Nano-Reinforcement of Aluminum Alloys

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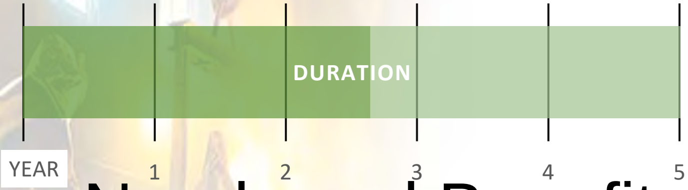
Emergent Metal Casting Technologies
(EMCS)

AMC Technology Review

June 24-25, 2026

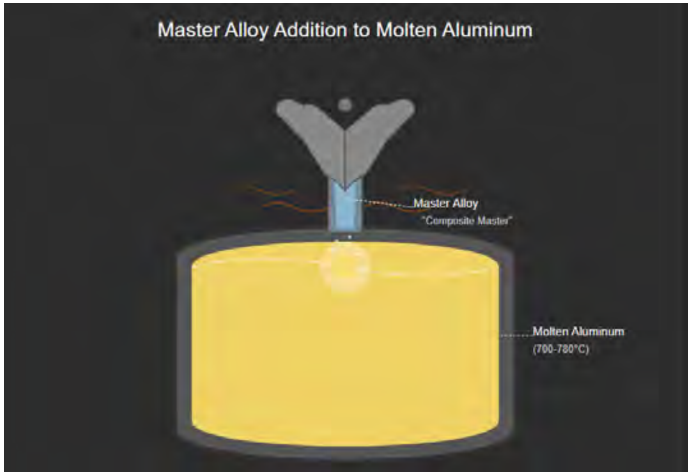


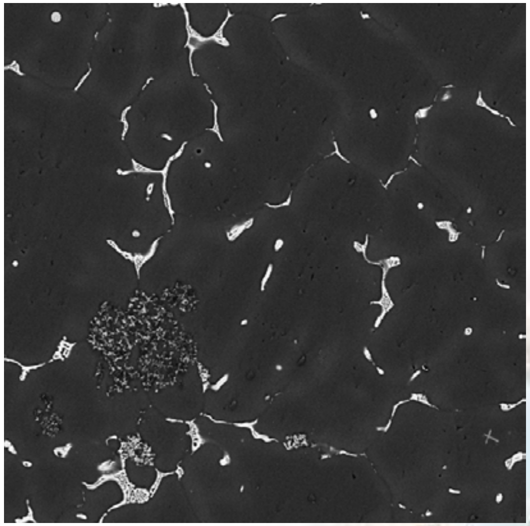
Overview

- Needs and Benefits-Lightweight alloys meeting specific mechanical properties (strength, CTE, toughness) utilizing casting or various types of additive manufacturing.
- Specifically, work to reduce CTE in large castings improving durability and overall function while maintaining or improving mechanical properties.
- Progress-*Significant CTE reduction and property improvements enabled by de-clustering of nano-reinforcements.*
- Transition-
  - Ongoing work with ARL eventually resulting in field test of large components
  - Commercial-Development for piston applications
- Cost Share - $87,632 provided to date of $150,000 proposed

Needs

- The *problem-* Field failures can impact warfighter readiness. In aluminum alloys, those problems can be caused by strength issues, high CTE and/or low modulus.
- The *objective* of our project is to create a simplified but reliable method to produce nano-composite castings that is scalable.
- The *technology* approach is twofold:
  - Use a master alloy additive to introduce the composite.
  - Develop methods to insure homogenous dispersion of particles in the melt and castings.





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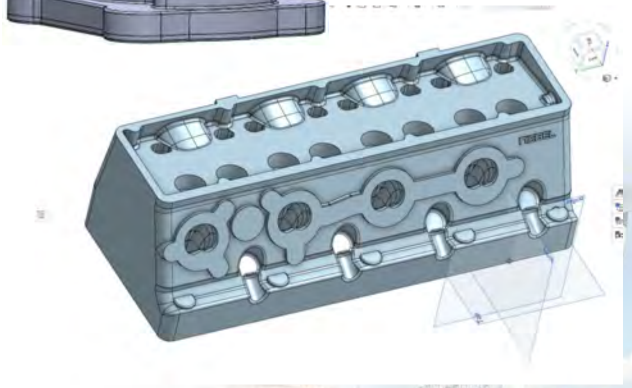
Benefits

“Based on the data you provided, the reduction in CTE is a game changer for large aluminum castings such as gearboxes and transmission cases”
B.C. -ARL

“If I can reduce weight using a higher strength alloy that is castable, in a cylinder head or piston, it gives me a competitive advantage”
Doug Van Klompenburg - President - Niebel Engines

“I am happy to report that the cylinder liners you produced from the composite material performed as well as steel liners. This will help meeting the performance goals of the drone engine we are working on”
Steve Bethel-President-Leadfoot Engineering

- ***Lightweighting-***
  - 20% weight reduction vs. conventional Al alloy components
  - 50% weight reduction by replacement of heavier alloys
- ***Reliability-***
  - Improvement in toughness and damage tolerance
  - Improvement in operating temperatures
  - Reduced CTE
- ***Cost-***
  - Reduction is scrap rates
  - Lower thermal processing costs
  - Improved corrosion performance
- ***Procurement-***
  - Master alloy or in mold process gives flexibility in sourcing



Milestones/Tasks

- Completed
  - Task 1-Manufacturing methods for nano-master alloys
  - Task 2-Microstructural analysis and modeling
  - Task 3-Homogenous dispersion of nano-particles
- In Progress
  - Task 4-Scale-up activities for Tasks 1-3
- Planned
  - Task 5-In mold distribution of particles, ex-situ additions, hydro-solidification

De-clustering and Dispersion

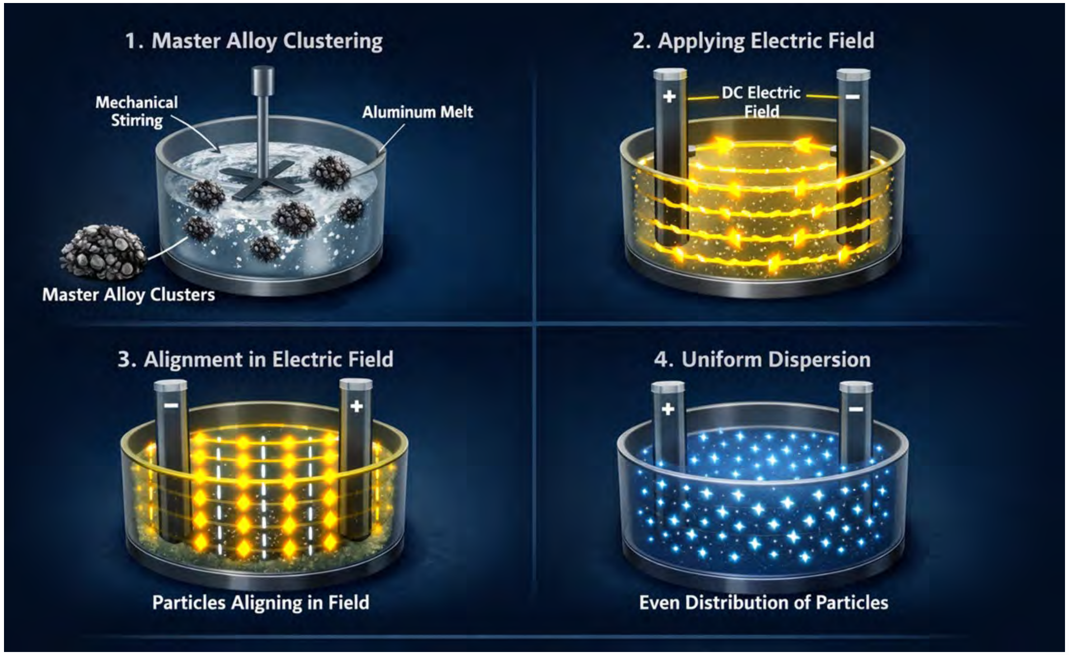
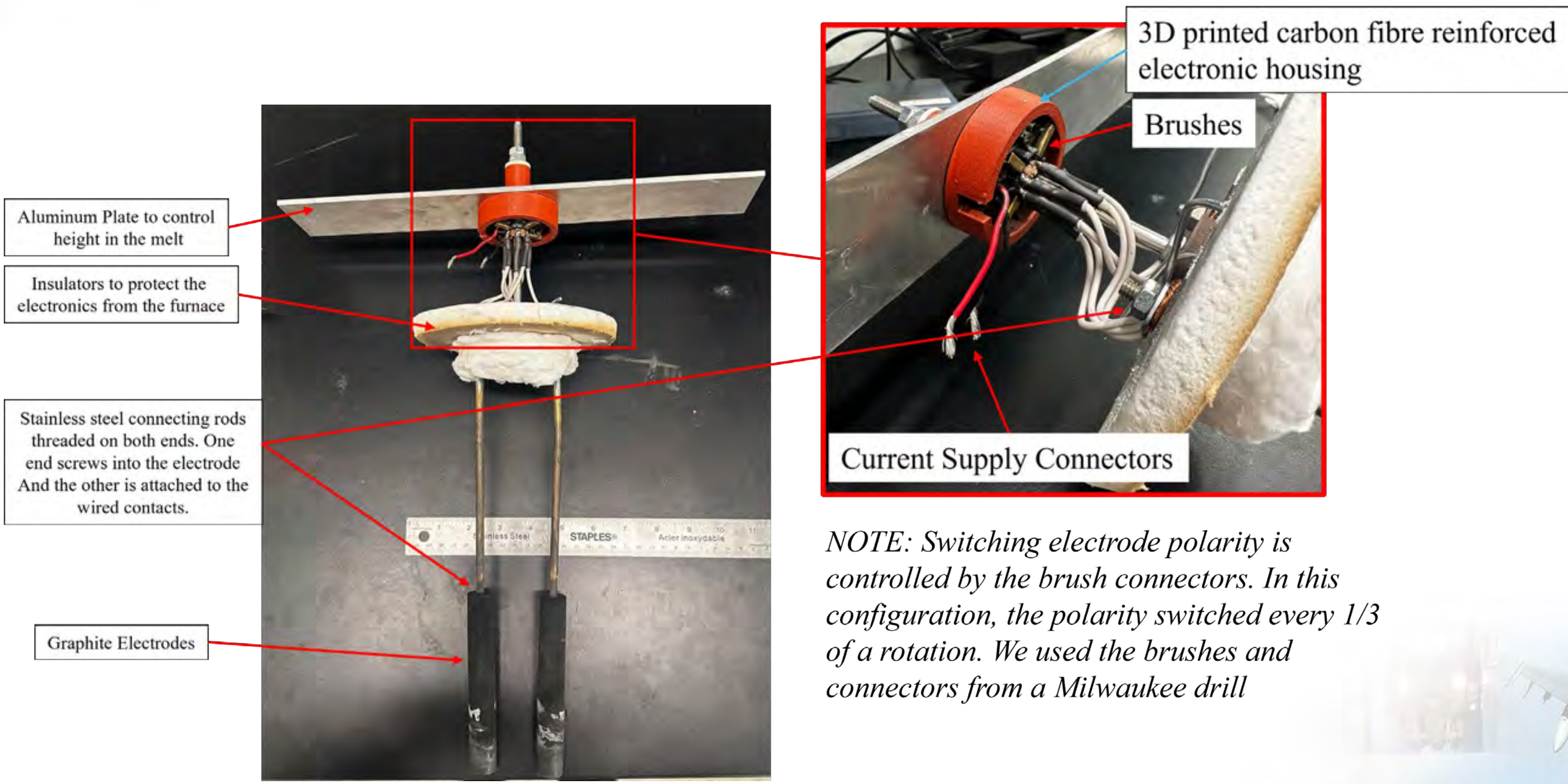


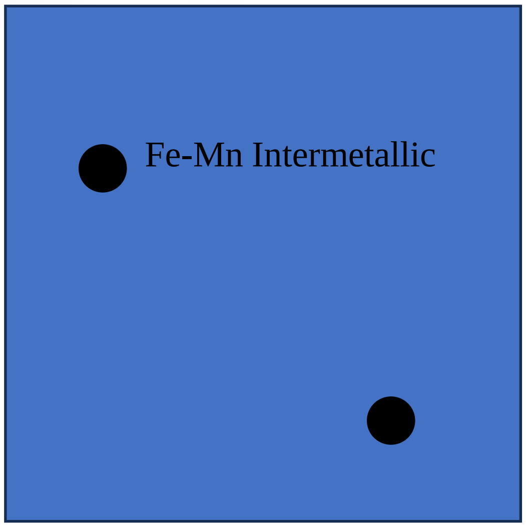
Illustration of Device



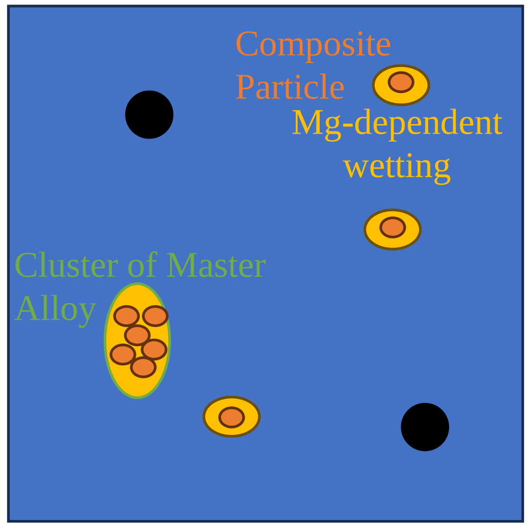
NOTE: Switching electrode polarity is controlled by the brush connectors. In this configuration, the polarity switched every 1/3 of a rotation. We used the brushes and connectors from a Milwaukee drill

DC Nanocomposite Schematic

T4 B206

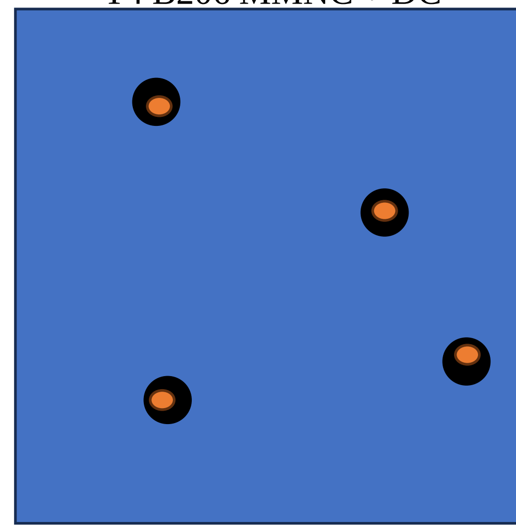


T4 B206 MMNC (No DC)



- Limited effective homogenous dispersion.
- Most benefits are masked by the fragments of the sintered master alloy not breaking down

T4 B206 MMNC + DC



- Master alloy clustering is eliminated.
- Intermetallics form around particles, showing improved wettability
- Significant benefits at RT and HT (YS, UTS, Modulus).

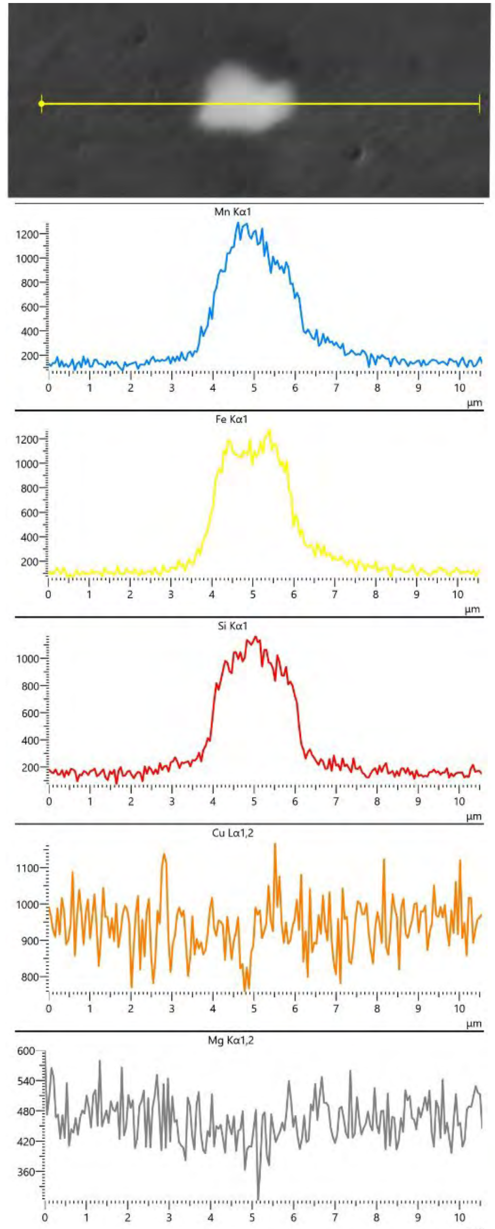
Impact of Alloying Elements

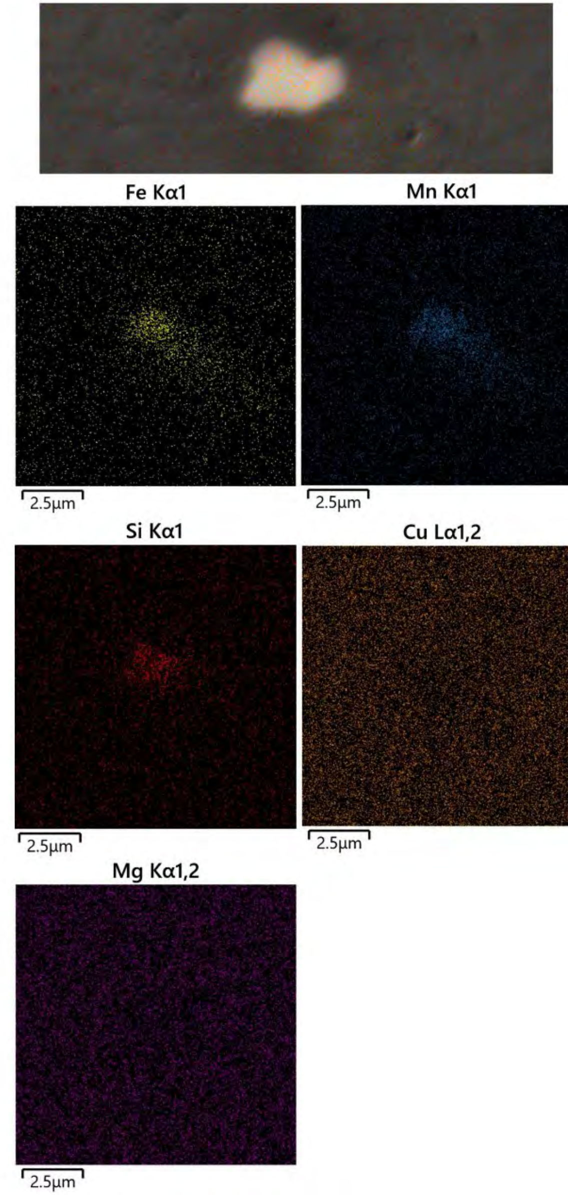
Other elements may impact the wettability and dispersion of reinforcements.

In the case of SiC, Mn,Fe and Si improve wetting with less impact on Mg depletion or tying up Cu.

This only happens in the presence of an applied field!

Reference alloy B206

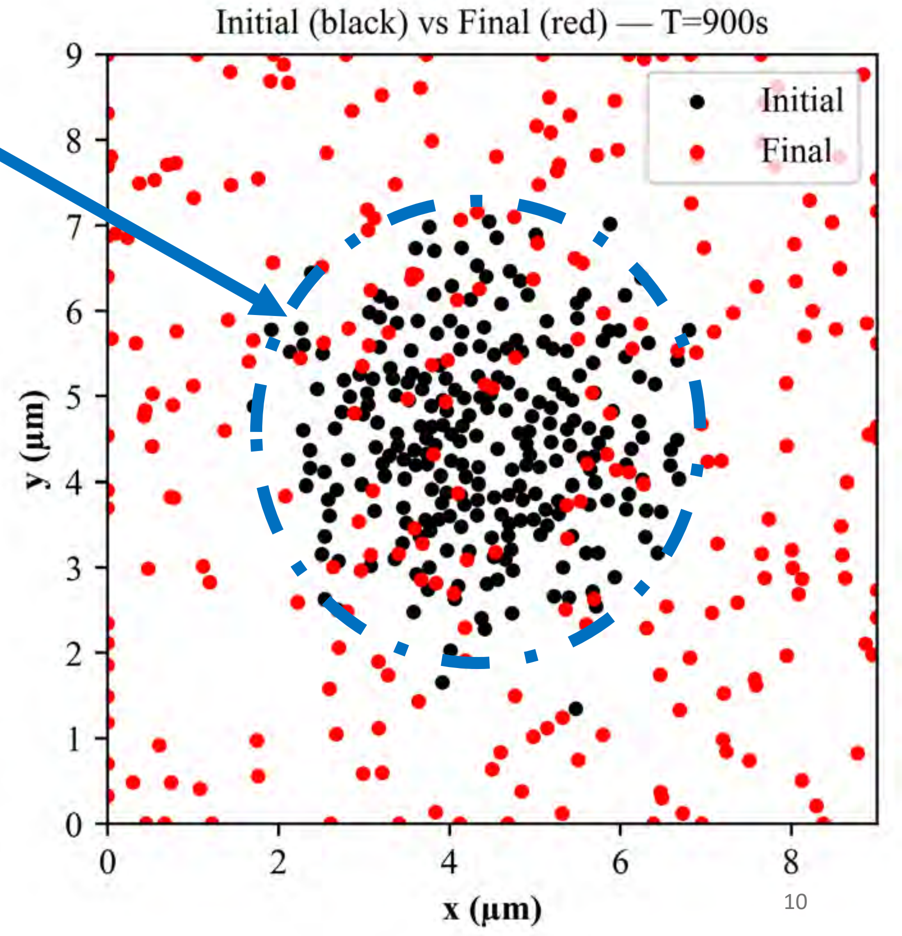




Spatial Distribution Visual

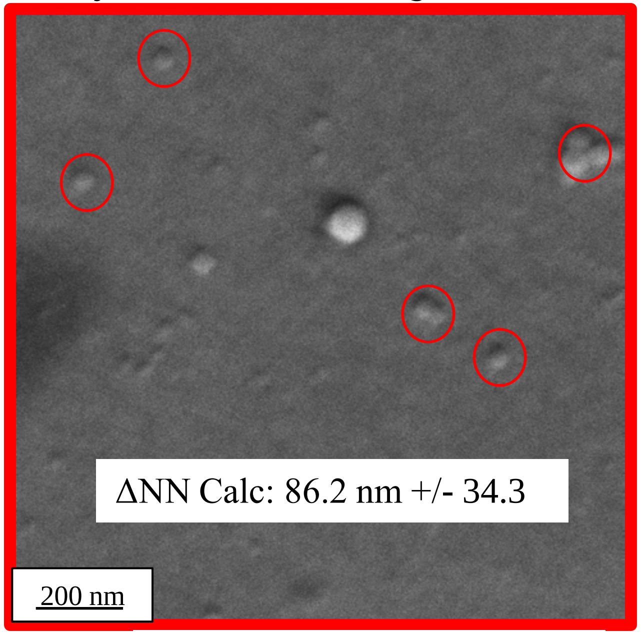
Particles start at a random orientation with 0-2% separation before the electric field is applied

Time (s/min)	ΔNN (nm)
60s/1min	96.8 +/- 9.3
300s/5 min	91.9 +/- 7.7
600s/10 min	87.4 +/- 10.2
900s/15 min	97.4 +/- 10.5
1800s/30 min	95.8 +/- 7.0
2700s/45 min	91.9 +/- 7.3



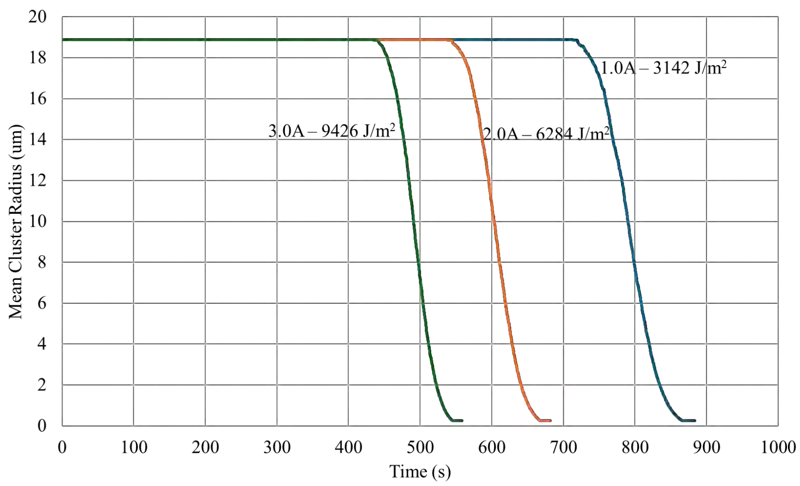
Measured vs simulated dispersion shows good correlation

Adjusted Contrast in Single Phase



ΔNN Sim: 97.4 nm +/- 10.5

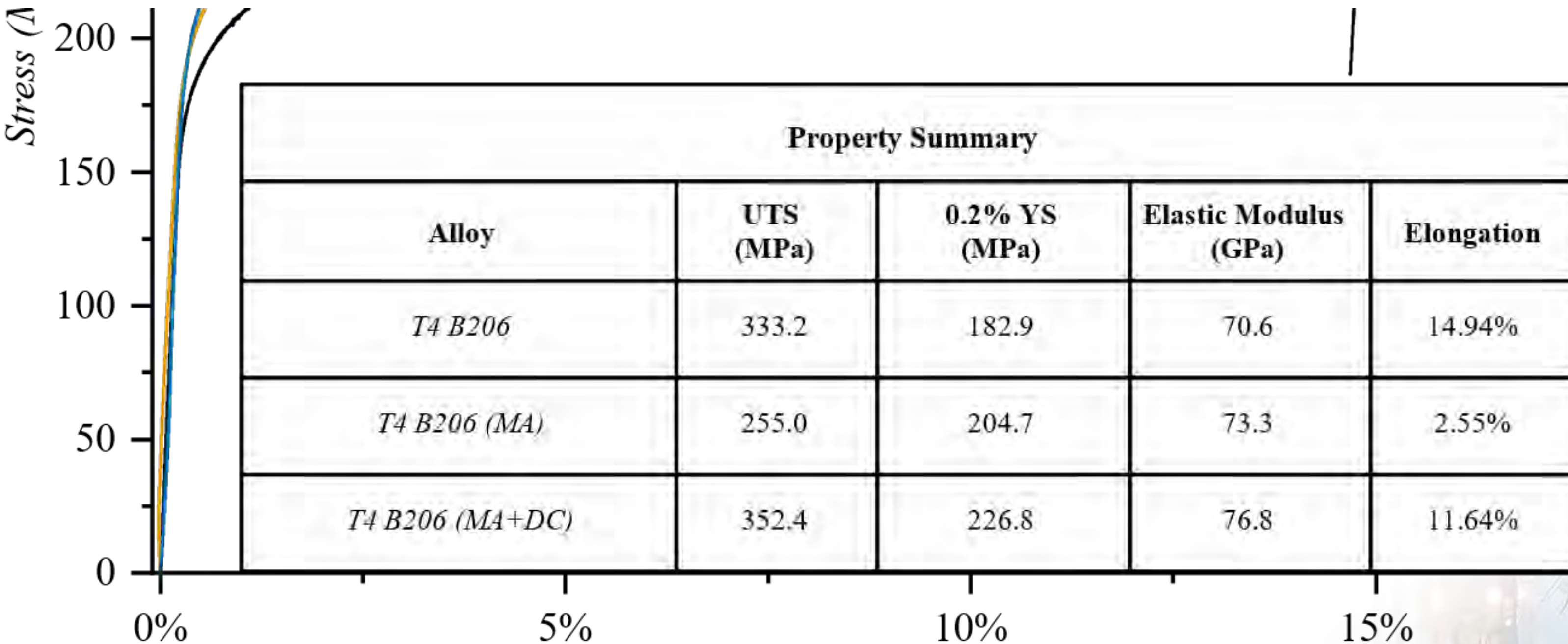
Modeling of Cluster Break-Up



Sintered master-alloy clusters behave like a porous network of particles connected by necks and oxide/film bridges. With stirring alone, the shear stresses in molten aluminum are low—often on the order of ~1 Pa—so the network only partially breaks. When we apply current during rotation (EMC), we don't necessarily add a large bulk electromagnetic force: only 2–3 A.

The current modifies the cluster interfaces and neck regions over time: it accelerates melt infiltration into pores, disrupts or destabilizes oxide/film bridges, and can introduce localized heating and polarization effects at constricted contact points. The net effect is a **time-dependent reduction in effective cohesive strength**, so after ~10 minutes the same mechanical shear becomes sufficient to rapidly fragment the clusters. That's why we see an incubation period followed by a sharp breakdown—consistent with the mechanical property optimum at ~10–15 minutes.

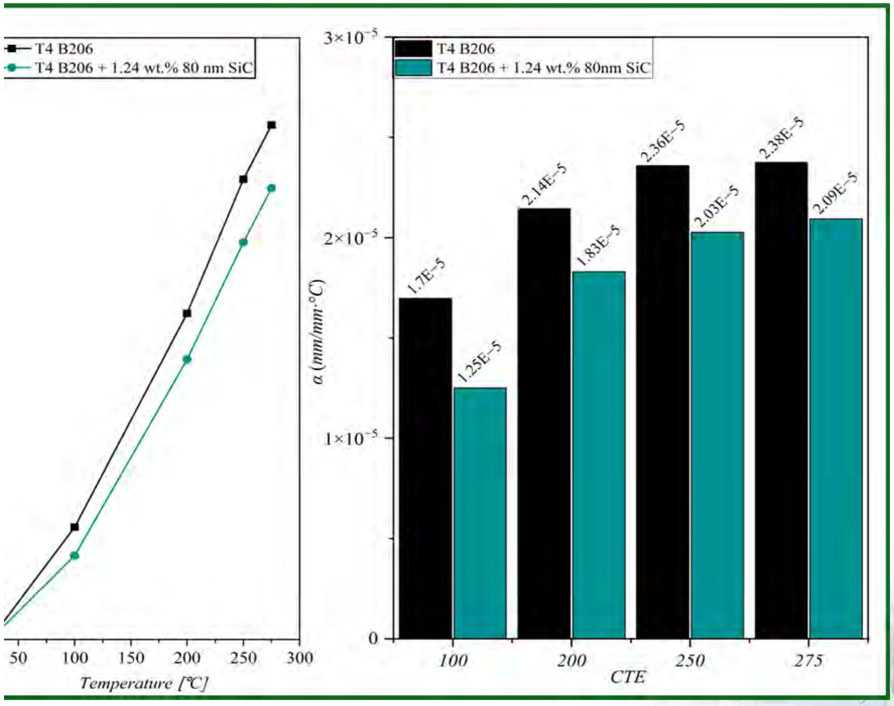
De-Clustering Key to Higher Mechanical Properties



Property Summary				
Alloy	**UTS (MPa)**	**0.2% YS (MPa)**	**Elastic Modulus (GPa)**	**Elongation**
T4 B206	333.2	182.9	70.6	14.94%
T4 B206 (MA)	255.0	204.7	73.3	2.55%
T4 B206 (MA+DC)	352.4	226.8	76.8	11.64%

Applications-Lower CTE

- Larger castings can develop significant stresses at higher temperatures
- CTE Data is often misapplied or incomplete
- Why do nano-particle reinforced alloys not follow the rule of mixtures?



CTE in Nano-Composites-Percolation Theory

- CTE reduction is not purely volumetric-it's about mechanical constraint.
- Key is strong bonding and lack of clustering
- When nanoparticles are well dispersed and wetted within an aluminum matrix, they act as a mechanically connected system that effectively constrains thermal expansion, more effectively than simple rule-of-mixtures models would predict.
- By contrast, rule-of-mixtures approaches essentially average the matrix and reinforcement CTEs based on volume fraction and do not capture these percolation effects.
- Well bonded nanoparticles can have 100X the effect on CTE compared to micron size particles at equivalent weight percents.

Does the Process Scale

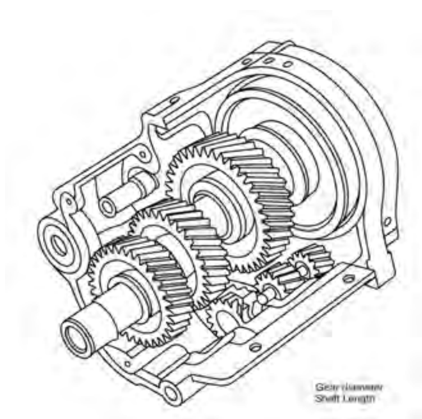
- Yes!

Melt size	Current (~2.0 V)	Power (~2.0 V)
1 kg	2.5 A	5.0 W
2 kg	3.2 A	6.4 W
5 kg	4.2 A	8.4 W
20 kg	6.6 A	13.2 W
50 kg	8.9 A	17.8 W
100 kg est.	11.1 A	22.2 W
150 kg est.	12.7 A	25.4 W
200 kg est.	13.9 A	27.8 W
250 kg est.	14.9 A	29.8 W

Applications

Thermal expansion in aluminum gearboxes can induce side loads on bolts, causing bolt breakage.

Expansion can cause gear engagement issues, lowering efficiency or increasing wear.



Project Plans

- Scale manufacturing techniques to produce DLA components in the 100-200# range.
  - Improving throughput of master alloy production.
  - Furnace modifications.
- Produce components for testing.
- Revisit
  - Non-master alloy ex-situ techniques
  - In-mold distribution
  - Hydrosolidification

Transition Plan

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- *Army and BAE Systems will test a nano-reinforced gear case.*
  - *Castings produced third quarter 2026*
  - *Testing first quarter 2027*

- *Leadfoot Engineering will test nano-reinforced pistons and cylinders.*
  - *Castings produced third quarter 2026*
  - *Testing fourth quarter 2026*

LEADFOOT ENGINEERING

Army Research Lab

BAE SYSTEMS

Leveraging

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- Industrial interest and advise
- American Foundry Society expertise
- U Michigan NSF program on in-situ composites
- ARL interest and testing [MELD Processing]
- Loukus-(2) Phase 3 SIBR’s
- University of California-Advanced Ultrasonic Processing
- Total Cost Share $135,000 from Loukus-All equipment usage is cost shared. ~$15,000 from American Foundry Society

Project Metrics

Description	Baseline	Threshold	Goal	How Measured	Target Date	Progress	How Demonstrated
Making master alloys with higher proportion of reinforcement	7%	14%	20%	Microstructure Processability	EOP	Still Using 7% as baseline- running experiments at 50% loading	Successful distribution in base alloy
Mechanical Property Enhancement, **Improved Castability**	QI 555 Castability 3/10	615 5/10	700 7/10	Tensile and %E Hot Tearing	EOP EOP	Fundamental Studies 7/10	640 Casting Studies
Achieving better distribution of reinforcements in the melt	10% Un-clustered	50%	75%	Microstructure Modulus	EOP	>80%	Tensile improvement with minimum modulus change-property testing
Demonstration of in-mold distribution of reinforcement	0	25%	50%	Microstructure Strength Metrics	EOP	10% Successfully produced pucks with 99% reinforcement but difficult to dissolve	Tensile improvement Reduction of ex-situ alloying

Acknowledgements

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Nano-Reinforcement of Aluminum Alloys

DLA - POC: DLAR.DPR@dla.mil

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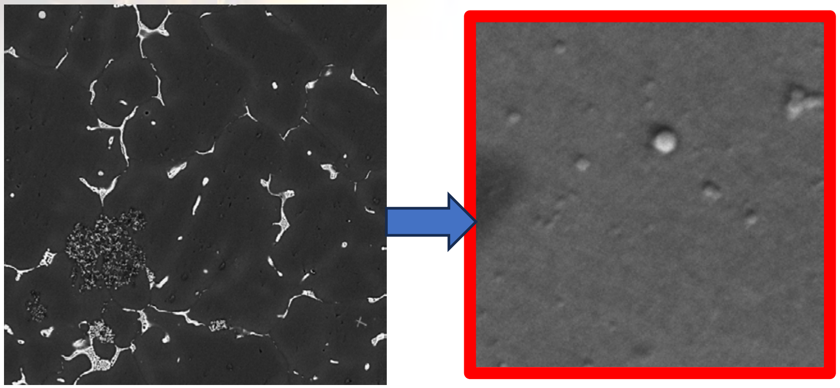

Effective de-clustering key to properties

Problem

- Optimum casting methods and materials need to be determined for nano-reinforced aluminum alloys to be used confidently, resulting in improvements in strength, toughness and other properties.

Objectives

- Reduce costs associated with better castability of the alloy by 25%, reduce costs of casting rejections caused by hot tearing by 50%, reduce lead times for complicated components by 30%, and enhance service performance through improvements in mechanical(including CTE reduction) properties by 20%

Benefits to Warfighter

- Use of nano-reinforced alloys will enable casting designs that reduce weight by 20% and improve toughness by more than 10%

Description of Project

This project will increase the strength of castings via the cost-effective addition of nano-sized particles into the melt

Team: American Foundry Society, ATI, Loukus Technologies

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AFS

loukustech

Milestones / Deliverables

- Validate master alloy addition of nanoparticles
- Validate nanoparticle addition through use of ceramic foam filters
- Validate mechanical properties/nanoparticulate distribution in test castings