

Computational analysis of adhesive squeeze flow during joint assembly on rough substrates

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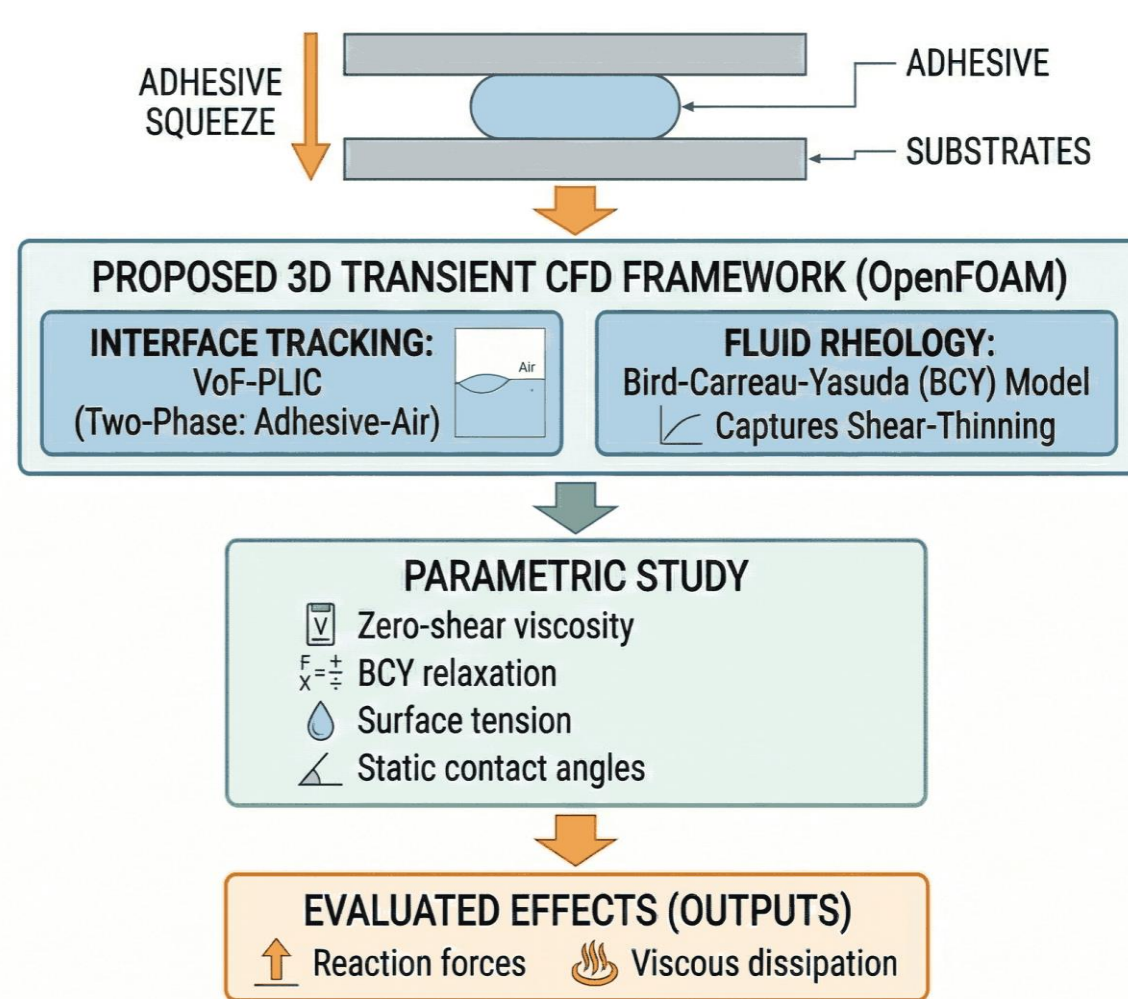
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1. Introduction

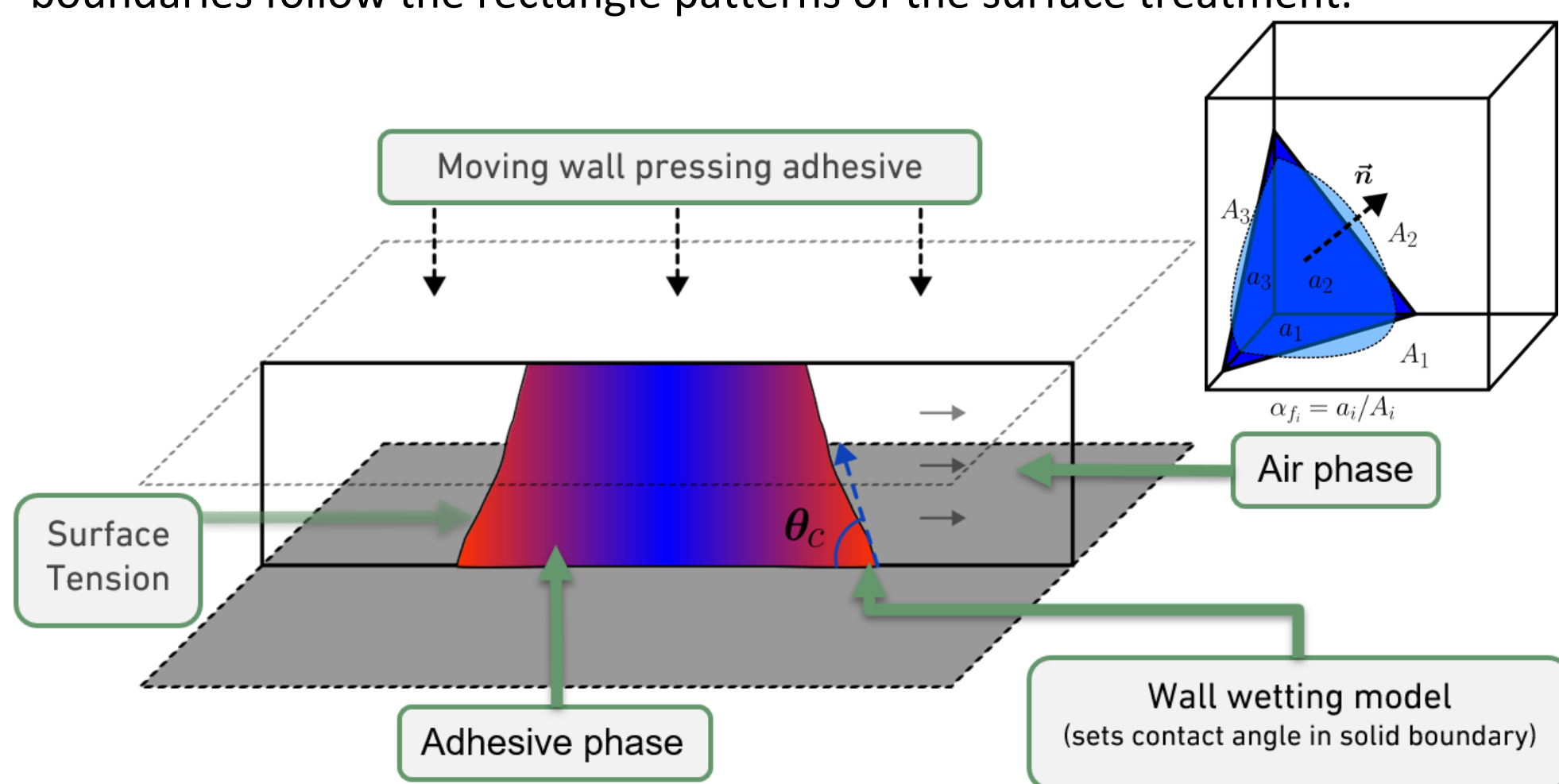
The squeeze flow of uncured adhesives during assembly dictates joint reliability and uniform stress transfer. Currently, much of the existing literature on numerical models relies on idealized flat conditions, failing to capture complex shear-thinning rheology, localized surface forces at the adhesive-substrate interface, and the physical influence of substrate micro-texture.

2. Materials and Methods

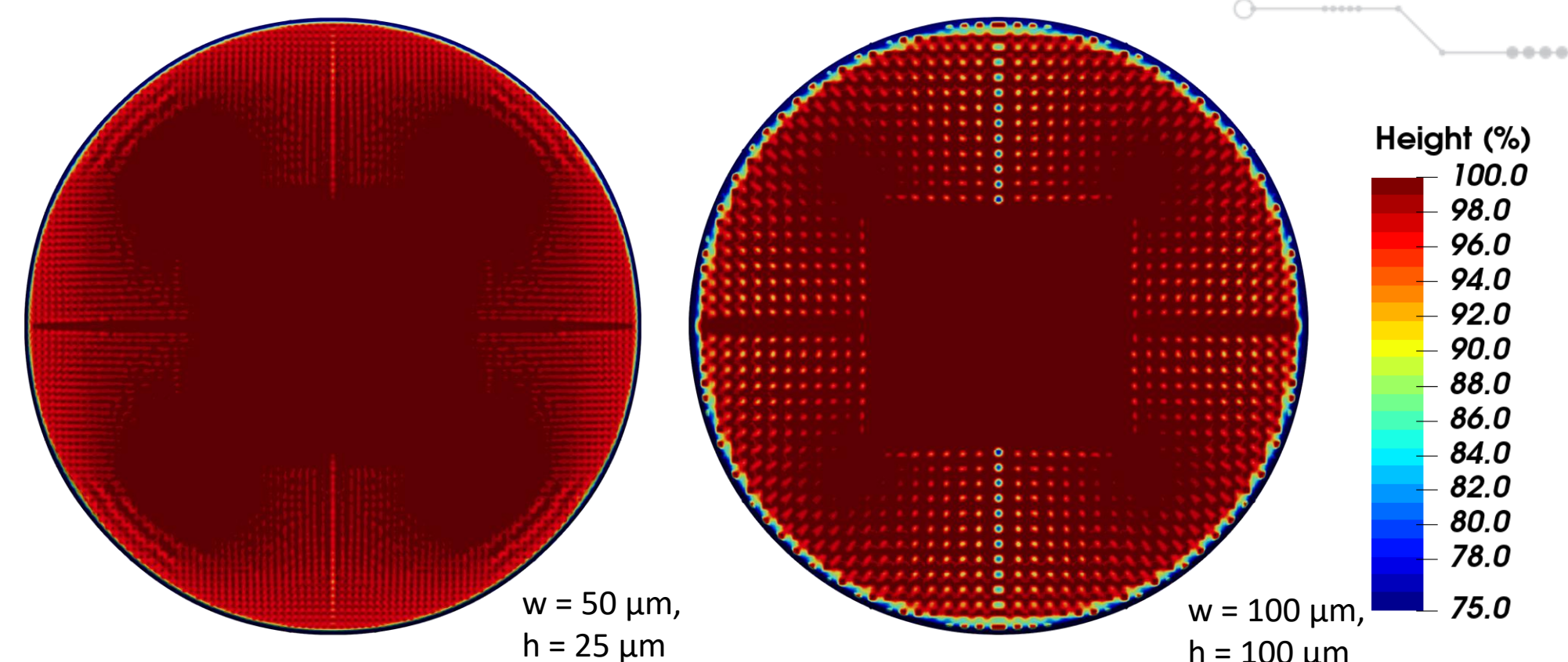
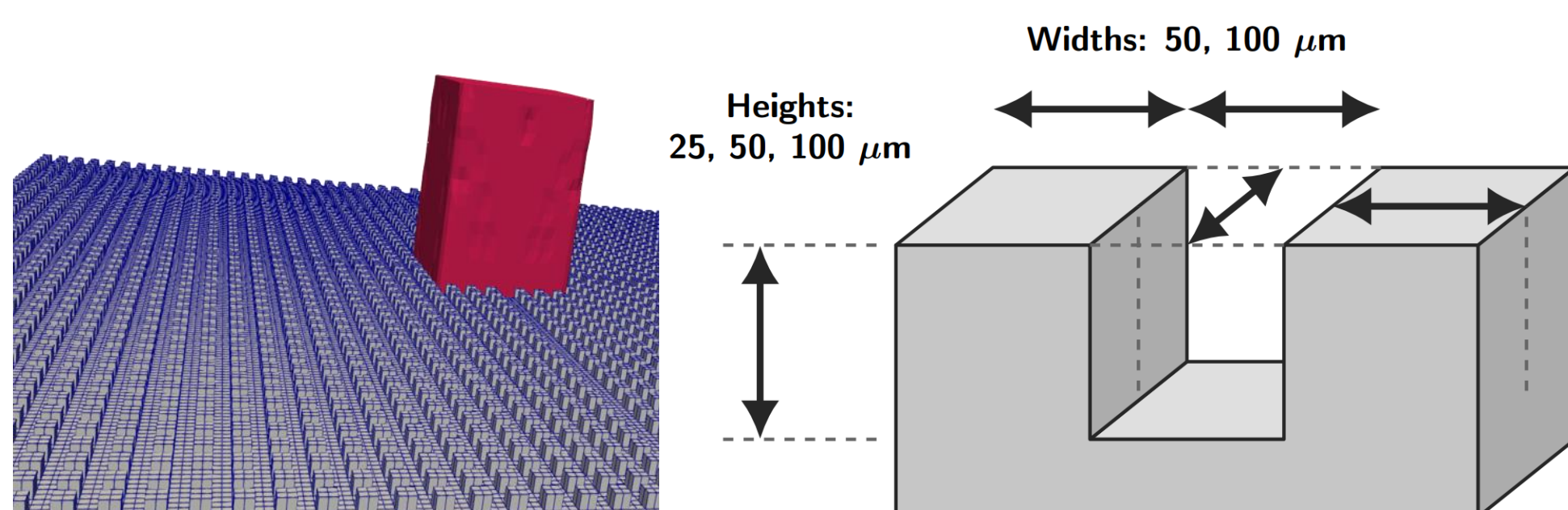
To address this gap, a fully 3D transient computational fluid dynamics (CFD) framework was developed, modeling the adhesive as a Bird-Carreau-Yasuda (BCY) fluid. A parametric study evaluates the isolated effects of the micro-textured geometry, zero-shear viscosity, BCY relaxation, surface tension, and static contact angles over the discretely patterned surfaces.



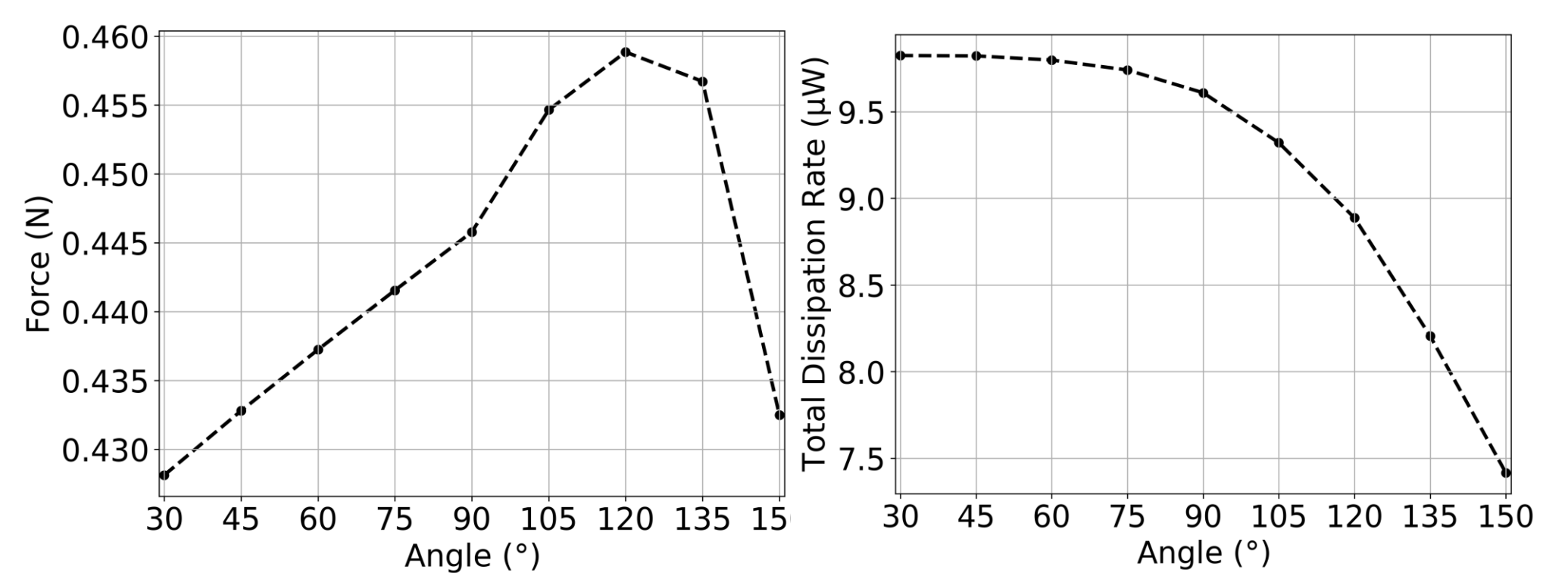
The system is modeled using a two-phase Volume of Fluid (VoF) solver based on the Finite Volume framework of OpenFOAM, with interface properties tracked via a Piecewise Linear Interface Construction (PLIC) algorithm. Transient simulations are ran on a dynamic mesh, whose boundaries follow the rectangle patterns of the surface treatment.



3. Results



Air plane cross-sections for the 100 μm width and 100 μm height pattern reveal significant arrays of regular entrapped bubbles. Thickness maps comparing shallower and deeper patterns indicate that deeper cavities retain a high-viscosity core, which shields the fluid from bulk shear, preventing capillary filling and leaving pronounced void footprints.



The wetted-area-ratio by pattern exhibits an initial contact drop during the squeeze onset, with narrower and shallower patterns showing much stronger recovery. Reaction forces decrease on deeper patterns due to a higher effective film thickness. Furthermore, maximum reaction force exhibits a non-monotonic dependence on the final contact angle, peaking at 120° due to optimal capillary resistance against gap entry. Conversely, the final viscous dissipation rate decreases parabolically with the contact angle, as reduced wettability promotes slip and lowers total energy dissipation.



4. Conclusions

Substrate topography largely governs air entrapment; deeper channels inhibit the adhesive from the influence of shear fields, lowering texture compliance. While increasing texture depth lowers reaction forces, it disproportionately increases trapped void volumes. Shear-thinning behavior and high interfacial tension are the main drivers for mitigating squeeze loads while improving substrate impregnation. If patterned modifications are used, narrower gaps are strictly preferable to minimize air voids and bubble formation. Identifying these geometric and rheological dependencies streamlines numerical modeling for defect prediction in manufacturing applications involving rough substrates.