

Microcrack Formation and Mitigation in Anodized Aluminum: Mechanisms, Contamination Consequences, and Engineering Strategies

Aravindh Sadhanandham

Independent Researcher, Fremont, USA

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ABSTRACT

Anodized aluminum is essential for precision mechanical, optical, and semiconductor applications where corrosion resistance, hardness, and surface cleanliness must be maintained across thermal cycling. The fundamental reliability challenge arises from thermomechanical incompatibility between the ductile aluminum substrate (coefficient of thermal expansion, CTE ≈ 23 ppm/K) and the brittle anodic alumina coating (CTE $\approx 5\text{--}8$ ppm/K). This CTE mismatch of $\approx 15\text{--}18$ ppm/K generates biaxial tensile stress in the oxide during heating, concentrating at pore junctions where stress amplification can initiate cracks in the inherently brittle oxide. Two secondary mechanisms determine whether primary stress translates into observable cracking: dehydration-induced stress reversal in hot-water-sealed coatings, which amplifies CTE-mismatch stress synergistically, and sub-critical fatigue propagation during repeated thermal cycling, enabling crack coalescence and eventual spallation. Microcracks are not merely structural defects—they are active contamination pathways, bypassing the tortuous pore network and exposing the internal pore reservoir through short-circuit diffusion, accelerating outgassing and generating particulates. This review provides: (1) a mechanism hierarchy linking thermal cycling to crack initiation, outgassing, and particulate release; (2) a hierarchical engineering framework mapping each mechanism to its most effective mitigation; and (3) a qualification approach linking crack evolution to contamination risk over service lifetime. The three highest-impact strategies are nickel acetate sealing, coating thickness reduction to $10\text{--}25\ \mu\text{m}$, and post-treatment bakeout at $100\text{--}150^\circ\text{C}$. Thermal stability is not an implicit property of anodized aluminum but an engineered requirement.

Keywords: Anodic Alumina; Microcracking; Thermal Expansion Mismatch; Sealing Chemistry; Outgassing; Contamination; Semiconductor Processing; Fatigue Crack Growth

1. Introduction

Aluminum and its alloys are ubiquitous in precision engineering—optical mounts, semiconductor process equipment, and high-reliability mechanical assemblies—where surface durability directly determines system performance and service life. Anodizing creates a structured alumina layer offering high surface hardness, corrosion resistance, dielectric insulation, and exceptional adhesion to secondary coatings [1], [8]. Type III hard anodizing is the preferred process for mechanically and thermally demanding applications [1].

Despite these advantages, anodized aluminum faces a fundamental reliability problem: the aluminum substrate has high thermal expansion (CTE ≈ 23 ppm/K), while anodic alumina is a rigid ceramic with much lower thermal expansion (CTE $\approx 5\text{--}8$ ppm/K). During thermal cycling, this mismatch generates biaxial in-plane tensile stresses in the oxide that can initiate microcracking [4], [9]. Microcracks are not merely structural defects—they are active contamination pathways. By

bypassing the tortuous pore network, cracks expose the internal pore reservoir to short-circuit diffusion, dramatically accelerating outgassing. [19] Crack propagation and coalescence also generate submicron particulates threatening semiconductor yield and optical performance [6], [9]. Establishing this contamination consequence is essential: the engineering problem is not merely one of coating mechanical integrity but of surface cleanliness reliability over the component's thermal service history.

The scientific literature on anodic alumina structure and thermal stress is substantial [1], [3], [8]–[10]. However, microcrack mechanisms have largely been studied in isolation; the contamination consequences of cracking remain disconnected from crack morphology; and engineering solutions in the literature lack systematic prioritization. This review addresses these gaps through a mechanism hierarchy, a contamination traceability chain, a hierarchical engineering framework, and a qualification approach linking crack evolution to contamination risk.

Study	Focus	Gap Addressed Here
Thompson (1997) [1]	Pore fabrication and structure	Thermal stress, crack hierarchy, contamination
Lee & Park (2014) [3]	Anodization and nanostructure synthesis	Mechanism-to-mitigation integration
Ruiz-Clavijo et al. (2021) [7]	AAO template applications	Engineering qualification procedures
Li et al. [9]	Pore growth kinetics	Cyclic fatigue and crack evolution under service
Hu et al. (2015) [11]	Sealing morphology	Sealing chemistry vs. stress reversal
Ofoegbu et al. (2020) [12]	Sustainable sealing strategies	Trade-off analysis under thermal cycling
Luo et al. (2020) [6]	Surface-outgassing relationship	Crack morphology linked to contamination pathways
He (1995) [16]	Preventing cracking in anodized coatings	Integrated hierarchy: material, process, design, qualification

Table 1: Literature Positioning – Research Focus and Gaps Addressed [19]

2. Background: Anodic Alumina Structure, Crack Mechanisms, and Contamination

This section integrates the structural foundation and mechanism hierarchy required to understand how thermal cycling leads to microcrack formation and contamination generation. Each structural feature is directly relevant to stress generation, crack initiation, or contamination pathways.

2.1 Microstructure and Thermomechanical Incompatibility

Anodic alumina produced by sulfuric acid anodizing exhibits a bilayer microstructure. A thin, non-porous barrier layer at the metal–oxide interface provides primary electrical resistance during anodizing [1], [8]. Overlying it is a thicker porous layer of hexagonally close-packed columnar cells, each containing a central pore oriented perpendicular to the substrate surface. Type III hard anodizing, conducted at lower temperatures and higher current densities, generally produces smaller, denser pores than Type II [1], [3]. The oxide as initially formed is predominantly amorphous.

The CTE mismatch between substrate (≈ 23 ppm/K) and coating ($\approx 5\text{--}8$ ppm/K) is the fundamental crack driver. During heating, the aluminum substrate expands more rapidly than the constrained oxide, placing the oxide under biaxial tensile stress. The pore structure concentrates this global stress at pore tips and junctions, where multiple pores converge, creating the critical conditions for crack initiation. Because anodic alumina has a very low fracture toughness—substantially below that of dense crystalline alumina—only modest stress amplification at pore sites is sufficient to initiate cracking [4], [8], [10]. Once initiated, cracks propagate laterally along columnar boundaries perpendicular to the pore axes, explaining the network morphology observed by SEM in thermally cycled coatings.

Coating thickness is a key modulator of crack susceptibility because elastic strain energy stored in the oxide increases with thickness. Thicker coatings store substantially more energy, making crack initiation and propagation thermodynamically more favorable. For thermally critical applications, reducing thickness to 10–25 μm provides a large reduction in crack driving force compared to the 25–75 μm produced by standard Type III processing [5], [13].

Structural Parameter	Type II Anodizing	Type III Hard Anodizing
Outer layer architecture	Porous, columnar hexagonal cells	Porous, denser columnar structure
Pore alignment	Perpendicular to substrate	Perpendicular to substrate
Relative porosity	Higher	Lower
Crack susceptibility note	Higher porosity concentrates stress at pore junctions	Lower porosity but thicker standard coatings store more elastic energy; net susceptibility depends on thickness specification

Table 2: Structural Characteristics of Anodic Alumina by Anodizing Type [1], [3], [8]

2.2 Sealing Chemistry and Stress State

The sealing step profoundly modifies the oxide's stress state and its thermal behavior in service. Hot water sealing (90–95°C) converts amorphous alumina pore walls into boehmite (AlOOH) through hydration, incorporating substantial structural water. This introduces initial compressive stress that is beneficial early in life. However, upon exposure to elevated temperatures or low humidity in service, boehmite dehydrates with significant volumetric contraction, reversing the stress from compressive to tensile. This dehydration-induced tensile stress acts simultaneously with CTE-mismatch tensile stress during heating, synergistically amplifying the total crack driving force—the dominant reason why hot-water-sealed coatings perform poorly under thermal cycling [11], [12].

Nickel acetate sealing deposits precipitate into the pores with substantially lower water content and lower volumetric change than boehmite, eliminating the dehydration-driven stress reversal. Cold sealing with fluorozirconate chemistry bypasses the hydration reaction entirely, introducing the lowest sealing-induced stress. Table 3 summarizes these distinctions.

Sealing Parameter	Hot Water Sealing	Nickel Acetate Sealing	Cold Sealing
Primary reaction product	Boehmite (AlOOH)	Nickel hydroxide / basic nickel acetate	Fluorozirconate-based precipitate
Water content of sealed phase	High (~15 wt%) – large structural water reservoir	Moderate (5–8 wt%)	Minimal
Stress reversal under thermal cycling	Yes – dehydration reverses compressive sealing stress to tensile; amplifies CTE-mismatch stress	Avoided; lower dehydration vulnerability	Hydration reaction bypassed entirely
Thermal cycling suitability	Not recommended – highest crack and outgassing risk	Preferred – well-validated for thermally cycled applications	Promising; limited long-term data for critical applications

Table 3: Sealing Chemistry and Thermomechanical Implications [2], [11], [12]

2.3 Mechanism Hierarchy

Microcrack formation in anodized aluminum is governed by a hierarchy of mechanisms rather than a single cause. CTE-mismatch-driven biaxial tensile stress is the primary and unavoidable driver: it develops during every heating event and concentrates at pore junctions where crack initiation is thermodynamically favorable. Two secondary amplification mechanisms determine whether this primary stress produces observable cracking at practical temperature excursions. First, boehmite dehydration stress reversal—present only in hot-water-sealed coatings—acts synergistically with CTE-mismatch stress and is the single most impactful controllable risk factor. Second, sub-critical fatigue crack propagation under repeated thermal cycling enables cracks to advance incrementally each cycle even at stress intensities that would not cause single-cycle fracture; over many cycles, isolated microcracks coalesce into extended networks, eventually promoting spallation. Coating thickness and substrate grain size act as tertiary modulators: thicker coatings store more elastic energy per cycle, accelerating both initiation and propagation; coarse-grained substrates introduce grain boundary steps that create additional stress concentration sites [4], [9], [14], [15].

Mechanism	Classification	Modifiability	Dominant Mitigation
CTE-mismatch biaxial tensile stress	Primary driver — unavoidable	Low — material-fixed	Substrate alloy selection; fine grain; thin coating
Pore-assisted stress concentration	Secondary amplifier — initiation	Moderate — pore geometry controlled by anodizing parameters	Controlled anodizing; fine-grain substrate
Boehmite dehydration stress reversal	Secondary amplifier — initiation	High — sealing-chemistry-dependent	Nickel acetate or cold sealing; eliminates mechanism
Sub-critical fatigue crack propagation	Secondary amplifier — propagation	Moderate	Thickness reduction; compliant assembly design
Elastic strain energy (scales with thickness)	Tertiary modulator — propagation	High — thickness-controlled	Reduce coating thickness to 10–25 μm
Substrate grain boundary steps	Tertiary modulator — initiation	High — alloy and prep controlled	Fine-grain substrate; pre-anodize surface preparation

Table 4: Mechanism Hierarchy and Classification for Thermal Microcrack Formation

3. Outgassing and Contamination Consequences of Microcracking

The contamination consequences of microcracking manifest through two primary pathways: accelerated outgassing and particulate generation. Both evolve over component lifetime as crack density increases.

3.1 Accelerated Volatile Release

Even after sealing, anodic coatings retain moisture and volatile compounds within their porous structure. Under intact conditions, these are released slowly through the tortuous pore network. Microcracks fundamentally alter this transport: they bypass the pore network entirely, exposing the vast internal pore surface area and conditions and circuit diffusion pathways. The internal pore reservoir—orders of magnitude larger than the external geometric surface—can rapidly desorb through these open cracks [6].

The consequence is directly observable: coatings with higher microcrack density exhibit substantially elevated outgassing rates, particularly during and immediately after the thermal cycle in which cracking initiates. In hot-water-sealed coatings, the dehydration of boehmite contributes an additional chemical source of water vapor on top of the mechanical acceleration—producing the highest transient outgassing rates, especially in low-humidity environments [11]. Nickel acetate sealing eliminates this chemical outgassing source because the primary water reservoir is absent, though cracks still accelerate diffusion of residual volatiles [2], [11].

Crack-enabled outgassing also eliminates the coating's barrier function against corrosive species. The intact anodic coating forces chloride ions and dissolved oxygen to traverse the long tortuous pore path before reaching the substrate; microcracks provide direct access, substantially accelerating localized corrosion in aggressive environments.

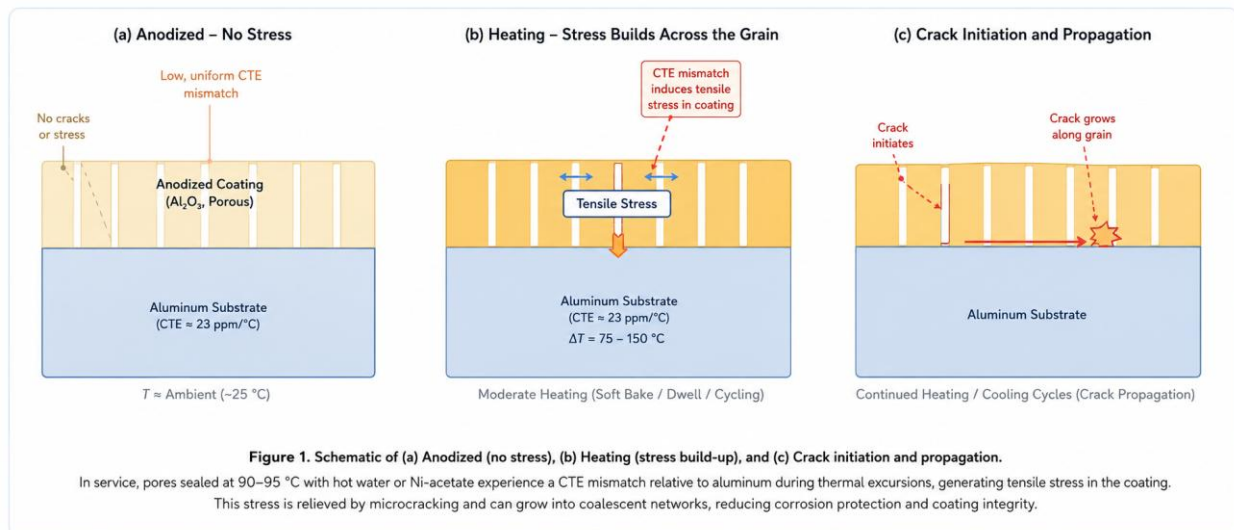


Figure 1. Schematic of CTE-Mismatch-Driven Microcrack Formation in Anodized Aluminum. (a) Ambient: porous oxide on substrate, no thermal stress. (b) Heating: The aluminum substrate expands freely while the constrained oxide develops biaxial tensile stress (~110 MPa globally; 300-500 MPa at pore junctions, $K_t = 2-5$). (c) Crack initiation at pore junctions, lateral propagation along columnar boundaries, vertical channel propagation, and particulate generation from spallation. [16] [6]

3.2 Particulate Generation from Crack Coalescence and Spallation

As thermal cycling continues, adjacent microcracks interact. Oxide ligaments between approaching crack fronts experience elevated stress and progressively fracture, converting isolated microcracks into extended networks. When bridging oxide between large cracks eventually fractures, it releases oxide fragments—spallation. Released particles span from nanometer-scale fragments from individual microcracking events to micron-scale or larger particles from oxide bridge fracture. In semiconductor processing chambers, particles on wafer surfaces cause direct yield loss; in optical systems, particles scatter light and degrade performance [9], [16].

3.3 Temporal Evolution and Environmental Sensitivity

Contamination risk from microcracking evolves over component lifetime in a manner that depends on crack density, thermal history, and environmental humidity. A component that passes initial outgassing qualification may generate unacceptable contamination after accumulating service cycles as sub-critical fatigue progresses and crack density increases. Environmental humidity significantly influences this evolution: in low-humidity environments, boehmite dehydration occurs rapidly, producing high initial transient outgassing even before significant thermal cycling. In high-humidity environments, dehydration is slower, but sustained moisture availability maintains a persistent outgassing source throughout the component's lifetime [11], [12]. This temporal and environmental dependence is the reason that qualification procedures must assess crack evolution under representative service conditions, not merely the initial delivered condition.

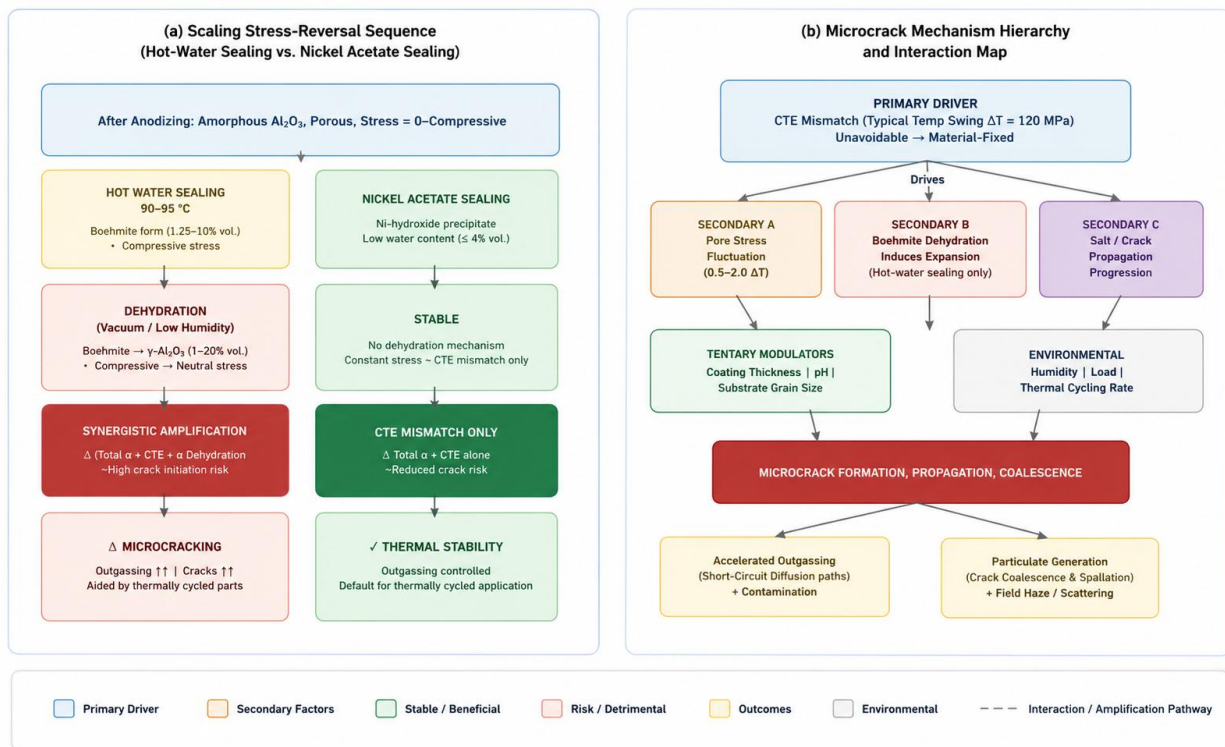


Figure 2. Sealing Stress-Reversal Sequence and Microcrack Mechanism Hierarchy. (a) Hot-water sealing introduces boehmite (+25-30% vol. expansion, compressive stress), which dehydrates under thermal exposure (-25% vol. contraction), reversing stress to tensile and amplifying CTE-mismatch stress synergistically. Nickel acetate sealing avoids this pathway entirely. (b) Complete mechanism hierarchy: primary CTE-mismatch driver (unavoidable) amplified by pore stress concentration, boehmite dehydration reversal, and sub-critical fatigue propagation, leading to accelerated outgassing and particulate generation. [16] [6]

4. Engineering Strategies for Mitigation: A Hierarchical Framework

The CTE-mismatch stress cannot be eliminated—it is an unavoidable consequence of the material pairing. However, the amplification of that stress into observable cracking, and the contamination consequences of cracking, can be managed through engineering interventions at four levels: material selection, process control, design, and qualification. Table 5 provides the mechanism-to-mitigation mapping.

4.1 Material Selection

Grain size optimization is the primary practical lever at the material level. Fine-grained substrates (grain size $< 50 \mu m$) distribute stress more uniformly across the coating, reducing the probability that any site reaches the critical stress intensity for crack initiation [15]. Substrate microstructure should be explicitly specified rather than accepted as a byproduct of standard processing.

Anodizing type selection involves a trade-off: Type III hard anodizing produces lower porosity and smaller pores, reducing stress concentration, but also produces thicker coatings, increasing elastic energy storage. The net effect on crack susceptibility depends on whether porosity reduction or energy storage increase dominates—a balance that shifts with thickness specification. Type III anodizing is

therefore not unconditionally superior for thermal stability; coating thickness must be explicitly controlled in either case.

4.2 Process Control

Sealing chemistry is the single most powerful controllable parameter for managing thermal crack susceptibility. Nickel acetate sealing eliminates the dehydration-induced stress reversal mechanism entirely and should be the default specification for any application involving thermal cycling [2], [11]. Hot water sealing should be explicitly excluded from thermally active environments because it produces the highest outgassing rates under cycling and introduces the problematic dehydration-amplification mechanism. Cold sealing is a promising alternative with the lowest sealing-induced stress, but its operational history under long-term thermal cycling remains limited relative to nickel acetate and requires application-specific qualification before use in critical applications [2].

Coating thickness reduction to 10–25 μm for thermally critical applications without significant wear contact substantially reduces elastic strain energy relative to the 25–75 μm produced by standard Type III processing [5], [13]. This is an explicit trade-off decision: reduced thickness decreases corrosion barrier depth and wear resistance. These trade-offs must be evaluated through qualification testing covering all functional requirements alongside the desired reduction in crack susceptibility.

Post-treatment bakeout, applied between sealing and service exposure, is one of the most cost-effective interventions available. Bakeout at 100–150°C in dry nitrogen or dry air for 2–24 hours removes moisture from the porous structure and sealed phases before service begins, preventing moisture-driven stress evolution during early service cycles and reducing initial outgassing rates. The upper temperature limit of 150°C is critical: exceeding it risks partial crystallization of the amorphous oxide, which can paradoxically increase crack susceptibility. Optimal bakeout conditions should be validated through small-scale trials for specific coating and material combinations [12].

4.3 Design-Level Interventions

Sharp internal corners amplify thermal stress locally. Corner radii of ≥ 1 mm (minimum) to ≥ 3 mm (preferred) substantially mitigate this effect. Abrupt thickness transitions between wall sections create differential heating rates that superimpose bending stresses on the CTE-mismatch field; gradual tapers are preferred [4]. When anodized aluminum is assembled with dissimilar materials, compliant joints using elastomer isolators or flexible fastening allow differential thermal expansion without transmitting stress to the anodized coating surface [3], [14].

4.4 Qualification and Service Validation

Engineering controls are necessary but not sufficient for reliable service. Qualification procedures must validate that combined interventions achieve required thermal stability under representative conditions.

Initial outgassing qualification measures the as-delivered outgassing rate (e.g., per ASTM E595) to establish the baseline contamination hazard profile. Accelerated thermal cycling qualification cycles components between service temperature limits for a number of cycles representative of mission duration, then re-measures outgassing rates and assesses surface condition via optical or SEM inspection. The key metric is the rate of outgassing increase per cycle, reflecting crack evolution. Acceptance criteria must require that outgassing rates remain within specification after cycling, not merely at initial delivery. For ultra-critical applications, humidity cycling combined with thermal cycling captures the dehydration-driven failure mode under representative service conditions, enabling construction of degradation curves that predict contamination risk throughout component lifetime [6].

Mechanism	Mitigation Strategy	Level	Effectiveness	Key Constraint
CTE-mismatch tensile stress	Substrate alloy selection; fine-grain specification	Material	Low–Medium	Limited alloy options; mechanical property trade-offs
Pore-assisted stress concentration	Fine-grain substrate; controlled anodizing parameters	Material / Process	Medium	Pore geometry cannot be eliminated without losing coating function
Boehmite dehydration stress reversal	Nickel acetate or cold sealing	Process	Very High — eliminates mechanism	Cold sealing: limited long-term data; Ni-acetate: well-validated
Elastic strain energy storage	Reduce coating thickness to 10–25 μm	Process	Very High	Trade-off: reduced wear resistance and corrosion barrier
Sub-critical fatigue crack propagation	Thickness reduction; compliant joint design	Process / Design	Medium	Manages energy; does not eliminate fatigue mechanism
Moisture-driven outgassing	Post-treatment bakeout (100–150°C, dry atmosphere)	Process	Very High	Must not exceed 150°C; low implementation complexity
Local thermal gradients	Corner radii ≥1–3 mm; uniform thermal design	Design	Medium	Constrained by component function and assembly envelope
Interface stress from dissimilar materials	Compliant joints; elastomer isolators	Design	High	Requires design space; may conflict with stiffness requirements

Table 5: Mechanism-to-Mitigation Mapping with Effectiveness and Practical Constraints

Across all levels, the three highest-impact interventions are sealing chemistry selection (nickel acetate: eliminates the dominant secondary amplification mechanism), coating thickness reduction (10–25 μm: directly reduces elastic energy storage), and post-treatment bakeout (100–150°C, dry atmosphere: removes moisture before service with low implementation complexity). These three interventions should be implemented together; they address distinct mechanisms and their benefits

compound. Design-level interventions provide additional protection wherever the design envelope permits.

5. Environmental and Operational Factors

Environmental humidity during storage and service profoundly influences crack formation and contamination evolution, particularly through effects on boehmite dehydration kinetics in hot-water-sealed coatings. In low-humidity environments, dehydration occurs rapidly, reversing sealing stress to tensile before significant thermal cycling has accumulated—effectively pre-loading the coating in the crack-prone state at service entry. In high-humidity environments, dehydration is slower but sustained moisture availability maintains a persistent outgassing source and complicates residual stress through re-adsorption. Environmental stress screening procedures should therefore include humidity cycling alongside thermal cycling to capture the dehydration-driven failure mode under conditions representative of actual service humidity [6], [11], [12].

Beyond outgassing, microcracking also affects long-term corrosion resistance. The intact anodic coating forces corrosive species to traverse the tortuous pore path before reaching the substrate interface. Crack formation converts this effective barrier into a direct-access pathway, substantially accelerating localized corrosion in marine or chemically aggressive environments. This dual implication—contamination vulnerability in clean environments and accelerated corrosion in aggressive ones—provides a strong engineering justification for investing in thermal crack mitigation across a wide range of application types.

Conclusion

This review has established that microcracking in anodized aluminum is not a single-cause phenomenon but the result of a hierarchy of mechanisms acting on a brittle, porous oxide. CTE-mismatch-driven biaxial tensile stress is the unavoidable primary driver; its translation into observable cracking is mediated by two controllable secondary mechanisms—boehmite dehydration-induced stress reversal and sub-critical fatigue propagation—and by the tertiary modulator of coating thickness. Critically, microcracks impose two distinct contamination penalties that evolve over service lifetime: accelerated outgassing through short-circuit diffusion pathways, and particulate generation through crack coalescence and spallation. A component that passes initial qualification may generate unacceptable contamination after accumulating service cycles.

The three immediately actionable, highest-impact engineering interventions are: (1) specify nickel acetate sealing for all thermally cycled applications, eliminating the dehydration stress-reversal mechanism entirely and excluding hot water sealing from thermally active environments; (2) specify coating thickness as a primary design parameter—10–25 μm for thermally critical applications, with explicit acknowledgment of corrosion and wear trade-offs; and (3) apply post-treatment bakeout at 100–150°C in a dry atmosphere, removing moisture before service at low implementation cost. Supporting these are fine-grained substrates, design-level interventions (corner radii $\geq 1\text{--}3$ mm, thermal gradient minimization, and compliant joints at dissimilar-material interfaces), and qualification procedures that characterize crack evolution under representative thermal and humidity histories—not merely initial outgassing—complete the engineering framework.

The conceptual shift required is straightforward: sealing chemistry, coating thickness, bakeout, and qualification must be treated as integrated system-level design variables rather than independent material choices. Thermal stability of anodized aluminum coatings is an engineered requirement, and the mechanisms and mitigations reviewed here are fully within reach of current manufacturing and design practice.

Key areas requiring further investigation include quantitative fatigue crack growth rate data under representative thermal cycling amplitudes, systematic characterization of cold sealing performance under long-term cycling, and development of standardized test protocols correlating accelerated qualification cycles to real service lifetime for semiconductor and optical applications.

References

- [1] G. E. Thompson, "Porous anodic alumina: Fabrication, characterization and applications," *Thin Solid Films*, vol. 297, no. 1-2, pp. 192-201, 1997.
- [2] P. G. Sheasby and R. Pinner, *The Surface Treatment and Finishing of Aluminium and its Alloys*, 5th ed. Finishing Publications Ltd., 1987.
- [3] W. Lee and S.-J. Park, "Porous anodic aluminum oxide: Anodization and templated synthesis of functional nanostructures," *Chem. Rev.*, vol. 114, pp. 7487-7556, 2014.
- [4] A. M. Huntz et al., "Evidence of stress relaxation in thermally grown oxide layers--experiments and modelling," *Mater. Sci. Eng.*, 1998.
- [5] J. W. Hutchinson and Z. Suo, "Mixed mode cracking in layered materials," *Adv. Appl. Mech.*, vol. 29, pp. 63-191, 1991.
- [6] Y. Luo et al., "Comparative study on surface influence to outgassing performance of aluminum alloy," *Appl. Surf. Sci.*, vol. 502, 144166, 2020.
- [7] A. Ruiz-Clavijo, O. Caballero-Calero, and M. Martin-Gonzalez, "Revisiting anodic alumina templates: From fabrication to applications," *Nanoscale*, vol. 13, pp. 2227-2265, 2021.
- [8] D. Landolt, *Corrosion and Surface Chemistry of Metals*. EPFL Press / Taylor & Francis, 2007.
- [9] N. Hu et al., "Effect of sealing on the morphology of anodized aluminum oxide," *Corros. Sci.*, vol. 97, pp. 17-24, 2015.
- [10] S. U. Ofoegbu, F. A. Fernandes, and A. B. Pereira, "The sealing step in aluminum anodizing: A focus on sustainable strategies for enhancing both energy efficiency and corrosion resistance," *Coatings*, vol. 10, 226, 2020.
- [11] A. Belwalkar et al., "Effect of processing parameters on pore structure and thickness of anodic aluminum oxide (AAO) tubular membranes," *J. Membr. Sci.*, 2008.
- [12] S. Suresh, *Fatigue of Materials*, 2nd ed. Cambridge University Press, 1998.
- [13] J. Humphreys, G. S. Rohrer, and A. Rollett, *Recrystallization and Related Annealing Phenomena*. Elsevier, 2017.
- [14] C. C. He, "Preventing cracking of anodized coatings," NASA Goddard Space Flight Center, 1995.
- [15] X. Zhang et al., "Effect of anodizing parameters on pore morphology and oxide density of sulfuric acid anodized aluminum," *Surf. Coat. Technol.*, vol. 385, 125430, 2020.