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Hybridisation effect on flexural properties of single- and double-gated injection moulded acrylonitrile butadiene styrene (ABS) filled with short glass fibres and glass beads particles

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Abstract The present study investigated the effect of hybridisation on flexural strength and modulus of single-gated (SG) and double-gated (DG) injection moulded acrylonitrile butadiene styrene (ABS) polymer reinforced with both short glass fibres (GF) and spherical glass beads (GB). It was observed that flexural strength and modulus of SG and DG ABS/GF/GB hybrids increased with increasing the total concentration of the glass in the hybrid as well as the concentration of glass fibres in the hybrid (χ_f). Results indicated that hybrid flexural properties for both SG and DG mouldings obey the simple rule of mixtures. The presence of weldlines in DG mouldings had a negative effect on flexural properties. It was noted that weldline integrity factor (weld to unweld property ratio) for flexural modulus and strength decreased with increasing the total concentration of the glass in the hybrid. However, whilst weldline integrity factor for flexural modulus decreased with increasing χ_f, weldline integrity factor for flexural strength showed no significant variation with respect χ_f. Weldline integrity factors indicated that the hybrid flexural strength is more affected by the presence of weldline than the hybrid flexural modulus.

Introduction

It is well recognised 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 and the aspect ratio of filler and the degree of interfacial adhesion between the filler and the matrix [e.g. 1–12]. For example, whist the addition of short fibres to polymer matrices enhances strength, addition of spherical-shaped particles (e.g. glass beads) cause deterioration. On the other hand, spherical particles with aspect ratio of unity provide isotropic mouldings, whereas short fibres having aspect ratio much greater than unity provide mouldings which although are strong and stiff when loaded longitudinally (along the length of the fibres) they are quite weak and less stiff when loaded transversely (normal to the fibres). Dimensional stability and non-uniform shrinkage is also a problem with thick mouldings containing short fibres.

Hybridisation with more than one type of filler [e.g. glass fibres (GF) and spherical glass beads (GB)] provides other dimensions to the potential versatility of composite materials. For example, by incorporating GF and GB in the same matrix, one may obtain a moulding that may not be as stiff as the fibre-reinforced system but stronger than the GB system [13, 14].

The study by Philips [15] raised the issue surrounding the possible synergistic hybrid effects, in which the properties of the hybrid composite might not follow from a direct consideration of the independent properties of the individual components. A positive or negative hybrid effect was then defined as a positive or negative deviation of a certain mechanical property such as tensile strength from the rule-of-mixtures behaviour. In general, tensile and flexural strengths and moduli of hybrid systems do conform to rule of mixtures [e.g. 13, 14]. However, as polymer composites are often fabricated by an injection moulding process, the presence of weldlines is a major design

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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 for this weakness. Weldlines are often observed in the 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 [e.g. 1–10]. In general, the presence of a weldline reduces tensile strength by up to 60% and tensile modulus by up to 40% depending on the polymer, the characteristic features of the reinforcing filler and the processing conditions being used. For example, whilst the addition of spherical-shaped fillers (e.g. glass spheres) has shown to have little effect upon tensile strength of injection-moulded thermoplastics with weldlines, addition of cylindrical-shaped fillers (e.g. short fibres) has led to a considerable reduction in weldline strength due to the alignment of the fibres parallel to the weldline. The processing conditions such as melt temperature, injection speed and mould temperature could also play an important role in determining the integrity of the welded components and many studies have addressed this issue for both amorphous and semi-crystalline polymers [e.g. 16–20].

The majority of hybrid studies have been conducted in the absence of weldline. Indeed, little is known about the way in which weldline influences mechanical properties. A recent work by Hashemi [21] examined the effect of hybridisation on tensile properties of ABS/GF/GB hybrids manufactured by injection moulding process using single-gated (SG) and double-gated (DG) mouldings. However, since products are mostly subjected to bend when in use, it is of importance to have some understanding of the way in which SG and DG mouldings react to bend forces. In this paper, we first analyse flexural properties of SG and DG ABS/GF and ABS/GB composites. We then study the effect of hybridisation on flexural properties and the influence of weldlines in DG mouldings on the measured properties of ABS/GF/GB hybrids. Comparisons are made between the experimentally observed values and the predictions based on the rule-of-mixtures.

Experimental details

Materials

Owens Corning chopped E-GF of ~6.0 mm in length and 10 μm in diameter and Potters Ballatoni spherical GB of ~12–26 μm in diameter were used as reinforcing fillers for acrylonitrile butadiene styrene (ABS) copolymer received from Bayer. The ABS and the reinforcing fillers were used to produce a series of ABS/GB, ABS/GF composites and ABS/GB/GF hybrids with nominal glass contents of 10, 20 and 30% w/w.

Compounding

The formulations listed in Table 1 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 formulation was passed through a Leistritz twin-screw extruder at an average screw speed of 60 rpm to produce a homogeneous dispersion of bead and or fibre throughout the ABS 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 were 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 bars were produced using a Negri Bossi NB60 injection-moulding machine at the processing conditions as listed in Table 2. The mould used consisted of SG and DG cavities each of nominal dimensions shown

Table 1 Composites and hybrids formulations

Formulation	Hybrid ratio χ_f
ABS/GB composites	
ABS + 10 wt% glass beads	0
ABS + 20 wt% glass beads	0
ABS + 30 wt% glass beads	0
ABS/GF composites	
ABS + 10 wt% glass fibres	1.0
ABS + 20 wt% glass fibres	1.0
ABS + 30 wt% glass fibres	1.0
Hybrids	
ABS + 5 wt% glass fibres + 5 wt% glass beads	0.50
ABS + 5 wt% glass fibres + 15 wt% glass beads	0.25
ABS + 10 wt% glass fibres + 10 wt% glass beads	0.50
ABS + 15 wt% glass fibres + 5 wt% glass beads	0.75
ABS + 10 wt% glass fibres + 20 wt% glass beads	0.33
ABS + 15 wt% glass fibres + 15 wt% glass beads	0.50
ABS + 20 wt% glass fibres + 10 wt% glass beads	0.67

Hybrid ratio χ_f is defined as ϕ_f / ϕ_g where ϕ_f is the volume fraction of the fibres in the hybrid and ϕ_g is the total volume fraction of glass in the hybrid

Table 2 Injection moulding processing conditions

Processing condition	100% ABS matrix	Composites and hybrids with 10% total filler	Composites and hybrids with 20% total filler	Composites and hybrids with 30% total filler
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

in Fig. 1. In the latter, the two opposing melt fronts met to form a cold weldline approximately mid-way along the gauge length of the specimen.

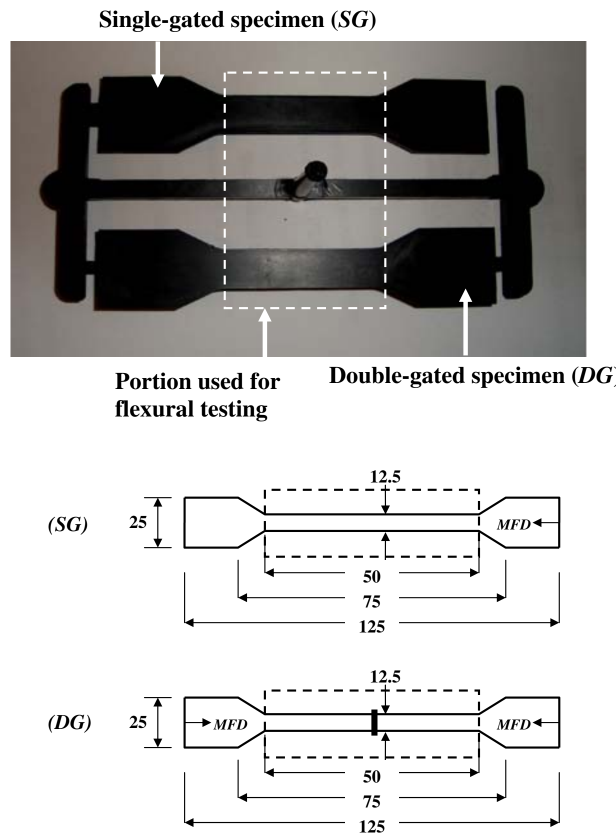

Fig. 1 Dimensions of SG and DG specimens in millimetres

Filler concentration measurements

The exact weight fraction of the fibres and the glass beads in ABS/GF and ABS/GB composites specimens 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 ash of glass residue was weighed and the exact weight fraction of glass (w_g) was determined. The w_g values were subsequently converted into glass volume fractions ϕ_g 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 density of pure ABS matrix (ρ_m) as 1,120 kg m^{-3} and that of glass (ρ_g) as 2,540 kg m^{-3} gave ϕ_f values of 4.4, 9.5 and 15.5% for ABS/GF composites and ϕ_b values of 4.2, 9.1 and 14% for ABS/GB composites. The volume fraction of glass fibres in each hybrid was calculated from ϕ_g and the hybrid ratio.

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. Fibre length distribution curves gave average fibre length (L_f) values of 550, 430 and 360 μm for ϕ_f values 4.4, 9.5 and 15.5%, respectively. Clearly, L_f has decreased from an initial unprocessed value of 6 mm. The increased damage to fibre length with increasing ϕ_f is attributed to a greater degree of fibre–fibre interaction as well as increased in the melt viscosity at higher fibre loadings. The latter gives rise to higher bending forces on the fibres during compounding and moulding processes causing further fibres breakage.

Mechanical testing

Flexural tests were performed on rectangular coupons cut from the gauge length of both SG and DG dumbbell specimens as depicted in Fig. 1. Tests were carried out in a three-point bend configuration over a span width of 64 mm by flexing the coupons flat-wise at a crosshead speed of 50 mm/min using a Tinius Olsen H10KS testing machine. The DG specimens were positioned on the rig such that weldline was at mid-span, i.e. under the loading nose. The flexural modulus and strength were calculated from the following linear elastic equations:

$$\text{Flexural strength} = \frac{3P_{max}S}{2BD^2}, \quad (2)$$

$$\text{Flexural modulus} = \frac{k}{4B}\left(\frac{S}{D}\right)^3, \quad (3)$$

where P_{max} is the load at maximum and k is the flexural stiffness given by initial slope of the load-deflection curve.

Results and discussion

Flexural modulus

The load-deflection curves for SG and DG ABS and ABS/GF and ABS/GB composites indicated linear elastic type deformation during the early stage of loading. The stiffness of SG and DG ABS/GF and ABS/GB composites increased as the concentration of glass particles was increased. Figure 2a, b shows the effect of glass fibre and glass bead concentration on flexural modulus of SG and DG ABS/GF and ABS/BG composites, respectively. It can be seen that flexural modulus of the two composite systems increases linearly with increasing filler concentration for both SG and DG mouldings. The data also reveal that whilst the presence of weldlines in DG mouldings had no significant effect on flexural modulus of ABS/GB composites, it significantly reduced the flexural modulus of ABS/GF composites. Indeed, as shown in Fig. 2a, for the same volume fraction of fibres, modulus of the SG ABS/GF is always greater than its DG counterpart. Comparison of the data for the two composite systems shows that modulus of ABS/GF is always greater than ABS/GB and there is much greater rise in modulus with increasing ϕ_f than ϕ_b.

The effect of weldline on flexural modulus is shown in Fig. 3 in terms of weldline integrity factor defines as;

$$F_E = \frac{\text{Modulus of specimen with weldline}}{\text{Modulus of specimen without weldline}}. \quad (4)$$

It can be seen from Fig. 3 that modulus of the ABS matrix and ABS/GB composites is not significantly affected by the presence of weldline in DG specimens as indicated by the weldline integrity, F_E, values close to unity. However, as can be seen, modulus of the ABS/GF composites is deteriorated quite significantly in the presence of weldlines as indicated by the F_E values of less than unity. It is worth noting also that F_E decreases quite significantly as concentration of glass fibres increases. This reduction in stiffness with increasing fibre concentration is attributed to a greater number of fibres preferentially aligned parallel to the weldline region at higher fibre loadings.

The linear dependence between modulus of ABS/GF composites and volume fraction of glass fibres, ϕ_f, as shown in Fig. 2a suggests data for both specimen types can be modelled using a simple "rule-of-mixtures" equation:

$$E_{cf} = E_m + (\eta_E E_f - E_m)\phi_f, \quad (5)$$

where E_m is the modulus of the matrix and E_f the modulus of the glass fibres whose value in this study was taken as 75 GPa. The parameter η_E is termed the overall fibre efficiency parameter for composite modulus. The value of η_E

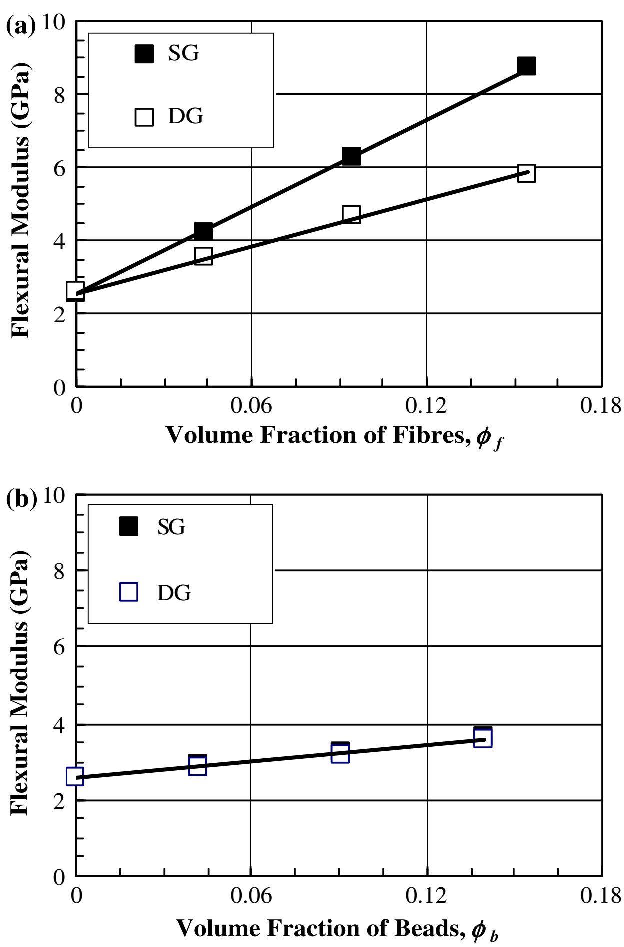

Fig. 2 Flexural modulus for SG and DG specimens versus volume fraction of glass particles; (**a**) ABS/GF composites, (**b**) ABS/GB composites

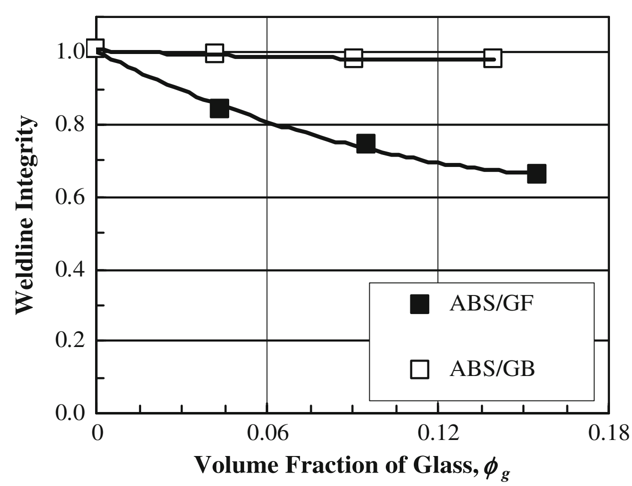

Fig. 3 Weldline integrity factor for flexural modulus, F_E, versus volume fraction of glass particles for ABS/GF and ABS/GB composites

for both SG and DG specimens can be obtained from Eq. 5 using slops of linear regression lines in Fig. 2a. This gives a η_E value of 0.561 for SG and 0.317 for DG specimens thus indicating that the presence of weldlines reduces the efficiency of the fibres as a reinforcing filler.

The parameter η_E is the product of two efficiency parameters as given by Eq. 6; one associated with the orientation of the fibres (η_o) and the other with the shortness of the fibres (η_L);

$$\eta_E = \eta_L \eta_o. \tag{6}$$

Fibre efficiency parameter, η_L, may be evaluated using the Cox shear lag model [22] which gives the following expressions for η_L:

$$\eta_L = 1 - \frac{\tanh na}{na}, \tag{7}$$

where a is the aspect ratio of fibre and n is defined as;

$$n = \left(\frac{2G_m}{E_f \ln \lambda} \right)^{1/2}. \tag{8}$$

G_m is the shear modulus of the matrix whose value was calculated here as $E_m/2(1+\upsilon_m)$ taking the Poisson's ratio of matrix, υ_m, as 0.35.

If the packing arrangement of the fibres in composites is assumed to be square, then λ can be evaluated from the following relationship;

$$\lambda = \sqrt{\frac{\pi}{4\phi_f}}. \tag{9}$$

The average η_L computed for the three fibre composites using Eq. 7 is 0.852 ± 0.011. Using this η_L value one obtains from Eq. 6 an average η_o value of 0.659 ± 0.009 for SG and 0.372 ± 0.005 for DG specimens ($\eta_o = \eta_E/\eta_L$).

The linear dependence between the flexural modulus of ABS/GB composites (E_{cb}) and ϕ_b as shown in Fig. 2b can be expressed as

$$E_{cb} = E_m + \xi \phi_b. \tag{10}$$

The slope of the linear regression line passing through both sets of the data in Fig. 2b gave ξ value of 7.28. It is worth pointing out that this value corresponds to Einstein coefficient, K_E, of 2.92 as opposed to 2.50 proposed by Einstein for spherical-shaped fillers [23].

The flexural data for ABS/GF/GB hybrids are expressed here in terms of hybrid ratio χ_f defined as;

$$\chi_f = \frac{\phi_f}{\phi_g}, \tag{11}$$

where ϕ_f is the volume fraction of the fibres in the hybrid and ϕ_g is the total volume fraction of glass in the hybrid. Figure 4a–c shows the effect of χ_f on flexural modulus of ABS/GF/GB hybrids for both SG and DG specimens for total glass

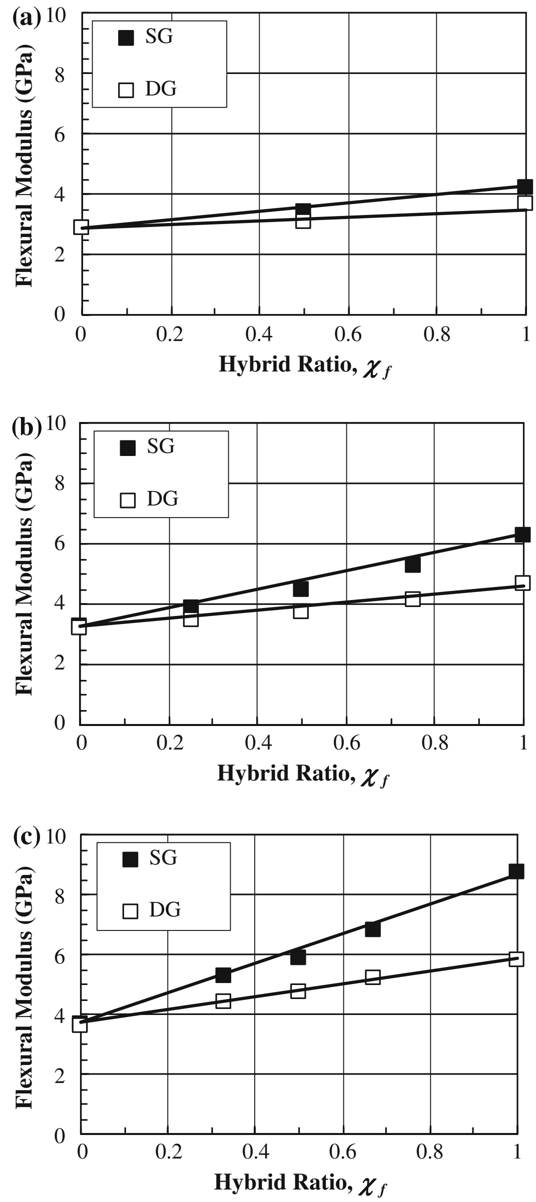

Fig. 4 Flexural modulus for SG and DG hybrid specimens, E_h, versus hybrid ratio, χ_f, for total glass contents of (**a**) 10, (**b**) 20 and (**c**) 30% w/w

concentration values of 10, 20 and 30% w/w. As can be seen, flexural modulus of both SG and DG mouldings increases linearly with increasing χ_f. It is also evident that flexural modulus of DG mouldings is lower than that of SG counterparts due to the presence of weldlines. As illustrated in Fig. 5a, b, for a given hybrid ratio, χ_f, flexural modulus of both SG and DG mouldings increases with increasing ϕ_g.

The effect of weldline on the flexural modulus of ABS/GF/GB hybrids is shown in Fig. 6 in terms of weldline integrity factor, F_E. As can be seen, F_E decreases with increasing χ_f as well as the total concentration of the glass in the hybrid, ϕ_g.

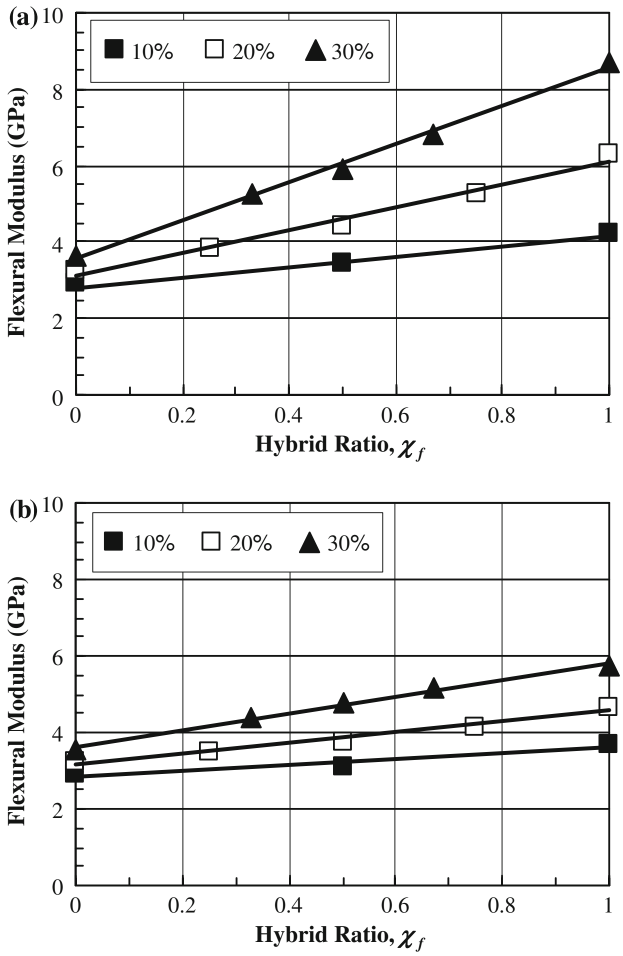

Fig. 5 Flexural modulus versus hybrid ratio, χ_f, for total glass contents of 10, 20 and 30% w/w; (**a**) SG, (**b**) DG

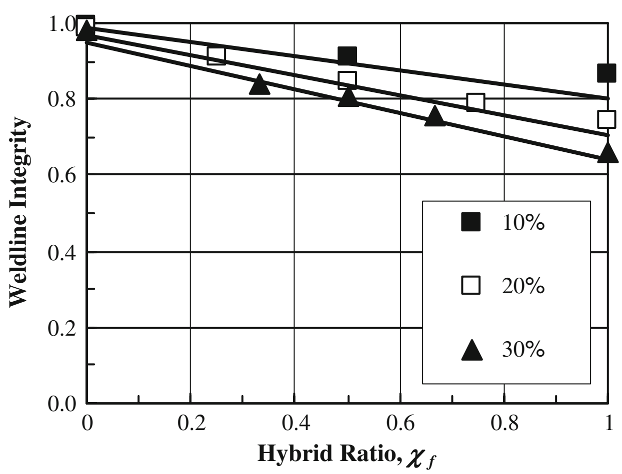

Fig. 6 Weldline integrity factor for flexural modulus, F_E, versus hybrid ratio, χ_f, for total glass contents of 10, 20 and 30% w/w

The linear dependence between modulus of the ABS/GF/GB hybrids, E_h, and the hybrid ratio, χ_f, suggests data for both specimen types can be described using a simple additive "rule-of-mixtures" of the form:

$$E_h = E_{cf}\chi_f + E_{cb}(1 - \chi_f). \quad (12)$$

By substituting E_{cf} and E_{cb} into Eq. 12, one obtains the following relationships for hybrid flexural modulus;

$$E_h = E_m\left[1 + (2.92 + 12.51\chi_f)\phi_g\right] \text{ (single-gated)}, \quad (13)$$

$$E_h = E_m\left[1 + (2.92 + 5.36\chi_f)\phi_g\right] \text{ (double-gated)}. \quad (14)$$

The lines drawn in Fig. 4a–c represent the fit according to Eqs. 13 and 14 and as can be seen, rule-of-mixtures describes the data for both SG and DG mouldings very well.

Using Eqs. 13 and 14, one obtains the following expression from which weldline integrity factor for hybrid modulus, F_E, can be predicted for any combination of χ_f, and ϕ_g.

$$F_E = \frac{1 + (2.92 + 12.51\chi_f)\phi_g}{1 + (2.92 + 5.36\chi_f)\phi_g}. \quad (15)$$

The lines in Fig. 6 show that fit according to Eq. 15.

Flexural strength

Figure 7a, b shows the effect of glass fibre and glass bead concentration on flexural strength of SG and DG ABS/GF and ABS/BG composites, respectively. It can be seen that whilst flexural strength of SG ABS increases quite significantly with increasing fibre concentration, ϕ_f, it decreases marginally with increasing glass bead concentration, ϕ_b. It is also evident that for the same concentration of filler, flexural strength of the SG mouldings is greater than their DG counterparts. As shown in Fig. 7a, flexural strength of DG ABS/GF composites rises initially, before decreasing with increasing ϕ_f. On the other hand, flexural strength of the DG ABS/GB composites decreases progressively with increasing ϕ_b. These observations suggest that the presence of weldlines in DG mouldings causes deterioration in flexural strength of both composite systems. The extent to which flexural strength of the two composite systems is affected by the weldline is shown in Fig. 8 in terms of weldline integrity parameter F_σ defined as;

$$F_\sigma = \frac{\text{Flexural strength of specimen with weldline}}{\text{Flexural strength of specimen without wedline}}. \quad (16)$$

It can be seen from Fig. 8 that weldline integrity factor, F_σ, for both composite systems decreases with increasing filler concentration. It is interesting to note also that F_σ is not significantly affected by the type of filler being incorporated.

The nonlinear dependence between flexural strength of SG and DG ABS/GF composite, σ_{cf}, and volume fraction

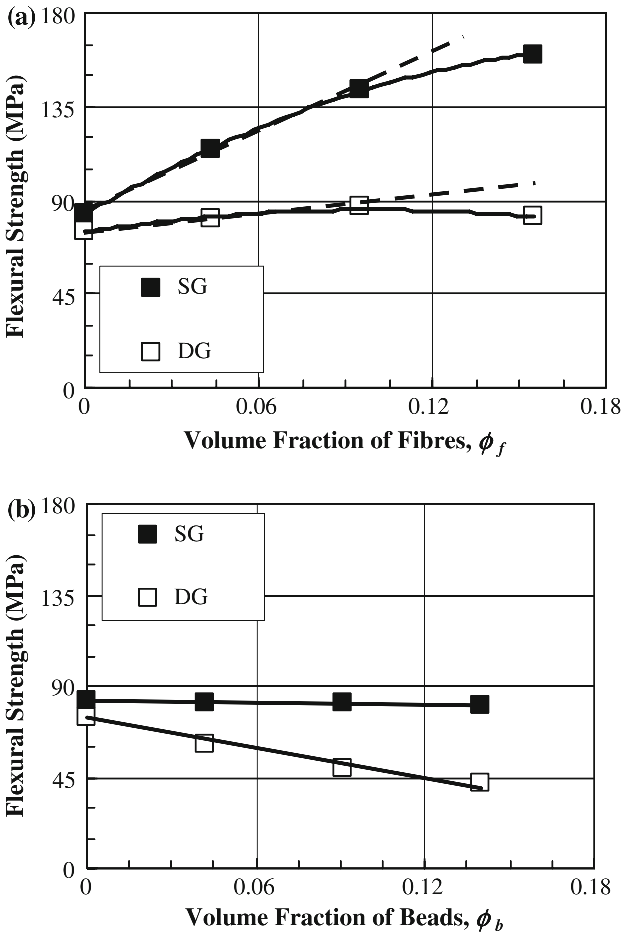

Fig. 7 Flexural strength for SG and DG specimens versus volume fraction of glass particles; (**a**) ABS/GF composites, (**b**) ABS/GB composites

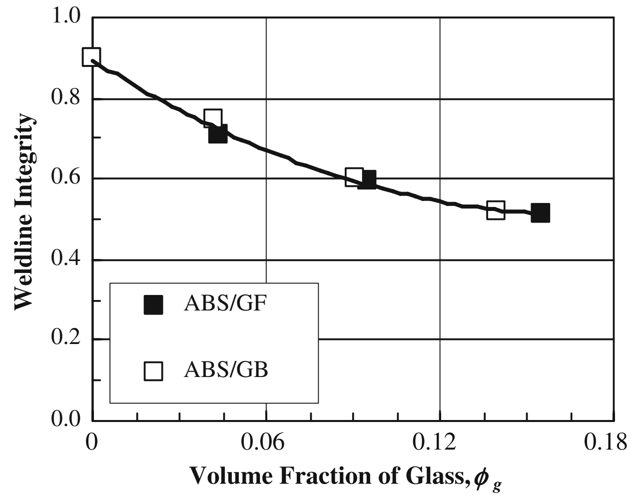

Fig. 8 Weldline integrity factor for flexural strength, F_σ, versus volume fraction of glass particles for ABS/GF and ABS/GB composites

of glass fibres, ϕ_f, as shown in Fig. 7a can be expressed by the following polynomial functions:

$$\sigma_{cf} = 82.80 + 827.32\phi_f - 2113.10\phi_f^2 \text{ (single-gated)}, \quad (17)$$

$$\sigma_{cf} = 74.80 + 214.13\phi_f - 1081.60\phi_f^2 \text{ (double-gated)}. \quad (18)$$

Using the above functions, one predicts that flexural strength of SG ABS/GF composite reaches a maximum at fibre concentration value of 20% v/v and that of DG composites at fibre concentration value of 10% v/v. The negative reinforcement effect at high fibre concentrations which has also been reported for other injection moulded glass reinforced polymer systems [10–13] arises mainly due to the separation distance between the fibres becoming sufficiently small at high ϕ_f to restrict the flow of the matrix material between the fibres. This effect and the higher stress concentration in the matrix, due to the greater number of fibre ends at high ϕ_f, could reduce the gain in strength which one would expect otherwise.

Figure 7a further reveals that for fibre concentration values in the range 0–10% v/v, variation of σ_{cf} with ϕ_f for both SG and DG mouldings is highly linear (regression coefficients of 0.99). This observation is consistent with the rule-of-mixtures for composite strength which may be written in the form of:

$$\sigma_{cf} = \sigma_m + (\eta_\sigma \sigma_f - \sigma_m)\phi_f, \quad (19)$$

where σ_m is flexural strength of the matrix and σ_f is that of the fibre. The intercept values at $\phi_f = 0$, obtained from the best linear regression lines shown in Fig. 7a is within 1% of the matrix flexural strength with regression coefficient of 0.990.

The parameter η_σ in Eq. 19 is termed the overall fibre efficiency parameter for composite strength. The value of η_σ like η_E depends on the length and the orientation of the short fibres in the moulded specimen. Using slopes of the linear regression lines in Fig. 7a and assuming flexural strength of glass fibres in flexure is the same as in tension and is 2,470 MPa, one obtains η_σ of 0.294 for SG and 0.081 for DG mouldings. These values are significantly smaller than the corresponding η_E values of 0.561 and 0.317, thus indicating that flexural strength of the ABS/GF composite is affected more than its modulus by the shortness of the fibres. It must be said however that in evaluating η_σ we assumed that glass fibre has the same strength in tension and in flexure. This assumption may not necessarily be correct as statistical analysis has shown that for same specimen volume, flexural strength of a brittle material is greater than its tensile strength by a such much 1.50 times. This difference in the two strengths arises because whilst in tension the entire volume of the specimen is under tensile stress, in flexure only some fraction of the volume is subjected to tensile stress. Taking the flexural strength of glass fibre as 3,705 MPa, gives $\eta_\sigma = 0.196$ for SG and $\eta_\sigma = 0.0054$ for DG composite mouldings.

The overall efficiency parameter η_σ like η_E is the product of two efficiency parameters as defined by Eq. 20:

$$\eta_\sigma = \eta_L \eta_o. \tag{20}$$

In the above equation, η_L and η_o represent the efficiency parameters for composite strength. If it is assumed, that fibre orientation efficiency parameter for composite strength, η_o, is the same as for composite modulus (i.e. $\eta_o \approx 0.659$), we obtain from Eq. 20 that fibre length efficiency parameter for composite strength, η_L, is 0.446 for SG mouldings and 0.123 for DG mouldings (based on η_σ of 0.294 and 0.081 for SG and DG mouldings).

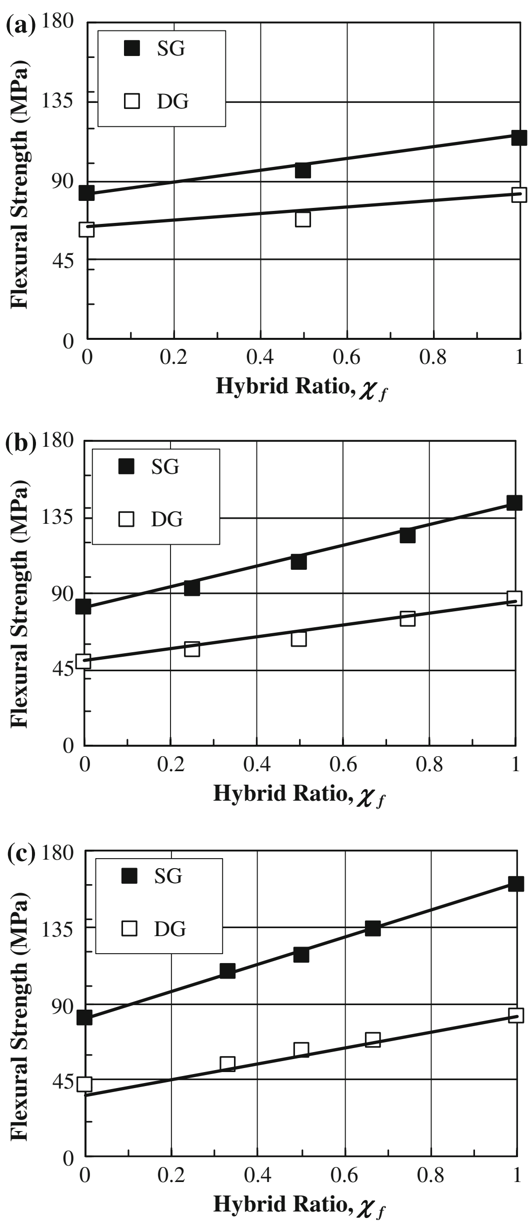

Fig. 9 Flexural strength for SG and DG specimens versus hybrid ratio, χ_f, for total glass contents of (**a**) 10, (**b**) 20 and (**c**) 30% w/w

The linear dependence between flexural strength of SG and DG ABS/GB composites as shown in Fig. 7b follows the Piggott and Leidner relationship [24];

$$\sigma_{cb} = K\sigma_m - b\phi_b, \tag{21}$$

where K is a stress concentration factor and b a constant whose value depends upon particle–matrix adhesion. Fitting the best regression lines to the data in Fig. 7b gives K and b values of 1.0 and 16.89 for SG mouldings and K and b values of 1.0 and 253.65 for DG mouldings.

Figure 9a–c shows the flexural strength of ABS/GF/GB hybrids for both SG and DG specimens versus χ_f for the total glass concentration values of 10, 20 and 30% w/w. As can be seen, flexural strength for both specimen types increases linearly with increasing χ_f. It is also evident that flexural strength of DG mouldings is considerably lower than SG counterparts due to the presence of weldlines. Figure 10a, b also reveals that for a given hybrid ratio, χ_f, flexural strength for both specimen types increases with increasing ϕ_g.

The effect of weldline on hybrid flexural strength is illustrated in Fig. 11 in terms of weldline integrity factor,

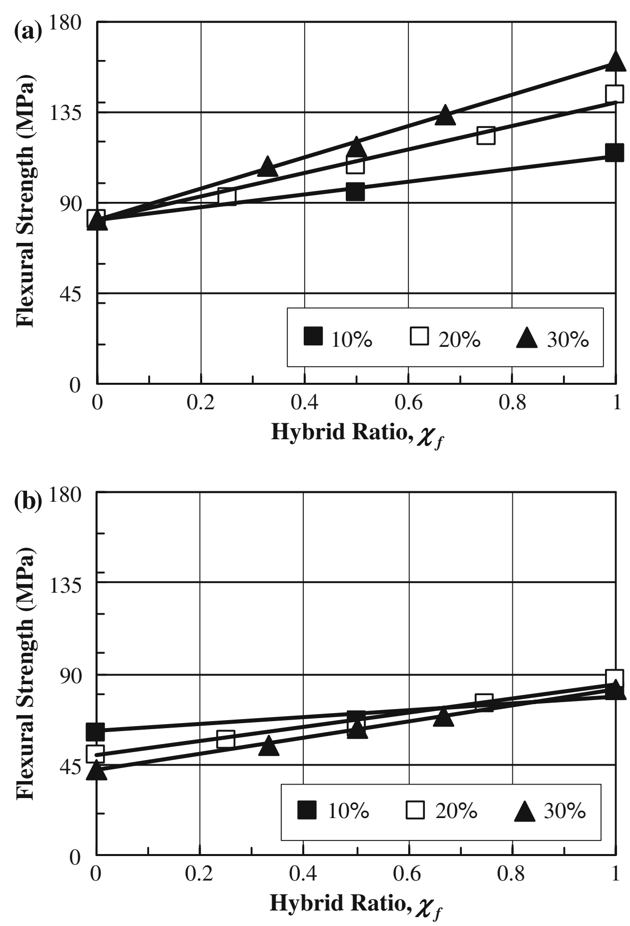

Fig. 10 Flexural strength versus hybrid ratio, χ_f, for total glass contents of 10, 20 and 30% w/w; (**a**) SG, (**b**) DG

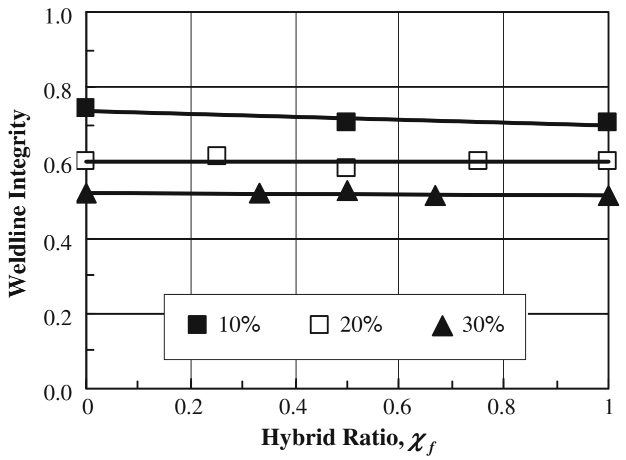

Fig. 11 Weldline integrity factor for flexural strength, F_σ, versus hybrid ratio, χ_f, for total glass contents of 10, 20 and 30% w/w

F_σ. It can be seen that F_σ decreases with increasing ϕ_g but shows no significant variation with increasing χ_f.

The linear dependence between hybrid flexural strength, σ_h, and the hybrid ratio, χ_f, suggests that the data for both specimen types can be modelled using a simple additive "rule-of-mixtures" of the form:

$$\sigma_h = \sigma_{cf}\chi_f - \sigma_{cb}(1 - \chi_f). \tag{22}$$

By substituting E_{cf} and E_{cb} into Eq. 22, one obtains the following relationships for hybrid flexural strengths;

$$\sigma_h = \sigma_m\left[1 + (10.2\chi_f - 25.52\phi_g\chi_f - 0.2)\phi_g\right] \quad \text{(single-gated)}, \tag{23}$$

$$\sigma_h = \sigma_m\left[1 + (6.253\chi_f - 14.46\phi_g\chi_f - 3.39)\phi_g\right] \quad \text{(double-gated)}, \tag{24}$$

The lines drawn in Fig. 7a–c represent Eqs. 23 and 24 and as can be seen, rule-of-mixtures describes the data for both SG and DG mouldings very well.

Using Eqs. 23 and 24, one obtains the following expression from which weldline integrity factor for hybrid flexural strength, F_σ, can be predicted for any combination of χ_f, and ϕ_g.

$$F_\sigma = \frac{1 + (6.253\chi_f - 14.46\chi_f\phi_g - 3.39)\phi_g}{1 + (10.20\chi_f - 25.52\chi_f\phi_g - 0.20)\phi_g}. \tag{25}$$

Conclusions

Hybridisation effect on flexural properties of SG and DG injection moulded ABS containing both GF and GB was investigated. Results led to the following conclusions:

(i) Flexural modulus (E_h) and flexural strength (σ_h) of ABS/GF/GB hybrid increase with the total concentration of the glass in the hybrid, ϕ_g, and the hybrid ratio, χ_f $\left(= \phi_f/\phi_g\right)$. The variation of E_h and σ_h with χ_f obeys rule-of-mixtures.

(ii) Presence of weldlines in DG mouldings affected E_h and σ_h. Although values of E_h and σ_h were reduced in the presence of weldlines, both increased with increasing χ_f in a linear manner; thus indicating that weldline properties like their unweld counterparts obey rule of mixtures.

(iii) Weldline integrity for hybrid flexural modulus, F_E, decreased with increasing χ_f in a linear manner. F_E decreased as total concentration of the glass in the hybrid increased.

(iv) Weldline integrity for hybrid flexural strength, F_σ, decreased as total concentration of the glass in the hybrid increased but showed no significant variation with respect to χ_f.

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