Effect of testing speed on the crack growth resistance properties of nylon 6/ABS polymer blends

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Crack growth resistance values are measured at three loading rates for blends of Nylon 6 and ABS with varying levels of compatibilizer using the generalized locus method [14]. Load against load point deflection curves are obtained at loading rates of 5 mm min^{-1} and 500 mm min^{-1} using a tensile testing machine. An instrumented drop weight impact testing machine is used to obtain data at a loading rate of 1.2×10^5 mm min^{-1}. Dynamic effects can be considered negligible for the three testing speeds used and the effects of these speeds on crack growth resistance values can be observed. The results of these tests help determine the optimum compatibilizer level for high rate loading applications.

1. Introduction

The influence of loading rate on material performance is an important consideration in material selection whether the part design is expected to endure repeated impact or only accidental drops [1]. Unfortunately, there is presently no standard method of testing which will accurately predict the response of a designed part to impact loading. As a result, specialized high speed tests must be devised for each new design and the results of these tests are often difficult to reproduce and seldom applicable to other situations.

Common practice is to measure the total fracture energy using a Charpy impact test, an Izod impact test, or a falling weight impact test. These tests are effective in showing the general trends in high speed performance, but due to the complexity [2] of the factors involved, they have not clarified the mechanisms of high speed fracture greatly and their results are useful only for comparison purposes [3, 4]. What is needed is a test methodology which can determine a useful fracture property over a wide range of test speeds.

Crack growth resistance is a material property that can be used to predict the response of a given material to loading [5]. Material failures can usually be categorized as brittle, ductile, or a combination of both [6]. For materials subject to brittle fracture, total failure can rapidly follow crack initiation without any further energy input. For a material which consistently fails in a ductile manner, the resistance to crack propagation will be the important fracture property. Resistance to crack initiation is therefore of primary importance for brittle fracture and resistance to crack propagation is of primary importance for ductile fracture. The purpose of this study is to measure crack growth resistance as a function of loading rate.

The materials chosen for this research are nylon 6/ABS blends with four levels of compatibilizer. Compatibilizers alter the interface between incompatible materials sufficiently so that the resulting blend has a useful balance of properties [7–10]. It is known that the fracture properties of nylon 6/ABS blends depend on the amount of compatibilizer present [11].

In this paper, crack growth resistance as a function of compatibilizer level will be measured using three different loading rates in order to determine the effectiveness of the compatibilizer as loading rates are increased.

2. The generalized locus method

One method for calculating crack growth resistances is the locus method developed by Kim and Joe [12]. The generalized form of this method can determine the resistance to crack propagation during crack growth ($\tilde{G}$) [13] based on the following equation [14]

$$\tilde{G} = -\frac{1}{B}\frac{\Delta U}{\Delta a} \qquad (1)$$

where B is the specimen thickness, a is the initial crack length, and U (the energy required for crack propagation) is the area bounded by the loading curve, the locus line of characteristic points, and the x-axis. Because Equation 1 is only valid when the amount of

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kinetic energy imparted into the system is negligible (quasi-static loading), loading rates must be kept low enough to satisfy that condition.

For tests in which crack initiation can be detected visually, Equation 1 can be used to find the resistance value at crack initiation (J_c) using sets of load and load point deflection curves obtained from specimens which vary only in initial crack length. If J_c is constant for the given specimen thickness then a plot of U_c/B against a (where U_c is the area surrounded by the locus line of crack initiation points, the load against load point deflection curve, and the x-axis) should yield a linear fit. The slope of this linear fit line represents the fracture toughness J_c for this material.

Similarly, Equation 1 can be used to find the resistance value at maximum load (R_{max}) using the maximum load points of the load against load point deflection curves as characteristic points for constructing the locus line. This R_{max} represents the crack resistance at maximum load, not the maximum crack resistance value. For ductile materials whose R-curves display a sharp transition in slope, the crack growth resistance at maximum load (R_{max}) can be fairly constant [14]. If a plot of U_L/B against a (where U_L is the area surrounded by the locus line of maximum load points, the load against load point deflection curve, and the x-axis) yields a linear fit then R_{max} is constant and the slope of this plot represents R_{max}. The maximum load point in displacement controlled loading occurs at the tangential point between the constant-load crack driving force line and the crack growth resistance curve (R-curve) [14]. For brittle materials R_{max} can represent fracture toughness since the maximum load point is often the point of crack initiation, but for all materials R_{max} represents the instability point for constant load applications.

The resistance to steady state crack propagation (R_p) may also be obtained using Equation 1 if the total energy (U_t) required to fracture each specimen is known [14]. U_t may be determined using each specimen's load against load point deflection curve. The total area enclosed by this curve and the x-axis represents U_t.

Once the energy values are determined, they are then plotted as a function of crack extension. If R_p is a constant for steady crack growth, then the plot of energy values with respect to crack extension will be linear. The slope of this line will yield R_p in accordance with Equation 1.

3. Experimental procedure

Materials used in this study were four blends of nylon 6 and ABS with compatibilizer levels of 0, 1, 2, and 6% provided by Monsanto Chemical Company. Test specimens measuring 125.0, 12.5, and 12.5 mm for length, width, and thickness, respectively were moulded on an Arburg 300 injection moulding machine. In preparation for crack resistance testing, the specimens were given a range of initial crack sizes by machining notches into them and then pushing a razor blade into the blunt notch. The total initial crack lengths including the razor notching were 1.9, 4.8, 6.5, 7.3, and 8.5 mm. It should be noted that the depth of the razor notch varied from 0.6 to 0.9 mm in order to obtain a consistent initial crack length.

The three point bending test was chosen due to its simplicity and mechanical stability. Temperature was maintained between 22 and 26 °C, and the relative humidity was between 50 and 56% during testing.

For the 5 mm min^{-1} and 500 mm min^{-1} testing speeds, an Instron model 1011 tensile testing machine (Instron Co., Canton MA) was used to obtain the load against load point deflection curves. A three point bend fixture with a span of 76 mm was used and the load against load point deflection curves were recorded on a strip chart recorder. These curves were then digitized for computer analysis.

For a testing speed of 1.2×10^5 mm min^{-1} (2 m s^{-1}), a Fractovis instrumented impact testing machine (by CEAST, Italy) was used to obtain the load against load point deflection curves. A drop weight of 8 kg with a tup diameter of 12.7 mm was used. The specimens were centered on a fixture with an inside diameter of 76 mm. The specimens were not clamped and enough clearance was given so that the specimens could bend freely.

4. Results and discussion

An instrumented impact test [15] can yield a load against load point deflection curve as determined by a load cell on the impact hammer. Traditional Charpy testing can only yield a total energy value for the impact event. Data from instrumented impact tests can therefore be used for generalized locus method analysis whereas Charpy test data cannot [16]. It is then possible to determine R_{max} and R_p based on Equation 1 using instrumented impact test data provided that dynamic effects [17] are negligible. Visual observation of crack initiation [11, 12] was only practical at a loading rate of 5 mm min^{-1}, but by applying the analogy given by R_{max} and R_p, some conclusions may be drawn about the effect of loading rate on J_c.

Figs 1–3 show some typical load against load point deflection curves obtained for blend containing 6% compatibilizer at the three loading rates used. Figs 1 and 2 show the smooth loading and unloading characteristic of quasi-static fracture. Fig. 3 also shows the characteristics of quasi-static fracture in accordance with the requirements of the test despite initial vibration and ringing in the test equipment. The high speed curves were therefore analysed in exactly the same way as the lower speed curves.

Specimens containing 0% compatibilizer failed in an unstable, brittle manner at a loading rate of 1.2×10^5 mm min^{-1}. Considerable kinetic energy was imparted into these specimens during testing thus violating the quasi-static assumption. Data from any specimen which fails in an unstable or partially unstable manner would also have to be disregarded.

The total energy for fracture (U_t) and the essential energy up to maximum load (U_L) for each specimen was determined and plotted in accordance with Equation 1. These plots are shown in Figs 4–11. Circles represent data obtained at a loading rate of

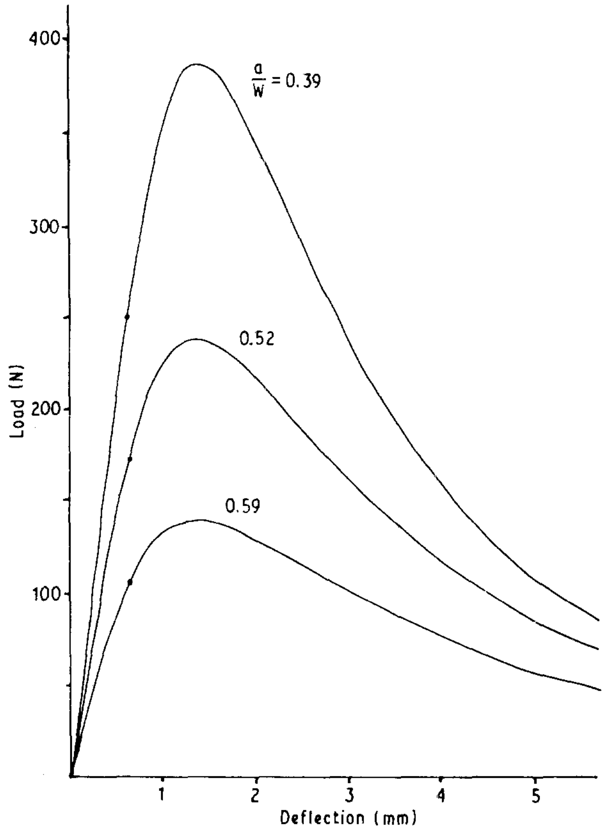

Figure 1 Typical load against load point deflection curves for nylon 6/ABS blend with 6% compatibilizer tested at $5\,mm\,min^{-1}$ on Instron.

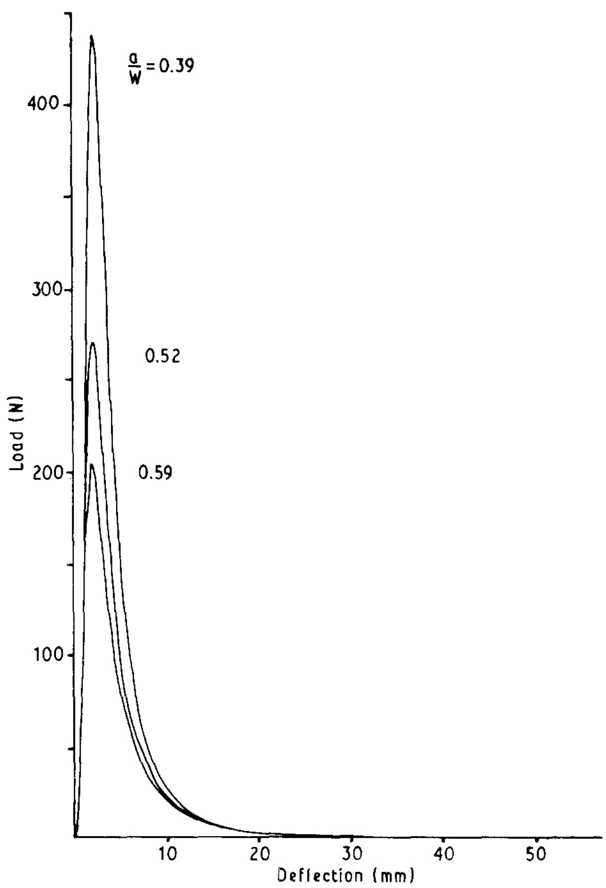

Figure 2 Typical load against load point deflection curves for nylon 6/ABS blend with 6% compatibilizer tested at $500\,mm\,min^{-1}$ on Instron.

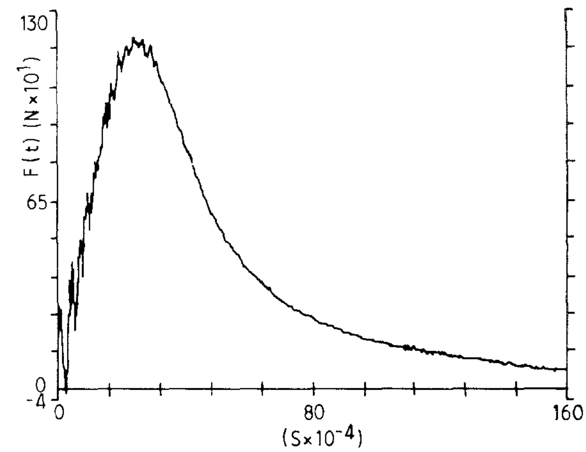

Figure 3 Typical load against load point deflection curve for a nylon 6/ABS blend with 6% compatibilizer tested at $2\,m\,s^{-1}$ on Fractovis.

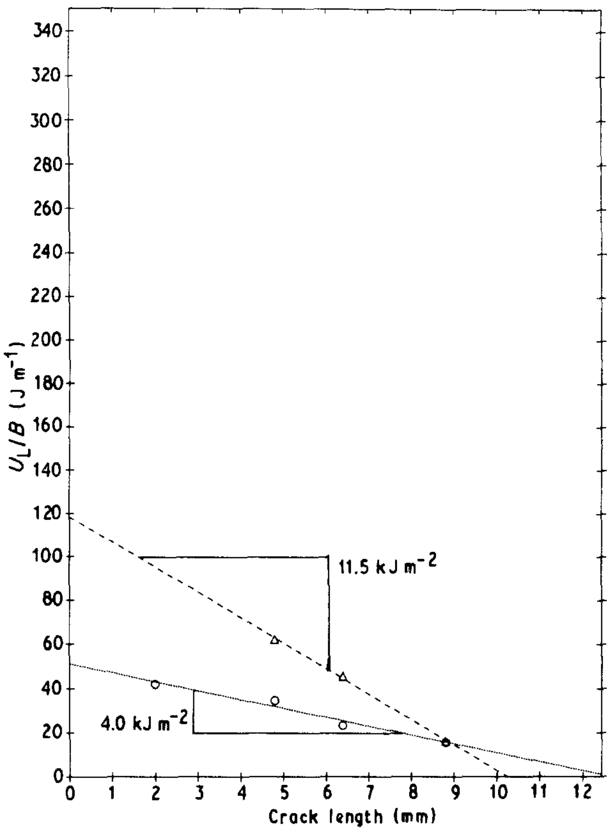

Figure 4 U_L/B against initial crack length for specimens with 0% compatibilizer tested at $5\,mm\,min^{-1}$ and $500\,mm\,min^{-1}$. The slopes yield R_{max} values.

$5\,mm\,min^{-1}$. Triangles represent data obtained at a loading rate of $500\,mm\,min^{-1}$, and squares represent data obtained at a loading rate of $1.2 \times 10^5\,mm\,min^{-1}$. The slopes of these plots represent R_{max} and R_p for each material and these values are given in Table I. At $5\,mm\,min^{-1}$, R_{max} was found to be 4.0, 9.2, 12.1, and $10.8\,kJ\,m^{-2}$ and R_p was found to be 11.2, 41.3, 43.0, and $44.1\,kJ\,m^{-2}$ for blend containing 0, 1, 2, and 6% compatibilizer, respectively. At $500\,mm\,min^{-1}$, R_{max} was found to be 11.5, 16.5, 19.2, and $19.6\,kJ\,m^{-2}$ and R_p was found to be 27.0, 72.5, 74.2, and

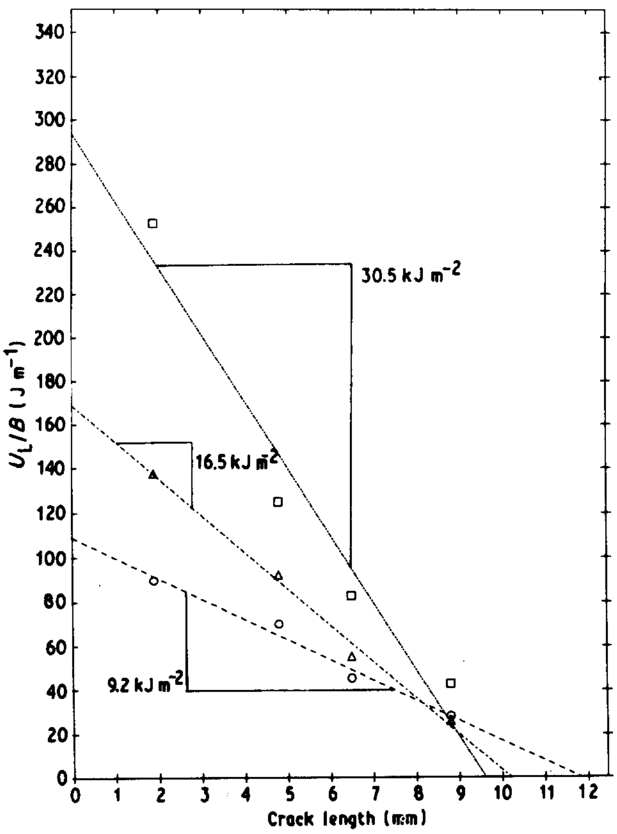

Figure 5 U_L/B against initial crack length for specimens with 1% compatibilizer tested at 5 mm min^{-1}, 500 mm min^{-1}, and 1.2×10^5 mm min^{-1}. The slopes yield R_{max} values.

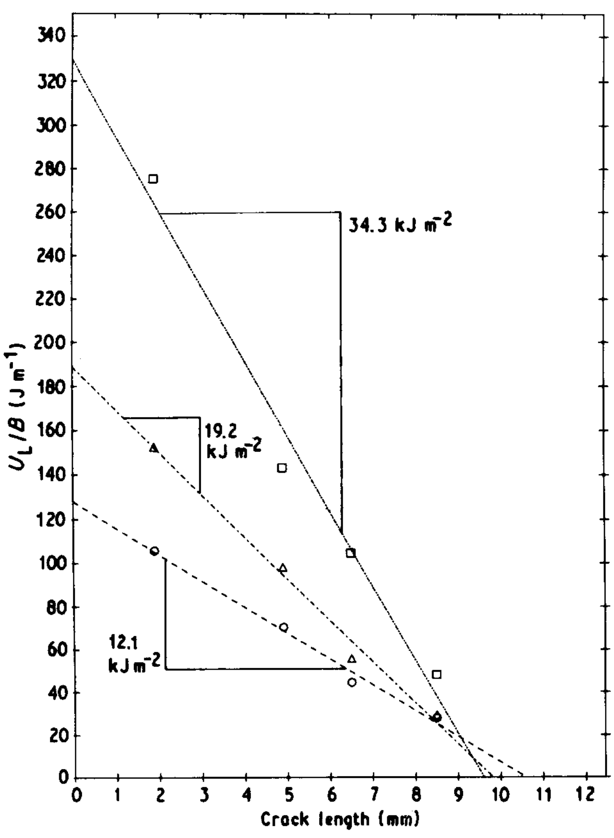

Figure 6 U_L/B against initial crack length for specimens with 2% compatibilizer tested at 5 mm min^{-1}, 500 mm min^{-1}, and 1.2×10^5 mm min^{-1}. The slopes yield R_{max} values.

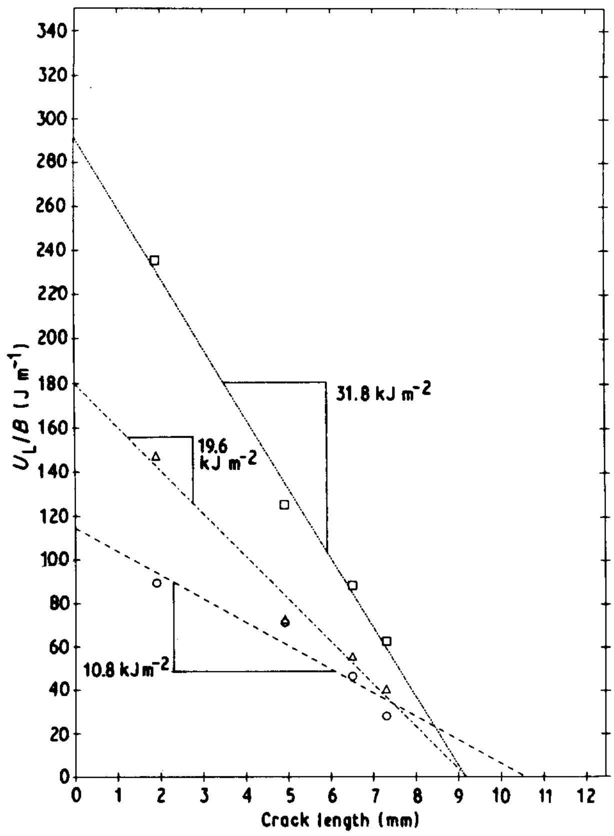

Figure 7 U_L/B against initial crack length for specimens with 6% compatibilizer tested at 5 mm min^{-1}, 500 mm min^{-1}, and 1.2×10^5 mm min^{-1}. The slopes yield R_{max} values.

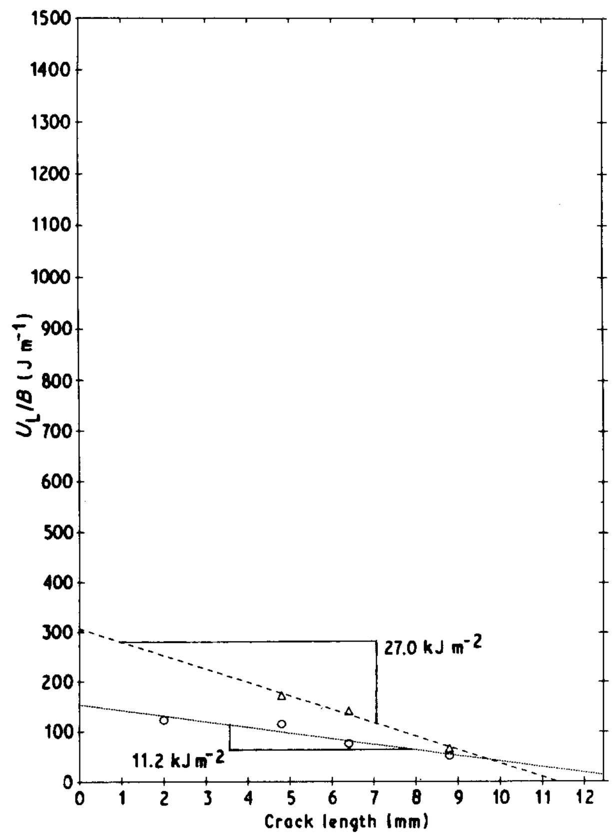

Figure 8 U_L/B against initial crack length for specimens with 0% compatibilizer tested at 5 mm min^{-1} and 500 mm min^{-1}. The slopes yield R_p values.

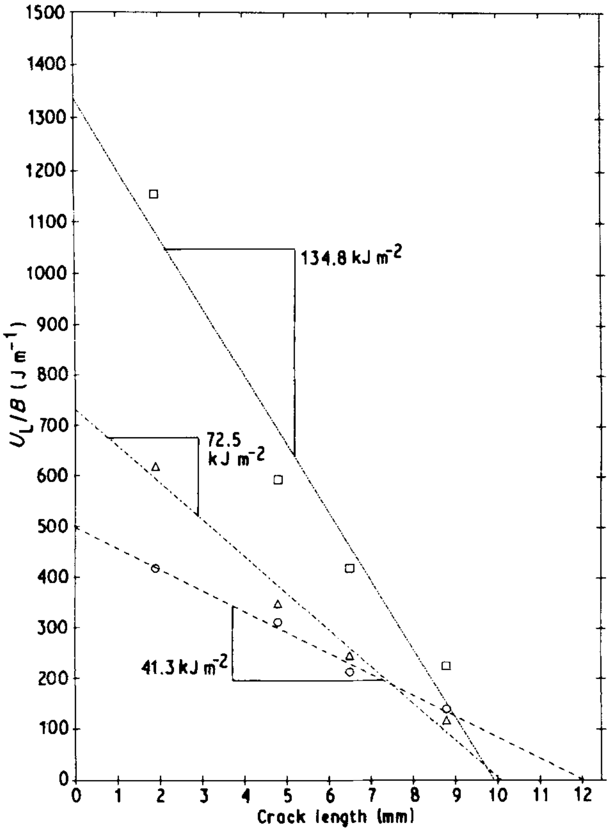

Figure 9 U_t/B against initial crack length for specimens with 1% compatibilizer tested at 5 mm min^{-1}, 500 mm min^{-1}, and 1.2×10^5 mm min^{-1}. The slopes yield R_p values.

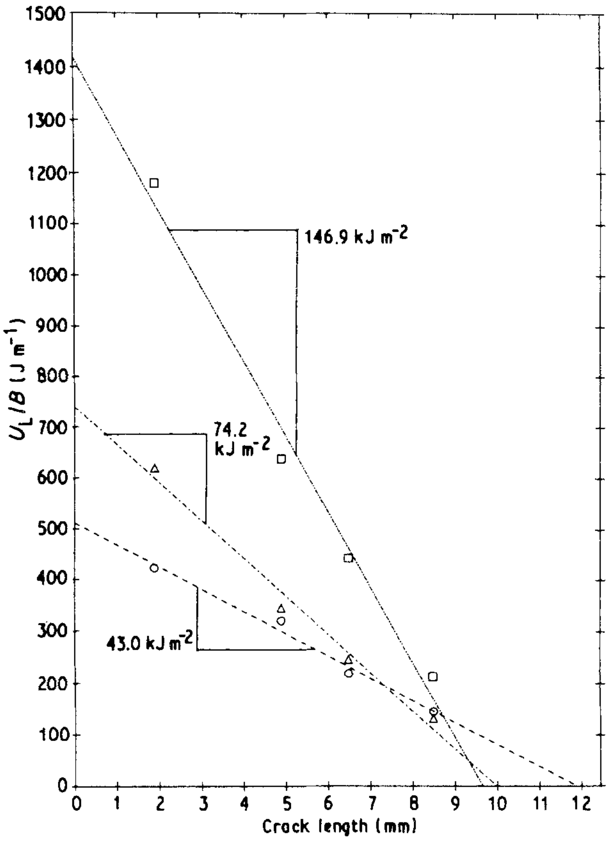

Figure 11 U_t/B against initial crack length for specimens with 6% compatibilizer tested at 5 mm min^{-1}, 500 mm min^{-1}, and 1.2×10^5 mm min^{-1}. The slopes yield R_p values.

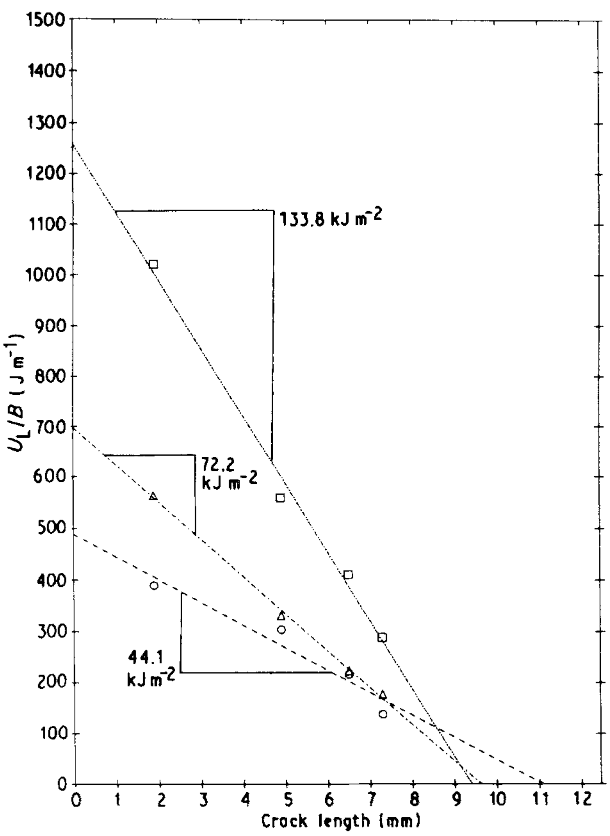

Figure 10 U_t/B against initial crack length for specimens with 2% compatibilizer tested at 5 mm min^{-1}, 500 mm min^{-1}, and 1.2×10^5 mm min^{-1}. The slopes yield R_p values.

72.2 kJ m^{-2} for blend containing 0, 1, 2, and 6% compatibilizer, respectively. It can be seen that blend with 0% compatibilizer has much lower crack growth resistance than blend containing small amounts of compatibilizer. At 1.2×10^5 mm min^{-1}, R_{max} was found to be 30.5, 34.3, and 31.8 kJ m^{-2} and R_p was found to be 134.8, 146.9, and 133.8 kJ m^{-2} for blend containing 1, 2, and 6% compatibilizer, respectively.

From the data obtained it can be seen that significant increases in crack growth resistance occur for all four blends as the loading rate is increased. The crack growth resistance at 500 mm min^{-1} is approximately double the crack growth resistance at 5 mm min^{-1} and

TABLE I Resistance values as a function of testing speed and compatibilizer level

Compatibilizer level	Crosshead speed		
	5 mm min^{-1}	500 mm min^{-1}	120 000 mm min^{-1}
R_{max} (kJ m^{-2})			
0%	4.0	11.5	–
1%	9.2	16.5	30.5
2%	12.1	19.2	34.3
6%	10.8	19.6	31.8
R_p (kJ m^{-2})			
0%	11.2	27.0	–
1%	41.3	72.5	134.8
2%	43.0	74.2	146.9
6%	44.1	72.2	133.8

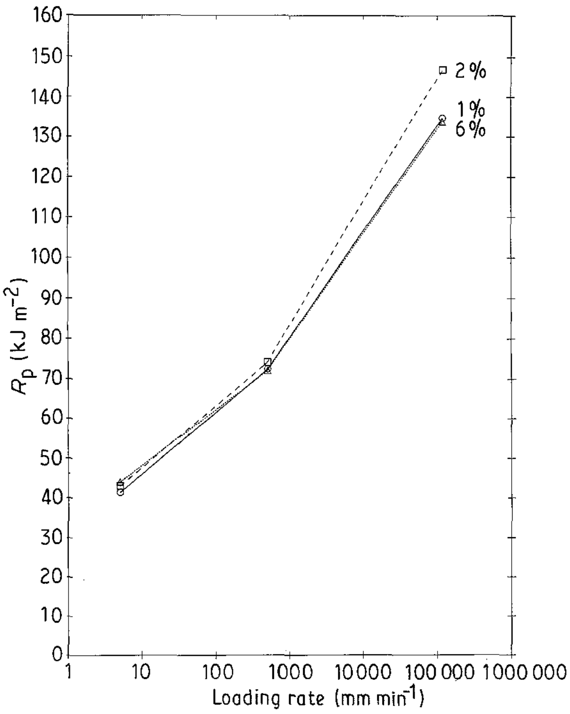

Figure 12 R_{max} against loading rate.

the crack growth resistance at 1.2×10^5 mm min^{-1} is approximately three times the crack growth resistance at 5 mm min^{-1}.

In addition it can be seen from Figs 12 and 13 that the crack growth resistance values for the 6% blend appear to be rising less rapidly than the resistance values for the blends with lower compatibilizer levels. From this we can conclude that a blend of nylon 6 and

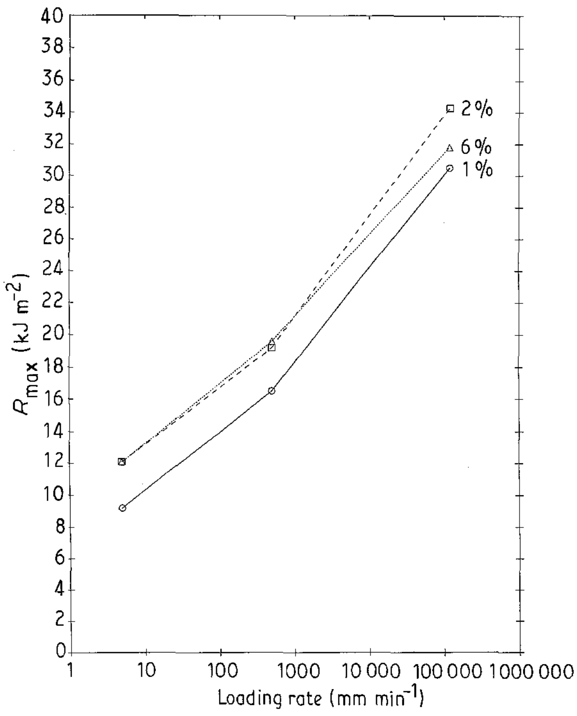

Figure 13 R_p against loading rate.

ABS with 2% compatibilizer may better sustain high speed loading then a blend with 6% compatibilizer.

5. Conclusion

Instrumented impact testing can produce data which is suitable for crack growth resistance measurement using the generalized locus method. Quasi-static analysis is acceptable for nylon 6/ABS blends containing 1, 2, and 6% compatibilizer up to a loading rate of 1.2×10^5 mm min^{-1}. Crack growth resistance values calculated using the generalized locus method at three testing speeds are given in Table I. From the data presented it can be seen that for testing speeds of 500 mm min^{-1} and 1.2×10^5 mm min^{-1}, crack growth resistances are approximately two and three times higher respectively than crack growth resistances determined at a loading rate of 5 mm min^{-1}. It can also be seen that the crack growth resistance values of blend with 2% compatibilizer are greater than those of the blend with 6% compatibilizer for a testing speed of 1.2×10^5 mm min^{-1}.

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