Advanced Lightweight Injection-Molded Polymer Composites: Recycling, Hybrid Manufacturing, and Integration of Industry 4.0

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Abstract

As global industries seek to minimize environmental impact while maintaining high production efficiency at the same time, there is a growing demand for advanced plastic-forming technologies capable of producing recyclable, lightweight, and structurally optimized polymer composites. Our research addresses this demand by developing hybrid manufacturing processes, advanced simulation tools, and tailored material systems, which enable more sustainable and energy-efficient production [1].

The foundation of our work lies in integrating injection molding, thermoplastic resin transfer molding (T-RTM), 3D printing, and now injection-compression molding into unified hybrid manufacturing platforms. When used individually or in combination, these technologies allow the design and production of warp-free, high-performance components, even with recycled, highly filled, or fiber-reinforced materials. Recognizing the limited geometric versatility of traditional T-RTM, our research group pioneered the combination of flat T-RTM plates with overmolded reinforcements and 3D-printed fiber preforms to create structurally efficient and geometrically complex parts. We developed a custom continuous fiber 3D printer capable of placing fiber bundles with controlled orientation, enabling the fabrication of directed reinforcement elements compatible with injection molding and T-RTM [2].

Our team established computational models to support these processes, which couple filling simulation including preform infiltration, and crystallization kinetics. We also introduced a novel

method to predict interfacial bonding strength in overmolded polymers. This calculation model has been partially integrated into Moldex3D simulation software [3-5].

A critical bottleneck in sustainable manufacturing is the limited understanding and predictability of the behavior of recycled materials. Our research investigates how fiber fragmentation affects mechanical and rheological properties during recycling. We have developed material models that capture the deviation from the ideal mixing laws when recycled content is blended with virgin material, which is essential for accurate simulation and robust design. We demonstrate that fiber degradation reduces mechanical properties and impacts the environmental footprint, emphasizing the trade-offs involved in designing for recyclability [1].

The transition toward Industry 4.0 has increased attention to real-time data acquisition and closed-loop control in injection molding. In this context, integrating in-mold sensors is a key to enhancing process transparency and ensuring product quality. Our earlier studies have demonstrated how pressure and temperature sensors embedded directly in the mold cavity can provide high-resolution data for monitoring critical stages such as filling, packing, and cooling [6]. Recent advancements extended this approach to multi-sensor systems capable of correlating locally measured information process phenomena with part quality and material behavior [7]. Beyond monitoring, machine learning techniques have also been applied to these sensor datasets, enabling predictive quality control and adaptive process optimization, thus fulfilling key principles of smart manufacturing [8]. These sensor-driven developments are essential to bridge the gap between material science, processing, and digitalization in producing fiber-reinforced polymer composites.

To demonstrate our hybrid technology, we designed and produced lightweight bipolar plates for open-cathode proton exchange membrane fuel cells (PEMFCs). This application set demanding requirements regarding dimensional precision, gas flow management, and electrical conductivity. We produced bipolar plates from heat-conducting material and optimized them using computational fluid dynamics and injection molding simulations. The result is a fully polymeric bipolar plate geometry suited for portable fuel cell applications such as drones and small electric vehicles, offering substantial weight reduction and recyclability compared to metal-based counterparts.

Our work bridges materials science, process engineering, simulation, and sustainability, and addresses the systemic challenge of transitioning to a circular polymer economy. By integrating AI, real-time monitoring, and LCA into manufacturing development, we aim to establish robust, scalable methods that empower the use of recycled materials without compromising product performance or design freedom. Our long-term vision is to enable the autonomous optimization of polymer processing, turning recycling from a liability into a reliable engineering asset.

Keywords: injection molding, hybrid composites, thermoplastic resin transfer molding, recycling, simulation

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