My research focuses on advancing the fundamental understanding of solid-state manufacturing processes, particularly friction stir welding (FSW) and additive friction stir deposition (AFSD). These techniques offer transformative potential in materials processing due to their ability to achieve refined microstructures and superior mechanical properties, all while avoiding issues associated with melting and solidification. Through a combination of multi-physics modeling and experimental characterization, my work aims to uncover the underlying mechanisms governing material flow, phase transformations, and microstructural evolution in solid-state processes.

Research Vision and Contributions

Solid-state manufacturing processes uniquely enable grain refinement through dynamic recrystallization and exhibit distinct material flow behaviors influenced by thermomechanical conditions. Understanding these behaviors is essential to controlling final microstructures and mechanical performance. My research agenda builds on this foundation, bridging computational modeling with microstructural analysis to answer fundamental questions and inform process optimization.

During my Ph.D. at IIT Bombay and current postdoctoral work at Virginia Tech, I have developed and validated advanced CFD-based numerical models for both FSW and AFSD. My contributions can be grouped as follows:

1. Material Flow and IMC Formation in Dissimilar FSW

My doctoral research addressed the complex flow phenomena and intermetallic compound (IMC) evolution during FSW of dissimilar materials (e.g., Al-Cu[1], Al-Mg[2], SS-Ti[3]). I created a 3D thermo-fluid model using Volume of Fluid (VOF) methodology to simulate interface behavior and material transport across the weld seam. Coupling this with thermodynamic models based on Fick's Law and Gibbs free energy, I predicted IMC formation with spatial and temporal resolution[4].

Key experimental validations involved optical microscopy, SEM, EBSD, and X-ray tomography, which confirmed numerical predictions and provided insight into how tool parameters influence IMC thickness and distribution.

2. Multiscale Microstructure Characterization and Simulation

Through collaborative efforts, I investigated dynamic recrystallization, texture evolution, and phase transformation during FSP and rotary friction welding. Notable outcomes include:

- Phase transformation mapping in DP600 steel under FSP[5]
- Microstructure evolution in multi-pass FSP of Mg alloys[6][7]
- Interface analysis in Al–Steel rotary friction welding and SS304 AFSD[8]
- Friction stir deposition of stainless steel[9]

3. Advanced Modeling of Additive Friction Stir Deposition

At Virginia Tech, I developed a 3D CFD model to analyze asymmetric helical flow paths and thermomechanical histories during AFSD of aluminum alloys[10]. This modeling effort was coupled with experiments to validate predicted temperature fields and grain structures, revealing consistent material behavior across deposition layers.

Future Research Agenda

Building on my current expertise, I propose to extend my research in the following directions:

1. Heterogeneous Lamellar Microstructures via AFSD

Achieving a balance between strength and ductility remains a materials design challenge. I aim to engineer heterogeneous lamellar microstructures using AFSD by exploiting its mixing capabilities and thermal gradients. This work will involve modeling temperature–strain rate gradients and validating with EBSD-based orientation mapping.

2. Tool Wear and Contamination in High-Strength Alloys

AFSD of titanium and stainless steel introduces challenges related to tool degradation. I plan to develop wear prediction models for different tool materials (PCBN, WC, W-Re), combined with metallurgical analysis to quantify contamination effects on deposition quality.

3. Phase Transformation Modeling in AFSD of High-Strength Alloys

Using kinetic models (e.g., JMAK, Koistinen-Marburger), I will explore solid-state phase evolution during deposition of Ti and steel alloys, integrating thermal histories from CFD simulations with in-situ microstructure tracking.

Broader Impact and Collaborations

I actively collaborate with interdisciplinary teams including mechanical engineers and materials scientists, to link simulation with advanced characterization. I intend to continue such partnerships and mentor students in cross-disciplinary manufacturing research.
In summary, my research explores the physics of solid-state processing, guided by computation and validated through experimentation. I am committed to addressing both fundamental scientific questions and application-driven challenges in modern manufacturing.

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