

# Anti-Icing, Icephobic and Condensation-Managing Photopolymer Surfaces: Wetting State, Thermal Cycling and Service Durability

*A state-resolved framework from environmental pathway and water state to retained surface function*

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## Abstract

An anti-icing claim for a printed photopolymer is not established by a high water contact angle, a single freezing-delay experiment or a low initial ice-adhesion result. The service response depends on the printed and post-cured substrate, surface chemistry and texture, humidity, droplet or vapour supply, thermal history, freezing pathway, ice morphology, loading mode and accumulated environmental damage. Condensation can replace an initially non-wetted state with a water-filled texture; frost can form by condensation followed by freezing or by direct vapour deposition; and repeated thermal, icing, deicing, cleaning and wear cycles can alter chemistry, roughness and coating attachment.

This review defines a non-compensatory qualification architecture for anti-icing, icephobic and condensation-managing photopolymer surfaces. It separates freezing delay, frost suppression, ice adhesion, passive shedding and active deicing; requires wetting to be measured in the relevant thermal and humidity state; and treats contamination, condensate invasion, thermal mismatch and interfacial damage as changes in material state. Direct evidence from LCD-printed acrylate surfaces is combined with bounded adjacent evidence from thermoplastic additive manufacturing and nanoengineered or coated substrates. The result is a claim-specific framework rather than a formulation or geometry recipe. No universal contact angle, freezing delay, ice-adhesion strength, feature size, cycle count or service lifetime is established.

**Keywords:** printed photopolymer; anti-icing; icephobicity; condensation; frost; wetting state; ice adhesion; thermal cycling; durability

## 1. Significance and scope

Ice-related failure can begin before visible ice appears. Water vapour may condense within a texture, droplets may bridge features, a supercooled liquid may nucleate at defects, or frost may grow by a pathway different from the one used in a screening test. After ice forms, the engineering question changes from delaying formation to controlling adhesion, shedding or deicing energy. These functions share a surface but are not interchangeable.

ER-229 addresses already printed and post-processed photopolymer surfaces exposed to declared icing and condensation conditions. Its central decision is whether the claimed function remains supported after the environmental pathway and service challenges have changed the wetting, chemical, topographic and interfacial state.

### 1.1 Corpus boundary

ER-022 retains ophthalmic surface, ageing and application requirements. ER-040 retains general tribology and wear qualification. ER-072 retains general environmental ageing. ER-088 retains general topography and roughness metrology. ER-104 retains fluorinated photopolymer chemistry and PFAS boundaries. ER-168 retains general coating, encapsulation and adhesion qualification. ER-170 retains general accelerated-ageing design. ER-208 retains general surface-chemistry mapping. ER-225 retains plasma, corona and UV-ozone activation. ER-227 retains lubricity and friction. ER-229 is restricted to formation, retention and loss of anti-icing, icephobic and condensation-managing function under declared thermal and moisture histories.

## 2. Define the claimed function before selecting a test

At least five claims must be separated. Freezing delay concerns the time or temperature at which a specified liquid event freezes. Frost management concerns nucleation, coverage, growth, bridging or removal of a frost layer. Icephobicity concerns the force or energy required to detach a defined ice body. Passive shedding concerns removal under gravity, aerodynamic force or substrate motion. Active deicing concerns the energy and time required by heating, vibration or another applied mechanism.

A surface can perform well in one category and poorly in another. Delayed droplet freezing does not prove low adhesion of bulk ice. Low adhesion does not prevent frost bridging. A condensate-draining texture may sacrifice an initially high apparent contact angle yet improve recovery after a humidity event. Qualification therefore begins with a written claim, exposure path and failure mode, not with a preferred metric.

The LCD-printed acrylate study demonstrates that printed microgeometry and subsequent surface functionalisation can be investigated together for wetting, freezing and ice adhesion [1]. It does not collapse those endpoints into a single anti-icing property or make its numerical results transferable to another resin, geometry or climate.

### 3. Declare the complete environmental pathway

Record air temperature, substrate temperature, relative humidity or vapour pressure, cooling rate, thermal dwell, airflow, water source, droplet volume or impingement condition, nucleation protocol, ice-growth time and deicing route. The order matters. Cooling a dry surface before introducing humid air is not equivalent to cooling a pre-wetted surface. A static deposited droplet is not equivalent to freezing rain, fog, frost or condensate generated from the gas phase.

Nanoengineered-surface work distinguishes condensation-freezing from desublimation and shows that nanoscale texture can influence frost formation differently across environmental regimes [3]. This is a mechanism boundary, not a design rule for photopolymers. A qualification program should reproduce the intended vapour and thermal trajectory and document which phase-transition pathway actually occurred.

### 4. Preserve the printed and post-cured substrate state

Photopolymer surfaces inherit layer orientation, voxel or pixel exposure, wash history, post-cure, residual species, oxygen inhibition, support removal, polishing and storage. These variables can change surface chemistry, roughness, modulus, thermal response and coating attachment. Intentional microfeatures also depend on print fidelity and may round, clog or distort during washing and post-curing.

Record resin family and batch, printer and orientation, layer thickness, exposed face, washing, drying, post-cure spectrum and thermal history, storage, polishing and any activation or functionalisation. Where a texture is central to the claim, measure the printed feature rather than relying on the design file. Where a coating or graft supplies the function, characterise the underlying printed state and the completed interface separately.

The direct LCD study used a commercial acrylate-based printing route followed by functionalisation with a perfluoroalkylsilane [1]. Its PFAS classification, fluorinated-chemistry boundary and alternatives belong to ER-104; the reported result cannot be transferred to non-fluorinated functionalisation without requalification. The FDM polylactide study used silsesquioxane-modified thermoplastic material and is therefore adjacent evidence only [2]. Its value is to show that printing route, composition, wetting and ice response must remain linked; its composition and processing do not transfer to vat-cured networks.

### 5. Treat wetting as a state, not a single angle

A room-temperature sessile-drop contact angle measures one prepared state. It does not establish whether humid air condenses inside a texture, whether a droplet advances or recedes under cooling, whether pinning increases after contamination, or whether a metastable composite interface collapses into a fully wetted state. Static angle, advancing and receding angle, hysteresis, roll-off or sliding response and condensate morphology answer different questions.

Wetting measurements should be tied to temperature, humidity, fluid composition, droplet history and time. Image condensation at a scale capable of resolving where liquid first appears and whether droplets coalesce or invade features. Repeat wetting measurements after icing, deicing, abrasion, cleaning and thermal cycling. An initial high apparent angle cannot compensate for condensate retention or chemical loss.

The long-standing caution that superhydrophobic behaviour does not automatically equal ice repellency is supported by comparative icing evidence [7]. Durable-icephobic design work likewise treats interfacial mechanics, not contact angle alone, as the governing detachment problem [6].

### 6. Distinguish condensation, droplet freezing and frost

Condensation supplies liquid locally and can erase the air pockets on which some textured wetting states depend. Droplet-freezing tests begin with a prescribed liquid body and may be sensitive to placement, substrate defects and stochastic nucleation. Frost evolves across many nucleation sites and can bridge initially isolated features. These conditions must not be reported as equivalent.

For condensation, report onset relative to dew point, nucleation density, droplet-size distribution, coalescence, drainage and retained water after warming. For droplet freezing, report the nucleation protocol, censoring rule, number of replicates and the full distribution rather than only a mean delay. For frost, report pathway, coverage, thickness or mass, growth time, bridging and removal method. Desublimation research shows why the pathway must be verified rather than inferred from final appearance [3].

### 7. Separate nucleation delay from ice adhesion

Freezing delay is probabilistic and sensitive to droplet history, impurities, defects and thermal control. Ice adhesion is a mechanical measurement sensitive to ice geometry, growth procedure, loading mode, area definition, rate, temperature and interfacial fracture. A long delay does not set the detachment force, and low detachment force does not establish delayed nucleation.

Report individual freezing events, sample count, substrate-temperature trace and statistical treatment. For adhesion, define ice type and geometry, nominal and real contact area where defensible, loading configuration, rate, temperature and failure locus. Examine whether failure was interfacial, cohesive in ice, cohesive in the coating or within the printed substrate. The direct printed-photopolymer study addresses both icing delay and adhesion in a controlled architecture [1], but its values remain specific to that system.

### 8. Resolve surface architecture and mechanism

Four architectures are common: chemistry modified through the printed surface, designed texture, a deposited or grafted low-energy layer, and a liquid-like or lubricant-bearing layer. They can be combined, but each introduces distinct retention and failure questions. Texture may reduce real contact in one regime while trapping condensate in another. A thin coating may preserve geometry while failing by abrasion or delamination. A liquid-like layer may lower ice adhesion while depleting or contaminating its surroundings.

The ultralow-adhesion surface study combines superhydrophobic and liquid-like characteristics and evaluates a specific engineered architecture [4]. Robust-coating work emphasises toughness, substrate adhesion and self-healing in addition to initial ice response [5]. These sources support architecture-specific qualification; they do not establish that their chemistry, thickness or threshold applies to a printed photopolymer.

## 9. Include thermal mismatch and thermal cycling

Cooling and warming strain the printed substrate, any coating and their interface according to their thermal expansion, modulus, thickness and constraint. Water within pores or cracks can add hydraulic and freeze-expansion stresses. Repeated excursions can create microcracks, edge lifting or topographic change without an obvious loss in initial room-temperature contact angle.

Define minimum and maximum temperatures, ramps, dwells, number and sequencing of cycles, humidity during cycling and whether ice is present. Inspect the same locations where possible. Measure cracking, delamination, thickness or coverage, roughness and chemistry, then repeat the claim-specific icing test. General coating adhesion remains under ER-168 and ageing acceleration under ER-170; ER-229 requires those controls only as they determine retained ice-management function.

## 10. Challenge wear, contamination and cleaning

Dust, oils, salts, cleaning residues and biological or industrial films can change nucleation and pinning. Abrasion can flatten features or expose a higher-energy substrate. Cleaning can restore a contaminated surface, remove a functional layer or drive liquid deeper into a texture. Service durability therefore requires a defined sequence of contamination, cleaning, physical wear and icing rather than a single pristine test.

Outdoor icephobic-coating research demonstrates the need to connect protective mechanism with extended environmental exposure [8]. Durable-icephobic design also shows that repeated mechanical challenge must be part of the claim [6]. Report the contaminant, deposition amount, cleaning chemistry and mechanics, abrasion contact and cycle sequence. Test recovery as well as degradation. A surface that is initially excellent but cannot be cleaned without loss is not equivalent to a recoverable surface.

## 11. Evaluate retention after coupled cycles

Independent tests can miss interaction. Thermal cycling may weaken an interface before abrasion; abrasion may open paths for condensation; condensate may freeze within defects and extend them. A defensible program therefore includes coupled sequences that reflect service: condition, cool, condense or ice, remove ice, warm, clean and repeat.

At selected intervals, measure both function and state. Functional endpoints may include freezing distribution, frost coverage, detachment force and deicing energy. State endpoints may include chemistry, feature fidelity, roughness, coating coverage, cracks, mass change and failure locus. Plot response against accumulated sequence, not merely calendar time. No cycle count becomes a general lifetime claim without an application-specific acceleration model.

## 12. Build a non-compensatory qualification matrix

| Gate                    | Required evidence                                                                  | Unsupported shortcut prevented                    |
|-------------------------|------------------------------------------------------------------------------------|---------------------------------------------------|
| Printed substrate       | Resin, orientation, wash, post-cure, storage and feature fidelity                  | Treating all printed photoresins as one surface   |
| Environmental pathway   | Temperature and humidity history, water source, cooling and phase-transition route | Calling every cold-water exposure an icing test   |
| Wetting state           | Dynamic and thermal wetting plus condensate location and retention                 | Inferring service state from one static angle     |
| Claim-specific function | Separate freezing, frost, adhesion, shedding or deicing endpoint                   | Using one endpoint as universal icephobicity      |
| Retained architecture   | Post-cycle chemistry, texture, coating coverage and interface integrity            | Accepting pristine performance as durability      |
| Coupled challenge       | Icing, thermal cycling, wear, contamination and cleaning sequence                  | Adding isolated cycle counts as lifetime evidence |

The gates are independent. A high contact angle cannot compensate for high ice adhesion; low adhesion cannot compensate for rapid frost bridging; and good initial performance cannot compensate for loss of the functional layer.

## 13. Minimum reporting set

Report resin or controlled formulation family; print route, orientation, layer thickness and exposed face; washing, drying, post-cure and storage; designed and measured texture; functionalisation or coating architecture; thickness, coverage and attachment evidence; initial chemistry, roughness and wetting metrics; substrate and air temperature histories; humidity or vapour pressure; airflow; water composition and delivery; cooling rate and dwell; phase-transition pathway; droplet, frost or ice geometry; replicate count and statistical treatment; freezing, frost, adhesion, shedding or deicing endpoint with apparatus and analysis; failure locus; thermal-cycle profile; icing/deicing sequence; abrasion, contamination and cleaning challenges; interval measurements; and post-challenge surface state.

Every number must retain the associated material, surface, environment and test state. No contact angle, hysteresis, freezing delay, frost coverage, detachment stress, deicing energy, feature size or cycle count becomes a transferable target when those qualifiers change.

## 14. Knowledge boundary

The corpus directly supports joint evaluation of printed geometry, surface treatment, wetting, icing delay and adhesion for one LCD-printed acrylate system [1]. Additively manufactured thermoplastic evidence supports the need to bind composition, process and ice response but remains adjacent [2]. Nanoengineered-surface evidence supports separation of condensation-freezing and desublimation [3]. Engineered coatings and interfaces support the roles of liquid-like behaviour, toughness, substrate adhesion, interfacial mechanics and outdoor durability [4-8]. Most of those substrates are not printed photopolymers. Their mechanisms can structure qualification, but their chemistries, numerical values and lifetimes cannot be transferred.

## 15. Limitations

Only one source in the frozen corpus directly studies an anti-icing surface produced on an LCD-printed acrylate photopolymer [1]. The remainder concern thermoplastic additive manufacturing or nanoengineered and coated substrates. Sources [1], [2], [5] and [6] were read at full-text version-of-record depth; [3] at full-text author-manuscript depth with version-of-record metadata; and [4], [7] and [8] at abstract plus publisher-metadata depth. Claims based on [4], [7] and [8] are therefore limited to abstract-visible architecture, wetting/ice-repellency and outdoor-durability statements. No common resin, printer, post-cure, texture, coating, humidity path, ice geometry, detachment method or durability sequence spans the sources. Stochastic nucleation complicates small-sample comparisons. Accelerated cycles do not establish service life without validated equivalence. The review supplies no commercial formulation, fluorinated-treatment recommendation, texture recipe, universal threshold or safety conclusion.

## 16. Conclusions

Anti-icing and icephobic performance on a printed photopolymer is a conditional, evolving surface response. The claim must specify whether it concerns condensation, freezing, frost, adhesion, shedding or active deicing. Wetting must be evaluated under the relevant thermal and humidity path, not inferred from a room-temperature static angle. Printed state, surface architecture, environmental pathway and failure locus must remain connected. Thermal mismatch, icing/deicing, wear, contamination and cleaning can interact, so retained function requires coupled cycling and post-challenge surface evidence. A defensible claim is limited to the declared resin, post-cure, surface architecture, environment, icing pathway and accumulated service sequence.

## References

1. Zgaren R, Hosseini M, Jafari R, Momen G. Nanoparticle-Free 3D-Printed Hydrophobic Surfaces for Ice Mitigation Applications. **Molecules**. 2025;30:3185. <https://doi.org/10.3390/molecules30153185>
2. Konieczna R, Przekop RE, Pakuła D, Głowacka J, Ziętkowska K, Kozera R, Sztorch B. Functional Silsesquioxanes-Tailoring Hydrophobicity and Anti-Ice Properties of Polylactide in 3D Printing Applications. **Materials**. 2024;17(19):4850. <https://doi.org/10.3390/ma17194850>
3. Walker C, Lerch S, Reininger M, Eghlidi H, Milionis A, Schutzius TM, Poulikakos D. Desublimation Frosting on Nanoengineered Surfaces. **ACS Nano**. 2018;12(8):8288-8296. <https://doi.org/10.1021/acsnano.8b03554>
4. Ouyang M, Guo R, Fan Y, Zhou Y, Wu C, Chen L, Huang S, Tian X. Ultralow-adhesion icephobic surfaces: Combining superhydrophobic and liquid-like properties in the same surface. **Nano Research**. 2023;16(1):589-598. <https://doi.org/10.1007/s12274-022-4746-z>
5. Zhuo Y, Håkonsen V, Liu S, Li T, Wang F, Luo S, Xiao S, He J, Zhang Z. Ultra-robust icephobic coatings with high toughness, strong substrate adhesion and self-healing capability. **Science China Materials**. 2023;66(5):2071-2078. <https://doi.org/10.1007/s40843-022-2340-9>
6. Golovin K, Kobaku SPR, Lee DH, DiLoreto ET, Mabry JM, Tuteja A. Designing durable icephobic surfaces. **Science Advances**. 2016;2(3):e1501496. <https://doi.org/10.1126/sciadv.1501496>
7. Kulinich SA, Farhadi S, Nose K, Du XW. Superhydrophobic surfaces: Are they really ice-repellent? **Langmuir**. 2011;27(1):25-29. <https://doi.org/10.1021/la104277q>
8. Boinovich LB, Emelyanenko AM, Emelyanenko KA, Modin EB. Modus Operandi of Protective and Anti-icing Mechanisms Underlying the Design of Longstanding Outdoor Icephobic Coatings. **ACS Nano**. 2019;13(4):4335-4346. <https://doi.org/10.1021/acsnano.8b09549>

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