39	5.14
191	0.27	0.25	120	0.70	1.28	4.83
175	0.32	0.20	126	0.69	1.41	5.71
150	0.27	0.20	81	0.88	1.24	5.30
151	0.27	0.18	68	0.77	1.00	3.34

†c_2 = 1240 m/sec for Homalite 100.
‡c_2 = 1135 m/sec for epoxy KTE$_2$.

Instantaneous values of the stress intensity factor K at the crack tip were determined from the dynamic isochromatic fringe loops by employing a modified two-parameter method of data analysis due to Etheridge[8]. Typical results showing the variation in K with crack tip position for Model No. 178 are presented in Fig. 5. As the crack approaches the adhesive joint at nearly constant velocity, the value of K decreases. However, after the crack arrests there is a significant increase in K (i.e. in this instance K increased by a factor of 2.1). After the crack extends through the adhesive and reinitiates in the epoxy or arrest section, K decreases to 0.87 MNm$^{-3/2}$ and then increase to 0.92 MNm$^{-3/2}$ on the last frame recorded. It is believed that K decreases to K_{Im} = 0.70 MNm$^{-3/2}$ in the post test period and the crack arrested.

The values of K as the crack arrests at the adhesive joint and the values just after reinitiation are presented in Table 2. The magnitude of K just prior to arrest depends upon K_Q and is independent of the adhesive joint which exhibits a toughness which greatly exceeds the instantaneous K as the crack tip reaches the joint. The value of K achieved prior to reinitiation is a function of the energy in the specimen, the toughness of the adhesive and the adhesive joint thickness. Variations in K required for reinitiation ranged from 1.00 to 1.41 MNm$^{-3/2}$ well above K_{Im} = 0.7 MNm$^{-3/2}$ for KTE$_2$.

The change in K with respect to time is presented in Fig. 6. These results show a monotonic

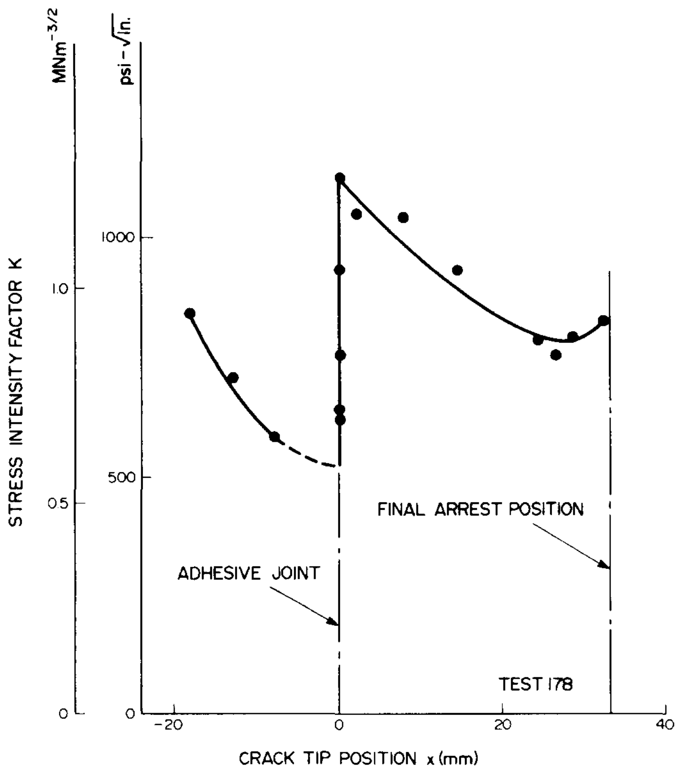

Fig. 5. Stress intensity factor as a function of position of the crack tip in a duplex specimen.

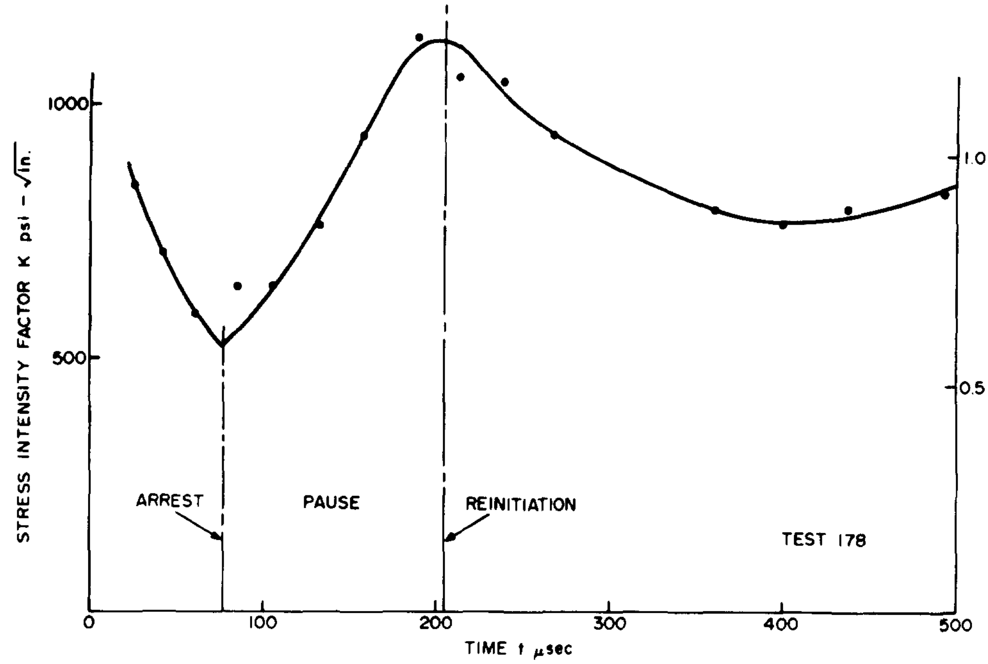

Fig. 6. Stress intensity factor as a function of time in a specimen with reinitiation.

increase in K over the pause period. The average rate of change, $\dot{K}$, given in Table 2 ranges from 3.34 to 5.15×10^3 $\mathrm{MNm}^{-3/2}$/sec. Additional tests were conducted with instrumented duplex specimens to simutaneously measure the applied load and the crack opening displacement. The oscilloscope record shown in Fig. 7 indicates that the crack opening displacement is constant for 2000 μsec which is much longer than the time required for arrest, pause and reinitiation. The force applied by the split D fixture oscillates with a large amplitude during the initial run-arrest portion of the experiment. It is clear from these results that the applied crack opening displacement is constant and the increase in K is due to a transfer of kinetic energy to strain energy.

Further indications of oscillations in K with time are evident in Fig. 6. A slight increase in K was recorded over the interval from $400 < t < 500$ μsec as the crack extended into the arrest section (statically a decreasing stress field) just prior to crack arrest. The magnitude of this oscillation is small (5%) and is the same order as the accuracy of the experiments.

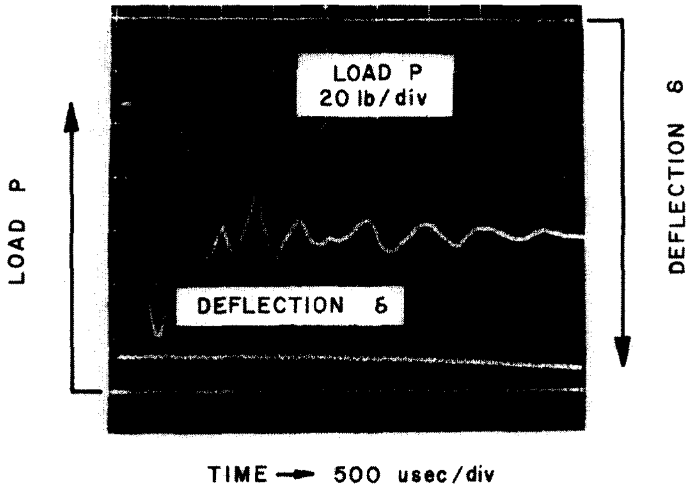

Fig. 7. Load and deflection as a function of time for the duplex specimen.

RESULTS FOR CRACK ARREST

In three of the experiments, the crack arrested at the adhesive joint and did not reinitiate. Inspection of Tables 1 and 2 show that that relatively low loads P_Q/h and thick adhesive joints are the conditions necessary for stable arrest. The variation of K with time for Model No. 179, a case of stable arrest, is presented in Fig. 8. It is evident that K decreases until the crack arrests, and following this arrest increases to a peak value of 1.21 $\text{MNm}^{-3/2}$. Apparently the toughness of the adhesive exceeded this maximum value of K and the crack remained fixed. The K value then decreased with time during the remaining part of the observation period.

A supplementary experiment was conducted to observe an extended time-period following arrest. In this instance, the camera was delayed 300 μsec after initiation of the crack in the starter section and the isochromatic fringe loops at the tip of the arrested crack were observed for $300 < t < 1000$ μsec. The results for K as a function of time in this post-arrest period are shown in Fig. 9. The oscillation of K with time has a frequency of approximately 1800 Hz. The maximum value of K, estimated at approximately 1.4 $\text{MNm}^{-3/2}$ was not sufficient to produce crack reinitiation in the adhesive joint.

APPEARANCE OF CRACK TIP

The appearance of the crack tip in the adhesive joint for two specimens was determined by taking photomicrographs. The procedure was to polish the surface of the specimen in the local neighborhood of the adhesive joint where the crack had arrested. Photomicrographs were made using obliquely reflected light and a magnification ratio of 100. The results obtained are illustrated in Fig. 10(a) and (b). In Fig. 10(a), the crack is shown to penetrate a distance of about 0.02 mm into the 0.36 mm thick adhesive joint. Ahead of the crack tip is a light region approximately circular in shape. This light region is due to crazing or microvoids which have developed in the fracture affected zone in front of the crack. The reflected light is intensified due to the presence of the craze and/or microvoids producing a light region on the photomicrograph. It is interesting to note that the diameter of the fracture affected zone is only about one-half the thickness of the adhesive joint. Thus it appears that arrest would have occurred under similar K conditions for a much thinner adhesive joint.

The photomicrograph for crack arrest in a thinner adhesive joint is presented in Fig. 10(b). In this instance, the crack has propagated only about 0.01 mm into the joint which was 0.15 mm thick. The light region, representing the fracture affected zone, approximately 0.14 mm in diameter, extends across the unfractured portion of the adhesive joint.

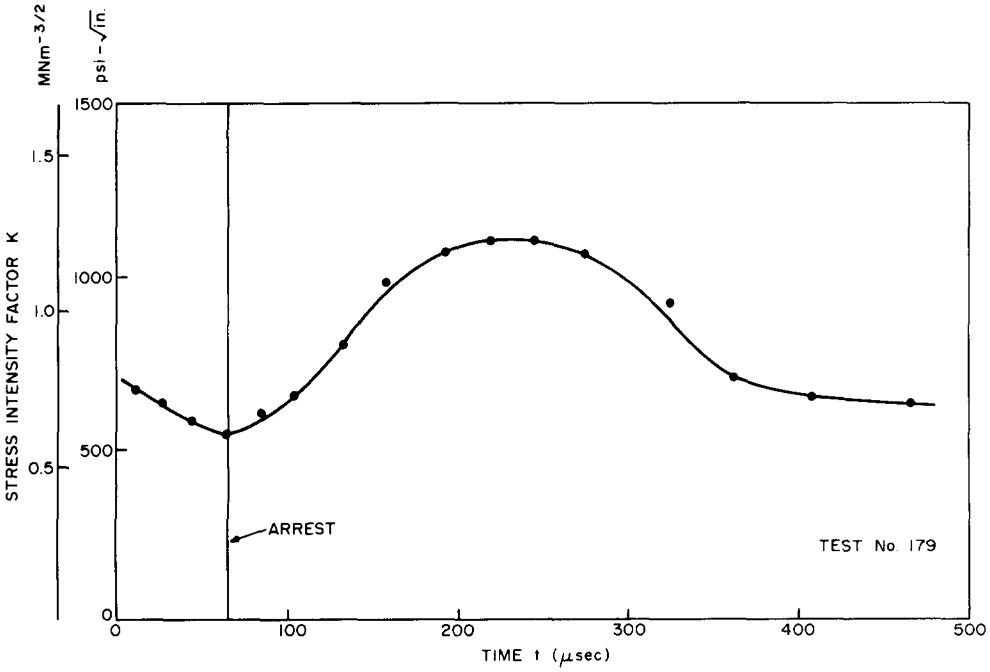

Fig. 8. Stress intensity factor as a function of time for a specimen with stable arrest.

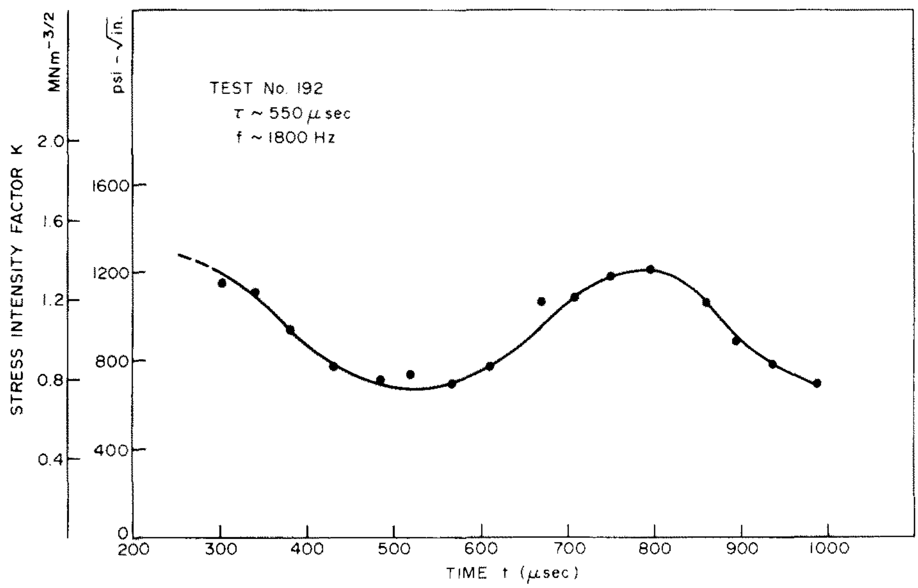

Fig. 9. Oscillation of K with time in the post-arrest period.

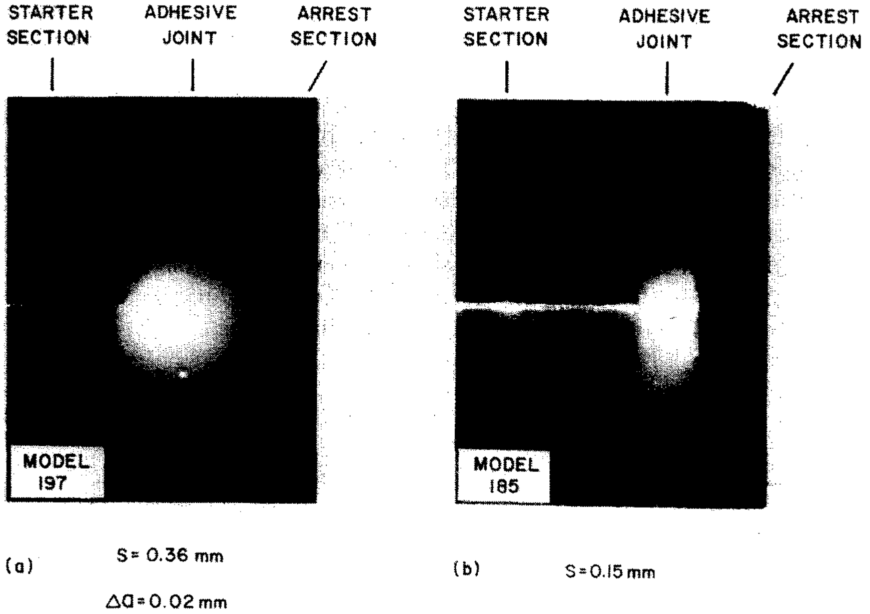

Fig. 10. Photomicrographs of the arrested crack in the adhesive joint (×100).

These results indicate that very thin layers of tough material serve to arrest cracks. The arrest occurs abruptly with extension into the arrest layer being only 0.01 to 0.02 mm.

CONCLUSIONS AND DISCUSSION

The duplex specimen offers many advantages in experiments to characterize the dynamic fracture characteristics of materials. However, the joint which fastens the brittle starter section to the tougher arrest section can markedly affect the behavior of the propagating crack. The experiments described here covered the case where the material in the joint was much tougher than either the starter section or the arrest section of the duplex specimen.

Experimental observations made with dynamic photoelasticity, instrumented test specimens and photomicrographs showed:

(1) The cracks arrest very abruptly. Several measurements showing the crack just prior to or after arrest indicate that the arrest time is about 1 μsec or less.

(2) The extension of the crack into the adhesive is quite small (0.01 to 0.02 mm) even when the crack is propagating at high velocity (381 m/sec) in the starter section.

(3) The average deceleration of the crack during arrest may be approximated by $\Delta\dot{a}/\Delta t$ which gives a values of 4×10^7 g's.

(4) The fracture affected zone exhibits a diameter of about 0.15 mm, indicating that adhesive layers of this thickness should be effective in arresting cracks. Even thinner adhesive joints will serve to arrest cracks but the K value required for reinitiation of the crack may be less if the joint thickness is less than 0.15 mm.

(5) After arrest the K value increases rapidly with respect to time as kinetic energy in the duplex specimen is converted to strain energy. If K is sufficiently high, the crack will reinitiate in the adhesive and extend into arrest section of the duplex specimen. If K is not sufficient for reinitiaition the crack remains at arrest and the K field at the crack tip oscillates at a frequency of approximately 1800 Hz.

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