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Laser-Textured Superbiphilic Aluminum Surfaces: Fabrication, Wettability Evolution, and Potential for Flow Boiling Enhancement

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Abstract

This study investigates the fabrication of laser-textured superbiphilic surfaces on Aluminum for potential flow boiling enhancement. A nanosecond fiber laser was used to generate various micro-patterns, with surface morphology and wettability evolution characterized over a 20-day period using SEM, EDS, profilometry, and contact angle measurements. Results demonstrate the successful creation of surfaces with extreme and stable wettabilities. Superhydrophobic regions were achieved, with one spot evolving from a hydrophilic state (51.2°) to a superhydrophobic state (150.2°) after 12 days. Concurrently, robust superhydrophilic regions (<5°) were created. This temporal evolution is attributed to specific micro-textures (Sa = 7.392 µm) enabling air trapping and hydrocarbon adsorption. Superhydrophilicity was linked to a more extensive oxide layer (O = 53.05 wt% vs. 30.85 wt%). These findings highlight the potential of laser texturing for engineering superbiphilic surfaces.

Key words: Superbiphilic Surfaces, Laser Texturing, Wettability, Surface Modification

1. Introduction

While flow boiling is a highly effective cooling mechanism vital for advanced electronics, traditional smooth surfaces struggle to control the complex two-phase phenomena, leading to challenges like high incipience superheats and premature Critical Heat Flux (CHF) [1]. To address these, various surface modification strategies have been developed to manipulate interfacial phenomena [2].

Among these engineered surfaces, biphilic surfaces—those integrating distinct regions of hydrophilic and hydrophobic wettability on a single substrate—have emerged as a particularly promising strategy. The strategic patterning of these zones is hypothesized to create a synergistic effect: hydrophilic regions can serve as stable sites for bubble nucleation, while adjacent hydrophobic regions can facilitate easier bubble departure [3]. Laser texturing, with its precision and versatility, offers a direct-write capability to fabricate such complex patterns directly onto metallic substrates [4]. This study focuses on using nanosecond laser texturing to create surfaces with controlled superbiphilic characteristics on Aluminum and to characterize the temporal evolution of surface properties.

2. Experimental Approach

Commercially pure Aluminum (Al H111) plates were cut in to 50x50x1mm^3, polished using a multi-stage procedure to a final thickness of 0.89 mm, and ultrasonically cleaned in Ethanol.

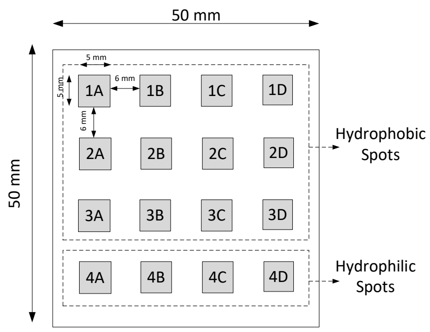


Fig. 1. Schematic of the 4x4 array of textured spots on an Aluminum sample plate.

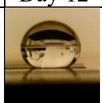
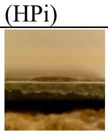
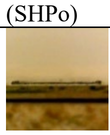
Surface texturing was performed using a fibre nanosecond laser system in 4x4 array of distinct

5x5 mm^2 patterns on Aluminum plates (Fig. 1). For patterns intended to promote hydrophobicity (2C, 3B), triangular and intersecting circular designs were used with varied laser parameters (speed, power, frequency, etc.). For patterns intended to promote hydrophilicity (4C, 4D), parallel linear grooves with a fine pitch (1 µm) were targeted.

3. Results and Discussion

Contact angle measurements revealed a significant temporal evolution, as summarized for key spots in Table 1. Most freshly textured spots were initially hydrophilic (HPi). However, patterns designed for hydrophobicity (HPo) transitioned significantly over several days. For example, Spot 2C evolved from a CA of 51.2° on Day 1 to a superhydrophobic (SHPo) state of 150.2° by Day 12. In contrast, hydrophilic-designed spots like Spot 4D rapidly achieved and maintained robust superhydrophilicity (SHPi) with <5° by Day 12. Further measurements on Day 20 showed only minimal changes from Day 12 values, indicating that the surface wettability had largely stabilized.

Table 1. Summary of CA measurements on selected spots at Day 1 to Day 20.

	Day 1	Day 6	Day 12	Day 20
2C	 CA = 51.2° (HPi)	 CA = 146.6° (HPo)	 CA= 150.2° (SHPo)	 CA = 151.6° (SHPo)
4D	 CA = 17.6 (HPi)	 CA = 11.9 (HPi)	 CA = ~ 4° (SHPi)	 CA = ~ 3° (SHPi)

Energy Dispersive Spectroscopy analysis on Day 12 revealed significant differences between the superhydrophobic Spot 2C and the superhydrophilic Spot 4D. Was observed a substantially higher oxygen content on Spot 4D indicates a more extensive aluminum oxide (Al_2O_3) layer. This inherently hydrophilic oxide, combined with the increased micro-roughness from texturing, promotes extensive water spreading and stable superhydrophilicity (Wenzel state), overriding any minor effects from adsorbed hydrocarbons. For Spot 2C, while an oxide layer is present, its evolution to superhydrophobicity is driven by its specific hierarchical micro-texture (observed via SEM) creating stable air pockets (Cassie-Baxter state), a condition facilitated by the adsorbed layer of non-polar hydrocarbons lowering the surface energy.

4. Conclusion

Preliminary investigation successfully demonstrated that nanosecond laser texturing is an effective method for modifying Aluminum surfaces to achieve controlled and extreme wettability states. It was confirmed that laser texturing can produce both stable superhydrophobic (>150°) and superhydrophilic (<5°) regions on a single metallic substrate by modulating laser parameters. The temporal was quantified, with wettability stabilizing after approximately 12 days. This transition was attributed to the synergistic effects of the specific hierarchical micro-topography created by the laser, which facilitates air entrapment, and the adsorption of airborne hydrocarbons on the high-energy oxide surface, as supported by elemental and chemical analysis.

5. Acknowledgements

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6. References

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