J Mater Sci (2008) 43:721–731
DOI 10.1007/s10853-007-2187-4

Tensile and flexural properties of injection-moulded short glass fibre and glass bead ABS composites in the presence of weldlines

S. Hashemi

Received: 18 June 2007 / Accepted: 24 September 2007 / Published online: 31 October 2007

Abstract The effect of weldline on tensile and flexural properties of ABS reinforced with short glass fibres (ABS/GF) and spherical glass beads (ABS/GB) was investigated as a function of glass fibre and glass bead concentrations. The weldline was formed in the moulded specimens by direct impingement of two opposing melt fronts (i.e. cold weld). It was found that elastic modulus of ABS/GF composites, with or without weldlines increased linearly with increasing volume fraction of fibres (ϕ_f), according to the rule-of-mixtures for moduli. The presence of weldline reduced tensile and flexural modulus of the ABS/GF composites. Weldline integrity factor for elastic modulus of ABS/GF composites decreased linearly with increasing ϕ_f. Results showed that tensile and flexural strength of ABS/GF increased with increasing ϕ_f in a nonlinear fashion. Flexural strength was consistently greater than tensile strength for the same ϕ_f. Weldline affected both strengths in a significant way; weldline integrity factor decreased with increasing ϕ_f and was independent of loading mode. Tensile and flexural modulus of ABS/GB composites increased linearly with increasing volume fraction of glass beads (ϕ_b), showing no loading mode dependency. Although modulus of the ABS/GB system was not affected significantly by the weldline, its strength was affected, and more so in flexure than in tension. Weld and unweld strengths decreased with increasing ϕ_b in both tension and flexure according to Piggott and Leidner relationship; for the same ϕ_b, flexural strength was always greater than tensile strength. Weldline integrity factor for tensile strength of ABS/GF system was considerably lower than that for ABS/GB system but weldline integrity factor for flexural strength was almost the same for the two composite systems.

Introduction

It is well established that the mechanical properties of polymer composites such as strength and modulus are derived from a combination of the filler 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, such as the concentration of the filler, geometrical shape of the filler, filler aspect ratio and the degree of interfacial adhesion between the filler and the matrix [1–14]. However, as most polymer composites are fabricated by an injection moulding process, the presence of weldlines is a major design concern as weldlines could lead to a considerable reduction in mechanical properties and designers often need to accommodate liberal safety factors in design analysis to compensate this weakness. Weldlines are often 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. The cold weldlines are formed when two melt fronts meet head on and this type of weld provides 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]. In general, the presence of a weldline reduces the strength by 10–60% depending on the polymer and

S. Hashemi (✉)
London Metropolitan Polymer Centre, London Metropolitan University, Holloway Road, London N7 8DB, UK
e-mail: s.hashemi@londonmet.ac.uk

the characteristic features of the reinforcing filler. However, whilst the majority of weldline studies have been conducted in tension, very few have examined the integrity of weldlines in flexure. This article studies the effect of weldline on elastic modulus and strength of ABS reinforced with short glass fibres (ABS/GF) and spherical glass beads (ABS/GB) in both tension and flexure. The weldline effect is quantitatively expressed in terms of weldline integrity factor whose value as a function of glass concentration is examined.

Experimental details

Materials

Owens Corning chopped E-glass fibres (GF) of approximately 6.0 mm in length and 10 μm in diameter and Potters Ballatoni spherical glass beads (GB) of approximately 12–26 μm in diameter were used as reinforcing fillers for Acrylonitrile Butadiene Styrene (ABS) copolymer received by Bayer. The ABS and the reinforcing fillers were used to produce a series of ABS/GB and ABS/GF compounds with nominal glass contents of 10, 20 and 30% w/w.

Compounding

Compounds were at first dry blended to the desired glass content and then dried in an oven at 80 °C for 4 h. After drying, each compound was passed through a Leistritz twin-screw extruder at an average screw speed of 60 rpm to produce a homogeneous dispersion of glass particles throughout the matrix. The extruder temperature profile was 203/232/232/235 (°C) and the die diameter was 4 mm. The extrudates emerging from the die exit was continuously cooled in a water bath and fed through a granulator to produce pellets for injection moulding process. Pellets were dried in an oven at 80 °C for 4 h before being injection moulded into test specimens.

Specimen preparation

Dumbbell shaped tensile specimens were produced using a Negri Bossi NB60 injection moulding machine at the processing conditions listed in Table 1. The mould used consisted of a single- and a double-feed cavity each of nominal dimensions 1.7 mm × 12.5 mm × 125 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 specimen as shown in Fig. 1.

Mechanical testing

At least six dumbbell specimens with weldline (WL) and five without weldline (WF) were tested for each composite in tension using a Tinius Olsen H10KS testing machine. Tests were carried out at 25 °C at constant crosshead speed of 50 mm/min (i.e. strain rate of 1.11×10^{-2} s^{-1}) using an extensometer with gauge length of 50 mm. The load–extension curve for each specimen was recorded from which tensile strength and elastic modulus were determined using the maximum load and the initial of the curve, respectively.

Flexural tests were carried out by flexing the dumbbell specimens flatwise on a three-point bend rig over a span width of 40 mm (span-to-depth ratio of approximately 23:1). Tests were carried out at 25 °C at a constant crosshead speed of 50 mm/min (i.e. strain rate of 6.25×10^{-3} s^{-1}). At least six specimens of each type (i.e. WL and WF) were tested for each composite. In the

Table 1 Injection moulding processing conditions

Processing condition	100% ABS matrix	Composites with 10% w/w glass	Composites with 20% w/w glass	Composites with 30% w/w glass
Barrel temperature (°C)				
Zone 1	230	230	230	230
Zone 2	230	230	232	232
Zone 3	232	232	235	235
Mould temperature (°C)	70.00	70.00	80.00	80.00
Injection pressure (MPa)	8.50	8.50	9.00	9.00
Holding pressure (MPa)	3.00	3.00	3.00	3.00
Cooling time (s)	30.00	30.00	30.00	30.00
Cycle time (s)	33.00	33.00	33.00	33.00
Shot weight (g)	27.00	27.00	28.00	29.00

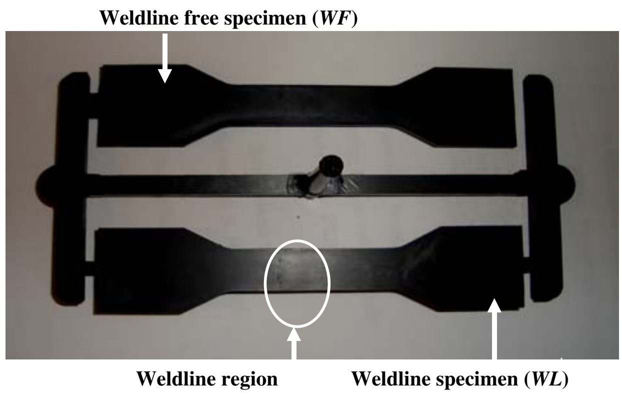

Fig. 1 Single and double gate mouldings

case of WL specimens, weldline was positioned at mid-span hence the load was applied directly on to the weldline. The load–deflection curve for each specimen was recorded from which flexural strength and modulus values were determined from the maximum load and the initial slope of the curve, respectively.

Filler concentration measurements

The concentration of total glass in each material was determined from the glass residue remained by ashing at 550 °C weighed samples cut from the gauge length of the dumbbell specimens. After cooling, the ash of glass residue (glass fibre or glass bead) was weighed and the exact weight fraction of glass (w_g) was determined. The w_g value was subsequently converted into glass volume fraction ϕ_g (ϕ_f in the case of glass fibres and ϕ_b in the case of glass beads) using the following equation:

$$\phi_g = \left[1 + \frac{\rho_g}{\rho_m}\left(\frac{1}{w_g} - 1\right)\right]^{-1} \quad (1)$$

Taking the density of the matrix (ρ_m) as 1.12 kgm^{-3} and density of glass (ρ_g) as 2.54 kgm^{-3}, glass fibre concentration values of 4.4, 9.5 and 15.5% v/v, and glass bead concentration values of 4.2, 9.1 and 14% v/v were determined.

Fibre length measurements

The ash of fibrous material was subsequently spread on a glass slide and placed on the observation stage of a microscope. Magnified fibre images were transmitted to a large screen, and the fibre images were then automatically digitised. From the fibre length distributions, the average length of the fibre ($\bar{L}_f$) in each composite was determined.

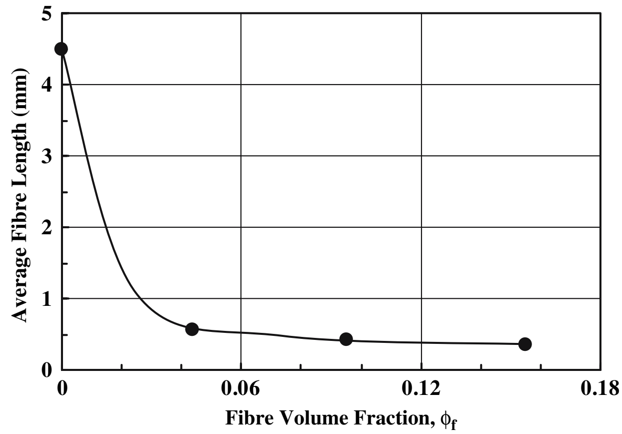

Fig. 2 Effect of fibre volume fraction on average fibre length

Figure 2 shows that $\bar{L}_f$ decreases with increasing ϕ_f from an initial value of 6 mm. The increased damage to the fibre length with increasing ϕ_f was attributed to a greater degree of fibre–fibre interaction as well as increased in the melt viscosity at higher fibre loadings. The latter give rise to higher bending forces on the fibres during compounding and moulding processes causing the fibres to break.

Results and discussion

Effect of filler concentration on composite modulus

The load–extension and load–deflection curves for ABS and its GF and GB composites indicated linear elastic type deformation during the early stage of loading in both tension and flexure. The addition of GF and GB particles to ABS increased extensional and flexural stiffness of

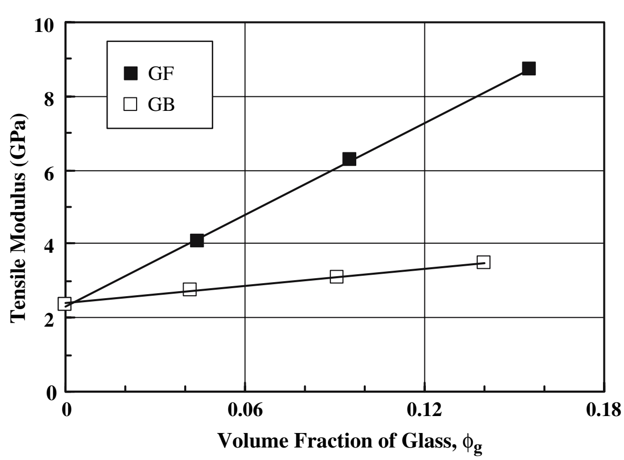

Fig. 3 Tensile modulus of ABS/GF and ABS/GB composites versus volume fraction of glass, ϕ_g (ϕ_f for short glass fibres and ϕ_b for glass beads)

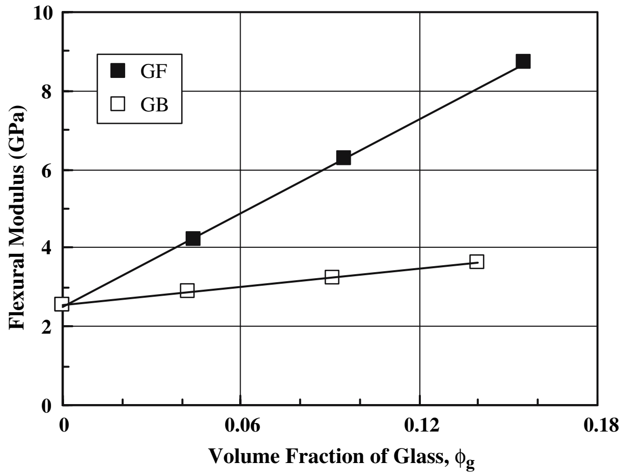

Fig. 4 Flexural modulus of ABS/GF and ABS/GB composites versus volume fraction of glass particles, ϕ_g ($\phi_g = \phi_f$ for short glass fibres and $\phi_g = \phi_b$ for glass beads)

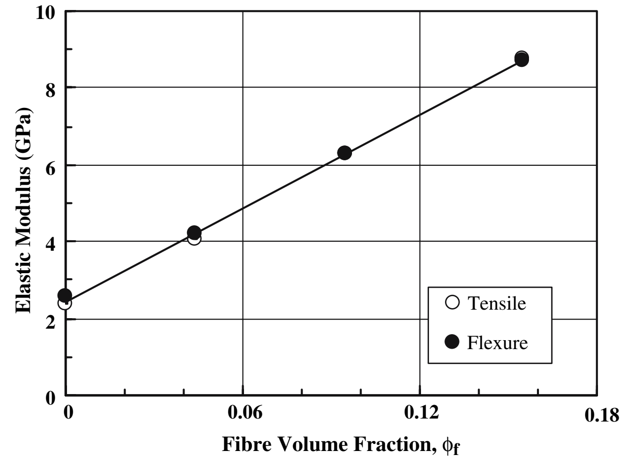

Fig. 5 Elastic modulus of ABS/GF composite in tension and in flexure against volume fraction of glass fibres, ϕ_f

both composite systems. Figures 3 and 4 show the way in which elastic modulus of ABS/GF and ABS/GB composites in tension and in flexure is affected by the volume fraction of the filler. It can be seen that modulus of the two composite systems increased with increasing filler concentration in both tension and flexure. However, for the same filler concentration, modulus of the ABS/GF composites was consistently higher than that of ABS/GB composites due to greater aspect ratio and the preferential orientation of fibres along the mould fill direction. The comparison between tensile and flexural modulus values for the two composite systems is shown more explicitly in Figs. 5 and 6, where it can be seen that composite modulus is not significantly affected by the manner in which it is loaded.

The linearity observed in the modulus of ABS/GF system (E_{cf}) with increasing ϕ_f is consistent with the "rule-of-mixtures". For short fibre composites, rule-of-mixtures for moduli may be written as:

$$E_{cf} = E_m + (\lambda_E E_f - E_m)\phi_f \tag{2}$$

where E_m is the modulus of the matrix material and E_f is the modulus of the glass fibres taken in this study as 75 GPa. The term λ_E is defined as the overall fibre efficiency factor for composite modulus whose value depends on the length and the orientation of fibres in the moulded composite. Using Eq. 2 and the slope of the best regression line passing through the data in Fig. 5, gives an average λ_E value of 0.584. This value is in the same range reported for several short fibre composite systems [1–13].

The overall efficiency parameter λ_E defined by Eq. 2 is the product of two other efficiency parameters, namely fibre length efficiency parameter, λ_L, and the fibre orientation efficiency parameter, λ_o, i.e.

$$\lambda_E = \lambda_L \lambda_o \tag{3}$$

The efficiency parameter, λ_L, can be evaluated from the Cox shear lag model [15] which defines λ_L as,

$$\lambda_L = 1 - \frac{\tanh\beta}{\beta} \tag{4}$$

where

$$\beta = \frac{\bar{L}_f}{2}\left(\frac{4E_m}{E_f d^2 ln\, p}\right)^{\frac{1}{2}} \tag{5}$$

For an assumed square packing arrangement of fibres of diameter d, parameter p is

$$p = \sqrt{\frac{\pi}{4\phi_f}} \tag{6}$$

Using Eq. 4, one obtains λ_L values of 0.855, 0.841 and 0.834 with decreasing ϕ_f. Substituting these values and the average λ_E value of 0.584 into Eq. 3 gives an average λ_o value of 0.692 (fibre volume fraction had no significant effect upon λ_o).

It is possible to estimate the fibre angle, θ, with respect to the direction of the applied stress using the Krenchel [16] definition of λ_o in terms of θ;

$$\lambda_o = \sum_{i=1}^{i=n} a_n \cos^4\theta_n \tag{7}$$

Assuming a perfect alignment of fibres (i.e. $a_n = 1$), we obtain from Eq. 7 that λ_o value of 0.692 corresponds to a fibre orientation angle, θ of approximately 24°.

Several theories have been proposed for predicting the elastic modulus of composites filled with spherical shaped fillers. One of the earliest theories is that of Einstein [17] who proposed the relationship between the composite modulus, E_{cb}, matrix modulus, E_m, and the volume fraction of the spherical filler, ϕ_b as:

$$E_{cb} = E_m(1 + k_E\phi_b) \tag{8}$$

where k_E is the Einstein coefficient having value of 2.5. The elastic modulus values predicted for ABS/GB composites using Eq. 8 with k_E of 2.5 underestimated E_{cb} by 3% at low ϕ_b and by 8% at high ϕ_b as illustrated in Fig. 6. The best regression line through the data as shown in Fig. 6 gives k_E value of 3.13.

Another theory which has been used extensively in predicting modulus of filled composite systems is the extended Kerner equation [18]. This equation gives the relationship between composite modulus, E_{cb}, matrix modulus, E_m, and the volume fraction of the spherical filler, ϕ_b as:

$$E_{cb} = E_m\left(\frac{1 + AB\phi_b}{1 - B\psi\phi_b}\right) \tag{9}$$

where constants A and B are defined as:

$$A = \frac{7 - 5\upsilon_m}{8 - 10\upsilon_m} \tag{10}$$

$$B = \frac{E_b - E_m}{E_b + AE_m} \tag{11}$$

In the above equations, E_b is modulus of the glass beads taken as 75 GPa and υ_m is the Poisson's ratio of the polymer matrix taken as 0.35. The parameter Ψ takes into account the maximum packing fraction of the glass beads ϕ_{max} and is defined as:

$$\Psi = 1 + \left(\frac{1 - \phi_{max}}{\phi_{max}^2}\right)\phi_b \tag{12}$$

For random packing of single-size spheres $\phi_{max} = 0.64$ [19]. The theoretical prediction based on Eq. 9 also under estimates E_{cb} by 3–8% as illustrated in Fig. 6. One reason for Eqs. 8 and 9 underestimating E_{cb} could be due to strong interfacial adhesion between the glass beads and the matrix which is not considered by the equations. It must be said, that since the values predicted by the two models are within 0.05 GPa of each other, either value may be considered appropriate for estimating E_{cb}.

Effect of filler concentration on composite strength

The addition of GB and GF to ABS reduced the amount of plastic deformation in both tension and flexure. It was noted that whilst deformation curves for the two composite systems were linear at low stresses, they were nonlinear at high stresses. This observation indicated that interfacial microfailure had occurred around the glass particles in the two systems before failure.

Figures 7 and 8 show the effect of filler concentration on tensile and flexural strengths of ABS/GF and ABS/GB composites. It can be seen that whilst the addition of glass fibres to ABS enhances tensile and flexural strengths, addition of glass bead particles causes deterioration of both strengths. It can be seen also, that difference between the strength of the two composite systems in tension and in flexure increases with increasing filler concentration.

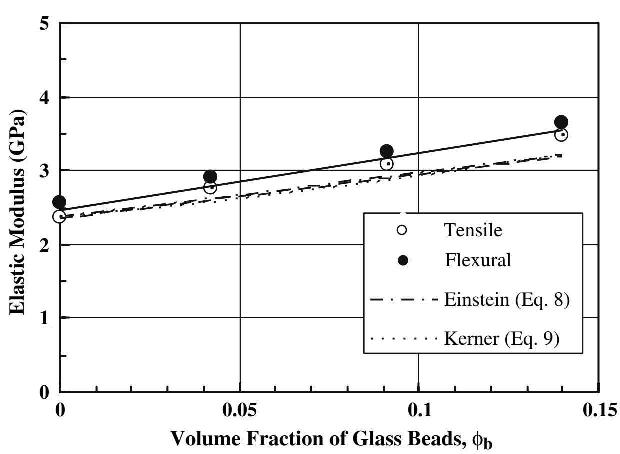

Fig. 6 Elastic modulus of ABS/GB composite in tension and in flexure against volume fraction of glass beads, ϕ_b

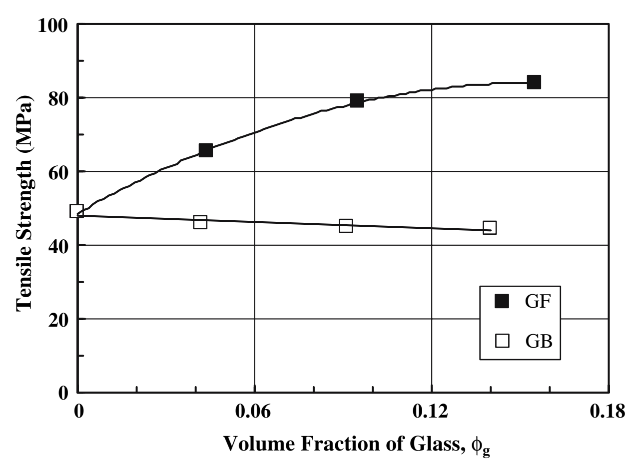

Fig. 7 Tensile strength of ABS/GF and ABS/GB composites versus volume fraction of glass particles, ϕ_g ($\phi_g = \phi_f$ for short glass fibres and $\phi_g = \phi_b$ for glass beads)

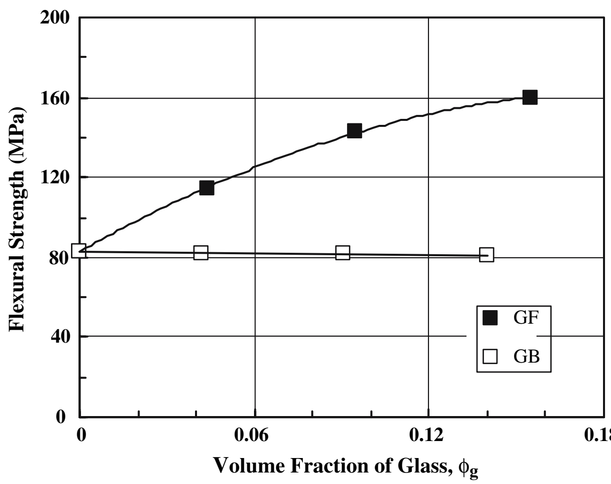

Fig. 8 Flexural strength of ABS/GF and ABS/GB composites versus volume fraction of glass particles, ϕ_g ($\phi_g = \phi_f$ for short glass fibres and $\phi_g = \phi_b$ for glass beads)

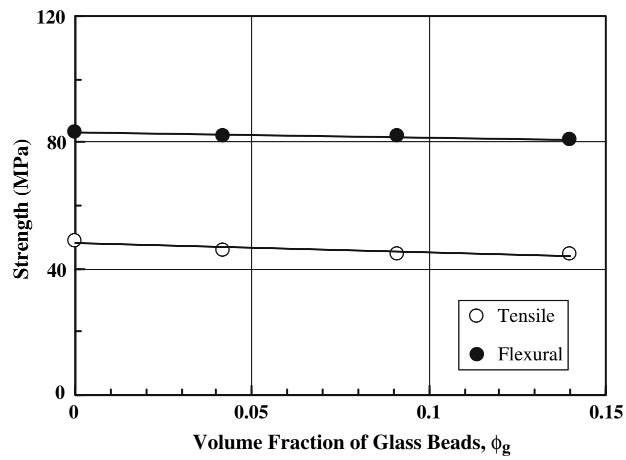

Fig. 10 Tensile and flexural strengths of ABS/GB composite versus volume fraction of glass beads, ϕ_b

The effect of loading mode on composite strength is shown more explicitly in Figs. 9 and 10 for ABS/GF and ABS/GB composites, respectively. It can be seen that for the same amounts of filler, flexural strength is consistently higher than tensile strength. The strength ratio for ABS/GF composites increased from 1.70 at $\phi_f = 0$ (i.e. the matrix) to 1.9 at $\phi_f = 0.155$ and for ABS/GB composites increased to 1.82 at $\phi_b = 0.144$. The ratio of two strengths is often referred to as the load factor and it arises from differences in specimen volume that is exposed to tensile stress (i.e. the volume effect). In tension, the entirety of a specimen is under tensile stress, where as only some volume fraction of a flexural specimen is subjected to tensile stresses which are regions in the vicinity of the specimen surface opposite to the point of load application. This volume effect causes the flexural strength to be greater than tensile strength.

The nonlinear dependence between the strength of ABS/GF composites, σ_{cf}, and ϕ_f in both tension and flexure as depicted in Fig. 9 can be expressed by the following polynomials:

$$\sigma_{cf} = 48.65 + 455.30\phi_f - 1462.38\phi_f^2 \quad \text{(Tensile)} \qquad (13)$$

$$\sigma_{cf} = 82.80 + 827.32\phi_f - 2113.10\phi_f^2 \quad \text{(Flexural)} \qquad (14)$$

Data also show a tendency for strength values to level off at high ϕ_f. Using the polynomials, it is possible to predict the ϕ_f value at which composite strength may reaches its maximum. Equations 13 and 14 predict a maximum in tensile strength at ϕ_f value of 0.16 and a maximum in

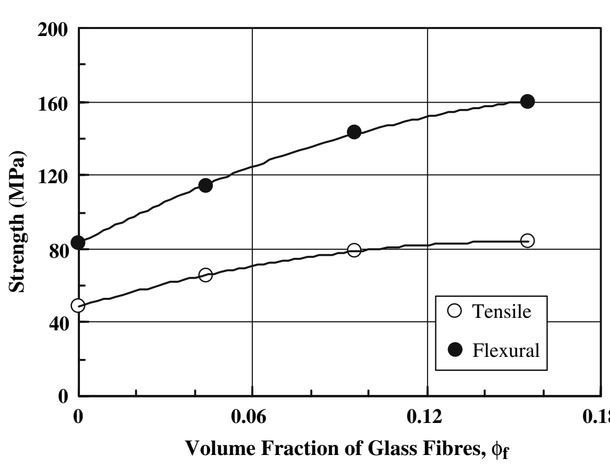

Fig. 9 Tensile and flexural strengths of ABS/GF composite versus volume fraction of short glass fibres, ϕ_f

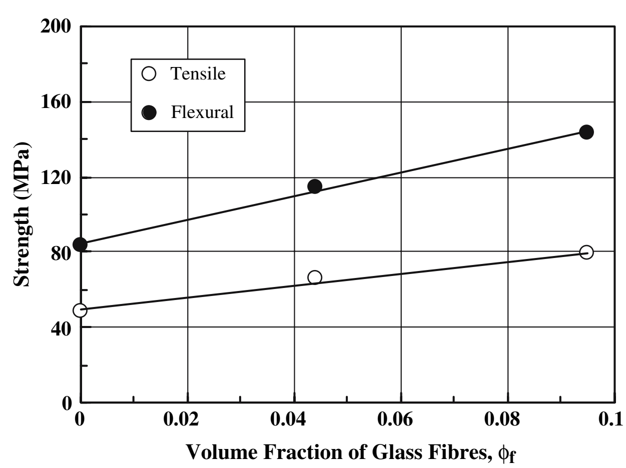

Fig. 11 Tensile and flexural strengths of ABS/GF composite versus volume fraction of short glass fibres, ϕ_f ($0 \le \phi_f \le 0.1$)

flexural strength at ϕ_f value of 0.20. It can be said, that as far as the strength of ABS/GF composites is concerned, no advantage is gained by adding fibres in excess of 16–20% v/v to ABS.

The strength data for ABS/GF as shown in Fig. 11, further reveals that for fibre concentration values of less than 10% v/v, variation of σ_{cf} with ϕ_f in both tension and flexure is highly linear (regression coefficients of 0.99). This observation is consistent with rule-of-mixtures for composite strength which may be written in the form of:

$$\sigma_{cf} = \sigma_m + (\eta_\sigma \sigma_f - \sigma_m)\phi_f \quad (15)$$

σ_m is the strength of the matrix and σ_f is the strength of the fibre. λ_σ is the overall fibre efficiency parameter for composite strength whose value like λ_E depends on the length and the orientation of the short fibres in the moulded specimen. Using Eq. 15 and the slope of the lines in Fig. 11 and assuming that strength of the glass fibre in tension is 2470 MPa and the load factor is 2.0, one obtains an average λ_σ of 0.148 for tensile strength and 0.145 for flexural strength, thus indicating that λ_σ is not affected by the mode of loading. It is worth noting that the efficiency parameter for composite strength (λ_σ) is significantly lower than for composite modulus (λ_E). This is because λ_E depends only on the average length of the fibre whereas λ_σ depends on the average length as well as the critical fibre length which is often much greater than the average value.

The efficiency parameter λ_σ like λ_E is defined as:

$$\lambda_\sigma = \lambda_L \lambda_o \quad (16)$$

where λ_L and λ_o are fibre length and fibre orientation efficiency parameters for the composite strength. Substituting the average λ_o value of 0.692 as obtained from the modulus data and the average λ_σ of 0.147 into Eq. 16 gives λ_L value of 0.212 for composite strength. When this λ_L value is substituted into the Kelly–Tyson [20] relationship (Eq. 17), we obtain fibre critical length values (L_c) of 1.30, 1.01 and 0.85 mm with increasing ϕ_f. The decreasing value of L_c with increasing ϕ_f is attributed to the reduction in $\bar{L}_f$ with increasing ϕ_f as in Fig. 2

$$L_c = \frac{\bar{L}_f}{2\lambda_L} \quad (17)$$

As for predicting the strength of the ABS/GB composites, several theories have been suggested, of which Nicolais–Narkis [21] has been frequently used for glass bead filled polymer composites. According to Nicolais–Narkis, strength of the glass bead filled composite, σ_{cb}, with poor interfacial adhesion can be evaluated from the matrix strength, σ_m, and the volume fraction of glass beads, ϕ_b, using the following equation:

$$\sigma_{cb} = \sigma_m \left(1 - 1.21\phi_b^{2/3}\right) \quad (18)$$

The example shown in Fig. 12, reveals ABS/GB tensile strength is closer to the tensile strength of the matrix (σ_{cb}, = σ_m implies perfect adhesion) than the Nicolais–Narkis prediction (poor adhesion). Piggott and Leidner [22] argued that the uniform filler arrangement assumed in the Nicolais–Narkis model was unlikely in practice and proposed the following empirical relationship for composite strength;

$$\sigma_{cb} = K\sigma_m - b\phi_b \quad (19)$$

where K is a stress concentration factor and b is a constant whose value depends upon particle–matrix adhesion.

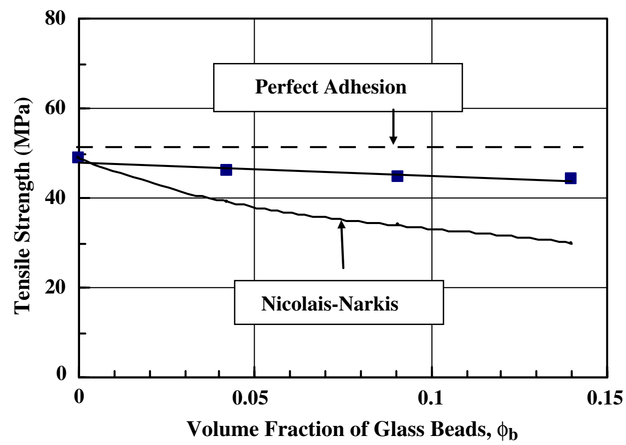

Fig. 12 The comparison between the measured tensile strength of ABS/GB composite and the Nicolias–Narkis prediction

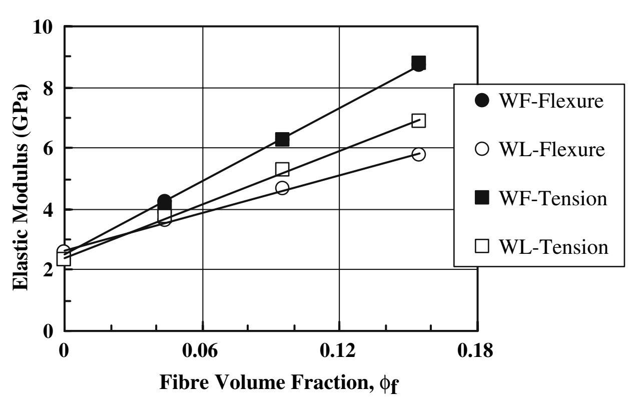

Fig. 13 Elastic modulus of weldline free specimens (WF) and weldline specimens (WL) in tension and in flexure versus volume fraction of glass fibres in ABS/GF composite

Fitting the best regression line to the data in Fig. 10 gave K and b values of 0.98 and 29.82 for tensile strength and values of 0.99 and 14.70 for flexural strength. With linear regression coefficients of 0.92, it can be said that Eq. 19 provides a reasonable estimation for the strength of ABS/GB composites.

Influence of weldlines on composite modulus

Figure 13 shows the modulus of ABS/GF composites as a function of ϕ_f for both weld and unweld specimens (WL and WF, respectively) in tension and in flexure. It can be seen that modulus of ABS/GF composites in tension and in flexure is significantly affected by the presence of weldline. The weldline effect was qualitatively expressed in terms of "weldline integrity factor for modulus, F_E" defined as:

$$F_E = \frac{\text{Modulus of specimen with weldline}}{\text{Modulus of specimen without weldline}} \quad (20)$$

The variation of F_E with ϕ_f for ABS/GF composites is shown in Fig. 14 for both tensile and flexural moduli where it can be seen that F_E decreases linearly with increasing ϕ_f. The linear dependence between F_E and ϕ_f is reasonably expressed as

$$F_E = F_{Em}(1 - 1.39\phi_f) \quad \text{(Tension)} \quad (21)$$

$$F_E = F_{Em}(1 - 2.27\phi_f) \quad \text{(Flexure)} \quad (22)$$

where F_{Em} is the weldline integrity factor for matrix modulus.

It is worth noting that modulus of ABS/GF specimens with weldline like weldline free specimens increased linearly with increasing ϕ_f. This implies that the rule-of-mixtures for moduli may also be applied to specimens with weldlines, i.e.

$$E_{cfw} = E_{mw} + (\lambda_{Ew} E_f - E_{mw})\phi_f \quad (23)$$

where E_{cfw} is modulus of ABS/GF composites with weldlines, E_{mw} is modulus of the matrix with weldline and λ_{Ew} is the fibre efficiency parameter for composite modulus in presence of weldlines. From the slope of the lines in Fig. 13, we obtained that $\lambda_{Ew} \approx 0.422$ for tensile modulus and $\lambda_{Ew} \approx 0.310$ for flexural modulus. Using Eqs. 3 and 4, we determined that for weldline specimens in tension $\lambda_{Lw} \approx 0.852$ and $\lambda_{ow}, \approx 0.50$ and in flexure $\lambda_{Lw} \approx 0.845$ and $\lambda_{ow}, \approx 0.364$. The λ_{ow}, value of 0.50 corresponds to average fibre angle, θ, of 33° and λ_{ow}, value of 0.364 corresponds to average fibre angle, θ, of 39°.

Figure 15 shows that the tensile and flexural modulus of ABS/GB composites with weldlines as for weldline free specimens increased linearly with increasing ϕ_b. However, with weldline integrity factors, F_E, in the range 1.02–0.98, it can be said that weldline had no significant effect on the elastic modulus of the ABS/GB composites.

Influence of weldlines on composite strength

Tensile and flexural specimens of ABS/GF and ABS/GB specimens with WL always broke at the weldline region. Figure 16 shows examples of the broken WL specimens in tension for both composite systems. Figures 17 and 18 compare weld (WL) and unweld (WF) strengths for ABS/GF composites as a function of ϕ_f in tension and in flexure where it can be that weldline significantly reduced the strength of ABS/GF composites in tension and in flexure. It is also evident that weldline strength (in tension and flexure) initially increases with increasing ϕ_f and reaches a maximum before decreasing with further increase in ϕ_f.

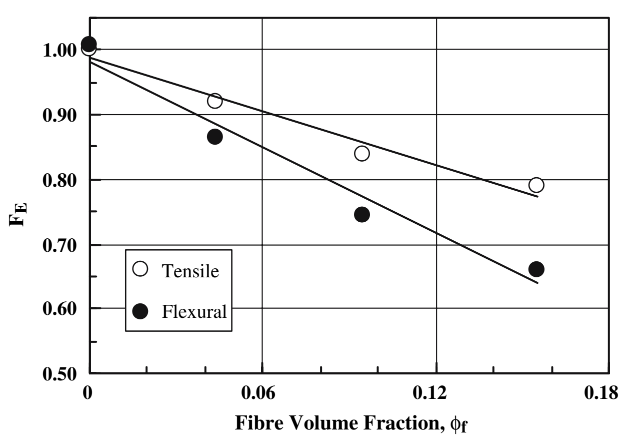

Fig. 14 Weldline integrity factor for elastic modulus of ABS/GF composite in tension and in flexure versus volume fraction of glass fibres

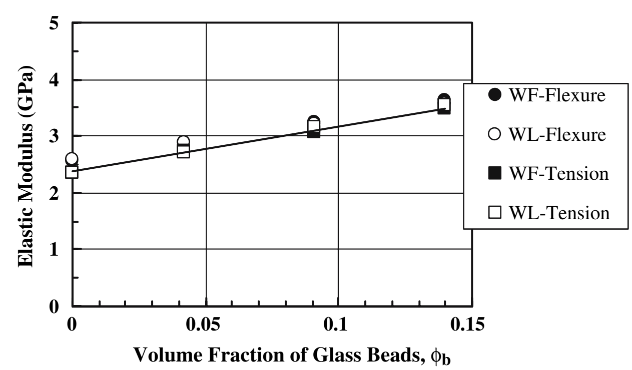

Fig. 15 Elastic modulus of weldline free specimen (WF) and weldline specimen (WL) in tension and in flexure versus volume fraction of glass beads

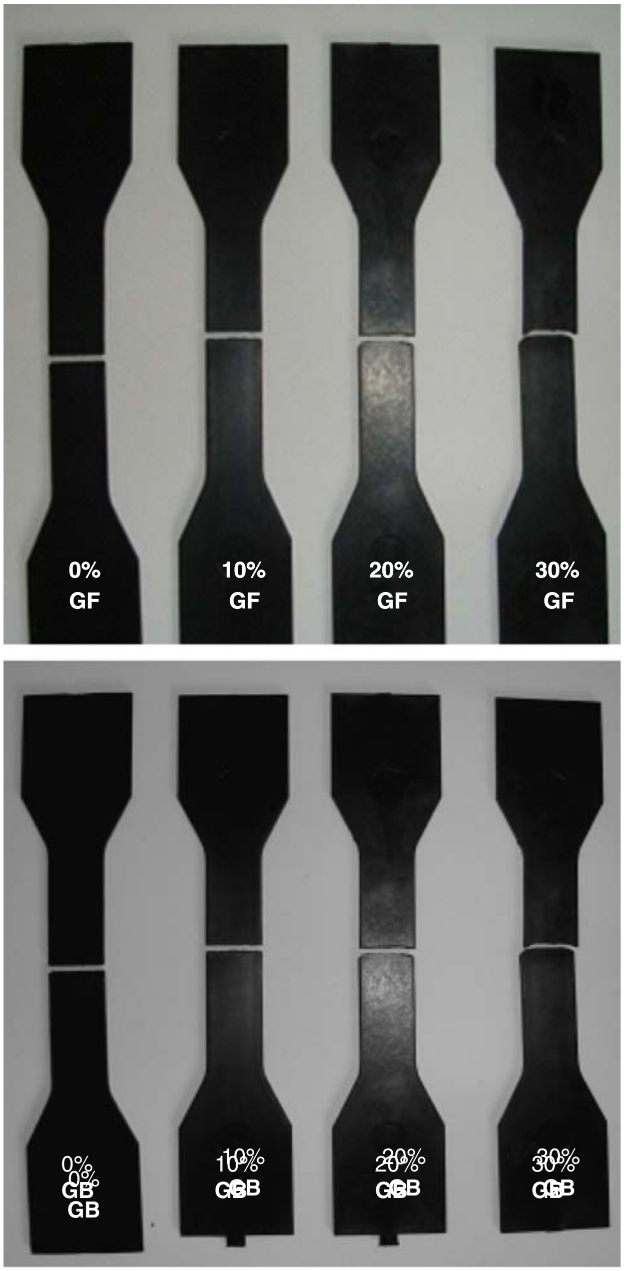

Fig. 16 Examples of the Broken tensile ABS/GF and ABS/GB specimens with weldlines (WL specimens)

The effect of ϕ_f on weldline strength, σ_{cfw}, can be reasonably approximated by the following polynomials;

$$\sigma_{cfw} = 48.48 + 88.81\phi_f - 593.39\phi_f^2 \quad \text{(Tensile)} \qquad (24)$$

$$\sigma_{cfw} = 74.31 + 225.22\phi_f - 1133.70\phi_f^2 \quad \text{(Flexural)} \qquad (25)$$

The above polynomials predict a maximum in tensile strength at $\phi_f \approx 0.75$ and in flexural strength at $\phi_f \approx 0.10$ for ABS/GF composites with weldlines.

The effect of weldline on strength was qualitatively expressed in terms of weldline integrity factor for strength,

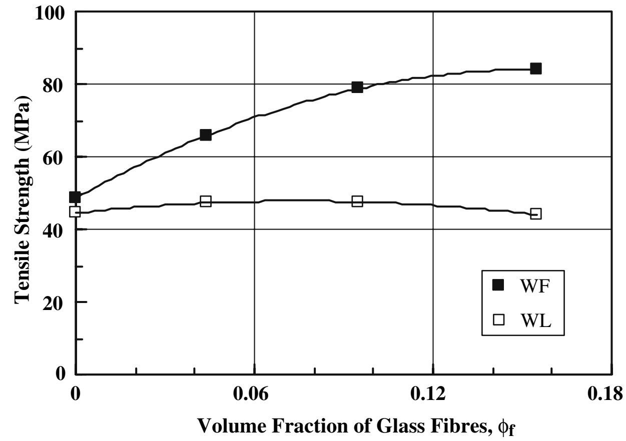

Fig. 17 Tensile strength of weldline free specimens (WF) and weldline specimens (WL) of ABS/GF composite versus volume fraction of glass fibres

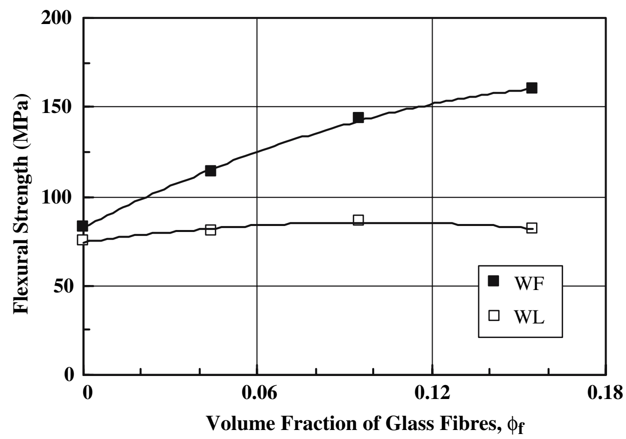

Fig. 18 Flexural strength of weldline free specimens (WF) and weldline specimens (WL) of ABS/GF composite versus volume fraction of glass fibres

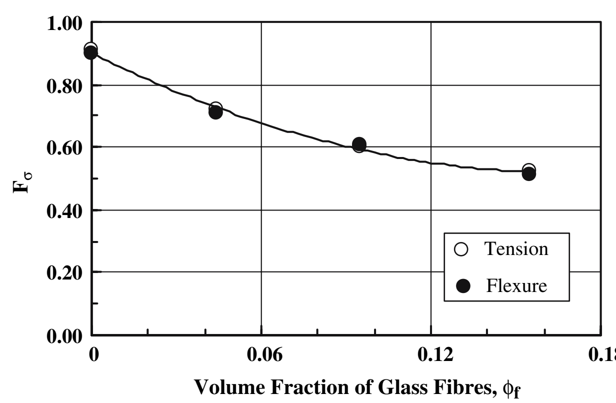

Fig. 19 Weldline integrity factor for strength of ABS/GF composite in tension and in flexure versus volume fraction of glass fibres

F_σ defined as strength of WL specimens divided by the strength of WF specimens. This ratio is plotted as a function of ϕ_f in Fig. 19 where it can be seen that F_σ is almost

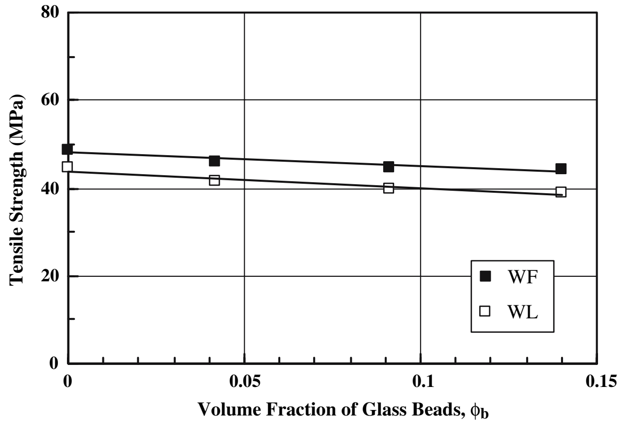

Fig. 20 Tensile strength of weldline free specimens (WF) and weldline specimens (WL) of ABS/GB composite versus volume fraction of glass beads

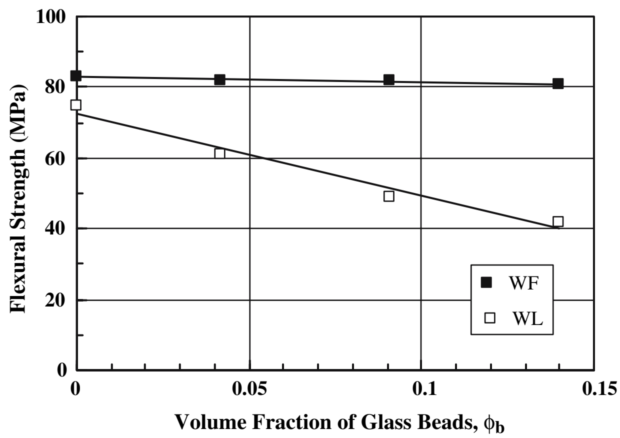

Fig. 21 Flexural strength of weldline free specimens (WF) and weldline specimens (WL) of ABS/GB composite versus volume fraction of glass beads

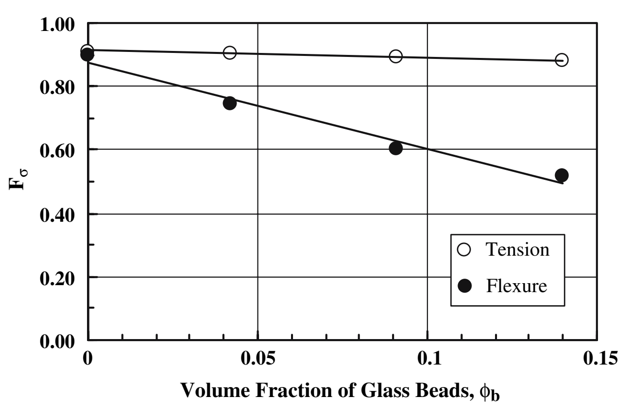

Fig. 22 Weldline integrity factor for strength of ABS/GB composite in tension and in flexure versus volume fraction of glass fibres

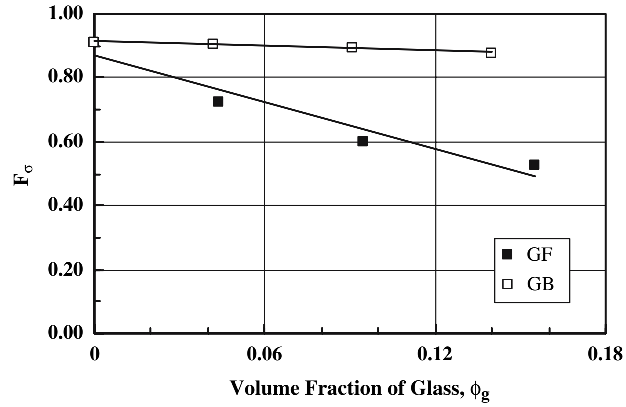

Fig. 23 Weldline integrity factor for tensile strength of ABS/GF and ABS/GB composites versus volume fraction of glass

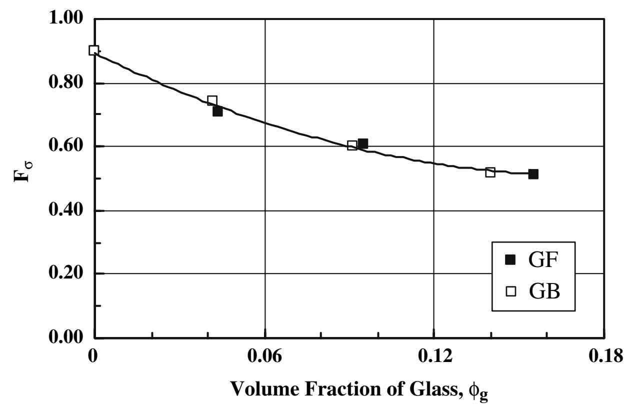

Fig. 24 Weldline integrity factor for flexural strength of ABS/GF and ABS/GB composites versus volume fraction of glass

independent of the loading mode and decreases with increasing ϕ_f. The relationship between F_σ and ϕ_f is expressed as:

$$F_\sigma = F_{\sigma m}(1 - 5\phi_f + 14.68\phi_f^2) \quad (26)$$

where $F_{\sigma m}$ is the weldline integrity factor for matrix strength.

Figures 20 and 21 compare weld and unweld strengths for ABS/GB compositse in tension and in flexure, respectively as a function of ϕ_b. It can be seen that weldline reduces tensile and flexural strengths, however, the effect is more significant in flexure than it is in tension as highlighted by the weldline integrity factors shown in Fig. 22. Evidently, F_σ for tensile strength is almost independent of ϕ_b having an average value of 0.90, whereas F_σ for flexural strength drops from a value of 0.90 at $\phi_b = 0$ to a value of 0.52 at $\phi_b = 0.144$. It is worth noting that whist weldline integrity factor for of ABS/GF system is significantly lower than that of ABS/GB system in tension as shown in Fig. 23, weldline integrity factor for flexural strength is almost the same for the two composite systems as shown in Fig. 24.

This observation indicates that Eq. 25 may also be used to predict F_σ of ABS/GB system in flexure, i.e.

$$F_\sigma = F_{\sigma m}(1 - 5\phi_b + 14.68\phi_b^2) \quad (27)$$

Finally, as illustrated in Figs. 20 and 21, weldline strength for ABS/GB composites, σ_{cbw}, decreases linearly with increasing ϕ_b in both tension and flexure. The behaviour for both strengths can be expressed by Piggott and Leidner equation as:

$$\sigma_{cbw} = K_w \sigma_{mw} - b_w \phi_b \quad (28)$$

where $K_w = 0.99$ and $b_w = 37.79$ for weldine tensile strength and $K_w = 0.97$ and $b_w = 234.10$ for weldline flexural strength.

Conclusions

In this work, the effect of weldline on tensile and flexural properties of ABS/GF and ABS/GB was investigated as a function of GF and GB concentrations. The following conclusions were obtained;

- Elastic modulus of weldline free ABS/GF composites in tension and in flexure increased linearly with increasing ϕ_f according to the rule-of-mixtures for moduli. There was no significant difference between the two modulus values. The fibre efficiency parameter of 0.585 was found for both cases.
- Weldline significantly affected elastic modulus of ABS/GF composites. Modulus of the weldline specimens followed rule-of-mixtures with fibre efficiency parameter of 0.422 in tension and 0.310 in flexure. Weldline integrity factor tensile and flexural modulus decreased linearly with increasing ϕ_f.
- Unweld tensile and flexural strengths of ABS/GF composites increased with increasing ϕ_f in a nonlinear fashion. A linear dependence for both strengths with respect to ϕ_f was found for ϕ_f values in the range 0–10% v/v. Within this range, rule-of-mixtures for strengths was applicable giving fibre efficiency parameters of approximately 0.148 for both strengths.
- Weldline integrity parameter for strength of ABS/GF composites decreased with increasing ϕ_f and was independent of the loading mode.
- Elastic modulus of ABS/GB composites was independent of loading mode and increased with increasing volume fraction of glass beads, ϕ_b.
- Weldline had no significant effect upon the elastic modulus of ABS/GB composites.
- Weld and unweld tensile and flexural strengths of ABS/GB composites decreased linearly with increasing ϕ_b according to Piggott and Leidner relationship.
- Weldline reduced tensile and flexural strengths of ABS/GB composites. Flexural strength was more affected by the weldline than tensile strength.
- Weldline integrity factor for flexural strength of ABS/GB composites decreased with increasing ϕ_b.

References

1. Hashemi S, Gilbride MT, Hodgkinson JM (1996) J Mater Sci 32:5017
2. Din KJ, Hashemi S (1997) J Mater Sci 32:375
3. Hashemi S, Elmes P, Sandford S (1997) Polym Eng Sci 37:45
4. Chrysostomou A, Hashemi S (1998) J Mater Sci 33:1165
5. Chrysostomou A, Hashemi S (1998) J Mater Sci 33:4491
6. Nabi ZU, Hashemi S (1998) J Mater Sci 33:2985
7. Hashemi S (2002) Plast Rubber Compos 31:1
8. Hashemi S, Lepessova Y (2007) J Mater Sci 42:2652
9. Necar M, Irfan-ul-Haq, Khan Z (2003) J Mater Process Technol 142:247
10. Fu SY, Lauke B, Mader E, Yue CY, Hu X (2000) Compos Part A 31:1117
11. Fisa B (1985) Polym Compos 6:232
12. Thomason JL (2002) Compos Sci Technol 62:1455
13. Thomason JL (2001) Compos Sci Technol 61:2007
14. Yilmazar U (1992) Compos Sci Technol 44:119
15. Cox HL (1952) Br Appl Phys 3:72
16. Krenchel H (1964) Akademisk, Forlag, Copenhagen
17. Einstein A (1906) Ann der Phys 19:289
18. Kerner EH (1956) Proc Phys Soc 69B:908
19. Kolarik J, Jancar J (1992) Polymer 33:4961
20. Kelly A, Tyson WR (1965) J Mech Phys Solids 13:329
21. Nicolais L, Narkis M (1971) Polym Eng Sci 11:194
22. Piggott MR, Leidner J (1974) J Appl Polym Sci 18:1619