NOTE

Flexural Behavior of Unidirectional Polyethylene–Carbon Fibers–PMMA Hybrid Composite Laminates

INTRODUCTION

High-performance polyethylene fibers (PEF) are currently produced by solution (gel) spinning of ultrahigh molecular weight polyethylene and possess unique mechanical properties in terms of high strength-to-weight ratios and stiffness-to-weight ratios.[1] Moreover, these PEF possess a relatively high energy to break compared with glass, aramid, and carbon fibers (CF).[2] Because of these unique properties, PEF has a high potential for use in composite structures. Unfortunately, however, the low shear and flexural strength associated with PEF is one of the major limitations for its use in certain composite applications. CF are well known for their high specific strength and stiffness both in tension and in compression. Therefore, CF are being used in combination with PEF to obtain a good balance of flexural behavior.

A few workers have used PEF as one of the reinforcing fibers in hybrid composites, but these works are mainly based on a thermoset matrix.[2-7] Composites based upon thermoplastic polymeric matrices potentially offer several advantages compared with those based upon thermosetting resins.[8,9] Thus, one could expect a unique structural material based on poly(methyl methacrylate) (PMMA), a thermoplastic polymer, as the matrix in PEF/CF-reinforced composite.

The present work reports the unidirectional (UD) laminates based on PEF and CF and their hybrid with partially polymerized methyl methacrylate (MMA) well below the softening point of PEF. The work carried two objectives: (1) to obtain flexural properties of UD laminates cast from MMA–PEF, MMA–CF, and MMA–PEF/CF (hybrid) and (2) to study the role of PEF ply/plies in the hybrid laminates toward the flexural and interlaminar shear strength (ILSS) behavior, depending on the relative position of the ply/plies.

EXPERIMENTAL

MMA (Western Chemical Corp., Calcutta, India) was purified by a standard technique[10,11] and benzoyl peroxide

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(Bz_2O_2) was recrystallized from chloroform[12] and dried in a vacuum. The purification of *N,N*-dimethylaniline (NDA) was achieved by distillation under reduced pressure before use.

The PEF (spectra 900, Allied-Signal Corp., Petersburg, USA) used for the preparation of composites were surface-treated with chromic acid following Refs. 2, 13, and 14. The surface of CF (Indcarf-30, 6K, IPCL, Boroda, India) was already treated by a standard treatment used directly for making composites. The wetting characteristics of PMMA on treated and untreated PEF and CF have been studied by contact angle determination.[15-17] Improved wetting was found when the treated fibers were investigated.

The UD plies were made on a glass sheet using partially polymerized MMA as the resin and an amine–peroxide (NDA–Bz_2O_2) initiator system in bulk at room temperature.[18-20] The preimpregnated plies were used to construct multiple-layer systems. Laminated structures were prepared by stacking these plies of PEF and CF unidirectionally in the mold and the composites were made using the same resin at room temperature until it solidified within the mold and shrinkage was controlled using extra resin in the mold. Finally, the composite was heated to a temperature of 55°C for a stipulated time to ensure the completion of MMA polymerization.

UD laminates were prepared up to three plies for PEF (designated as S_1–S_3, respectively) and CF (designated as C_1–C_3, respectively). The nomenclature and geometry of the different hybrid laminates which were studied are given in Figure 1(a). The first and second digits within the brackets stand for the number of CF plies and PEF plies, respectively, present in those hybrid laminates. In the nomenclature, "*I*" is used for the hybrid laminates consisting of three plies in all: *I*(21) say, where the two CF plies have been placed at one side ("*L*" side) and one PEF ply placed at the other side ("*U*" side). Similar nomenclature was used for sample *I*(12). When a single type of ply, either CF or PEF, is placed in between the two plies of PEF or CF, respectively, the "*CS*" nomenclature is given to them. When a load was applied to the specimen such as *I*(21) on the "*U*" side, the sample is designated as *I*(21)/*U*. When the load direction is reversed such that it is applied on the "*L*" side, then the sample is designated as *I*(21)/*L* [Fig. 1(b)]. Similar nomenclature is applied for sample *I*(12). It may be noted that both sides are equivalent for samples *CS*(21) and *CS*(12). Samples for measurements

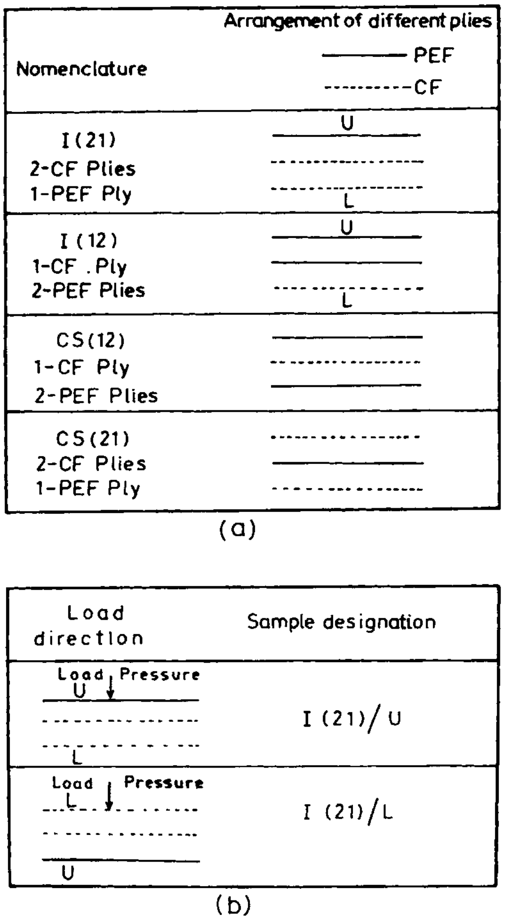


Figure 1 Schematic representation of hybrid laminates: (a) nomenclature and geometry of hybrid laminates; (b) load direction with sample designation.

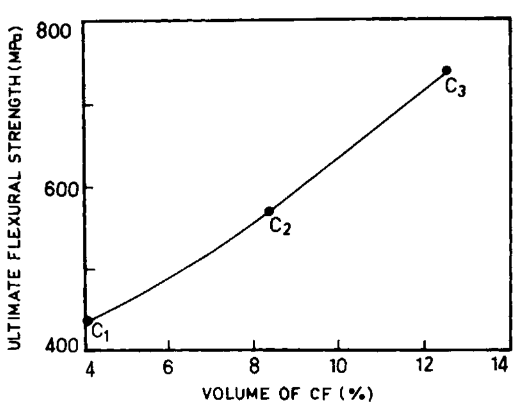


Figure 2 UFS dependence on volume (%) of CF. C_1 to C_3 are one to three ply laminates, respectively.

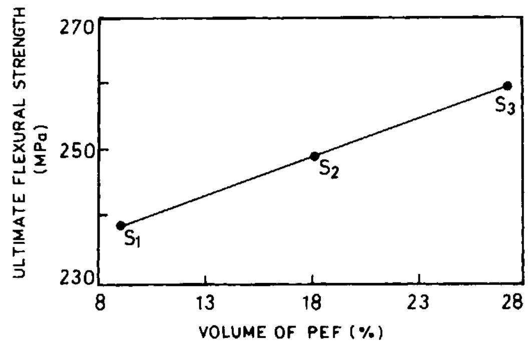


Figure 3 UFS dependence on volume (%) of PEF. S_1 to S_3 are one to three ply laminates, respectively.

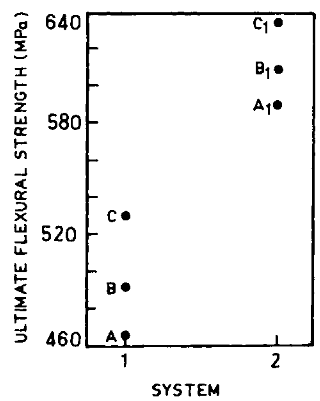


Figure 4 Plot of UFS vs. systems 1 and 2. System 1: (*A*) *I*(12)/*U*; (*B*) *CS*(12); (*C*) *I*(12)/*L*. System 2: (A_1) *I*(21)/*U*; (B_1) *CS*(21); (C_1) *I*(21)/*L*.

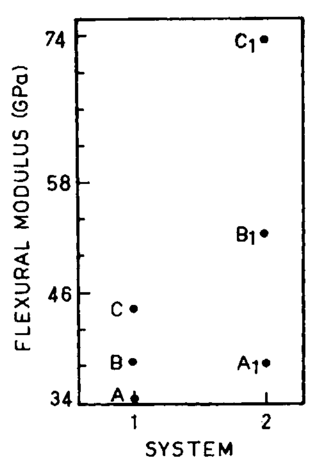


Figure 5 Plot of FM vs. systems 1 and 2 (same as Fig. 4).

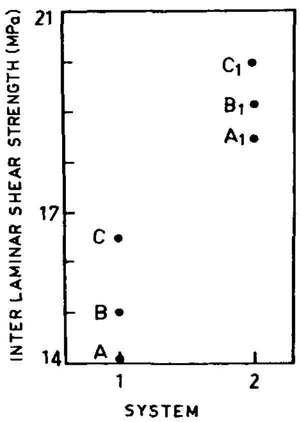


Figure 6 Plot of ILSS vs. systems 1 and 2 (same as Fig. 4).

were cut to dimensions of 80 × 10 × 1.7 mm (for flexural tests) and 21 × 10 × 3 mm (for ILSS tests).

All measurements were performed on an Instron universal testing machine (Model 4301). A strain rate of 5 mm/min was used throughout the investigation. The flexural properties of the composites were measured in a three-point bending mode, the direction of reinforcement lying perpendicular to the loading and support rods. The span length of 40 mm was fixed in all measurements except for the ILSS test. ILSS was measured with a span-to-depth ratio of 5 : 1. In all cases, 12 specimens were tested and average values are reported.

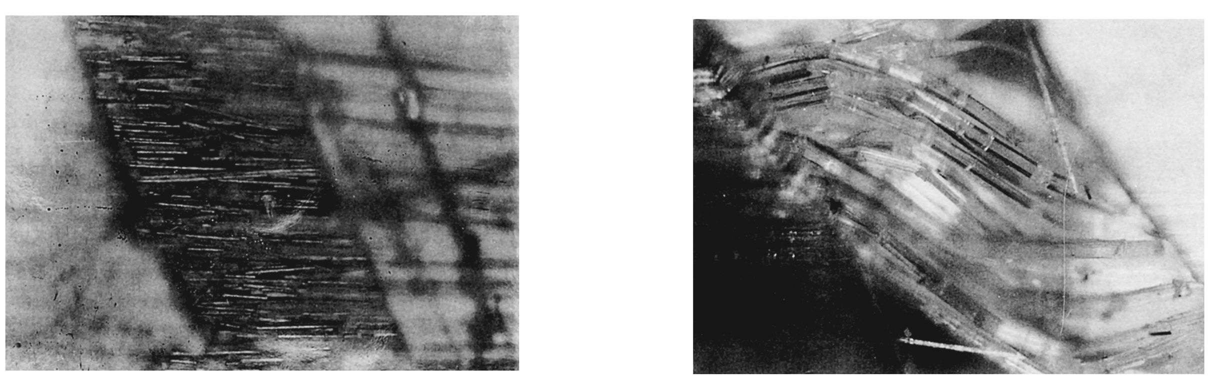
RESULTS AND DISCUSSION

The ultimate flexural strength (UFS) of CF–PMMA and PEF–PMMA laminates were increased with the volume of the respective fibers in an almost linear manner (Figs. 2 and 3). The ultimate failure is governed by tension-side failure of the laminates. The UFS increases linearly with volume fraction of fibers following the rule-of-mixture failure law. An interesting feature of the present study is that the flexural behavior remarkably changed when the relative position of the PEF and CF ply/plies are altered in the hybrid laminates.

In Figure 4, the UFS is plotted against Systems 1 and 2. When two PEF plies and one CF ply are used together in different positions (system 1), the UFS increases from 466 ± 11 MPa [*I*(12)/*U*] to 530 ± 10 MPa [*I*(12)/*L*], whereas sample *CS*(12) showed an UFS of 491 ± 12 MPa. For system 2 (one PEF ply and two CF plies are used), the UFS of the hybrid laminate increases from 591 ± 13 MPa [*I*(21)/*U*] to 635 ± 14 MPa [*I*(21)/*L*], whereas sample *CS*(21) showed an UFS of 609 ± 11 MPa.

From the above studies, it may be concluded that when load pressure is applied to the side containing PEF ply/plies of hybrid laminates, the UFS always remains at a lower value. If the case is just reversed, UFS shows a higher value compared to the former one. When load pressure is applied through the crosshead to the beam, the load is transferred to the outermost layer (tension side) from the compression side; as a result, maximum fiber stress at failure occurs on the tension side. When CF ply/plies are present at the tension side of the hybrid laminate, the composites fail mainly due to the brittle nature of the CF. If the PEF ply/plies are present at the tension side, the UFS increases due to the ductile nature of the PEF filled layer or layers.[19]

The flexural modulus (FM) of the hybrid laminates is presented in Figure 5; the trend of variation of the FM with systems 1 and 2 is found to be similar to that of Figure 4. The hybrid laminates are stiffer when load pressure is applied to the side containing CF ply/plies, i.e., PEF ply/plies are present at the tension side. These facts may be explained by the load (stress) absorption characteristics of PEF compared with CF in hybrid laminates. When PEF ply is on the tension side, it absorbs the applied stress, causing the enhancement of the FM,[19] whereas



(a) (b)

Figure 7 Optical micrographs of the fracture surface: (a) CF at outermost side; (b) PEF at outermost side.

when CF is on the tension side, it cannot readily absorb the applied stress and transmit it to the composites, owing to its brittle nature.

The above experimental results may also be understood by following the ILSS test of the hybrid laminates of systems 1 and 2 (Fig. 6). The nature of ILSS remains unaltered to that of Figure 4.

Figure 7 represents the optical micrographs of fracture surfaces of the hybrid laminates. When the CF is at the outermost side, ultimate failure occurs mainly because of the fiber failure [Fig. 7(a)]. But in the case when PEF ply is at the outermost side, fibers do not fracture but extension and buckling takes place; the fracture mode is due mainly to matrix cracking[19] [Fig. 7(b)].

CONCLUSIONS

From the above studies, the following conclusions may be drawn:

1. Addition of PEF ply/plies to the tension side results in structural hybrid laminates exhibiting a significantly better resistance to failure compared with the system where CF ply/plies are present on the tension side.
2. The flexural fracture mode of CF can be minimized by placing PEF ply/plies at the outermost side of the hybrid laminates.

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