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TITLE: Enabling Circular Economy in Wind and Tidal Energy: Rheological Assessment of Recycled Elium® Based Thermoplastic Composites for Large-Format Additive Manufacturing (LFAM)

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ABSTRACT:

Over the last two decades, wind and tidal stream energy have emerged as highly promising green energy resources, playing an increasingly important role in the transition toward low-carbon power generation [1,2]. Fibre reinforced composite materials, and in particular thermoset (TS) matrix systems, constitute the dominant choice in commercial wind turbine blade architectures since they offer an optimal combination of low density, high structural integrity, and superior mechanical performance. The primary concern regarding turbine blades is the large volume of end-of-life waste they generate. Given an average operational duration of 20 years per turbine blade, the cumulative global waste from end-of-life blades is expected to reach approximately 43.4 million tonnes by 2050 [3]. However, thermoset composite systems exhibit limited recyclability due to their irreversible cross-linked polymer chain structures [2]. Consequently, the industry has been moving towards thermoplastic (TP) matrix composites, which are intrinsically remeltable and recyclable, thereby enabling a circular economy, where the recovery and reuse of materials are prioritised [1,4].

Elium®, an acrylic thermoplastic resin developed by Arkema Chemicals, is a novel fully recyclable composite matrix with exceptionally low viscosity [5,6]. Elium® composites can be recycled via several routes, including fully depolymerizing the resin back to monomeric units and extracting the fibers from matrix resulting in two recoverable components: reusable fibers and virgin resin. It can also be recycled via dissolution or regrinding into short fibre composite recyclate [7]. Leveraging its recyclability, Elium® represents a promising alternative for large-scale structures, as demonstrated by the ZEBRA (Zero wastE Blade ReseArch) consortium through the fabrication of a high-performance, fully recyclable Elium®/glass fiber composite wind turbine blade [8], which can be mechanical reprocessed into material for additive manufacturing [9].

Large-format additive manufacturing (LFAM) presents a promising approach for the production of scaled-up structures such as wind and tidal turbine blades. Utilizing recycled materials from end-of-life blades in LFAM production could contribute substantially to sustainability and reduce the environmental impact of these components. LFAM is a granule-based manufacturing process, where polymer pellets are melted along a heated screw and subsequently deposited as a continuous molten polymer bead [10]. Since polymers used in printing applications exhibit viscoelastic behaviour, rheological response becomes one of the governing physics in additive manufacturing processes. A thorough understanding of melt viscosity, shear-rate response, and thermal stability is critical in LFAM, as these parameters directly govern melt flow stability at the nozzle and interlayer adhesion, thereby influencing flow-related defects including nozzle clogging and bead spreading. Furthermore, insufficient viscosity can induce geometric instabilities such as warpage, shrinkage, and dimensional inaccuracy, particularly under high throughput and thermal gradients characteristic of LFAM [11].

In the aspect of recycled materials, variations in molecular-weight distribution and thermal history further modify the rheological response, necessitating preliminary characterization prior to process implementation.

This study develops a detailed rheological framework for recycled Elium®/glass fiber (GF) composites, with laboratory-scale additive manufacturing trials serving to connect material behaviour to eventual LFAM performance. Temperature sweeps using parallel-plate oscillatory rheometry will determine process-relevant melt windows, frequency sweeps will quantify linear viscoelastic (LVE) behaviour and transitions to non-linear regimes, and time-dependent tests will capture potential degradation or viscoelastic aging occurring during recycling. Particular attention is placed on interpreting complex viscosity, storage and loss moduli, and shear-rate-equivalent behaviour, allowing direct translation of rheological insights into extrusion-based deposition scenarios. Moreover, where feasible, the implications of extensional flow behaviour for filament stretching and bead stability in LSAM will be considered.

To bridge the gap between material characterisation and LFAM-scale processing, the recycled composites will be tested on a lab-scale fused-granulate fabrication (FGF) additive manufacturing platform. This intermediate system allows controlled evaluation of flow behaviour during actual deposition, providing insight into how rheological properties translate into process performance. To better reflect real conditions, the print geometries will replicate a scaled components from an existing tidal turbine blade design. Extrusion temperature, nozzle geometry, screw speed, and deposition rate will be parametrically varied in accordance with the rheological findings. Outcomes such as bead shape stability, interlayer contact quality, degree of bonding, surface integrity, and flow-related defects will be measured to establish process–structure relationships for LFAM applications.

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