

Lightweight Poly(phenylene oxide)/Polyamide 6/Carbon Fiber Microcellular Composites with Enhanced Thermal Resistance and Electromagnetic Interference Shielding Performance

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Electronic Supplementary Information

Abstract Poly(phenylene oxide) (PPO), an engineering plastic with excellent comprehensive performance, faces significant processing challenges owing to its high melt viscosity, which severely limits its large-scale applications. The introduction of polyamide 6 (PA6) effectively improved its processability, but inevitably compromised the inherent heat resistance of PPO. In this study, high-modulus, heat-resistant, and electromagnetically shielded carbon fiber (CF)-reinforced PPO/PA6 (PPO/PA6/CF) microcellular composites were fabricated using chemical foaming injection molding. The effects of CF content on the foaming behavior, thermal properties, mechanical properties, and electromagnetic interference (EMI) shielding performance of the composites were systematically investigated. The results indicated that when the CF content was 5 wt%, the PPO/PA6/CF microcellular composite exhibited the optimal cell structure with an average cell diameter of 49.44 μm and a cell density of 3.48×10^6 cells/ cm^3 . In addition, the synergistic effect of the fiber network structure and improved crystallinity significantly enhanced the heat resistance of the PPO/PA6/CF foams. Compared with the PPO/PA6 foam, the PPO/PA6/CF foams exhibited an increase in heat deflection temperature (HDT) of 84.7 °C, reaching 181.2 °C, along with a flexural modulus as high as 8509.16 MPa and an EMI shielding effectiveness of 37.02 dB, demonstrating remarkable multifunctionality. This study provides a feasible pathway for the efficient and scalable production of lightweight PPO-based composites with superior thermal deformation resistance and EMI shielding performance.

Keywords Poly(phenylene oxide)/polyamide 6 (PPO/PA6) composites; Carbon fiber; Chemical foaming injection molding; Heat deflection temperature; Electromagnetic interference (EMI) shielding

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INTRODUCTION

Lightweight polymer foams have crucial applications in aerospace, automotive, and electronics, which require both light-weight and mechanical performance.^[1–4] However, conventional polymer foams often suffer from insufficient strength and poor thermal resistance, which restrict their applicability in high-temperature or load-bearing environments. The development of foamed materials that simultaneously offer low density, high mechanical modulus, and elevated heat deflection tem-

perature (HDT) remains a significant challenge, particularly for high-viscosity engineering polymers.^[5–8]

Poly(phenylene oxide) (PPO) is an engineering thermoplastic with high chemical resistance and mechanical strength, making it an attractive candidate for advanced structural foams.^[9–11] Nevertheless, its inherently high melt viscosity significantly affects melt processing and foam formation. To improve its processability and expand the scope of its applications, PPO is frequently blended with other polymers such as polystyrene (PS),^[12–14] polyamide 6 (PA6)^[15,16] and poly(phenylene sulfide) (PPS).^[17] This helps achieve a balance between melt flow behavior, thermal resistance, and mechanical performance. Among these systems, PPO/PA6 blends have gained attention because of their balance of

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strength, toughness, and thermal resistance, offering potential for manufacturing structural foams. Several studies have focused on the preparation of PPO-based foams by employing physical foaming techniques, such as supercritical CO₂ batch foaming.^[18–21] However, this method generally suffers from low production efficiency and limited capability to manufacture complex geometries, which hampers its industrial scalability. Chemical foaming injection molding with core-back functionality has recently emerged as a promising manufacturing approach for highly productive microcellular polymer foams with complex geometries.^[22,23] For example, PPO/PA6 microcellular foams prepared by injection foaming using a blend of two chemical blowing agents have shown improved toughness and balanced mechanical properties.^[24] However, the heat deflection temperature of this PPO/PA6 microcellular foam remained typically below 100 °C, limiting its applicability in high-temperature environments.

Fiber reinforcement is an effective strategy for overcoming the strength-thermal resistance trade-off in polymer composites and achieving multifunctional integration.^[25,26] Particularly, carbon fibers (CFs) have been widely used in polymer composites because of their high modulus, excellent thermal stability, and electrical conductivity.^[27–30] In melt-processing systems, CFs can not only enhance the load-bearing capability but also act as a heterogeneous nucleating agent that promotes polymer crystallization and restricts chain mobility. Recent studies^[31,32] further suggested that fiber redistribution may occur owing to cell growth and melt flow during the foaming process. This could potentially lead to the formation of interconnected fiber networks along the cell walls. This foaming-induced CF rearrangement significantly affected the mechanical performance and thermal stability of the foamed composites.

In this study, lightweight, high-modulus, heat-resistant, and electromagnetic interference (EMI) shielding PPO/PA6/CF microcellular composites were prepared using chemical foaming injection molding technology. The influence of CF on the crystallization, melt viscoelasticity, and cell morphology of PPO/PA6 was systematically investigated. The mechanical properties, HDT, and EMI shielding performance of the PPO/PA6/CF microcellular composites prepared with similar weight reduction rates were evaluated. This study provides an effective strategy for designing lightweight PPO-based composites with enhanced strengths and thermal resistances for advanced structural applications.

EXPERIMENTAL

Materials

Poly(phenylene oxide) (PPO, LXR040, $\rho=1.06$ g/cm³) was obtained from Nantong Xingchen Synthetic Materials Co., Ltd., Ruicheng. Polyamide 6 (PA6, M32800, $\rho=1.14$ g/cm³) was purchased from Guangdong Xinhui Meida Nylon Co., Ltd. Maleic anhydride-grafted PPO (MAH-*g*-PPO, Fine-Blend® FB820, $\rho=1.06$ g/cm³), with a grafting degree of 0.5 wt%–1.0 wt%, was supplied by Jiayirong Polymer (Shanghai) Co., Ltd. A toughening agent (A659, $\rho=1.05$ g/cm³) was purchased from Guangdong Jindaquan Technology Co., Ltd. Carbon fiber (CF) masterbatch (SP600-CG80, 40 wt% CF in a PA6 matrix) was provided by Kingfa Science and Technology Co., Ltd. The foaming masterbatch (F-5160 (F-5160)), which primarily generates N₂ and has a

gas evolution of 25 mL/g, was purchased from Yonghe Fine Chemical (Changshu) Co., Ltd.

Preparation of PPO/PA6 Composites

PPO and PA6 were dried in an oven at 120 and 105 °C, respectively, for 4 h. PPO, PA6, toughening agent, and MAH-*g*-PPO were then uniformly mixed and compounded using a co-rotating twin-screw extruder (CTE35, screw diameter: 35.6 mm; Coperton Keya Machinery Co., Ltd. Nanjing, China).^[24] The extrusion temperatures from the hopper to die were set as 230, 240, 245, 250, 255, 250, 240, and 230 °C. The screw speed was maintained at 300 rpm and the feeding rate was 12 r/min to obtain homogeneous PPO/PA6 composites.

Preparation of Foamed PPO/PA6/CF Samples

The PPO/PA6 particles and CF masterbatch were separately dried at 105 °C for 4 h prior to processing. The dried PPO/PA6 particles and the CF masterbatch were then blended according to the formulations listed in Table S1 (in the electronic supplementary information, ESI). This was followed by adding 2.5 wt% foaming masterbatch. The mixture was compounded uniformly and fed into an injection molding machine (EM120-V, Chen Hsong Machinery Co., Ltd.) with core-back functionality to produce PPO/PA6/CF foamed samples with varying CF contents (Fig. 1a). During the core-back process, the cavity thickness was initially set to 3.4 mm, and then expanded to a final thickness of 4 mm (Fig. 1b). The foamed samples were obtained after cooling (Fig. 1c). The processing parameters are summarized in Table S2 (in ESI). For comparison, the unfoamed PPO/PA6/CF composites were prepared under identical conditions, without the addition of a foaming masterbatch. All the samples were conditioned at ambient temperature for 48 h prior to characterization.

Characterization

Morphological analysis

Microstructural characterization of the PPO/PA6/CF samples was conducted using scanning electron microscopy (SEM, KYKY-EM6000, Beijing KYKY Technology Co., Ltd.). The samples were first immersed in liquid nitrogen for 4 h, then removed and immediately fractured. After allowing the fracture surfaces to dry naturally, they were sputter-coated with gold for 120 s and then placed in the SEM apparatus for observation. Additionally, the foamed samples were chemically etched by placing them in formic acid at room temperature for 5 min to expose the morphology of the CF and gain an insight into its 3D network structure. This process involved partial removal of PA6 without the dissolution of PPO matrix. Finally, the etched samples were sputter-coated with gold and analyzed using SEM. Cell size and cell density were measured using image analysis software. The cell density (N_0) was calculated using Eq. (1):

$$N_0 = \left(\frac{n}{A}\right)^{\frac{3}{2}} V_f \quad (1)$$

where n is the number of cells in the SEM image, A is the actual area of the image (cm²), and V_f is the volume expansion ratio (VER) of the sample, determined by Eq. (2)^[34]:

$$V_f = \frac{\rho_0}{\rho_f} \quad (2)$$

where ρ_0 and ρ_f are the apparent densities of the sample before and after foaming, respectively. Density measurements were performed using a pycnometer (PTX-FA210S, Huazhi (Fu-

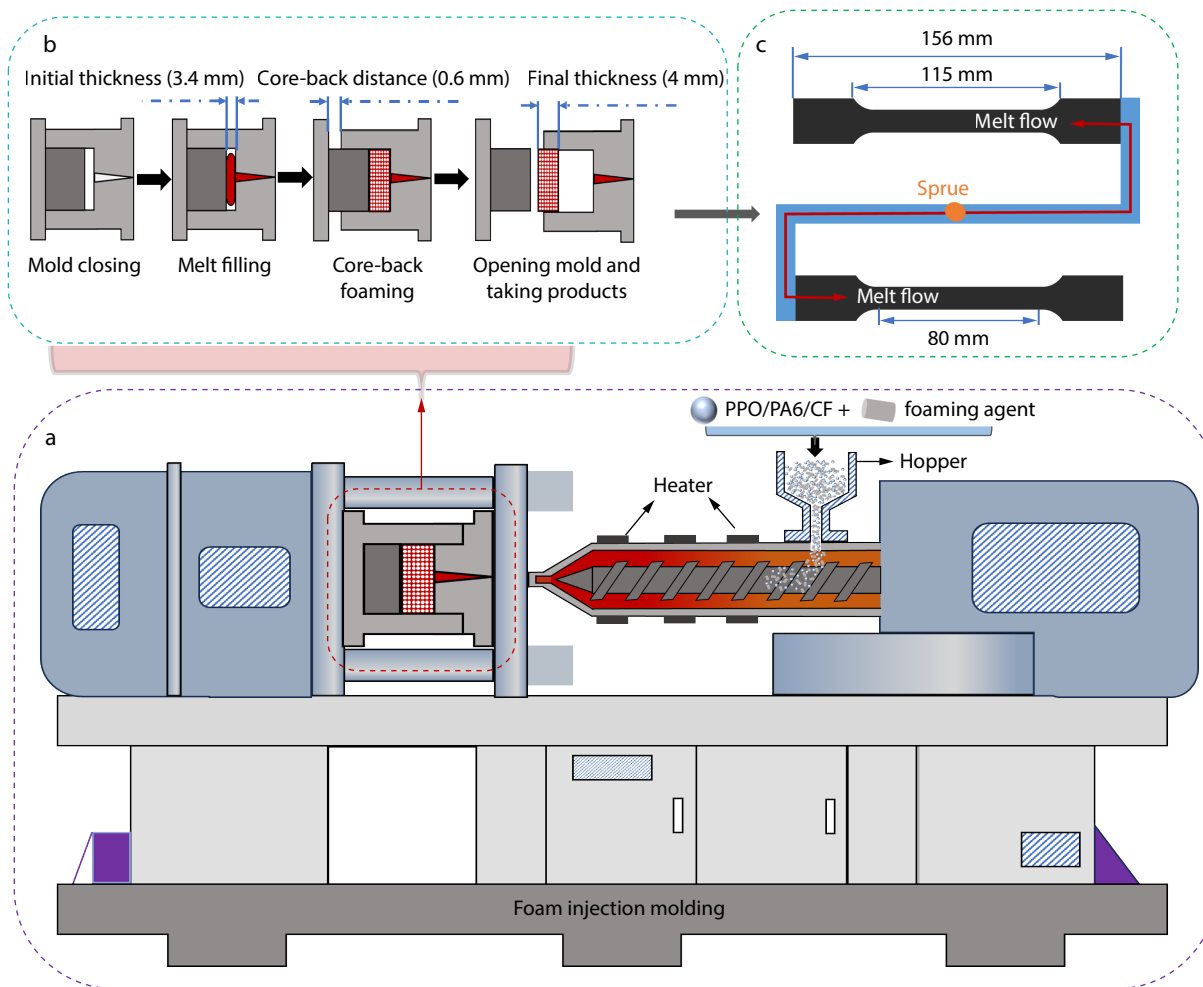


Fig. 1 Schematic illustration of the preparation process of the foamed PPO/PA6/CF sample:^[33] (a) injection molding device, (b) core-back process, (c) foamed sample.

jian) Electronic Technology Co., Ltd.), and the average value from five replicates was reported.

Rheological properties

Rheological testing was conducted using a rotational rheometer (MARS 60, Thermo Fisher Scientific) in oscillatory frequency sweep mode. Tests were conducted at 255 °C at a constant strain of 1% over a frequency range of 0.1–100 Hz. The samples were tested for complex viscosity (η^*), storage modulus (G'), loss modulus (G''), and loss factor ($\tan\delta$) of different samples as functions of frequency.

Differential scanning calorimetry (DSC)

DSC (TA Q25, TA Instruments, USA) was employed to study the effect of CF content on the crystallization and melting behaviors of the unfoamed and foamed PPO/PA6/CF samples. Approximately 5–10 mg of each sample was sealed in an aluminum crucible, heated from room temperature to 260 °C at 10 °C/min and held at 260 °C for 5 min to eliminate the thermal history. Subsequently it was cooled to 30 °C at a rate of 10 °C/min. Then reheat the samples to 260 °C at a rate of 10 °C/min. The degree of crystallinity (X_c) was calculated using Eq. (3):

$$X_c = \frac{\Delta H_f}{\Delta H_f^* w} \times 100\% \quad (3)$$

where ΔH_f is the measured enthalpy of fusion (J/g), ΔH_f^* is the enthalpy of fusion for fully crystallized PA6 (230.1 J/g), and w is the weight fraction of PA6.

Mechanical properties

The tensile properties of the PPO/PA6/CF samples were measured using an electronic universal testing machine (CMT 6104, MTS Industrial Systems (China) Co., Ltd.) at a crosshead speed of 50 mm/min, according to ISO 527-2:2012. The flexural properties were determined at 2 mm/min following ISO 178:2019. Notched Izod impact tests were conducted at room temperature using a pendulum impact tester (ZBC-4B, Shenzhen SANS Measurement Technology Co., Ltd., China), according to ISO 180:2000. A cantilever beam pendulum type was selected. At least five specimens were tested per group, and their average values were reported.

Heat deflection temperature (HDT)

The HDTs were measured using a Vicat softening point tester (ZWK1302-B, MTS Industrial Systems (China) Co., Ltd.) under a load of 1.82 MPa, according to ISO 75-2:2003.

Electrical conductivity and electromagnetic shielding performance

The electrical conductivities of the foamed and unfoamed

PPO/PA6/CF composites were measured using a SM7110 super megohm meter (Hioki Company, Japan). The dimensions of each sample were 10 mm × 8 mm × 4 mm. EMI shielding performance of the foamed and unfoamed PPO/PA6/CF composites were measured in the X-band (8.2–12.4 GHz) using a vector network analyzer (N5225B, Keysight Technologies) via the waveguide method. The samples had dimensions of 22.8 mm × 10 mm × 4 mm.

RESULTS AND DISCUSSION

Distribution of CF in PPO/PA6/CF Composites

The dispersion, length, and interfacial adhesion of the CF within the PPO/PA6/CF composites are critical for the mechanical and thermal performance of the materials. Good dispersion of CF, effective encapsulation by the polymer matrix, and strong fiber–matrix interactions (both chemical and physical) facilitate efficient load transfer and the formation of a reinforcing network. Longer fibers undergo further interlocking to create a quasi-continuous skeleton capable of bearing an external load. Fig. 2 shows the cross-sectional SEM images of the PPO/PA6/CF composites. The incorporation of the MAH-*g*-PPO compatibilizer eliminated distinct phase boundaries, indicating an improved compatibility between PPO and PA6. The composite with 5 wt% CF showed a sparse distribution of fibers, along with holes left owing to the pull-out of CFs. Notably, the surrounding matrix was clearly pulled out along with the CFs, indicating strong interfacial interactions between the CFs and matrix. At 10 wt% CF, the CF content increased significantly and exhibited a relatively uniform distribution. With higher CF loading, the number of holes owing to the pull-out of the CF increased. Thus, the SEM images revealed that (i) the CF surfaces were uniformly coated with the matrix resin (green circles in Fig. 2f) and (ii) the matrix resin was pulled out from the holes left by the extraction of CF (orange circles in Fig. 2). These observations confirm the robustness of fiber–matrix adhesion, which is essential for enhancing the mechanical properties and eventually for the formation of foaming-induced fiber networks in microcellular foams.

Influence of CF Content on Rheological Behavior and Crystallization Behavior

CF acts as a rigid filler and alters the viscoelastic properties of the PPO/PA6 matrix. As shown in Fig. 3(a), across the tested frequency range, the storage modulus (G') of all the PPO/PA6/CF composites exceeds that of neat PPO/PA6. Interestingly, the composite with 5 wt% CF showed the highest G' at low frequencies, whereas higher CF loadings showed only a marginal increase. In Figs. 3(b) and 3(c), similar trends in the loss modulus (G'') and complex viscosity (η^*) are observed, wherein neat PPO/PA6 shows the lowest values, 5 wt% CF displays intermediate values, and the PPO/PA6 composites with 10 wt%–20 wt% CF have comparably higher values. This behavior could be attributed to the reduction of the PPO fraction at higher CF loadings, which partially offset the reinforcing effect of CF. Additionally, the loss factor ($\tan\delta$) provided insight into the elasticity and foamability: a lower $\tan\delta$ value corresponded to a higher elastic response and superior cell growth potential. As shown in Fig. 3(d), the composite with 5 wt% CF shows the lowest $\tan\delta$ value across the entire frequency range, indicating that it has optimal elasticity for foaming. Neat PPO/PA6 and the composite with 10 wt% CF display intermediate $\tan\delta$ values, whereas the composites with 15 wt%–20 wt% CF show higher $\tan\delta$ values, suggesting reduced elasticity and less favorable foamability. These results indicate that moderate CF loadings not only reinforced the matrix, but also facilitate efficient microcellular structuring by preserving the elasticity of the PPO/PA6 matrix.

Figs. 3(e) and 3(f) show the changes in the heat flow of the PPO/PA6 and PPO/PA6/CF composites during crystallization and melting, respectively. The crystallization temperature (T_c) increased from 189.53 °C (neat PPO/PA6) to 190.85 °C (20 wt% CF) with an increase in CF content, while the melting temperature (T_m) remained almost unchanged, as shown in Table 1. This indicated that CF mainly affected the crystallization kinetics rather than the crystal structure of PA6.^[35] Meanwhile, the melting enthalpy (ΔH_m) increased continuously from 27.43 J/g to 36.12 J/g, resulting in an increase in crystallinity (X_c) from 11.92% to 19.62%. This enhancement was attributed to the abundant polymer/fiber interfaces provided by CF, which reduced the energy barrier for crystal nucleation and

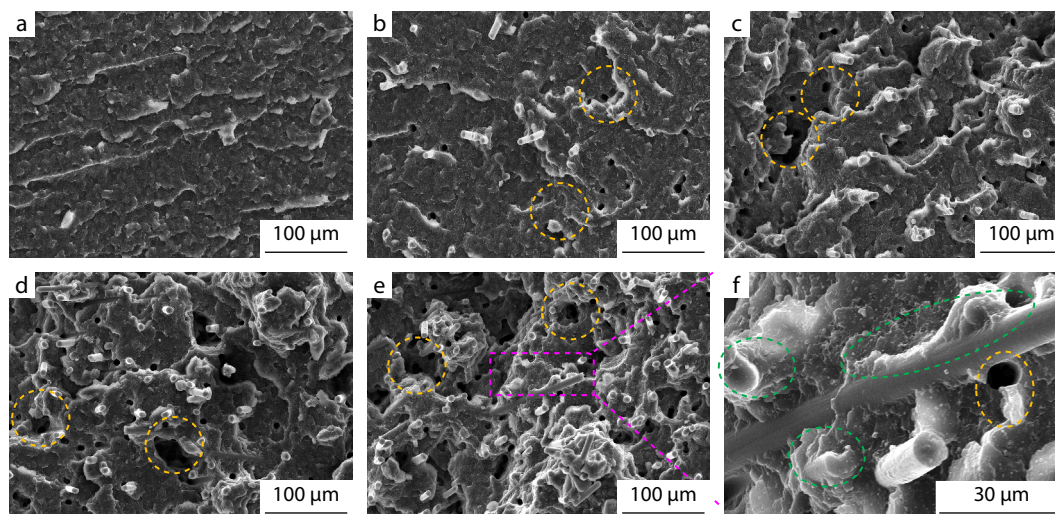


Fig. 2 Microstructural morphologies of PPO/PA6/CF composites: (a) PPO/PA6, (b) 5 wt% CF, (c) 10 wt% CF, (d) 15 wt% CF, (e) 20 wt% CF, and (f) local magnification of (e).

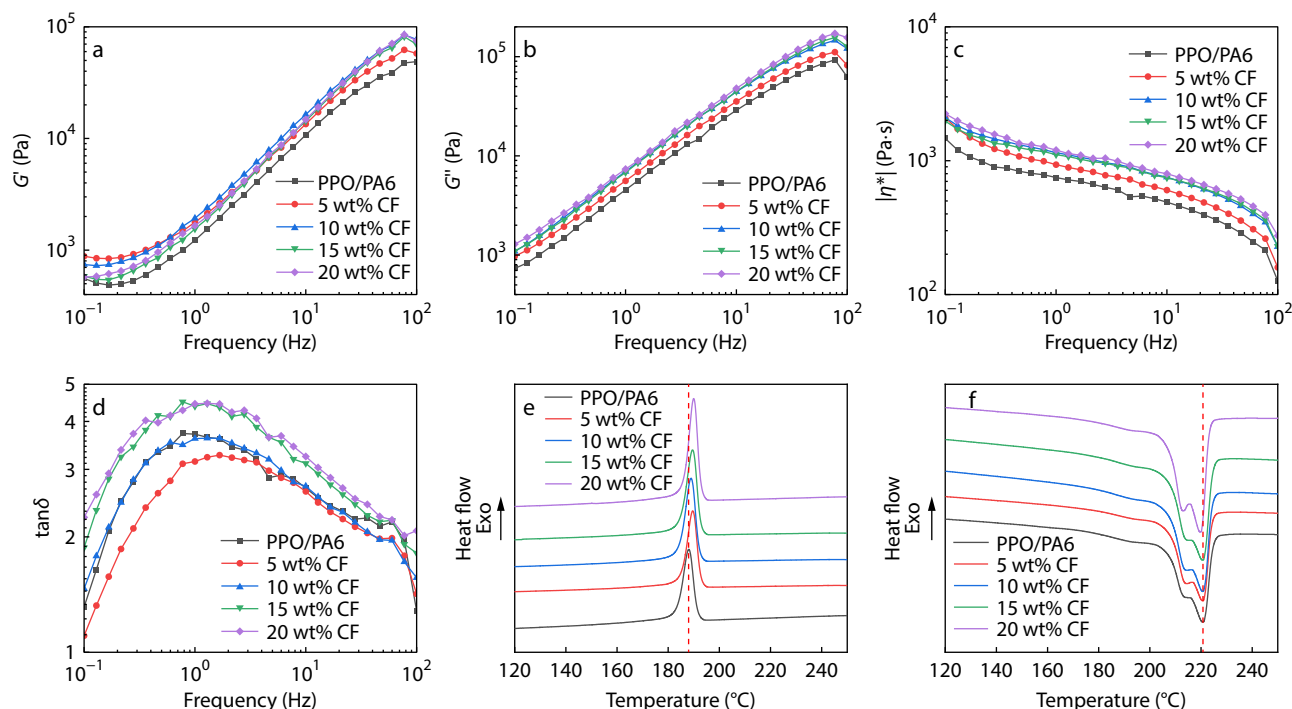


Fig. 3 Rheological properties of unfoamed PPO/PA6/CF composites: (a) storage modulus, (b) loss modulus, (c) complex viscosity, (d) loss tangent factor. DSC curves of unfoamed PPO/PA6/CF composites: (e) crystallization and (f) melting.

Table 1 Melt and crystallization parameters of PPO/PA6/CF composites.

Group	T_c (°C)	T_m (°C)	ΔH_m (J/g)	X_c (%)
PPO/PA6	189.53	221.17	27.43	11.92
5 wt%CF	189.76	222.03	30.88	14.13
10 wt%CF	190.38	221.24	31.7	15.3
15 wt%CF	190.42	221.48	34.61	16.71
20 wt%CF	190.85	220.82	36.12	19.62

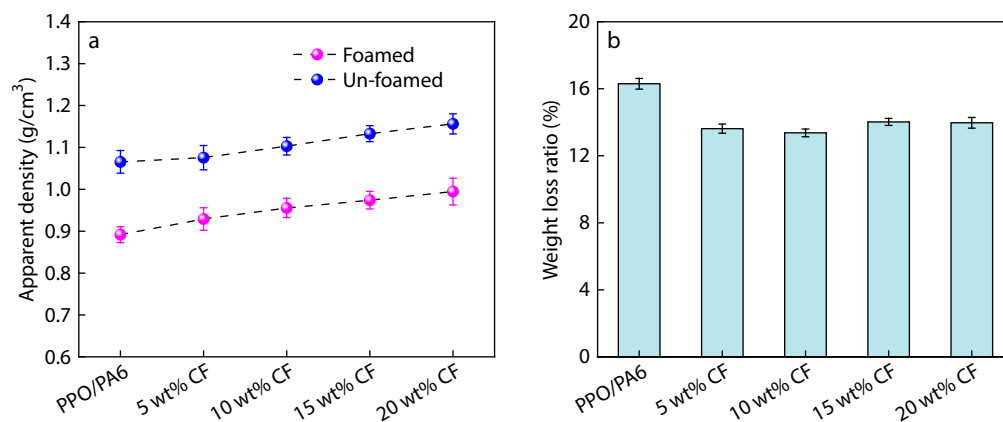


Fig. 4 (a) The apparent density of unfoamed and foamed PPO/PA6/CF composites; (b) Weight loss ratio of PPO/PA6/CF composite foams.

facilitated the formation of crystalline regions within the PA6 phase.^[32,36]

Influence of CF Content on Foaming Performance

The difference in the weight loss rate has a significant impact on the cellular structure and mechanical properties of the polymer foams.^[29,37] To ensure the reliability of the experimental results, the cavity thickness was consistently expanded from 3.4 mm to 4.0 mm in this study, thereby controlling the theoretical weight

loss rate of all foamed samples to approximately 15%. Fig. 4 shows the changes in the density of the unfoamed and foamed PPO/PA6/CF composites, as well as the actual weight loss rates of the foams. As shown in Fig. 4(a), the material density exhibits a linear increase with increasing carbon fiber content regardless of foaming. The nearly parallel trends indicated strong consistency in the weight loss rates across all samples. Notably, the foamed PPO/PA6 composite in Fig. 4(b) shows the highest

weight loss rate, reaching 16.3%. In contrast, the introduction of carbon fibers reduces the weight loss rate of the foamed PPO/PA6/CF composites to approximately 14%, which could be

attributed to the elevated melt viscosity caused by the CFs (Fig. 3c).

Figs. 5 and 6 present SEM images, cell diameter distribu-

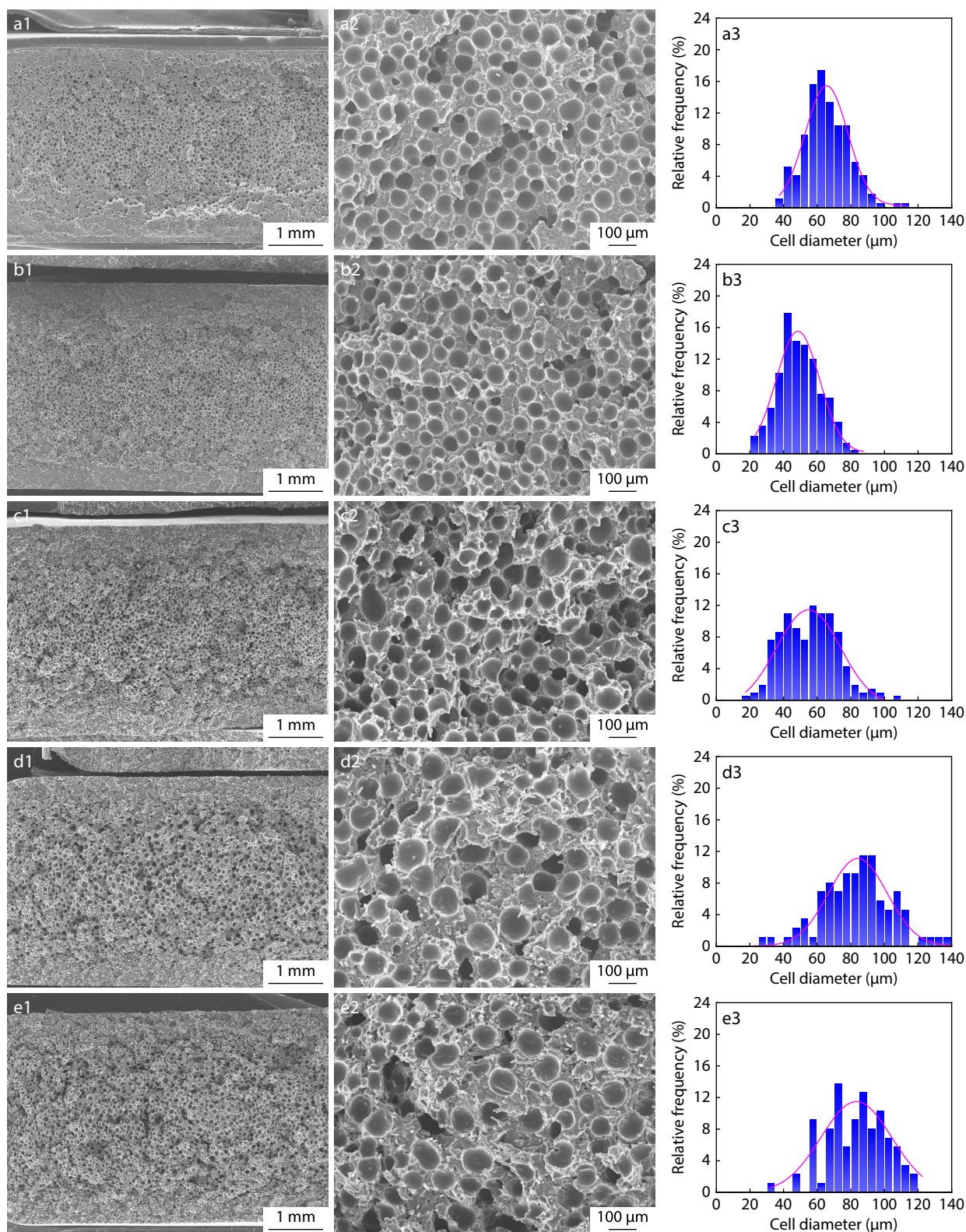


Fig. 5 SEM images and cell distribution of the foamed PPO/PA6/CF composites: (a1–a3) PPO/PA6, (b1–b3) 5 wt% CF, (c1–c3) 10 wt% CF, (d1–d3) 15 wt% CF, and (e1–e3) 20 wt% CF.

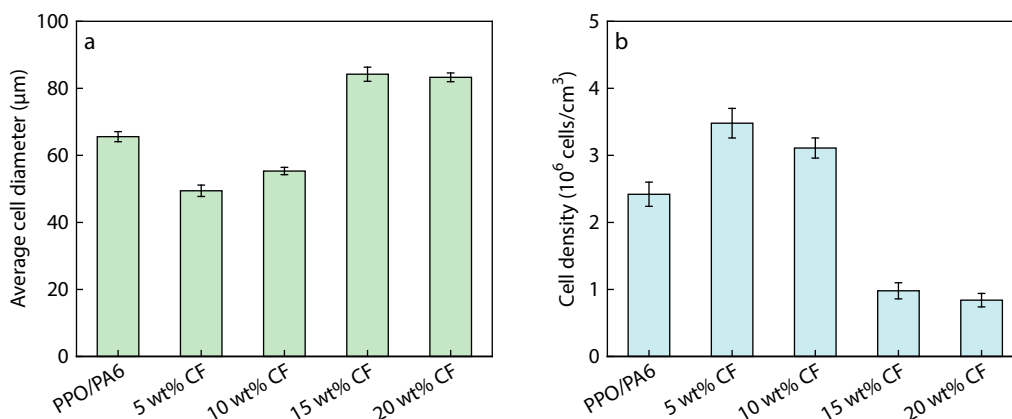


Fig. 6 (a) Average cell diameter and (b) cell density of the foamed PPO/PA6/CF composites.

tions, and quantitative information on the cell structure of the foamed PPO/PA6 and PPO/PA6/CF composites. The PPO/PA6 foam exhibited a regular and uniform cell morphology, with an average cell diameter of 65.58 μm and a cell density of 2.42×10^6 cells/ cm^3 . Evidently, the introduction of carbon fibers significantly influenced cell morphology. Compared with the foamed PPO/PA6, the addition of a small amount of CF (5 wt%–10 wt%) led to a marked increase in cell density, a reduction in cell diameter, and a more concentrated size distribution, indicating that an appropriate CF content effectively improved the cellular structure. For example, at 5 wt% CF, the average cell diameter decreased to 49.44 μm , and the cell density increased to 3.48×10^6 cells/ cm^3 . This was because the low fiber content was uniformly dispersed in the matrix, providing a large number of heterogeneous nucleation sites,^[38] which effectively decreased the nucleation energy barrier and promoted the formation of more cells. In addition, the physical entanglement between the CF and PA6 molecular chains moderately enhanced the melt strength and stabilized the cell walls, thereby suppressing excessive cell growth.^[39] However, as the CF content increased to 15 wt%–20 wt%, the cellular morphology gradually deteriorated, as evidenced by the broadening of the size distribution and the appearance of locally enlarged cells. Specifically, compared with the foamed composites containing 5 wt% CF, the cell diameters of the 15 wt% and 20 wt% CF foamed composites increased to 84.21 and 83.29 μm , respectively, while the cell densities decreased to 0.98×10^6 and 0.84×10^6 cells/ cm^3 , respectively. This change was attributed to the substantial increase in melt viscosity at high fiber contents, which hindered gas diffusion and induced localized gas accumulation, ultimately leading to the formation of fewer but larger cells.^[40]

Heat-resistant Performance of PPO/PA6/CF Composites

Engineering plastics used in aerospace, electronics, and automotive applications require a high resistance to thermal deformation. In this study, the heat deflection temperature (HDT) of the PPO/PA6 and PPO/PA6/CF composites was examined through thermal deformation testing, and the results are shown in Fig. 7(a). Compared to the HDT of 100 $^{\circ}\text{C}$ for the unfoamed PPO/PA6, the HDT of the foamed PPO/PA6 decreased to 96.5 $^{\circ}\text{C}$ because the cells reduced the load-bearing cross-sectional area and compromised the resistance to thermal deformation. No-

tably, when the CF content was below 15 wt%, the HDT of the foamed samples was lower than that of the unfoamed. However, when the CF content exceeded 15 wt%, the foamed samples exhibited a higher HDT than the unfoamed samples. Specifically, at a CF content of 20 wt%, the HDT of the foamed PPO/PA6/CF composite reached 181.2 $^{\circ}\text{C}$, representing an increase of 84.7 $^{\circ}\text{C}$ compared to the HDT of the foamed PPO/PA6. The substantial improvement in the HDT of the foamed PPO/PA6/CF composites is closely related to their crystallinity.^[41,42] With increasing CF content, the crystallinity of the foamed samples became higher than that of the corresponding unfoamed samples (Fig. 7b and Fig. S1 in ESI, Table 2). For instance, at 20 wt% CF, the crystallinity of the foamed PPO/PA6/CF composite was 22.17%, which was 13% higher than that of the unfoamed composite. This enhancement was ascribed to the heterogeneous nucleation effect of the CFs, which provided abundant nucleation sites and promoted the formation of PA6 crystals. Meanwhile, the biaxial stretching of the polymer matrix during cell growth facilitated molecular chain orientation, thereby accelerating the crystallization process upon cooling. The increased crystallinity increased the proportion of rigid crystalline regions, effectively restricted chain mobility, and thus enhanced the thermal deformation resistance of the composites. However, at CF contents below 15 wt%, the foamed composites exhibited lower HDT values than their unfoamed composites, despite their higher crystallinity. At low CF contents, the sparsely distributed CFs were insufficient to establish an effective load-bearing framework, whereas the introduced cells reduced the effective load-bearing cross-sectional area and promoted the local deformation of the cell walls as the matrix softens. Consequently, the structural weakening induced by foaming outweighs the beneficial effect of the increased crystallinity, resulting in a lower HDT. In contrast, at CF contents of 15 wt%–20 wt%, the enhanced fiber connectivity provided more effective load-transfer pathways and constrained the thermally induced deformation of the cellular structure. Together with the increased crystallinity, this reinforcement progressively compensated for the weakening effect of the cells, eventually resulting in a higher HDT than that of the corresponding unfoamed composites.

To further elucidate the mechanism, PA6 in the foamed PPO/PA6/CF samples was selectively removed by formic acid etching, and the SEM images are shown in Fig. 7(c) and Fig.

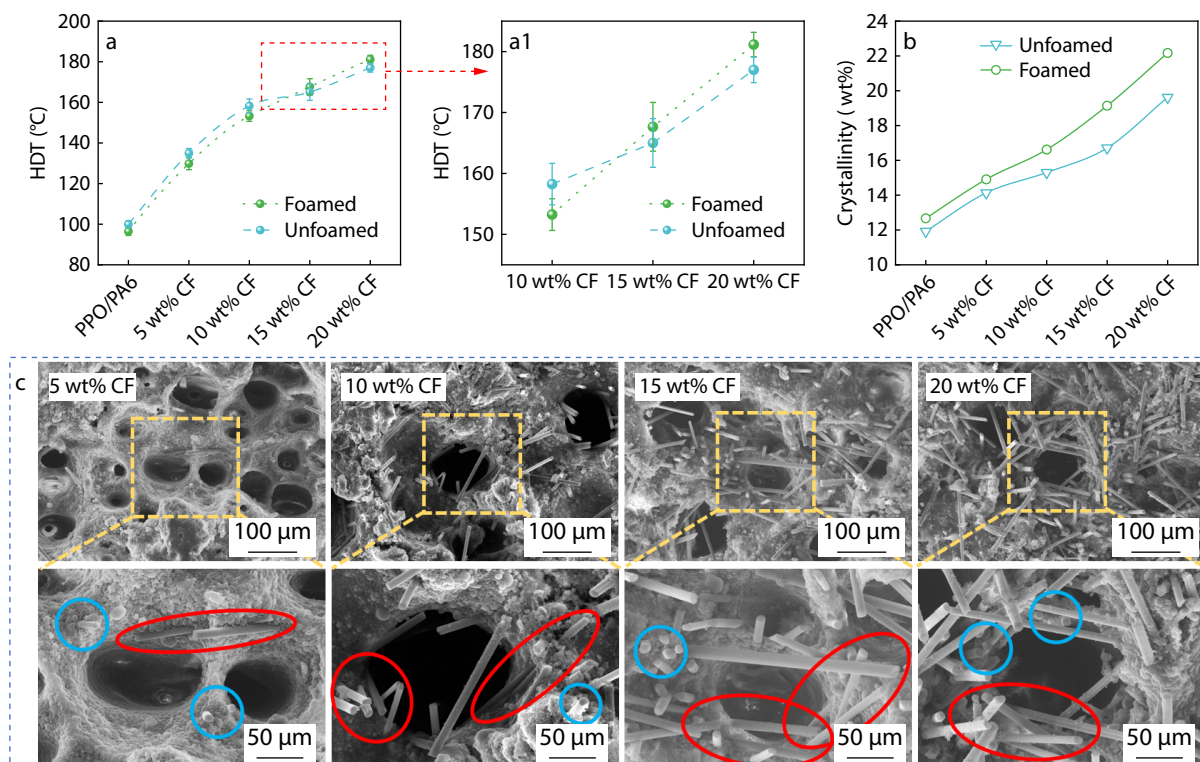


Fig. 7 Thermal properties of the unfoamed and foamed PPO/PA6/CF composites: (a, a1) heat deflection temperatures, (b) crystallinity, (c) CF three-dimensional network skeleton.

Table 2 HDT and crystallinity (X_c) of the foamed PPO/PA6/CF composites.

Group	HDT (°C), unfoamed	HDT (°C), foamed	X_c (%), unfoamed	X_c (%), foamed
PPO/PA6	100.00	96.45	11.92	12.67
5 wt% CF	134.95	129.85	14.13	14.91
10 wt% CF	158.25	153.25	15.30	16.63
15 wt% CF	165.00	167.65	16.71	19.14
20 wt% CF	177.00	181.15	19.62	22.17

S2 (in ESI). At low CF contents, the CFs were randomly dispersed in the matrix and primarily acted as isolated reinforcing units. As the CF content increased, cell expansion gradually pushed the CFs toward the cell walls, leading to the enrichment and interconnection of CFs around the adjacent cells. Particularly at CF contents of 15 wt%–20 wt%, a large number of CFs bridged across the cell walls, forming a continuous three-dimensional load-bearing skeleton (Fig. S2 in ESI). This percolating CF network significantly shortens the stress-transfer distance and provides continuous load-transfer pathways throughout the cellular structure. Consequently, even when the PA6 matrix began to soften at elevated temperatures, the interconnected CF skeleton could sustain the applied load and effectively suppress the local deformation of the cell walls, thereby delaying the onset of thermal deflection.

Mechanical Properties

Fig. 8 shows the mechanical properties of the unfoamed, foamed PPO/PA6, and PPO/PA6/CF samples. As shown in Figs. 8(a) and 8(b), the tensile and flexural properties of the unfoamed PPO/PA6 composites improved significantly with increasing CF content. As the CF content increased from 0 wt% to 20 wt%, the tensile and flexural strength increased from

45.66 and 60.58 MPa to 144.04 and 201.44 MPa, respectively, representing increases of 215% and 232%. After foaming, the tensile and flexural strengths of all foamed PPO/PA6/CF composites decreased slightly compared to those of their unfoamed composites. This indicated that the introduction of cells reduced the effective load-bearing at the cross-sections, leading to localized stress concentrations.^[43,44] Notably, the effect of CF content on the flexural modulus of both the unfoamed and foamed PPO/PA6/CF composites exhibited a clear critical threshold effect (Fig. 8c). When the CF content was below 15 wt%, foaming reduced the flexural modulus of the PPO/PA6/CF composites; however, when the CF content exceeded 15 wt%, the foamed samples showed a higher flexural modulus than their unfoamed counterparts, indicating a significant fiber-network reinforcement effect. For example, at 20 wt% CF, the flexural modulus of the foamed sample increased from 7751.47 MPa to 8509.16 MPa compared with the unfoamed sample, representing an increase of approximately 9.77% and a 521.69% increase compared to PPO/PA6 foam. This enhancement was attributed to the quasi-continuous skeletal network formed by CFs bridging across the cell walls, which not only provided continuous stress transfer pathways throughout the

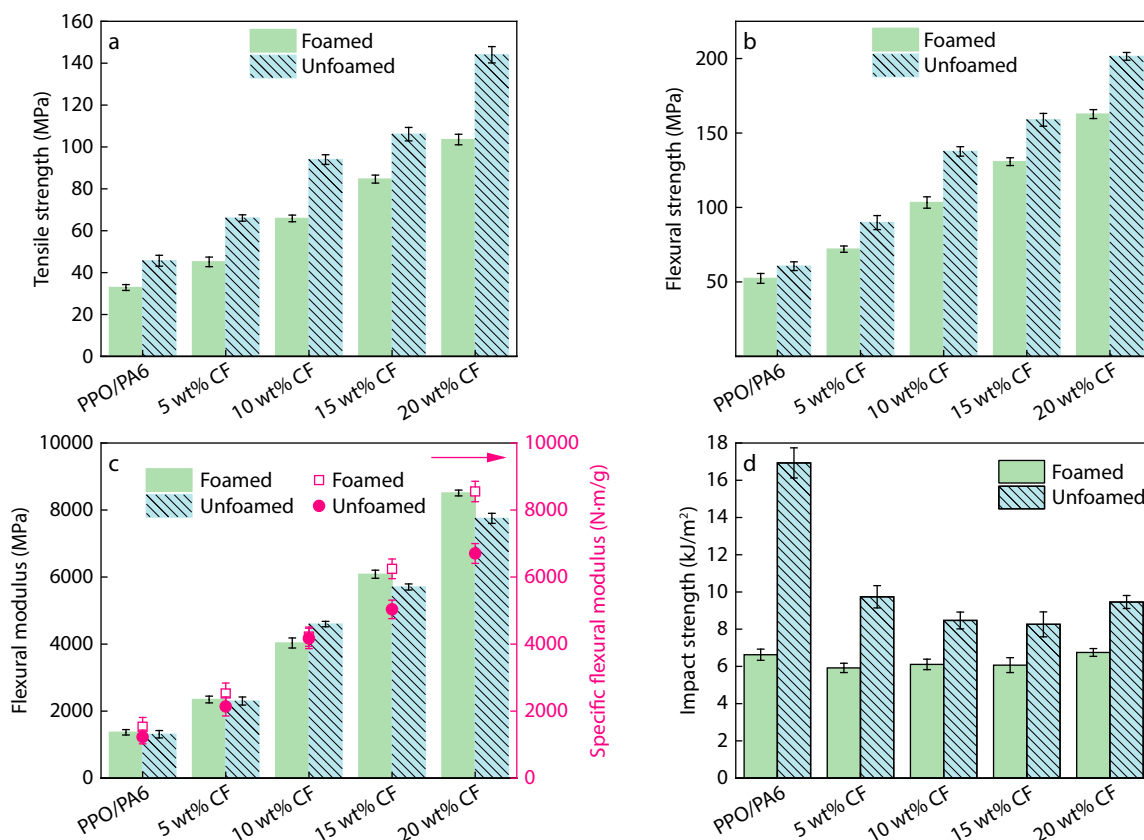


Fig. 8 Mechanical properties of the unfoamed and foamed PPO/PA6/CF composites: (a) tensile strength, (b) flexural strength, (c) flexural modulus and specific flexural modulus, and (d) impact strengths.

cellular structure but also effectively compensated for the adverse effects of the cells on the mechanical properties of the material. To eliminate the influence of density differences on the reinforcement effect of the flexural modulus, the specific flexural modulus was calculated, as shown in Fig. 8(c). All the foamed composites exhibited higher specific flexural modulus values than the unfoamed samples. For example, at 20 wt% CF, the specific flexural modulus of the foamed PPO/PA6/CF composite reached 8554.76 N·m/g, which was 27.61% higher than that of the unfoamed sample, indicating a significant enhancement in the deformation resistance of the foamed composites. Additionally, the notched impact strength of the unfoamed PPO/PA6 sample was found to be 16.93 kJ/m² (Fig. 8d), while that of the foamed PPO/PA6 sample was 6.63 kJ/m², which represented only 39.2% of the unfoamed sample. After the addition of CF, the notched impact strength of the unfoamed PPO/PA6/CF composite remained approximately 9.00 kJ/m². The foamed PPO/PA6/CF composite exhibited a notched impact strength of approximately 6.00 kJ/m², which was 66.7% of that of the unfoamed.

Electrical Conductivity and Electromagnetic Interference Shielding Performance

The electrical conductivities and EMI shielding effectiveness values of the PPO/PA6/CF unfoamed and foamed composites are shown in Fig. 9. The electrical conductivity of the PPO/PA6/CF composites demonstrated typical percolation behavior with an increase in the CF content (Fig. 9a). At low CF loading (5 wt%–10

wt%), both foamed and unfoamed samples showed low conductivity (10^{-10} – 10^{-7} S/m), which indicated the absence of continuous conductive pathways. Within this loading range, the electrical conductivity of the foamed composite was slightly lower than that of the unfoamed composite because of the hindrance to electron transport by the insulating cells.^[37,45] A significant transition in the electrical conductivity occurred when the CF loading was approximately 15 wt%, wherein the conductivity increased by several orders of magnitude, which corresponded to the formation of a percolation network.^[31,46,47] At this threshold, the electrical conductivity of the foamed composite material reached 7.15×10^{-2} S/m, which was higher than that of the unfoamed counterpart (1.09×10^{-2} S/m), although both had the same order of magnitude. A similar trend was observed for the composite with 20 wt% CF, wherein the conductivity of the foamed sample (0.697 S/m) was higher than that of the unfoamed composite (0.145 S/m). This enhancement was attributed to the more perfect CF network architecture (Fig. 7c).

The EMI shielding performance of the unfoamed and foamed PPO/PA6/CF composites in the X-band frequency range (8.2–12.4 GHz) was investigated. As shown in Figs. 9(b) and 9(c), EMI exhibits a marked increasing trend with increasing the CF content. Notably, when the CF content was 15 wt%, the EMI SE_T of the unfoamed PPO/PA6/CF sample was only 17.56 dB (Fig. 9d), whereas it increased significantly to 20.01 dB after foaming, reaching the approximately 20 dB shielding level commonly regarded in the literature as a practical benchmark for general commercial EMI shielding appli-

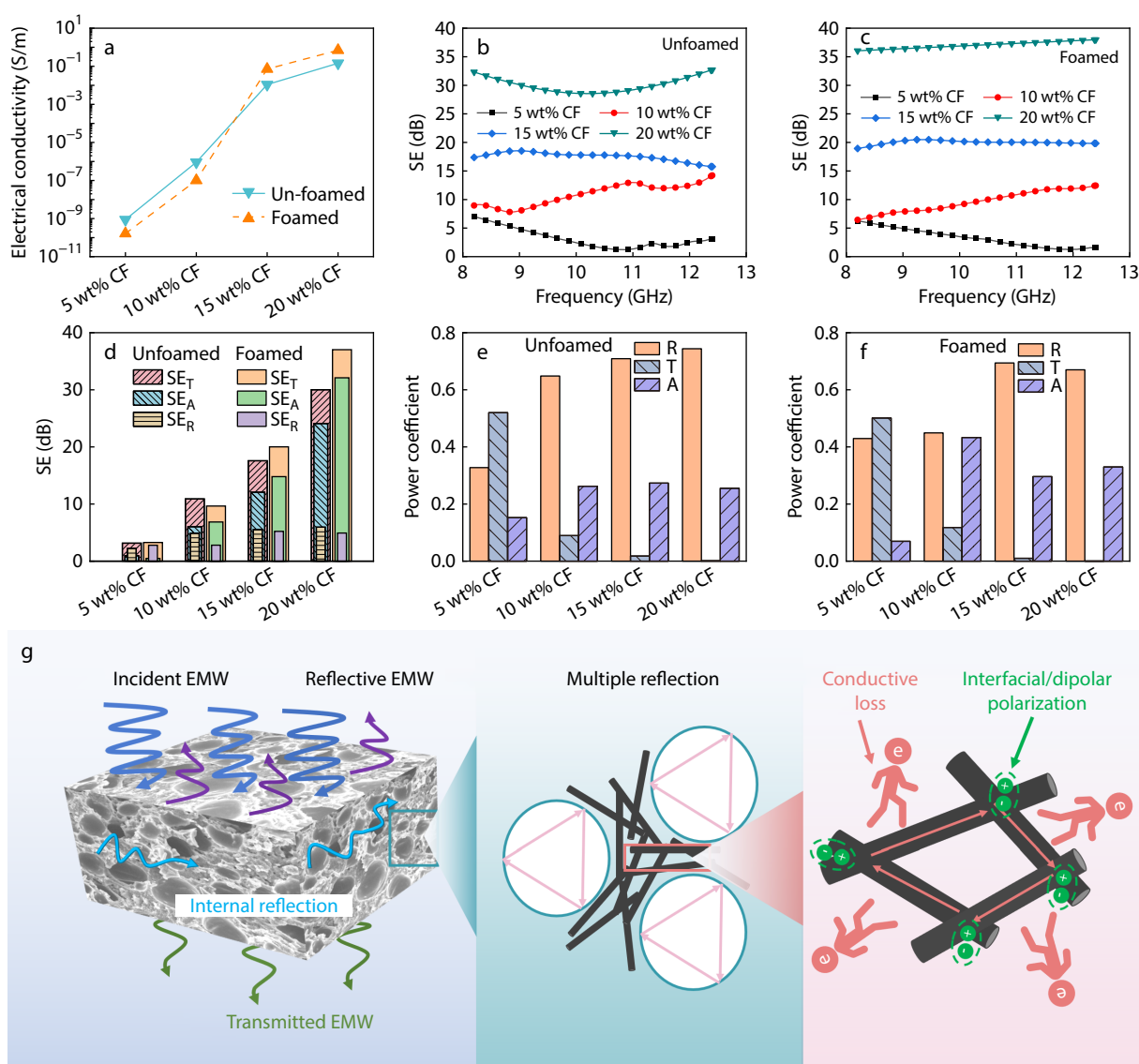


Fig. 9 Electrical conductivity and EMI shielding performance of unfoamed and foamed PPO/PA6/CF composites as a function of CF content: (a) electrical conductivity, (b, c) SE values in the X-band frequency range, (d) SE_R , SE_A , SE_T , (e, f) the averaged R, T, and A values, and (g) a schematic diagram of the EMI shielding mechanism for foamed composite.

cations.^[48,49] Furthermore, the EMI SE_T of the foamed PPO/PA6/CF sample at 20 wt% CF was 37.02 dB, which was higher than the 29.99 dB value of the corresponding unfoamed sample. The above results indicate that the three-dimensional conductive network constructed by the CF skeleton during foaming endowed the PPO/PA6/CF foam with an excellent EMI shielding performance. For both the unfoamed and foamed composites, EMI SE_A was consistently higher than EMI SE_R . For example, the foamed PPO/PA6/CF composite exhibited EMI SE_T , SE_A , and SE_R values of 37.02, 32.1, and 4.92 dB, respectively. Figs. 9(e) and 9(f) show that the power coefficient R was always greater than A , indicating that the shielding mechanism was dominated by microwave reflection rather than absorption. However, the A value of the foamed PPO/PA6/CF composite was higher than that of the unfoamed sample. For example, at 20 wt% CF, the A value increased from 0.26 for the unfoamed sample to 0.33 after

foaming. The introduction of the cell structure enhanced the multiple reflections and scattering of electromagnetic waves, thereby improving microwave absorption.^[45,50]

Fig. 9(g) schematically illustrates the EMI shielding mechanism of the PPO/PA6/CF composite foam. When electromagnetic waves (EMW) impinge on the surface of the composite foam, a portion is directly reflected by the impedance mismatch, whereas the remainder penetrates the surface layer and enters the material interior. Benefiting from the cell structure, the incident EMW undergoes multiple reflections and scattering within the cells, significantly extending the propagation path and increasing the transmission loss.^[51] In addition, the conductive network formed by CFs along the cell walls effectively enhances conduction loss, further attenuating the EMW energy. Meanwhile, the interfacial polarization between the CFs and the PPO/PA6 matrix, as well as the dipole polarization of the fibers themselves, also contribute

significantly to the dissipation of the EMW energy.^[52] The synergistic action of these multiple loss mechanisms endows the foamed PPO/PA6/CF composites with superior EMI shielding performance.

CONCLUSIONS

CF-reinforced PPO/PA6 (PPO/PA6/CF) microcellular composites with enhanced thermal resistance and EMI shielding performance were fabricated using chemical foaming injection molding. Rheological and crystallization analyses revealed that the incorporation of CF increased the melt elasticity and promoted the heterogeneous nucleation of PA6 crystals, thereby facilitating stable cell growth during foaming. As a result, the foamed PPO/PA6/CF composites exhibited a well-defined microcellular structure with an average cell diameter of 49.44 μm and a cell density of 3.48×10^6 cells/ cm^3 . The apparent density was less than 1 g/ cm^3 , corresponding to a weight reduction of 14%. The foamed PPO/PA6/CF composite with 20 wt% CF achieved excellent comprehensive performance: the flexural modulus and heat deflection temperature reached 8509.16 MPa and 181.2 $^{\circ}\text{C}$, respectively, representing increases of 521.69% and 87.8% compared with the foamed PPO/PA6. Furthermore, the interconnected CF network formed conductive pathways around the cell walls, endowing the foamed PPO/PA6/CF composite with an electrical conductivity of 0.697 S/m and EMI shielding effectiveness of 37.02 dB. This study provides an efficient and scalable strategy for the preparation of lightweight PPO-based engineering plastic foams with excellent heat deflection temperatures and EMI shielding performance.

Conflict of Interests

The authors declare no interest conflict.

Electronic Supplementary Information

Electronic supplementary information (ESI) is available free of charge in the online version of this article at <http://doi.org/10.1007/s10118-026-3839-7>.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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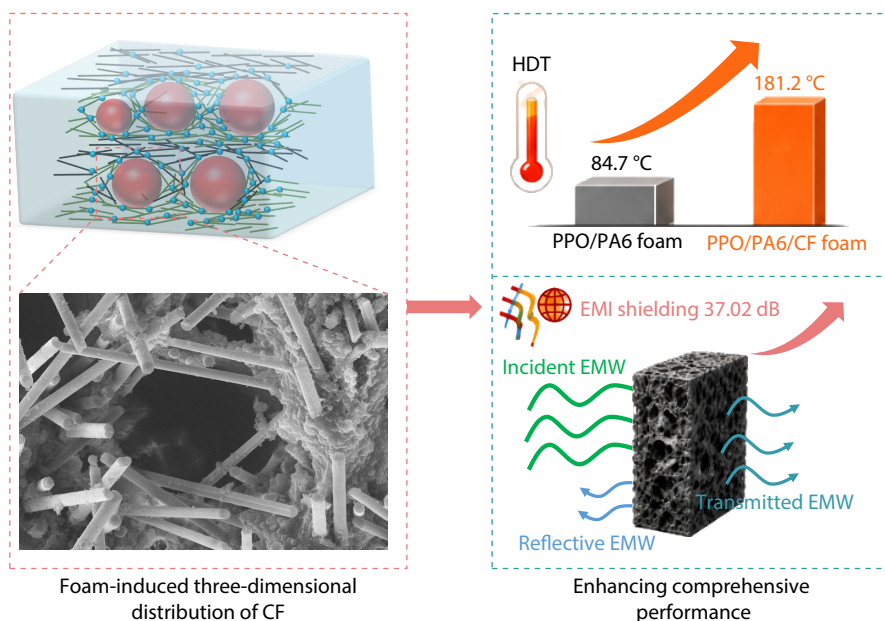
Graphical Abstract

Lightweight Poly(phenylene oxide)/Polyamide 6/Carbon Fiber Microcellular Composites with Enhanced Thermal Resistance and Electromagnetic Interference Shielding Performance

Tuan-Hui Jiang, Jing-Fu Xing, Yue He, Feng Yu, Zhang-Qin Mu, Xiang-Bu Zeng, Sheng-Nan Li, Xiao-Die Zhang, Bu-Jin Liu, Chun Zhang, Li He, and Wei Gong

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Foaming-induced carbon fiber (CF) redistribution in lightweight poly(phenylene oxide) (PPO)/polyamide 6 (PA6)/CF microcellular composites creates an interconnected reinforcement structure, thereby simultaneously achieving high heat resistance and effective electromagnetic interference shielding.



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