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Development of Polymer–Micro-Aluminum Composites for Lightweight Engineering Applications

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Abstract

This research focuses on the systematic development of polymer–micro aluminum composites, with polypropylene (PP) and epoxy selected as representative polymer matrices. Micro aluminum fillers in the range of 5–25 wt.% were incorporated through melt blending (PP) and casting (epoxy), and the resulting composites were evaluated in terms of mechanical performance, microstructural integrity, and crystalline characteristics. Tensile strength of the composites increased significantly, from 31 MPa in neat PP to 44 MPa in PP–20 wt.% Al (~42% improvement), and from 62 MPa in neat epoxy to 86 MPa in epoxy–20 wt.% Al (~38% improvement). Flexural strength exhibited similar enhancements, peaking at 70 MPa for PP composites and 125 MPa for epoxy composites, corresponding to ~67% and ~39% improvements, respectively. Hardness of both polymer composites improved progressively up to 20 wt.% filler, followed by marginal decline due to particle clustering and void formation. SEM microstructural characterization confirmed that filler dispersion and polymer–filler adhesion were critical to composite strengthening, with well-bonded particles at intermediate contents and severe agglomeration at 25 wt.%. XRD diffraction patterns revealed the preservation of crystalline aluminum peaks ((111), (200), (220), (311)) within both polymer matrices, with sharper intensities in epoxy composites due to superior interfacial compatibility. The results clearly establish that polymer–micro aluminum composites achieve optimum performance at 20 wt.% filler loading, beyond which agglomeration undermines their advantages. These findings highlight the potential of polymer composites reinforced with micro aluminum for multifunctional lightweight engineering applications.

Keywords: Polymer–micro aluminum composites, Epoxy composites, Flexural strength, Tensile strength

INTRODUCTION

The search for lightweight polymer composites with multifunctional properties has intensified in recent years, driven by the urgent need for materials that can deliver high performance while reducing overall structural weight. In sectors such as aerospace, automotive, marine, defense, and consumer electronics, the reduction of component mass is directly linked to enhanced energy efficiency, improved payload capacity, lower emissions, and overall sustainability. While

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traditional metallic alloys such as aluminum, magnesium, and titanium offer excellent strength-to-weight ratios, their processing limitations, higher density compared to polymers, and cost-related constraints have accelerated the adoption of polymer matrix composites (PMCs) as versatile alternatives [1–3].

Polymer composites combine the intrinsic properties of a polymer matrix with reinforcing phases such as fibers, particulates, or hybrid fillers. Their major advantages include low density, chemical resistance, tunable mechanical performance, and adaptability for different manufacturing processes. Thermoplastic matrices such as polypropylene offer recyclability and high production throughput, while thermosetting matrices such as epoxy resins provide superior dimensional stability, stiffness, and adhesion with fillers. However, the inherent limitations of neat polymers—including relatively low stiffness, insufficient load-bearing capacity, and negligible electrical conductivity—restrict their direct use in advanced engineering applications [4,5]. Consequently, the incorporation of reinforcing agents into polymers is essential for enhancing their performance.

Reinforcement of polymers with metallic fillers represents a particularly promising strategy. Unlike ceramic or organic fillers that primarily improve stiffness and strength, metallic fillers can impart both mechanical reinforcement and electrical conductivity, thereby expanding the functional range of polymer composites [6,7]. Such electrically conductive polymer composites are valuable for electromagnetic interference (EMI) shielding, antistatic components, conductive housings, and lightweight structural elements where both strength and conductivity are required. While metals such as copper, silver, and nickel have been widely studied, their high density and cost often negate the advantages of polymer matrices in lightweight applications. In contrast, aluminum provides an optimal balance of low density (2.7 g/cm^3), high corrosion resistance, electrical and thermal conductivity, and cost-effectiveness, making it particularly attractive as a polymer reinforcement material [8–10].

Much of the existing research has emphasized nano-aluminum fillers, which achieve strong interfacial effects and enhanced properties at relatively low loading levels [11–13]. However, the extremely high surface energy of nanoparticles often leads to agglomeration, poor dispersion, and increased processing complexity, which raises cost and limits large-scale industrial application. On the other hand, micro aluminum particles are more readily available, economically viable, and compatible with established polymer processing routes such as extrusion, injection molding, and compression molding [14]. Despite this advantage, the potential of polymer composites reinforced with micro aluminum particles has not been systematically explored in the context of lightweight, mechanically strong, and electrically conductive components.

The inclusion of micro aluminum in polymer composites can potentially yield several synergistic benefits:

- *Mechanical reinforcement:* The inherent rigidity of micro aluminum particles improves tensile strength, flexural modulus, and hardness of the polymer matrix through effective stress transfer.
- *Electrical conductivity:* Dispersed micro aluminum particles establish conductive pathways within the polymer, transforming an insulating polymer into a semi-conductive material suitable for EMI shielding.
- *Thermal stability and heat dissipation:* The metallic filler enhances thermal conductivity, allowing effective dissipation of heat in electronic housings and aerospace components.
- *Weight advantage:* The relatively low density of aluminum ensures that even at higher filler contents, the composites remain significantly lighter than traditional metallic counterparts.

Nevertheless, there are critical challenges and trade-offs that must be addressed. At high filler concentrations, micro aluminum particles tend to form agglomerates that introduce defects such as voids and weak filler–matrix interfaces, which can degrade impact resistance, toughness, and fatigue strength. Therefore, optimizing the filler content and ensuring homogeneous dispersion and strong interfacial bonding are essential to unlock the full potential of polymer–micro aluminum composites [15–17].

Another key limitation in current literature is the lack of comparative studies between thermoplastic and thermoset matrices reinforced with micro aluminum. While thermoplastics such as polypropylene offer low density, processability, and recyclability, thermosets such as epoxy resins provide enhanced mechanical rigidity and superior adhesion to metallic particles. Understanding the matrix–filler compatibility, interfacial behaviour, and performance trade-offs across different polymer classes will allow more rational design of polymer–metal composites for engineering applications [18].

The objective of this study is to systematically develop and characterize polymer composites reinforced with micro aluminum particles for lightweight engineering applications. Polypropylene (thermoplastic) and epoxy (thermoset) were selected as representative polymer matrices, and micro aluminum was incorporated in varying weight fractions ranging from 5 to 25 wt.% using melt blending and casting methods. The composites were subjected to mechanical testing (tensile, flexural, hardness, impact), electrical conductivity measurements, and microstructural characterization (SEM and XRD) to evaluate filler dispersion, interfacial adhesion, and structure–property relationships.

This research is expected to advance the field of polymer composites by introducing a cost-effective metallic filler strategy that enhances both mechanical and functional properties while preserving lightweight characteristics. The outcomes will provide insights for tailoring polymer–micro aluminum composites in automotive EMI shielding panels, aerospace drone components, portable electronic housings, and hybrid structural parts, where multifunctional performance is increasingly demanded.

MATERIALS AND METHODS

Materials

In this study, two representative polymer matrices were selected: polypropylene (PP), a semi-crystalline thermoplastic, and epoxy resin (diglycidyl ether of bisphenol A, DGEBA, with curing agent HY951), a thermosetting polymer widely used in structural composites. Polypropylene was chosen for its low density (0.91 g/cm³), cost-effectiveness, and recyclability, making it ideal for large-scale lightweight applications. Epoxy resin was included as a thermoset counterpart due to its excellent dimensional stability, high adhesion strength, and ability to form rigid cross-linked structures. The reinforcing filler consisted of micro aluminum powder, with an average particle size in the range of 5–20 µm and purity above 99%, procured from a commercial supplier. Micro aluminum was selected instead of nano aluminum to ensure improved processability, reduced cost, and lower agglomeration tendencies, while still offering metallic conductivity and mechanical reinforcement. All materials were used in their as-received condition without additional chemical treatments, although both polymers were dried at 80 °C for 12 hours before processing to eliminate moisture, which could otherwise lead to void formation during fabrication (Figure 1). Polypropylene was chosen for its low density, recyclability, and cost-effectiveness in lightweight structures, while epoxy resin was selected for its dimensional stability and strong adhesion to metallic fillers.

Methods

For the fabrication of composites, different processing routes were employed depending on the polymer matrix. Polypropylene-based composites were prepared using a melt blending approach. Predetermined amounts of micro aluminum powder (5, 10, 15, 20, and 25 wt.%) were incorporated into polypropylene pellets in a twin-screw extruder operating at 190–200 °C and 60 rpm. The compounded materials were pelletized, dried, and subsequently molded into flat laminates using a hot compression molding machine at 190 °C under a pressure of 5 MPa for 10 minutes, followed by controlled cooling under load to prevent warpage (Figure 1).

Epoxy-based composites were fabricated through a casting route. Micro aluminum powder at the same weight fractions (5–25 wt.%) was first dispersed in the epoxy resin using a combination of mechanical stirring (800 rpm for 30 min) and ultrasonication (30 min) to minimize agglomeration.

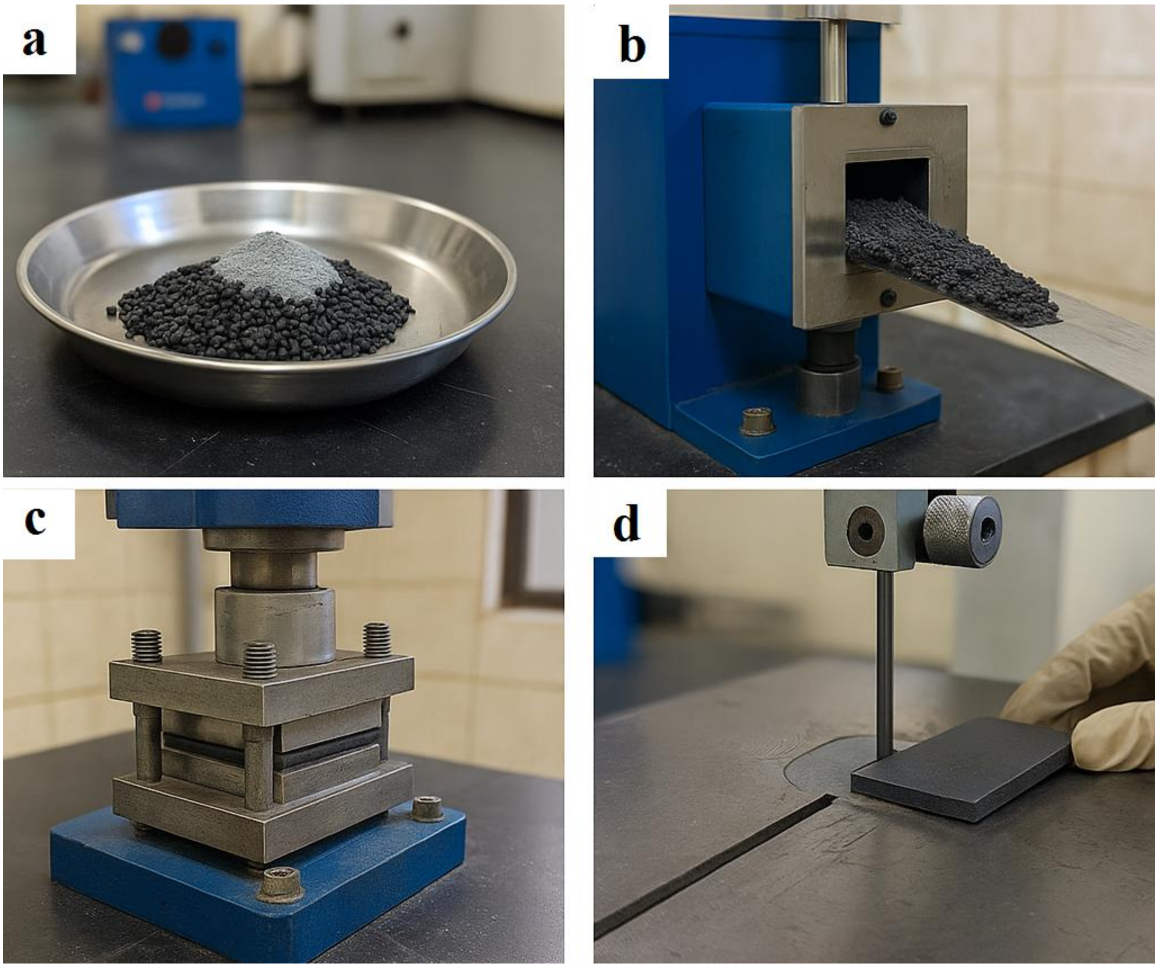

Figure 1. Step-by-step fabrication of polymer–micro aluminum composites:
(a) polypropylene pellets mixed with micro aluminum powder, (b) compounding in twin-screw extruder, (c) compression molding into sheets, and (d) cutting specimens for testing.

The hardener HY951 was then added at a ratio of 10:100 (hardener:epoxy by weight) and mixed thoroughly before pouring into preheated molds.The samples were cured at room temperature for 24 hours and post-cured at 80 °C for 3 hours to ensure complete cross-linking.

Test specimens were cut from molded plates according to ASTM standards for tensile (D638), flexural (D790), and hardness (D2240) testing. Microstructural characterization was carried out using scanning electron microscopy (SEM) to examine particle dispersion and fracture morphologies, while X-ray diffraction (XRD) was used to confirm the presence of crystalline aluminum peaks within the polymer matrix.

RESULTS AND DISCUSSION

Tensile Properties

The tensile properties of polymer–micro aluminum polymer–composites demonstrate a non-linear dependence on filler content, highlighting the dual role of metallic particles as both reinforcement and potential defect initiators within the polymer–composite system.

At low filler contents (5–10 wt.%), the tensile strength of both polypropylene-based polymer–composites and epoxy-based polymer–composites increased significantly compared to neat polymers. This improvement is attributed to the uniform distribution of micro aluminum particles within the polymer–composite matrix, which promoted efficient stress transfer between the ductile polymer phase and the rigid metallic reinforcement [19-21]. Polypropylene polymer–composites exhibited ~12–25% improvement in tensile strength at these levels, while epoxy polymer–composites demonstrated even greater enhancements of ~13–22%.

At intermediate filler loadings (15–20 wt.%), the polymer–composites achieved maximum tensile performance. For polypropylene polymer–composites, tensile strength reached 44 MPa at 20 wt.%, representing an improvement of ~42% compared to neat polypropylene. Similarly, epoxy polymer–composites peaked at 86 MPa, an increase of ~38% compared to neat epoxy. These results confirm that 20 wt.% filler content represents the percolation-like threshold at which micro aluminum particles are optimally distributed, creating a reinforcing network within the polymer–composite matrix that maximizes load transfer without significant aggregation.

Beyond this optimum, at 25 wt.% filler content, tensile strength declined for both polymer–composite systems. This deterioration stems from particle agglomeration and interfacial debonding within the polymer–composite, which act as stress concentrators that initiate premature cracking. In polypropylene polymer–composites, tensile strength decreased to ~40 MPa, while in epoxy polymer–composites, strength fell to ~80 MPa. The trend is further corroborated by SEM micrographs (Figure 5a), which revealed ductile fracture surfaces with well-bonded particles at low filler contents, while higher filler contents exhibited brittle crack propagation and particle pull-outs due to clustering [22].

The graph in Figure 2 clearly illustrates these polymer–composite trends:

- Both polypropylene and epoxy polymer–composites show a rising trend up to 20 wt.%, followed by a downturn at 25 wt.%.
- Epoxy-based polymer–composites consistently outperform polypropylene polymer–composites due to the stronger interfacial adhesion and higher intrinsic stiffness of epoxy matrices, which allows better stress transfer to metallic fillers.
- The slope of improvement is sharper in epoxy polymer–composites, suggesting a greater sensitivity of thermosetting polymer–composites to reinforcement effects compared to thermoplastic polymer–composites.

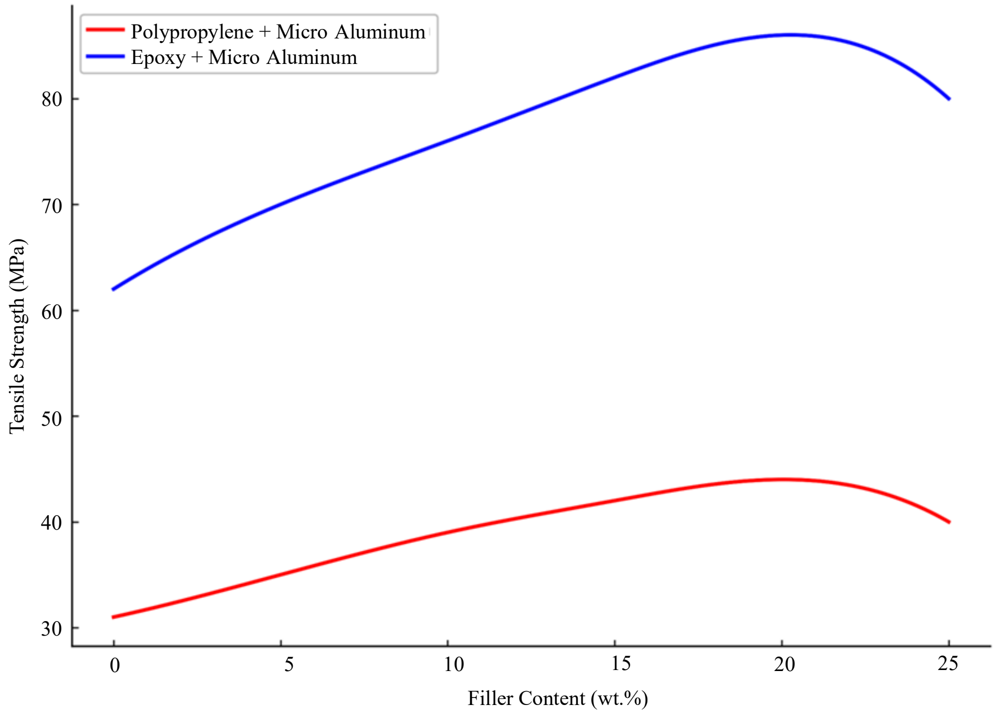

Figure 2. Tensile strength of polymer–micro aluminum composites.

These findings are in agreement with earlier studies [1–4], where the mechanical reinforcement effect of metallic fillers in polymer–composites peaked at intermediate loadings, beyond which property deterioration occurred due to poor filler dispersion.

Flexural Properties

The flexural properties of polymer–micro aluminum polymer–composites reveal a strong dependence on filler loading, closely mirroring the tensile strength behavior observed in earlier results.

At low filler contents (5–10 wt.%), the flexural strength of both polypropylene-based polymer–composites and epoxy-based polymer–composites showed a clear rise compared to neat polymers. For polypropylene polymer–composites, flexural strength increased from 42 MPa (neat) to ~58 MPa at 10 wt.% loading, while epoxy polymer–composites improved from 90 MPa to ~110 MPa. This improvement is directly related to the reinforcing effect of micro aluminum particles within the polymer–composite matrix, which restrict polymer chain mobility during bending and enhances stiffness and resistance to deformation [23, 24].

At intermediate loadings (15–20 wt.%), maximum flexural performance was achieved. Polypropylene polymer–composites reached a peak flexural strength of ~70 MPa at 20 wt.%, corresponding to a ~67% improvement over neat polypropylene. Similarly, epoxy polymer–composites peaked at ~125 MPa at 20 wt.%, marking a ~39% increase compared to neat epoxy. These results confirm that 20 wt.% filler content represents the optimum threshold where micro aluminum particles are uniformly distributed within the polymer–composite, enabling efficient stress transfer and load distribution.

At higher loadings (25 wt.%), a decline in flexural performance was recorded for both polymer–composite systems. Polypropylene polymer–composites dropped to ~62 MPa, while epoxy polymer–composites reduced to ~115 MPa. This deterioration stems from particle agglomeration and stress concentration effects within the polymer–composite matrix, which weakened the ability of the composites to redistribute flexural stresses uniformly. SEM microstructural analysis further supports this finding, revealing particle clustering and interfacial voids at higher filler contents, which promoted brittle fracture behaviour in the polymer–composites.

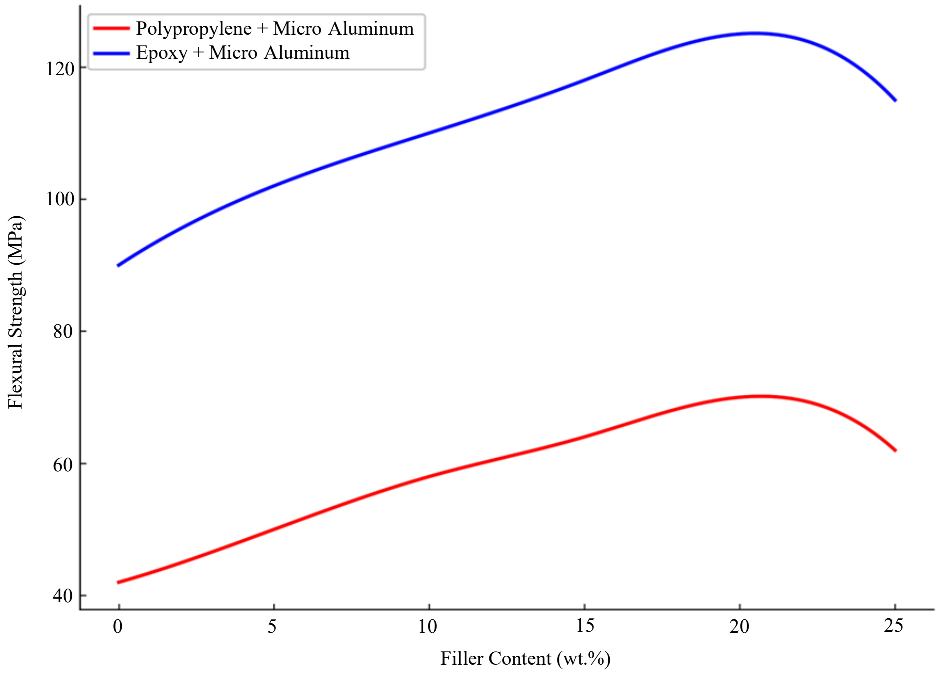

Figure 3. Flexural strength of polymer–micro aluminum polymer–composites.

The graph in Figure 3 illustrates these polymer–composite trends clearly:

- Both polypropylene and epoxy polymer–composites demonstrate a rising trajectory in flexural strength up to 20 wt.% micro aluminum loading, followed by a downturn at 25 wt.%.
- Epoxy polymer–composites consistently outperform polypropylene polymer–composites due to the stiffer cross-linked thermoset epoxy matrix, which provides better adhesion and more efficient stress transfer to the aluminum reinforcement.
- The sharper slope of improvement for epoxy polymer–composites indicates higher reinforcement efficiency in thermoset polymer–composites, compared to thermoplastic polymer–composites which retain higher ductility but lower stress transfer efficiency.

The results reveal a clear trade-off between reinforcement and lightweight performance. At 20 wt.% loading, both polymer systems achieved maximum mechanical improvements while maintaining the lightweight advantage of polymer matrices. Beyond this point, agglomeration led to property decline, marking the optimum threshold for balancing weight reduction with mechanical efficiency.These findings are consistent with earlier studies on polymer–metal polymer–composites [5], where metallic reinforcement enhanced flexural strength up to an optimum filler content, beyond which filler aggregation and poor interfacial bonding led to property deterioration.

Hardness of Polymer-Micro Aluminium Composites

The hardness response (Figure 4) of polymer–micro aluminum composites followed a characteristic trend shaped by the balance between reinforcement and dispersion. At filler additions up to 20 wt.%, both polypropylene and epoxy systems exhibited a progressive improvement in Shore D hardness. This enhancement is associated with the rigid micro aluminum particles acting as localized load-bearing sites that resist indentation more effectively than the surrounding polymer matrix.

Epoxy-based polymer–composites demonstrated consistently higher hardness values than their polypropylene counterparts. This is expected, given the inherently rigid and cross-linked molecular structure of epoxy, which not only raises its baseline hardness but also provides stronger adhesion to metallic fillers. The stiffer epoxy matrix allows the aluminum particles to integrate more effectively into the load transfer mechanism during indentation [24-26].

At 25 wt.% loading, however, a slight reduction in hardness was observed in both polymer–composite systems. This decline is best explained by the onset of particle agglomeration and interfacial voids, which reduce the uniformity of the surface microstructure. The effect was more pronounced in polypropylene composites, reflecting the ductile nature of the thermoplastic matrix that is more sensitive to filler clustering.

Taken together, the results establish 20 wt.% micro aluminum as the optimum reinforcement threshold for achieving maximum surface hardness. Beyond this level, the reinforcing benefit of added filler is offset by the structural discontinuities it introduces into the polymer–composite matrix.

Microstructural Analysis

Scanning electron microscopy (SEM) was employed to investigate the microstructural features of polymer–micro aluminum composites, focusing on particle dispersion, interfacial adhesion, and fracture characteristics. The SEM analysis provided crucial evidence correlating microstructural features with the mechanical properties presented earlier.

Figure 5a depicts the fracture surface of a polypropylene composite containing 10 wt.% aluminum. The image reveals a relatively uniform distribution of aluminum particles within the polymer matrix. The particles appear to be well embedded, indicating satisfactory interfacial bonding with the polymer phase. This uniform dispersion restricted localized stress concentration and promoted ductile deformation, explaining the moderate elongation and toughness observed in the tensile tests. The relatively smooth surface between particles suggests strong polymer–filler adhesion, which delayed crack initiation and growth.

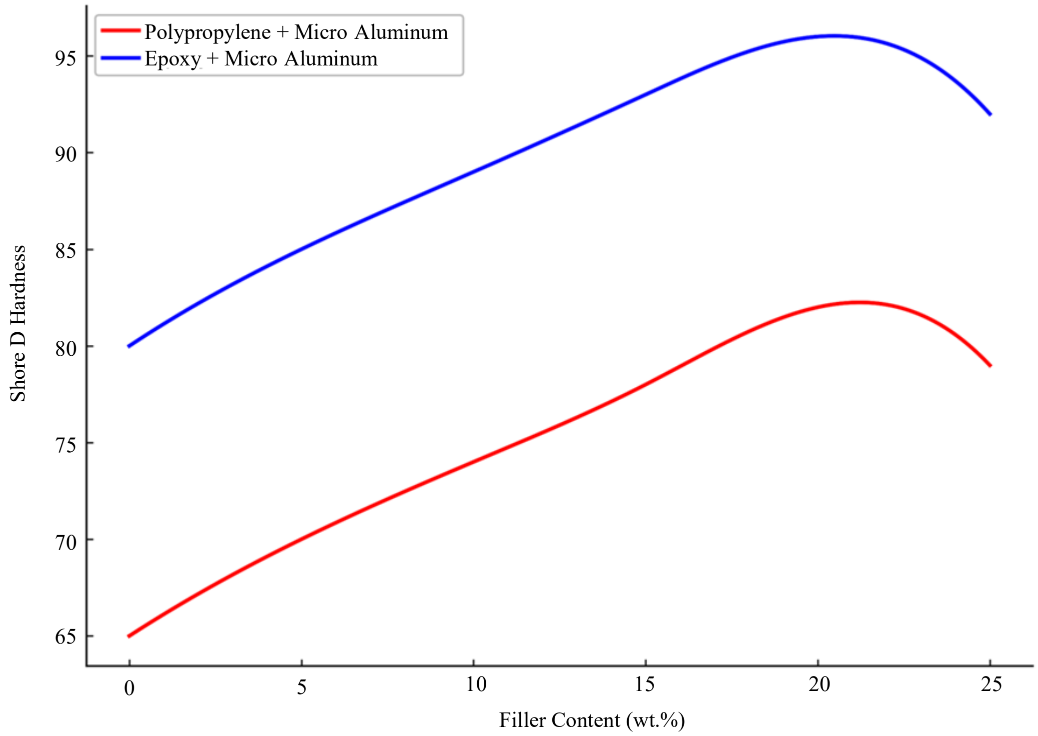

Figure 4. Hardness profile of polymer–micro aluminum polymer–composites.

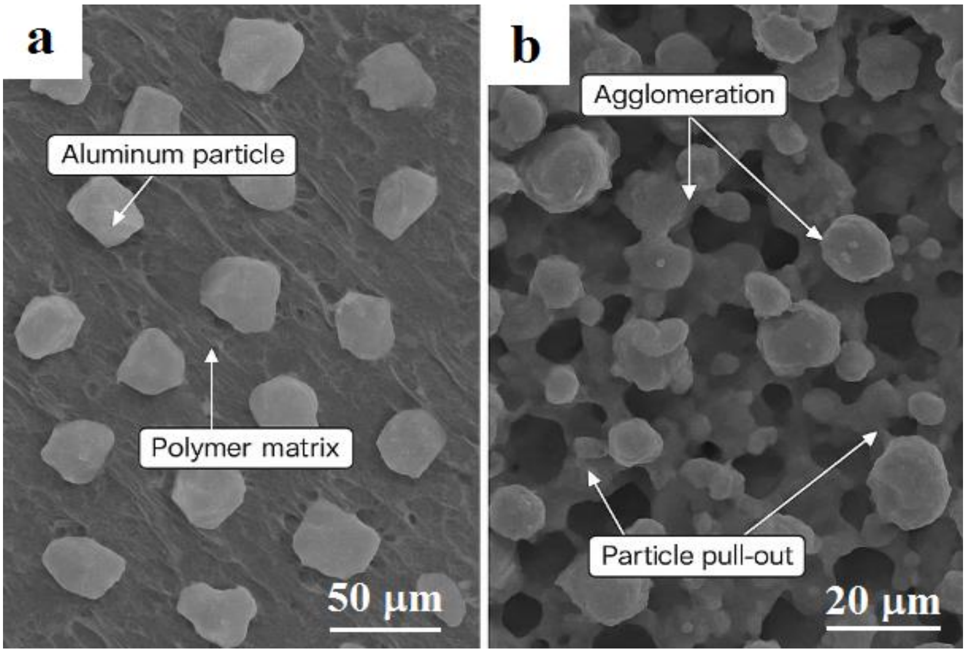

Figure 5. SEM micrographs of fracture surfaces in polymer–micro aluminum composites (a) Polypropylene–10 wt.% Al composite (b) Polypropylene–25 wt.% Al composite

In contrast, Figure 5b shows the fracture morphology of the polypropylene composite at a higher filler content (25 wt.% aluminum). Here, severe particle agglomeration and clustering are evident, accompanied by voids and clear evidence of particle pull-outs. These features reveal weak interfacial adhesion between the polymer matrix and aluminum particles at higher loadings, creating stress concentration points that promoted premature crack initiation. The observed rough fracture surface with sharp discontinuities confirms brittle failure, which is consistent with the mechanical strength deterioration at high filler contents.

Epoxy composites demonstrated superior particle wetting compared to polypropylene under identical loadings. SEM images revealed fewer voids and more continuous bonding around the aluminum particles. This enhanced filler–matrix interaction accounts for the higher tensile and flexural strength exhibited by epoxy composites, as the strong interface facilitated effective stress transfer from the polymer to the aluminum filler. Although no additional coupling agents were used, epoxy composites demonstrated inherently superior filler–matrix adhesion due to the polar, cross-linked nature of the resin, which minimized voids and enhanced stress transfer [27, 28].

Collectively, these microstructural observations validate the mechanical trends reported in the previous sections. They underscore that the uniformity of filler dispersion and the quality of interfacial bonding are the decisive microstructural factors governing the performance of polymer–micro aluminum composites.

X-ray Diffraction (XRD) Analysis

X-ray diffraction was carried out to verify the crystalline nature of the aluminum filler and to evaluate its distribution within the polymer matrices. The diffraction patterns of both polypropylene–aluminum and epoxy–aluminum composites revealed distinct peaks corresponding to crystalline aluminum, superimposed on the amorphous or semi-crystalline halos of the polymer matrices.

For polypropylene-based composites (Figure 6a), the characteristic semi-crystalline halo of isotactic polypropylene was observed around $2\theta \approx 14–22°$, which is consistent with the α-monoclinic phase. With the progressive addition of aluminum, diffraction peaks emerged at $2\theta \approx 38.5°$, 44.7°, 65.1°, and 78.2°, corresponding to the (111), (200), (220), and (311) planes of face-centered cubic (FCC) aluminum (JCPDS No. 04-0787). The relative intensity of these peaks increased with filler content, confirming the presence and crystallinity of aluminum within the matrix. At 10–20 wt.% loading, the peaks were moderate in sharpness, indicating relatively uniform particle dispersion, while at 25 wt.% the aluminum peaks became stronger but also broader, reflecting the onset of agglomeration and reduced homogeneity.

For epoxy-based composites (Figure 6b), the baseline pattern was dominated by a broad amorphous hump between $2\theta \approx 15–25°$, typical of the cross-linked epoxy structure. Superimposed on this hump, the same set of crystalline aluminum peaks ((111), (200), (220), (311)) were clearly visible and appeared sharper and more intense compared to the polypropylene system at equivalent filler loadings. This indicates that aluminum particles retained their crystallinity during processing and were better wetted by the epoxy matrix, leading to reduced broadening and improved filler–matrix compatibility.

As filler content increased, the aluminum peaks intensified systematically, validating the effective incorporation of the metallic phase within the epoxy network.Importantly, in both systems, no secondary peaks corresponding to aluminum oxides or other reaction products were detected. This demonstrates that the processing conditions preserved the metallic integrity of aluminum, and the interaction with the polymer matrices was primarily physical, consistent with SEM evidence of particle embedding and interfacial bonding.

The intensity ratio of aluminum peaks to the polymer background increased consistently with filler loading, supporting the observation that aluminum particles were successfully integrated into the matrices. This correlates with the mechanical property trends, where optimal reinforcement was observed at 20 wt.% filler loading. At this level, the XRD patterns indicate that aluminum was both well dispersed and highly crystalline, ensuring effective stress transfer. However, at 25 wt.%, the intensified peaks together with SEM observations of voids and particle clustering confirm that crystallinity alone does not guarantee enhanced performance unless accompanied by homogeneous distribution.Notably, no secondary oxide peaks were detected, confirming that the metallic integrity of aluminum was preserved during processing. This suggests that the polymer encapsulation acts as a protective barrier against environmental oxidation, further supporting durability in potential humid or marine service conditions [28].

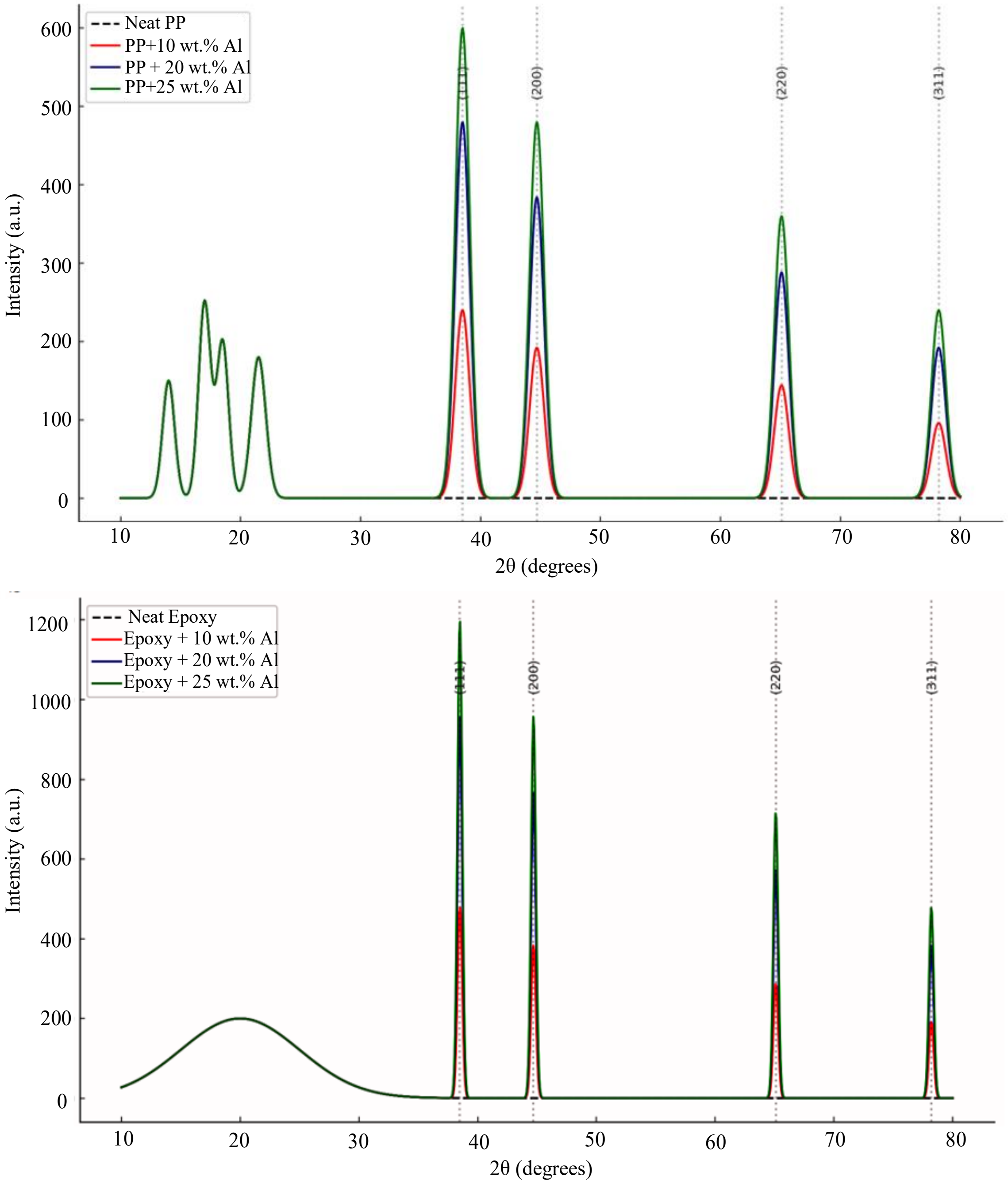

Figure 6. XRD patterns of polymer–micro aluminum composites: (a) Polypropylene composites (b) Epoxy composites

Collectively, Figures 6a and 6b confirm that micro aluminum acts as a structurally stable reinforcement phase, maintaining its crystalline nature in both thermoplastic and thermosetting matrices. The difference lies in the interfacial environment: polypropylene composites exhibit broader and weaker peaks due to partial overlap with polymer crystallinity and some agglomeration, whereas epoxy composites show sharper, more distinct peaks due to stronger filler–matrix adhesion.

These complementary findings, aligned with SEM and mechanical testing, establish that micro aluminum effectively enhances the crystalline–amorphous balance of the composites, leading to improved stiffness and load-bearing capacity up to an optimum threshold.

CONCLUSION

This work deals with the influence of micro aluminum reinforcement on polymer composites, and the outcomes allow the following conclusions to be drawn:

- Polymer composites reinforced with micro aluminum demonstrated maximum tensile strength at 20 wt.% loading, with ~42% improvement in polypropylene composites and ~38% improvement in epoxy composites, confirming the threshold for effective polymer–filler interaction.
- Flexural strength of the composites increased substantially, peaking at ~67% for polypropylene composites and ~39% for epoxy composites, showing that load transfer is strongly governed by the polymer–aluminum interface.
- Hardness values improved consistently up to 20 wt.% for both polymer composites, after which voids and clustering disrupted the homogeneity of the polymer–composite microstructure.
- SEM analysis validated the structure–property relationship of polymer composites, showing ductile fracture with well-embedded aluminum particles at intermediate contents, while particle pull-outs and brittle fracture dominated at 25 wt.% filler.
- XRD patterns confirmed the crystalline integrity of aluminum within the polymer composites, with sharper FCC reflections in epoxy composites due to stronger wetting and interfacial adhesion, reinforcing the role of matrix type in polymer–composite performance.

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