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Effect of fibre concentration and strain rate on mechanical properties of single-gated and double-gated injection-moulded short glass fibre-reinforced polypropylene copolymer composites

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Abstract The effect of fibre concentration, strain rate and weldline on tensile strength, tensile modulus and fracture toughness of injection-moulded polypropylene copolymer (PPC) reinforced with 10, 20, 30 and 40% by weight short glass fibre was studied. It was found that tensile modulus of single- and double-gated mouldings increased with increasing volume fraction of fibres, ϕ_f, according to additive rule-of-mixtures, and increased linearly with natural logarithm of strain rate ($\ln \dot{e}$). The presence of weldlines in double-gated mouldings led to reduction in tensile modulus which for composite containing 40% by weight short fibres was as much as 30%. A linear dependence was obtained between fibre efficiency parameter for composite modulus and $\ln \dot{e}$ for both single- and double-gated moulding. Tensile strength of single-gated mouldings, σ_c, increased with increasing ϕ_f in a nonlinear manner. However, for ϕ_f in the range 0–12% a simple additive rule-of-mixtures adequately described the variation of σ_c with ϕ_f. A linear dependence was obtained between fibre efficiency parameter for tensile strength and $\ln \dot{e}$. The presence of weldlines in double-gated mouldings reduced tensile strength by as much as 70%. Tensile strength of both single- and double-gated mouldings increased linearly with $\ln \dot{e}$. Fracture toughness of single-gated mouldings increased linearly with increasing ϕ_f. The presence of weldlines in double-gated mouldings reduced fracture toughness by as much as 60% for composite containing 40% by weight short glass fibres.

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Introduction

The mechanical properties of short fibre polymer composites such as strength, modulus and fracture toughness 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 multi-gate 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 [1–9]. To this end, the present work was undertaken to examine the influence of fibre concentration, strain rate and weldlines on tensile strength, tensile modulus and fracture toughness of injection-moulded short glass fibre-reinforced polypropylene copolymer (PPC) composites.

Experimental details

Materials

PPC and its composites containing 10, 20, 30 and 40% by weight short glass fibres were supplied by PolyOne in the form of injection-moulded compounds.

Injection moulding

Materials were injection moulded in a Klockner Ferromatik F-60 injection moulding machine at the processing conditions listed in Table 1 to produce a series of dumbbell-shaped test specimens. The mould used consisted of a single-gate (SG) and a double-gate (DG) cavities as illustrated in Fig. 1 with nominal dimensions 4 × 10 × 120 mm (thickness, width, length). In the case of double-gated cavities, the two opposing melt fronts met to form a weldline approximately mid-way along the gauge length of the specimen.

Differential scanning calorimetric

Thermal characterisation was carried out by differential scanning calorimetry (DSC) using a Perkin-Elmer DSC-6 modulated instrument. Samples of PPC and PPC composites, in the range 9–10 mg, were cut from the injection-moulded specimens and submitted to the following thermal cycles: (1) heating from −60 to 220 °C at 10 °C/min (2) cooling from 220 to −60 °C at 5 °C/min to obtain crystallisation data and reheating to 220 °C. The DSC curves were used to obtain the melting temperature (T_m), crystallisation temperature (T_c), enthalpy of crystallisation (ΔH_c) and the enthalpy of melting (ΔH_m). Values of ΔH_c, ΔH_m and percentage crystallinity (χ_c) were calculated from the following equations:

$$\Delta H_m = \frac{\Delta H_m}{w_p} \quad (1a)$$

$$\Delta H_c = \frac{\Delta H_c}{w_p} \quad (1b)$$

$$\chi_c\,(\%) = \frac{\Delta H_m^o}{\Delta H_m} \times 100 \quad (1c)$$

where ΔH_m^o is the heat of fusion for 100% crystalline polypropylene taken as 148 J/g and w_p is the weight fraction of PPC in the composite ($w_p = 1$ for 100% PPC).

Table 1 Processing condition for injection-moulded PPC and its composites

Processing condition	0 wt%	10 wt%	20 wt%	30 wt%	40 wt%
Barrel temp. (°C)					
Nozzle	220	220	220	210	220
Zone 2	210	210	210	207	210
Zone 3	210	210	210	207	210
Zone 4	210	210	210	207	210
Mould temperature (°C)	30	30	30	30	30
Injection pressure (%)	95	95	95	95	95
Injection speed (%)	85	85	85	85	85
Cooling time (s)	15	15	15	15	15

Fig. 1 Single- and double-gated cavities with nominal dimensions of 4 × 10 × 120 mm (thickness, width, length)

Fibre concentration and length measurements

The exact weight fraction of the fibres in as received compounds (ARC) and in injection-moulded dumbbell specimens (IMDS) 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 for both ARC and IMDS are within 1% of the manufacturer's specification.

The measured weight fractions, w_f, were subsequently converted into volume fractions, ϕ_f, using Eq. 2:

$$\phi_f = \frac{\rho_c}{\rho_f} w_f \quad (2)$$

Table 2 gives values of ϕ_f obtained via Eq. 2, taking density of glass fibre, ρ_f, as 2,540 kg m^{-3} and composite densities, ρ_c, as provided by the manufacturer.

The ashes of fibrous material were subsequently spread on glass slides and placed on the observation stage of a microscope. Approximately 500 hundred fibre lengths were measured for each composite (ARC and IMDS) using an image processing system. From the fibre length distributions, examples of which are given in Fig. 2, the effect of fibre concentration and processing conditions on the average fibre length (L_f) was assessed.

Tensile tests

The effect of fibre concentration and strain rate on welded and unweld tensile strength and modulus was studied at

Table 2 Fibre concentration and the average fibre lengths in as received compounds (ARC) and in injection-moulded dumbbell specimens (IMDS)

Composites	PPC			
	10% w/w GF	20% w/w GF	30% w/w GF	40% w/w GF
%w/w (ARC)	9.50	20.03	30.05	39.70
%w/w fibre (IMDS)	8.60	20.10	28.30	39.70
Density (kg/m^3)	960	1030	1130	1220
%v/v (IMDS)	3.80	8.10	13.30	19.20
Average fibre length, ARC (mm)	0.389 (485)	0.353 (453)	0.350 (500)	0.347 (492)
Average fibre length, IMDS (mm)	0.374 (534)	0.326 (479)	0.309 (424)	0.281 (400)
Reduction in fibre length	5%	8%	12%	19%

Values given in the parenthesis are the total number of fibre lengths measured

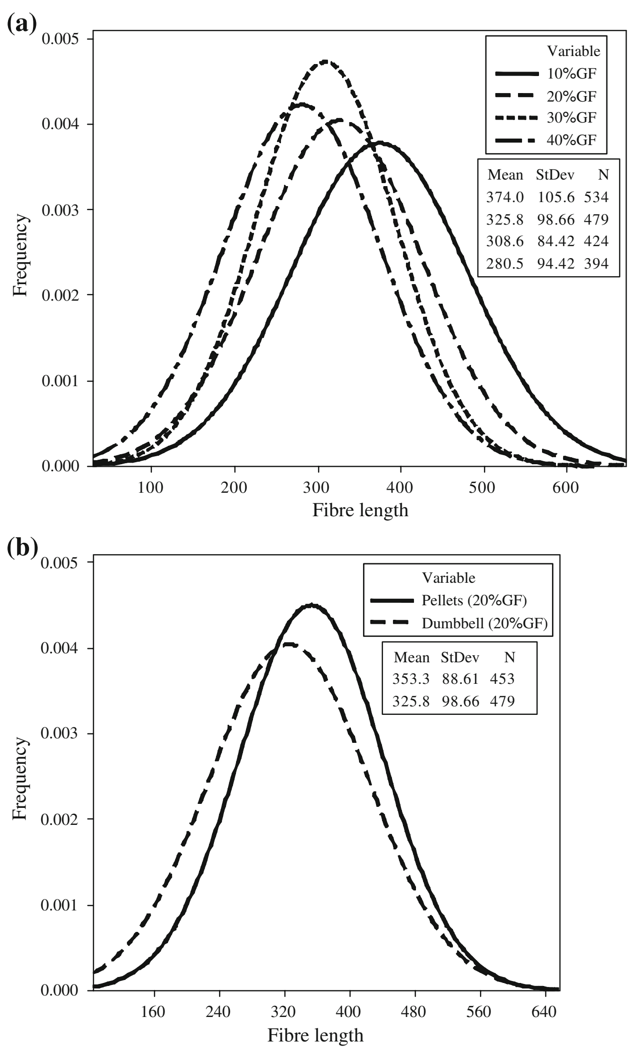

Fig. 2 **a** Fibre length distribution in IMDS. **b** Fibre length distribution in IMDS and ARC for PPC containing 20% by weight short fibres

23 °C using a Tinius Olsen H10KS testing machine. All the tests were performed using an extensometer with an initial gauge opening of 50 mm. At least six specimens were tested for determining an average value. Tests were performed at crosshead speeds of 0.05, 0.5, 5, 50 and 500 mm/min, giving nominal strain rate values of 7.58×10^{-6}, 7.58×10^{-5}, 7.58×10^{-4}, 7.58×10^{-3} and 7.58×10^{-2} s^{-1}, respectively.

Fracture toughness (K_C) tests

Fracture toughness tests were performed on rectangular coupons cut from the gauge length of both single- and double-gated mouldings (the shaded region in Fig. 1). Coupons were razor notched to various *a*/*W* ratios (crack length-to-width ratio) to produce series of 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 tested to failure in a Tinius Olsen H10KS testing machine at a crosshead speed of 50 mm/min. The load–displacement curve for each specimen was recorded and the fracture toughness, K_{IC} was calculated using the following relationship:

$$K_{\mathrm{IC}} = \frac{P_{\mathrm{f}}}{BW} Y(x)\sqrt{a} \tag{3}$$

where $x = a/W$ and P_{f} is load failure. The term $Y(x)$ is the finite width correction whose value was obtained using the following relationship:

$$Y(x) = \frac{5\sqrt{\pi}}{\sqrt{20 - 13x - 7x^2}} \tag{4}$$

Results and discussion

Thermal properties

Analysis of DSC thermograms are summarised in Table 3. Results show that melting temperature (T_{m}) of the PPC matrix is almost unaffected by the addition of fibres and the

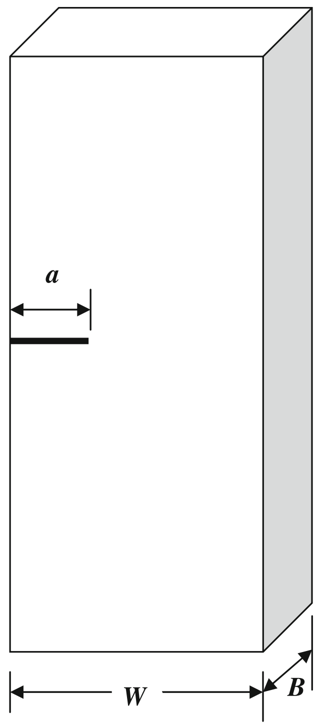

Fig. 3 Single edge notched tension specimen

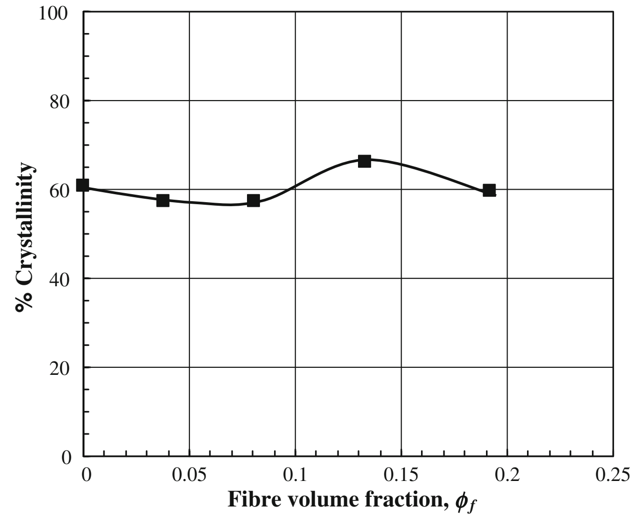

Fig. 4 Effect of fibre concentration on % crystallinity

heating cycle. However, heat of fusion (ΔH_m) in the 2nd heating cycle for PPC and its composites is greater than in the 1st heating cycle, and is much closer to ΔH_c value. It is also evident that ΔH_m and ΔH_c both decrease initially with increasing fibre concentration showing similar trend to that of percentage crystallinity (χ) versus fibre volume fraction (ϕ_f) as shown in Fig. 4. The striking feature of Fig. 4 is the higher χ for composite containing 30% by weight fibres. The percentage crystallinity, χ, for this composite is 9% higher than for the unreinforced PPC.

Effect of fibre concentration and processing on fibre length

The average fibre length, L_f, in IMDS and in ARC as determined from the distribution curves is given in Table 2 and compared in Fig. 5 as a function of fibre concentration, ϕ_f. It can be seen that the average fibre length in IMDS is consistently lower than in ARC. It is also evident that fibre concentration plays a major role in the shortening of the fibres particularly in IMDS as reduction in the average fibre length due to processing increases from 5 to 19%, as fibre concentration increases from 10 to 30% by weight. As stated by Thomason [10, 11], this is likely to be due to the fact that increased fibre loadings has led to an increase probability of fibre–fibre and fibre–machine interactions as well as increased in the apparent melt viscosity resulting in higher bending forces on the fibres during moulding.

Effect of fibre concentration and strain rate on tensile modulus of single-gated mouldings

Stress–strain curves for single-gated mouldings indicated that modulus of the PPC composites increases with increasing the concentration 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 0.05, 0.5, 5, 50 and 500 mm/min is shown in Fig. 6. In all cases, tensile modulus increased linearly with increasing fibre concentration with correlation coefficients

Table 3 Thermal analysis results for PPC and PPC composites

w_f	T_m (°C)		T_c (°C 1st cycle)	ΔH_m (J/g)		ΔH_c (J/g)	% χ_c
	1st cycle	2nd cycle		1st cycle	2nd cycle	1st cycle	
0	163.44	166.47	119.25	85.85	89.69	91.61	60.60
10%	165.56	166.30	130.92	75.92	85.06	87.94	57.47
20%	165.41	165.76	129.99	74.16	84.75	82.86	57.26
30%	164.89	165.12	129.47	84.46	97.74	99.64	66.04
40%	164.43	164.82	130.92	75.20	88.07	88.07	59.50

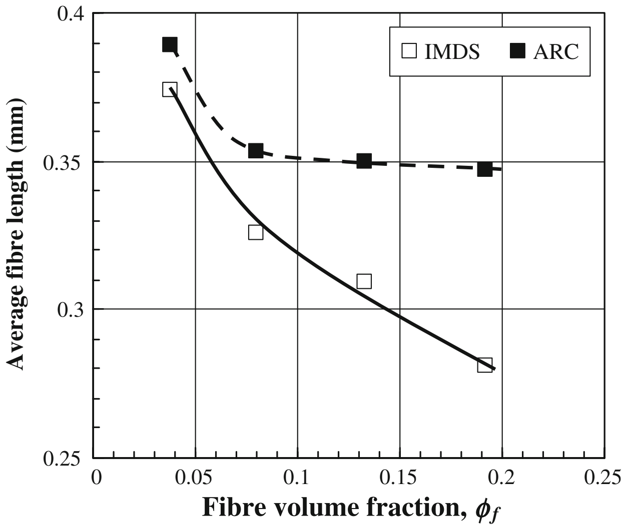

Fig. 5 Effect of fibre concentration and injection moulding on the average fibre length in PPC composites

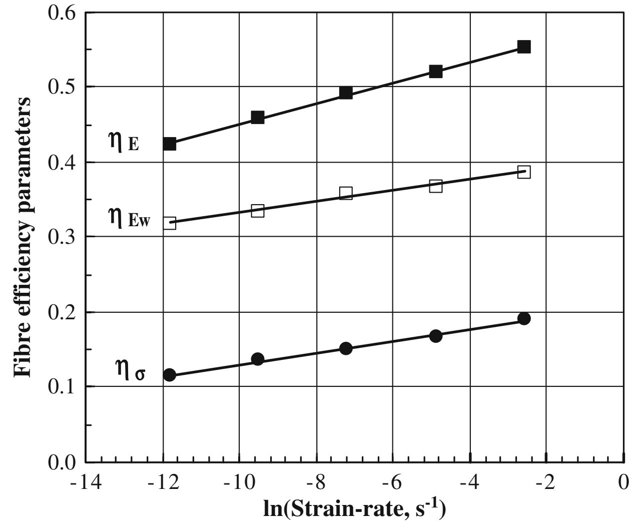

Fig. 7 Strain rate effect on fibre efficiency parameters for tensile modulus and strength for both single- and double-gated mouldings

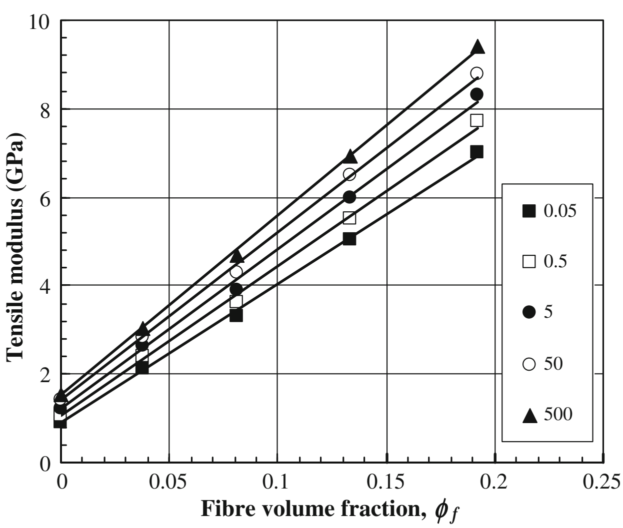

Fig. 6 Effect of fibre volume fraction on tensile modulus of single-gated mouldings at crosshead speeds of 0.05, 0.5, 5, 50 and 500 mm/min

$R^2 = 0.997$. The linear dependence between tensile modulus, E_c, and volume fraction of fibres, ϕ_f, implies that tensile modulus can be modelled using the modified rule-of-mixtures equation;

$$E_c = \eta_E E_f \phi_f + (1 - \phi_f) E_m \tag{5}$$

where E_m is tensile modulus of the PPC matrix and E_f is the tensile modulus of the glass fibre. The parameter η_E is termed the overall 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.

The linearity between E_c and ϕ_f suggests that η_E is not significantly affected by the concentration of glass fibres. Rearranging Eq. 5 gives:

$$E_c = E_m + (\eta_E E_f - E_m) \phi_f \tag{6}$$

Values of η_E obtained from the slope of the linear regression lines in Fig. 6 with $E_f = 76$ GPa are plotted in Fig. 7 as a function of natural logarithm of strain rate, $\ln \dot{e}$, and as can be seen η_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.

The overall efficiency parameter η_E is the product of two efficiency parameters as shown by Eq. 7; one associated with the orientation of the fibres (η_o) and the other with the shortness of the fibres (η_L).

$$\eta_E = \eta_L \eta_o \tag{7}$$

The parameter η_L may be evaluated using the Cox shear lag model [13] which defines η_L as

$$\eta_L = 1 - \frac{\tanh na}{na} \tag{8}$$

where a is the aspect ratio of the fibre (fibre length to diameter ratio) and n is given as

$$n = \left(\frac{E_m}{(1 + \upsilon_m) E_f \ln \lambda} \right)^{\frac{1}{2}} \tag{9}$$

If packing arrangement of fibres is assumed square, then parameter λ can be obtained from the following relationship:

Table 4 Fibre efficiency parameters for tensile modulus at crosshead speeds of 0.05, 0.5, 5, 50 and 500 mm/min

ϕ_f	η_L				
	0.05	0.5	5	50	500
0.038	0.653	0.678	0.700	0.719	0.732
0.08	0.655	0.679	0.701	0.720	0.733
0.133	0.678	0.701	0.722	0.739	0.751
0.192	0.685	0.707	0.728	0.745	0.756
	η_o				
	0.05	0.5	5	50	500
0.038	0.647	0.679	0.701	0.722	0.722
0.08	0.646	0.678	0.700	0.721	0.721
0.133	0.624	0.656	0.680	0.702	0.702
0.192	0.618	0.651	0.675	0.697	0.697
	θ^o				
	0.05	0.5	5	50	500
0.038	26.24	24.81	23.78	22.81	21.19
0.08	26.29	24.86	23.83	22.86	21.24
0.133	27.29	25.83	24.75	23.74	22.14
0.192	27.55	26.08	24.99	23.97	22.38

$$\lambda = \sqrt{\frac{\pi}{4\phi_f}} \tag{10}$$

Values of η_L obtained via Eqs. 8–10 for fibre diameter of 10 μm and matrix Poisson's ratio (υ_m) of 0.35 are presented in Table 4 together with the corresponding η_o values obtained from Eq. 7 as η_E/η_L. As can be seen, fibre efficiency parameters η_L increases whilst η_o decreases with increasing fibre concentration. It is also evident that η_L and η_o both decrease with increasing strain rate. The decrease in η_o with increasing ϕ_f indicates a mutual influence of the fibres hindering the orientation formation. Using the Krenchel [14] definition of η_o, one can determine the average fibre orientation angle, θ with respect to the loading direction as

$$\theta = \cos^{-1}[\eta_o]^{\frac{1}{4}} \tag{11}$$

The values of θ calculated via Eq. 11 are also presented in Table 4, where it can be seen that θ increases with increasing ϕ_f but decreases with increasing strain rate.

The effect of strain rate on tensile modulus is shown more explicitly in Fig. 8, where it can be seen that tensile modulus of the PPC matrix and its composites increases linearly with $\ln\dot{e}$ as

$$E = A + B\ln\dot{e} \tag{12}$$

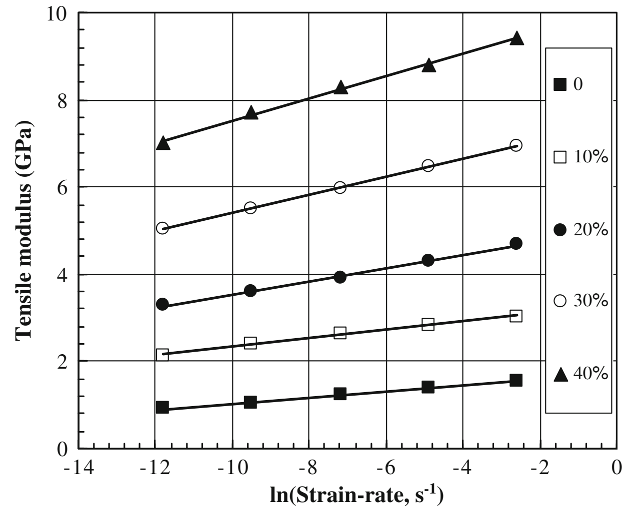

Fig. 8 Strain rate effect on tensile modulus of the single-gated PPC mouldings containing 0, 10, 20, 30 and 40% by weight short glass fibres

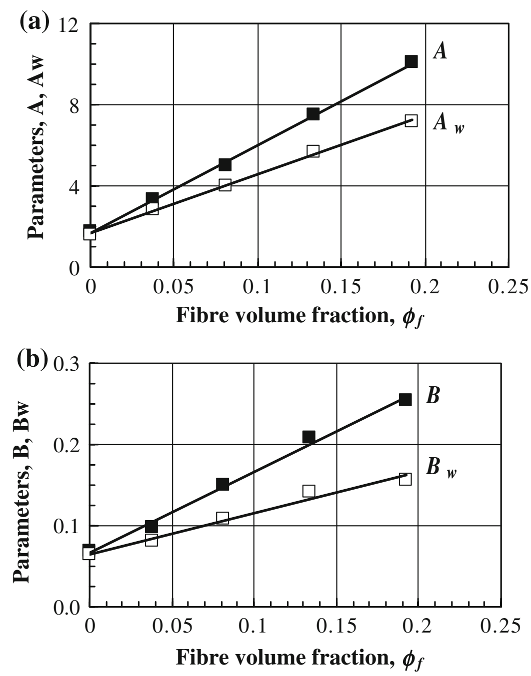

Fig. 9 Effect of fibre volume fractions on parameters A, B for single-gated and A_w, B_w for double-gated mouldings

where A and B both increase linearly with increasing fibre concentration as depicted in Fig. 9 according to the following relationships:

$$A = 1.65 + 43.55\phi_f \tag{13a}$$

$$B = 0.067 + 1.0\phi_f \tag{13b}$$

Using Eqs. 12, 13a and 13b one can generate the plot of E versus $\ln\dot{e}$ for any given value of ϕ_f.

Effect of fibre concentration and strain rate on tensile modulus of double-gated mouldings

Stress–strain curves for double-gated mouldings indicated that modulus of PPC composite increases with increase in the concentration of glass fibres. This behaviour was consistently observed for all double-gated mouldings over the entire crosshead speed range studied here. As shown in Fig. 10, tensile modulus of the double-gated specimen (e.g. weldline modulus) like its unweld counterpart increases linearly with increasing fibre concentration, ϕ_f, and therefore likewise may be modelled using the modified rule-of-mixtures equation:

$$E_{cw} = \eta_{Ew} E_f \phi_f + (1 - \phi_f) E_{mw} \tag{14}$$

where E_{cw}, E_{mw} and η_{Ew} are the respective values of E_c, E_m and η_E in the presence of the weldline. As illustrated in Fig. 8, values of η_{Ew} as obtained from the slope of the lines in Fig. 10 are smaller than η_E but likewise increase linearly with increasing $\ln \dot{e}$. This observation implies the effectiveness of the fibre as reinforcing filler is reduced by the weldline.

The effect of strain rate on modulus of double-gated mouldings, E_w, is shown more explicitly in Fig. 11 where it can be seen that modulus of the double-gated mouldings (E_w) like their single-gated counterparts (E) increases linearly with increasing $\ln \dot{e}$ and likewise can be reasonably expressed as

$$E_w = A_w + B_w \ln \dot{e} \tag{15}$$

where A_w and B_w both increase linearly with increasing fibre concentration as shown in Fig. 9 according to the following relationships:

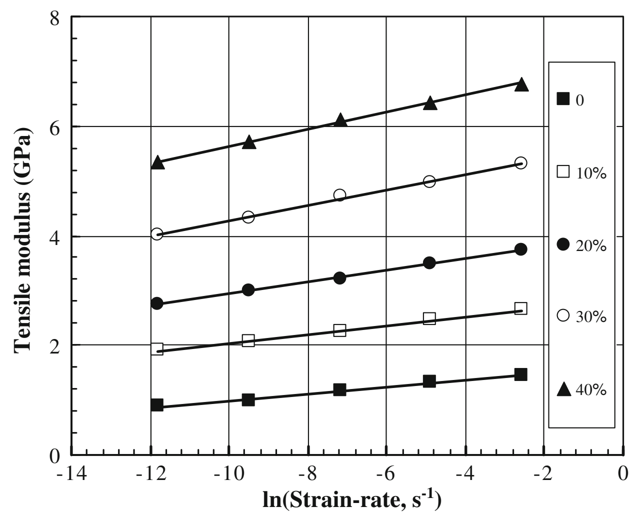

Fig. 11 Strain rate effect on tensile modulus of double-gated PPC mouldings containing 0, 10, 20, 30 and 40% by weight short glass fibres

$$A_w = 1.69 + 29.07\phi_f \tag{16a}$$

$$B_w = 0.065 + 0.508\phi_f \tag{16b}$$

Using Eqs. 15, 16a and 16b one can generate the plot of E_w versus $\ln \dot{e}$ for any given value of ϕ_f.

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

$$F_E = \frac{E_w}{E} \tag{17}$$

where E and E_w are tensile modulus of single-gated (i.e. weldline free) and double-gated (with weldline) mouldings, respectively, of the same material. As illustrated in Fig. 12,

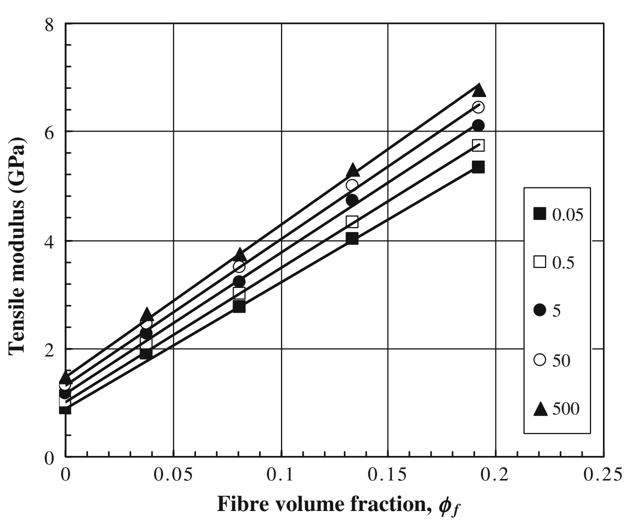

Fig. 10 Effect of fibre volume fraction on tensile modulus of double-gated mouldings at crosshead speeds of 0.05, 0.5, 5, 50 and 500 mm/min

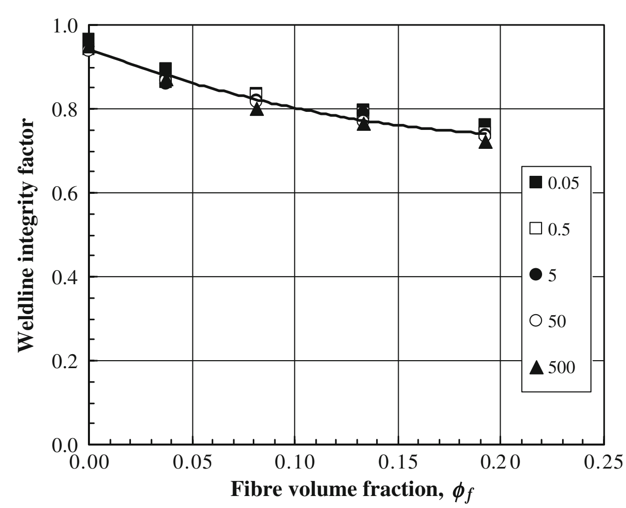

Fig. 12 Effect of fibre volume fraction on weldline integrity factor for tensile modulus, F_E, at crosshead speeds of 0.05, 0.5, 5, 50 and 500 mm/min

whilst F_E decreases with increasing fibre concentration, it is not affected significantly with increasing strain rate. The value of F_E for the unreinforced PPC is in the range 0.96–0.94 whereas for the composite containing 40% by weight short fibres it is in the range 0.76–0.72. Meaning, that the presence of weldline has reduced the modulus of the unreinforced PPC matrix by not more than 6%, whereas it has reduced the modulus of the composite containing 40% by weight short fibres by as much as 28%. Given that the effect of strain rate on F_E is not very significant, the data in Fig. 12 can be reasonably expressed by the following polynomial function:

$$F_E = 0.942 - 1.79\phi_f + 3.88\phi_f^2 \quad (18)$$

Effect of fibre concentration and strain rate on tensile strength of single-gated mouldings

Stress–strain curve revealed that single-gated mouldings failed after exhibiting a clear yield point (referred to in the following text as tensile strength). It was noted also that whist tensile strength increased, elongation to failure decreased, with increasing fibre concentration. This behaviour was consistently observed over the entire crosshead speed range studied here.

The effect of fibre volume fraction, ϕ_f, on tensile strength of single-gated mouldings at crosshead displacement rates of 0.05, 0.5, 5, 50 and 500 mm/min is shown in Fig. 13. Results show that in all cases tensile strength of the composite system, σ_c, increases nonlinearly with increasing ϕ_f and therefore it does not conform to the modified rule-of-mixtures for strengths. The data presented here, as for many polymer composite systems [4, 6, 10], can best be described by a second order polynomial function of the form:

$$\sigma_c = a_0 + a_1\phi_f + a_2\phi_f^2 \quad (19)$$

The polynomials functions describing the data in Fig. 13 are given in Table 5. The polynomials may be used to obtain some indication regarding the optimum value for ϕ_f ($\phi_{f,max}$) in order to achieve the maximum strength, at a given strain rate. Values of, $\phi_{f,max}$, at $d\sigma_c/\phi_f = 0$ can be found in Table 5. It must be said, however, that although it seems advantageous to increase the fibre concentration in the composite up to 30% by volume, the processing difficulties and the possible strength loss due to fibre–fibre interaction may limit the optimum value below 30%.

Figure 14 shows the strength data in Fig. 13 re-plotted for fibre concentration value in the range of 0–30% by weight. It can be observed within this range, tensile strength is a linear function of ϕ_f (regression coefficients R^2 of 0.996) and like tensile modulus can be reasonably expressed by a simple rule-of-mixtures:

Table 5 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	$\phi_{f,max}$
0.05	$\sigma_c = 16.32 + 331.05\phi_f - 602.88\phi_f^2$	0.27
0.5	$\sigma_c = 18.62 + 386.56\phi_f - 648.48\phi_f^2$	0.30
5	$\sigma_c = 22.11 + 421.15\phi_f - 700.66\phi_f^2$	0.30
50	$\sigma_c = 25.17 + 459.84\phi_f - 717.61\phi_f^2$	0.32
500	$\sigma_c = 26.69 + 538.81\phi_f - 901.86\phi_f^2$	0.30

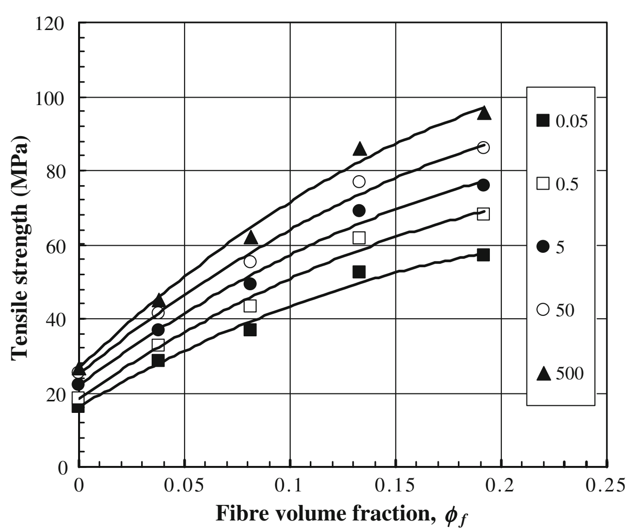

Fig. 13 Effect of fibre volume fraction on tensile strength of single-gated mouldings at crosshead speeds of 0.05, 0.5, 5, 50 and 500 mm/min

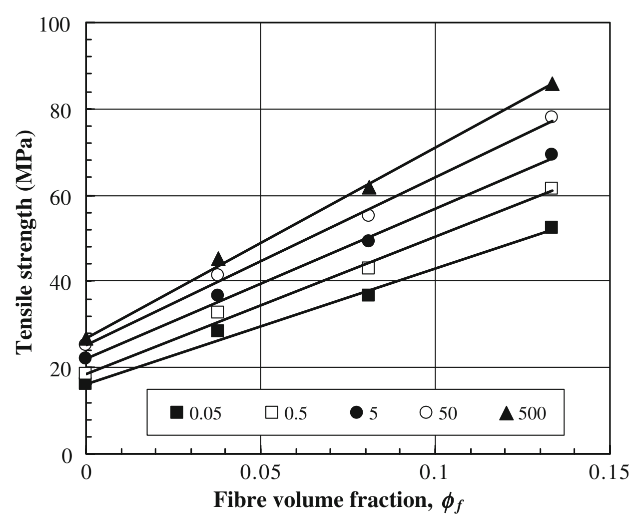

Fig. 14 Effect of fibre volume fraction on tensile strength of single-gated mouldings at crosshead speeds of 0.05, 0.5, 5, 50 and 500 mm/min for fibre concentration value in the range 0–30% by weight

$$\sigma_c = \eta_\sigma \sigma_f \phi_f + (1 - \phi_f)\sigma_m \quad (20)$$

where σ_f is tensile strength of the glass fibre and σ_m is tensile strength of the unreinforced PPC (i.e. the matrix). The term η_σ like η_E takes into consideration the effects on tensile strength due to shortness and misalignment of the fibres, in the moulded specimen. Rearranging Eq. 20 gives

$$\sigma_c = \sigma_m + (\eta_\sigma \sigma_f - \sigma_m)\phi_f \quad (21)$$

The average values of η_σ as obtained from the slope of the linear regression lines in Fig. 14 with $\sigma_f = 2{,}470$ MPa are plotted in Fig. 7 as a function of ln $\dot{e}$. It can be seen, that although η_σ like η_E increase linearly with increasing ln $\dot{e}$, it is considerably smaller than η_E meaning that composite strength is more affected by the shortness and misalignment of the fibres than its modulus.

The effect of strain rate on tensile strength of single-gated mouldings is shown more explicitly in Fig. 15 where it can be seen that tensile strength of the PPC matrix and its composites increases linearly with the natural logarithm of strain rate, ln $\dot{e}$. This linear relationship suggests that tensile strength, σ, conforms to the Eyring's model of the flow of solids which may be written as

$$\sigma = C + D \ln \dot{e} \quad (22)$$

According to Eyring, $D = \frac{2RT}{V^*}$ where R is molar gas constant, T is temperature (= 296 K) and V^* is the activation volume (m^3/mol). Values of V^* calculated from the slope of the lines (i.e. D) in Fig. 15 are plotted as a function of ϕ_f in Fig. 16 where it can be seen that V^* decreases with increasing ϕ_f. A similar observation has been reported for glass fibre-reinforced polyamide 6,6 [12] and glass fibre-reinforced TPU [4].

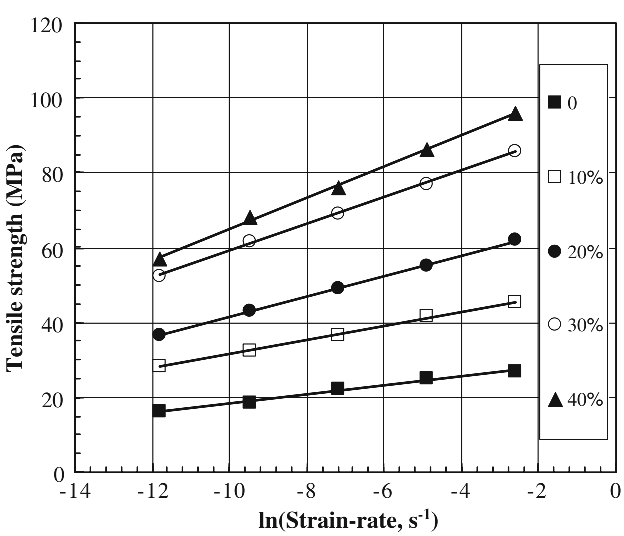

Fig. 15 Strain rate effect on tensile strength of single-gated PPC mouldings containing 0, 10, 20, 30 and 40% by weight short glass fibres

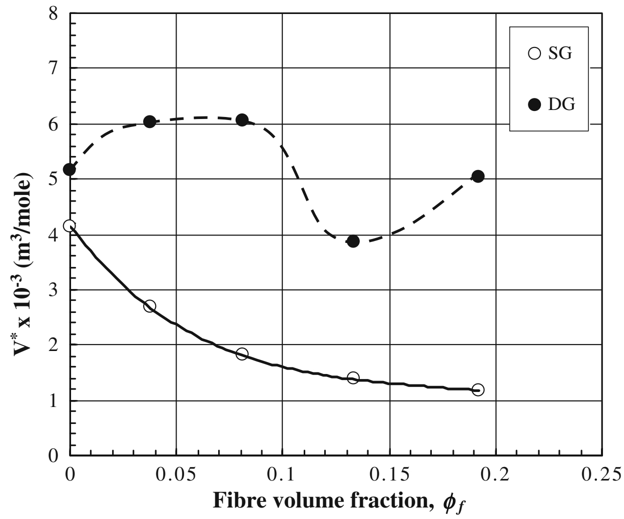

Fig. 16 Effect of fibre concentration on activation volume

Effect of fibre concentration and strain rate on tensile strength of double-gated mouldings

Stress–strain curves for double-gated specimens revealed 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. 17, weldline strength decreases with increasing ϕ_f for fibre concentration values in the range 0–10%. At fibre concentration value of 12%, weldline strength shows a maximum value which is significantly higher than weldline of the matrix material. The striking similarity between the way in which percentage

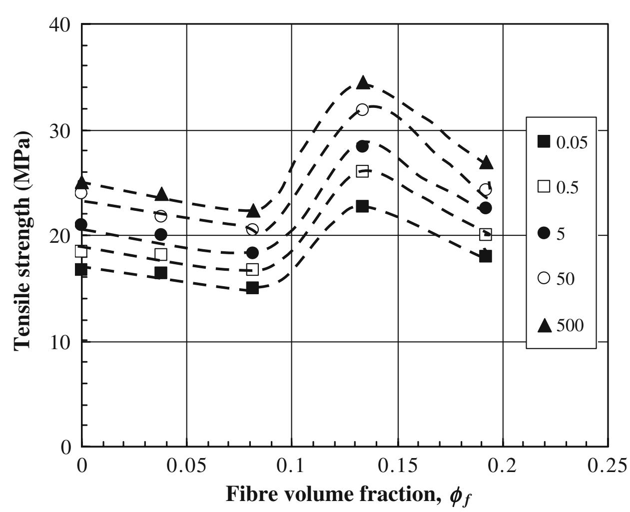

Fig. 17 Effect of fibre volume fraction on tensile strength of double-gated mouldings at crosshead speeds of 0.05, 0.5, 5, 50 and 500 mm/min

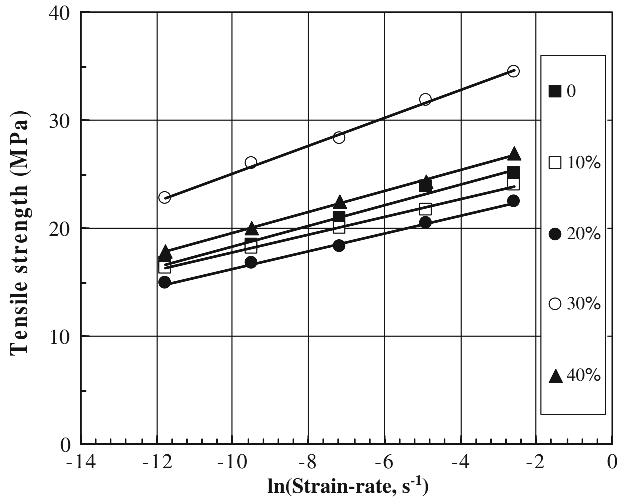

Fig. 18 Strain rate effect on tensile strength of double-gated PPC mouldings containing 0, 10, 20, 30 and 40% by weight short glass fibres

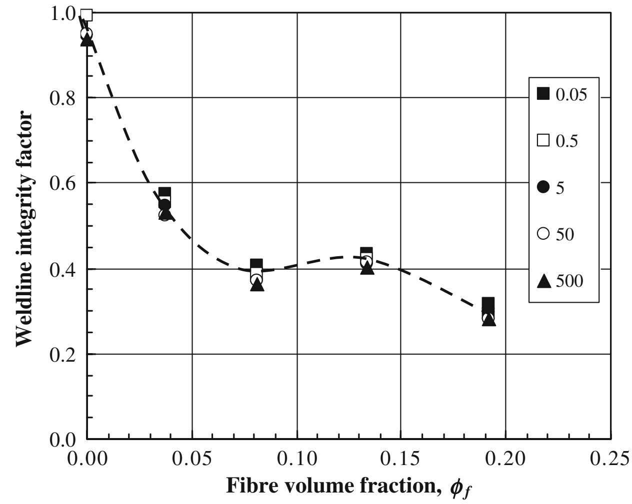

Fig. 19 Effect of fibre volume fraction on weldline integrity factor for tensile strength, F_σ, at crosshead speeds of 0.05, 0.5, 5, 50 and 500 mm/min

crystallinity and weldline strength vary with ϕ_{f} implies that weldline strength is controlled to a large extent by the percentage crystallinity in the moulded specimens, i.e. increase in crystallinity increases weldline strength and vice versa.

The effect of strain rate on weldline strength is shown in Fig. 18 where it can be seen that tensile strength of the welded specimens like their unwelded counterpart increases linearly with $\ln \dot{e}$ and likewise conforms to Eyring equation:

$$\sigma_{\mathrm{w}} = C_{\mathrm{w}} + D_{\mathrm{w}} \ln \dot{e} \tag{23}$$

where V_{w}^* is the activation volumes of the double-gated moulding whose value for PPC and its composites can be obtained from the slope of the lines in Fig. 18 i.e. $D_{\mathrm{w}} = \frac{2RT}{V_{\mathrm{w}}^*}$. As shown in Fig. 16, activation volume for double-gated mouldings is significantly higher than that of the single-gated counterparts and follows an inverse trend to that of crystallinity versus fibre concentration (e.g. higher crystallinity lowers the V_{w}^*).

The effect of weldline on tensile strength is expressed quantitatively in terms of weldline integrity factor for tensile strength, F_σ, defined as

$$F_\sigma = \frac{\sigma_{\mathrm{w}}}{\sigma} \tag{24}$$

where σ is tensile strength of single-gated moulding (i.e. unweld strength) and σ_{w} is tensile strength of the double-gated counterpart (i.e. weldline strength). Figure 19 shows that F_σ decreases quite significantly with increasing fibre concentration, ϕ_{f}, and whilst the value of F_σ is 1.0 or there about for unreinforced PPC, it reduces to around 0.3 for composite containing 40% by weight fibres, meaning 70% reduction in tensile strength due to weldline. This observation reveals that tensile strength of PPC composite is affected more by the presence of weldlines than its tensile modulus but likewise is not affected significantly by strain rate.

Fracture toughness

In all cases, initial crack propagated normal to the direction of the applied load. All single- and double-gated composite specimens exhibited brittle type failure. The failure load of double-gated composite specimens was found to be consistently lower than that of single-gated counterpart. However, single- and double-gated matrix specimens failed in a ductile manner with load–extension curves exhibiting a clear maximum load which was used here for evaluating fracture toughness, K_{IC}. Figures 20 and 21 show the variation of K_{IC} and K_{ICw} for PPC and its composites as function of a/W, for single and double-gated mouldings, respectively. Plots show that K_{IC} and K_{ICw} for PPC and its composites is independent of a/W, thus verifying the applicability of the linear elastic fracture mechanics (LEFM). It is also evident from the figures, that K_{ICw} is significantly lower than K_{IC}. This observation implies that the material inside the weldline region offers less resistance to crack propagation than the bulk material. This is due to the alignment of the fibres in the weldline region being predominantly parallel to the weldline hence in line with crack propagation direction as opposed to being predominantly normal to crack propagation direction in the bulk material which is the case for single-gated mouldings.

Figure 22 shows the effect of fibre concentration on K_{IC} and K_{ICw}. As can be seen variation in each case is similar to

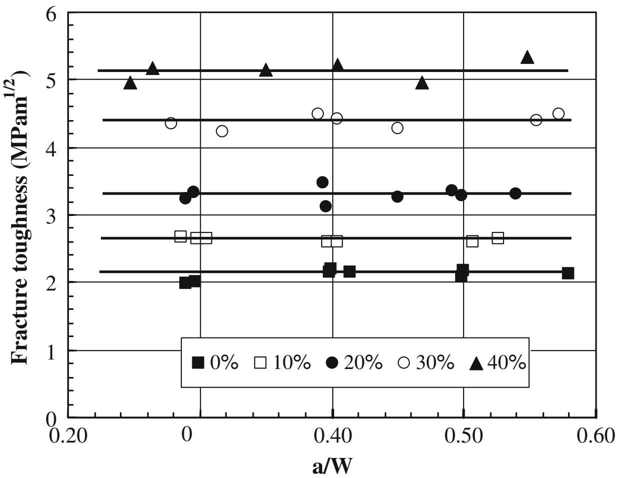

Fig. 20 Fracture toughness versus *a/W* for single-gated PPC mouldings containing 0, 10, 20, 30 and 40% by weight short glass fibres

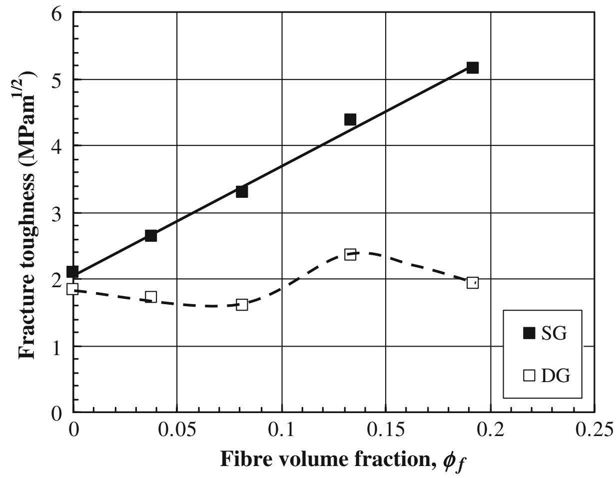

Fig. 22 Effect of fibre volume fraction on fracture toughness of single and double-gated mouldings

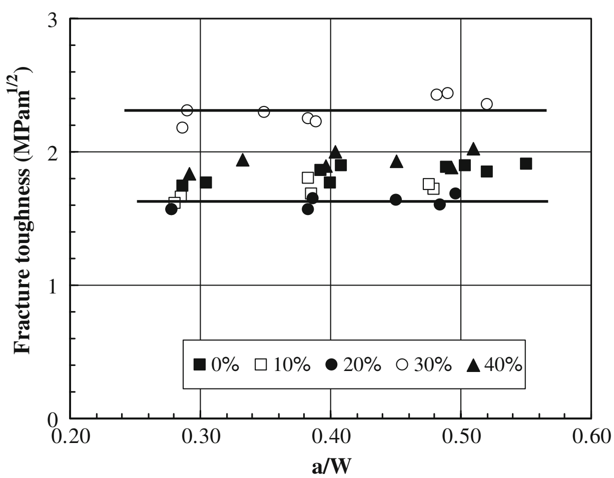

Fig. 21 Fracture toughness versus *a/W* for double-gated PPC mouldings containing 0, 10, 20, 30 and 40% by weight short glass fibres

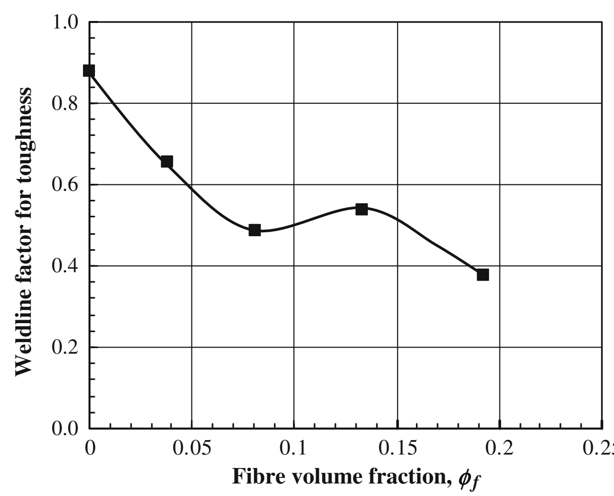

Fig. 23 Weldline integrity factor for fracture toughness, F_K, versus volume fraction of glass fibres

that of tensile strength versus fibre concentration. The K_{IC} variation with ϕ_f can be reasonably expressed as

$$K_{IC_c} = K_{IC_m} + \Psi\phi_f \tag{25}$$

where Ψ depends on fibre length and fibre orientation distributions in the mouldings and its value according to the slope of the line in Fig. 22 is 16.16 for the composite system studied here.

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

$$F_K = \frac{K_{ICw}}{K_{IC}} \tag{26}$$

Figure 23 shows that F_K decreases quite significantly with increasing fibre concentration, ϕ_f, showing a similar trend to that of F_σ versus ϕ_f as in Fig. 19.

Conclusions

Mechanical and fracture properties of single- and double-gated PPC 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 ϕ_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 PPC matrix was not significantly affected by the weldline, that of composite containing 40% by weight short fibres decreased as much as 30% giving weldline integrity factor of 0.7. Weldline integrity factor for tensile modulus decreased with increasing ϕ_f but showed no significant strain rate effect. The fibre efficiency parameter for tensile modulus increased linearly with increasing $\ln \dot{e}$ for both welded and unwelded specimens. However, fibre efficiency parameter for unwelded specimen was found to be considerably greater than that of the welded specimen.

- Tensile strength of single-gated mouldings, σ_c, increased with increasing ϕ_f in a nonlinear manner. However, for ϕ_f in the range 0–12%, simple additive rule-of-mixtures adequately described the variation of σ_c with ϕ_f. A linear dependence was obtained between fibre efficiency parameter for tensile strength and $\ln \dot{e}$. The presence of weldline in double-gated mouldings reduced tensile strength by as much as 70%. Tensile strength of both single- and double-gated mouldings increased linearly with $\ln \dot{e}$.
- Fracture toughness of the single-gated mouldings increased linearly with increasing ϕ_f. The reduction in fracture toughness due to the presence of weldlines in double-gated mouldings was as much as 60% for composite containing 40% by weight short glass fibres.

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