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Comparison of the fast fracture properties of acrylonitrile–butadiene–styrene and styrene–acrylonitrile

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The resistance of polymers, with toughening agents, to fast crack propagation under steady load conditions was studied, and the fracture resistance of acrylonitrile–butadiene–styrene (ABS) was compared with styrene–acrylonitrile (SAN). Small laboratory specimens were used which could be precisely loaded and allowed to stress relax before being fractured. It was important for these experiments to achieve good isolation between crack initiation and crack propagation.

1. Introduction

The ratio of impact toughness to crack propagation toughness varies greatly between different materials. Also, geometric factors affect impact and crack propagation toughness conditions to different degrees. Many methods for evaluating fracture toughness of materials employ an impacting device to initiate a crack and also to drive a crack through the specimen. The Charpy and Izod methods are two examples of this technique but there are several others [1–3]. There are many advantages in being able to use small laboratory specimens to evaluate the fast fracture properties of materials, provided good isolation between crack initiation and crack propagation can be obtained. An important point is that in large stressed products, a propagating crack can distance itself from its point of initiation and then the only energy available to the crack tip is that stored in the stressed material. There is considerable interest in a material's resistance to fast crack propagation in large products as this can lead to catastrophic failure.

Polymers are viscoelastic materials which have widely different degrees of stress relaxation and this needs to be considered in evaluating the crack propagation resistance of different materials. It is important, therefore, to be able to control precisely the loading and stress relaxation of specimens before a crack is initiated. Such precise loading is easier and more convenient if the specimens are small. It is essential that the established loading conditions are not disturbed by the crack initiation process. Also, the only energy available to the crack tip must be that stored in the specimen. For polymers that have good thermal insulation properties, the frozen tongue technique can be used [4] and this is the method employed for the study of ABS and SAN material. A small tongue of material extends the intended crack path in a rectangular specimen which is loaded normal to the crack path. Liquid nitrogen cooling is used to embrittle the tongue so that it is easy to fracture with a low force and then launch a crack into the main section of the specimen. This method provides for studying crack propagation from the threshold up to the limiting crack velocity condition.

The frozen tongue technique was originally devised to study polyethylene [4] and then developed for researching the fracture properties of polycarbonate, polymethylmethacrylate and similar materials [5]. Further developments of the frozen tongue technique were needed to research the fracture properties of ABS materials. The first part of this research was to make these new developments to the fracture technique and then to move on to compare the fracture properties of ABS with SAN, the latter being the host material for the toughening rubber particles.

2. Experimental procedure

Fig. 1 shows the general arrangement of the frozen tongue specimen and the three-point bend device used to initiate a crack in the tongue section after it had been freeze-cooled with liquid nitrogen. With ABS specimens, the problem was that when the whole of the tongue section was cooled with liquid nitrogen, the tongue had a propensity to shatter rather than fracture along the intended crack path. This was overcome by devising a new freezing method which only cooled the material along the crack path in the tongue. Fig. 2 shows the new freezing device which consists of two metal blocks, with triangular protrusions to fit into the side-grooves of the tongue. The metal blocks were cooled in liquid nitrogen and then lightly clamped into position on the tongue of the specimen. In this way, the crack path in the tongue was quickly frozen without reducing the temperature of the whole of the tongue or the main section of the specimen for more than 5 mm along the crack path. Also, it was verified that when fracturing the tongue with the

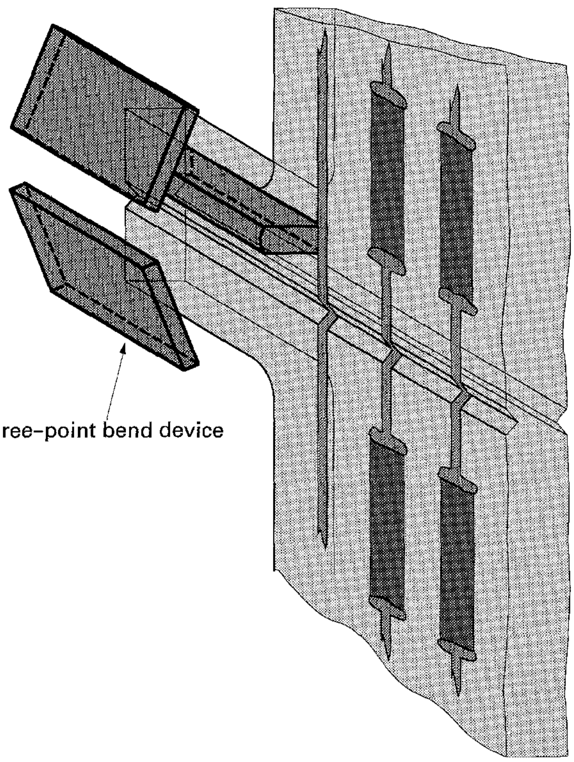

Figure 1 The three-point bend crack initiation device and its positioning on the tongue section of the specimen.

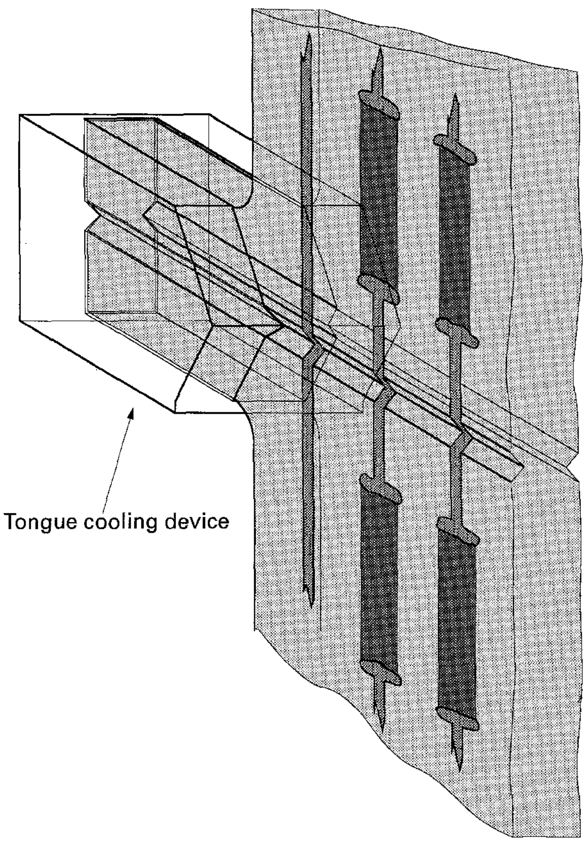

Figure 2 The method of freeze-cooling the material along the side-grooved section of the tongue using two specially shaped metal blocks that had been cooled in liquid nitrogen.

three-point bend device, there was negligible disturbance of the loading of the main section of the specimen. Another assessment made was that the disturbance of the stress field in the main section of the specimen, by the presence of the tongue, was confined to a region of 10 mm in extent from the root of the tongue.

A different problem was that when the ABS specimens were subject to a high load to achieve very fast cracks, there was a propensity for slow cracks to be generated in the side-grooved region of the specimen at the far end of the crack path. This was overcome by machining two stress-relieving reductions on this side of the specimen as shown in Fig. 3. A crack approaching the limiting crack velocity condition could then be achieved from crack initiation in the tongue. However, before commencing the ABS fracture experiments, other options for avoiding premature cracking of the specimen were investigated. The final choice was to provide the specimen with a tongue section at the beginning and end of the crack path in the main section of the specimen as shown in Fig. 4. This conveniently also provided for the crack to be initiated from either end of the specimen as well as stopping pre-cracking problems. It was also useful for some studies for the second tongue to be used to arrest the propagating crack.

To monitor the build up and then constant crack velocity, as the crack length in the main section of the specimen increased, a series of conducting strip monitors were located along the crack path as shown in Fig. 5. It was found important to achieve a sharp and clean breaking of the conducting strips as the crack opened. This required the ability to form narrow conductive strips across the crack path which had to be strong enough not to be damaged when handling the specimen and mounting it in the Instron loading machine. To achieve these narrow strips and to space them precisely along the crack path, a painting technique was developed. The conducting silver paint used was manufactured by Acheson Colloids (Electrodag 915). Each strip had a graphite resistor and this was formed on the specimen using a masked spraying

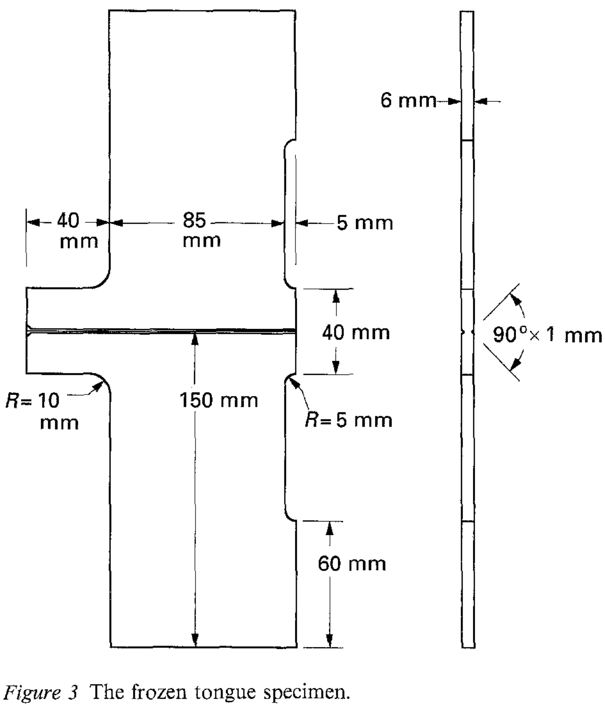

Figure 3 The frozen tongue specimen.

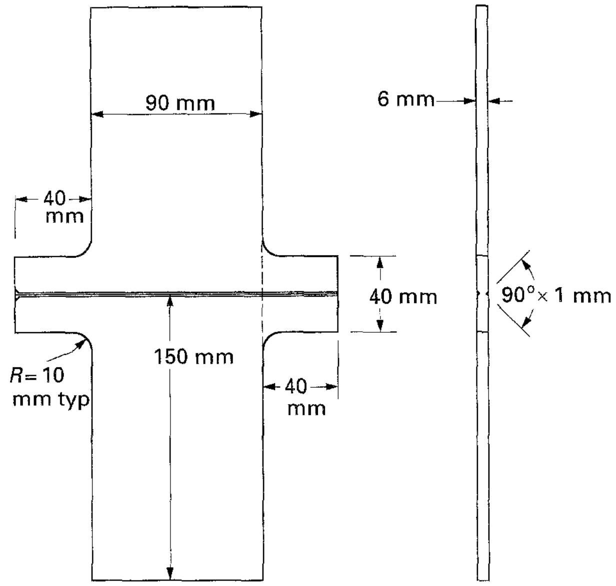

Figure 4 The modified frozen tongue specimen.

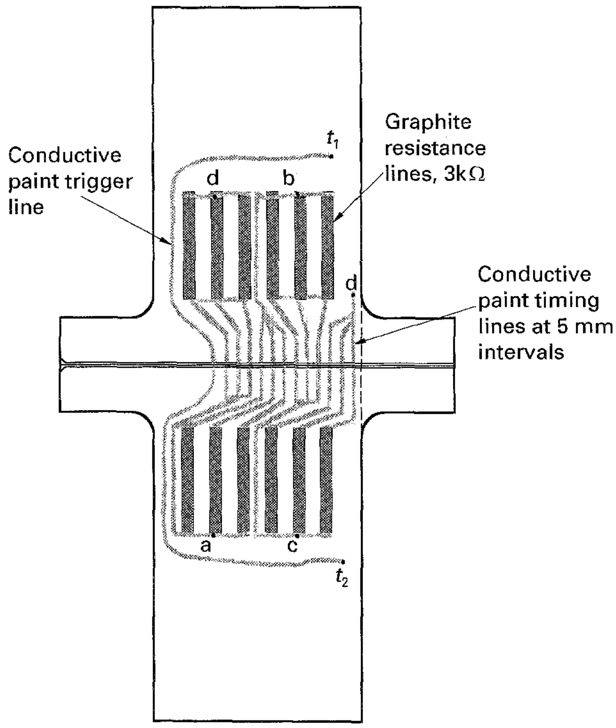

Figure 5 Positioning of conducting strips on the frozen tongue specimen.

technique. Two separate sets of conducting strip monitoring were formed with one on each side of the specimen to obtain confirmatory outputs. The conducting strips and their graphite resistors were incorporated into a Wheatstone bridge network as shown in Fig. 6a. As each conducting strip was broken by the propagating crack, this changed the balance of the Wheatstone bridge to produce a staircase stepping of the voltage output as shown in Fig. 6b. These outputs from the Wheatstone bridge were monitored using a Digital Storage Scope (Gould Instrument Systems–DataSYS 740) which was equipped with facilities for transfer of the captured data to a personal computer (PC) for processing.

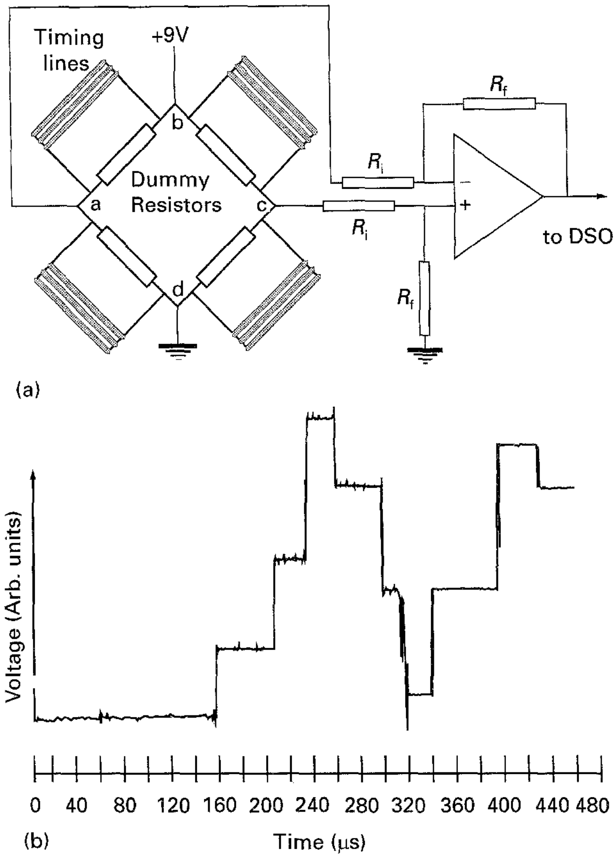

Figure 6 The Wheatstone bridge for conducting strip crack velocity measurement: (a) bridge configuration, (b) voltage output from the bridge produced by a propagating crack.

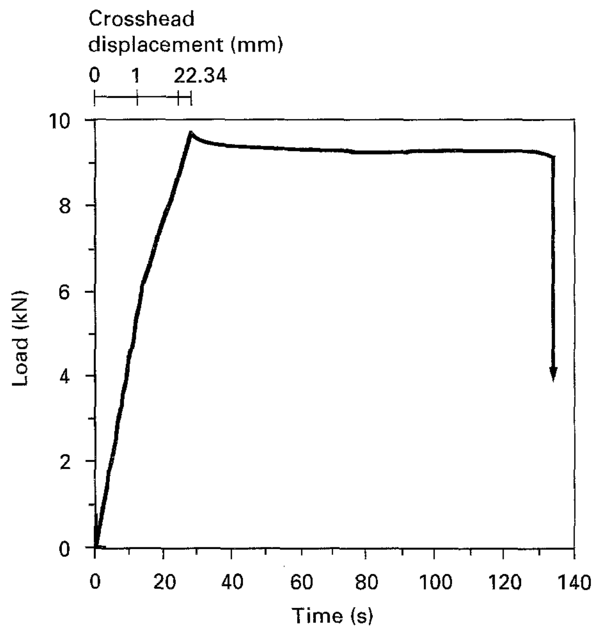

Figure 7 Load–time trace for a frozen tongue specimen of ABS.

In addition, a completely separate monitoring of the crack tip was achieved by using a high-speed camera (Hadlands–IMACON 468). This was equipped with an optical fibre link for transfer of the photographic images to a PC. These photographic data could be correlated with those from the conducting strips.

3. Results

For all the frozen tongue ABS and SAN specimens, side-grooves were introduced of depth 1 mm on each side of the specimens of thickness, $B = 6$ mm. The load was applied to the specimens at a rate of 5 mm min^{-1}, in an Instron machine, up to the required load level and then the Instron crosshead was stopped. The specimen was allowed to stress relax before being fractured. Fig. 7 shows a loading and stress relaxation curve for an ABS specimen. The SAN specimens exhibited a similar loading and stress relaxation behaviour. After a period of time to allow the required stress relaxation, the frozen tongue technique was used to initiate a crack. Fig. 8 shows for ABS specimens, the variation of crack length with time for three different stress-relaxed load conditions using the conducting strip method. It can be seen that the crack upon leaving the tongue increased its velocity until full stress intensity at the crack tip was reached when, thereafter, near to constant crack velocity was achieved. Fig. 9 shows an example of a high-speed photographic sequence of fracture in an ABS specimen to confirm crack velocities and other measurements made by the conducting strip method. Back-lighting of the specimen was used so that the crack appeared as a bright streak of light passing through the specimen from left to right. Fig. 10 shows the same photographic data after they have been processed to obtain a higher definition of the crack profile. To obtain crack velocity versus stress-relaxed load information for SAN material, the same experimental procedure was used as employed for ABS. Fig. 11 shows a comparison of the crack velocity, $\mathrm{d}a/\mathrm{d}t$, versus stress relaxed load, p, for ABS and SAN both having a thickness, B, of 6 mm. To these experimental data for ABS and SAN, relationships were fitted of the form

$$(\mathrm{d}a/\mathrm{d}t)^2 = C_L^2[1 - (p_0^2/p^2)] \quad (1)$$

where C_L is the limiting crack velocity and p_0 is the threshold stress relaxed load for crack propagation. Fig. 12a presents the crack velocity, $\mathrm{d}a/\mathrm{d}t$, versus stress relaxed load, p, for the ABS material in a different way as a plot of $(\mathrm{d}a/\mathrm{d}t)^2$ versus $(1/p)^2$ and Fig. 12b shows the same plot for the SAN material. The comparison of Fig. 12a and b reveals that the two

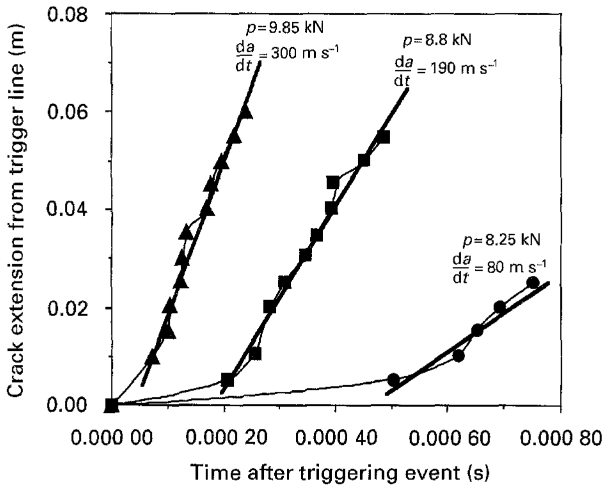

Figure 8 Crack length versus time from conducting strips for three different load conditions on ABS frozen tongue specimens.

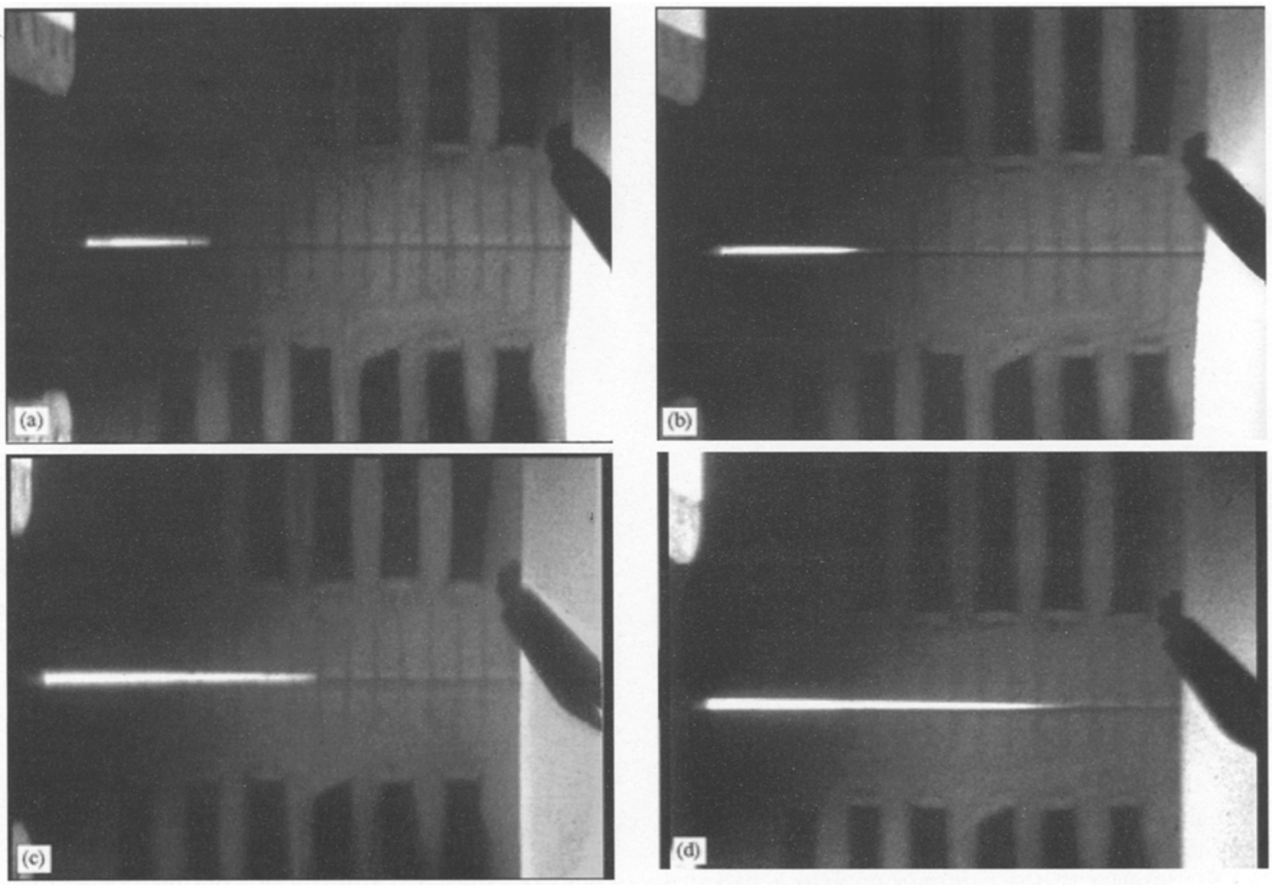

Figure 9 High-speed photographic sequence from an IMACON 468 camera of fracture of an ABS frozen tongue specimen.

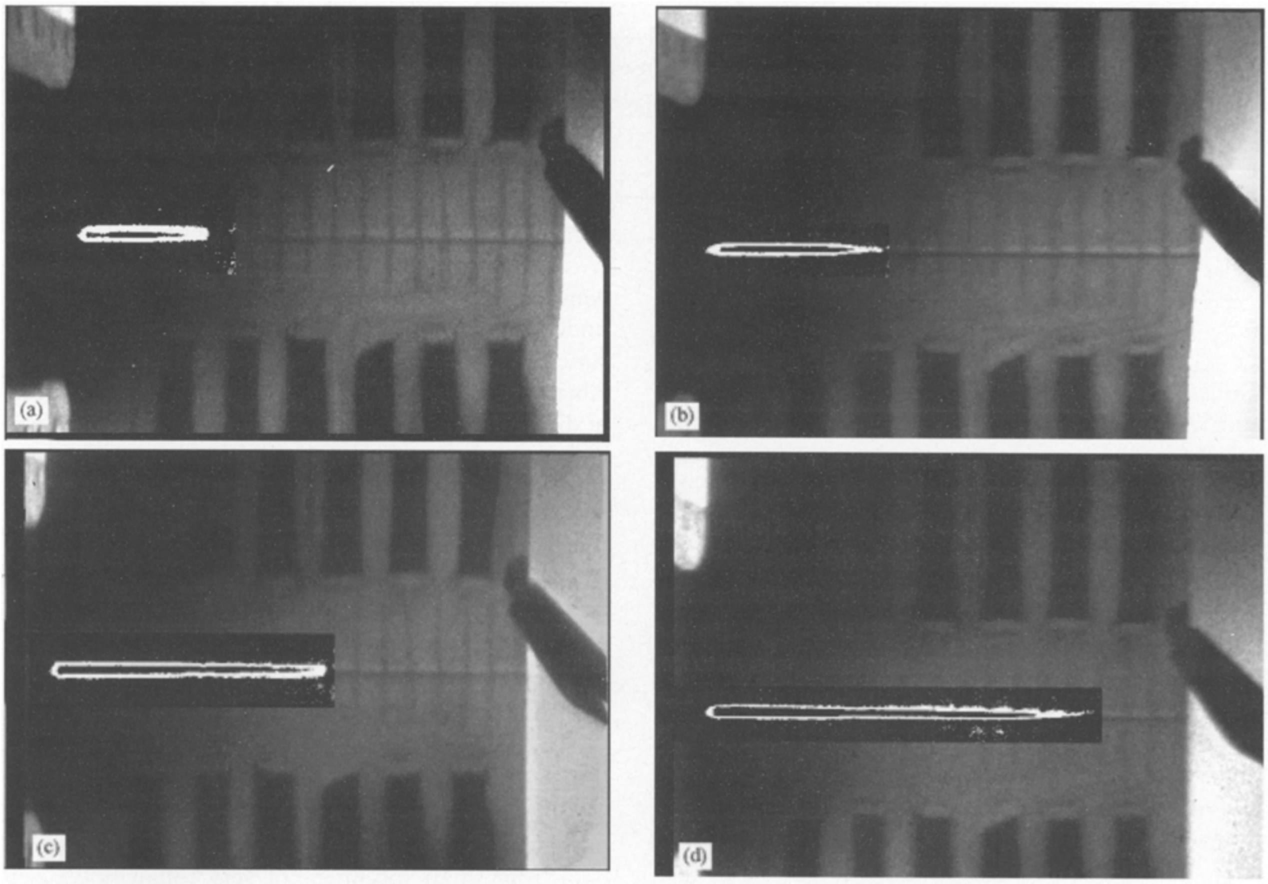

Figure 10 Processed high-speed photographic sequence of Fig. 9 to define the crack tip.

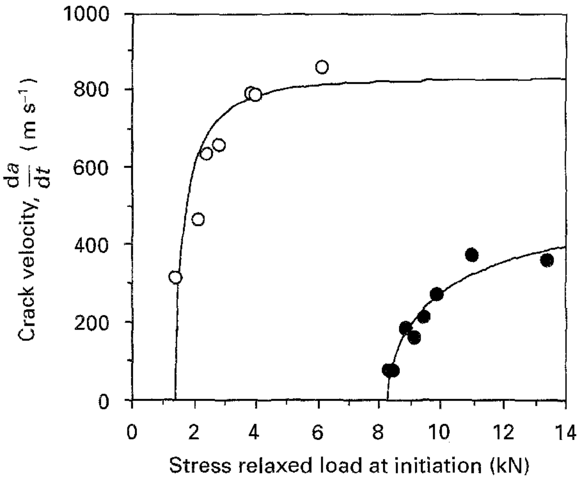

Figure 11 Crack velocity, da/dt, versus stress relaxed load, p, for frozen tongue experiments on ABS and SAN.

materials do not have a common gradient of $(da/dt)^2$ versus $(1/p)^2$ as is the case, for example, for different toughness grades of polyethylene [6]. The toughness, R, can be determined from [6]

$$R = (\pi p_0^2)/4EBB_nD) \qquad (2)$$

where D is the specimen width, B is the overall thickness of the specimen and B_n is the crack thickness after side-grooving. The value of E used was determined by longitudinal and transverse wave-velocity measurements and for an excitation frequency of 2 MHz: E for ABS was 2.7 GPa and for SAN it was 3.3 GPa. The stress intensity factor, K, was determined from the

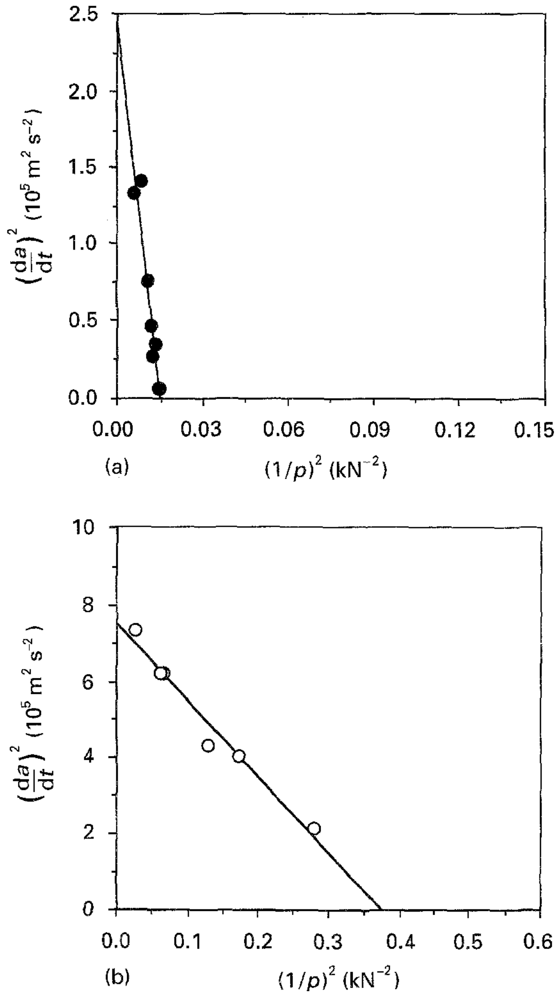

Figure 12 Plots of $(da/dt)^2$ versus $(1/p)^2$ for frozen tongue experiments on (a) ABS, (b) SAN.

TABLE I Frozen tongue fracture parameters for ABS and SAN

	p_0 (kN)	C_L ($m\,s^{-1}$)	E (GPa)	R ($kJ\,m^{-2}$)	$K = (ER)^{1/2}$ ($MPa\,m^{1/2}$)
ABS	8.2	495	2.7	9.1	5.0
SAN	1.6	869	3.3	0.3	1.0

relationship

$$K = (ER)^{1/2} \quad (3)$$

Table I summarizes the fracture parameters for ABS and SAN determined by the frozen tongue technique.

4. Discussion

To obtain from small laboratory specimens definitive information about a material's resistance to crack initiation and crack propagation, presents many problems. A major difficulty is achieving good isolation between crack initiation and crack propagation conditions. This is particularly so for rubber-toughened and other soft particle-toughened materials. A feature of the frozen tongue technique is that it also tends to inhibit the toughening effect of these particles in the tongue section making it easier to start a crack in ABS. The development of the frozen tongue technique has provided a useful method of obtaining fast fracture data from small specimens of polymeric materials. The isolation between crack initiation and crack propagation is very good and prior to initiating a crack, the material is allowed to stress relax. This represents well the working state of the material in many stressed products.

The improved frozen tongue technique has been useful in studying the fast fracture properties of ABS and SAN materials. It is evident in the experimental results that the effect of the rubber particles is to significantly increase the threshold load, p_0, that is required to maintain crack propagation, whereas the limiting crack velocity, C_L, is not so dramatically reduced. It should be noted that the toughness of a material is often calculated at the threshold load for crack propagation as has been done for Table I. This observed toughening effect of rubber particles fits in well with the research findings of Donald and Kramer [7] who showed cavitation processes in rubber particles when the ABS material was subject to a high stress concentration. These cavitation and other particle-toughening processes in ABS mostly occur in the intensified stress zone about the crack tip and these stress-zone conditions vary with crack velocity. When comparing the effect of different toughening agents in materials including their size and distribution, the fast fracture data obtained by the frozen tongue methods are very informative and cover the whole crack velocity range. Making comparisons of toughened material using impact fracture techniques is complicated by the overall response of the specimen to the impact, including the transient reflection of stress waves from free and constrained edges of the specimens. Often, of particular interest, are those toughness parameters which relate to the inherent properties of the material under defined fracture conditions. The stress-relaxed state of the specimen is often that achieved by materials in working products and the degree of relaxation of different materials can vary greatly. Another point is that, in service, fast cracks in tough materials can occur from fatigue or other slowly growing cracks. The way materials fail under a variety of working conditions is an important aim of this research. The frozen tongue technique can be varied to simulate a variety of fracture conditions. Research is now continuing to relate the impact properties of ABS and other toughened materials to their propagation toughness.

5. Conclusion

The development of the frozen tongue technique has provided a useful method of obtaining fast fracture data from small specimens of very tough polymeric materials. Fast crack propagation information, which has been obtained from experiments where there has been a good isolation between crack initiation and propagation, is particularly useful as these fracture data relate more closely to the inherent properties of the material. Obtaining these fracture data, from conveniently small specimens, is very helpful when researching the effect of making small changes to an existing material or developing a new material. This is when a large number of experiments need to be performed under identical and precisely defined conditions.

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