Abstract

Recent advancements in lightweight structural and functional materials have intensified the demand for aluminum matrix composites with enhanced mechanical, tribological, and electrical performance. Conventional liquid-state fabrication routes for carbon fiber-reinforced aluminum (CF/Al) composites are constrained by poor wettability, interfacial reactions, fiber degradation, and porosity. Although solid-state friction stir processing (FSP) alleviates melting-related defects, intrinsic asymmetry in material flow and the limited width achievable in a single pass restrict uniform reinforcement distribution, dimensional control, and scalability for industrially deployable component sizes. Such limitations necessitate a controlled tool offsetting strategy to regulate material transport, expand the processing zone, and achieve dimensional integrity beyond single-pass capability.

The present thesis explores the fabrication, microstructural evolution, and multi-functional performance of CF/Al matrix composites developed using an upward friction stir processing (UFSP) technique. Emphasis is placed on establishing the tool offsetting as a critical process control parameter which governs material flow behaviour, reinforcement transport, and metallurgical consolidation during UFSP. The effects of tool offset direction, number of processing passes, and carbon fiber content (1-4 wt.%) on reinforcement distribution, grain refinement, defect evolution, and resultant mechanical, tribological, and electrical properties are investigated.

Multi-scale microstructural characterization using 2D scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and 3D X-ray computed tomography (XCT) reveal that tool offset direction plays a decisive role in controlling CF distribution and internal integrity. The retreating-side (RS) offset promotes stable and symmetric material flow, resulting in uniform CF dispersion, effective suppression of tunnel and wormhole defects, and superior metallurgical properties. In contrast, the advancing-side (AS) offset leads to CF-rich banding and CF-depleted regions. Progressive grain refinement is achieved with increasing processing passes, with the optimized double-pass RS (2PRS) condition producing the finest grain size (~5.05 μm) through severe plastic deformation and dynamic recrystallization (DRX). Density measurements confirm with minimal porosity, while XRD analysis verifies CF chemical stability without carbide formation or fiber degradation.

Mechanical testing demonstrates that the composite containing 3 wt.% CF fabricated under the RS offset condition exhibits the best overall performance. This achieves a 14-20%

improvement in ultimate tensile strength with controlled ductility reduction. The highest hardness (~92 HV) is obtained under the 2PRS condition due to the combined influence of Hall-Petch strengthening and effective load transfer from carbon fibers. Fractographic analysis reveals mixed-mode ductile fracture with deep dimples, confirming efficient stress transfer to the reinforcement prior to fiber fracture or interfacial debonding.

Tribological investigations identify the RS tool offset strategy yield up to 67% reduction in wear rate and 46% reduction in friction coefficient compared to Al matrix. This is attributed to the formation of a stable CF-based solid lubricating tribolayer. Electrical characterization demonstrates that tool offsetting enables the formation of continuous CF networks, reducing electrical resistivity by up to 30% and minimizing resistive heating under high current loading, thereby enhances thermal-electrical coupling.

Overall, this thesis establishes tool offsetting as a scalable process variable in UFSP, enabling precise control over reinforcement distribution, microstructural refinement, dimensional integrity, and property optimization. The proposed UFSP-tool offset strategy offers a robust solid-state manufacturing route for producing high-performance CF/Al composites suitable for lightweight structural, tribological, and electrical applications.

Keywords: Friction Stir processing, Metal matrix composite, carbon fiber, Material flow, Grain size, light weight material