Optimization of Homogenization Treatments for 2024 Aluminum Extrusions

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Manganese varies positionally within 2024 Aluminum (AA2024) ingot, yet its effect on homogenization response remains poorly characterized. Two alloys representing lower (0.40 wt.%) and higher (0.73 wt.%) Mn content within the specification limits were single-step homogenized across six conditions parameterized by a dimensionless degree of homogenization, Dt/L^2. Optical microscopy, SEM/EDS, hardness tracking during natural aging, and quantitative image analysis were used to assess microstructural evolution. Near-complete dissolution of as-cast phases was observed for $Dt/L^2 \geq 1.0$, with the Cu segregation index reduced by 85%. Doubling Mn content doubled the dispersoid number density without any change in particle size, confirming that higher Mn directly enhances Zener pinning capacity.

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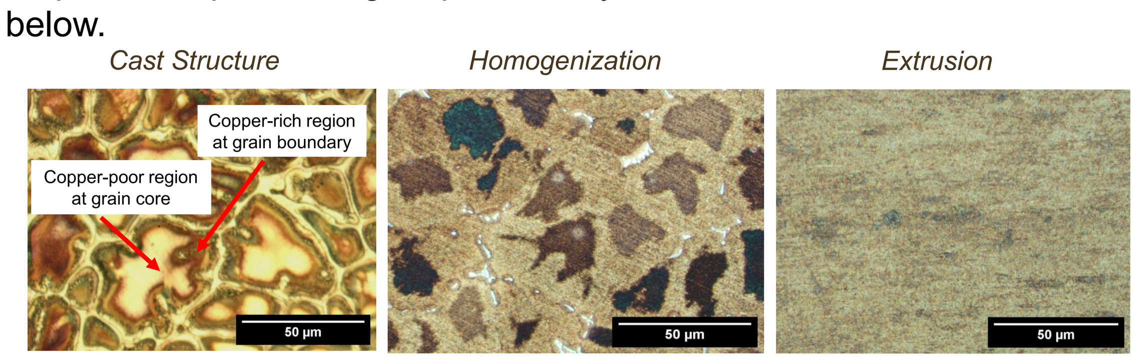
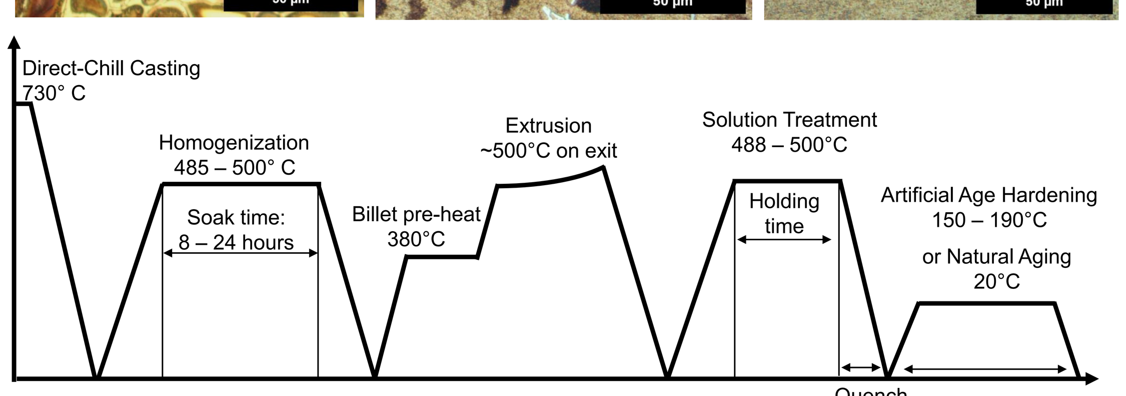
Background & Motivation

AA2024 is a high strength fatigue-resistant aluminum alloy widely used in aerospace applications. In this alloy, two of the most important alloying elements are copper and manganese. A major challenge in producing AA2024 is that these elements segregate during casting, resulting in a heterogeneous composition that inhibits precipitation hardening later in production. Homogenization is the process used to redistribute alloying elements and reduce this compositional heterogeneity.

Manufacturing Process: Following direct chill casting, AA2024 billets must be homogenized to redistribute segregated elements prior to extrusion. This ensures a uniform solute, which is critical for successful final strengthening heat treatment after extrusion [1]. The sequence of processing steps with key microstructures is shown below.





Homogenization Parameters: The degree of Homogenization is quantified using the Segregation Index (SI):

$$SI = \frac{C_{max} - C_{min}}{C_{max}}$$

where C_{max} and C_{min} are the peak solute concentrations at grain boundaries and dendritic cores. Effective homogenization minimizes the SI by achieving full diffusion through each grain.

The degree of homogenization can be predicted by the dimensionless number Dt/L^2, where D = mass diffusivity, t = time of diffusion, and L = distance over concentration gradient. When Dt exceeds the average grain radius, full diffusion has occurred. This measure is used to explore the time and temperature dependence of the homogenization process.

When Cu diffuses into the matrix, Mn migrates towards Cu-rich sites to form stable secondary phases known as Mn dispersoids. These dispersoids are beneficial, as they pin grain boundaries (Zener pinning) to inhibit growth during subsequent processing. By analyzing the interaction between composition and homogenization parameters, the homogenization process can be optimized to promote Mn-dispersoid formation and ensure microstructural stability during extrusion.

Experimental Methods

Alloys: Two AA2024 alloys were analyzed, representing lower and higher Manganese (0.40 wt.% - 0.73 wt.%) within the specification limits. To isolate Mn-driven microstructural changes, both alloys were selected for their low Iron (Fe) and Silicon (Si) content. Small specimens were sectioned from book-mold ingots and homogenized in an air furnace with a calibrated Type-K thermocouple in direct contact with the samples. Treatments were designed to achieve a range of diffusion parameters (Dt/L^2) from 0.14 to 1.90.

Homogenization Experimental Matrix

Temp (°C)	Time (hrs)	Dt/L^2
440	8	0.14
470	8	0.36
490	8	0.64
470	24	0.97
490	14	1.10
490	24	1.90

- L = 38 µm based on direct measurements.
- T_{max} was selected to maintain a buffer below the $T_{eutectic}$ = 502˚C eutectic melting point
- Samples water quenched

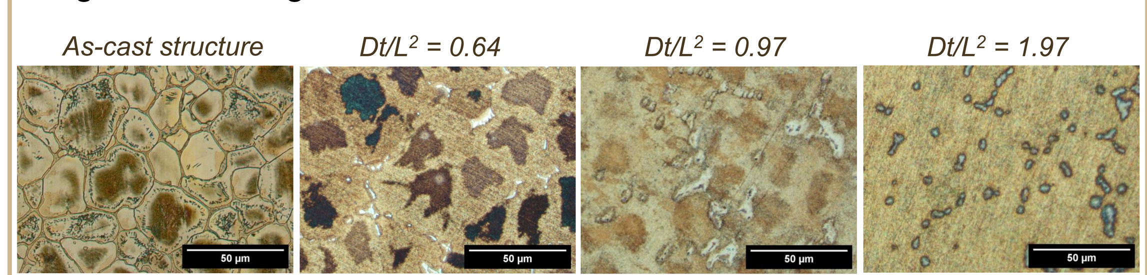
Characterization:

- **Rockwell Hardness (HRB):** Natural aging response was tracked via Rockwell Hardness (HRB) for 48 hours post-quench as a proxy for homogenization extent.
- **Microstructural & Chemical Analysis:** Scanning Electron Microscopy (SEM) in Backscattered Electron (BSE) mode, Optical Microscopy (OM), and Energy Dispersive Spectroscopy (EDS) were utilized to characterize grain morphology and quantify the Segregation Index (SI) of Cu, and Mn.

Results & Discussion

Homogenization Microstructural Evolution:

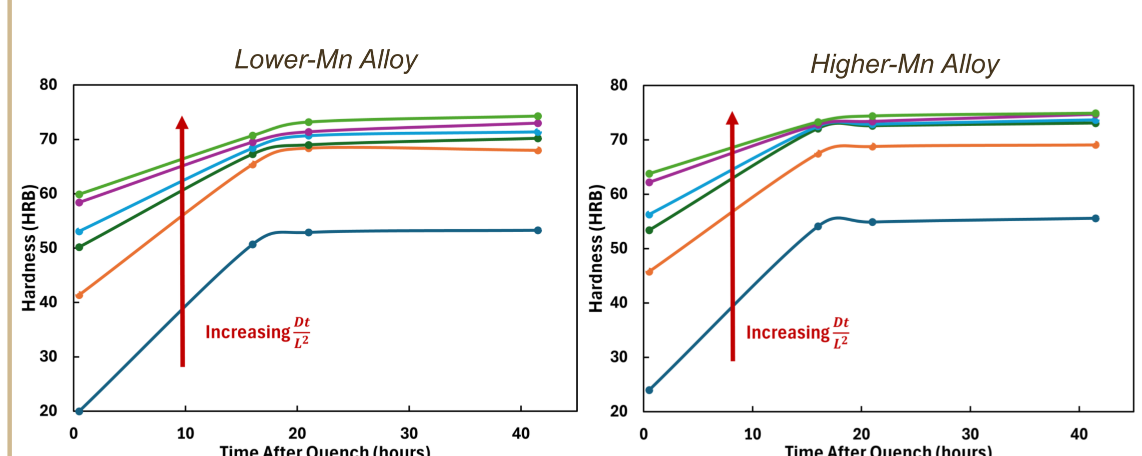
Optical images of the as-cast structure show a consistent fine grain structure from edge to center, typical of an alloy which includes a grain refiner. A permanganate color-etch clearly shows the chemical segregation of copper within each grain, with large dark regions indicative of copper-poor grain centers, which slowly shrink as the degree of homogenization increases.



At lower degrees of diffusion, copper-poor grain centers remain visible as dark regions. Full homogenization is visible in the rightmost image as a lack of contrast between grain boundary and center.

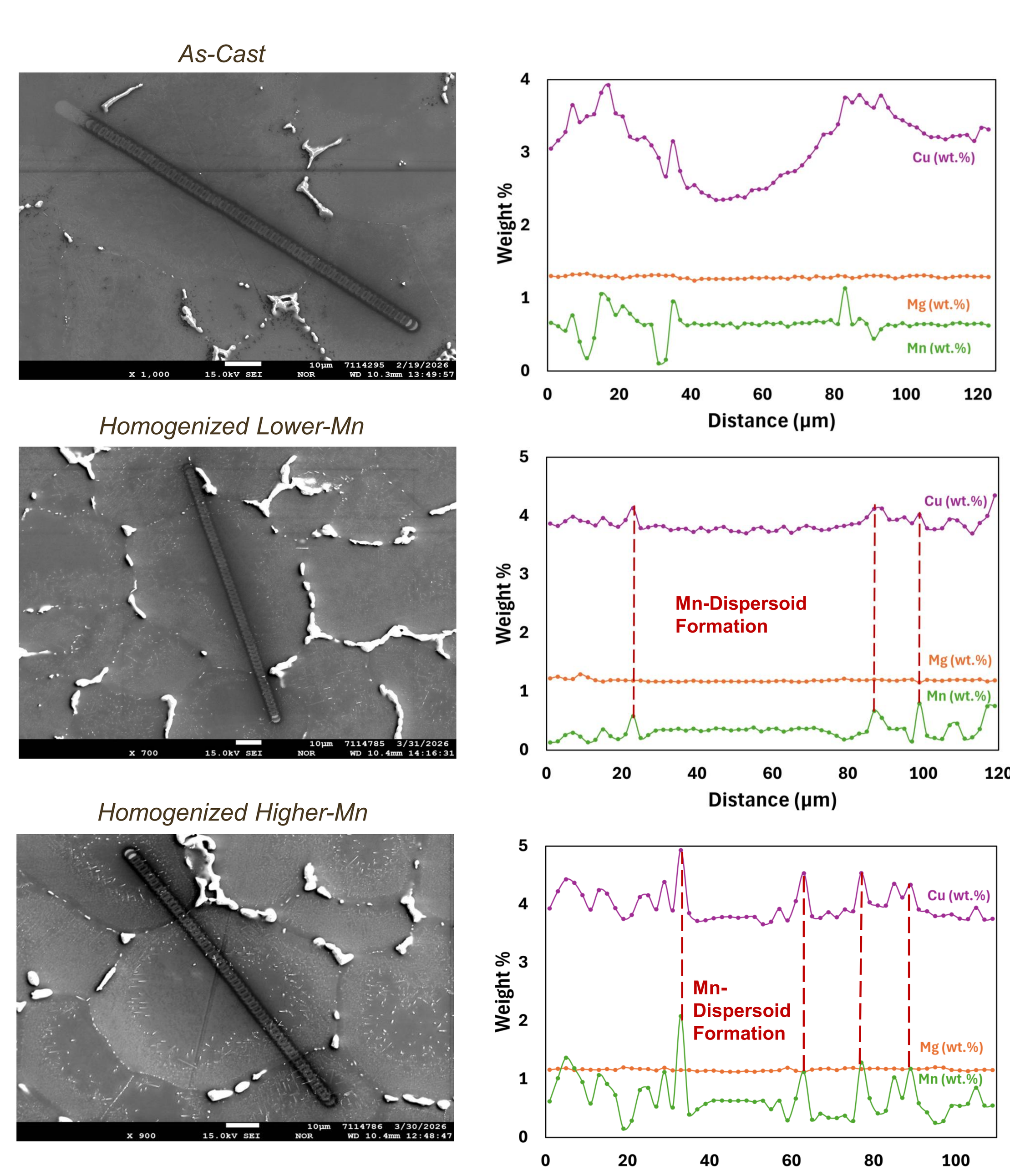
Hardness Evolution as a Proxy for Homogenization:

Hardness tracking directly after quenching indicated a consistent trend between the initial hardness and the degree of homogenization (Dt/L^2). Increased parameters facilitate the complete dissolution of as-cast phases [2], maximizing the solute supersaturation (Cu and Mg).The convergence of the two alloys, indicates that the matrix has reached the maximum effective supersaturation allowed.



Segregation Analysis:

EDS point scans confirm the transition from a highly segregated as-cast state to a more stabilized solid solution. The Cu peaks characteristic of inter-dendritic regions at the grain boundaries were reduced, showing that more Cu successfully diffused into the aluminum matrix.



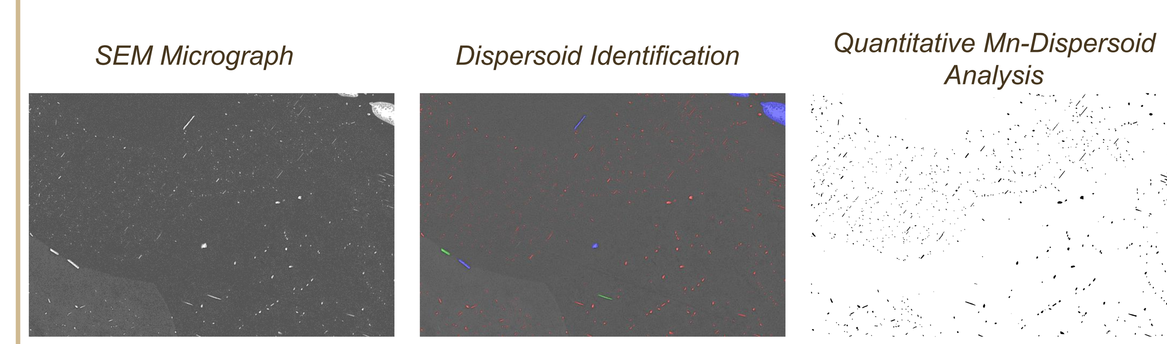
Copper Segregation Index: At a diffusion parameter of Dt/L^2 = 0.97, EDS confirmed an 85% reduction in Copper SI, decreasing from an as-cast value of 1.33 to a minimum of 0.149, indicating a near-complete redistribution of Cu into the aluminum matrix.

Manganese Segregation Index: In contrast to Copper, the Manganese SI showed a slight increase from 0.862 to 0.928. This increase, paired with the alignment of Mn and Cu peaks in the EDS line scan, reveals that the Mn atoms migrate towards the Cu-rich sites to form stable Mn-dispersoids.

Results & Discussion Cont.

Quantitative Mn-Dispersoid Characterization:

To evaluate the impact of Mn in microstructural stability, image analysis was performed over 60 frames per alloy. This quantified the volume fraction and distribution of Mn-dispersoids, which are critical for controlling grain structure during deformation. To isolate the dispersoids from larger constituent phases, a size threshold of <0.4µm was applied.



Alloy	Dispersoid Count per Area	Area Fraction (f)	Average Radius (r) (µm)	Zener Ratio (f/r) (µm⁻¹)
Lower Mn	~50,100	0.94%	0.058	0.16
Higher Mn	~103,000	1.89%	0.058	0.33

Correlation Between Mn-Content and Dispersoid Density: Doubling the Mn content (0.40% to 0.73%) doubled the dispersoid number density. Confirming that higher Manganese availability promoted dispersoid nucleation rather than particle coarsening, directly scaling the number of available pinning sites within the matrix.

Zener Pinning Pressure: The Higher Mn alloy achieved a Zener Ratio (f/r) of 0.33 μm^{-1}, providing twice the theoretical pinning pressure of the Lower-Mn alloy. Because the particle radius remained stable, the increased area fraction can be attributed to the enhanced microstructural resistance against recrystallization during downstream processing.

Conclusions & Future Work

Conclusions:

- Homogenization at $Dt/L^2 \geq$ 0.97 achieved near-complete dissolution of as-cast phases, resulting in an 85% reduction in the Copper Segregation Index.
- Doubling Manganese content (0.40 wt.% to 0.73 wt.%) doubled the Mn-dispersoid number density without particle coarsening. Confirming that higher Mn directly scales the Zener pinning capacity required for grain stability.
- Both alloys converged toward a 73-75 HRB saturation plateau. This indicates that the matrix reached maximum effective supersaturation, establishing hardness tracking as a viable proxy for homogenization extent.

Future Work:

- Investigate the impact of varied Si and Fe content on the formation of insoluble constituent phases and their interaction with Mn-dispersoids.
- Compare homogenization and quench results with naturally aged and solutionized samples to clarify the role of homogenization in the broader processing sequence.
- Measure recrystallized grain fraction post-extrusion to validate whether optimized schedules successfully suppress recrystallization.

Acknowledgements & References

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References

[1] M. Voncina et al., "Homogenization Efficiency Assessed with Microstructure Analysis and Hardness Measurements in the EN AW 2011 Aluminum Alloy," *Metals,* 11(8), p. 1211, 2021.

[2] H. Zhou et al., "Effects of double-step homogenization on precipitation behavior of Al3Zr dispersoids and microstructural evolution in 2196 aluminum alloy," *Metals,* 13(6), p. 1018, 2023.