General paper

EFFECTS OF CONSOLIDATIONS ON MECHANICAL PROPERTIES OF KNITTED FABRIC REINFORCED THERMOPLASTIC COMPOSITES

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Abstract: A study was conducted on the effects of cooling conditions on flexural properties of aramid fiber knitted fabric (AFKF) and glass fiber knitted fabric (GFKF) reinforced thermoplastic polypropylene composites. To study these effects, composite laminates were fabricated under a molding pressure of 3MPa for 20 min, then consolidated from the melt at different cooling conditions: rapid cooling i.e., quasi-quenching and gradual cooling. Flexural tests were carried out on specimens in two directions: wale and course. Evaluation on thermal properties and morphology was studied using a differential scanning calorimetry (DSC). Flexural properties were little sensitive to the cooling rates; however, gradually cooled specimens showed higher level of crystallinity than rapidly cooled specimens. Furthermore, flexural strengths displayed higher in the wale than in the course directions. SEM micrographs of fracture surfaces revealed poor adhesion between the fiber and polypropylene matrix.

Key words: *Knitted fabric composites, Wale and course directions, Rapid cooling, Gradual cooling, Crystallinity, Flexural properties.*

1. INTRODUCTION

It has been found that the mechanical properties of semi-crystalline thermoplastic composites greatly depend on material processing conditions. The effect of cooling rate on crystallinity, morphology and mechanical properties of high performance semi-crystalline thermoplastic composites have been investigated in recent years [1-4]. However, most of studies on thermoplastic composites have involved the use of unidirectional fiber yarns and rigid semi-crystalline polymers due to their high modulus and yield strength, such as semi-crystalline polyetheretherketone (PEEK), polyphenylene sulphide (PPS) and many others. Composite materials based on polypropylene matrix resins (PP) reinforced with knitted fabrics that have large deformation and low modulus are suitable to membranous composite materials. The objective of this study was to investigate the mechanical behavior of flexible composite materials based on a combination of knitted fabrics (fiber preforms) with polypropylene matrix resins. Knitted fabrics with excellent drape-ability and net-shape manufacture ability are finding applications in composite materials [5]. In recent years, many research works on mechanical properties of knitted fabric composites have been investigated but most of these studies used composite materials based on epoxy resin [6-8]. Recently, Ramakrishna et al [9-10] has investigated the fabrication of glass fiber knitted fabric reinforced polypropylene matrix composites. The effects of impregnation time and stitch densities on tensile properties of knitted fabric composites have been identified.

In the work reported here, aramid fiber knitted fabric reinforced polypropylene (AFKF/PP) and glass fiber knitted fabric reinforced polypropylene (GFKF/PP) composites were fabricated by controlling cooling conditions. The effects of the cooling conditions on flexural properties of AFKF/PP and GFKF/PP were studied. The degree of crystallinity of the PP matrix as well as fracture surfaces of knitted fabric composite laminates were examined using differential scanning calorimetry (DSC) and scanning electron microscope (SEM), respectively.

1. EXPERIMENTAL PROCEDURES

2.1. Materials

Fig.1. Schematic diagram of a plain knitted fabric.

Aramid fiber yarns of 1140 denier (Kevlar 49, type 965) were supplied by Toray Dupon Co. Ltd. Japan. Glass fiber yarns (ECD 450 1/2 4-45Y-23) with $D_y = 1600$ denier were supplied by Nippon Electric Glass Co. Ltd. Japan. Two types of these yarns were used to produce plain knit fabrics. Unmodified polypropylene (PP) sheets of 0.5 mm in thickness obtained from Idemitsu NSG Co. Ltd. Japan were used as polymer matrix.

2.2. Knitted Fabrics

The research work described in this paper was mainly concerned with a plain weft knitted fabric. A schematic diagram of this knitted fabric is illustrated in Fig.1. The knitted fabric produced on a flat bed weft knitting machine with a single set of needles using aramid and glass fiber yarns consists of the row of knit loops in the width direction and the column of knit loops in the longitudinal direction of the fabric. Respective directions are called 'course direction' and 'wale direction'. Knitted fabrics are often specified using stitch density (S.D.) that is defined as the total number of knitted loops per unit area of the fabric. In this study, the knitted fabric with a stitch density of 22 loops/cm² was produced.

2.3. Composite Fabrication

Four plies of the knitted fabric aligned with respect to each other were stacked together with PP layers then

Fig.2. Schematic diagram for fabrication of knitted fabric composites.

placed into a mold. The mold was first heated to 220°C; after reaching this molding temperature, a compressive pressure of 3MPa was applied over a period of 20 min. Then, the mold was instantly immersed in a large volume of iced water (cooling rate: 140°C/min, Type-R) for the quasi-quenched specimens. The mold was also subjected to the same processing conditions for the gradually cooled specimens (Type-G) before cooling to the room temperature (RT) at a cooling rate of 5°C/min. Neat PP samples of 3mm in thickness were also fabricated with the same processing conditions like the knitted fabric composites. Fiber volume fractions of AFKF/PP and GFKF/PP panels were determined by a specific gravity and a combustion method, respectively.

2.4. Flexural Tests

Three-point flexural tests were carried out with a support length to thickness "h" ratio of 10:1 so that the effect of shear stresses can be excluded. The specimen geometry prepared by cutting parallel to the wale and course directions of the fabric was 10h+20 mm long, 25 mm wide and 3mm in thickness. The experiment was repeated on a set of five specimens at room temperature using an Instron testing-machine (Type-4206) at a cross-head rate of 1mm/min. Fracture surfaces of the flexural specimens coated with a thin layer of gold were observed by using a scanning electron microscope (JEOL, model JSM-5200).

2.5. Differential Scanning Calorimetry (DSC)

The degree of crystallinity of the PP matrix in the neat PP samples as well as the knitted fabric laminates was assessed by using differential scanning calorimetry (DSC) carried out on a Perkin Elmer DSC7. A sample of 5 mg sealed in aluminum pans was heated to 220°C at the heating rate of 20°C/min and also crystallized at a cooling rate of 20°C/min. Thermal properties such as melting temperature, crystallization temperature and heat of diffusion were all determined from DSC thermograms. The experiment was conducted on three samples and the results were averaged. The degree of crystallinity of the composite was computed from

$$X_c = \frac{\Delta H}{\Delta H^0 (1 - W_f)} \times 100 \quad (1)$$

where ΔH is the experimental heat of fusion, ΔH^0 is the heat of fusion of the complete crystalline PP ($\Delta H^0 = 190$ J/g [11]) and W_f is the weight fraction of fiber. In this study, volume fraction was used; hence, this was converted into weight fraction using the expression:

$$W_f = \frac{V_f \rho_f}{V_f \rho_f + V_r \rho_r} \quad (2)$$

Where V and ρ are the volume fraction and density, subscripts f and r refer to fiber and resin (aramid fiber: $\rho_f = 1.45\text{g/cm}^3$, glass fiber: $\rho_f = 2.56\text{g/cm}^3$ and polypropylene $\rho_r = 0.9\text{g/cm}^3$ [12]). Fiber volume fractions of GFKF/PP and AFKF/PP are measured as 25% and 27%, respectively.

3. RESULTS AND DISCUSSION

3.1. Relation between Cooling Conditions and Thermal Properties

Table 1 summarizes the thermal properties of GFKF/PP and AFKF/PP composites measured at the different cooling conditions. The melting temperature (T_m) and the crystallization temperature (T_c) of Type-R compared to those of Type-G were not considerably changed. Hence it can be said that different cooling rates had little or no effect on changes of these temperatures. The heat of fusion (ΔH) was higher in neat resins than composite samples. These were due to larger specific heat of the neat PP matrix than that of the fibers. Thus the specific heat and the thermal capacity of neat PP were larger than those of composite materials. The higher degree of crystallinity resulted in Type-G than in Type-R for both glass fiber and aramid fiber knitted fabric composites showed that the degree of crystallinity of the PP matrix in the composite laminates was sensitive to the cooling rates.

Table 1. Thermal properties of the composites with different cooling conditions.

Samples	Neat PP		GFKF/PP		AFKF/PP	
	R	G	R	G	R	G
T_m , °C	161.1	161.2	160.8	161.3	161.9	160.4
T_c , °C	102.7	101.5	101.3	101.7	101.7	101.7
ΔH , J/g	65.5	84.0	29.8	33.9	34.5	38.5
X_c , %	34.4	44.2	30.6	34.3	29.0	32.4

3.2. Flexural Properties

The typical flexural stress-deflection curves of Type-R and Type-G for GFKF/PP composites in the wale direction are shown in Fig.3. When the deflection was small, flexural stresses of Type-G seem to be slightly higher than those of Type-R. With larger deflection, stress values of Type-G were lower than stress values of Type-R. Higher failure strength and deflection of Type-R

Fig. 3. Typical flexural strength-deflection curves of GFKF/PP at different cooling conditions

Fig.4. Flexural strength and flexural modulus of AFKF/PP composites with different cooling conditions.

may be attributed to higher amorphous contents in rapid cooling. It would be clearly explained in the next paragraph. The same tendency of the Type-R and the Type-G was also obtained for AFKF/PP composites.

Flexural moduli and strengths of AFKF/PP are presented in Fig.4. It can be seen that the flexural properties of both the wale and course specimens were slightly affected by the cooling rates. Flexural strengths of type-R were higher than those of Type-G while their flexural moduli were lower than those of Type-G. The enhancement of flexural strengths for Type-R may be attributed to two possible reasons: one was improvement of properties of the matrix itself and the other was a change of interfacial strength between fiber and matrix.

The improvement of properties came from the matrix itself due to changes in the degree of crystallinity or spherulite morphology. The slightly decreasing the degree of crystallinity resulted in higher amorphous contents for Type-R compared to Type-G is displayed in Table 1.

Another possibility was the improvement of interfacial strength between fiber and matrix. This is attributed to the higher amorphous contents of Type-R resulted in the larger wetted fiber surface area due to smaller spherulite size which made an increase in the fiber/matrix adhesive quality. It has already been proved by Hocker et al. [13], they have studied the effects of crystallinity on the fiber/matrix adhesion in single glass-fiber/PP composites at rapid (Type-R) and gradual cooling (Type-G) conditions. The interfacial shear strength of Type-R for pulling out a single fiber embedded in a flat block PP matrix was higher than that of Type-G. This was due to fine spherulite size of Type-R [14] improved the interfacial strength between fiber and PP matrix.

Also, both the Type-R and Type-G specimens displayed higher flexural strength in the wale direction than in the course direction. It might be that the higher proportion of fiber bundles of the knitted fabric was oriented in the wale than in the course direction.

Not being similar tendency to the flexural strengths, flexural moduli of Type-R for both the wale and course specimens indicated lower values than those of Type-G. It seems that matrix of type-R was more ductile than that of Type-G. This might be attributed to the effect of reducing the crystalline degree of Type-R in the polymer matrix i.e., the lower degree of crystallinity, smaller spherulite and lower flexural modulus of Type-R.

Flexural properties of the GFKF/PP composites are presented in Fig.5. Being similar to the flexural properties of AFKF/PP composites in the case of the GFKF/PP composites, flexural strengths of Type-R also displayed higher values than those of Type-G in both

Fig.5. Flexural strength and flexural modulus of GFKF/PP composites with different cooling conditions.

wale and course specimens while flexural moduli reversed to AFKF/PP mentioned above.

SEM micrographs of fracture surfaces on the tensile side of both composites at the different cooling conditions, i.e. Type-R and Type-G, are shown in Figs.6 and 7, respectively. It can be seen that matrix fractures of both composites at resin rich regions occurred in various ways. Matrix of Type-R failed in the typical ductile manner, while matrix of Type-G displayed de-bonding due to sample's failure edges that appeared to be relatively smooth. The ductility of Type-R is illustrated by plastic deformation of PP matrix pulled out in the form of small hills (Fig.6(a), Fig.7(a)). Their fracture surfaces look rather coarse whereas the fracture surfaces of Type-G seem to be relatively smooth and on a macroscopic scale, without any significant matrix deformation (Fig.6(b), Fig.7(b)). Fiber surfaces in two cases

(a) Type-R, AFKF/PP composites.

(a) Type R, GFKF/PP composites. 100 μm

(b) Type-G, AFKF/PP composites.

Fig.6. SEM micrographs of fracture surfaces of AFKF/PP composites for both Type-R and Type-G on tensile side.

(b) Type-G, GFKF/PP composites.

Fig.7. SEM micrographs of fracture surfaces of GFKF/PP composites for both Type-R and Type-G on tensile side.

(a) Type-R

(b) Type-G

Fig.8. SEM micrographs of fracture surfaces showing fiber/matrix adhesion of GFKF/PP, (a) Type-R and (b) Type-G.

rapid and gradual cooling conditions of both composites were also observed by using SEM. It is clear that some small pieces of matrix resin like small heaps were attached to glass fiber surfaces of Type-R of GFKF/PP composites (Fig.8 (a)) whereas the fiber surface of Type-G looks rather clean and smooth (Fig. 8(b)) as none of small matrix pieces were attached. Hence, little or non-retention of the matrix on the fiber surface shows the poor adhesion between fiber and matrix especially between aramid fiber and matrix resins.

4. CONCLUSIONS

The results described above have shown the effects of the cooling conditions on flexural properties of aramid fiber and glass fiber knitted fabric reinforced thermoplastic polypropylene composites (AFKF/PP and GFKF/PP). The cooling conditions had a little effect on flexural properties. The thermal properties indicated that the melting temperature and the crystallization temperature of the matrix resins were not affected by cooling conditions. Crystallinity was lower in rapid cooling than gradual cooling and the flexural properties were little sensitive to the level of crystallinity in the matrix resin. SEM micrographs of the fracture surfaces revealed poor fiber/matrix adhesion.

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