

Article

Effects of Thermal Cycling and Environmental Exposure on Mechanical Properties of 6061 and 7075 Aluminum Alloys

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Abstract

This work quantifies the environmental sensitivity of tartaric–sulfuric acid (TSA) anodized and sealed 6061 and 7075 aluminum. Five alloy–temper states (6061-T4, 6061-T62, 7075-T0, 7075-T62, and 7075-T73) were TSA-treated, pore sealed and then exposed for eight weeks (56 days) to ambient air, 11 wt.% NaCl brine, or a microbiological medium, with weekly +20 °C/−20 °C freeze–thaw cycles. Tensile tests assessing yield strength, ultimate strength, and elongation were conducted. Strength losses were modest in ambient conditions (<5%) but increased to ≈5–10% for yield and ≈2–9% for ultimate under saline and microbial conditions, particularly in the annealed 7075-T0 and peak-aged 7075-T62 states. Ductility was more sensitive, declining up to ≈30% for 6061-T4 and 6061-T62 in harsh media. Permutation-based inference within an additive screening model indicated that environmental exposure is strongly associated with the dominant share of the observed variability ($R^2_{\text{env}} \approx 0.91\text{--}0.93$ for yield, ultimate strength, and elongation), within the limits of the present dataset. These results suggest that freeze–thaw cycling, chloride exposure, and microbiological activity are consistent with the observed degradation trends. Over-aged 7075-T73 retained properties better than T62, highlighting the roles of temper and pore sealing quality in cold, saline, and microbiologically active service.

Keywords: aluminum alloys; mechanical degradation; environmental exposure; thermal cycling; microbial corrosion; strength-ductility loss



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1. Introduction

Aluminum alloys from the 6000-series and 7000-series are widely used in aerospace and structural applications with differing roles: 6000-series alloys are often employed for lighter structural roles, secondary support elements, brackets, fittings or assemblies where machinability, weldability and a balance between mechanical performance and corrosion resistance are required. Meanwhile, 7000-series alloys serve in heavily-loaded, high-stress structural components, such as aircraft skins, fuselage frames, wing spars, landing-gear structural members and high-strength fittings, thanks to their superior strength-to-weight

ratio and fatigue performance [1–7]. Understanding their degradation under combined environmental and thermal cycling is essential for ensuring long-term reliability in demanding service conditions.

However, environmental exposure, especially in marine/coastal atmospheres with chloride-rich aerosols, humidity, and cyclic wetting/drying or thermal/humidity-cyclin pose a serious threat to aluminum structural integrity. Recent long-term exposure work in a cold-climate atmospheric environment demonstrated that both 6061 and 7075 alloys develop corrosion products (oxides, hydroxides), pitting, and surface degradation after one year of exposure [8]. Marine-atmosphere exposure experiments on 7075 have shown microstructural degradation and a measurable decrease in tensile properties after corrosion, confirming that high-strength 7000-series alloys are particularly vulnerable under marine/coastal conditions [9]. Similarly, 6061 alloy subjected to cyclic temperature and humidity variation exhibited localized corrosion, degradation of passive layers, and reduction of mechanical strength [10].

The 6061 alloy, valued for its balanced mechanical properties and weldability, becomes vulnerable under alternating humidity and temperature. Environmental fluctuations can weaken the protective oxide film, promote galvanic corrosion, and shift fracture behavior from ductile to brittle [1,2]. Surface modifications such as Ti-based coatings, plasma nitriding, and ceramic-particle reinforcement improve strength and corrosion resistance, while plasma electrolytic oxidation (PEO) offers durable protection in chloride-rich environments [3–6]. Thermal and cryogenic cycling can refine the microstructure and enhance strength through β'' precipitation, although welding or alkaline exposure may locally reduce corrosion resistance [7,11,12].

In contrast, the 7075 alloy, known for its superior strength, exhibits higher susceptibility to environmental degradation, especially in saline and microbial media. Prolonged exposure promotes pitting, exfoliation, and intergranular corrosion linked to its Zn- and Cu-rich microstructure [13,14]. Microbiologically influenced corrosion (MIC) further accelerates damage; biofilm formation and fungal metabolites locally acidify the surface, increasing pit depth and altering dislocation behavior [15–19]. At low temperatures, freeze–thaw cycles exacerbate grain-boundary corrosion and stress-corrosion cracking (SCC), while additive manufacturing and accelerated test methods reveal morphology-dependent corrosion mechanisms [20–22]. In cold or marine environments, corrosion of 7075 intensifies, and the absence of robust design standards still limits its wider adoption [23,24].

Both 6061 and 7075 aluminum alloys experience performance losses influenced by their microstructure, environment, and thermal history. While 6061 maintains moderate intrinsic corrosion resistance, the 7075 alloy's superior strength is often offset by complex degradation behavior under saline and microbial exposure. Therefore, this study investigates how combined thermal cycling (+20 °C / −20 °C) and environmental exposure affect the mechanical integrity of TSA-anodized and sealed 6061 and 7075 alloys. Five temper states (6061-T4, 6061-T62, 7075-T0, 7075-T62, and 7075-T73) were exposed for eight weeks to ambient air, 11 wt.% NaCl brine, and a microbiological medium containing *Aspergillus* fungi. Tensile tests evaluated yield strength, ultimate tensile strength, and elongation at break, allowing for a comprehensive assessment of how the combination of pore sealing, chloride attack, and microbial activity degrades alloy performance.

Given that critical load-bearing components in aerospace structures may be exposed to such aggressive environments, and that even secondary-role parts made from 6000-series alloys may not be immune, there is a justified need to evaluate how surface-protected (e.g., anodized and sealed) 6000- and 7000-series aluminum alloys behave under combined environmental stressors (chloride exposure, marine/coastal atmosphere, cyclic thermal/humidity stress, potential biological exposure).

The novelty of this study resides in the simultaneous application of multiple aggressive stressors—chloride-rich environment, microbiological exposure, and cyclic freeze–thaw thermal loading—on TSA-anodized and sealed aerospace aluminum alloys belonging to both the 6000- and 7000-series. The work provides a quantitative assessment of the coupled influence of these combined conditions on the tensile strength and ductility of 6061 and 7075 alloys across several temper states, establishing a mechanical degradation screening framework under operational environments.

2. Materials and Methods

2.1. Materials, Mechanical Properties, and Chemical Composition

The aluminum alloys used in this study were AA6061-T4 and AA7075-T0, supplied as rolled products by AMAG (Braunau-Ranshofen, Austria) and Aleris Rolled Products Germany GmbH (Koblenz, Germany), respectively. Sheets with a thickness of 1.6 mm were used and subsequently cut into the required specimen geometry using an Oreelaser PH3015 CNC laser system (Oreelaser, Jinan, China), in accordance with the configuration illustrated in Figure 1. These alloys were selected due to their widespread application in the aerospace industry [4,11–14].

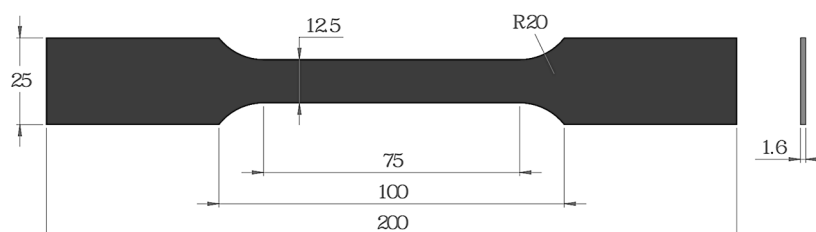


Figure 1. Geometry of the tensile specimen used in this study (all dimensions in mm).

Before surface treatment, the alloys were subjected to standard industrial heat-treatment cycles to obtain the required temper conditions. The 6061-aluminum alloy was solution heat-treated at 540 ± 5 °C for 1 h, water quenched, and subsequently artificially aged at 170 ± 5 °C for 8 h to achieve the T62 condition. The 7075 aluminum-alloy was solution treated at 475 ± 5 °C for 1 h, water quenched, and then artificially aged under two different regimes: 120 ± 5 °C for 24 h for the peak-aged T62 temper, and 160 ± 5 °C for 16 h for the over-aged T73 temper. These heat-treatment cycles conform to aerospace standards [20,25,26].

The artificial aging durations were selected according to the distinct precipitation kinetics characteristic of the two alloy systems. In 6061-aluminum, artificial aging at 170 ± 5 °C for 8 h promotes the formation of fine, coherent β'' (Mg_2Si) precipitates, which are responsible for the peak-aged strengthening condition. The precipitation sequence in Al–Mg–Si alloys (solute clusters $\rightarrow$ GP zones $\rightarrow \beta'' \rightarrow \beta' \rightarrow \beta$) is well established, and the β'' phase is recognized as the primary contributor to peak strength [21,27].

For The 7075 aluminum-alloy, two artificial aging regimes were employed to obtain different microstructural states. Aging at 120 ± 5 °C for 24 h promotes the dense formation of metastable η' (MgZn_2) precipitates, corresponding to the peak-aged T62 condition. In contrast, aging at 160 ± 5 °C for 16 h accelerates precipitate coarsening toward the stable η phase, producing the over-aged T73 condition, which is known to improve stress-corrosion resistance by reducing the width of precipitate-free zones and modifying grain-boundary precipitate morphology [28–30].

The difference in aging duration between the two temperatures is therefore a direct consequence of thermally activated diffusion and precipitation kinetics. Lower aging temperatures require extended times to allow sufficient solute diffusion and controlled

nucleation of fine strengthening precipitates, whereas higher temperatures accelerate precipitate transformation and coarsening, enabling the formation of an over-aged microstructure within shorter times. This approach is supported by multiple studies demonstrating that artificial aging at elevated temperatures significantly accelerates precipitation kinetics and strongly influences the final microstructure and mechanical and corrosion properties of aluminum alloys [31,32].

Mechanical characteristics were established using uniaxial tensile testing on an INSTRON 8801 servo-hydraulic fatigue testing system with a 100 kN load cell and a 2630-107 axial clip-on extensometer (INSTRON, Norwood, MA, USA). The loading was applied parallel to the rolling direction. The values reported in Table 1 represent the average of three independent tensile tests performed for each alloy and temper condition prior to environmental exposure. These baseline mechanical properties were established to serve as reference values for normalization and comparative analysis of the environmentally exposed specimens. The experimentally obtained baseline properties were additionally cross-validated against the technical datasheets and standard specifications provided by the aluminum producers, ensuring consistency between the measured mechanical behavior and the nominal material performance.

Table 1. 6061-T4, 6061-T62, 7075-T0, 7075-T62, and 7075-T73 mechanical properties before the 8-week thermal cycle.

Alloy	Ys _{0.2%} (MPa)	UTS (MPa)	A (%)
6061-T4	153	246	24
6061-T62	268	317	10
7075-T0	123	228	16
7075-T62	518	585	11
7075-T73	465	525	9

The specimen-to-specimen variation observed within each set of three baseline tests remained within the typical scatter range for wrought aerospace aluminum alloys, namely ± 3 –5% for yield strength, ± 2 –4% for ultimate tensile strength, and ± 5 –10% for total elongation [33,34].

The nominal chemical composition, as received with the technical documentation of the investigated alloys, is presented in Table 2. AA6061-T4 is an Al–Mg–Si–Cu alloy containing moderate levels of magnesium and silicon, with chromium as a minor addition to improve corrosion resistance and toughness. In contrast, AA7075-T0 belongs to the Al–Zn–Mg–Cu system, characterized by a higher zinc and magnesium content combined with copper, providing significantly greater potential for precipitation hardening. The balance of aluminum content differs accordingly, with AA6061 containing approximately 95.8–98.6 wt.% Al, while AA7075 contains 87.1–91.4 wt.% Al, the remainder consisting primarily of strengthening elements and minor alloying additions.

Table 2. Chemical composition ranges (wt.%) of wrought alloys 6061-T4 and 7075-T0.

Alloy	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other
6061-T4	95.8–98.6	0.4–0.8	≤ 0.7	0.15–0.4	≤ 0.15	0.8–1.2	0.04–0.35	≤ 0.25	≤ 0.15	≤ 0.15
7075-T0	87.1–91.4	≤ 0.4	≤ 0.5	1.2–2.0	≤ 0.3	2.1–2.9	0.18–0.28	5.1–6.1	≤ 0.2	≤ 0.15

2.2. Tartaric-Sulfuric Acid Anodizing and Pore Sealing

The alloys underwent the same TSA anodizing and sealing procedure, forming a sulfate-containing porous oxide film that, upon sealing, transformed into boehmite or Ni(OH)₂, depending on the sealing route.

The specimens investigated in this study were subjected to tartaric–sulfuric acid anodizing (TSA) followed by hydrothermal pore sealing, as indicated in Figure 2.

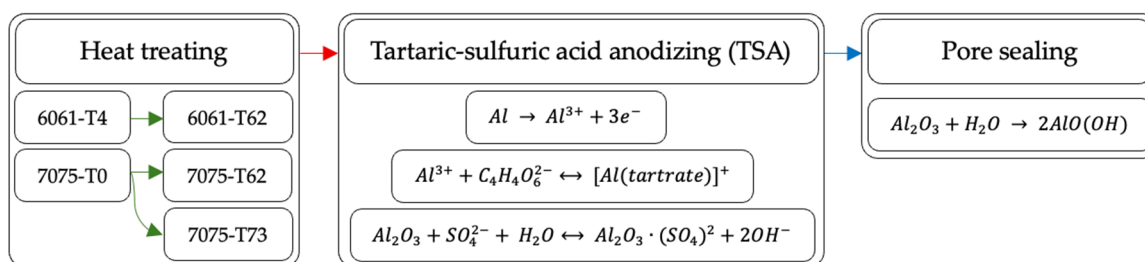


Figure 2. Overall processing route and key reactions: from 6061-T4 and 7075-T0 to temper conditions (6061-T62; 7075-T62/-T73), followed by tartaric–sulfuric acid anodizing (TSA) and pore sealing.

The TSA anodizing process followed EN 4704:2012 specifications [12]. The electrolyte was an aqueous solution of $35 \pm 2 \text{ g L}^{-1}$ sulfuric acid (H_2SO_4) and $20 \pm 2 \text{ g L}^{-1}$ tartaric acid ($\text{C}_4\text{H}_6\text{O}_6$). Anodizing is performed under a constant current density of $2.0 \pm 0.2 \text{ A/dm}^{-2}$ and a voltage ramp limited to 18–22 V [11]. The bath was maintained at $20 \pm 2^\circ\text{C}$ with continuous agitation. Each cycle lasted $45 \pm 5 \text{ min}$, yielding an oxide layer thickness of approximately 12–15 μm [35,36]. Following anodizing, specimens were hydrothermally sealed in deionized water at $98\text{--}100^\circ\text{C}$ for 30 min to convert the porous alumina to boehmite (AlO(OH)) and seal residual pores [12,13,19,37].

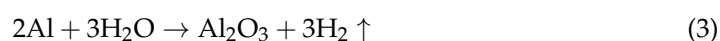
These conditions align with standard aerospace TSA practice, ensuring reproducible oxide morphology and corrosion resistance [37–40]. The general anodic reaction involves:



The aluminum ions subsequently hydrolyze and condense to form hydrated alumina:



The overall anodizing reaction, combining oxidation at the anode with hydrogen evolution at the cathode, is:



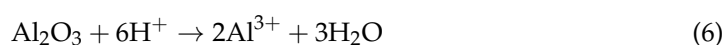
At higher voltages or temperatures, oxygen evolution at the anode may occur:



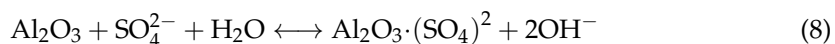
At the cathode, protons are discharged, evolving hydrogen gas:



Simultaneously, controlled dissolution of the anodic oxide occurs in the acidic electrolyte, generating porosity:



Meanwhile, sulfate ions can become incorporated into the barrier and pore walls, creating Al–O–SO₃ linkages:



These reactions occur in a mixed electrolyte of tartaric and sulfuric acids. The tartrate ions form complexes with Al³⁺, moderating the dissolution rate and promoting pore regularity [4,17]. Simultaneously, sulfate ions can be incorporated into the anodic oxide, creating Al–O–SO₃ linkages within the porous film [4,16,18].

The TSA process has been standardized in the European aerospace specification EN 4704:2012 [12], and its application as a replacement for chromic acid anodizing has been reviewed extensively in the literature [11]. In parallel, ISO standards provide general frameworks for sulfuric acid anodizing (ISO 8078:2025) and hard anodizing (ISO 10074:2021) [13,16].

Following anodizing, the porous anodic oxide films were subjected to sealing treatments, a critical step for improving corrosion resistance and durability [13]. When the anodized film is transferred into hot deionized water (98–100 °C), the amorphous parts of Al₂O₃ (which include sulphate fragments and hydratable regions) transform into boehmite (AlO(OH)):



After anodizing, the aluminum surface is covered by a porous Al₂O₃·xH₂O film containing complexed tartrate and incorporated sulfate within the barrier and pore walls. Sealing drives a hydration-driven phase transformation: the porous oxide swells and converts to boehmite AlO(OH), progressively closing the pore channels. In essence, anodizing forms an Al₂O₃ matrix “doped” with SO₄^{2−} and stabilized by tartrate and sealing hydrates this doped oxide into boehmite for pore closure. Separately, the underlying alloy microstructures use distinct strengthening pathways: 6061-T62 is hardened primarily by β” (Mg₂Si) precipitation, while 7075 tempers are hardened by η’ (MgZn₂) precipitates.

Specifically, following anodizing, aluminum alloys possess a porous oxide layer. To enhance corrosion resistance and durability, these pores are commonly sealed via immersion in boiling water, hot nickel acetate solution, or similar methods. The specifics of these sealing processes are detailed in Table 3.

Table 3. Summary of initial (6061-T4, 7075-T0) and heat-treated tempers (6061-T62, 7075-T62, 7075-T73), showing solution heat treatment, quench, artificial aging, dominant precipitates, and representative room-temperature mechanical properties.

Pre-Treated Condition	Characteristics	Treated Condition	Characteristics
6061-T4	natural aging at room temperature → slow clustering of solute atoms (very fine Guinier–Preston zones, limited β''). - Al matrix retains most Mg and Si in solid solution. - only a small fraction forms early GP zones/incipient β''. - no significant coarsening of precipitates. - yield strength: ~150 MPa. - ultimate tensile strength: ~240 MPa. - elongation at break: ~20% (high ductility). - good toughness and corrosion resistance, but low strength. - solution heat-treated and naturally aged. Most Mg and Si remain in supersaturated solid solution, with only limited formation of Guinier–Preston (GP) zones.	→ 6061-T62	- solution heat treatment (~530–550 °C) → dissolves Mg and Si into the Al matrix. - rapid quench → supersaturated solid solution. - artificial aging (typically 160–180 °C for 6–18 h) → precipitation hardening sequence. - formation of fine, coherent β'' (Mg_2Si) precipitates → primary strengthening phase. - with further aging, β'' may evolve into semi-coherent β' and eventually coarse, incoherent β (Mg_2Si). - T62 is tuned to stay near the peak-aged condition, where β'' dominates. - the Al matrix is depleted in Mg and Si, stabilizing the microstructure. - yield strength: ~260–270 MPa (vs. ~150 MPa in T4); ultimate tensile strength: ~310–320 MPa; elongation at break: ~8–10% (reduced compared to T4's ~23%) [20]. - good corrosion resistance, weldability preserved, fatigue strength improved. - compared to over-aged states (like T7x in 6xxx alloys), T62 maintains higher strength but lower toughness. - after artificial aging, Mg and Si segregate to form β'' (Mg_2Si), which subsequently transforms to β' and stable β phases [21,22]. The Al matrix is depleted of Mg and Si, resulting in higher strength but lower ductility.
7075-T0	- annealed condition: heated then slow cooled. - no strengthening precipitation. - Zn, Mg, and Cu remain largely in solid solution. - very low precipitate content. - coarse equilibrium particles at grain boundaries are possible. - yield strength: ~120–130 MPa. - ultimate tensile strength: ~220–230 MPa. - elongation at break: ~16–18% (very ductile). - easy to form, but very low strength. - fully annealed (softest state); structure: equilibrium distribution, solute-rich Al matrix with Zn, Mg, Cu in solid solution, very few precipitates; mechanical properties: low strength, very high ductility, easily formable.	→ 7075-T62	- artificial aging to peak strength; solution heat treatment (~470–480 °C): dissolves Zn, Mg, Cu into solid solution. - quenching: traps solute atoms + vacancies in a supersaturated solid solution. - artificial aging (~120–160 °C for a couple of hours): controlled precipitation of η' (MgZn_2) and S-phase (Al_2CuMg). - high density of fine, coherent η' (MgZn_2) precipitates. - strong interaction with dislocations → maximum strengthening (peak-aged). - very high strength, but reduced toughness. - susceptible to stress-corrosion cracking (SCC). - artificial aging produces a dense precipitation of η'/η (MgZn_2) phases and minor S-phase (Al_2CuMg) [23,24]. This precipitation significantly reduces solute content in the Al matrix, increasing hardness and strength.
		→ 7075-T73	- over-aging for SCC resistance: similar solution treatment and quench as above, but artificial aging is carried out longer and/or at higher temperature (160–200 °C). - precipitates coarsen: η' transforms to larger, semi-coherent η (MgZn_2); lower precipitate number density → fewer obstacles to dislocations. - matrix further depleted of Zn, Mg. - lower strength than T62. - much improved toughness and resistance to SCC, because coarse precipitates reduce micro-galvanic coupling at grain boundaries. - over-aging causes the η' precipitates to coarsen into stable η (MgZn_2), lowering the precipitate number density but improving resistance to stress-corrosion cracking (SCC) [11,14,41]. Strength is reduced compared to T62, but toughness and environmental resistance are enhanced.

2.3. Thermal and Environmental Exposure Conditions

The interaction between aluminum alloys and microbiological environments is an increasing research focus. *Aspergillus* spp. accelerates alloy degradation by secreting organic acids, notably oxalic acid, which reduces interfacial pH, chelates Al^{3+} ions, and compromises the stability of passive alumina films, promoting localized pitting and mass loss [1,2]. Oxalic acid is confirmed as the principal driver of MIC (Microbiologically Influenced Corrosion) in aluminum, with biofilm formation enhancing acidification and pit development [42]. Recent reviews (2024–2025) emphasize that oxalate–aluminum complexation is critical in the degradation of anodic oxide layers and sealed films [1,11].

A fungal inoculum of *Aspergillus* spp. was prepared and maintained under controlled conditions. Cultures were grown for four days on potato dextrose broth (PDB), supplemented with 7 wt.% NaCl to replicate saline osmotic stress. The mature culture was filtered to yield a spore suspension with an initial concentration of approximately 1.5×10^8 CFU mL^{−1}.

In this study, test specimens were immersed in an accelerated chloride environment using a saline solution with 11 wt.%, which is about three times the salinity of natural seawater ($\approx 3.5\%$) [43]. This concentration represents an accelerated chloride environment relative to the artificial seawater formulations specified in ASTM D1141 (2013) [43] and its European equivalent EN ISO 11380:2020 [44]. The chosen conditions were designed to promote corrosion processes within the relatively short exposure period, thereby amplifying the potential for chloride-induced breakdown of anodic films, particularly when coupled with microbiological metabolites. Similar concentrations have been adopted in accelerated corrosion and chloride-induced degradation studies of aluminum and stainless-steel alloys [36,45,46].

The experimental design included weekly freeze–thaw cycling between +20 °C and −20 °C (Figure 3), simulating environmental fatigue. Freezing saline solutions concentrates brines, leading to local chloride enrichment upon thawing and intensifying pit chemistry. For TSA-anodized alloys, which rely on hydrated boehmite, these cyclic thermal stresses may induce microcracks in the sealing structure or reopen pores, allowing fungal acids to penetrate and accelerate localized attack.

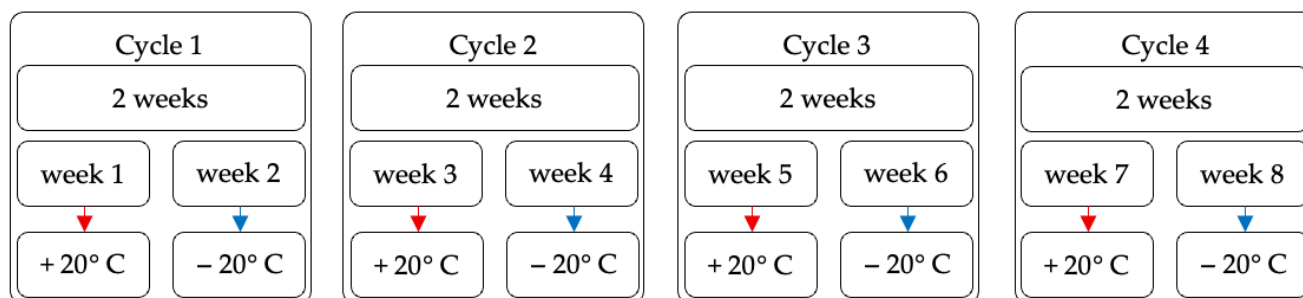


Figure 3. Thermal-cycling schedule used in this study: four consecutive 2-week cycles (weeks 1–8), alternating weekly between +20 °C and −20 °C.

To simulate aggressive service conditions, three controlled environments were established: ambient air (control), saline solution (11 wt.% NaCl in sealed vessels), and a microbiological medium (saline solution inoculated with oxalic-acid-producing *Aspergillus* strains from the family Trichocomaceae). All specimens underwent simultaneous thermal cycling for a total exposure of eight weeks (Figure 3), comprising four two-week cycles, each with one week at +20 °C followed by one week at −20 °C. This induced repeated freeze–thaw stresses, intensifying the likelihood of crack formation, pore reopening, and chloride concentration effects.

During exposure in the microbiological and saline environments, specimens were fully submerged in sealed glass test tubes. Ambient control specimens were exposed directly

to the surrounding atmosphere. All containers were under strict, continuously monitored temperature control, enabling a direct comparison between baseline ambient exposure, saline immersion, and microbiological attack under identical thermal cycling conditions.

Representative frames across the weekly exposure cycles showed only subtle, spatially uniform changes in the ambient environment (Figure 4). From Week 1 (days 1–7), specimens retained a metallic luster with a matte finish and slight edge darkening, consistent with native oxide hydration. By Week 3 (days 15–21), a gentle, homogeneous dulling was visible without preferential discoloration, implying uniform oxide growth and negligible pit nucleation. Through Week 5 (days 29–35), specular reflection slightly decreased, and weak grey banding—likely condensation/drying marks from cycling—appeared near lower edges, but no particulate deposits or crevice products formed. The Week 7 images (days 43–49) indicated a stabilized appearance with no tubercles, under-deposit features, or directional streaking, confirming minimal corrosion progression in ambient exposure.

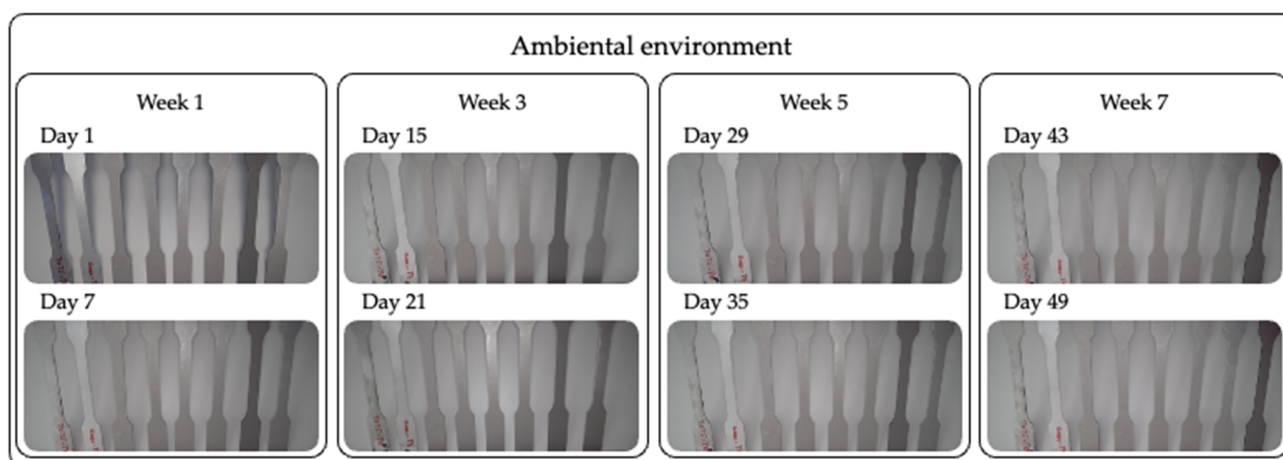


Figure 4. Ambient environment representative images of the specimens (in each image from left to right 6061-T62-1-A, 6061-T62-2-A, 7075-T62-1-A, 7075-T62-2-A, 7075-T73-1-A, 7075-T73-2-A, 6061-T4-A, 7075-T0-A) during the 8-week exposure (Days 1–49), showing the start and end of Weeks 1, 3, 5, and 7.

The time-lapse imaging in Figure 5 spanning 8 weeks clearly indicates progressive biofilm development under weekly +20/−20 °C cycling. Week 1 showed low-contrast speckles evolving into discrete dark spots, marking initial colonization and the start of extracellular polymeric substance (EPS) formation as microbes attached to the surface.

By Week 3, spot density and size increased, with neighboring colonies merging into irregular, opaque patches, establishing differential aeration cells and localized microenvironments. In Week 5, deposits thickened and became tonally heterogeneous, showing dark cores, pale halos, and streaks that suggest periodic sloughing and redeposition. By Week 7, broad, coalesced areas dominated the surface; the high contrast between deposits and bare metal, along with the persistence of dark regions, indicated sustained under-film activity and features consistent with the development of localized corrosive conditions beneath mature biofilms.

Under saline exposure (Figure 6), the surface response was dominated by salt deposition and redistribution. By Week 1, bright crystalline speckling and thin translucent films appeared, primarily along lower edges and drainage paths, consistent with evaporation/deliquescence. In Week 3, salt crusts covered larger areas, forming bands and streaks aligned with runoff; darker sub-regions beneath lighter crystalline fields indicated the onset of under-deposit corrosion. Week 5 showed heavy encrustation with coarser crystals and pronounced streaking; dark interstices between bright salt zones suggested the accumulation of corrosion products where oxygen transport was hindered. By Week

7, deposits were thicker and partially homogenized, crystal coarsening was evident, and overall reflectance was reduced—features consistent with the transition from initiation to propagation of localized corrosion driven by repeated wetting and salt redistribution.

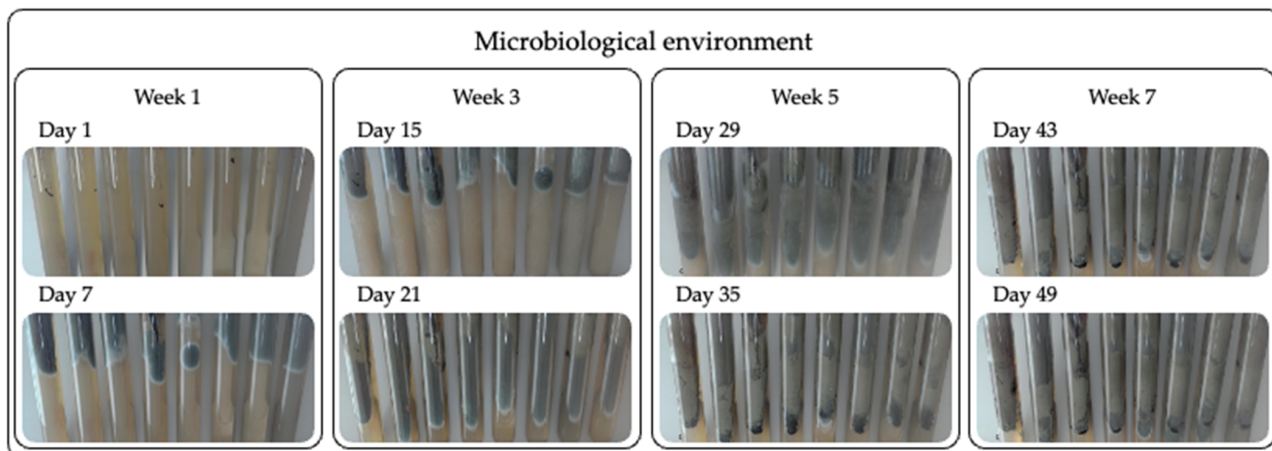


Figure 5. Microbiological environment representative images of the specimens (in each image from left to right 6061-T62-1-M, 6061-T62-2-M, 7075-T62-1-M, 7075-T62-2-M, 7075-T73-1-M, 7075-T73-2-M, 6061-T4-M, 7075-T0-M) during the 8-week exposure (Days 1–49), recorded at the start and end of Weeks 1, 3, 5, and 7.

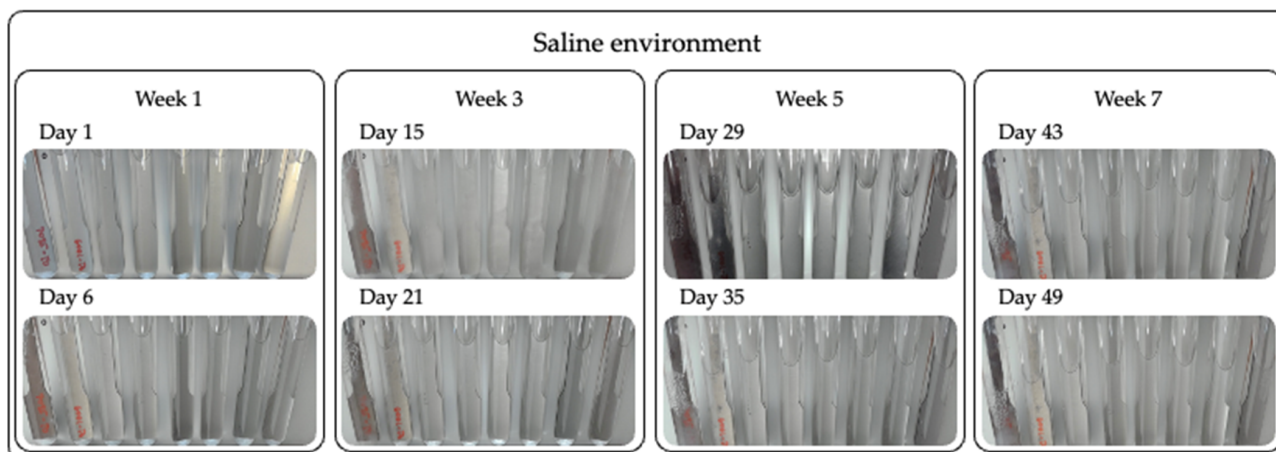


Figure 6. Saline environment representative images of the specimens (in each image from left to right 6061-T62-1-S, 6061-T62-2-S, 7075-T62-1-S, 7075-T62-2-S, 7075-T73-1-S, 7075-T73-2-S, 6061-T4-S, 7075-T0-S) during the 8-week exposure (Days 1–49), recorded at the start and end of Weeks 1, 3, 5, and 7.

2.4. Tensile Test

All tensile tests followed aerospace (Boeing) standards, using the ASTM E8/E8M methodology [47], which is equivalent to the international ISO 6892-1 standard [48]. Tensile loading was applied under controlled strain-rate conditions. Initially, the crosshead displacement was set to achieve the ASTM E8/E8M default strain rate of approximately 0.015 min^{-1} (about 1 mm/min crosshead speed) in the elastic region [47]. Maintaining this low strain rate up to the yield point is essential for accurately determining the 0.2% proof stress. Once the yield strength was found, the crosshead speed was increased, in accordance with the standard, up to approximately 5 mm/min to complete the test more efficiently [49].

Complete stress–strain curves were recorded, from which the following standard mechanical properties were extracted: yield strength (MPa, 0.2% plastic strain offset), ultimate tensile strength (UTS) (MPa, maximum stress), and elongation at break (A as %, total strain at failure) [47,48]. These values provide the standard set of tensile properties

used for aerospace materials characterization and serve as a basis for comparing the performance of the alloys after TSA anodizing and sealing.

2.5. Data Processing and Analysis

Due to unequal sample sizes (single for untreated, duplicate for treated), permutation tests were conducted within balanced alloy blocks to prevent bias. Mechanical responses (yield strength, UTS, and elongation) were normalized within each alloy group before model fitting. Normalization ensured that observed environmental effects reflected genuine exposure influences, not baseline variability or group size differences. For small sets, all possible label permutations were enumerated for exact p -values; for larger sets, permutation subsets were used, preserving alloy identity while evaluating the incremental contribution of the environment factor.

To quantify the influence of environment across all alloys, the change in model fit (Δ SSE) was evaluated when the environment term was added to a global additive model. Δ SSE = $SSE_{\text{Alloy}} - SSE_{\text{Alloy+Environment}}$ measures the reduction in unexplained variability attributable to the environment. The $R^2_{\text{env}} = \Delta$ SSE/ SSE_{Alloy} reports the proportion of residual variance (after accounting for alloy) associated with the environment term. In the present screening dataset, R^2_{env} values ranged from 0.89 to 0.93, indicating that a dominant fraction of the observed variability was linked to environmental exposure. These values should be interpreted as trend-level indicators rather than population-level estimates, given the limited replication.

Statistical significance was assessed via permutation testing of Δ SSE. The p -value, which is the fraction of permutations where the Δ SSE was at least as large as the observed value, established the statistical credibility of the improvement.

For within-alloy comparisons, the one-way ANOVA F-statistic was computed. Inference was based primarily on permutation p -values due to limited group sizes, with F reported for interpretability (large F implies high between-environment variation). Complementing F, the effect size η^2 (eta squared), defined as the ratio of the sum of squares between environments to the total sum of squares, was used. η^2 values often exceeded 0.85 for yield and tensile strength, where replicates were available, signifying very large, practically meaningful environment effects. These metrics provide a coherent framework: Δ SSE and R^2_{env} quantify model improvement from including environment; permutation p -values establish the statistical credibility; and F with η^2 characterize the magnitude and practical significance of environmental differences within each alloy. This quantitative framework complements the qualitative surface evolution (time-lapse images) and the quantitative retention patterns (Table 4).

Table 4. Mechanical properties at Week 8 of thermal cycling, by environment and environment-to-environment comparison for 6061-T4, 6061-T62, 7075-T0, 7075-T62, and 7075-T73.

Alloy	Y _{s0.2}		UTS		%	A		Y _{s0.2}		UTS		A	
	MPa	% Diff.	MPa	% Diff.		% Diff.	% Diff.	% Diff.	% Diff.	% Diff.			
Ambiental environment						Ambiental vs. Microbiologic							
6061-T4	149	−2.61%	231	−6.10%	19	−20.83%	−2.68%	−1.73%	−13.16%				
6061-T62-1	265	−1.12%	309	−2.52%	9.1	−9.00%	−2.26%	−4.53%	−26.37%				
6061-T62-2	266	−0.75%	311	−1.26%	8.9	−11.00%	−3.38%	−6.39%	−20.22%				
7075-T0	112	−8.94%	215	−5.70%	16	−0.62%	−3.57%	−4.19%	−11.95%				
7075-T62-1	517	−0.19%	582	−0.51%	10.3	−6.36%	−1.55%	−1.55%	−8.74%				
7075-T62-2	511	−1.35%	584	−0.17%	10.8	−1.82%	−2.74%	−3.25%	−6.48%				
7075-T73-1	459	−1.29%	519	−1.14%	8.2	−8.89%	−1.31%	−1.93%	−6.10%				
7075-T73-2	461	−0.43%	521	−0.76%	8	−11.11%	−1.94%	−1.15%	−1.25%				

Table 4. Cont.

Alloy	Y _{s0.2} MPa	% Diff.	UTS MPa	% Diff.	%	A % Diff.	Y _{s0.2} % Diff.	UTS % Diff.	A % Diff.
Saline environment					Ambiental vs. Saline				
6061-T4	138	−9.80%	224	−8.94%	17.7	−26.25%	−7.38%	−3.03%	−6.84%
6061-T62-1	248	−7.46%	287	−9.46%	8.4	−16.00%	−6.42%	−7.12%	−7.69%
6061-T62-2	247	−7.84%	285	−10.09%	8.2	−18.00%	−7.14%	−8.95%	−7.87%
7075-T0	107	−13.01%	200	−12.28%	12.3	−23.13%	−4.46%	−6.98%	−22.64%
7075-T62-1	492	−5.02%	568	−2.91%	10.2	−7.27%	−4.84%	−2.41%	−0.97%
7075-T62-2	493	−4.83%	558	−4.62%	9.7	−11.82%	−3.52%	−4.45%	−10.19%
7075-T73-1	444	−4.52%	501	−4.57%	7.8	−13.33%	−3.27%	−3.47%	−4.88%
7075-T73-2	448	−3.66%	504	−4.00%	7.5	−16.67%	−3.24%	−3.26%	−6.25%
Microbiological environment					Microbiological vs. Saline				
6061-T4	145	−5.23%	227	−7.72%	16.5	−31.25%	−4.83%	−1.32%	7.27%
6061-T62-1	259	−3.36%	295	−6.94%	6.7	−33.00%	−4.25%	−2.71%	25.37%
6061-T62-2	257	−4.10%	293	−7.57%	7.1	−29.00%	−3.89%	−2.73%	15.49%
7075-T0	108	−12.20%	206	−9.65%	14	−12.50%	−0.93%	−2.91%	−12.14%
7075-T62-1	509	−1.74%	573	−2.05%	9.4	−14.55%	−3.34%	−0.87%	8.51%
7075-T62-2	497	−4.05%	565	−3.42%	10.1	−8.18%	−0.80%	−3.00%	−3.00%
7075-T73-1	453	−2.58%	509	−3.05%	7.7	−14.44%	−1.99%	−1.57%	1.30%
7075-T73-2	454	−2.37%	515	−1.90%	7.9	−12.22%	−1.32%	−2.14%	−5.06%

3. Results

After 8 weeks of exposure, the tensile behavior of both 6061-T4, -T62 and 7075-T0, -T62 and -T73 alloys under different environmental conditions is illustrated by the stress–strain curves in Figure 7. The baseline reference curves indicate the expected elastic–plastic response and strain-hardening behavior characteristic of each temper state. Specimens exposed to ambient conditions show deviations from the baseline response, indicating mechanical degradation.

The stress–strain curves further indicate a reduced strain-hardening capacity after aggressive exposure, reflecting the cumulative effects of surface damage, localized corrosion, and environmentally assisted microstructural degradation. These mechanical trends are fully consistent with the quantitative strength and ductility reductions reported in Table 4 and confirm the sensitivity of both alloy systems to coupled chemical, biological, and thermal stressors.

3.1. Mechanical Properties Comparison of the Aluminum Alloys

The initial mechanical response of each alloy–temper combination provided a reference baseline for assessing the environmental degradation in Table 4. This framework was used to quantify how the Week-8 thermal-cycling exposures (ambient, microbiological, and saline; ± 20 °C, weekly) altered those properties.

The analysis of the uniaxial tensile data recorded after 8 weeks of cyclic exposure confirmed the expected baseline material performance hierarchy. The highest strength was exhibited by the peak-aged 7075-T62 condition, followed sequentially by 7075-T73, 6061-T62, 6061-T4, and the annealed 7075-T0, with ductility inversely proportional to this ranking. Evaluation of the exposed specimens established a consistent environmental severity ranking for strength retention: ambient $\ll$ microbiological $\leq$ saline. This comparison revealed that the two aggressive environments induced distinct and separable degradation modes in the alloys.

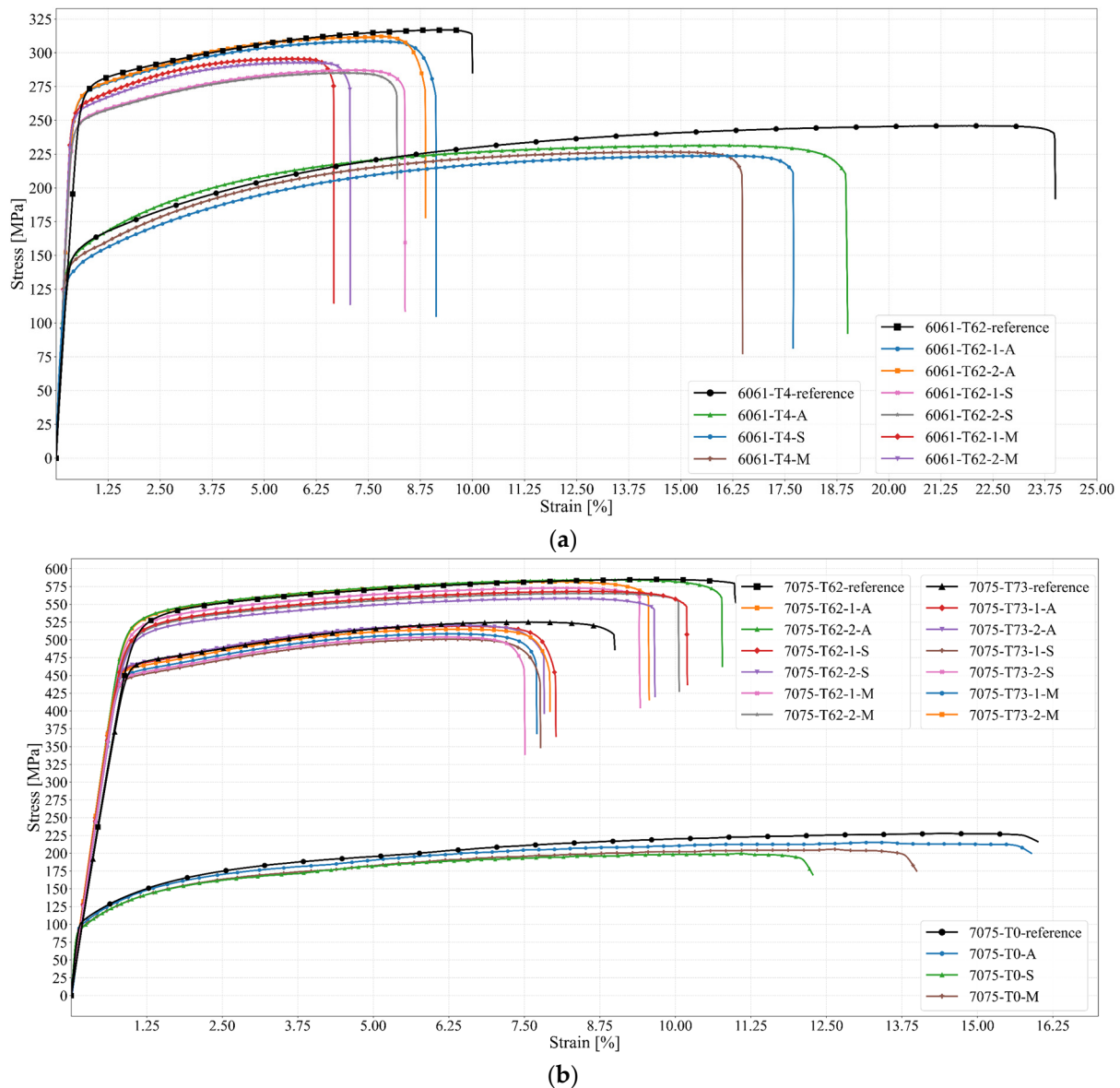


Figure 7. Stress–strain curves comparative effects of environmental exposure on elastic response, yield behavior, ultimate tensile strength, and elongation at failure of aluminum alloys 6061-T4 and -T62 (a) and 7075-T0, -T62 and -T73 (b) for the baseline reference condition and after 8 weeks of exposure to ambient air (A), microbiological medium (M), and saline solution (S) under cyclic $\pm 20^\circ\text{C}$ thermal loading.

For the 6061-alloy family, the two aggressive media induced contrasting primary failure mechanisms. Ambient exposure largely preserved the baseline mechanical properties; for instance, the stable T62 condition showed only marginal ambient losses ($Y_{s0.2} \approx -0.8\%$ to -1.1% , $UTS \approx -1.3\%$ to -2.5% , and $A \approx -9\%$ to -11%).

However, microbiological exposure (biofilm formation) was shown to primarily penalize ductility. For 6061-T62, the average properties shifted from $\approx 265.5\text{ MPa } Y_{s0.2}/310\text{ MPa } UTS/9.0\% A$ (ambient) to $\approx 258\text{ MPa}/294\text{ MPa}/6.9\% A$ (microbiological). Expressed as changes relative to ambient, this represented modest strength losses ($Y_{s0.2} \approx -2.8\%$, $UTS \approx -5.2\%$), but a disproportionate and pronounced ductility penalty of $\approx -23\%$ in elongation. T62 replicates specifically showed A reductions of -33.0% and -29.0% . 6061-T4 followed the same tendency, with a notable -13.16% ductility drop. This severe reduction in fracture strain correlates strongly with biofilm development and the formation of localized microenvironments observed in the time-lapse images.

In contrast, Saline exposure (salt crusts) produced the largest systematic strength penalties. For 6061-T62, saline exposure resulted in average properties of ≈ 247.5 MPa/286 MPa/8.3% A. This translated to larger strength losses ($Y_{s0.2} \approx -6.8\%$, $UTS \approx -7.7\%$) than the microbiological medium, while the ductility loss ($\approx -7.8\%$) was comparatively smaller. 6061-T62 replicates showed $Y_{s0.2}$ reductions between -7.5% and -7.8% , aligning with the observed salt deposition and under-deposit attack features.

The pairwise comparison (microbiological-saline) further underscored this mechanistic split. The switch caused an additional strength decrease (e.g., 6061-T62 $Y_{s0.2}$ dropped by another -3.9% to -4.3%), but critically, it caused a significant recovery in ductility (A increased by $+15\%$ to $+25\%$, or $+1.1$ to $+1.7$ percentage points). This confirms that biofilm maturation uniquely suppresses ductility in Al-Mg-Si alloys, whereas chloride-rich deposits drive uniform strength degradation.

For the 7075-alloy family, the environmental sensitivity was generally more balanced and moderate, although state-dependent. The peak-aged T62 temper successfully retained the highest strengths across all conditions, with comparatively small ambient deltas ($Y_{s0.2} \approx -0.2\%$ to -1.4%). Exposure to the aggressive media resulted in modest strength decreases (microbiological: $Y_{s0.2} \approx -1.7\%$ to -4.1%) while ductility fell to a lesser extent than in 6061 (A reduction of -8% to -15%). Relative to ambient, T62 shifts were approximately -2.1% / -2.4% / -7.6% for $Y_{s0.2}$ /UTS/A in the microbiological medium, and -4.2% / -3.4% / -5.7% in saline.

The over-aged T73 temper showed the anticipated trade-off of lower initial strength for increased stability. This state exhibited small, nearly parallel decrements in both aggressive media, reinforcing its damage tolerance. Relative to ambient (≈ 460 MPa/520 MPa /8.1% A), T73 values shifted to ≈ 453.5 MPa/512 MPa/7.8% A (microbiological) and ≈ 446 MPa/502.5 MPa/7.65% A (saline), with strength losses mostly ranging between -1.9% and -4.6% and ductility losses between -12% and -16.7% .

The annealed 7075-T0 proved to be the most environment-sensitive state overall. Ambient exposure alone significantly reduced its properties ($Y_{s0.2} \approx -8.9\%$, $UTS \approx -5.7\%$). These losses intensified in the aggressive media, reaching up to UTS reductions of $\approx -12.3\%$ and the most severe ductility penalty of the table (A reduced by $\approx -23.1\%$ in saline exposure), consistent with its low baseline stability. Although the annealed 7075-T0 condition exhibited the highest environmental sensitivity, this state is not representative of industrial structural use. In contrast, the over-aged T73 temper demonstrated only limited strength and ductility degradation in aggressive environments, confirming its well-known damage-tolerant behavior.

Replicate-to-replicate variation was consistently small (on the order of $\approx 0.2\%$ to 1.2% for strength and $\approx 1\%$ to 4% for elongation across duplicates), lending strong trend-level confidence to the observed environment-specific effects and supporting the consistency of the established severity ordering within the present dataset. The data collectively shows that Al-Mg-Si alloys are particularly susceptible to biofilm-induced ductility loss, while chloride-rich environments lead to a broader, more systematic loss of strength in both alloy families.

3.2. Statistical Analysis

The influence of exposure environment (ambient, saline, and microbiological) on the mechanical properties of TSA-anodized aluminum alloys was evaluated using non-parametric permutation methods implemented in Python v3.12.0 (Beaverton, OR, USA) For each alloy-temper combination and each mechanical response (yield strength, ultimate tensile strength, and elongation at break), a one-way permutation ANOVA was performed. Computations were carried out with numerical and data-analysis libraries, including NumPy for array operations and Pandas/Microsoft Excel v16.10 (Redmond, WA, USA)

for data management. Reported values of ΔSSE , R^2_{env} , and p -value were derived after normalizing specimen data within each alloy group to ensure that unequal replication among conditions did not influence the statistical significance.

The importance of this analysis lies in its ability to separate the contributions of the alloy and the environment. Analysis of the fitted data reveals that certain alloys exhibit superior initial strength or ductility compared to others. This makes it possible to attribute observed changes (and their statistical significance) to the exposure conditions rather than to underlying alloy differences. The permutation tests assess whether the Environment term explains a meaningful portion of the observed variance (R^2_{env}). Within the limits of the present screening dataset and the available replication, the analysis indicates that the environment accounts for a dominant share of the observed variability (approximately 89–93%, depending on the property). However, this proportion should be interpreted as a trend-level indicator rather than a population-level estimate, and it reflects the strong sensitivity of the studied responses to saline and microbiological exposure under the constraints of the experimental sample size.

The global additive model showed that environment was a significant factor for all responses: for yield strength the improvement in sum-of-squared error when adding environment to the alloy-only model was $\Delta\text{SSE} = 977.1$ and the permutation p -value was 0.0002, corresponding to an R^2_{env} of 0.91; for ultimate tensile strength $\Delta\text{SSE} = 1376.1$, $p = 0.0002$ and $R^2_{\text{env}} = 0.93$; for elongation $\Delta\text{SSE} = 8.04$, $p = 0.0024$ and $R^2_{\text{env}} = 0.89$. Within individual alloys, the effect of environment was also large: for example, in alloy 6061-T6, the permutation ANOVA yielded $F \approx 163.5$ for yield strength with a p -value of 0.037 and $\eta^2 \approx 0.99$, and similar trends were observed for UTS ($F \approx 81.5$, $\eta^2 \approx 0.98$) and A ($F \approx 57.2$, $\eta^2 \approx 0.97$). For 7075-T62, the environment effect was less pronounced (p -values around 0.047 and η^2 between 0.78 and 0.84), while in 7075-T73 it remained sizeable ($\eta^2 \approx 0.93$ for $Y_{S0.2}$). Although some p -values are close to 0.05 because of limited replication (two specimens per environment), the consistently high η^2 values and the significant global tests support, within the limits of the present dataset, the conclusion that saline and microbiological exposures systematically degrade mechanical properties relative to the ambient condition.

3.3. Effect of Environmental Exposure on Yield Strength

The analysis of yield strength, as illustrated in Figure 8, confirmed the expected mechanical hierarchy, with the peak-aged 7075-T62 samples registering the highest baseline strength (around 520 MPa), while the annealed 7075-T0 exhibited the lowest (around 120 MPa). A consistent and systematic decline in $Y_{S0.2}$ was observed across all alloy/temperatures as the exposure environment became more aggressive (Initial $\rightarrow$ Ambient $\rightarrow$ Microbiologic $\rightarrow$ Saline).

This degradation is quantified by examples showing 6061-T62 falling from 268 MPa (unexposed) to 248 MPa (saline exposure), and 7075-T62 decreasing from 518 MPa to 492 MPa over the same sequence. These trends are congruent with the previously discussed additive model, which found that the environmental factor accounted for a substantial and statistically significant fraction of the variance in yield strength.

The strength decline was smallest under ambient conditions (less than 1% loss for 7075-T62), moderate under microbiologic exposure (ranging from 2.9% to 12.2%), and greatest under saline conditions, where reductions spanned roughly -4.9% for 7075-T73 to -13.0% for 7075-T62. The 7075-T0 condition proved the most sensitive, recording the largest losses across all environments (e.g., -13.0% in saline), while the robust 6061-T62 retained much of its strength (losing about 7.6% in saline). These patterns provide visual corroboration for the permutation ANOVA conclusions: the magnitude of strength loss

depends critically on both the inherent metallurgical state (with annealed states being most vulnerable) and the aggressiveness of the exposure.

Figure 9 further clarifies this degradation by plotting the percentage change in $Y_{S0.2}$ relative to the initial state, with negative values dominating all environments.

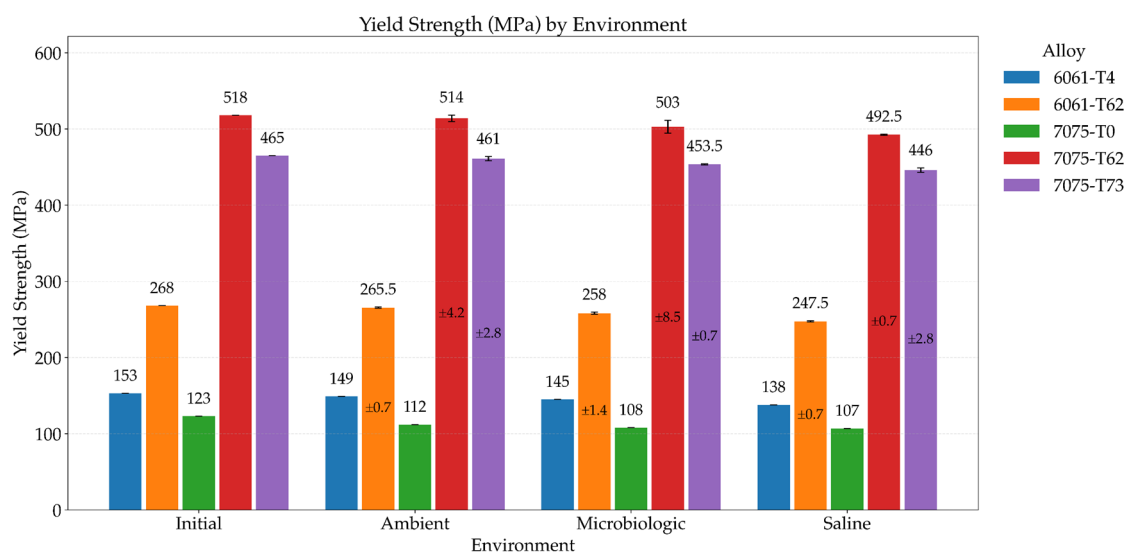


Figure 8. Comparison of the mean yield strength of aluminum alloys 6061-T4, 6061-T62, 7075-T0, 7075-T62, and 7075-T73 across Initial, Ambient, Microbiological, and Saline conditions. Bars represent the mean strength, and error bars for replicated tempers (T62 and T73) denote the standard deviation (SD).

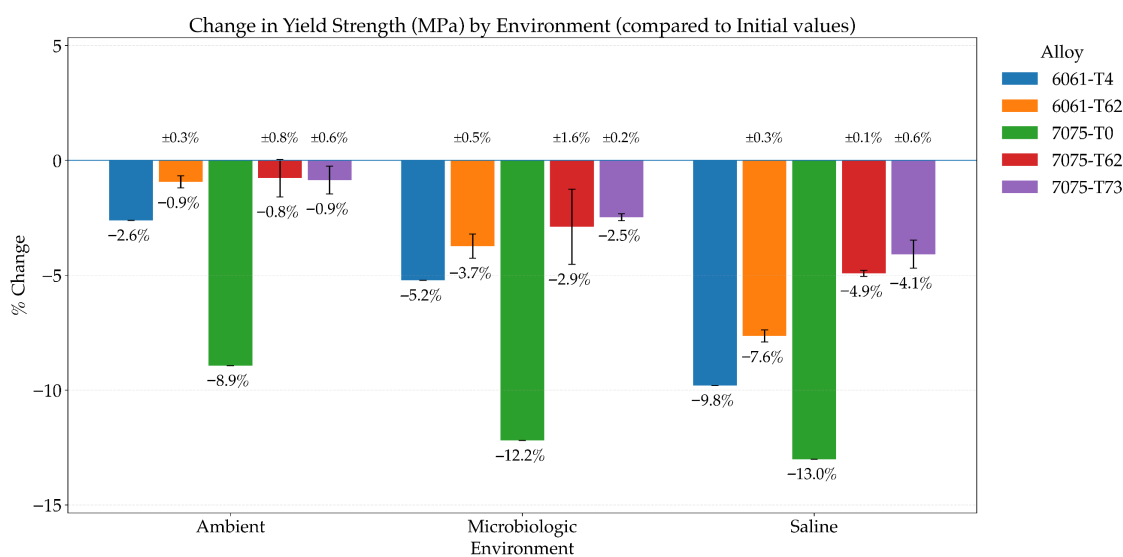


Figure 9. Comparison of the mean percentage difference in yield strength relative to the Initial state under Ambient, Microbiological, and Saline conditions. Bars for replicated tempers (T62 and T73) represent the mean percentage change, with error bars denoting the propagated standard deviation (SD) of the change (negative values indicate percentage loss).

3.4. Effect of Environmental Exposure on Ultimate Tensile Strength

The analysis of the Ultimate Tensile Strength (UTS), as presented in Figure 10, confirms the expected strength hierarchy, mirroring the yield strength results. The peak-aged 7075-T62 samples exhibit the highest initial UTS (approximately 580–590 MPa), with the over-aged 7075-T73 slightly lower (around 520 MPa). The 6061-T62 alloy occupies an intermediate strength position, while the 6061-T4 and annealed 7075-T0 exhibit the lowest strengths. Across all alloys, the UTS trend with environment is monotonic: ambient

exposure yields a minor reduction from the initial state, the microbiological medium introduces a further, modest decrease, and saline exposure consistently produces the largest drop. For example, the 7075-T62 sample declines only slightly (less than ~5%) from the initial value to the saline condition, whereas the lower-strength states like 6061-T4 and 7075-T0 show larger proportional losses. These monotonic decreasing trends are consistent with the retention analyses, which found the environmental effect on UTS to be statistically significant but moderate, suggesting UTS is comparatively more resilient than yield strength or elongation at break under the tested cycling and exposure regimes.

Figure 11 recasts the data by presenting the percentage change in UTS relative to the initial state, with all values extending below zero to denote strength reductions. Ambient exposure yields the smallest losses, ranging from 0.3% to 6% depending on the alloy. Microbiological exposure produces intermediate reductions (e.g., 7.7% for 6061-T4 and 2.7% for 7075-T62), while saline immersion causes the largest overall declines.

The annealed 7075-T0 condition experiences the most pronounced degradation, with UTS dropping by $\approx 5.7\%$ in ambient conditions, 9.6% under microbiological attack, and 12.3% in saline. Conversely, the high-strength 7075-T62 and 7075-T73 conditions retain much of their strength, losing less than 5% even under severe saline exposure. The percentage plot emphasizes that, although UTS decreases with environmental aggressiveness, the relative losses are smaller than those observed for $Y_{S0.2}$ or A . This outcome aligns with the permutation ANOVA results, which indicated that the environment factor was associated with a significant but relatively modest proportion of the overall variance in ultimate tensile strength, reflecting the alloy-dependent resilience of this mechanical property.

3.5. Effect of Environmental Exposure on Elongation at Break

The ductility analysis, summarized by the elongation at break (A) in Figure 12, reveals that this property is highly sensitive and heterogeneous across the exposure regimes. In the unexposed state, the naturally aged 6061-T4 condition exhibits the highest initial elongation (around 24%), followed by the annealed 7075-T0 (~16%). The heat-treated 6061-T62 and the two high-strength 7075 tempers start at lower, comparable values ($\approx 9\%$ to 11%). Exposure to ambient conditions induced only modest initial declines: 6061-T4 fell to ~19% and 6061-T62 to ~9%, with 7075 alloys dropping only slightly.

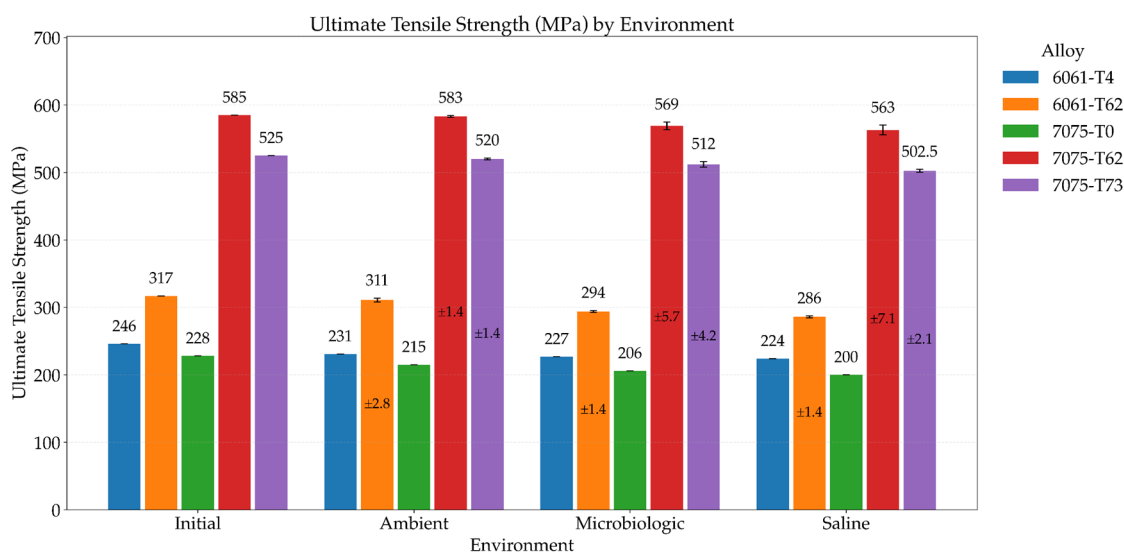


Figure 10. Comparison of the mean ultimate tensile strength of aluminum alloys 6061-T4, 6061-T62, 7075-T0, 7075-T62, and 7075-T73 across Initial, Ambient, Microbiological, and Saline conditions. Bars represent the mean strength, and error bars for replicated tempers (T62 and T73) denote the standard deviation (SD).

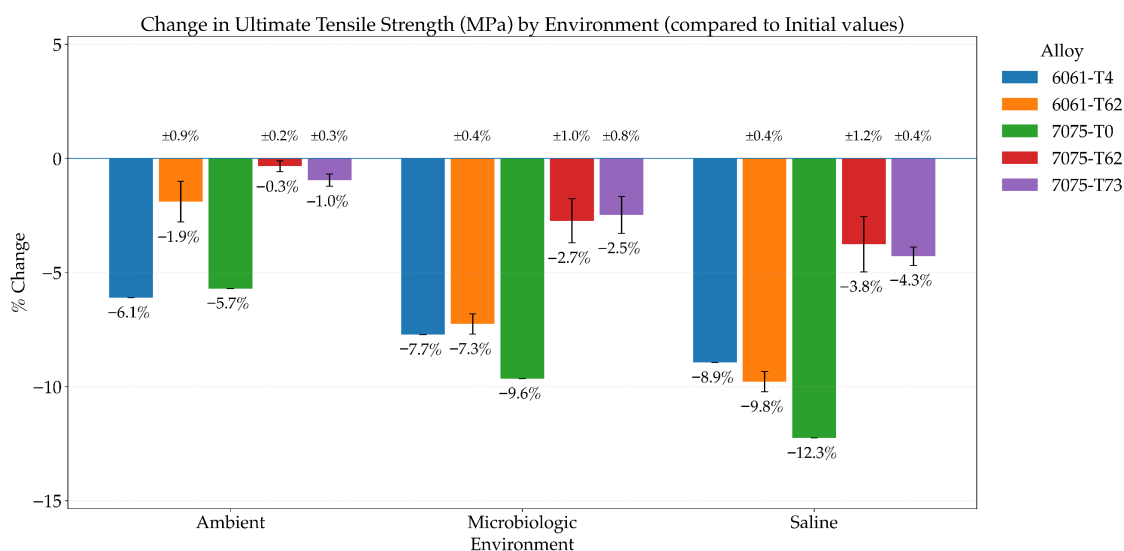


Figure 11. Comparison of the mean percentage difference in ultimate tensile strength relative to the Initial state under Ambient, Microbiological, and Saline conditions. Bars for replicated tempers (T62 and T73) represent the mean percentage change, with error bars denoting the propagated standard deviation (SD) of the change (negative values indicate percentage loss).

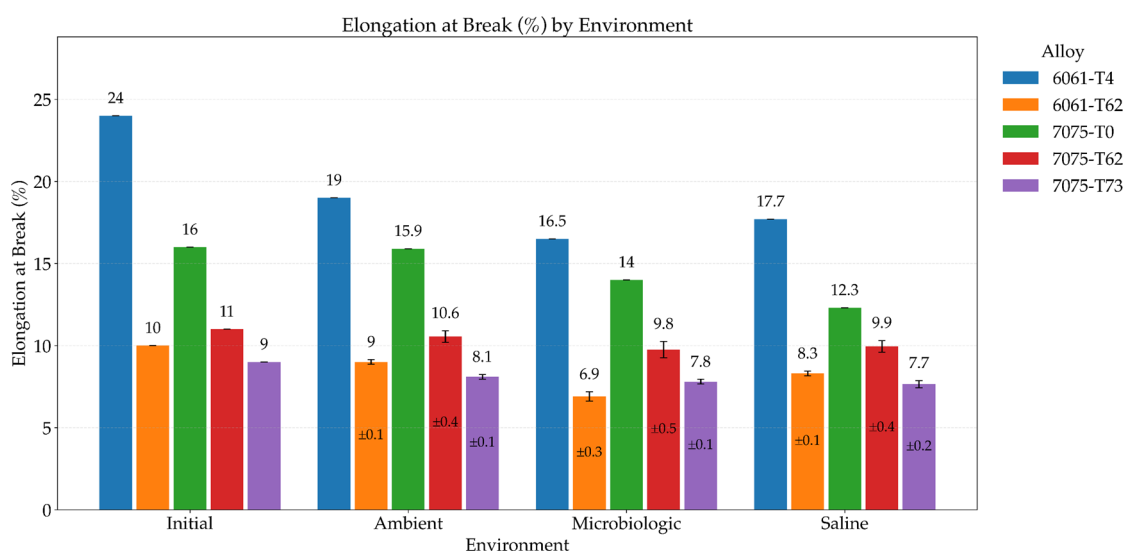


Figure 12. Comparison of the mean elongation at break of aluminum alloys 6061-T4, 6061-T62, 7075-T0, 7075-T62, and 7075-T73 across Initial, Ambient, Microbiological, and Saline conditions. Bars represent the mean strength, and error bars for replicated tempers (T62 and T73) denote the standard deviation (SD).

Microbiological immersion resulted in the most pronounced reductions in ductility for several alloys, confirming its particularly detrimental nature. 6061-T4 dropped by roughly one-third of its initial ductility (to ~16.5%), 6061-T62 experienced a severe reduction, halving its elongation (to ~6.9%), and 7075-T0 was reduced to about 14%. Intriguingly, saline exposure did not uniformly exacerbate this loss: 6061-T4 presents slightly increased values in saline (to 17.7%), though 6061-T62 and the 7075 tempers remained suppressed at 8% to 10%. These trends underline that ductility is more sensitive than strength to aggressive environments, with the response being strongly dependent on alloy composition and temper.

Figure 13 expresses these changes as the percentage difference in elongation at break relative to the initial state, where all bars are negative, signaling universal reductions. The

largest proportional losses occurred for the 6061 alloys: 6061-T4 lost roughly 20.8% of its ductility in ambient conditions, 31.2% in the microbiologic environment, and 26.3% in saline. 6061-T62 similarly dropped by 31% in the microbiologic environment.

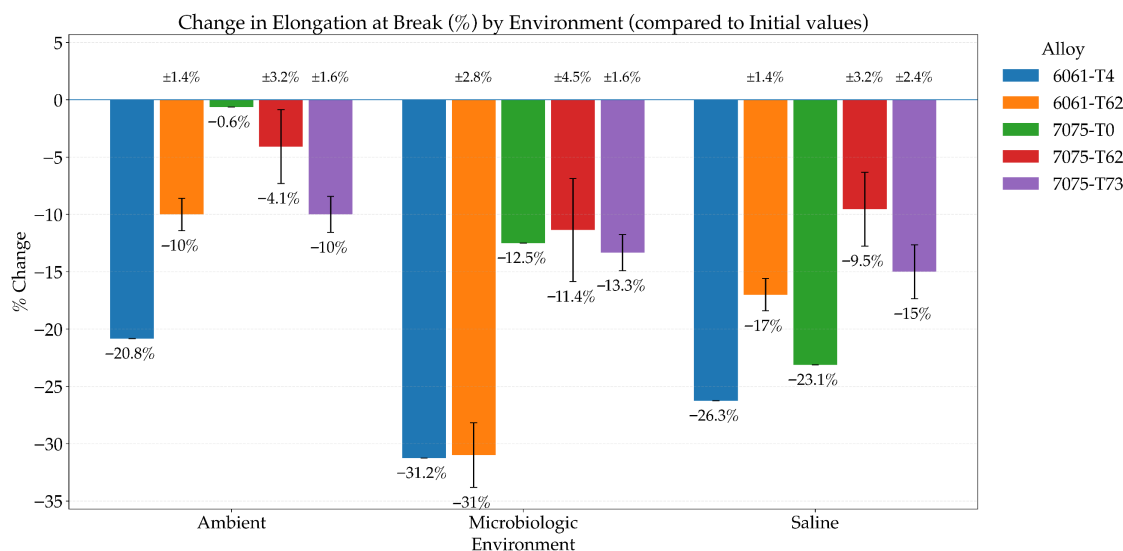


Figure 13. Comparison of the mean percentage difference in elongation at break relative to the Initial state under Ambient, Microbiological, and Saline conditions. Bars for replicated tempers (T62 and T73) represent the mean percentage change, with error bars denoting the propagated standard deviation (SD) of the change (negative values indicate percentage loss).

The 7075-T0 alloy, initially more resistant (only 0.6% loss in ambient), suffered markedly under aggressive exposures (12.5% in microbiologic and 23.1% in saline). The high-strength 7075-T62 and 7075-T73 tempers were comparatively more robust, with total losses ranging from 4.1% to 11.4% in microbiologic and 9.5% to 15% in saline. Collectively, these percentage plots reinforce that elongation at break is the most environmentally sensitive mechanical property studied: the environmental factor is associated with a very large proportion of the observed variability, with the microbiologic exposure often producing the greatest relative damage. The heterogeneity in response across alloys mirrors the differences in microstructure and underscores the necessity of considering both alloy and protective measures where maintaining high ductility is critical.

In chloride-rich environments, aggressive ions penetrate and compromise the integrity of the anodic oxide layer, particularly at structural discontinuities or reopened pores. This degradation mechanism facilitates localized pitting and under-deposit corrosion, ultimately diminishing load-bearing capacity and initiating crack propagation. Cyclic thermal exposure between +20 °C and −20 °C exacerbates these effects by inducing freeze-thaw concentration of brines and generating mechanical stresses. The volumetric expansion of ice within surface defects and sealed pores promotes microcrack formation, oxide spallation, and reactivation of pore channels, thereby accelerating corrosion ingress [50,51]. Concurrently, microbiologically influenced corrosion arises from biofilms produced by fungi such as *Aspergillus*, which secrete organic acids (e.g., oxalic acid) that locally reduce pH and chelate Al^{3+} ions. This biochemical interaction compromises the integrity of the anodic oxide, enhances pit nucleation, and establishes differential aeration cells that intensify localized attack [42,52–54]. The susceptibility of alloys to these processes is strongly dependent on their chemical composition and temper state; for instance, Zn- and Cu-enriched 7075 alloys exhibit pronounced vulnerability to intergranular corrosion and stress-corrosion cracking, whereas 6061 alloys experience significant ductility loss under microbial exposure due to embrittlement phenomena [50,55,56].

Furthermore, when the environment involves cyclic thermal or humidity/temperature variation (as in freeze–thaw or wet-dry cycles), the repeated expansion and contraction of corrosion products and oxides promote the nucleation and growth of microcracks inside the passive film or the metal substrate. Over time, microstructural defects progressively accumulate and coalesce, resulting in a reduction of load-bearing capacity. Recent work using time-resolved X-ray microtomography on 7075 (7000-series) has directly demonstrated that cyclic freeze–thaw in a chloride-containing environment causes internal micro-cracking and structural degradation [8,52,57].

In high-strength 7000-series alloys (e.g., 7075), this damage is exacerbated by their known sensitivity to stress-corrosion cracking (SCC) under chloride exposure: tensile-testing after marine-atmosphere exposure showed intergranular cracks, exfoliation, and a severe reduction in elongation and strength. Combined, these mechanisms—pitting, corrosion-induced microcracking, cyclic-stress amplification, and environment-assisted embrittlement—provide a plausible, literature-backed explanation for the experimentally observed mechanical degradation under our simulated aggressive conditions [9,51,58].

4. Discussion

The surface treatment process began with TSA anodizing, which utilizes an aqueous mixture of sulfuric and tartaric acids, following EN 4704:2012 specifications [9], and serves as a REACH-compliant alternative to chromic acid anodizing for aerospace alloys. This process forms a duplex oxide composed of a compact barrier and a porous alumina layer, where tartrate complexation promotes uniform pore nucleation and partial incorporation of sulfate ions (Al-O-SO_3 -moieties) into the anodic film affects its subsequent hydration [10,12,13]. The specimens were subsequently subjected to hydrothermal sealing at 98–100 °C, which converts the porous alumina to boehmite ($\text{AlO}(\text{OH})$), reducing porosity and improving corrosion resistance, although nickel-salt sealing is also effective, while chromate remains efficient yet restricted. The integrity of this sealed layer is critical, as chloride ions and microbiological metabolites may still propagate along pore channels, which necessitates extended environmental testing to capture realistic degradation. The exposure protocol intentionally intensified service-relevant damage: an 11 wt.% NaCl brine ($\sim 3.5 \times$ seawater) accelerated chloride attack; weekly $+20 \rightarrow -20$ °C thermal cycling induced freeze–thaw concentration and mechanical disruption, known to promote pit-to-crack transitions in AA7075 through ice expansion within defects and oxide spallation [48]; and *Aspergillus* biofilms introduced microbiologically influenced corrosion. The higher Zn- and Cu-rich microstructures of 7xxx alloys increase their susceptibility to localized attack, explaining the greater degradation observed [2,8,30]. After this aggressive exposure, the analysis of mechanical properties consistently showed ambient conditions caused only negligible degradation (e.g., 6061-T4 ambient yield dropped ~ 2 –3%, UTS ~ 6 %, A ~ 21 %), while saline and microbiological exposures led to noticeable reductions, with the robust trend that ductility (A%) suffered the most pronounced reductions, indicating corrosion damage tends to embrittle the material much more than it reduces load-carrying capacity [9,59,60]. This is evidenced by 7075-T73 losing only ~ 4 % of its UTS after saline exposure, but its elongation plummeting by ~ 15 %, and 6061-T62 in the microbiological environment seeing UTS drop by ~ 7 % whereas elongation dropped by ~ 33 % (from 10% to ~ 6.9 %). These losses are consistent with established data that hostile environments affect aluminum alloys [9] and confirm that minor surface corrosion can cause a sharp initial drop in UTS [7,9,53,59,61–64]. When comparing aggressive media, the MIC environment often caused equal or greater degradation in ductility than saltwater; for instance, 6061-T62's A% dropped by ~ 33 % in the microbial medium vs. ~ 16 % in saltwater, and 6061-T4 lost ~ 31 % A% vs. ~ 26 % in saltwater, supporting literature that microorganisms accelerate corrosion and pitting [12].

Strength losses were most pronounced for 7xxx tempers under saline and microbiological conditions (7075-T62 $\approx -9.8\%$, T0 $\approx -12.3\%$), whereas 6xxx tempers exhibited smaller declines. AA7075 retained a strength advantage, but both alloys converged toward similar low ductility levels (e.g., 6061-T62 dropped to $\sim 6.9\%$ A%, 7075-T62 retained $\sim 9.8\%$ A% after microbial exposure). The over-aged 7075-T73 showed improved tolerance and lost properties similarly to T6 (UTS $\sim 3\text{--}4\%$, A $\sim 10\text{--}15\%$), reinforcing that its advantage lies mainly in long-term SCC rather than general pitting corrosion [12]. 6061 tempers showed severe ductility reductions ($\sim 30\%$ relative loss), confirming that MIC can cause substantial degradation even in the generally more corrosion-resistant 6xxx series alloys [5,42,46,47]. Synthesizing the Week-8 data, two main observations are established: strength degradation followed the ranking ambient $\ll$ microbiological $\leq$ saline (most pronounced in 6061-T62 $Y_{s0.2}$ and UTS drops in saline), and ductility erosion (biofilm-mediated surface conditioning) was uniquely detrimental to the Al–Mg–Si alloy (6061), whereas Al–Zn–Mg–Cu (7075) tempers showed more balanced, moderate reductions in ductility across both media. The statistical analyses indicate that the environment is associated with a dominant influence on the observed mechanical responses, as reflected by high F-ratios and partial η^2 values together with low permutation p -values. Within the limits of the present screening dataset, these results suggest that chloride-driven film degradation, freeze–thaw effects on the sealed structure, and microbial biofilm activity are consistent with the observed alloy-specific strength losses and ductility reductions.

5. Conclusions

This study investigated the protective efficacy of Tartaric–Sulphuric Acid Anodizing (TSA) plus sealing on five aerospace aluminum alloys (6061-T4, 6061-T62, 7075-T0, 7075-T62, and 7075-T73) over eight weeks involving cyclic thermal stress ($+20\text{ }^{\circ}\text{C}/-20\text{ }^{\circ}\text{C}$) and exposure to ambient, saline ($\approx 11\text{ wt.}\%$ NaCl), and microbiological environments. TSA forms a protective oxide barrier and a porous alumina layer, which the sealing process converts to boehmite ($\text{AlO}(\text{OH})$), confirming TSA's role as a viable chromate-free replacement. The experimental conditions effectively mimicked service stressors, including high chloride load, brine concentration via freeze–thaw, and metabolite-driven microbiologically influenced corrosion (MIC).

Yield and tensile strengths showed moderate but systematic decreases in aggressive environments. The highest initial strength was held by peak-aged 7075-T62 ($Y_{s0.2} \approx 518\text{ MPa}$, UTS $\approx 585\text{ MPa}$), while the annealed 7075-T0 was the lowest ($Y_{s0.2} \approx 123\text{ MPa}$). Under aggressive exposure, strength generally declined by 5–10% for yield strength and 2–9% for UTS, with the largest drops in the annealed (7075-T0) and peak-aged 7xxx conditions. The 7075-T73 temper experienced smaller losses, consistent with its coarsened precipitate structures, mitigating localized corrosion.

Ductility demonstrated significantly greater sensitivity and was identified as the primary limiting mechanical property. Elongation at break (A) consistently suffered the most significant degradation, decreasing by 17–31% for 6061-T62 and 7075-T0. For instance, 6061-T4 A fell from 24% to $\approx 16.5\%$ (microbiological) and 17.7% (saline), representing reductions of 31% and 26%, respectively. MIC exposure introduced organic acids that accelerate the dissolution of the anodic film, proving to be particularly detrimental to ductility.

The statistical analysis indicates that the exposure environment is strongly associated with the observed degradation trends, with high partial R^2 values recorded for yield strength (0.91), UTS (0.93), and elongation (0.89), within the constraints of the present screening dataset. The underlying degradation mechanisms are consistent with chloride-assisted film breakdown, freeze–thaw-induced mechanical disturbance of sealed pores, and microbially influenced surface chemistry accelerating localized dissolution. The increased

susceptibility of the 7xxx alloys to localized attack is consistent with the presence of Cu-rich precipitates, which promote micro-galvanic coupling. Overall, TSA-sealed alloys retain useful levels of strength, but the substantial loss of ductility—particularly in peak-aged tempers—emerges as the primary design concern for components operating in cold, saline, or biologically active environments.

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Abbreviations

The following abbreviations are used in this manuscript:

AA	Aluminum alloy (prefix in AA6061, AA7075 designations)
ANOVA	Analysis of variance
ASTM	ASTM International (American Society for Testing and Materials)
CNC	Computer numerical control
EN	European Standard (European Norm)
EPS	Extracellular polymeric substances (biofilm matrix)
F	ANOVA test statistic (between/within variance ratio)
GP	Guinier–Preston zones
ISO	International Organization for Standardization
kN	Kilonewton
MIC	Microbiologically influenced corrosion
MPa	Megapascal
NaCl	Sodium chloride
PEO	Plasma electrolytic oxidation
$Y_{s0.2}$	0.2% proof/yield strength (yield strength at 0.2% offset)
R^2_{env}	Partial R-squared attributable to the Environment term
SCC	Stress-corrosion cracking
SSE	Sum of squared errors
ΔSSE	Change in sum of squared errors
TSA	Tartaric–sulfuric acid anodizing
UTS	Ultimate tensile strength
wt. %	Weight percent

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