Influence of Hybridization of Glass Fiber and Talc on the Mechanical Performance of Polypropylene Composites

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ABSTRACT: The effect of the hybridization of short glass fibers (GFs) and talc mineral filler on the tensile mechanical performance of injection-molded propylene-ethylene copolymer composites (PP_{cop}) with and without weld lines (WLs) was studied in this work. The fibrous reinforcement imparts high-tensile stiffness and strength to the molding but originates a highly anisotropic composite. The negative effect of this anisotropy is even worse when WLs occur in the molding, as the high aspect ratio GFs tend to be oriented on the weak plane of the WL. Through hybridization of GF and talc, combined in different proportions, it is possible to obtain improved mechanical properties in comparison to the standard GF reinforced PP_{cop} composites. The combination of GF with talc was shown to be beneficial for the WL strength of PP_{cop} composites, once a synergism effect was achieved with the expected optimization of the fibers/particles packing efficiency of the hybrid reinforcement. At a given constant total reinforcement concentration, the experimental data of both tensile modulus and strength properties of the hybrid composites without WL were above the predictions derived from the estimated rule of mixtures. J Appl Polym Sci 114: 3592–3601, 2009

Key words: composites; polypropylene (PP); hybrid reinforcement; weld lines; mechanical properties

INTRODUCTION

Polypropylene (PP) is a very versatile polymer with many qualities, such as excellent chemical resistance, good mechanical performance, and low cost. These characteristics make PP the polymer of choice for a wide variety of general purpose and engineering applications by suitable modification of the mechanical properties of the matrix polymer by addition of either mineral or fibrous reinforcements.[1] For engineering applications, short glass fibers (GFs) are widely added to PP compounds to enhance the mechanical properties of the matrix polymer. These thermoplastic composites are commonly processed by the injection-molding process because of its high production rate and versatility in producing simple or complex geometry moldings of different sizes and with dimensional accuracy.[1,2] Nevertheless, during the injection-molding process, the material is subjected to a severe thermo-mechanical processing history that originates residual stresses and creates preferential orientation of both the matrix polymer chains and the reinforcing fibers. The magnitude of these effects varies across the thickness and also with the position of the gating point in the molding.[3,4] Close to the mold walls, in the so-called "skin layer" of the molding, the polymer chains and the GF are highly oriented in the main direction of flow (MDF) during the mold cavity filling; whereas in the core region of the molding, the polymer chains and GF are preferentially oriented transverse to the MDF.[3–6] This differential orientation of the polymer chains and fibers across the thickness and length of the molding induces significant anisotropy on the physical and mechanical property fields and can lead to problems such as warpage of injection-molded parts.

Very often in the injection molding of thermoplastic parts, weld lines (WLs) are formed as a result of the meeting of two melt flow fronts due to the presence of an obstacle in the mold cavity, changes in the molding thicknesses, or when two or more injection gates are used. The WL is usually a region of less entanglement of the polymer molecules and unfavorable orientation of the polymer and the reinforcements. Because of their specific characteristics, WLs have a detrimental effect on the mechanical performance of the moldings.[3,4,7–11] This effect is particularly bad when a butt WL is formed, as a result of direct impingement of flow fronts coming from opposite injection gates. In this case, the

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polymer molecules and reinforcements tend to orient in the plane of the WL. When the main direction of mechanical loading in the molded part is transverse to this WL plane, the mechanical performance of the molding is greatly depreciated. This problem is further worsened if the polymer is compounded with high aspect ratio reinforcements like GF.[12,13] However, if lamellar fillers of relatively low aspect ratio such as talc are used, the anisotropy resulting from the orientation of the fillers in the plane of WL is expected to be less significant, and the reduction on mechanical properties should not be so critical. Talc is a lamellar mineral filler commonly used in PP compounds because of its enhancing effect on the stiffness and on the heat distortion temperature. In addition, its low aspect ratio contributes to more isotropic physical and mechanical properties of the moldings.[1,14–18]

The idea of combining short GFs with particulate minerals for use as reinforcing fillers for thermoplastic composites has been for long time suggested as a way of getting an adequate balance of improved mechanical properties without excessive anisotropic effects.[19-21] This hybrid-reinforcement principle is of special interest for engineering applications, as the hybridization of reinforcements with different properties and aspect ratios presents several advantages:

- Reduction in mechanical anisotropy of moldings by partially replacing high aspect ratio fibrous reinforcements, such as glass and carbon fibers, with particulate (calcium carbonate) or lamellar (talc or mica) mineral fillers;
- Wide combination of physical and mechanical properties can be obtained by changing the proportions of each type of reinforcement;
- Economic advantage resulting from diluting expensive reinforcements like glass or carbon fibers with cheaper mineral ones, such as $CaCO_3$, talc, or mica.
- Improved mechanical and other functional characteristics of the hybrid composite, in comparison with single reinforcement composites, derived from possible synergistic interaction effects between different reinforcements.

A particularly interesting synergistic effect derived from the combination of fibrous and particulate fillers is related to the expected increase in the hybrid filler's fibers/particles packing efficiency, as verified by Milewski,[22] when compared with that of fibers only filled composites. Thus, according to the well-known Mooney's eq. (1) that governs the rheology of concentrated suspensions[4] the relative viscosity (η_r) of a highly filled thermoplastic composite, at any given volume fraction (ϕ_f) of filler/reinforcement used, should decrease with increasing filler/reinforcement's maximum volume packing fraction ($\phi_{f\max}$) and also with decreasing Einstein coefficient (K_E), related to the flow restriction caused by the introduction of rigid particles/fibers, as demonstrated below:

$$\ln \eta_r = \left(\frac{K_E \phi_f}{1 - \dfrac{\phi_f}{\phi_{f\max}}} \right) \tag{1}$$

Thus, the partial substitution of high aspect ratio GFs by low aspect ratio mineral talc filler should contribute to the reduction in the viscosity of the hybrid composite during the injection-molding process and this synergistic effect should reflect directly on the state of fiber orientation of the composite molding, especially in its WL region.

Despite the fact that the mechanical behavior of polymers with hybrid fibrous-particulate reinforcements has been studied by various authors,[19,20,23,24] their influence on the mechanical performance of moldings with WLs has not been sufficiently studied.[25,26] Namely, doubts still remain on which effects are to be expected from the combination of high aspect ratio reinforcements, like GF, with lamellar mineral fillers, like talc, in composites based on PP, especially when WLs are present.

In this article, the tensile properties of propylene copolymer (PP_{cop}) composites reinforced with varying concentrations of GF-particulate talc mineral hybrid systems were analyzed. The mechanical performance was assessed using tensile test specimen with and without WLs.

EXPERIMENTAL

Materials

A heterophase propylene-ethylene copolymer (PP_{cop} matrix–PX 1955), with melt flow rate of 4.71 g/10 min and density of 0.866 g/cm^3, was chosen as the matrix polymer and was supplied by Braskem Brazil. The talc mineral filler (T-GM-10), with average particle size $d_{50} = 2.6$ μm (as measured by sedigraphy) and density of 2.78 g/cm^3, was supplied by Magnesita Brazil. Short GF (GF - E 968), with density of 2.58 g/cm^3 and nominal fiber diameter of 13 μm, was supplied by Vetrotex Brazil in the form of chopped roving of 4.5 mm length.

The hybrid compositions, presented in Table I, were chosen in a way to analyze:

- The influence of partial substitution of GF by talc on PP composite properties at constant total reinforcement (fiber + talc) concentration (40% wt).
- The influence of increasing talc content (0, 10, 20, and 30 wt %) on PP composite properties at constant fiber concentration (20 wt %).

TABLE I
Nominal Weight (and Calculated Real Volume) Concentrations of Reinforcements Used in PP_{cop} Composites

Nominal (wt %)	Composite codes (vol %) PP_{cop}		
Matrix Reinforcements	Glass Fiber	Hybrids	Talc
10	10GF(3.91)	–	10T(3.38)
20	20GF(8.06)	–	20T(7.23)
30	30GF(13.09)	20GF10T(12.53)	30T(11.40)
40	40GF(18.62)	10GF30T(17.25)	40T(16.16)
		20GF20T(17.91)	
		30GF10T(18.28)	
50	–	20GF30T(24.86)	–

Compounding

These formulations were compounded in a Werner-Pfleiderer ZSK-30 corotating twin-screw extruder. The PP_{cop} composites with talc only were prepared through the dilution of a previously prepared masterbatch of PP_{cop} with 40 wt % of talc (40T), to assure complete dispersion and distribution of the filler particles in the matrix. In the case of the composites with fiber, a single extrusion run was adopted to avoid excessive breakage of GFs. The hybrid composites were also prepared in a single extrusion run by incorporating fibers into a mix of pure PP_{cop} with the 40T masterbatch, in the proportions required to obtain the desired formulations.

Molding

Dog-bone-shaped tensile test specimens (ASTM D638 Type-1) with and without WLs were injection molded in an Arburg automatic injection machine (Allrounder V-270) with clamping force of 800 kN. The tensile bars could be single or double film gated by changing detachable parts of the mold. The double gating at opposite extremities caused a butt WL to be formed at the middle section of the specimen, as shown in Figure 1.

The injection-molding conditions were kept constant within possible limits for all formulations to allow the analysis of the influence of the composite material variables on the tensile performance, independently from the processing parameters. The specimens were molded with melt temperature of 250°C, mold temperature of 40°C, injection rate of 12 cm^3/s, and holding pressure of 46 MPa.

Characterisation and testing

The actual weight concentrations of the composites were determined through pyrolysis of the molded samples in a microwave oven at 620°C for 30 min. The volume concentrations were calculated using the equations related below for systems with single reinforcement (2) and for hybrid reinforcement (GF + T) systems (3). In the case of the hybrid systems, the weight concentration of each reinforcement system was estimated based on the nominal component fractions.

$$\phi_f = \frac{\frac{M_f}{\rho_f}}{\frac{M_f}{\rho_f} + \frac{(1-M_f)}{\rho_m}} \tag{2}$$

$$\phi_{f+t} = \frac{\frac{M_f}{\rho_f} + \frac{M_t}{\rho_t}}{\frac{M_f}{\rho_f} + \frac{M_t}{\rho_t} + \frac{1-(M_f+M_t)}{\rho_m}} \tag{3}$$

where M and ρ represent the weight fraction and the density of the materials and the suffixes m, f, and t are related to the matrix, fiber, and talc, respectively.

The fibers extracted from the pyrolysis residues of the composites were measured using optical microscopy analysis. The data for calculating the GF weight average fiber length (L_w) were acquired with the Pro-Plus image analyzer program. The calculation of the weight average fiber length was based on approximately 1200 fibers for each composition using the equation:

$$L_W = \frac{\sum_{i=1} l_i^2 n_i}{\sum_{i=1} l_i n_i} \tag{4}$$

where n_i is the number of fibers with l_i range of fiber length.

To verify the nucleating effect of talc on the PP_{cop} matrix, the degree of crystallinity of the PP_{cop} matrix in each composition was calculated from the heat flux of the endotherm peak from the first heating curve measured by differential scanning calorimetry in a Netzch 204 instrument. The samples were submitted to a cycle of heating, cooling and heating from 50 to 200°C, with heating and cooling rates of 10°C min^{-1}. The heat flux of 100% crystalline PP considered for crystallinity determination was 209 J/g.[27]

Scanning electron microscopy (SEM) observations were carried out over the plane parallel to the

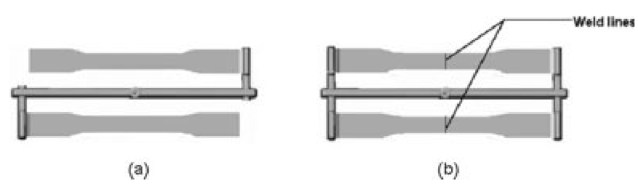

Figure 1 Dog-bone-shaped tensile test specimens (a) without and (b) with weld lines.

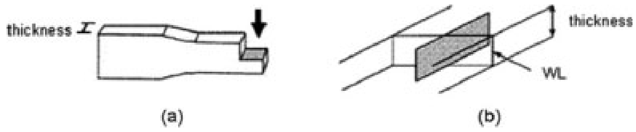

Figure 2 Planes parallel to the thickness of tensile specimen (a) observed by SEM in samples without and (b) with (b) weld line.[10]

thicknesses of the tensile bars, as shown in Figure 2, to observe the orientation of the reinforcements, in samples with and without WL. For this analysis, a Leica Cambridge microscope, model S360, was used on gold-coated cryo-fractured surfaces of PP_{cop} composite samples.

The tensile tests were carried out with an Instron universal testing machine, model 5569, according to ASTM D638 specifications, using a crosshead displacement rate of 5 mm min^{-1}.

RESULTS AND DISCUSSION

Crystallinity

The DSC results, depicted in Figure 3, indicate that the presence of the reinforcements does not influence significantly the crystalline fraction of the heterophase propylene copolymer matrix. As the observed variations in crystallinity content of PP_{cop} matrix are minor and within the deviations associated to this type of analysis, it is to be expected that these crystallinity variations should not influence the analysis of mechanical properties of the PP_{cop} composites.

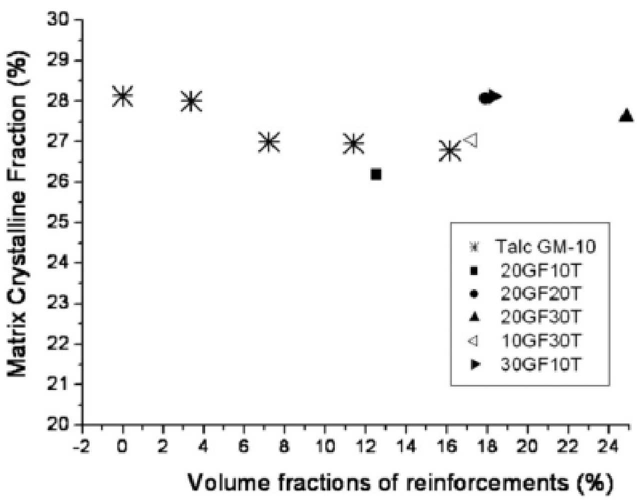

Figure 3 Crystalline content (%) of PP_{cop} matrix with different reinforcements. The results were normalized to consider only the mass of the matrix.

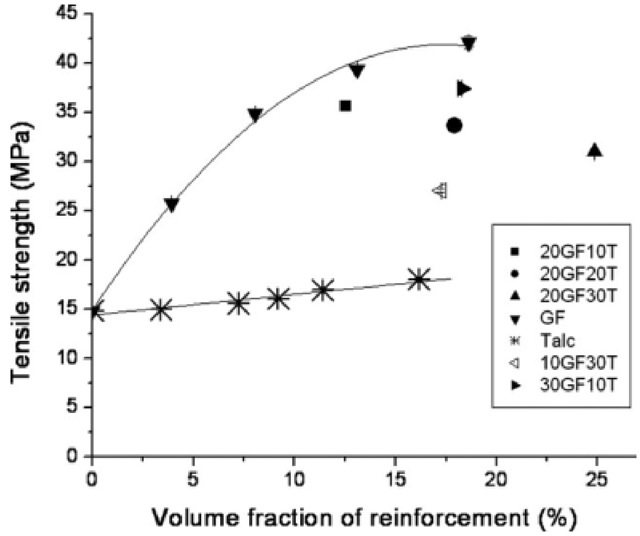

Figure 4 Tensile strength of the composites as a function of the volume fraction of GF and talc reinforcements in the moldings without WL.

Mechanical strength

The influence of the reinforcement volume concentration on the tensile strength (TS) of the composite moldings without WL is depicted in Figure 4. As one could expect, the addition of GF (high aspect ratio reinforcement) increases significantly the TS of PP_{cop} in comparison with the less efficient (lower aspect ratio reinforcement) talc-filled composites. Also, the observed increase in TS with the fiber volume fraction is not linear in the GF-reinforced PP composites. This behavior is associated to the substantial fiber breakage during processing when higher GF loading (30 and 40 wt %) is used and to the consequent reduction of the average fiber length (L_w), as shown in Table II. The fiber length decreased from 750 μm in the 10GF composite to 451 μm in the 40GF composite and, consequently, contributes to reduced fiber reinforcement efficiency at higher GF loadings.

In the case of the hybrid composites with equivalent total reinforcement content, the TS data were

TABLE II
Weight Average Length of GF in the Composites

Composites	L_w (μm)
10GF	750.5
20GF	654.5
30GF	508.7
40GF	451.0
20GF10T	569.9
20GF20T	521.8
20GF30T	515.0
10GF30T	548.9
30GF10T	466.7

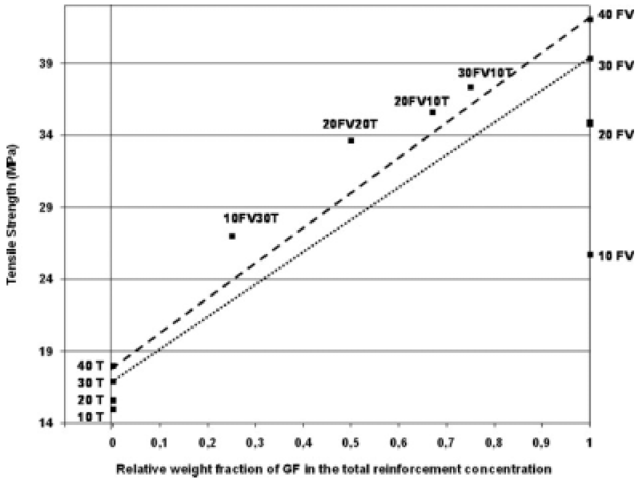

Figure 5 Tensile strength (TS) of PP_{cop} hybrid composites (without WL), as a function of the relative weight fraction of GF in the total reinforcement concentration. The traced lines represent an estimation of the TS behavior expected from applying the rule of mixtures.

always located between the "reference" composites data (GF only and talc only reinforced composites), as also shown in Figure 4. On replacing part of the GFs by talc (composites 40GF – 30GF10T – 20GF20T – 10GF30T), the TS of the resulting hybrid composites decreased.

When the GF concentration is kept constant at 20 wt %, the addition of talc causes a nearly linear decrease in the TS of the hybrid composite with increasing talc content (Fig. 4). This decrease in TS can be associated to the reduction of the GF length, as shown in Table II, which was probably induced by the increase in viscosity of the hybrid composite caused by the talc addition. Thus, considering that talc had a relatively small influence on the TS of the PP_{cop} matrix (Fig. 4), the reduction of the GF aspect ratio had apparently a greater influence on this property than the increase of the total hybrid (GF + T) reinforcement concentration. This same reduction may also justify the lower TS of the hybrid composite 30GF10T compared with the composite 30GF.

In Figure 5, the TS data are plotted as a function of the relative concentration of GF in the hybrid composites. The traced lines in this graph represent the TS predictions of the hybrid composites that would be expected from applying an approximation of the simple rule of mixtures for each specific total reinforcement concentration (30 or 40 wt %). Analyzing the TS data of the hybrid composites at constant 40 wt % of total reinforcement (GF + T) concentration (composites 30GF10T; 20GF20T; 10GF30T), it can be seen that these composites exhibit TS values above the predictions given by the rule of mixtures. This can indicate an interesting synergistic effect derived from the expected melt viscosity reduction of the hybrid composites, in comparison with the composite filled with fibers only (40GF), as previously discussed on the influence of hybridization of the reinforcement system (GF + T) on the melt viscosity predictions based on the Mooney's eq. (1). This reduced melt viscosity effect derived from partial substitution of GF by talc particles contributes to lower overall fiber attrition in the hybrid composites, as verified from the observed increase in the GF average length (L_w data in Table II). As this increase in the fiber length of the residual GF in the hybrid-reinforcement is not computed in the predictions from the rule of mixtures, the observed improvement in the TS values of these hybrid composites can only be attributed to the more effective stress transfer from the polymer matrix to the higher aspect ratio GFs. This same behavior is also verified in the composite 20GF10T, in comparison with the composite 30GF.

The effect of the weld lines

The TS data of the moldings with WLs investigated in this study are represented in Figure 6(a). This same TS data are also represented in Figure 6(b) in terms of WL integrity factor, which indicates the depreciative effect induced by WLs on the mechanical properties (i.e., TS and modulus) of the composites. The WL integrity factor (F_{WL}) is defined as:

$$F_{WL} = \frac{P_{WL}}{P} \tag{5}$$

where, P_{WL} is the mechanical property (e.g., TS $-\sigma_R$ or elastic modulus $-$ E) in the WL zone, and P is the same property in the molding without or away from the WL.

Thus, the maximum value of $F_{WL} = 1$ means that the WL does not influence the mechanical property of the molded part, whereas values of this factor below unity correspond to a reduction of the product performance as a consequence of the WL formed.

The influence of the reinforcement system on the mechanical performance is better shown in Figure 6(b), where the data are normalized in terms of the WL integrity factor F_{WL} for varying reinforcement volume fractions. The integrity factor F_{WL} of about 90% for the unfilled PP_{cop}moldings in Figure 6(b) and Table III confirms the lack of the polymer molecular cohesion/entanglement in the WL region. The negative influence of the higher aspect ratio reinforcement is confirmed by the lower values of F_{WL} for composites with GF, when compared with the same data for talc composites (Table III). Also, a steeper reduction of F_{WL} with increasing GF content (from 0.52 with 10 wt % of GF to 0.21 with 40 wt %

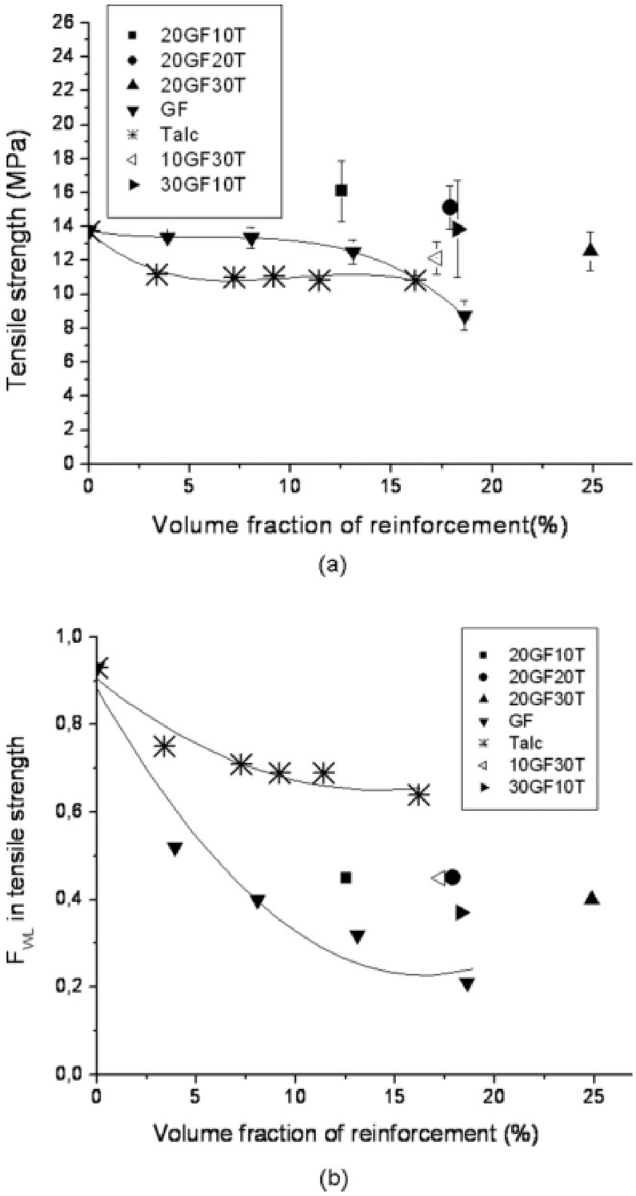

Figure 6 (a) Weld line tensile strength data and (b) weld line integrity factor (F_{WL}) of the composites, as a function of the volume fraction of reinforcements.

of GF) can be noticed in Figure 6(b), when compared with the data for the talc-filled composites (from 0.75 with 10 wt % of talc to 0.60 with 40 wt % of talc). At higher filler content, this contributes to the similarities of the TS values for GF and talc composites moldings with WL, as shown in Figure 6(a). Again, the above-mentioned observations also justify the lower TS of the 40GF composite with WL, when compared with the talc only composite (40T).

The values of F_{WL} for moldings from hybrid composites were intermediary to the data of their "reference" composites with a single reinforcement. However, all the hybrid composite moldings with WL presented TS values higher than that of single GF or talc reinforced composites, indicating a synergism effect. This effect is probably due to the expected melt viscosity decrease of the hybrid composites which, following the previously mentioned Mooney eq. (1), can be attributed to an increase of the maximum volume packing fraction ($\phi_{f\max}$) obtained through the combination of GF with talc. This explanation is coherent with the results of Leite,[28] who confirmed the increase of $\phi_{f\max}$ with the combination of GF and talc in a PP_{cop} matrix, compared to the $\phi_{f\max}$ values obtained with a single reinforcement (GF or talc). Therefore, at equivalent reinforcement concentrations, the hybrid reinforced composite melt has a viscosity lower than that of the composite with single reinforcement (GF or talc). As the lower viscosity permits higher molecular mobility at the same injection temperature, better polymer chains entanglement occurs during the formation of the WL in the hybrid composites than would be expected with the single GF composite, where adverse orientation arises in the WL plane.[7,9,10,12,26]

It is also possible to verify in Figure 6(a), a decrease in the TS of the hybrid composites with the increase of the total reinforcement content. This may well result from the higher viscosity of the more heavily filled composites. The higher viscosity implies reduced molecular mobility and, probably, the presence of more fibers aligned in the WL plane, leading to a poorer WL TS.

Stiffness

The influence of the reinforcement volume fraction on the elastic tensile modulus of the composites is shown in Figure 7 for all composites considered in this study. As previously observed for the TS data of PP composites, the higher reinforcement efficiency of the high aspect ratio GF, in comparison with the

TABLE III
Weld Line Integrity Factors (F_{WL}) for the Tensile Strength and Modulus of PP Composites

Compositions	F_{WL}	
	σ_R	E
PP_{cop}	0.93	0.91
10T	0.75	0.95
20T	0.71	0.86
30T	0.64	0.82
40T	0.60	0.82
20GF10T	0.45	0.69
20GF20T	0.45	0.63
20GF30T	0.40	0.62
10GF30T	0.45	0.73
30GF10T	0.37	0.56
10GF	0.52	0.73
20GF	0.40	0.59
30GF	0.32	0.53
40GF	0.21	0.41

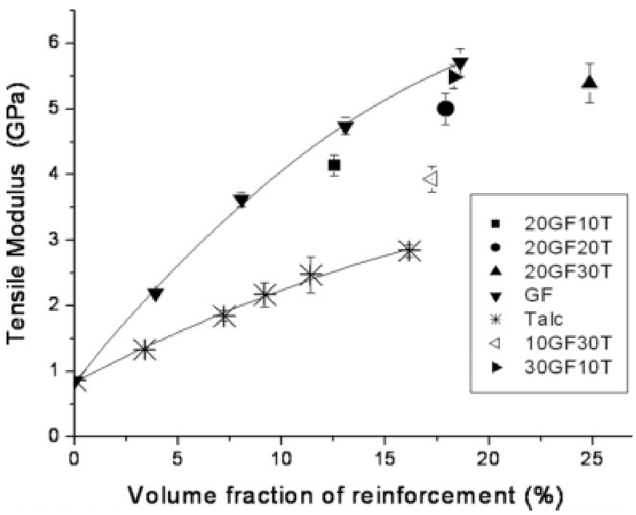

Figure 7 Elastic tensile modulus of PP_{cop} composites without weld lines.

much lower aspect ratio lamellar talc particles, is also verified in the elastic modulus data.

In the case of the elastic modulus data of the GF-reinforced composite, measured at very small test specimen deformations as compared to the higher deformation measurements for the TS data, the modulus increase was almost linear with the GF content as shown in Figure 7. Through these results, it can be concluded that the combined influence of the composite melt viscosity increase and the reduction of average fiber length was not as significant as observed for the TS property. The contribution of the talc to the composite stiffness was also higher than that observed for the TS properties, as the stress transfer from the matrix to the talc filler is more efficient at small deformations. Furthermore, there is the beneficial effect of the higher interfacial adhesion between the components, assured by the same nonpolar nature of the PP_{cop} and the talc lamellae.[1]

The hybrid composites presented values of tensile modulus also intermediate to those obtained for the GF or talc reference composites. In the hybrid composites with constant total reinforcement concentration (40 wt %), the partial substitution of GF by talc led to a decrease in the modulus, as it would be expected. Nevertheless, in the case of the hybrid composites with constant GF concentration of 20 wt %, a substantial increase in the modulus is achieved with talc addition, as observed in Figure 7. This indicates exactly an opposite effect to that observed on the TS properties of these same hybrid composites. A possible explanation for this opposite effect on the analyzed TS and modulus properties lies in the fact that the addition of rigid talc particles reduces significantly the mobility of the polymer matrix in the vicinity of the filler particles surface. This factor is now more significant for the hybrid composite's modulus enhancement than the reported reduction in the average GFs length (L_w in Table II), which influenced significantly the TS data.

Another factor that can be contributing to the modulus increment is the fiber orientation in the direction of the mechanical loading. In hybrid composites, the presence of small aspect ratio fillers like talc or calcium carbonate tend to influence the orientation profile of GF across the thickness of injection-molded parts. Previous studies[23,24] have demonstrated that the addition of talc or calcium carbonate in PP composites with constant concentration of GF led to an increase of fiber orientation in the main direction of the cavity filling (increase of the skin layer), induced by viscosity increase. Thus, in the analysis of tensile mechanical properties of hybrid fibrous-particulate polymer composites, it appears important to consider that the presence of the particulate fillers influences the viscosity of the composite melt, which in turn influences the average GF length and the degree of orientation of the reinforcing fibers in the moldings.

The tensile modulus data of the composites as a function of the relative concentration of GF in the total reinforcement concentration are summarized in Figure 8. Once more, it can be noted that the tensile moduli of the hybrid composites are higher than expected from the estimated rule of mixtures, when compared in composites with the same total reinforcement concentration. These results can be attributed to the previously discussed increase of GF length with the partial substitution of GF by talc in composites with constant total 40 wt % reinforcement content.

The effect of the weld lines

In the case of the moldings with WLs, as shown in Figure 9(a,b), the depreciative effect of the WL was higher in the case of GF composites (lower F_{WL}

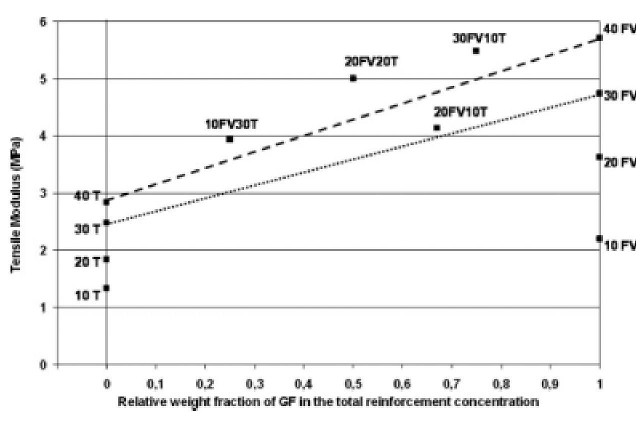

Figure 8 Tensile modulus of composites without WL, as a function of the relative weight fraction of GF in the total reinforcement concentration. The lines represent an estimation of the behavior predicted with the rule of mixtures.

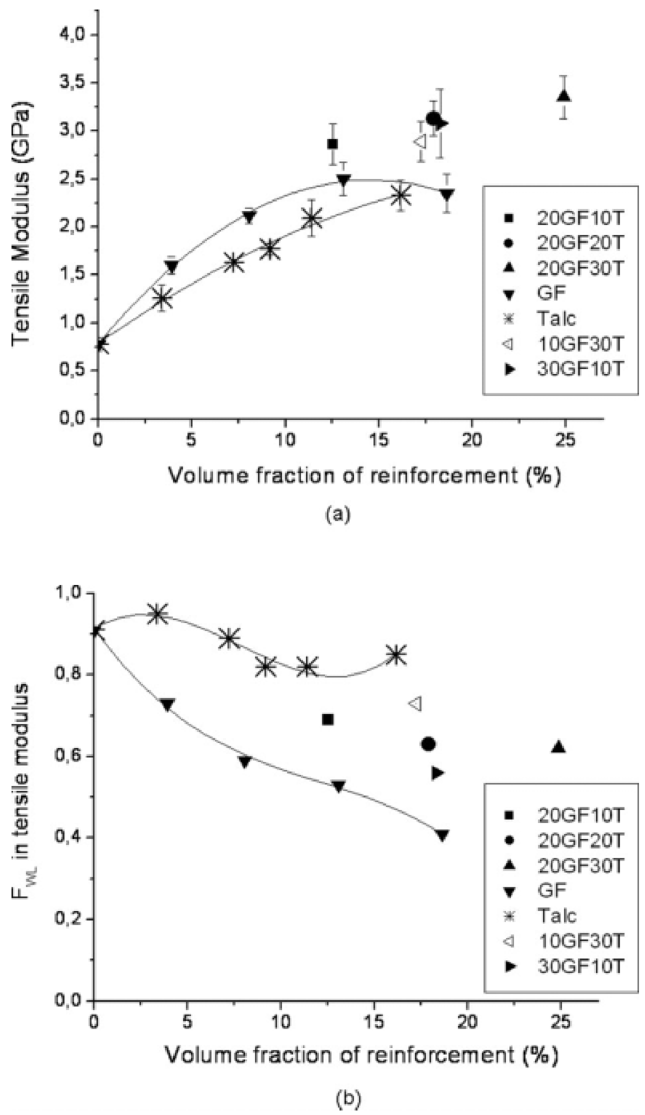

Figure 9 (a) Tensile modulus of PP_{cop} composites with weld line and (b) influence of weld line integrity factor (LW) on the tensile modulus of PP_{cop} composites versus the volume fraction of reinforcements.

values in Table III). The highest absolute values of the tensile modulus were observed for the hybrid composites. This is also a synergistic effect of the hybrid reinforcement with fibers and particulate fillers, resulting from lower WL depreciative effect on the tensile modulus due to the expected decrease of melt viscosities derived from higher $\phi_{f\max}$ values of these hybrid composites, as discussed previously in the case of the TS properties.

Morphology

Figure 10 exhibits SEM micrographs of cryo-fractured surfaces of PP composites along the thickness of tensile bars showing the orientation of GF in the WL region and away from it. In Figure 10(a), the formation of the well-established skin-core structure can be noted: (i) layers near the mold surfaces with the fibers oriented in the direction of the mechanical loading, parallel to the MDF and (ii) a central core layer with the fibers oriented preferentially in transverse direction to the mechanical loading. Between each skin and the core, there are transition layers with intermediary orientation of the reinforcements. This orientation profile is derived from the well-

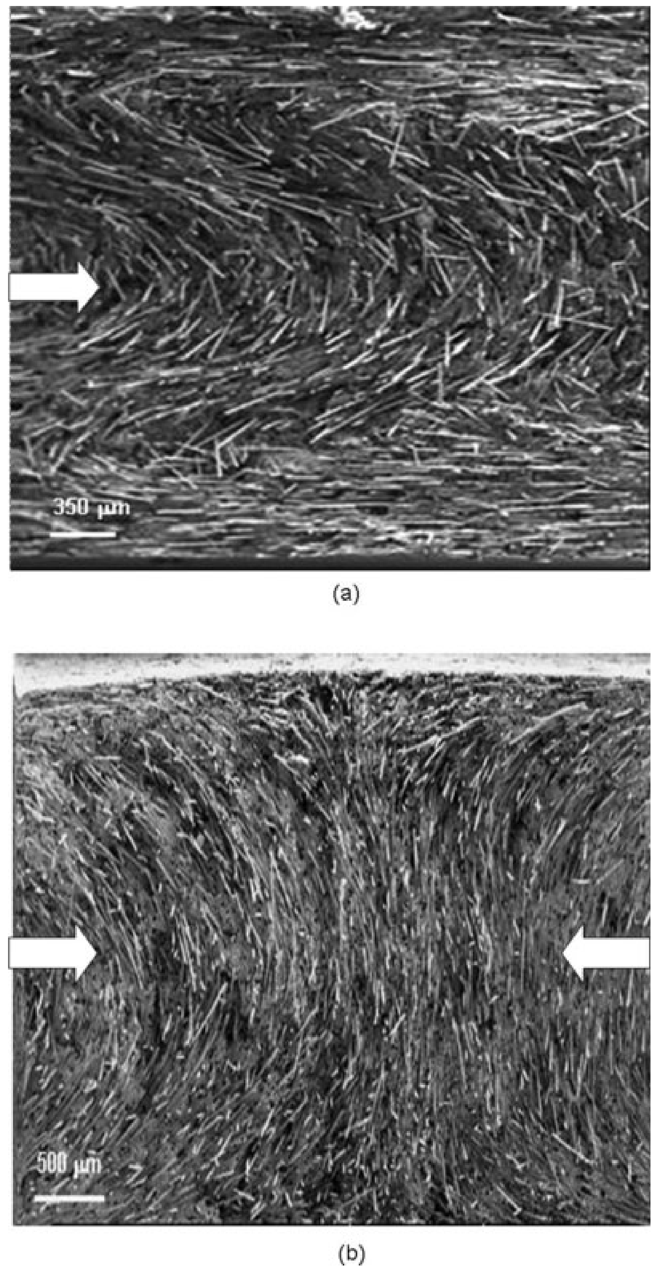

Figure 10 SEM micrographs showing: (a) the orientation of the glass fibers following the skin-core structure along the thickness of the 20GF20T hybrid composite; (b) the orientation of GF in the WL plane (in the center of the picture) of the 40GF composite, formed with the meeting of two flow fronts coming from opposite sides. The arrows indicate the melt flow direction.

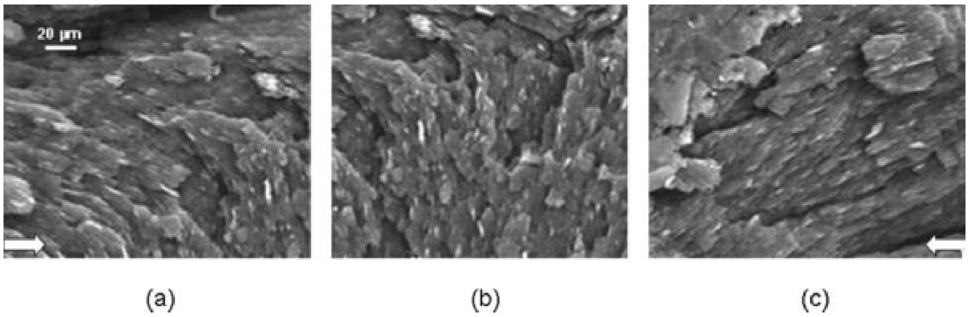

Figure 11 Sequence of SEM micrographs of the 20T composite, showing in: (a) and (c) flow fronts coming from opposite injection gates and (b) WL region. The arrows indicate the melt flow direction. The lamellae of talc are the white particles in the pictures.

known fountain flow effect verified at the melt flow front and also from the parabolic velocity profile formed during the filling of the injection-molding cavity.[3–5]

Figure 10(b) shows the region where the two flow fronts coming from opposite injection gates meet and form the WL. As it can be seen, the GF are oriented in the WL plane across the whole thickness of the sample and are, therefore, transverse to the direction of mechanical loading in tensile tests. This unfavorable orientation contributes to the substantial decrease in tensile properties measured in GF-reinforced PP_{cop} composites with WL, as already discussed before. In composites with talc, this same phenomenon is also observed with the talc lamellae aligned parallel to the weak WL plane, as shown in Figure 11. Nevertheless, their lower aspect ratio promotes only a small depreciative effect on the mechanical properties in the presence of WL, as could be verified from the tensile test results.

CONCLUSIONS

Through the hybridization of the reinforcement system of thermoplastics using various aspect ratio fillers, it is possible to obtain a improved mechanical performance of injection-molded composites. The properties for the hybrid GF/talc reinforced propylene copolymer hybrid composites were analyzed in terms of tensile modulus and strength.

At a given constant total reinforcement concentration, the experimental data of tensile modulus and strength of the hybrid composites without WL were above the predictions derived from the estimated rule of mixtures.

The combination of GFs with talc was shown to be beneficial even for the WL strength of PP_{cop} composites, once a synergism effect could be reached with the expected optimization of the fibers/particles packing efficiency of the hybrid reinforcement.

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