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Effect of fibre concentration, temperature and mould thickness on weldline integrity of short glass-fibre-reinforced polypropylene copolymer composites

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Abstract The effect of fibre concentration, temperature and mould thickness on tensile strength of single- and double-gated injection-moulded polypropylene copolymer reinforced with 0, 10, 20, 30 and 40 wt% short glass fibre was studied at a fixed strain-rate of 7.58×10^{-3} s^{-1} between 23 and 100 °C. It was found that tensile strength of single-gated mouldings, σ_c, increased with increasing volume fraction of fibres, ϕ_f in a nonlinear manner and decreased with increasing temperature in a linear manner. However, for ϕ_f values in the range 0–10% a simple additive rule-of-mixtures adequately described the variation of σ_c with ϕ_f over the entire temperature range 23–100 °C studied here. Tensile strength of double-gated mouldings like their single-gated counterparts decreased linearly with increasing temperature. The presence of weldlines significantly reduced tensile strength of double-gated composite mouldings but had little effect on tensile strength of the matrix. Weldline integrity factor, F_σ, defined as weldline strength divided by unweld strength, decreased with increasing ϕ_f but increased with increasing temperature. A linear dependence was found between F_σ and temperature. Mould thickness had no significant effect upon weld and unweld tensile strengths and consequently had no significant effect upon weldline integrity factor.

Introduction

Tensile strength of short fibre composites is derived from a combination of the fibre and matrix properties and the ability to transfer stresses across the interface between the two constituents. Tensile strength is 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 tensile strength 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 tensile is concerned. A serious reduction in strength has been reported for many polymers and their composites in the presence of cold weldlines [1–9]. However, very little information is available regarding the influence of temperature and to some extent mould thickness on weldline strength and therefore the integrity of the welded components. To this end, this study was undertaken to examine the influence of temperature and mould thickness on weld and unweld tensile strengths of injection-moulded short glass-fibre-reinforced polypropylene copolymer (PPC) composite with fibre concentration in range 0–40 wt%.

Experimental details

Materials

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

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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 moulds used consisted of a single-gate (SG) and a double-gate (DG) cavities as illustrated in Fig. 1 with nominal dimensions $4 \times 10 \times 120\ \text{mm}^3$ and $1.5 \times 10 \times 120\ \text{mm}^3$ (thickness, width and length, respectively). In the case of double-gated cavities, the two opposing melt fronts met to form a cold weldline approximately mid-way along the gauge length of the specimen.

Differential scanning calorimetric (DSC)

Thermal characterisation was carried out by 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 thermal cycles of heating from −60 to 220 °C at 10 °C/min and cooling from 220 to −60 °C at 5 °C/min to obtain crystallisation data. 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 relationships:

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

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

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

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).

Fig. 1 Single- and double-gated cavities with nominal dimensions of $4 \times 10 \times 120\ \text{mm}^3$ (thickness, width and length, respectively)

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 shows values of ϕ_f obtained via Eq. 2, taking density of glass fibre, ρ_f, as 2540 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 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.

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

Processing condition	0 wt%	10 wt%	20 wt%	30 wt%	40 wt%
Barrel temperature (°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

Table 2 Fibre concentration and the average fibre lengths in ARC and in IMDS

Composites	PPC 10% w/w GF	PPC 20% w/w GF	PPC 30% w/w GF	PPC 40% w/w GF
ARC (%w/w)	9.50	20.03	30.05	39.70
IMDS (%w/w fibre)	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

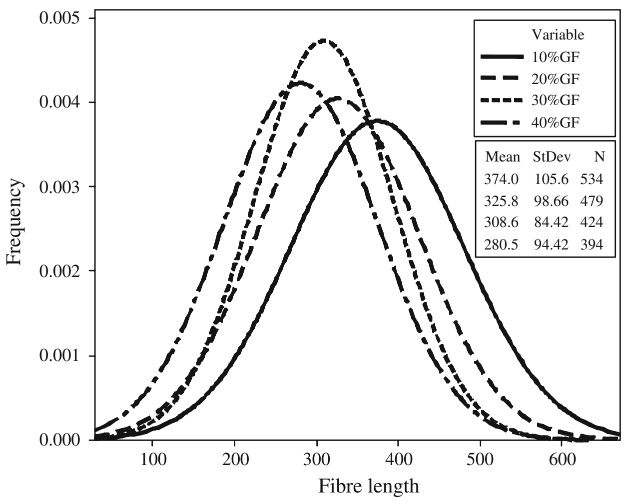

Fig. 2 Fibre length distribution in IMDS

Tensile tests

The effect of fibre concentration, moulding thickness and temperature on weld and unweld tensile strengths was studied using an Instron testing machine. All the tests were performed at a constant crosshead of 50 mm/min (strain-rate of 7.58×10^{-3} s^{-1}). At least six specimens were tested for determining an average value.

Results and discussion

Analysis of DSC thermograms shows that melting temperature (T_m) of the PPC matrix is not affected by the addition of fibres or by the heating cycle. However, as shown in Table 3, the heat of fusion (ΔH_m) in the second heating cycle is always greater than in the first heating cycle, and 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 the percentage crystallinity (χ_c) versus fibre volume fraction (ϕ_f) as shown in Fig. 4. The striking feature of Fig. 3 is higher, χ_c, for composite containing 30 wt% fibres, being 9% higher than for the unreinforced PPC.

Table 3 Thermal analysis results for PPC and PPC composites

w_f (%)	T_m (°C)		T_c (°C)	ΔH_m (J/g)		ΔH_c (J/g)	% χ_c
	1st cycle	2nd cycle	1st 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

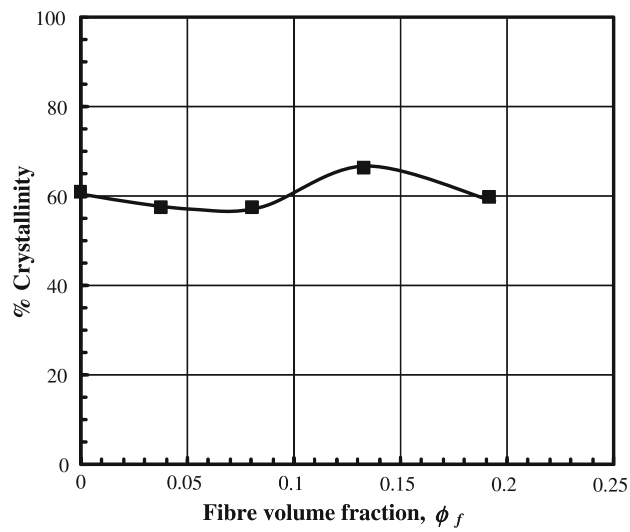

Fig. 3 Effect of fibre concentration on percentage crystallinity

The average length of the fibre length, L_f, in IMDS and ARC are compared in Fig. 4 as a function of fibre concentration, ϕ_f. It can be seen that L_f 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 where reduction in L_f due to processing increases from 5 to 19%, as fibre concentration increases from 10 to 30 wt%. This reduction in fibre length with increasing ϕ_f is attributed to increased probability of fibre–fibre and fibre–machine interactions as well as

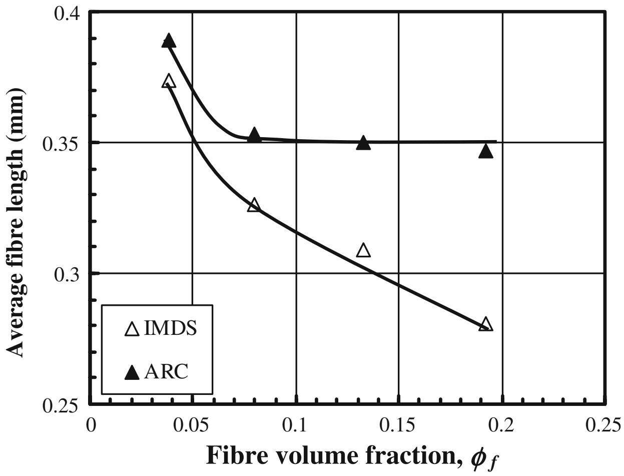

Fig. 4 Effect of fibre concentration and injection moulding on the average fibre length in PPC composites

increased in the apparent melt viscosity which gives rise to higher bending forces on the fibres during moulding.

Effect of fibre concentration, temperature and mould thickness on tensile strength of single-gated mouldings (unweld strength)

Single-gated mouldings (i.e. unweld specimens) failed after exhibiting a clear yield point referred to in the following text as tensile strength. It was also noted that whist tensile strength increased, elongation to failure decreased, with increasing fibre concentration. This behaviour was consistently observed over the entire temperature range considered here.

The effect of fibre volume fraction, ϕ_f, on tensile strength of single-gated mouldings, σ_c, at test temperatures ranging from 23 to 100 °C is shown in Fig. 5. Results

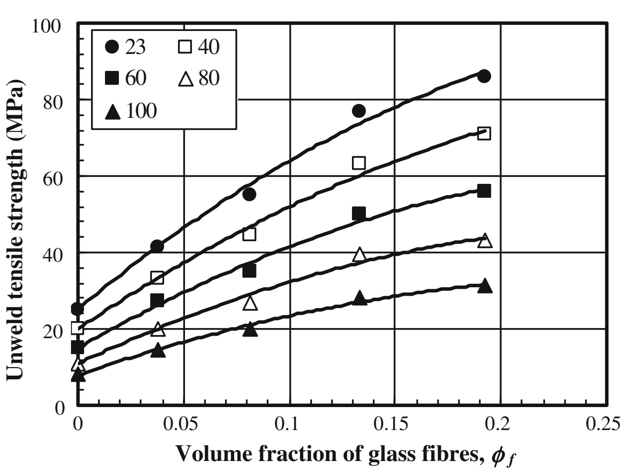

Fig. 5 Effect of fibre volume fraction on tensile strength of single-gated mouldings at 23, 40, 60, 80 and 100 °C

Table 4 Polynomial functions for tensile strengths and the optimum volume fraction of fibres for single-gated mouldings at various temperatures

Temperature (°C)	Polynomial function	$\phi_{f,max}$
23	$\sigma_c = 25.17 + 459.84\phi_f - 717.61\phi_f^2$	0.32
40	$\sigma_c = 19.98 + 372.68\phi_f - 584.67\phi_f^2$	0.32
60	$\sigma_c = 14.91 + 319.42\phi_f - 533.72\phi_f^2$	0.30
80	$\sigma_c = 10.91 + 260.21\phi_f - 464.61\phi_f^2$	0.28
100	$\sigma_c = 7.98 + 188.31\phi_f - 338.86\phi_f^2$	0.28

indicate that unweld tensile strength, σ_c, increases nonlinearly with increasing ϕ_f and therefore does not conform to rule-of-mixtures for strengths. The data presented here, as for many polymer composite systems [4, 5, 10], can best be treated using a second-order polynomial function of the form:

$$\sigma_c = a_0 + a_1\phi_f + a_2\phi_f^2. \tag{3}$$

The polynomial functions describing the data in Fig. 5 are given in Table 4. These polynomials may be used to obtain some indication of the optimum value of ϕ_f (i.e. $\phi_{f,max}$) for achieving the maximum tensile strength, at a given temperature. Values of, $\phi_{f,max}$, calculated at $d\sigma_c/\phi_f = 0$, suggest that it is advantageous to increase the fibre concentration in the composite up to 28–32% by volume. However, the processing difficulties and the possible strength loss due to fibre–fibre interactions at high fibre concentration may limit the optimum value of ϕ_f below that of $\phi_{f,max}$.

Figure 6 shows the data in Fig. 5 re-plotted for fibre concentration values in the range of 0–30 wt%. Clearly, within this range σ_c is a linear function of ϕ_f (regression coefficients $R^2 = 0.996$) and therefore it is reasonable to suggest that within this range, variation of σ_c with ϕ_f conforms to rule-of-mixtures for tensile strengths as given by Eq. 4.

$$\sigma_c = \lambda_s\sigma_f\phi_f + (1 - \phi_f)\sigma_m. \tag{4}$$

In the above equation, σ_f and σ_m are tensile strengths of the fibre and the matrix, respectively. The term λ_s is fibre efficiency parameter taking into account the effects on composite strength due to shortness of the fibres and their misalignment in the moulded specimen. Rearranging Eq. 4 gives

$$\sigma_c = \sigma_m + (\lambda_s\sigma_f - \sigma_m)\phi_f. \tag{5}$$

The average values of λ_s as obtained from the slope of the linear regression lines in Fig. 6 with $\sigma_f = 2470$ MPa are plotted in Fig. 7 as a function of temperature. As can be seen λ_s decreases linearly ($R^2 = 0.998$) with increasing temperature, thus indicating that fibres becoming less

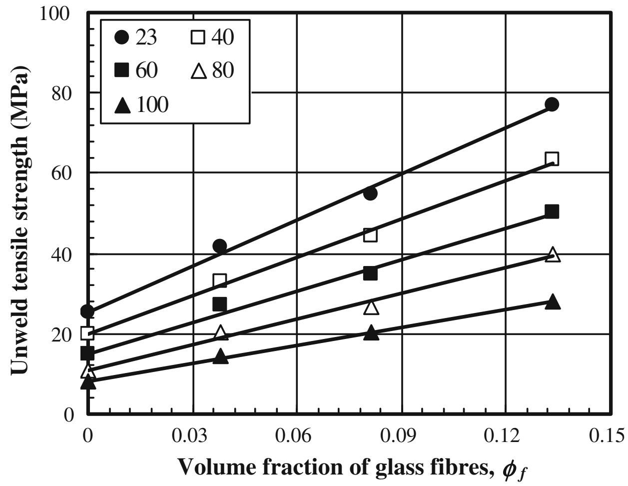

Fig. 6 Effect of fibre volume fraction on tensile strength of single-gated mouldings at 23, 40, 60, 80 and 100 °C for fibre concentration values in the range 0–30 wt%

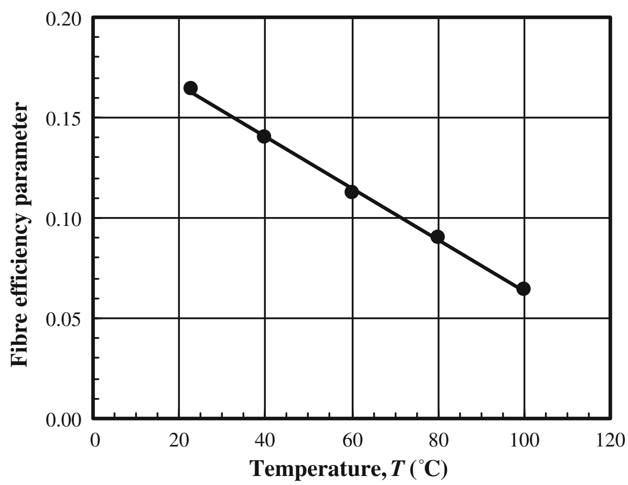

Fig. 7 Effect of temperature on fibre efficiency parameter, λ_s for unweld tensile strength

efficient as reinforcing fillers as temperature increases. The temperature dependence of λ_s can be expressed as:

$$\lambda_s(T) = A - BT \tag{6}$$

where $A = 0.192$ and $B = 1.28 \times 10^{-3}$ °C^{-1}.

The effect of temperature on σ_c is shown more explicitly in Fig. 8 where it can be seen that σ_c decreases linearly with increasing temperature. The effect of increasing ϕ_f is an upward vertical shift in σ_c—temperature curve. The effect of temperature on σ_c can be expressed as:

$$\sigma(T) = A - BT \tag{7}$$

where A and B are dependent upon volume fraction of fibres. The slope of the lines in Fig. 8 (i.e. $B = \mathrm{d}\sigma/\mathrm{d}T$) are plotted in Fig. 9 as a function of ϕ_f where it can be seen that variation is reasonably linear ($R^2 = 0.983$) and therefore can be expressed as:

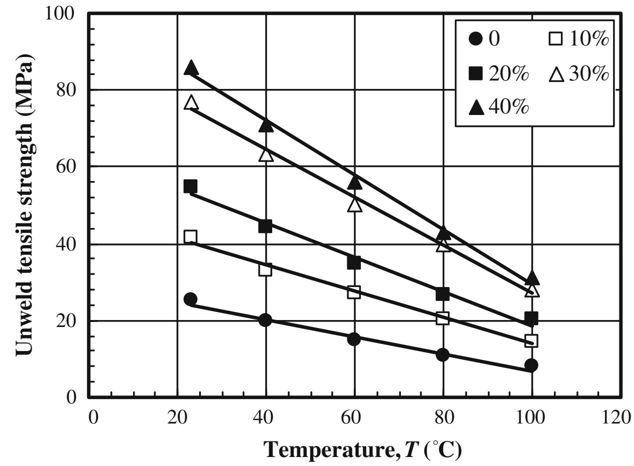

Fig. 8 Effect of temperature on tensile strength of single-gated mouldings for composites containing 0, 10, 20, 30 and 40 wt% short glass fibres

$$B = \frac{\mathrm{d}\sigma}{\mathrm{d}T} = A + B\phi_f \tag{8}$$

where $A = 0.24$ MPa °C^{-1} and $B = 2.573$ MPa °C^{-1} for the PPC composites under investigation.

The effect of mould thickness on σ_c is shown in Fig. 10 as a function of ϕ_f. Results show that mould thickness had little effect if any on the unweld tensile strength. This insensitivity to specimen thickness may be attributed to the fact that the average fibre length is much smaller than the mould thickness and therefore fibre orientation efficiency parameter, λ_s, is unaffected by the mould thickness.

Effect of fibre concentration, temperature and mould thickness on tensile strength of double-gated mouldings (weldline strength)

Stress–strain curves for double-gated specimens revealed that the presence of weldline in the double-gated

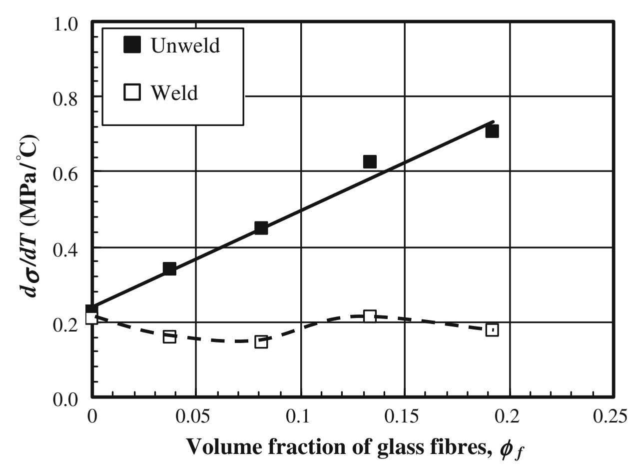

Fig. 9 Effect of fibre volume fraction on $\mathrm{d}\sigma/\mathrm{d}T$ for both weld and unweld specimens

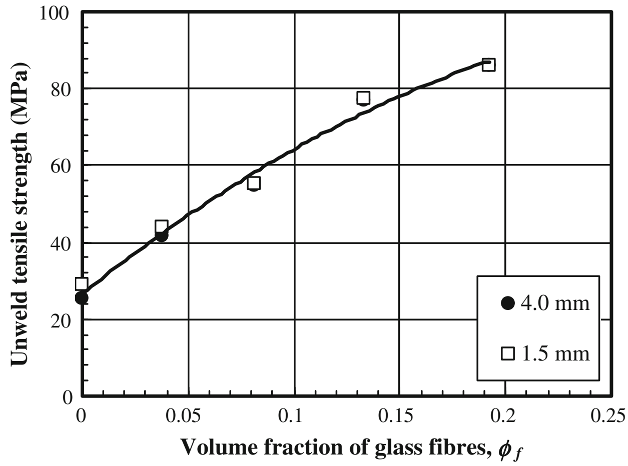

Fig. 10 Effect of mould thickness on tensile strength of single-gated mouldings

mouldings reduces elongation at failure (i.e. ductility) and in the case of composites causes a significant reduction in both tensile strength and elongation at break.

As illustrated in Fig. 11, for fibre concentration values in the range 0–10%, weldline strength, σ_{cw}, decreases with increasing ϕ_f at lower temperatures ($T \leq 40$ °C) but remains more or less independent of ϕ_f at higher temperatures ($T > 40$ °C). At fibre concentration value of about 12% (corresponding to 30 wt%), σ_{cw} shows a maximum value over the entire temperature range studied here; this value is higher than weldline strength of matrix material, σ_{mw}. The striking similarity between the way in which percentage 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.

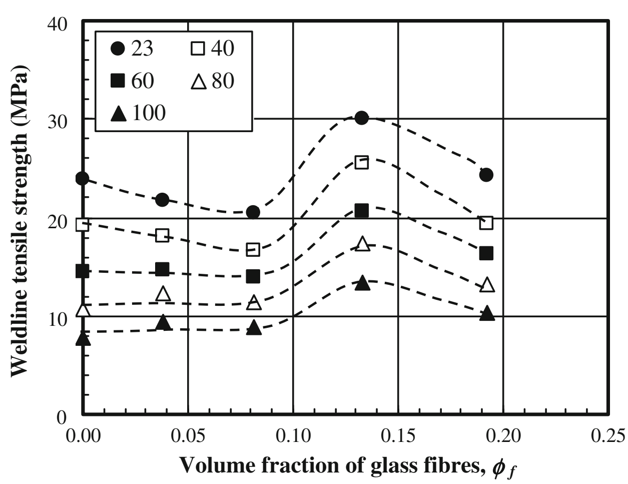

Fig. 11 Effect of fibre volume fraction on tensile strength of double-gated mouldings at 23, 40, 60, 80 and 100 °C

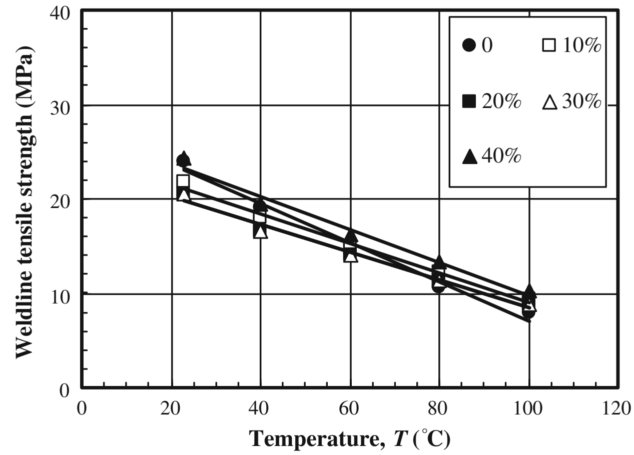

Fig. 12 Effect of temperature on tensile strength of double-gated mouldings for composites containing 0, 10, 20, 30 and 40 wt% short glass fibres

The effect of temperature on weldline strength is shown more explicitly in Fig. 12 where it can be seen that tensile strength of the double-gated specimens like their single-gated counterparts, decreases linearly with increasing temperature, and like wise can be expressed as:

$$\sigma_w(T) = A_w - B_w T \tag{9}$$

where A_w and B_w are dependent upon volume fraction of fibres. The slope of the lines in Fig. 12 (i.e. B_w) are plotted in Fig. 9 and compared with the corresponding values for single-gated mouldings (i.e. B). Clearly, variation of B_w with ϕ_f follows that of crystallinity versus ϕ_f as in Fig. 3. It is also worth noting that $B_w < B$ and the difference between the two increases with increasing ϕ_f.

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

$$F_\sigma = \frac{\sigma_w}{\sigma} \tag{10}$$

where σ is tensile strength of single-gated moulding (i.e. unweld tensile strength) and σ_w is tensile strength of the double-gated counterpart (i.e. weldline strength). Figure 13 shows the variation of F_σ with fibre concentration. Results show that F_σ decreases significantly with increasing fibre concentration, ϕ_f, and whilst the value of F_σ is near unity for the matrix, it reduces to around 0.3 for the composite containing 40 wt% fibres, i.e. the presence of weldline has caused 70% reduction in tensile strength. The reduction in composite strength in the presence of weldline is attributed to the alignment of the fibres at weldline region being preferentially parallel to the weldline hence normal to the direction of the applied stress. It is also notable that the variation of F_σ with ϕ_f like σ_w versus ϕ_f shows a maximum

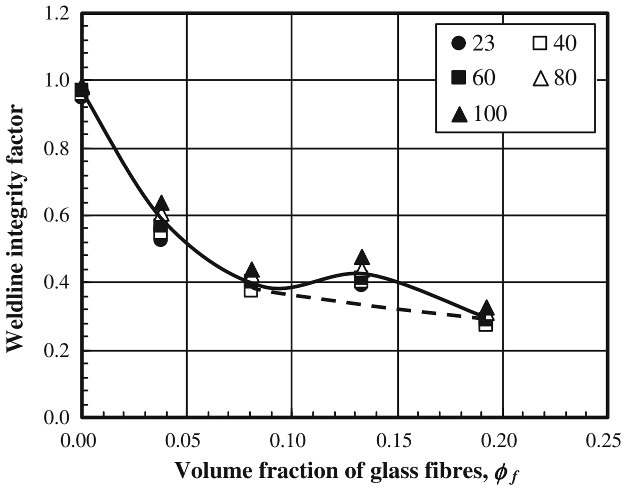

Fig. 13 Effect of fibre volume fraction on weldline integrity parameter for tensile strength, at 23, 40, 60, 80 and 100 °C

at ϕ_f value of about 12% rather than the expected decreasing trend shown by the broken line in Fig. 13.

The effect of temperature on weldline integrity factor is shown more explicitly in Fig. 14 where it can be seen that F_σ increases linearly with increasing temperature for both PPC and its composites. This observation indicates that weldline severity reduces with increasing temperature. The temperature dependence of F_σ can be expressed as:

$$F_\sigma(T) = A + BT \tag{11}$$

where A and B are both dependent upon volume fraction of fibres, ϕ_f. Variation of B with ϕ_f follows a similar trend to that of weldline strength versus ϕ_f as in Fig. 9. It is worth stating that weldline strength like unweld tensile strength did not show any significant variation with moulding thickness, as difference in strength values was less than 3%.

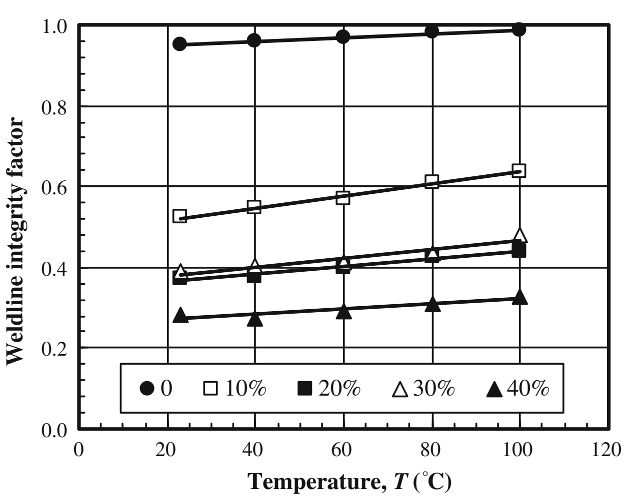

Fig. 14 Effect of temperature on weldline integrity parameter for tensile strength for composites containing 0, 10, 20, 30 and 40 wt% short glass fibres

Conclusions

Effect of fibre concentration, temperature and moulding thickness on tensile strength of single- and double-gated PPC composites containing 0, 10, 20, 30 and 40 wt% short glass fibres was studied. The following observations were made:

- Tensile strength of single-gated mouldings, σ_c, increased with increasing ϕ_f in a nonlinear manner over the entire temperature range (23–100 °C) studied here. Results indicated that for ϕ_f in the range 0–10%, a simple additive rule-of-mixtures can adequately described the variation of σ_c with ϕ_f. A linear dependence was obtained between fibre efficiency parameter for tensile strength, λ_s, and temperature. σ_c decreased with increasing temperature in a linear manner. The effect of ϕ_f on σ_c—temperature curve was a vertical shift in σ_c values.
- The presence of weldline in double-gated mouldings reduced tensile strength (weldline strength, σ_{cw}) by as much as 70% at upper end of fibre concentration level. Tensile strength of double-gated mouldings did not follow rule-of-mixtures for strengths; the trend observed was similar to that of crystallinity versus ϕ_f. It was also noted that weldline strength like unweld strength decreased linearly with increasing temperature.
- The effect of weldline on tensile strength was quantitatively expressed in terms of weldline integrity parameter, F_σ. The general trend observed was decreasing F_σ with increasing ϕ_f and increasing F_σ with increasing temperature.
- Mould thickness had no significant influence on weld and unweld tensile strengths. The thickness effect was less than 3%.

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