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SEM-XRD Aging Study of Pre-Stressed 2024-T3 Alloys for Oil and Gas Supporting Components

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ABSTRACT - AA2024-T3 aluminum alloy has a high strength-to-weight ratio and the potential for use in oil and gas support components that are not wetted and do not experience pressure, such as lightweight brackets, instrument guards, inspection equipment housings, and auxiliary structures of operational vehicles. This study evaluated the effects of 0%, 2%, 4%, and 6% pre-strain and artificial aging at 175 and 190 °C on material integrity using scanning electron microscopy (SEM), X-ray diffraction (XRD), Vickers hardness testing, tensile testing, and fractography. The aging duration is 8 hours. The P4-A175 condition yielded a hardness of 158 HV, a yield strength of 366 MPa, a maximum tensile strength of 505 MPa, and an elongation of 12.4%, so it was chosen as the best strengthening condition among aging conditions that still retain an elongation of at least 12% and a ductile fracture morphology. In contrast, P6-A190 produces a tensile strength of 437 MPa and an elongation of 7.8%, accompanied by shallow dimples and secondary cracking. These findings suggest that increased violence is not always synonymous with increased integrity. The implications of the study are limited to non-wet, non-pressure-retaining supporting components because exposure to CO₂, H₂S, brine, cyclic loads, and oil-and-gas service conditions has not been simulated.

Keywords: artificial aging, pre-tension, SEM-XRD, alloy 2024-T3, oil and gas components.

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1. Introduction

Material integrity is an important aspect in the oil and gas industry because component failures can affect safety, production continuity, and inspection and maintenance costs. It is not enough to evaluate the material based only on the initial strength, but it is also necessary to consider the stability of the microstructure and changes in mechanical properties after fabrication, initial deformation, and thermal exposure. In that context, the aging study of AA2024-T3 aluminum alloys undergoing pre-stretching is relevant to elucidate the relationship between thermomechanical history, precipitate evolution, and the mechanical response of non-wet supporting components (Md Kasim et al., 2026; Wahab et al., 2026). AA2024-T3 is an Al-Cu-Mg alloy with high specific strength, good fatigue resistance, and adequate damage tolerance. In this study, the material was not positioned as a substitute for steel for pipes, pressure vessels, or components that come into direct contact with CO₂, H₂S, brine, or corrosive production fluids. The scope of its application is limited to support components that are not wetted and do not resist pressure, such as lightweight brackets, instrument guards, inspection tool housings, field mobility panels, and auxiliary structures of operational vehicles. These restrictions are necessary so that the implications of the results are not generalized beyond the experimental conditions.

The research problem departs from the sensitivity of AA2024-T3 to thermomechanical history. T3 conditions include dissolution heat treatment, cold working, and natural aging. During fabrication or repair of supporting components, materials may be subjected to pre-stretching due to forming, bending, straightening, machining, or geometry correction. Pre-strain increases dislocation density and can strengthen materials through strain hardening, while also providing heterogeneous nucleation sites for precipitates during aging. Uncontrolled interactions can increase hardness, but also decrease elongation, accelerate precipitate coarsening, and change fracture morphology to be shallower or accompanied by secondary cracks (Harant et al., 2024; Imer et al., 2023; Siqueira et al., 2019).

The aging of AA2024 is mainly controlled by the evolution of Al-Cu-Mg-based phases. Zmywaczyk et al. (2020) identify MgCuAl₂ and Al₂Cu in AW-2024-T3 via XRD, whereas Staszczuk et al. (2019) and Zhu et al. (2020) show the role of precipitates and dispersoids in strengthening. The combination of time and temperature determines the transition from not reaching the peak to the peak of aging, and then to excessive aging (Esin et al., 2021). Zhang et al. (2025) report that cold-rolled 2024 sheets treated at 500 °C for 1 hour and then aged at 180 °C for 6 hours achieve 154 HV, tensile strength of 465 MPa, and elongation of 13%.

Although the AA2024 cold working and aging study has been developed, three gaps remain. First, most of the research is oriented towards aerospace and automotive applications, while the pre-stretch-aging pathway for non-wet oil- and gas-supporting components has not been explicitly discussed. Second, previous research has generally emphasized either heat treatment or precipitation characterization in isolation. The integration of SEM, XRD, hardness, yield strength, tensile strength, elongation, and fractography as the basis for integrity decisions is still limited (Imer et al., 2024; Sun et al., 2021, 2022). Third, oil and gas asset integrity studies more often focus on corrosion, pipelines, descale, blockages, and risk-based inspections than on the thermomechanical history of lightweight aluminum alloys (Hameed et al., 2021; Nofrizal & Tasliyana 2019; Novrianti et al., 2026).

The novelty of this study does not lie in the use of SEM or XRD individually, but in three integrated contributions, namely (1) evaluation of 0%, 2%, 4%, and 6% pre-strain thermomechanical pathways and aging of 175-190 °C in AA2024-T3; (2) an integrity assessment framework that incorporates fracture strength, ductility, and morphology, not just maximum hardness values; and (3) the translation of the results into initial selection criteria for non-wet and non-pressure retaining oil and gas supporting components. Thus, the optimal condition is the strengthening condition that yields the highest tensile strength while maintaining adequate elongation and avoiding secondary cracking. This study aims to analyze the effect of aging on the integrity of pre-strain AA2024-T3 through SEM-XRD characterization and mechanical testing. Its specific objectives are to evaluate precipitate morphological changes and fractures due to pre-strain variations and aging temperatures, identify Al₂Cu and Al₂CuMg phase indications as well as peak widening changes via XRD, measure hardness, yield strength, maximum tensile strength, and elongation, and determine the strengthening conditions that provide the best compromise between strength, ductility, and damage tolerance.

Theoretically, this study deepens understanding of pre-strain interactions, aging, precipitation, and the integrity of AA2024-T3. In practical terms, the results can serve as a laboratory screening basis for designers and maintenance engineers to assess the feasibility of using AA2024-T3 for non-critical support functions. However, operational recommendations still require additional validation through environmental testing and loading that represent oil and gas service conditions.

2. Methodology

2.1 Research design

This study uses a quantitative-experimental approach with a factorial design. The first factor is pre-stretching at 0%, 2%, 4%, and 6%, while the second factor is artificial aging temperature at 175 and 190 °C. The as-received (AR) group is used as a comparison. This design enables the systematic evaluation of the influence of each factor and its interactions on microstructures, diffraction characteristics, and mechanical properties (Esin et al., 2021; Staszczuk et al., 2019; Zmywaczyk et al., 2020).

Characterizations include Scanning Electron Microscopy (SEM) and fractography, X-ray Diffraction (XRD), Vickers hardness test, and tensile test. SEM is used to evaluate the morphology of microstructures, the distribution of intermetallic particles, the indication of precipitate coarsening, and the mechanism of fracture. XRD is used to identify crystalline phases and compare the position, intensity, and full width at half maximum (FWHM) of the peak. Mechanical tests are used to measure hardness, yield strength, maximum tensile strength, and elongation. Integration of all data is used to assess strength-ductility balance and damage tolerance (ASTM International 2022, 2025; Zhu et al., 2020).

2.2 Research materials

The research material consists of commercial AA2024-T3 plates from a single production batch. The nominal thickness of the plate is 1.6 mm, while the chemical composition is verified using the supplier's material certificate and confirmed by optical emission spectroscopy (OES), with an Al composition of 94.96%; 0.10%; Fe 0.20%; Cu 3.20%; Mn 0.50%; 1.00%; and Cr 0.04% by weight. The material is positioned as a candidate for non-wet and non-pressure-retaining support components.

The entire specimen is cut from the same sheet to minimize variations in composition and manufacturing history. The longitudinal axis of the specimen is arranged parallel to the direction of rotation (longitudinal/L). The tensile specimen is dog-bone with a total length of 160 mm, a measuring length of 50 mm, a width of the measuring area of 12.5 mm, a width of the clamp section of 25 mm, and a thickness of 1.6 mm. The specimen geometry follows the JIS Z 2201 sheet specimen and the principles of ASTM E8/E8M tensile testing. Before treatment, the specimen surface is cleaned with ethanol to remove oil and other surface contaminants.

2.3 Experimental matrix and replication

The grouping of specimens is based on a combination of pre-stretching and aging temperature. Pre-stretch rates of 0%, 2%, 4%, and 6% represent conditions without additional deformation to initial plastic deformation that may arise during geometry formation or correction. Aging is carried out at 175 and 190 °C. The treatment duration is 8 hours for all aging conditions. The complete experimental matrix is presented in Table 1. The AR group did not receive additional pre-stretching or artificial aging. Code P2-A175, for example, shows a 2% pre-stretch followed by aging at 175 °C.

Table 1.
Experimental matrix AA2024-T3.

Code	Pre-stretch (%)	Aging conditions	Replication/Characterization
AR	0	No aging	N pull ≥ 3 ; HV ≥ 3 ; SEM and XRD
P0-A175	0	175 °C; 8 hours	N pull ≥ 3 ; HV ≥ 3 ; SEM and XRD
P2-A175	2	175 °C; 8 hours	N pull ≥ 3 ; HV ≥ 3 ; SEM and XRD
P4-A175	4	175 °C; 8 hours	N pull ≥ 3 ; HV ≥ 3 ; SEM and XRD
P6-A175	6	175 °C; 8 hours	N pull ≥ 3 ; HV ≥ 3 ; SEM and XRD
P0-A190	0	190 °C; 8 hours	N pull ≥ 3 ; HV ≥ 3 ; SEM and XRD
P2-A190	2	190 °C; 8 hours	N pull ≥ 3 ; HV ≥ 3 ; SEM and XRD
P4-A190	4	190 °C; 8 hours	N pull ≥ 3 ; HV ≥ 3 ; SEM and XRD
P6-A190	6	190 °C; 8 hours	N pull ≥ 3 ; HV ≥ 3 ; SEM and XRD

Each condition is prepared in three replications for tensile testing. Hardness testing was performed at ten indentation points for each specimen, while SEM and XRD characterizations used one representative specimen per condition. Fracturography was performed on the fracture surface of the entire tensile test specimen. Mechanical data are reported as averages $\pm$ standard deviations to reduce the influence of local heterogeneity of intermetallic particles, precipitate distribution, and deformation.

2.4 Pre- Strain and aging procedures

Pre-strain is administered through controlled tensile loading until a nominal plastic strain of 2%, 4%, or 6% is achieved; 0% specimens are processed without additional deformation. The strain is determined from the extensometer extension at a measuring length of 50 mm. The crosshead speed during pre-stretch is set to 7 mm/min, corresponding to a nominal stretch rate of approximately $2.3 \times 10^{-3} \text{ s}^{-1}$. After loading, the specimen is examined to ensure there are no macroscopic cracks or necking that could interfere with subsequent treatment.

Artificial aging is performed in an electric furnace calibrated to 175 and 190 °C for 8 hours. The furnace temperature is raised at a heating rate of 10°C/min, and the holding time is calculated from the moment the temperature reaches the set point. After the holding time is over, the specimen is removed from the furnace and cooled in still air until it reaches room temperature. Temperature history and treatment time are recorded to ensure process repeatability. The interaction between pre-strain dislocation density and Al₂Cu/Al₂CuMg precipitation is the basis for the interpretation of the mechanical response (Staszczyk et al., 2019; Zhu et al., 2020; Zmywaczyk et al., 2020).

2.5 Metallographic preparation

SEM specimens are prepared through cutting, mounting, gradual grinding, polishing, and etching. The sequence of abrasive papers is 240, 400, 600, 800, 1,000, 1,200, 1,500, and 2,000 grit, followed by polishing using 3 μm and 1 μm diamond paste, then final polishing using 0.05 μm alumina suspension until a mirror surface is obtained. Preparation procedure following ASTM E3 (ASTM International 2026). Etching was performed using a Keller reagent consisting of 95 mL of aqueducts, 2.5 mL of HNO₃, 1.5 mL of HCl, and 1 mL of HF for 15 seconds to display the boundaries of grains and intermetallic particles without producing excess etching artifacts. The procedure refers to ASTM E407 (ASTM International 2023).

2.6 SEM and fractography characterization

SEM characterization was performed on metallographic surfaces and tensile test fracture surfaces using an acceleration voltage of 15 kV, a working distance of 10 mm, as well as secondary electron (SE) detectors for

fractography and backscattered electrons (BSE) to distinguish the contrast of particle composition. Observations were made at magnifications of 500×, 1,000×, 2,500×, and 5,000×, with at least five fields of view for each condition. EDS analysis is performed on selected particles and areas to qualitatively and semi-quantitatively identify Cu-, Mg-, Fe-, or Si-rich elements. Fractography is used to identify dimples, cracked particles, cavity coalescence, cleavage facets, as well as indications of transgranular or intergranular fractures. Image analysis was performed using ImageJ software on five fields of view per condition. The parameters evaluated included particle equivalent diameter, total density, and area fraction, then reported as the average $\pm$ standard deviation. This approach is used to support the interpretation of the relationship between microstructural evolution and fracture mechanisms (Tancogne-Dejean et al., 2021).

2.7 XRD characterization

XRD characterization was performed using Cu-K α radiation ($\lambda = 1.5406 \text{ \AA}$) in the range of 2θ 20°–90°, step size 0.02°, and scan rate of 2°/min. The X-ray tube is operated at a voltage of 40 kV and a current of 30 mA. The peaks of the α -Al matrix as well as the Al₂Cu and S'-Al₂CuMg phase indications were indexed using the International Centre for Diffraction Data database (ICDD PDF-4+).

Peak position, relative intensity, and FWHM are used to compare conditions. FWHM is not interpreted as an absolute microstrain value because the instrument's widening contribution and crystallite size have not been separated. Williamson-Hall analysis or refinement of grid parameters is only possible when multiple peak FWHM and instrumental corrections are available. Therefore, the discussion of XRD in this study is limited to a comparative indication of the evolution of lattice distortion and precipitation (Pachut et al., 2019; Zmywaczyk et al., 2020). The quantitative results of XRD characterization and mechanical testing at each treatment condition are summarized in Table 2.

Table 2.
XRD and mechanical quantitative data.

Code	FWHM (°)	Mechanical properties
AR	0,226	HV 137; YS 325; UTS 470; ϵ 16,8%
P0-A175	0,238	HV 145; YS 338; UTS 478; ϵ 14,7%
P2-A175	0,252	HV 151; YS 353; UTS 492; ϵ 13,5%
P4-A175	0,268	HV 158; YS 366; UTS 505; ϵ 12,4%
P6-A175	0,286	HV 162; YS 374; UTS 498; ϵ 10,9%
P0-A190	0,232	HV 143; YS 339; UTS 451; ϵ 13,8%
P2-A190	0,259	HV 153; YS 358; UTS 470; ϵ 11,9%
P4-A190	0,282	HV 159; YS 367; UTS 463; ϵ 9,6%
P6-A190	0,305	HV 160; YS 370; UTS 437; ϵ 7,8%

Note. YS = solubility strength; UTS = maximum tensile strength; ϵ = extension. The mechanical value is an average of three replications; The standard deviation is used in bidirectional statistical analysis.

2.8 Hardness testing

The Vickers microhardness was measured using a load of 0.1 kgf (0.981 N) with a hold time of 10 seconds. For each specimen, ten indentation points were made, namely five points in the horizontal direction and five points in the vertical direction, with a distance between them at least three times the length of the indentation diagonal to prevent the interaction of the deformation field. The hardness value is reported as the average $\pm$ the standard deviation in HV units. Hardness testing refers to ASTM E384, which governs micro-indentation hardness methods for materials using Knoop and Vickers indents (ASTM International 2022; Esin et al., 2021). Hardness is treated as a local indicator of resistance to plastic deformation and is not used singularly to infer material integrity. The interpretation has always been associated with tensile strength, elongation, and fracture morphology.

2.9 Engineering testing

The tensile test is carried out at room temperature using a universal testing machine with a capacity of 100 kN. The specimen is symmetrically mounted on the grip to minimize bending loading, then tested at a crosshead speed of 7 mm/min. Strain is measured using a clip-on extensometer with a 50 mm measuring length, while force is recorded continuously by the load cell. The calculated parameters include 0.2% yield strength, maximum tensile strength, and elongation after breakage. Testing refers to ASTM E8/E8M (ASTM International 2025). The strengthening condition is considered better if it increases strength without excessively reducing elongation and still exhibits the morphology of ductile or quasi-ductile fractures, without dominant secondary cracks (Zhang et al., 2025).

2.10 Data collection

Data were collected in four groups: (1) microstructural and fractographic SEM imaging; (2) XRD patterns, peak position, intensity, and FWHM; (3) Vickers hardness; and (4) yield strength, maximum tensile strength, and elongation. Each data point is linked to the specimen code, pre-strain rate, temperature, aging duration, and replication number. Documentation of tool parameters, furnace temperature history, raw imagery, raw diffraction patterns, and voltage-strain curves are stored as supporting data so that the results can be traced and reanalyzed.

2.11 Data analysis methods

The mechanical data were analyzed as the mean $\pm$ standard deviation across three replications. The normality and homogeneity of the variance were examined using the Shapiro–Wilk test and the Levene test, respectively. The effects of pre-strain level and aging temperature were evaluated using bidirectional ANOVA at $\alpha = 0.05$, followed by Tukey's HSD test if a significant main effect or meaningful interaction was detected. The magnitude of the influence was reported using partial eta-squares (partial η^2), while the difference between conditions was reported using the value of p . The term "significant" is only used when supported by inferential test results.

SEM analysis compares particle distribution, indications of coarsening, microvoids, and fracture characteristics. Quantitative conclusions about the size or fraction of precipitate volume can only be made if supported by raw image measurements. Deep and even dimples are interpreted as indicating tenacious characters, whereas superficial dimples, cracked particles, and secondary cracks indicate decreased damage tolerance. The following are the results of qualitative observations of microstructures, XRD phase indications, and fracture morphology in each treatment condition presented in Table 3.

Table 3.
Qualitative summary of microstructures and fractures.

Code	Summary of SEM-XRD-fractography
AR	SEM: scattered intermetallic particles; XRD: dominant α -Al, trace S/Al ₂ Cu; fractures: deep dimples, tenacious.
P0-A175	SEM: smooth features start evenly; XRD: Low S/Al ₂ Cu; Fracture: dimple tight, tenacious.
P2-A175	SEM: relatively homogeneous smooth features; XRD: S/Al ₂ Cu increased; Fracture: Fine microvoid.
P4-A175	SEM: the subtle features are qualitatively even; XRD: S/Al ₂ Cu clear; Fracture: dimple even, tenacious.
P6-A175	SEM: initial coarsening and microvoid; XRD: S/Al ₂ Cu clear; fracture: superficial dimples, small cracks.
P0-A190	SEM: early coarsening; XRD: Medium S/Al ₂ Cu; Fracture: Mixed dimples.
P2-A190	SEM: coarsening and microvoid; XRD: S/Al ₂ Cu is stronger; Fracture: Dimple is a bit superficial.
P4-A190	SEM: increased coarsening and grain boundary particles; XRD: S/Al ₂ Cu is stronger; fracture: local microcrack.
P6-A190	SEM: coarse particles and microvoids dominant; XRD: Strong S/Al ₂ Cu; fractures: quasi-ductile and secondary cracks.

Note. Image analysis was carried out on five fields of view per condition using ImageJ to obtain particle equivalent diameter, total density, and area fraction as data to support morphological interpretation.

XRD analysis includes the identification of dominant phases and the comparison of FWHM values. Increased FWHM is treated as a combined indication of microstrain, coherent domain size, and instrument dilation; not as a direct measurement of microstretches. The XRD results were then correlated with hardness and tensile properties. The best strengthening conditions are defined as the aging condition that yields the highest maximum tensile strength while maintaining an elongation of at least 12% and a ductile fracture morphology without dominant secondary cracking. This criterion distinguishes the increase in local strength from the overall improvement of material integrity.

3. Result and discussion

3.1 SEM-XRD data and mechanical integrity

The results of the study are presented in Table 4, which integrates quantitative XRD and mechanical data from Table 2, as well as qualitative observations from SEM, XRD phase indications, and fracture morphology in Table 3. The separation of quantitative and qualitative data is performed to improve readability and to avoid mixing numerical measures with morphological interpretations.

Table 4.
Results of SEM-XRD characterization and mechanical integrity - 2024-T3 pre-strain after aging.

Code	Treatment conditions	SEM micro structure	Phase XRD	FWHM (°)	HV	Yield strength (MPa)	Tensile Strength (MPa)	Renewal (%)	Morphology of fractures
AR	Accepted 2024-Q3	α -Al; Dispersed Cu-Mg-Fe Particles	α -Al; Trace S/Al ₂ Cu	0,226	137	325	470	16,8	Dimple enters; Tenacious
P0-A175	0% pre-tension, aging 175°C	Fine deposits begin to distribute evenly	Low α -Al + S/Al ₂ Cu	0,238	145	338	478	14,7	Tight dimples; Tenacious
P2-A175	2% pre-stretch, aging 175°C	Fine, tight-homogeneous deposits	α -Al+S/Al ₂ Cu increased	0,252	151	353	492	13,5	Tight dimples; Smooth microvoid
P4-A175	4% pre-tension, aging 175°C	Optimal fine deposits	α -Al+S/Al ₂ Cu clear	0,268	158	366	505	12,4	Dimples evenly distributed; Tenacious
P6-A175	6% pre-stretch, 175°C aging	Presbyterian meetings; The Rise of the Microvoid	α -Al+S/Al ₂ Cu clear	0,286	162	374	498	10,9	superficial dimples; Small cracks
P0-A190	0% pre-tension, aging 190°C	Rough initial look	α -Al+S/Al ₂ Cu medium	0,232	143	339	451	13,8	Mixed dimples
P2-A190	2% pre-stretching, aging 190°C	Rapid rainfall; Medium microvoid	High α -Al+S/Al ₂ Cu	0,259	153	358	470	11,9	The dimples are a bit shallow

Table 4.
Results of SEM-XRD characterization and mechanical integrity - 2024-T3 pre-strain after aging, (continued).

Code	Treatment conditions	SEM micro structure	Phase XRD	FWHM (°)	HV	Yield strength (MPa)	Tensile Strength (MPa)	Renewal (%)	Morphology of fractures
P4-A190	4% pre-tension, aging 190°C	increased roughness ; Grain Boundary Particles Coarse	High α -Al+S/Al ₂ Cu	0,282	159	367	463	9,6	superficial dimples; Local microcrack
P6-A190	6% pre-tension, aging 190°C	particles and microvoid dominant	α -Al+S/Al ₂ Cu strong	0,305	160	370	437	7,8	Quasi-tenacious ; Secondary cracks

Descriptively, low-to-moderate pre-stretching combined with 175 °C aging can increase hardness, yield strength, and maximum tensile strength. P4-A175 produces 158 HV, 366 MPa, 505 MPa, and 12.4% elongation. Compared to AR, this condition increases hardness by 15.3%, yield strength by 12.6%, and tensile strength by 7.4%, while decreasing elongation by 26.2%. P6-A190 retains high hardness (160 HV), but the tensile strength drops to 437 MPa and the elongation to 7.8%, accompanied by secondary cracking.

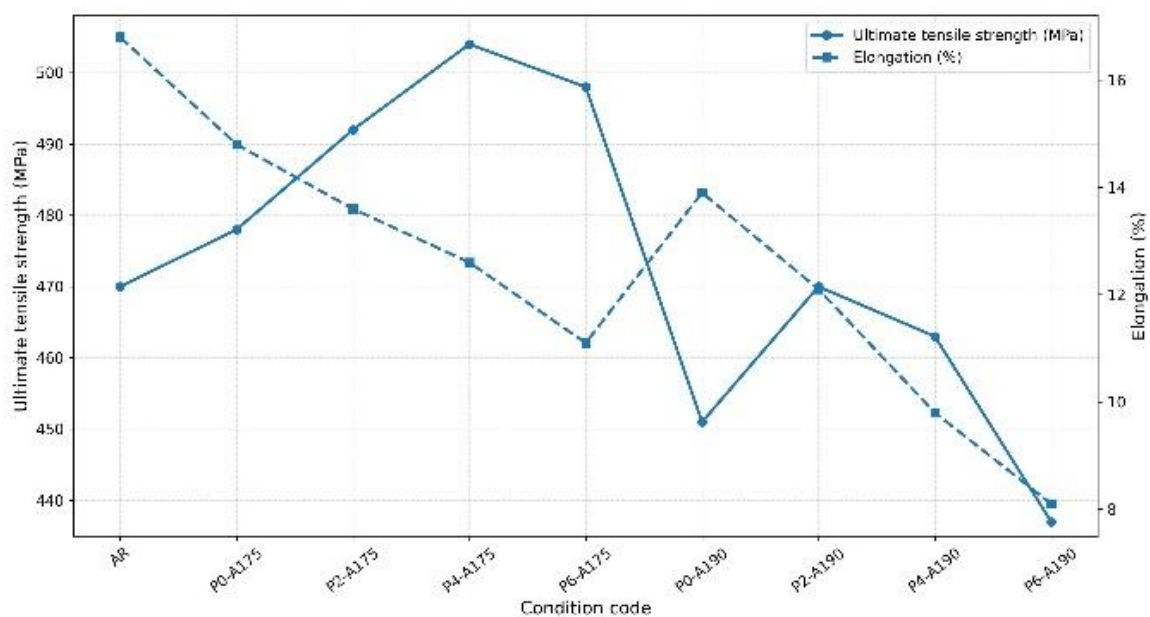
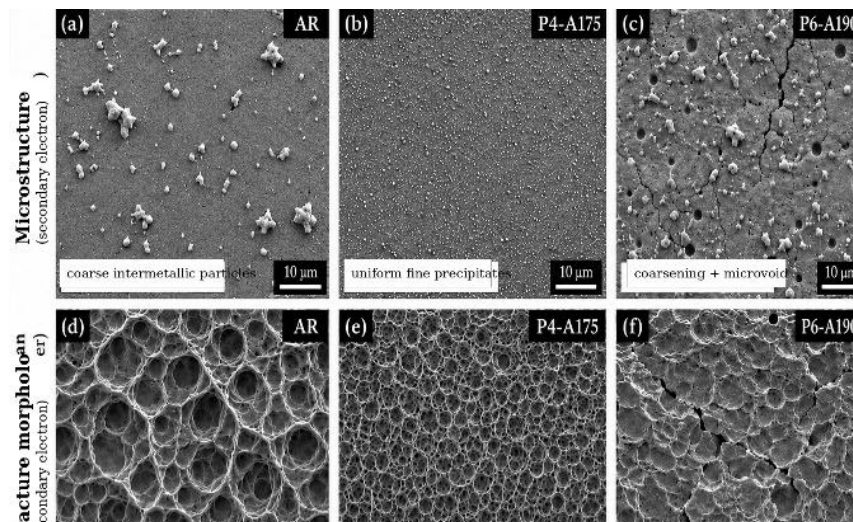


Figure 1.
Relationship of treatment conditions with maximum tensile strength and elongation of AA2024-T3.

Figure 1 shows that the tensile strength increases from 470 MPa at AR to a maximum of 505 MPa at P4-A175, then decreases at pre-stretch higher and/or aging of 190 °C. The renewal gradually decreased from 16.8% on AR to 7.8% on P6-A190. Thus, an increase in strength is not always followed by an increase in deformation ability. P4-A175 was chosen as the best gain condition, not as the superior condition in all indicators, as AR still had the highest elongation.



Note: the entire panel displays a 10 μm scale bar.

Figure 2.

SEM images of AA2024-T3 microstructure (top row) and fracture morphology (bottom row) at AR, P4-A175, and P6-A190 conditions.

Figure 2 shows that the AR condition has scattered coarse intermetallic particles and fracture morphology with deep dimples. The condition of P4-A175 shows a more even distribution of fine features and relatively uniform dimples, consistent with increased strength while still accompanied by plastic deformation. In contrast, the P6-A190 features coarser particles, microvoids, shallow dimples, and secondary cracks. Comparative evaluation of the field of view with the same magnification reinforces the tendency that P4-A175 has the most uniform distribution of fine features and relatively lower indications of microdefects, whereas P6-A190 shows more pronounced coarsening and microdamage. The interpretation is qualitative because the particle size, total density, and area fraction have not been calculated from the raw image.

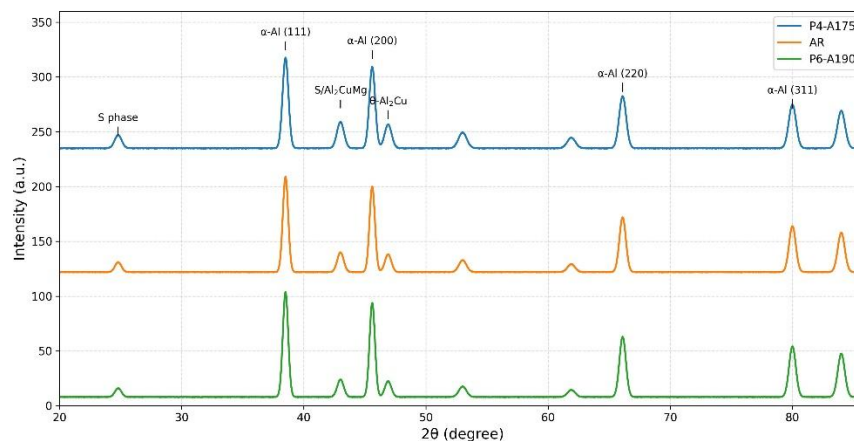


Figure 3.

XRD pattern of AA2024-T3 in AR, P4-A175, and P6-A190 conditions with peak indexing of α -Al as well as $\text{S}/\text{Al}_2\text{CuMg}$ and Al_2Cu phase indications.

The XRD pattern in Figure 3 is dominated by the α -Al peaks (111), (200), (220), and (311). P4-A175 showed a clearer indication of the peaks of the $\text{S}/\text{Al}_2\text{CuMg}$ and Al_2Cu phases compared to AR. P6-A190 shows a more pronounced secondary peak and a larger FWHM. However, the increase in FWHM cannot be attributed solely to microstrains, as the instrument dilation and domain size have not been corrected. Therefore, XRD data are used as supportive comparative evidence, not as a direct quantification of precipitate or dislocation density.

At 175°C, a pre-stretch increase of up to 4% increases maximum tensile strength while maintaining 12.4% elongation and ductile fractures. Mechanistically, pre-strains increase the dislocation density, which can serve as a location for the heterogeneous nucleation of precipitates. The interaction of strain hardening and precipitation hardening then increases the resistance to dislocation motion.

This interpretation is consistent with Staszczuk et al. (2019), who showed that aging treatment changes the amount, size, and distribution of precipitates and dispersoids in AA2024. Zhu et al. (2020) also explain the evolution of the S-series precipitate, in particular the transition to the S' and S phases, as an important mechanism of reinforcement. However, without measurements of the size and fraction of precipitate area, the microstructure-property relationship in this study should be understood as a correlation supported by qualitative evidence.

FWHM increased from 0.226° at AR to 0.268° at P4-A175 and 0.305° at P6-A190. This trend is consistent with changes in lattice defect states and precipitation evolution, and with the identification of MgCuAl₂ and Al₂Cu in AW-2024-T3 by Zmywaczyk et al. (2020). However, microstrains and coherent domain sizes are not separated because Williamson-Hall analysis and instrumental corrections are not yet available.

The comparison between P4-A175 and P6-A175 explains why higher hardness does not automatically lead to better tensile performance. P6-A175 increases hardness from 158 to 162 HV and yield strength from 366 to 374 MPa, but tensile strength drops from 505 to 498 MPa, and elongation drops from 12.4% to 10.9%. Hardness measures the local response to indentation, while tensile tests affect the ability of the entire cross-section to resist the propagation of damage. The shallower dimple and small cracks on P6-A175 suggest that earlier nucleation of damage may limit maximum tensile strength.

A stronger decline in P6-A190 is likely the result of a combination of precipitation/over-aging coarsening and damage accumulation due to high pre-strain. Compared to AR, the P6-A190 still showed a 16.8% increase in hardness and a 13.8% increase in yield strength, but the tensile strength decreased by 7.0%, and elongation decreased by 53.6%. The combination of coarse particles, microvoids, high FWHM, and secondary cracking supports the combined mechanism. These findings are consistent with the AA2024 aging response, which is influenced by time and temperature (Esin et al., 2021), as well as the results of thermal treatment of the 2024 cold-rolled sheets reported by Zhang et al. (2025).

Fractography confirms the difference in damage tolerance between conditions. AR is dominated by deep dimples, P4-A175 maintains relatively even dimples, while P6-A190 shows shallow dimples and secondary cracks. The mechanism is consistent with cavity nucleation, growth, and coalescence during damage in AA2024-T3 (Tancogne-Dejean et al., 2021). Therefore, integrity evaluation should incorporate the tensile nature and morphology of the fracture, not just the hardness.

In the context of oil and gas, these results only support the preliminary selection of AA2024-T3 for non-wet, non-critical, and non-pressure-holding support components. P4-A175 can be considered the best strengthening condition in this experimental chamber, as it provides the highest tensile strength, elongation above 12%, and ductile fracture. The findings do not prove resistance to CO₂, H₂S, brine, galvanic corrosion, fatigue, or service temperature fluctuations.

Overall, the integration of SEM, XRD, hardness, tensile test, and fractography suggests that thermomechanical history should be considered when AA2024-T3 is used in supporting components. Aging can increase strength, but excessive pre-stretching and higher aging temperatures can reduce the hardening strain capacity and accelerate damage. Statistical validation and environmental testing remain required before recommendations are applied to the design or maintenance of oil and gas assets.

4. Conclusion

This study shows that aging affects the integrity of pre-strained AA2024-T3 by altering microstructural characteristics, phase indicators, mechanical properties, and fracture morphology. At 175 °C, pre-stretching up to 4% increases strength, yields a more uniform distribution of microstructural features, and leaves fractures ductile.

The α -Al matrix remained dominant, while the indications of the S/Al₂CuMg and Al₂Cu phases increased after aging. P4-A175 is the best gain condition in this experimental chamber, with 158 HV, yield strength of 366 MPa, maximum tensile strength of 505 MPa, and elongation of 12.4%. This selection is based on the highest tensile strength among conditions that maintain an elongation of at least 12% and do not show a dominant secondary crack. P6-A190 exhibits degradation of tensile integrity, with tensile strength of 437 MPa, elongation of 7.8%, coarser particles, microvoids, and secondary cracking. Thus, high hardness should not be used as the only indicator of integrity.

The implications of the study are limited to non-wet, non-critical, and non-pressure-bearing oil and gas-supporting components. Key limitations include the lack of complete statistical analysis, quantification of SEM images, microstrain separation via Williamson-Hall, and simulations of CO₂, H₂S, brine, cyclic loads, galvanic corrosion, and temperature fluctuations. Follow-up research needs to include complete replication data, TEM/EBSD, fatigue and corrosion testing, and validation at representative service conditions.

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6. Declarations

6.1 Author contributions

W. Jatimurti, A.F Padmavati: Writing – Original Draft, Conceptualization, Investigation. Sulistijono, A.T. Wibisosno, A. Purniawan: Writing, Review & Editing, Validation. A Graduate: Writing, Review & Editing, Validation, Investigation. All authors read and agree to the final paper.

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6.3 Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

6.4 Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

6.5 Ethics statement

This study did not involve human participants, animals, or human-derived materials. Therefore, ethical approval was not required.

6.6 Informed consent statement

Not applicable.

6.7 The Use of AI or AI-assisted technologies

None

7. Glossary of terms and symbols

Terms & Symbols	Definition	Unit
AA2024-Q3	Aluminum-Copper-Magnesium alloys commonly used in aerospace; strengthened through precipitation hardening	
α -Al	Phase Aluminum Matrix Primer	
θ (Al ₂ Cu)	Copper-rich sediment phase contributes to the strength	
S/S' (Al ₂ CuMg)	Copper-Magnesium-rich sediment phase contributes to the strength	
Pre-stretch	Plastic deformation is applied before heat treatment to increase the dislocation density	% stretch
Artificial Aging	Heat treatment at high temperatures to accelerate the formation of deposits	°C, hours
Aging below	Aging conditions before peak hardness is reached	
Peak aging	Aging conditions produce maximum strength/hardness	
Excessive aging	Conditions where the sediment is coarse, reducing effectiveness	
Dislocation Density	The amount of dislocation in the crystal lattice	m ⁻²
Stretch Hardening	Increased material strength due to plastic deformation	—
Tensile Strength (σ)	Maximum tension material can withstand tension	MPa
Yield strength (σ_y)	The tension at which the material begins to deform the plastic	MPa
Renewal (ϵ)	Stretching during a fracture; Evaluating tenacity	%
SEM	Scanning electron microscope; Observing surface morphology & fractures	
XRD	X-ray diffraction; Identifying crystal phases and deposits	
dimples/microcavities	Surface features that show ductile fractures in metals	
Peak Intensity (XRD)	Measurement of crystalline phase fractions of diffractions	
HV	Vickers Hardness Unit	HV

8. References

- ASTM International. (2022). ASTM E384-22: Standard Test Method for Microindentation Hardness of Materials. In ASTM International. ASTM International. <https://doi.org/10.1520/E0384-22>
- ASTM International. (2023). ASTM E407-23: Standard Practice for Microetching Metals and Alloys. In ASTM International. ASTM International. <https://doi.org/10.1520/E0407-23>
- ASTM International. (2025). ASTM E8/E8M-25: Standard test methods for tension testing of metallic materials. ASTM International. https://doi.org/10.1520/E0008_E0008M-25
- ASTM International. (2026). ASTM E3-26: Standard Guide for Preparation of Metallographic Specimens. In ASTM International. ASTM International. <https://doi.org/10.1520/E0003-26>
- Esin, V. A., Briez, L., Sennour, M., Köster, A., Gratiot, E., & Crépin, J. (2021). Precipitation-hardness map for Al–Cu–Mg alloy (AA2024-T3). *Journal of Alloys and Compounds*, 854, 157164. <https://doi.org/10.1016/j.jallcom.2020.157164>
- Hameed, H., Bai, Y., & Ali, L. (2021). A risk-based inspection planning methodology for integrity management of subsea oil and gas pipelines. *Ships and Offshore Structures*, 16(7), 687–699. <https://doi.org/10.1080/17445302.2020.1747751>
- Harant, M., Verleysen, P., Forejt, M., & Kolomy, S. (2024). The Effects of Strain Rate and Anisotropy on the Formability and Mechanical Behaviour of Aluminium Alloy 2024-T3. *Metals*, 14(1), 98. <https://doi.org/10.3390/met14010098>
- Irmer, D., Moussa, C., Belkacemi, L. T., Sennour, M., Vaissière, A., & Esin, V. A. (2023). Effect of cold rolling on nucleation, growth and coarsening of S-phase precipitates in Al–Cu–Mg alloy (AA2024): From heterogeneous nucleation to homogeneous spatial distribution. *Journal of Alloys and Compounds*, 963, 171162. <https://doi.org/10.1016/j.jallcom.2023.171162>
- Irmer, D., Sennour, M., Sun, F., Vermaut, P., Moussa, C., & Esin, V. A. (2024). From heterogeneous nucleation to homogeneous spatial distribution of hardening precipitates: An in situ TEM study on cold-rolled AA2024-T3 (Al–Cu–Mg). *MRS Communications*, 14(4), 633–638. <https://doi.org/10.1557/s43579-024-00572-1>
- Md Kasim, M. A., Razali, M. A., Mohd Nor, N., Ismail, I. F., Suzuki, M., & Akhyan, A. (2026). Structural Integrity Assessment of A Low Temperature Separation Unit (LTSU) Strainer Handle-Plate in Oil and Gas Operations: Coupled CFD and FEA Analysis of Fluid-Induced Loads. *Scientific Contributions Oil and Gas*, 49(2), 81–111. <https://doi.org/10.29017/scog.v49i2.2033>
- Nofrizal, N & Tasliyana, K. (2019). Pengukuran kinerja inhibitor korosi menggunakan metode elektrokimia. *Lembaran Publikasi Minyak Dan Gas Bumi*, 53(2), 73–86. <https://doi.org/10.29017/LPMGB.53.2.356>
- Novrianti, Anggara P, A., Purnamawati, N., & Fikri, M. R. (2026). Scale Reduction in Oil Pipes Using Pineapple Peel Acetic Acid and HCL: A Laboratory Study. *Lembaran Publikasi Minyak Dan Gas Bumi*, 60(1), 27–38. <https://doi.org/10.29017/LPMGB.60.1.1811>
- Pachut, K., Żelechowski, J., & Boczkal, S. (2019). Application of X-Ray Diffraction to Analyse Phase Composition of Aluminium Alloys for Plastic Working. *Archives of Metallurgy and Materials*, 64(4), 1315–1319. <https://doi.org/10.24425/amm.2019.130096>
- Siqueira, M. L., Silva, A. da, Melo, M. de L. N. M., & Rodrigues, G. (2019). Mechanical Properties Analysis of Al2024 alloy Submitted to Different Aging Time and different Cold Plastic Deformation degree. *Materials Research*, 22(4). <https://doi.org/10.1590/1980-5373-mr-2018-0598>
- Staszczyk, A., Sawicki, J., & Adamczyk-Cieslak, B. (2019). A Study of Second-Phase Precipitates and Dispersoid Particles in 2024 Aluminum Alloy after Different Aging Treatments. *Materials*, 12(24), 4168. <https://doi.org/10.3390/ma12244168>

- Sun, L., Chen, L., Guo, Y., & Zhao, G. (2022). Experimental Study and Optimization on Solution and Artificial Aging of Cold-Rolled 2024 Al Alloy Sheet. *Journal of Materials Engineering and Performance*, 31(7), 5419–5431. <https://doi.org/10.1007/s11665-022-06619-5>
- Sun, L., Guo, Y., Chen, L., & Zhao, G. (2021). Effects of solution and aging treatments on the microstructure and mechanical properties of cold rolled 2024 Al alloy sheet. *Journal of Materials Research and Technology*, 12, 1126–1142. <https://doi.org/10.1016/j.jmrt.2021.03.051>
- Tancogne-Dejean, T., Roth, C. C., Morgenev, T. F., Helfen, L., & Mohr, D. (2021). Ductile damage of AA2024-T3 under shear loading: Mechanism analysis through in-situ laminography. *Acta Materialia*, 205, 116556. <https://doi.org/10.1016/j.actamat.2020.116556>
- Wahab, H., Asral, & Martin, A. (2026). Failure Mechanisms and Risk-Based Mitigation of Hydrocarbon Pipeline Blockages: A Comprehensive Review. *Scientific Contributions Oil and Gas*, 49(2), 529–552. <https://doi.org/10.29017/scog.v49i2.2011>
- Zhang, L., Liu, W., Xia, E., Chen, W., He, X., & Tang, D. (2025). Effect of Solution and Aging Treatment on the Microstructural Evolution and Mechanical Properties of Cold-Rolled 2024 Aluminum Alloy Sheets. *Coatings*, 15(10), 1139. <https://doi.org/10.3390/coatings15101139>
- Zhu, C., Lv, K., & Chen, B. (2020). On the S-phase precipitates in 2024 aluminum alloy: An atomic-scale investigation using high-angle annular dark-field scanning transmission electron microscopy. *Journal of Materials Research*, 35(12), 1582–1589. <https://doi.org/10.1557/jmr.2020.74>
- Zmywaczyk, J., Sienkiewicz, J., Koniorczyk, P., Godzimirski, J., & Zieliński, M. (2020). Investigation of Thermophysical Properties of AW-2024-T3 Bare and Clad Aluminum Alloys. *Materials*, 13(15), 3345. <https://doi.org/10.3390/ma13153345>