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TITLE: Manufacturing of Sustainable Carbon-Carbon composites: Integrating Recycled pyrolytic carbon, Natural Fibres and Energy Efficient Processing

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Carbon- Carbon composites are considered to be core materials for high-temperature and structural applications such as aerospace, automotive, and energy sectors [1]. Sustainable carbon composites align with the United Nations Sustainable Development Goals (SDGs) [2] which focusses on reducing the carbon footprints and emphasizes circular material utilization. Traditional manufacturing of carbon composites involve chemical vapour infiltration (CVI) alongside petroleum-derived polyacrylonitrile (PAN) or pitch precursors (resins). They are energy demanding processes, restricting recyclability. This review paper is a comprehensive review and experimental proof of concept (PoC) that walks through C/C processing with bio-based precursors, natural fibres, carbon nanotubes (CNTs), and recycled carbon sources.

Recent studies focus on sustainable processing methods that focus on natural fibres, along with maintaining structural integrity. Flax, hemp, bamboo and jute when carbonized at temperatures less than 1200°C have emerged as promising reinforcements showing dual-scale porosity, influencing the recent infiltration patterns [3][4][5]. Structural integrity can be introduced with the help of biomass carbon derived from lignin [6]. Shear thinning behaviour that aids dispersion during mechanical stirring can be induced with CNTs and pyrolytic carbon (0.5-2wt%). However, challenges such as uniform wetout in hand layup and resin transfer moulding (RTM) exist that cause agglomeration. Manufacturing processes -hand layup, vacuum assisted resin transfer moulding (VARTM), liquid composite moulding, and carbonisation density are analysed for their flow characteristics, which include resin front progression, race tracking risks and void formation (typically 2-8vol% in bio -preforms).

Energy conservation is a key parameter for sustainability assessment, via novel synthesis methods such as microwave-assisted curing induction, electrical heating with conducting pathways, Self-Resisting Electrothermal Curing (SRETC), infrared heating and catalytic polymerisation [7] [8] that aids in decreasing cycle time by 40 to 60% in contrast to conventional autoclave processing. Methods such as pyrolysis recovery (carbon yield 70-85%, 42 wt% char yield when heated under the influence of inert gasses) mechanical reclamation and solvolysis can be adopted to resolve recyclability by supporting close- loop re-impregnation of fragmented C/C scraps. The review links these material innovations to FPCM17 themes: energy-efficient processing through optimised rheology-cure coupling, recycled composites, bio-composites via natural fibre.

Complementing this synthesis, a proof of concept (PoC) validates the feasibility of sustainable C/C fabrication using recycled pyrolytic carbon reinforcement as shown in Figure 1. Mechanical properties of a conventional carbon composite and a pyrolytic carbon mixed composite are to be studied. Research reveals that, they are expected to show more abrasive properties and better density.

This approach demonstrates that controlling flow behaviour across all processing stages, covering stirring rheology, hand layup to curing process, and pyrolysis gas evolution, enables scalable manufacturing of C/C composites. The recycled tyre-derived pyrolytic carbon not only reinforces mechanical performance but exemplifies waste-to-value conversion aligned with SDG 12 (responsible consumption) [2]. Circular design principles are proposed, including modular preforms for selective recycling and hybrid RTM-pyrolysis for complex geometries. Future directions encompass process modelling and industrial RTM scaling. By bridging sustainable materials with FPCM17's flow process expertise, this work charts a practical roadmap for a sustainable C/C manufacturing.

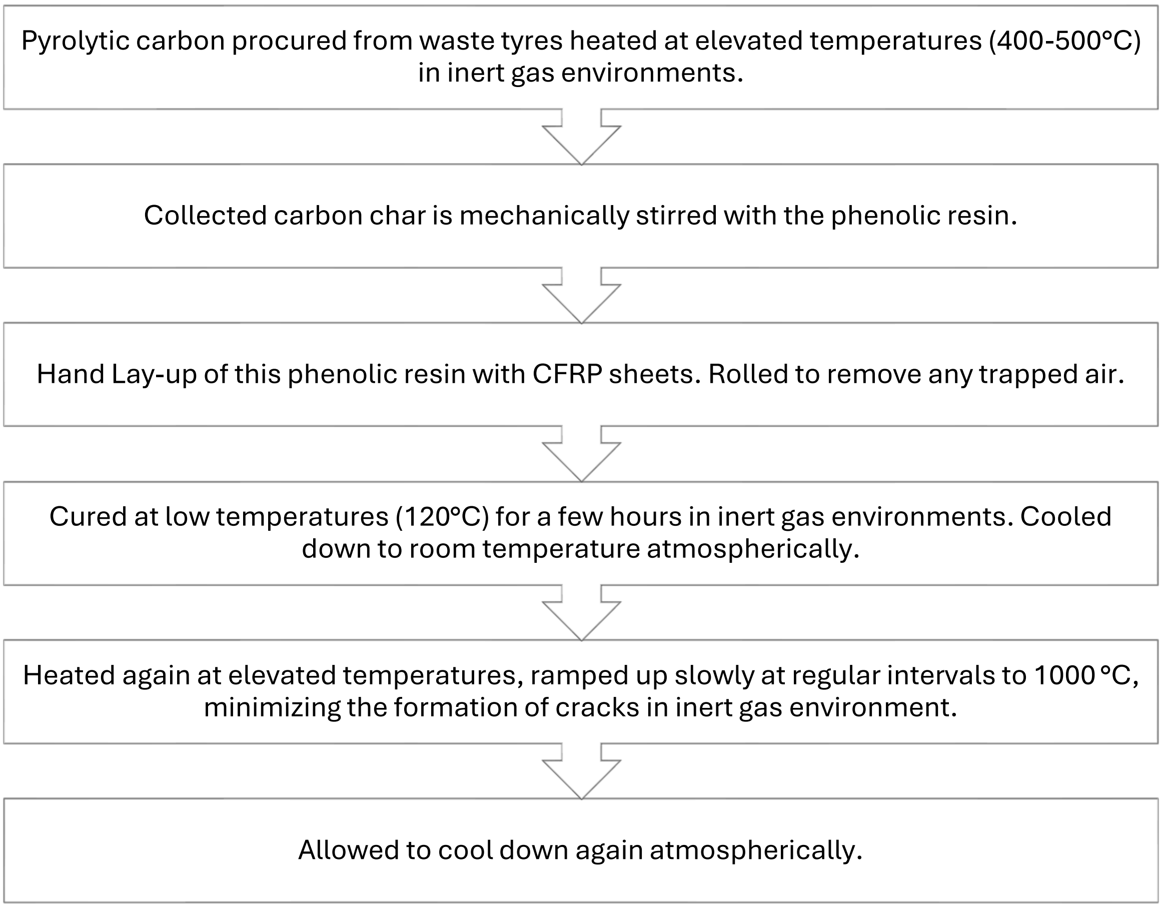

Figure 1: Flow process of the manufacturing of a sustainable C/C with pyrolytic carbon obtained from waste tyres

Keywords: sustainable C/C composites, pyrolytic carbon recycling, bio-based precursors, flow processes, energy-efficient pyrolysis

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