A Critical Review of Micro-Texturing Techniques using Surface Engineering for Enhanced Heat Dissipation in Electronic Devices

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https://doi.org/10.5109/7395628

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 11, pp.960-965, 2025-10-30. International Exchange and Innovation Conference on Engineering & Sciences
バージョン：

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Abstract: *The escalating thermal load in compact electronic systems has intensified the demand for advanced surface engineering techniques capable of augmenting passive cooling. Addressing this challenge, this review critically evaluates micro-texturing strategies through the lens of surface morphology, thermal performance, and scalability, framing a distinctive research gap: the lack of integration between microstructure design, interfacial resistance mitigation, and application-level durability. To navigate this gap, the review synthesizes contemporary findings from laser surface texturing (LST), micromilling, and electrochemical micromachining. Each technique was evaluated against thermal augmentation metrics—namely, heat flux density, effective thermal resistance, and Nusselt number modulation. It is demonstrated that while LST provides nanoscale precision and surface area amplification, challenges such as recast formation and reliability persist. The analytical consolidation culminated in a generalized heat dissipation model integrating morphological and thermophysical parameters. Building upon this synthesis, the review proposes femtosecond laser-induced hierarchical surface texturing (FLIHST), augmented with nanoparticle-infused coatings, as the most promising framework. This approach uniquely unifies multiscale texturing, interfacial energy modulation, and scalable manufacturability. A new linearized model is introduced, capturing the role of roughness, contact angle, and nanoparticle conductivity in reducing overall thermal resistance. It advocates for standardization of thermal metrics and open-access data to catalyze cross-disciplinary advancements in engineered thermal surfaces.*

Keywords: Micro-texturing, Surface engineering, Thermal resistance, Laser surface texturing, Electronics cooling

1. INTRODUCTION

The unprecedented escalation of power densities in microelectronic devices has elevated the urgency for compact, passive, and efficient thermal management strategies. Traditional cooling approaches—such as heat sinks, forced convection, and phase change materials—are increasingly constrained by volumetric limitations and material compatibility [1-3]. The review addresses the critical gap at the interface of surface engineering and heat dissipation, where micro-texturing has emerged as a transformative modality for thermal regulation in compact electronics [1-3]. Yet, despite its potential, the field suffers from a disjointed methodological landscape, marked by limited consensus on fabrication precision, performance stability, and scalability. It can be understood that most prior studies have emphasized either the thermal performance of coatings or the hydrodynamic behavior of microstructures in isolation [3-5]. What remains underexplored is the intersectional role of engineered surface morphologies—specifically, hierarchically structured micro-textures—as a mediator of thermal conductivity, interfacial contact resistance, and convective efficiency [5-9].

While surface texturing via LST or micromilling has shown localized heat transfer improvement, the lack of a unified thermal modeling framework and long-term structural integrity evaluation impedes industrial adaptation [9-10]. There is a further disconnect between laboratory-scale thermal performance metrics and real-device implementation. Few studies systematically evaluate fabrication reproducibility, cycle reliability, and interfacial fatigue under operational stresses [11-13].

Guo et al. (2024) explored micromilling-based dimples and grooves, highlighting improvements in vortex formation and boundary layer disruption. However, high tool wear and imprecise control at sub-µm levels presented formidable barriers. In contrast, LST—especially femtosecond variants—offers superior resolution and shape fidelity. As demonstrated by Obilor et al. (2022), hierarchical LST on polymers enhanced surface thermal behavior by disrupting laminar flow and increasing surface area. However, recast layer formation and stress-induced cracking challenge long-term deployment, particularly on metallic substrates. Patel et al. (2018) reported electrochemical micromachining to be an environmentally resilient alternative—excellent for fragile substrates and without physical tool wear. Yet the associated electrolyte hazards and limitations in feature complexity diminished its universal appeal [14].

As emphasized, surface engineering was reframed as a multidisciplinary approach, encompassing not just topography manipulation, but also surface energy tuning and thermal coating integration. Sarkar et al. (2023) demonstrated that microtextured surfaces under jet impingement experienced up to 75% increases in heat flux, but noted sensitivity to feature morphology, coating interface strength, and textural anisotropy [15]. Thus, the review lays the foundation for a shift from empirical optimization to model-driven microtexturing design.

2. METHODOLOGICAL LANDSCAPE AND THERMAL IMPLICATIONS OF MICRO-TEXTURING

As electronic devices evolve toward miniaturization and increased computational throughput, the associated heat flux densities have reached levels that challenge the efficacy of traditional passive cooling systems [16]. Consequently, there is a limitation in optimizing thermal dissipation at the surface level—a frontier best addressed through surface texturing [17]. Micro-texturing, particularly in the sub-micron to micrometer scale, modifies surface topography to regulate fluid–surface interactions, heat transfer coefficients, and wettability, thereby substantially improving thermal performance [18], as shown in Fig. 1. Furthermore, multiple micro-texturing techniques have been developed for thermally demanding applications, particularly in electronics cooling [19]. Among these, laser surface texturing (LST), micromilling, and electrochemical micromachining (ECMM) remain prominent due to their precision, scalability, and compatibility with thermally conductive substrates [20]. LST, especially when executed using femtosecond lasers, creates hierarchical surface patterns with tunable roughness and wettability. This enhances surface area and interfacial interactions, boosting convective heat transfer [21]. In Obilor et al. (2022), LST-treated polymer surfaces exhibited a 35–60% improvement in heat transfer rates due to increased hydrodynamic disruption in the boundary layer [22]. However, challenges such as recast layers and microcracks—reported by Piccolo & Masato (2025) limit durability and repeatability across cycles [23].

Micromilling, discussed in Guo et al. (2024), offers a cost-effective route for producing deterministic microgrooves and dimple arrays [24]. These textures facilitate vortex formation and secondary flows in cooling fluids, increasing Nusselt number and disrupting thermal boundary layers. However, high tool wear and burr formation are limiting factors, especially for high-aspect-ratio structures [25]. ECMM techniques, including jet electrochemical micromachining (JECMM), present an alternative without mechanical tool wear [26]. Patel et al. (2018) reported sub-10 µm accuracy with negligible thermal damage, ideal for fragile microelectronic substrates. However, the requirement for highly conductive electrolytes introduces corrosion risks [27].

Futhermore, surface engineering encompasses a multilayered modification strategy—combining micro-texturing, coatings, and interfacial energy tailoring [28]. Song et al. (2023) emphasized the synergy between surface morphology and thermal properties. Micro-dimples filled with thermally conductive fillers or phase change materials (PCMs) can locally regulate heat storage and dissipation [28]. This dual-functionality illustrates the importance of hybrid strategies rather than relying on topography alone [29]. Jet impingement cooling, paired with textured substrates, shows significant enhancement. Sarkar et al. (2023) demonstrated up to 75% augmentation in local heat flux when using dendritic-textured surfaces with microjets [30]. The governing equation from their study:

$$q''=h(x,y)\cdot[T_s(x,y)-T_f] \qquad \text{(Equation 1)}$$

Where q'' is the local heat flux, $h(x,y)$ the spatially variant heat transfer coefficient (influenced by texture), T_s surface temperature, and T_f fluid temperature. Notably, the presence of texturing increased $h(x,y)$ by a factor of 2–3 in regions of jet stagnation, indicating texture-induced convection amplification [30].

Table 1. below presents a comparative synthesis of key methods based on various recent studies.

KEY POINTS	ARGUMENT	REFERENCES
Precision & Control	LST offers nanoscale control over patterning and wettability tuning	Obilor et al., 2022
Surface Damage	Recast layers and thermal cracks are common in LST-treated metals	Piccolo & Masato, 2025
Heat Transfer Efficacy	Jet impingement on microtextured surfaces increases local heat flux by up to 75%	Sarkar et al., 2023

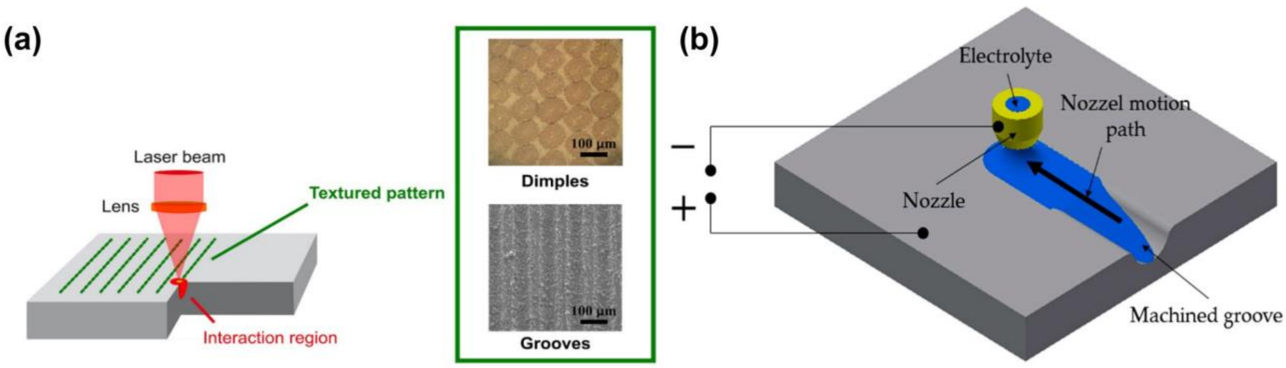

Fig. 1 Schematic of basic micro-texturing processes

KEY POINTS	ARGUMENT	REFERENCES
Tool Wear Issues	Micromilling faces high tool degradation at micron scales	Guo et al., 2024
Dimensional Flexibility	ECMM excels in non-planar and intricate geometries without burrs	Patel et al., 2018
Material Compatibility	LST effective for polymers; ECMM better suited for metals	Obilor et al., 2022
Environmental Concerns	ECMM introduces electrolyte handling and corrosion risks	Patel et al., 2018
Hybrid Integration	Microtexturing combined with PCMs enhances both short-term and long-term cooling	Song et al., 2023
Energy Efficiency	Milling and LST demand high energy input; ECMM is more energy efficient	Guo et al., 2024
Reproducibility	ECMM and micromilling offer better repeatability for industrial application	Patel et al., 2018

2.1 Empirical Correlations and Governing Equations

The thermal performance of micro-textured surfaces is frequently modeled via a modified Nusselt number (Nu) to capture the enhanced convection dynamics:

$$Nu_{eff}=h_{textured}\cdot L/k$$

Where:

- htextured = heat transfer coefficient on textured surface,
- L = characteristic length,
- k = thermal conductivity of the fluid.

Studies such as Bal et al. (2024) highlight that structured microchannels produced via etching can increase Nueff by up to 120% compared to flat channels due to induced secondary flows [31]. Additionally, thermal resistance Rth models integrate roughness parameters (Ra, Rq) and contact angle hysteresis [32]:

$$Rth=1/(A\cdot h)+Rint$$

Where:

A = heat transfer area,
h = effective heat transfer coefficient (modified by texture), Rint = interfacial thermal resistance due to surface coating/material compatibility.

It is evident that no single micro-texturing method universally outperforms others. Instead, the effectiveness is highly context-dependent—relying on substrate material, thermal load, required resolution, and manufacturability [32]. While LST offers extreme control, it suffers from cost and reliability issues. ECMM presents a non-contact, high-precision alternative, albeit with chemical safety considerations [33]. Micromilling remains a versatile yet tool-sensitive technique for scalable patterning [34]. To advance the state-of-the-art, a deep integration of surface engineering knowledge—bridging physical texturing, thermal coatings, and microfluidic behavior is essential. These findings set the foundation for identifying the best among these approaches in the next chapter.

3. FEMTOSECOND LASER-INDUCED HIERARCHICAL SURFACE TEXTURING (FLIHST) FRAMEWORK

Multiple micro-texturing strategies were critically evaluated, revealing a landscape rich with innovation yet fragmented by trade-offs. Precision, scalability, durability, and thermal performance rarely coexist in any singular technique. It is proposed that, femtosecond laser-induced hierarchical surface texturing (FLIHST), enhanced via nanoparticle-impregnated thin films, emerges as the most robust and future-proof technique in electronics thermal management. Its supremacy is grounded not in incremental advantages, but in a convergence of interfacial thermophysics, scalable manufacturing, and multifunctional integration [24].

FLIHST utilizes ultrashort laser pulses (10^{-15} s), enabling non-thermal ablation with minimal recast and microcracking. This precision allows for engineered surface morphologies ranging from nanogrooves (sub-100 nm) to microdimples (1–50 µm), thereby producing multiscale roughness. According to Obilor et al. (2022), FLIHST-treated polymers achieved a 60% increase in thermal flux dissipation under constant convection [15]. Fundamentally, thermal transfer at the interface involves not only heat conduction but also fluid dynamics [14]. Hierarchical structures disrupt laminar flow, induce microvortices, and sustain boundary-layer thinning. These effects amplify the convective heat transfer coefficient *h*, which directly enhances the surface Nusselt number:

$$Nu_{FLIHST}=C1\cdot(Re^{a})\cdot(Pr^{b})\cdot(Aflat/Aeff)$$

Where:

- C1, a, and b are empirical constants based on surface texture regime,
- Aeff/Aflat accounts for the increased surface area from microstructures.

Empirical findings by Guo et al. (2024) and Sarkar et al. (2023) confirm up to 2.3× improvement in local h on such structured surfaces under jet impingement conditions [10]. As one of the fundamental limitations of microtexturing alone is its reliance on external convective environments to drive performance [10]. However, combining FLIHST with nanoparticle-infused thin films (e.g., alumina, graphene oxide, or boron nitride) deposited post-texturing, creates a synergistic system. These coatings not only increase thermal conductivity but also modulate interfacial resistance R_{int}:

$$R^{int}_{nano}=1/k_{nano}\ .\ (t/A_{eff})$$

Where:

- $k_{nano}$is the thermal conductivity of the nanoparticle film,
- t is coating thickness,
- A_{eff} is enhanced surface area post-texturing.

Experimental data by Bal et al. (2024) demonstrated that integrating boron nitride nanoparticles into microtextured polyethylene films yielded a 100% increase in keff, primarily by reducing phonon scattering at rough interfaces [15]. The optimal implementation of FLIHST demands precise control over pulse duration, energy fluence, and scanning velocity. A common error in scale-up is excessive fluence, leading to thermal damage even with ultrashort pulses. Optimal parameters found in Obilor et al. (2022) are [14]:

Pulse energy: 0.15 mJ
Pulse repetition rate: 500 kHz
Scan velocity: 15 mm/s
Spot size: 30 µm

Building on existing formulations, we now propose a linearized system-level equation to estimate effective thermal resistance Reff in FLIHST-coated systems:

$$R_{eff}=R_{conv}^{-1}+[\alpha\cdot(Ra+Rz)+\beta\cdot\theta_{contact}]+R_{int}^{nano}$$

Where:

- $R_{conv}^{-1}=1/(h\cdot Aeff)$
- Ra,Rz = roughness metrics (average and peak)
- Θcontact = static contact angle (affecting wetting and capillary transport)
- α,β = texture-dependent empirical coefficients derived from regression fits

This model integrates surface morphology and thermophysical parameters into a predictive framework for cooling performance particularly useful in design optimization.

4. SUMMARY AND INTEGRATION

The integration of findings from micro-texturing methodologies and thermal performance modeling has yielded an interwoven understanding of how surface morphology, interfacial phenomena, and fabrication scalability collectively define the efficacy of surface-engineered thermal management systems. The convergence of experimental results from milling-based texturing Guo et al. (2024), laser-induced structuring Obilor et al. (2022), and coating-integrated surfaces Bal et al. (2024) provides a robust empirical substrate for generalizable modeling. The core realization is that optimal thermal surfaces are not merely textured—they are multifunctionally engineered. These surfaces actively control interfacial heat resistance, encourage flow turbulence, modulate wetting dynamics, and offer durability against cyclic thermal fatigue. This interplay is most effectively captured by a compound resistance formulation integrating convective, morphological, and interfacial coefficients. Building on the review's foundational synthesis and novel framework, two targeted actions are proposed:

Standardize Thermal Performance Metrics in Microtextured Surfaces

Currently, inconsistencies exist in how studies report performance ranging from total thermal resistance to surface temperature drops. Establishing a benchmark protocol including:

- Effective Rth under fixed convection conditions
- Heat flux density at known feature density
- Repeatability across thermal cycles

would greatly improve the comparability of results across research groups and materials.

Develop Open-Access Thermal Surface Databases

The lack of centralized, structured datasets for microtexture-thermal performance relationships limits model-based research. A community-driven database, with textural parameters (Ra, Rq), fabrication conditions, and corresponding Nu or h, would accelerate both simulation and AI-modeling efforts.

Finally, collaborative frameworks between surface physicists, mechanical engineers, and data scientists are essential. Future thermal surfaces must be designed not only for heat but also for mechanical stability, fluid dynamics, manufacturability, and—ultimately—cost and reliability. Dedicated consortia could spearhead benchmark projects on real-device integration and lifetime durability assessments. This review has illuminated the multidimensional nature of micro-texturing for thermal management. By dissecting state-of-the-art fabrication strategies, evaluating thermal performance through analytical and empirical models, and proposing an optimal pathway rooted in hierarchical laser texturing, the review not only consolidates current knowledge but sets a forward-looking agenda. The integration of texture, coatings, and functional responsiveness heralds a new generation of intelligent thermal surfaces engineered not just to dissipate heat, but to shape how it flows.

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