Hybrid fiber-reinforced composite with carbon, glass, basalt, and para-aramid fibers for light use applications

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Abstract

This study explores the possibility of incorporating carbon fibers (CFs), basalt fibers, glass fibers, and para-aramid reinforcement fibers into carbon fiber–reinforced composites for light use applications. Hybrid composites can overcome the weakness of CFs and provide flexibility to design materials with the desired properties. The mechanical properties (tensile, flexural, and puncture impact properties) of the prepared hybrid composite were evaluated according to the standards ASTM D3039, ASTM D790, and ISO 6603-2, respectively. The inherent properties of reinforcement fibers, weaving density, and impregnation of a thermoplastic matrix into the composite considerably impact the mechanical performance of the hybrid composite materials.

1. Introduction

Fiber-reinforced composite materials are in high demand in today’s material design owing to their outstanding properties, particularly excellent mechanical characteristics in terms of material toughness [1]. Carbon fiber–reinforced plastics (CFRPs) are the most widely used composite materials in high-end structures in the energy, construction, and transportation industries, owing to their remarkable stiffness and strength [2–4]. When CFRPs replace iron and steel in vehicles, several to tens of percent weight reduction can be achieved, affording improved energy efficiency. However, the brittleness, low fracture energy, and high cost of CFRPs have hindered their extensive application in structural materials, particularly for mid- or low-end products [5].

Hybrid composites can overcome these shortcomings and provide flexible design materials with the desired properties [5]. More than one type of reinforcement is introduced into the matrix of hybrid composites to compensate for the weakness of single-composite materials. Moreover, hybrid composites exhibit excellent mechanical properties, such as strength, stiffness, and toughness, and are cost-effective. The reinforcement material, waving pattern, and architecture are important factors for designing composite materials [6–8]. Combining different reinforcement materials can provide optimum inherent characteristics of individual materials as well as their synergistic effects. Compared with unidirectional fiber-reinforced composites based on interlaced warp and weft yarns, woven fabric composites show better mechanical properties and impact resistance along both in–plain and transverse directions [9]. The effect of the number of fabric layers, stacking sequence, and orientation of layers on mechanical properties has also been demonstrated in the literature.

Several studies have been conducted on hybrid fiber-reinforced composites using a combination of carbon fibers (CFs) [5, 10–12], glass fibers (GFs) [7, 13–15], basalt fibers (BFs) [6, 16–18], and para-aramid fibers [19, 20] as reinforcement materials with different weaving patterns, such as satin, plain twill, and three-dimensional (3D)-braided, and different polymer matrices to achieve the desired properties.

In this study, we prepared four hybrid composites using a combination of different reinforcement materials with polyamide 6 (PA6) as the common matrix. CFs were used in the warp in all the composites, and CFs, BFs, GFs, and p-aramid fibers were used in the weft. The effect of combining CFs, BFs, GFs, and p-aramid fibers on
the mechanical properties of the composites was investigated. This study aims to obtain thermoplastic composites for light use applications, such as mobile phone cases, electronic parts, and briefcases.

2. Materials and methods

2.1. Materials and fabrication

GF 12k (Toray, Japan), GF 600 tex (Owens Corning, USA), BF 1,200 tex (Kamenny Vek, Russia), and p-aramid fiber 1,500 D (DuPont, USA) were used as the reinforcement materials in the hybrid composites. PA6 powder (1011 grade, Hyosung, Korea) was used as the thermoplastic polymer matrix. The PA6 film was prepared in a twin-screw extruder machine (COLLIN Lab & Pilot Solutions, Germany) with an extruder temperature of 250 °C, a screw pressure of 36 bar, and a line speed of 3 m min^{-1}. The thickness and crystallinity of the prepared PA6 films were 100 μm and 9.8%, respectively.

The hybrid fabrics were woven in a dobby design (table 1 and figure 1). CFs were used in the warp in all the composites, and CFs, GFs, BFs, and p-aramid fibers were used in the weft. The weaving conditions were established based on a density of 400 g m^{-2}, similar to that of the most widely used CF 12k fabric. Based on this value, the warp was designed using 252 yarns and the 6.3 ends/inch warp density of 200 g m^{-2}, half the weight of the fabric to be woven. To evaluate the weft density, the density per inch was estimated using the weight of each yarn. Table 1 presents the detailed weaving design. For comparison, GF/GF, BF/BF, p-aramid/p-aramid fiber
The mechanical properties of the GF fabric composite were evaluated according to the standards ASTM D3039, ASTM D790, and ISO 6603-2, respectively. The specimens used in the mechanical testing were cut from the hybrid fabric composite using a router cutter. A minimum of five specimens was analyzed for each sample for all tests. The mechanical properties of the GF/GF, BF/BF, and p-aramid/p-aramid fiber woven fabrics are presented in the supplementary information (figures S2–S5).

3. Results and discussion

Figures 1 and 2 show the optical microscopic images of the woven hybrid fabric in the dobby design and its tensile strength. The dobby weave pattern is attributed to the usage of different fibers and can afford a unique pattern. It has different interlacing points between the fabrics, affording additional textures, and the gap between the warp and weft yarns in the woven hybrid fabric is not too tight compared with the plain weave pattern (figure 1).

The tensile strength of the reinforcement fibers and woven hybrid fabrics along the warp and weft directions is listed: CF (1,029 N), GF (259 N), BF (766 N), p-aramid fiber (312 N), CF/GF (11.06 and 9.92 kN), CF/GF (11.21 and 4.40 kN), CF/BF (13.21 and 5.75 kN), and CF/p-aramid fiber (9.10 and 13.69 kN). The tensile properties of the CF/GF and CF/BF hybrid fabrics were similar or higher than those of the CF/GF woven fabric along the warp direction. Alternatively, the CF/p-aramid fiber hybrid fabric showed a lower tensile strength value. This finding is possibly attributed to the influence of the weft density and properties of the reinforcement fiber itself. Because the interlacing point of the fabric changed depending on the weft density, more bending corresponded to a higher weft density [21]. Consequently, the number of stress points increased, yielding the inferior tensile properties of the CF/p-aramid fiber hybrid fabric compared to the CF/GF hybrid fabric. The tensile strength of the woven fabrics along the weft direction was affected by the type of reinforcement fiber. However, in the case of the CF/p-aramid fiber woven fabric, the weft density was considerably higher than those of the other three woven fabrics, achieving the highest tensile strength value. The tight gap between the warp and weft yarns in the woven fabric provided a considerably more consistent transfer of stress in the woven fabric. Furthermore, the stiff CF can help resist the breaking of the ductile reinforcement fiber [22]. Therefore, the woven hybrid fabrics showed enhanced tensile properties, and each reinforcement fiber itself showed a lower tensile strength than the CF.

Next, the prepared woven hybrid fabrics were subjected to a molding process to afford the hybrid composite. They were compacted under pressure and at a temperature above the $T_m$ of the PA6 film (220 °C). The molten PA6 component flowed into and impregnated the woven hybrid fabrics. Compared to thermosets, molten
thermoplastics exhibit high viscosity, owing to which impregnating them with reinforcement fibers is difficult. Figure 3 shows the optical microscopic and SEM images of the cross-section of the final composite with a fiber-to-matrix weight ratio of 4:6. In the case of fiber-to-matrix weight ratios of 6:4 and 5:5 adopted in previous research, PA6 was insufficient to properly impregnate the fabrics, and the resin was concentrated on one side. The prepared hybrid composites with a fiber-to-matrix weight ratio of 4:6 showed improved PA6 impregnation into the woven hybrid fabrics. The density of the woven fabric and the thickness of the reinforcement fibers considerably impact the penetration of resin into the woven fabric and interlayer yarns. The CF/ BF composite showed a low impregnation level owing to the high thickness of the BF (1,200 tex). Alternatively, the CF/p-aramid fiber composite exhibited the highest weft density and achieved a good impregnation level owing to the thin p-aramid fiber layer (1,500 D). The different thicknesses of reinforcement fibers and the weaving density afford uniform impregnation and distribution of thermoplastic resins in the final composite, which affected its mechanical strength. The thicknesses of the prepared CF/CF, CF/GF, CF/BF, and CF/p-aramid fiber composites with the fiber-to-matrix weight ratio of 4:6 were 0.83, 0.78, 0.78, and 0.85 mm, respectively.

The tensile strength and modulus of the hybrid composites were characterized using a universal testing machine based on ASTM D3039 (figure 4). The tensile strengths of the prepared CF/CF, CF/GF, CF/BF, and CF/p-aramid fiber hybrid composites along the warp direction were 451, 455, 377, and 417 MPa, respectively, and those along the weft direction were 419, 194, 213, and 315 MPa, respectively. The inherent properties of the reinforcement fibers and the impregnation of the thermoplastic matrix into the composite considerably impacted the mechanical properties of the composite materials. The results show a similar trend to that of the woven fabrics. Compared to the other reinforcement fibers, the relatively poor impregnation level in the CF/BF composite afforded decreased tensile properties. The thickness of the BF made it difficult to flow the molten resin into the interlayer yarns and to transfer stress in the composite. The tensile modulus is obtained by dividing the applied force by the deformation occurring in the specimen. A high tensile modulus corresponded to high stiffness. The tensile modulus also exhibited the same trend as the tensile strength. The tensile moduli of the
prepared CF/CF, CF/GF, CF/BF, and CF/p-aramid fiber hybrid composites along the warp direction were 25.5, 29.2, 26.9, and 33.7 MPa, respectively, and those along the weft direction were 24.9, 9.91, 9.81, and 13.6 MPa, respectively. The CF/CF composite achieved a higher tensile modulus along the weft direction because the CF is more stiff than the other reinforcement fibers.

To use a thermoplastic prepreg for various purposes, determining the flexural property data on how much load it can withstand is important. Three-point bending tests were performed according to ASTM D790 with a crosshead speed of 1.7 mm min$^{-1}$. The flexural properties exhibited the same trend as the tensile properties (Figure 5). As expected, the highest flexural strength of 232 MPa along the weft direction was achieved by the CF/CF hybrid composite. Furthermore, the flexural strength of 70.4 MPa was achieved by the CF/BF hybrid composite. Because the CF showed good resistance to mechanical stress and the CF/CF hybrid composite showed good adhesion between the CF and PA6 matrices, it could promote load transfer in the hybrid composite. The inherent brittle characteristic and relatively low impregnation level of the BF yielded the low flexural properties of the CF/BF hybrid composite. The addition of the p-aramid fiber into the CFRP structure facilitated to improve flexural properties. When the failure strain of the brittle CF reinforcement is reached in the hybrid structure, the load would be transferred to the ductile p-aramid fiber reinforcements [23].

The puncture impact behavior of the composites was determined using a CEAST 9350 drop tower impact system with the impact velocity, falling height, and total mass of 4.4 m s$^{-1}$, 978.085 mm, and 20.41 kg, respectively. The specimen was punctured at the center using a striker along the perpendicular direction. Figure 6 presents the peak energy during the puncture test of the prepared hybrid composites. The PA6 matrix and interlaced reinforcement fibers facilitated impact energy diffusion and variations in the impact resistance. The highest puncture resistance achieved by the CF/BF composite could be attributed to the inherent high toughness of the BF, affording increased stability during the penetration process and consequently increasing the energy absorption of the CF/BF composite. The introduction of the p-aramid fiber into the CFRP structure resulted in improved impact resistance compared with the addition of the GF because of the high elastic modulus of the p-aramid fiber (23 g/D, provided by DuPont) and high weft density. The BF and p-aramid fiber
reinforcements could help the CF withstand penetration forces, inducing the high peak energy. These results confirmed the positive hybrid effect on the impact resistance of the composite.

4. Conclusion

This study explored the possibility of incorporating CFs, BFs, GFs, and p-aramid reinforcement fibers into the CFRP composite. The effect of combining CFs, BFs, GFs, and p-aramid fibers on the mechanical properties of the hybrid composites at the same weight was investigated. The inherent properties of the reinforcement fibers, weaving density, and impregnation of the thermoplastic matrix into the composite have a considerable impact on the mechanical properties of the hybrid composite materials. The mechanical properties of the prepared hybrid composite varied in terms of the tensile strength and modulus, flexural stress and modulus, and impact resistance. Results showed the importance of hybrid fiber-reinforced composites with CFs, GFs, BFs, and para-aramid fibers in imparting flexibility to the design of composite materials with the desired properties for light applications.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest

The authors declare no conflict of interest.

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