J Mater Sci (2009) 44:1333–1343
DOI 10.1007/s10853-008-3233-6

# Effect of fibre concentration, strain rate and weldline on mechanical properties of injection-moulded short glass fibre reinforced thermoplastic polyurethane

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Received: 18 October 2008 / Accepted: 29 December 2008 / Published online: 7 February 2009


**Abstract** The effect of fibre concentration, strain rate and weldline on tensile strength, tensile modulus and fracture toughness of injection-moulded thermoplastic polyurethane (TPU) reinforced with different concentration levels of short glass fibres was investigated. It was found that tensile strength, $\sigma_c$, of single-gated mouldings increased with increasing volume fraction of fibres, $\phi_f$, according to a second order polynomial function of the form $\sigma_c = a_0 + a_1\phi_f + a_2\phi_f^2$ and increased linearly with natural logarithm of strain rate ($\ln\dot{e}$). Tensile modulus and fracture toughness (at initiation) of single-gated mouldings increased linearly with increasing $\phi_f$ (rule-of-mixtures) and $\ln\dot{e}$. A linear dependence was obtained between fibre efficiency parameter for composite modulus, $\eta_E$, and $\ln\dot{e}$. The presence of weldline in double-gated mouldings reduced tensile strength, tensile modulus and fracture toughness of TPU composites but had no significant effect upon properties of the TPU matrix. All the aforementioned properties increased with increasing fibre concentration and showed a linear dependence with respect to $\ln\dot{e}$. Weldline integrity factor for all three properties decreased with increasing fibre concentration showing no strain-rate effect of any significance. Results indicated that tensile strength was more affected by the presence of weldline than tensile modulus or fracture toughness. It was noted that composite properties in the presence of weldline were still much greater than those for the unweld matrix. Weldline integrity values close to unity indicated that measured properties for the matrix were not significantly affected by the weldline.

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## Introduction

The mechanical properties of short fibre polymer composites such as strength and modulus are derived from a combination of the fibre and matrix properties, and the ability to transfer stresses across the interface between the two constituents. These properties, however, are affected by a number of parameters, most importantly, concentration, length and orientation of the fibres as well as the degree of interfacial adhesion between the fibre and the matrix [1–12]. However, as most short fibre composites are fabricated by an injection-moulded process, a major design concern is the effect that weldlines may have on the mechanical properties of the polymer matrix and its composites. Weldlines are observed in injection-moulded components due to multigate moulding, existence of pins, inserts, variable wall thickness and jetting and are classified as either being cold or hot. A cold weldline is formed when two melt fronts meet head on and this type of weldline is the worst-case scenario as far as mechanical properties are concerned. A serious reduction in strength has been reported for many polymers and their composites in the presence of cold weldlines [1–8]. To this end, the present work was undertaken to examine the influence of fibre concentration, strain rate and weldlines tensile strength, tensile modulus and fracture toughness of injection-moulded short glass fibre reinforced TPU composites.

## Experimental details

### Materials

Polyester-based thermoplastic polyurethane (TPU) and its composites containing 10, 20 and 30% by weight short

E-glass fibres (GF) were supplied in the form translucent yellowish pellets for injection moulding. The TPU matrix for the composites with glass-transition temperature of −33 °C was supplied by Merquinsa (trade name Pearthane) and TPU composites were supplied by PolyOne (trade name Onflex). The pellets were dried in an air circulating oven for 2 h at 100 °C as recommended by the manufacturer before being injection moulded into test specimens.

## Injection moulding

Dumbbell-shaped tensile specimens were produced using a Klockner Ferromatik F-60 injection-moulding machine using the processing conditions given in Table 1. The mould used consisted of a single-gate (SG) and a double-gate (DG) feed cavity, each of nominal dimensions 4 × 10 × 120 mm (thickness, width, length). In the latter, the two opposing melt fronts met to form a weldline approximately mid-way along the gauge length of the double-gated specimens as shown in Fig. 1.

## Fibre concentration measurements

The exact weight fraction of the fibres in as received compounds (ARC) and in injection-moulded specimens (IMS) was determined by ashing a pre-weighed amount of material in a muffle furnace at 550 °C for at least 1 h. After cooling, the remnant was weighed and weight fraction of fibres $w_f$ was determined. It can be seen from Table 2 that the measured weight fractions in ARC and IMS is within 1% of the manufacturer's specification thus indicating that fibre concentration was not affected by the moulding process.

The measured weight fractions values as determined from the IMS were subsequently converted into volume fractions, $\phi_f$, using Eq. 1:

$$\phi_f = \left[1 + \frac{\rho_f}{\rho_m}\left(\frac{1}{w_f} - 1\right)\right]^{-1} \quad (1)$$

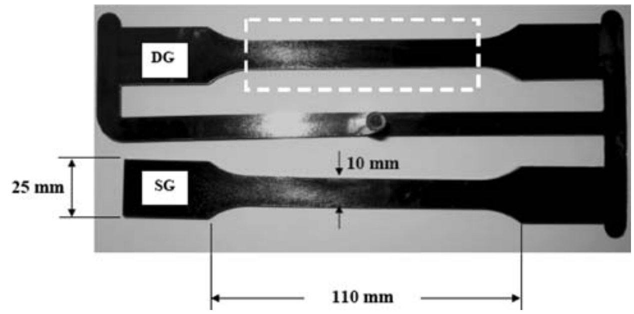



**Fig. 1** Single-gated (unweld) and double-gated (weld) tensile bars. Note that the actual mouldings were of translucent yellowish colour. The *shaded* portion is used as a rectangular coupon for fracture testing

**Table 2** Fibre concentration and the average fibre length in as received compounds (ARC) and in the injection-moulded specimens (IMS)

| Composites | TPU with 10% w/w fibres | TPU with 20% w/w fibres | TPU with 30% w/w fibres |
|---|---|---|---|
| % w/w (ARC) | 10.01 | 19.74 | 29.47 |
| % w/w fibre (IMS) | 9.52 | 19.03 | 29.28 |
| % v/v (IMS) | 4.72 | 9.96 | 16.14 |
| Average fibre length (ARC), µm | 209 | 197 | 180 |
| Average fibre length (IMS), µm | 175 | 160 | 139 |
| Reduction in fibre length, % | 16 | 19 | 23 |

Table 2 gives values of $\phi_f$ obtained via Eq. 1, using glass fibre density $\rho_f$ of 2540 kg m$^{-3}$ and the matrix density $\rho_m$ of 1190 kg m$^{-3}$.

## Fibre length distribution

The ashes of fibrous material obtained from ARC and IMS were subsequently spread on glass slides and placed on the observation stage of a microscope and their length was

**Table 1** Injection moulding processing conditions for TPU and TPU composites containing 10, 20 and 30% w/w short glass fibres

| Processing conditions | TPU | TPU with 10% w/w fibres | TPU with 20% w/w fibres | TPU with 30%w/w fibres |
|---|---|---|---|---|
| Barrel temperature (°C) | | | | |
| Zone 1 | 205 | 210 | 210 | 210 |
| Zone 2 | 205 | 210 | 210 | 210 |
| Zone 3 (nozzle) | 210 | 210 | 210 | 210 |
| Mould temperature (°C) | 40 | 35 | 35 | 35 |
| Injection pressure (%) | 50 | 40 | 35 | 35 |
| Injection time (s) | 3 | 3 | 3 | 3 |
| Cooling time (s) | 14 | 14 | 14 | 14 |

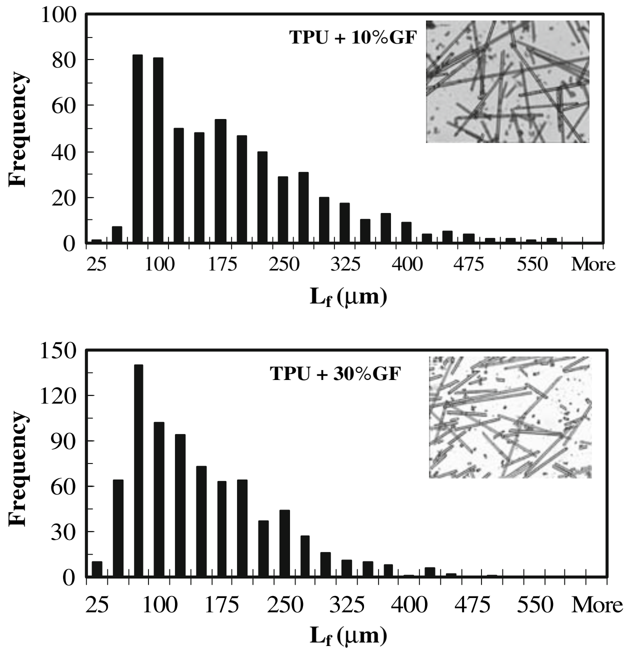



**Fig. 2** Typical examples of fibre length distributions in injection-moulded specimens

measured using an image processing system. Approximately 700 fibre lengths were measured for each composite. From the fibre length distributions, examples of which are shown in Fig. 2 the average fibre lengths, $L_f$, in ARC and IMS were determined. The measured values are given in Table 2 where it can be seen that average fibre lengths in IMS are consistently lower than in ARC. This observation suggests that the moulding process has led to shortening of the fibres. It is also evident, that the amount of damage caused to the fibres (fibre breakage) has increased with increasing fibre concentration. The likely causes of fibre damage are thought to be fibre–fibre interaction, fibre contact with processor surface and fibre interaction with the viscous polymer melt during processing.

## Tensile strength and modulus measurements

Single- and double-gated mouldings were tested in tension at 23 °C in a Tinius Olsen H10KS testing machine using pneumatic clamps with initial clamp separation of 115 mm. Tests were performed at crosshead displacement rates of 0.5, 5, 50, 250 and 500 mm/min giving nominal strain rate values of $7.25 \times 10^{-5}$, $7.25 \times 10^{-4}$, $7.25 \times 10^{-3}$, $3.62 \times 10^{-2}$ and $7.25 \times 10^{-2}$ $s^{-1}$, respectively. For each material, at least five single- and five double-gated specimens were tested at a given rate. The stress–strain curve for each specimen was recorded using an extensometer with gauge length of 50 mm. Tensile modulus was obtained from the initial slope of the stress–strain curve and the tensile strength from the maximum load, on the curve.

## Fracture toughness ($K_{IC}$) measurements

Fracture toughness tests were performed on rectangular coupons cut from the gauge length of both single- and double-gated dumbbell specimens as highlighted by the shaded areas in Fig. 1. Coupons were razor notched to various *a/W* ratios (crack length-to-depth ratio) to produce single-edge notched tension (SENT) specimens as shown in Fig. 3. In the case of double-gated specimens, care was taken to ensure the initial notch was placed inside the weldline region. SENT specimens were subsequently fractured in a Tinius Olsen H10KS testing machine at crosshead displacement rates of 5, 50 and 500 mm/min using pneumatic clamps with clamp separation of 40 mm. These crosshead speeds corresponds to strain-rate values of $2.083 \times 10^{-3}$, $2.083 \times 10^{-2}$ and $2.083 \times 10^{-1}$, respectively. At least 15 SENT specimens were tested for each material and the moulding type at a given strain rate.

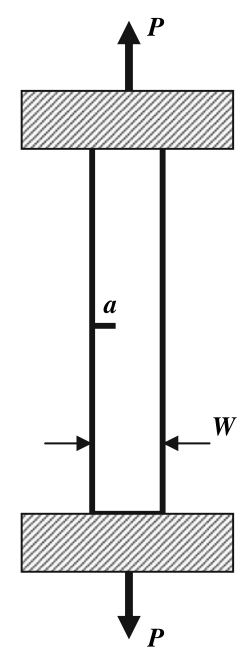
Fracture toughness, $K_{IC}$, for each specimen was calculated using the following equation:

$$K_{IC} = \frac{P_f}{BW} Y(x)\sqrt{a} \tag{2}$$

where $x = a/W$, $B$ is the specimen thickness and $P_f$ is the load at failure. The term $Y(x)$ is the finite width correction factor defined as:

$$Y(a/W) = \frac{5\sqrt{\pi}}{\sqrt{20 - 13(a/W) - 7(a/W)^2}} \tag{3}$$

**Fig. 3** Single-edge notched tension (SENT) specimen



## Results and discussions

### Analysis of tensile modulus

#### *Effect of fibre concentration*

Stress–strain curves for single-gated mouldings examples of which are presented in Fig. 4 show that stiffness of the TPU matrix is enhanced by the addition of glass fibres. This behaviour was consistently observed for all single-gated mouldings over the entire crosshead speed range studied here.

The effect of fibre concentration on tensile modulus of single-gated mouldings at crosshead displacement rates of 0.5, 5, 50, 250 and 500 mm/min is shown in Fig. 5. In all cases, tensile modulus increased linearly with increasing fibre concentration. The linear dependence between tensile modulus, $E_c$, and volume fraction of fibres, $\phi_f$, suggests that tensile modulus can be modelled using the modified rule-of-mixtures equation:

$$E_c = \eta_E E_f \phi_f + (1 - \phi_f) E_m \tag{4}$$

where $E_m$ is tensile modulus of the TPU matrix and $E_f$ is the tensile modulus of the glass fibre. The parameter $\eta_E$ is termed fibre efficiency parameter for composite modulus taking into account the effect on modulus due to fibre length and fibre orientation distributions in the moulded specimens. However, the linearity of $E_c$ with $\phi_f$ suggests that $\eta_E$ is not affected by the concentration of glass fibres.

Rearranging Eq. 4 gives

$$E_c = E_m + (\eta_E E_f - E_m)\phi_f \tag{5}$$

Values of $\eta_E$ obtained from the slope of the linear regression lines in Fig. 5 with $E_f = 76$ GPa are presented in Fig. 6 where it can be seen that $\eta_E$ increases linearly with $\ln \dot{e}$. This observation implies that effectiveness of the short fibres as the reinforcing filler is enhanced with increasing rate. This can be attributed to an increase in shear modulus of the matrix with increasing rate.

#### *Strain-rate effect*

The effect of strain rate on tensile modulus is shown more explicitly in Fig. 7 where it can be seen that tensile modulus of the TPU matrix and its composites increases linearly with $\ln \dot{e}$. The observed linearity between tensile modulus, $E$, and $\ln \dot{e}$ can be reasonably expressed as:

$$E = A + B \ln \dot{e} \tag{6}$$

$A$ and $B$ both increase with increasing fibre concentration.

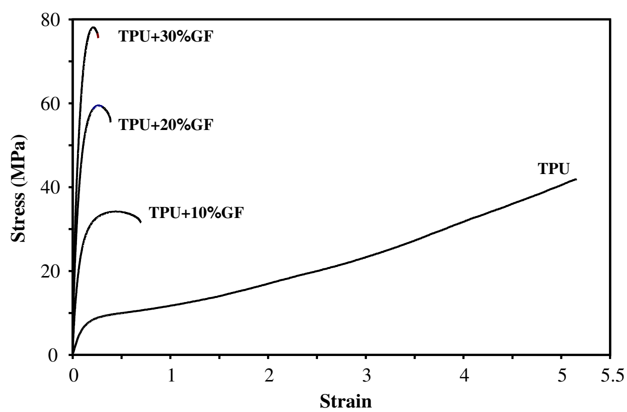



**Fig. 4** Tensile stress–strain curves for single-gated TPU matrix and its composites at crosshead displacement rate of 50 mm/min

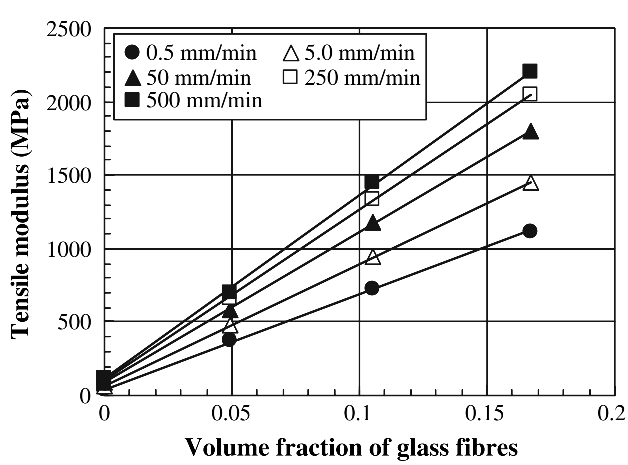



**Fig. 5** Effect of fibre volume fraction on tensile modulus of single-gated mouldings at crosshead speeds of 0.5, 5.0, 50, 250 and 500 mm/min

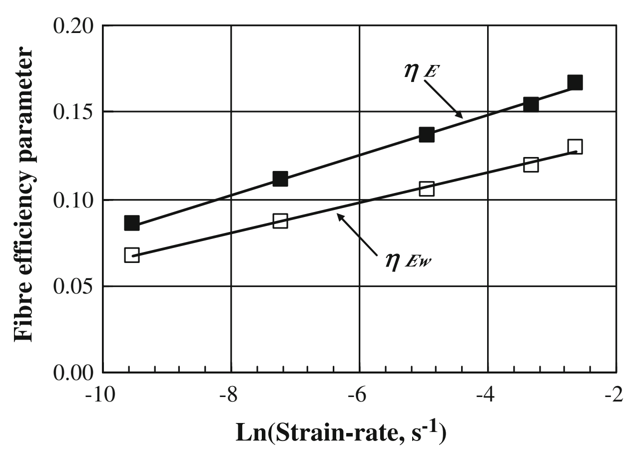



**Fig. 6** Strain-rate effect on fibre efficiency parameter for modulus of single- and double-gated mouldings

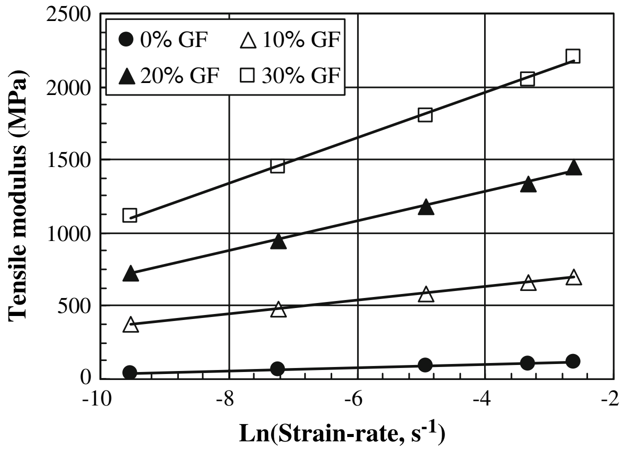



**Fig. 7** Strain-rate effect on tensile modulus of single-gated TPU mouldings containing 0, 10, 20 and 30% by weight short glass fibres

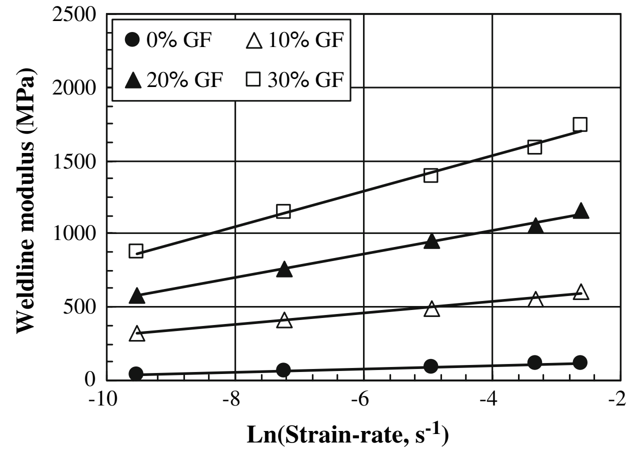



**Fig. 9** Strain-rate effect on tensile modulus of double-gated TPU mouldings containing 0, 10, 20 and 30% by weight short glass fibres

*Weldline effect*

Figure 8 shows that tensile modulus of the double-gated specimens, $E_{\mathrm{cw}}$ (e.g. weldline modulus) like their unweld counterparts ($E_c$) increases linearly with increasing fibre concentration, $\phi_{\mathrm{f}}$, and therefore likewise can be modelled using the modified rule-of-mixtures equation:

$$E_{\mathrm{cw}} = \eta_{\mathrm{Ew}} E_{\mathrm{f}} \phi_{\mathrm{f}} + (1 - \phi_{\mathrm{f}}) E_{\mathrm{mw}} \quad (7)$$

where $E_{\mathrm{mw}}$ is the tensile modulus of the matrix and $\eta_{\mathrm{Ew}}$ is the fibre efficiency parameter for composite modulus, both in the presence of weldlines. As illustrated in Fig. 6, values of $\eta_{\mathrm{Ew}}$ as obtained from the slope of the lines in Fig. 8 are smaller than $\eta_{\mathrm{E}}$ but likewise increase linearly with increasing $\ln \dot{e}$. This observation implies that the presence of weldlines reduces the effectiveness of the fibre as reinforcing filler.

The effect of strain rate on weldline modulus, $E_{\mathrm{w}}$, is shown more explicitly in Fig. 9 and as can be seen weldline modulus of the TPU matrix and its composites increases linearly with increasing $\ln \dot{e}$. The observed linearity can be reasonably expressed as:

$$E_{\mathrm{w}} = A_{\mathrm{w}} + B_{\mathrm{w}} \ln \dot{e} \quad (8)$$

$A_{\mathrm{w}}$ and $B_{\mathrm{w}}$ increase with increasing fibre concentration.

The effect of weldline on tensile modulus is quantitatively expressed in terms of weldline integrity factor, $F_E$, for modulus defined as:

$$F_E = \frac{E_{\mathrm{w}}}{E} \quad (9)$$

where $E$ is tensile modulus of single-gated moulding (i.e. unweld modulus) and $E_w$ is the tensile strength of the double-gated moulding (i.e. weldline modulus), of the same material. As shown in Fig. 10, $F_E$ decreases with

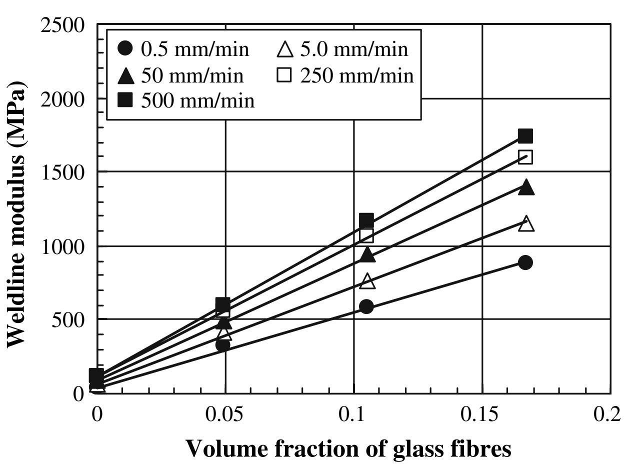



**Fig. 8** Effect of fibre volume fraction on tensile modulus of double-gated mouldings at crosshead speeds of 0.5, 5.0, 50, 250 and 500 mm/min

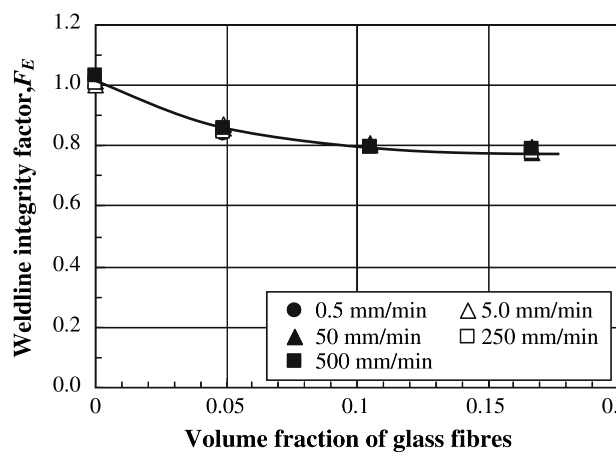



**Fig. 10** Weldline integrity factor for tensile modulus versus volume fraction of glass fibres at crosshead speeds of 0.5, 5.0, 50, 250 and 500 mm/min

increasing fibre concentration, $\phi_f$, and whilst the value of $F_E$ is 1.0 or there about for TPU matrix, it reduces to around 0.8 for composite containing 30% by weight short fibres thus indicating 20% reduction in tensile modulus due to weldline.

## Analysis of tensile strength

### *Effect of fibre concentration*

Stress–strain curves for single-gated mouldings in Fig. 4 reveal that tensile strength of the TPU matrix is enhanced by the addition of glass fibres whereas its elongation at failure is considerably reduced. It is also evident that TPU and its composites failed after exhibiting a yield point (referred to in the following text as tensile strength). This behaviour was consistently observed for all single-gated mouldings over the entire crosshead speed range studied here.

The effect of fibre volume fraction, $\phi_f$, on tensile strength of single-gated mouldings at crosshead displacement rates of 0.5, 5, 50, 250 and 500 mm/min is shown in Fig. 11. Results show that tensile strength of the composite system, $\sigma_c$, increases nonlinearly with increasing $\phi_f$ in all cases. This observation indicates that composite tensile strength does not conform to the modified rule-of-mixtures, for short fibre composites which is often expressed as:

$$\sigma_c = \eta_\sigma \sigma_f \phi_f + (1 - \phi_f)\sigma_m \tag{10}$$

where $\sigma_f$ is the tensile strength of the glass fibre and $\sigma_m$ is the tensile strength of the matrix. The term $\eta_\sigma$ is the fibre efficiency parameter for the composite strength, whose value like $\eta_E$ depends on the length and the orientation of the fibres in the moulded specimens. If parameter $\eta_\sigma$ does not show a significant variation with increasing $\phi_f$ then a linear relationship is expected between $\sigma_c$ and $\phi_f$ as expressed by Eq. 10, particularly at low-fibre volume fractions (typically less than 10–20% by volume) where fibre–fibre interaction is not an important consideration. The nonlinearity between $\sigma_c$ and $\phi_f$ as obtained here implies that $\eta_\sigma$ for the composite system under investigation varies with fibre concentration. It is worth stating that such nonlinearly between $\sigma_c$ and $\phi_f$ has also been reported for a wide range of injection-moulded polymer composite systems [11, 12]. In all cases, including the data presented here, the relationship between $\sigma_c$ and $\phi_f$ is best described by a second order polynomial function of the form

$$\sigma_c = a_0 + a_1\phi_f + a_2\phi_f^2 \tag{11}$$

The polynomials functions describing the data in Fig. 11 are given in Table 3.

It is worth noting that polynomials in Table 3 may be used to obtain some indication regarding the optimum value for the volume fraction of fibres ($\phi_{f,max}$) in order to achieve the maximum strength, at a given strain rate. The optimum values, $\phi_{f,max}$, at $d\sigma_c/\phi_f = 0$ are also given in Table 3 and show no significant variation with strain rate. It must be said, however, that although it seems advantageous to increase the fibre concentration in the composite to 30% by volume, the processing difficulties and the possible strength loss due to fibre–fibre interactions may limit the optimum value below this value.

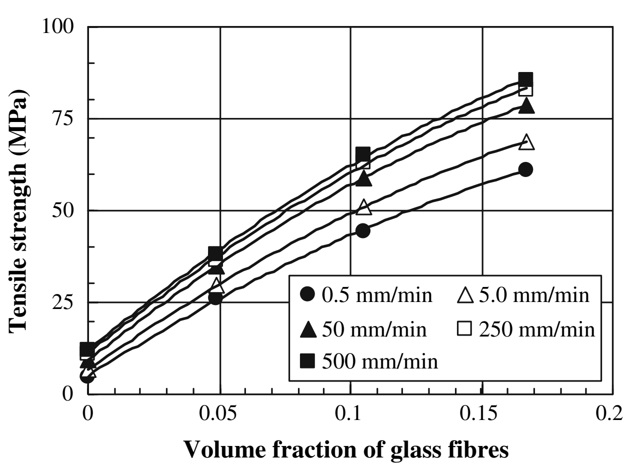



**Fig. 11** Effect of fibre volume fraction on tensile strength of single-gated mouldings at crosshead speeds of 0.5, 5.0, 50, 250 and 500 mm/min

### *Strain-rate effect*

The effect of strain rate on tensile strength of single-gated mouldings is shown more explicitly in Fig. 12 where it can be seen that tensile strength of the TPU matrix and its composites increases linearly with the natural logarithm of strain rate, $\ln \dot{e}$. This linear relationship suggests that tensile strength, $\sigma$, conforms to the Eyring's model of the flow of solids which may be written as:

$$\sigma = C + D \ln \dot{e} \tag{12}$$

**Table 3** Polynomial functions for tensile strengths and the optimum volume fraction of fibres for single-gated mouldings at various crosshead speeds

| Crosshead speed (mm/min) | Polynomial function | $\phi_{f,max}$ |
|---|---|---|
| 0.5 | $\sigma_c = 4.92 + 456.85\phi_f - 725.71\phi_f^2$ | 0.32 |
| 5.0 | $\sigma_c = 6.70 + 504.15\phi_f - 784.83\phi_f^2$ | 0.32 |
| 50 | $\sigma_c = 9.16 + 571.74\phi_f - 932.90\phi_f^2$ | 0.31 |
| 250 | $\sigma_c = 11.16 + 579.01\phi_f - 880.48\phi_f^2$ | 0.33 |
| 500 | $\sigma_c = 12.00 + 593.70\phi_f - 911.18\phi_f^2$ | 0.33 |

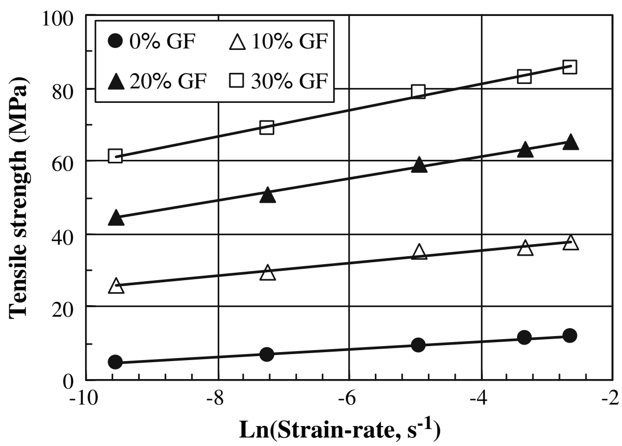



**Fig. 12** Strain-rate effect on tensile strength of single-gated TPU mouldings containing 0, 10, 20 and 30% by weight short glass fibres

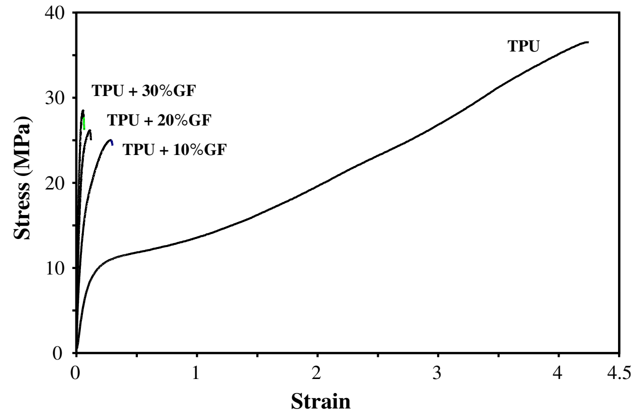



**Fig. 14** Tensile stress–strain curves for double-gated TPU and its composites at crosshead displacement rate of 50 mm/min

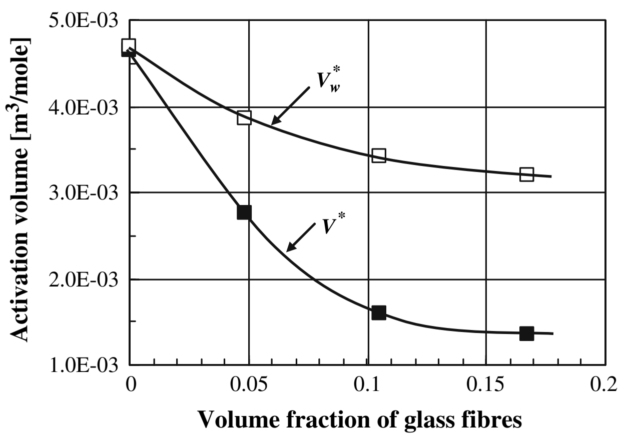



**Fig. 13** Effect of fibre concentration on activation volume

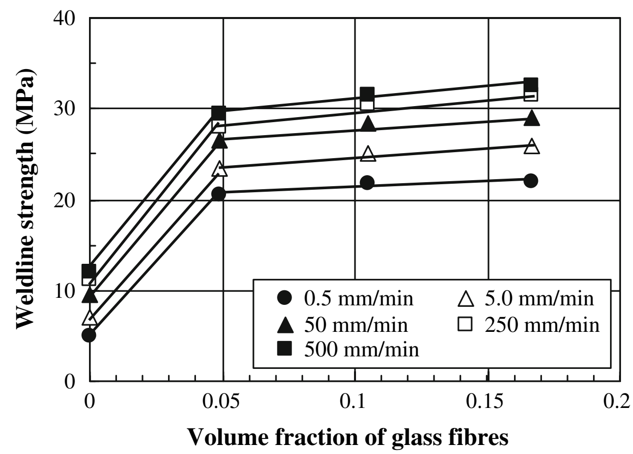



**Fig. 15** Effect of fibre volume fraction on tensile strength of double-gated mouldings at crosshead speeds of 0.5, 5.0, 50, 250 and 500 mm/min

According to Eyring, $D = \frac{2RT}{V^*}$ where $R$ is molar gas constant, $T$ is temperature (°K) and $V^*$ is the activation volume ($m^3$/mol). Values of $V^*$calculated from the slope of the lines (i.e. constant $D$) in Fig. 11 are plotted as a function of $\phi_f$ in Fig. 13. Results show that $V^*$ decreases with increasing $\phi_f$. A similar observation has been reported by Mouhmid et al. for glass fibre reinforced polyamide 6,6 [13].

*Weldline effect*

Figure 14 shows typical stress–strain curves for double-gated TPU and TPU composites. Comparison with the corresponding single-gated curves in Fig. 4 reveals that the presence of weldline in the double-gated mouldings reduces elongation at failure (i.e. ductility) and in the case of composites causes significant reduction in tensile strength and elongation at break.

As illustrated in Fig. 15, weldline strength of the TPU composite is consistently higher than that of TPU matrix, and increases with increasing fibre concentration, $\phi_f$. This observation reveals that weldline strength of the TPU matrix is indeed enhanced by the addition of glass fibres. It is also evident from Fig. 15, that weldline strength rises sharply for fibre concentration values of less than 5% by volume; above this concentration value, increase in weldline strength with $\phi_f$ take places at a much slower rate. As can be seen, this trend is consistent over the entire strain-rate range selected in this study.

The effect of weldline on tensile strength is expressed quantitatively in terms of weldline integrity factor for tensile strength, $F_\sigma$, defined as:

$$F_\sigma = \frac{\sigma_w}{\sigma} \quad (13)$$

where $\sigma$ is tensile strength of single-gated moulding (i.e. unweld strength) and $\sigma_w$ is the tensile strength of the double-gated moulding (i.e. weldline strength), of the same material. Figure 16 shows that $F_\sigma$ decreases quite

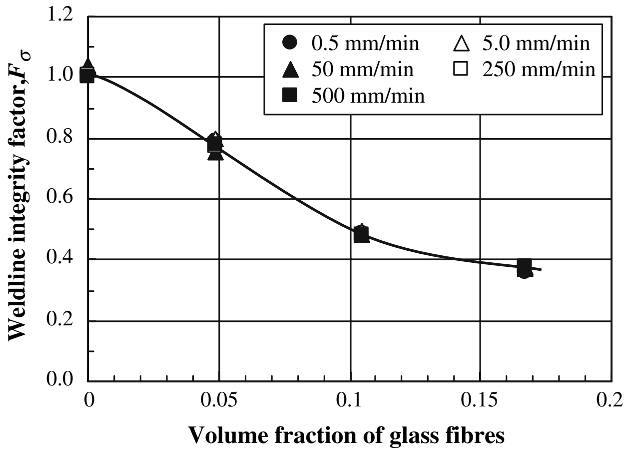



**Fig. 16** Weldline integrity factor for tensile strength versus volume fraction of glass fibres at crosshead speeds of 0.5, 5.0, 50, 250 and 500 mm/min

significantly with increasing fibre concentration, $\phi_f$, and whilst the value of $F_\sigma$ is 1.0 or there about for TPU matrix, it reduces to around 0.4 for composite containing 30% by weight fibre thus indicating 60% reduction in tensile strength due to weldline. This observation reveals that tensile strength of TPU composite is affected more by the presence of weldlines than its tensile modulus and likewise is not affected significantly by strain rate.

The effect of strain rate on weldline strength is shown more explicitly in Fig. 17. Evidently, weldline strength of the TPU matrix and its composites like tensile strength of their unweld counterparts increases linearly with $\ln \dot{e}$, and likewise can be expressed using the Eyring equation:

$$\sigma_w = C_w + D_w \ln \dot{e} \tag{14}$$

where $V_w^*$ is the activation volumes of the double-gated moulding whose value for TPU and its composites can be obtained from the slope of the lines in Fig. 17, i.e. $D_w = \frac{2RT}{V_w^*}$. As shown in Fig. 13, whilst $V_w^* = V^*$ for the matrix, $V_w^* > V^*$ for the composites and likewise decreases with increasing $\phi_f$. It is also evident that difference between the two values widens as $\phi_f$ increases.

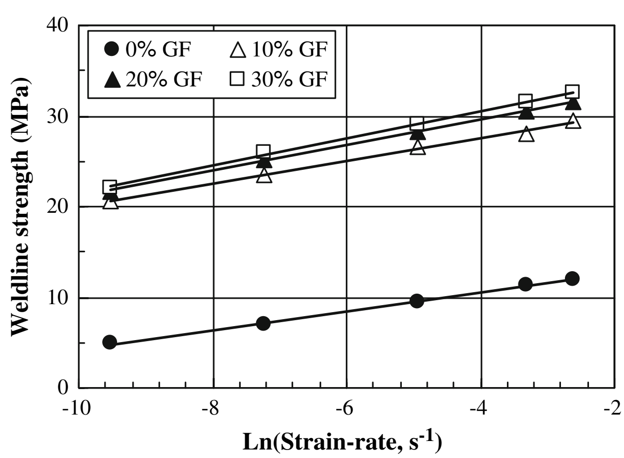



**Fig. 17** Strain-rate effect on tensile strength of double-gated TPU mouldings containing 0, 10, 20 and 30% by weight short glass fibres

## Analysis of fracture toughness

### *Effect of fibre concentration*

Single-edge notched tension specimens for single-gated TPU matrix showed extensive crack tip blunting at all three speeds and no crack propagation. This meant that fracture toughness for the matrix could not be determined under the testing conditions employed in this study. On the other hand, the initial notch in single-gated TPU composites propagated normal to the direction of the applied stress. The load-extension curves showed a clear maximum beyond which load decreased with increasing extension. Visual observation of the specimen during the test revealed that the initial notch began propagating near the maximum load or thereabout and therefore maximum load was used as $P_f$ in Eq. 2 for evaluating initiation fracture toughness for the composites, i.e. $K_{ICc}$.

Figure 18 shows plots of $K_{ICc}$ versus $a/W$ for TPU composites at crosshead speeds of 5, 50 and 500 mm/min, respectively. It can be seen that $K_{ICc}$ rises initially but becomes more or less independent of $a/W$ for ratios greater than 0.25. The average $K_{ICc}$ values for $a/W > 0.25$ are plotted in Fig. 19 as a function of fibre concentration, $\phi_f$. Results show that $K_{ICc}$ increases linearly with increasing $\phi_f$ as well as increasing with increasing speed. Assuming $K_{ICc}$ follows rule-of-mixtures, one obtains by linear extrapolation of the lines to $\phi_f = 0$, $K_{ICm}$ values of 1.81, 1.92 and 2.14 MPam$^{1/2}$ for TPU matrix with increasing speed.

### *Strain-rate effect*

The effect of strain rate on fracture toughness is shown more explicitly in Fig. 20 where it can be seen that fracture toughness of the TPU matrix (obtained by way of extrapolation) and its composites like their tensile strength and modulus increases with increasing rate and shows a linear dependence with respect to $\ln \dot{e}$ which may be expressed as:

$$K_{IC} = E + F \ln \dot{e} \tag{15}$$

where $E$ and $F$ are dependent upon the volume fraction of glass fibres.

### *Weldline effect*

The fracture behaviour of SENT specimens with weldlines was similar to that of the unweld counterparts. Similarly,

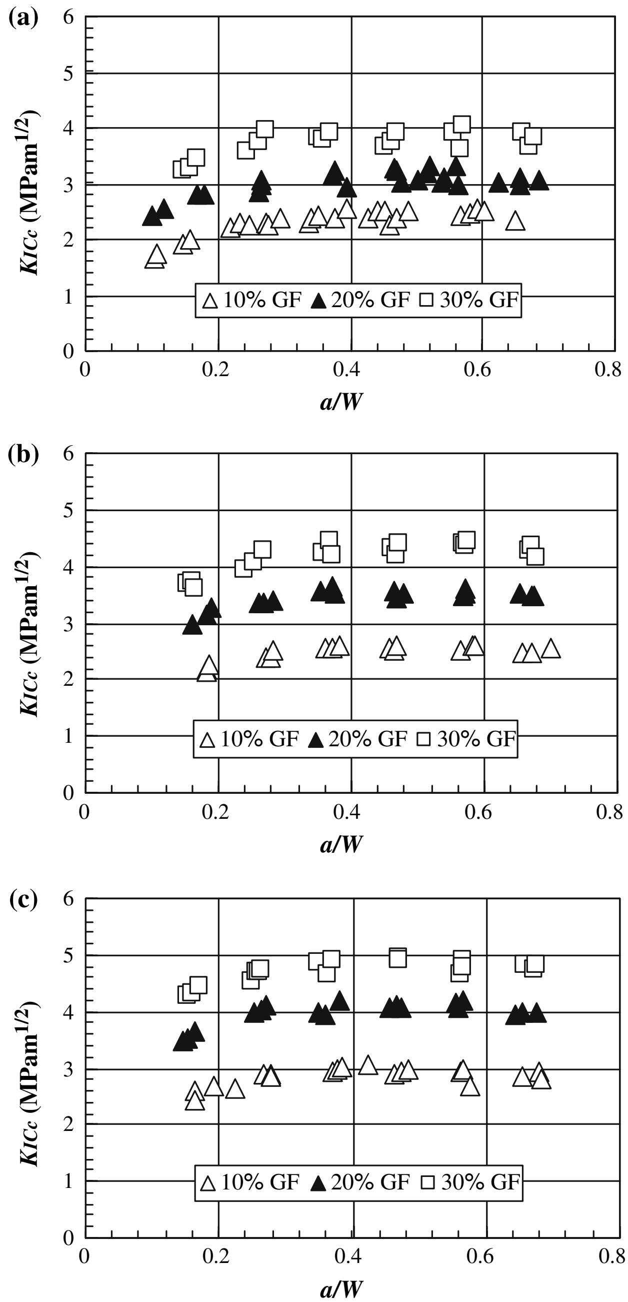



**Fig. 18** Fracture toughness at initiation versus *a/W* for single-gated composite mouldings containing 10, 20 and 30% w/w short glass fibres at crosshead speeds of: **a** 5 mm/min, **b** 50 mm/min and **c** 500 mm/min

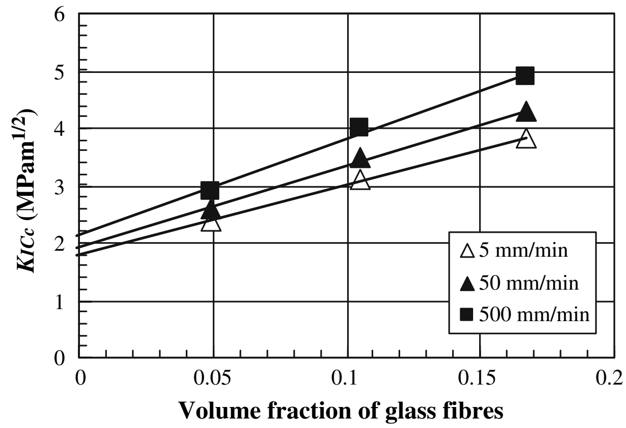



**Fig. 19** Effect of fibre volume fraction on fracture toughness at initiation for single-gated composite mouldings at crosshead speeds of 5, 50 and 500 mm/min

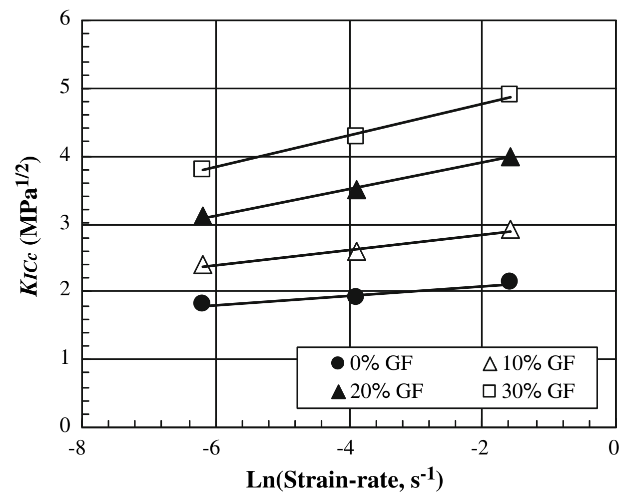



**Fig. 20** Strain-rate effect on fracture toughness at initiation for single-gated TPU mouldings containing 0, 10, 20 and 30% by weight short glass fibres

plots of fracture toughness at initiation for composites, $K_{\mathrm{ICcw}}$, versus *a*/*W* had similar characteristics to that of the unweld counterpart, $K_{\mathrm{ICc}}$, i.e. $K_{\mathrm{ICcw}}$ like $K_{\mathrm{ICc}}$ increased initially but became more or less independent of *a*/*W* for ratios greater than 0.3. As illustrated in Fig. 21, $K_{\mathrm{ICcw}}$ is not as strongly affected by the volume fraction of fibres as $K_{\mathrm{ICc}}$. It can be seen also that $K_{\mathrm{ICcw}}$ increases with increasing speed. The effect of strain rate on $K_{\mathrm{ICcw}}$ is shown more explicitly in Fig. 22 where it can be seen that $K_{\mathrm{ICcw}}$ like $K_{\mathrm{ICc}}$ increases linearly with increasing $\ln \dot{e}$ and therefore can be described as

$$K_{\mathrm{ICcw}} = E_{\mathrm{w}} + F_{\mathrm{w}} \ln \dot{e} \tag{16}$$

where $E_{\mathrm{w}}$ and $F_{\mathrm{w}}$ are dependent upon the volume fraction of glass fibres.

The effect of weldline on fracture toughness is quantitatively expressed in terms of weldline integrity factor, $F_K$, defined as:

$$F_K = \frac{K_{\mathrm{ICcw}}}{K_{\mathrm{ICc}}} \tag{17}$$

Figure 23 shows that $F_K$ decreases almost linearly with increasing fibre concentration and shows no significant variation with respect to test speed. It can be deduced from the figure, that weldline reduces fracture toughness quite

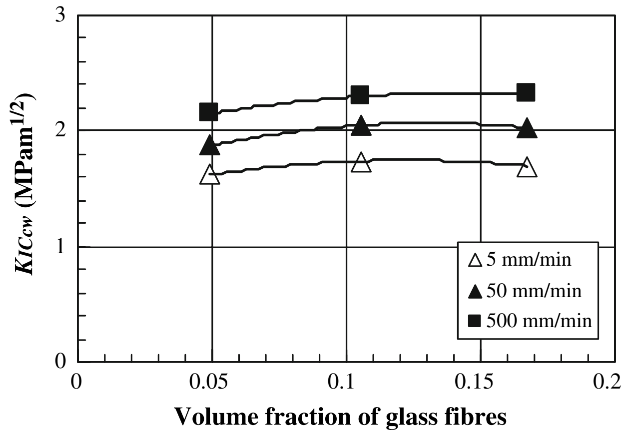



**Fig. 21** Effect of fibre volume fraction on fracture toughness at initiation for double-gated composite mouldings at crosshead speeds of 5, 50 and 500 mm/min

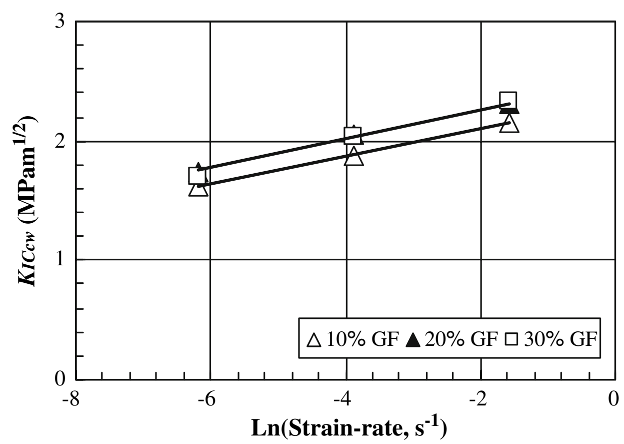



**Fig. 22** Strain-rate effect on fracture toughness at initiation for double-gated TPU composite mouldings containing 10, 20 and 30% by weight short glass fibres

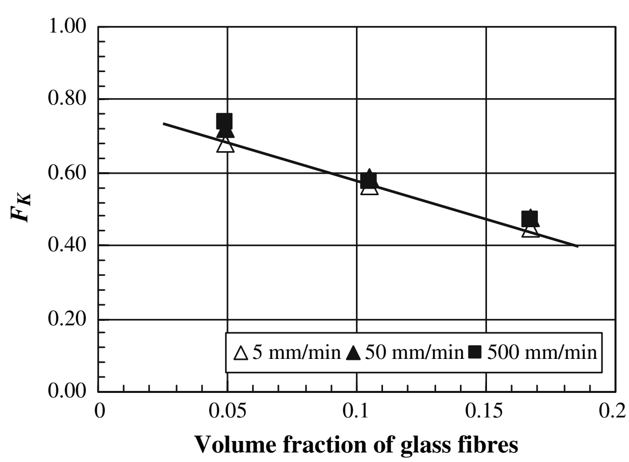



**Fig. 23** Weldline integrity factor for fracture toughness at initiation versus volume fraction of glass fibres at crosshead speeds of 5.0, 50 and 500 mm/min

significantly, e.g. approximately 60% reduction in value for composite containing 30% by volume short fibres.

## Conclusions

Mechanical and fracture properties of single- and double-gated PBT/PC and PBT/PC composites containing 10, 20 and 30% by weight short glass fibres were studied. The following observations were made:

- Tensile modulus of single- and double-gated mouldings increased linearly with increasing $\phi_f$ according to the modified "rule-of-mixtures" for short fibre composites and with increasing natural logarithm of strain rate, $\ln \dot{e}$. It was noted that whilst tensile modulus of the TPU matrix was not significantly affected by the weldline, that of composite containing 30% by weight short fibres decreased as much as 20% giving weldline integrity factor of 0.8. Weldline integrity factor for tensile modulus decreased with increasing $\phi_f$ but showed no significant strain-rate effect. The fibre efficiency parameter for tensile modulus increased linearly with increasing $\ln \dot{e}$ for both weld and unweld specimens. However, fibre efficiency parameter for unweld specimen was found to be considerably greater than that of the weld specimen.
- Tensile strength of single- and double-gated mouldings increased with increasing $\phi_f$ in a nonlinear manner but increased with increasing $\ln \dot{e}$ in a linear manner. It was noted that whilst tensile strength of the TPU matrix was not significantly affected by the weldline, that of composite containing 30% by weight short fibres decreased as much as 60% giving weldline integrity factor of 0.4. Weldline integrity factor decreased with increasing $\phi_f$ but showed no strain-rate effect of any significance.
- Fracture toughness of the single-gated mouldings at initiation increased linearly with increasing $\phi_f$ and $\ln \dot{e}$. Weldline integrity factor for fracture toughness decreased almost linearly with increasing $\phi_f$ showing no significant strain-rate effect.

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