Thermal and Electrical Transport Measurements in Wrought and Cast Aluminum Alloys

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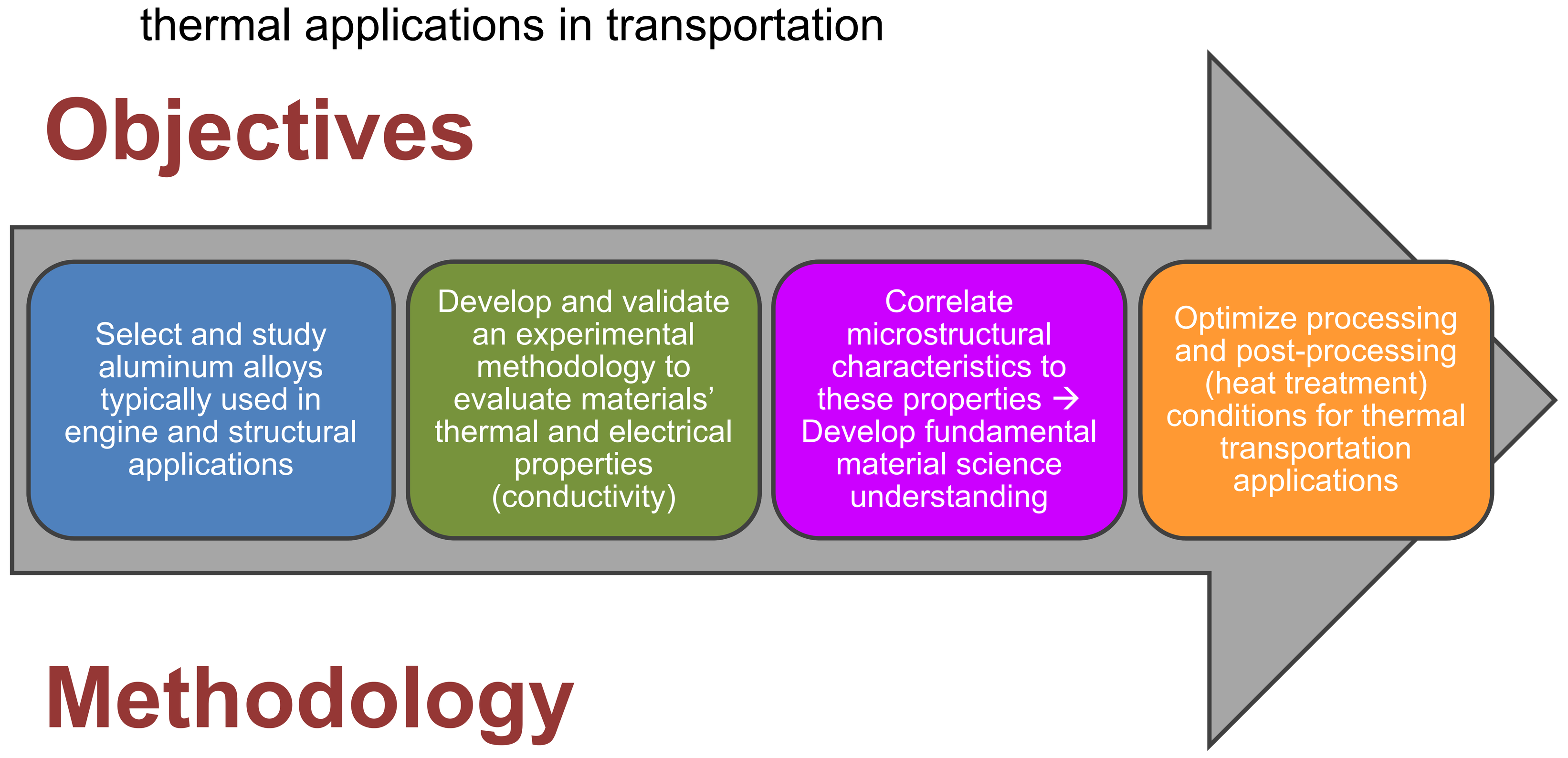
Problem Statement

- Engine efficiency is currently limited by the ability of the engine materials to dissipate heat
- Material thermal management is a critical consideration for design
- Develop knowledge necessary to optimize the material/process for thermal applications in transportation

Objectives

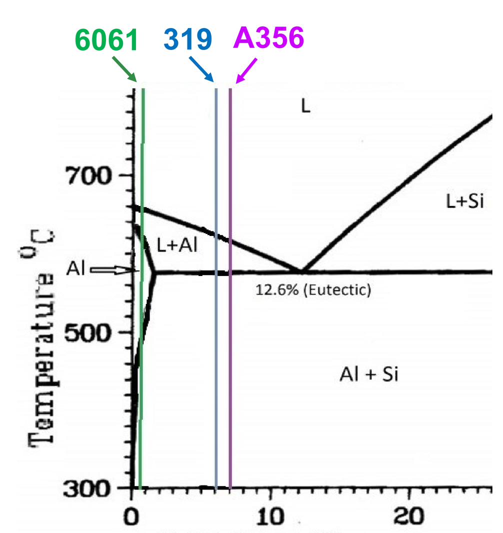


Methodology

1. Materials and Processing

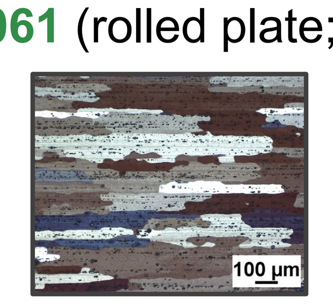
- Aluminum Alloys: Wrought **6061** and cast **319** and **A356**

Composition [wt%]										
Material	**Al**	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Si**	**Ti**	**Zn**	**Other**
6061 (Al-Mg-Si)	95.8-98.6	0.04-0.35	**0.15-0.40**	<0.70	**0.80-1.2**	<0.15	**0.40-0.80**	<0.15	<0.25	<0.15
319 (Al-Si-Cu-Mg)	83.8-91.5	0	**3.0-4.0**	<1.0	**<0.10**	<0.50	**5.5-6.5**	<0.25	<3.0	<0.50
A356 (Al-Si-Mg)	91.1-93.2	0	**<0.20**	<0.15	**0.30-0.45**	<0.10	**6.5-7.5**	<0.20	<0.10	<0.15

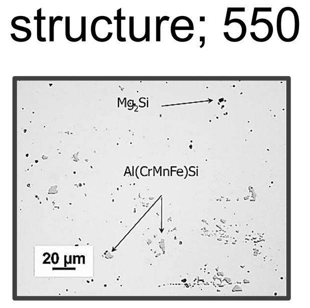


Al-Si phase diagram

- Microstructural characteristics of the alloys
  - **6061** (rolled plate; pancake grain structure; 550 µm x 50 µm)

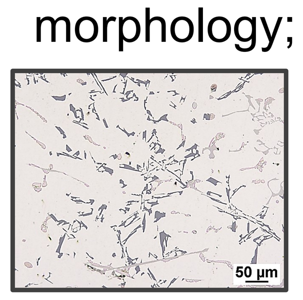


6061 grain structure

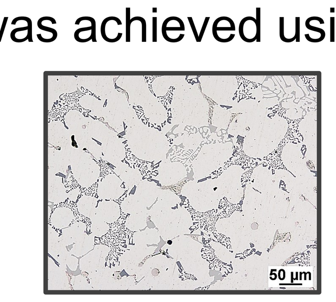


6061 microstructural phases

  - **319** (SDAS = 60 µm & unmodified and modified eutectic Si morphology; modification was achieved using Sr additions)

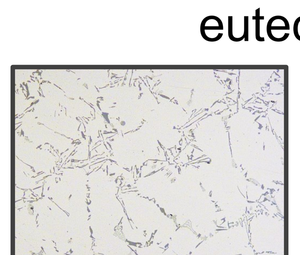


319 Unmodified (60 µm SDAS)

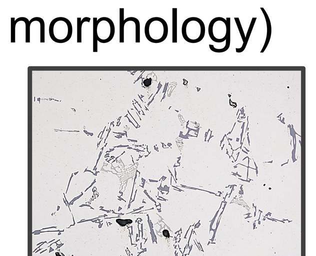


319 Sr Modified (60 µm SDAS)

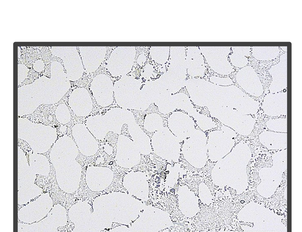
  - **A356** (SDAS = 60 µm and 100 µm & unmodified and modified eutectic Si morphology)



A356 Unmodified (60 µm SDAS)



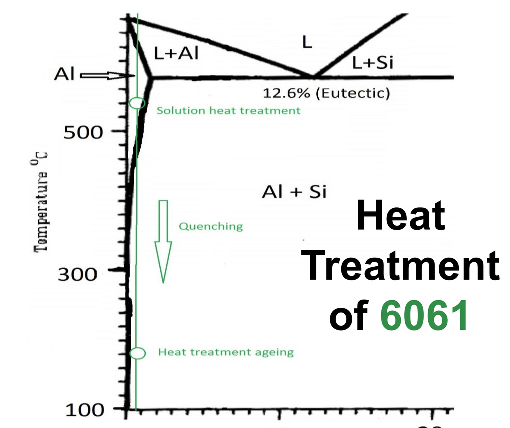
A356 Unmodified (100 µm SDAS)



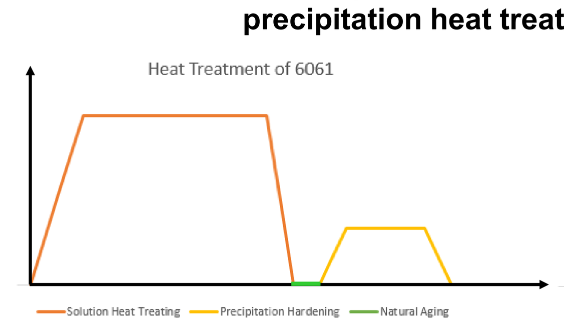
A356 Sr Modified (60 µm SDAS)

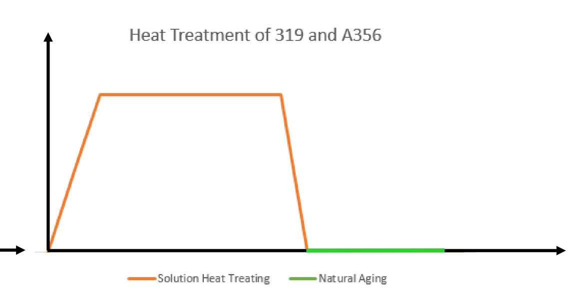
Methodology cont.

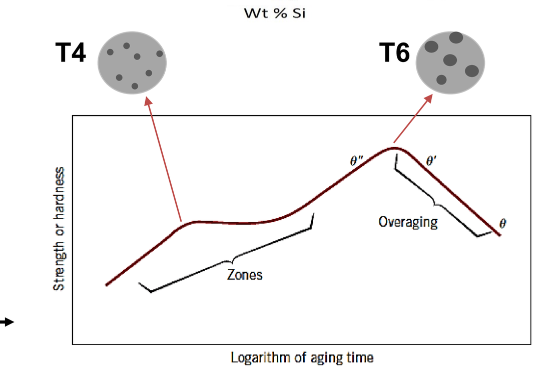
Sample	Solution Treatment			Natural Aging		Artificial Aging	
	T [°C]	Time [hours]	Quench	T [°C]	Time [hours]	T [°C]	Time [hours]
6061	540	4	Boiling water	25	24	180	1.5, 4, 8, 16
319	500	4	Boiling water	25	24	-	-
A356	540	4	Boiling water	25	24	-	-



Schematic Temperature vs time showing solution and precipitation heat treatment schedules

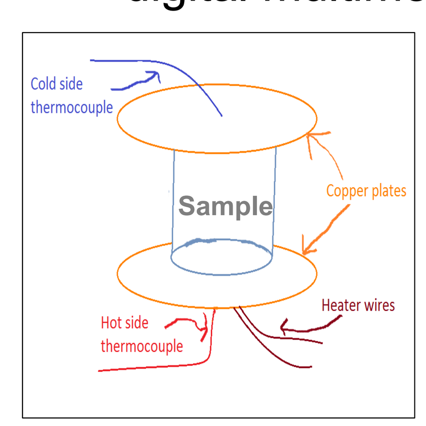






2. Apparatus: Design and Construction

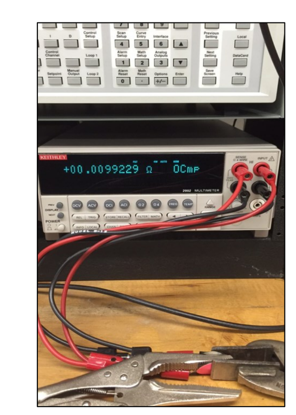
- Custom-built apparatus by our team to measure thermal resistance of the studied materials
- Electrical resistance measurements conducted using a 4-wire digital multimeter (DMM)



Schematic of apparatus

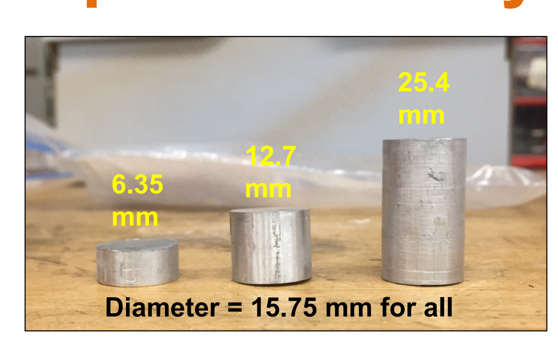
Cannister

Electronic Components



Multimeter

3. Sample Geometry



All thermal and electrical measurements have been conducted at room temperature

4. Fundamental Equations for the calculation of thermal and electrical conductivities

A. Thermal conductivity equation:

$$R_t = \frac{kL}{A}$$

$$\Delta T - \Delta T^o = (R_S + R_C)(P_o - P_l)$$

where

$$\Delta T = T_H - T_C$$
$$\Delta T^o = T_H - T_C \ (when \ P_o = 0)$$
$$P_o = I \cdot V$$

$k = thermal\ conductivity \left[\frac{W}{m \cdot K}\right]$
$L = Length$ [m]
$A = Cross\ sectional\ area$ [m^2]
$T_H = Temp.\ of\ the\ hot\ side$ [K]
$T_C = Temp.\ of\ the\ cold\ side$ [K]
$R_S = Sample\ resistance$ [K/W]
$R_C = Contact\ resistance$ [K/W]
$P_o = Applied\ heating\ power$ [W]
$P_l = Heating\ power\ leak$ [W]
$I = Currrent$ [A]
$V = Voltage$ [V]

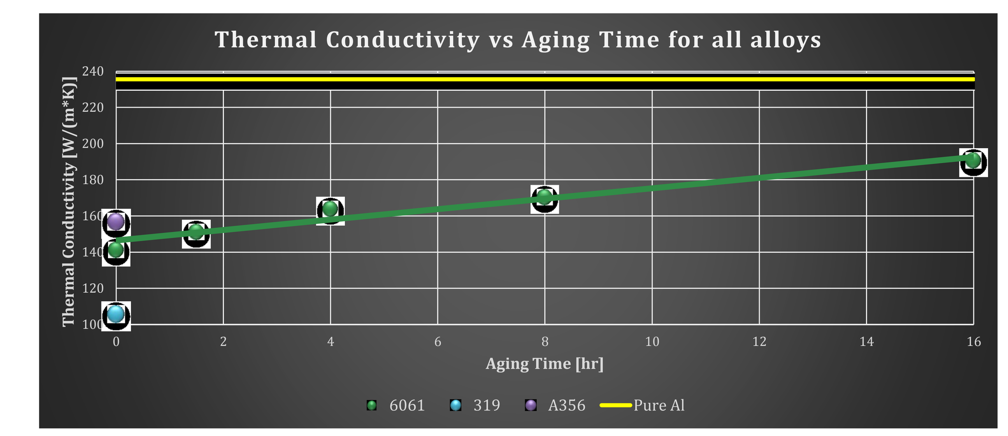
B. Electrical conductivity equation:

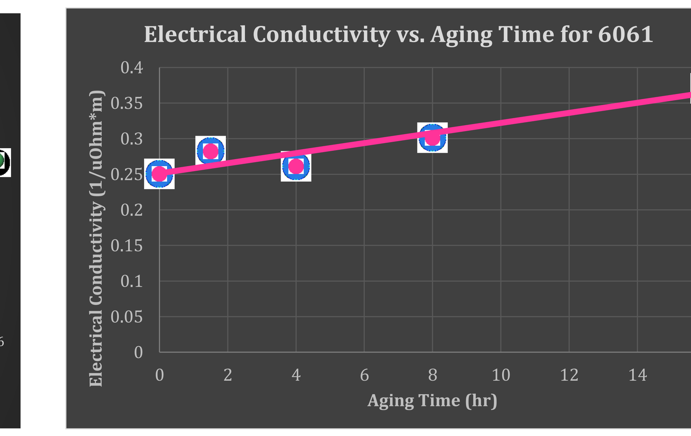
$$R_e = \frac{\rho L}{A}$$

$\rho = resistivty\ [\Omega \cdot m]$
$\rho^{-1} = electrical\ conductivity\ [\Omega^{-1} \cdot m^{-1}]$

Results and Discussion

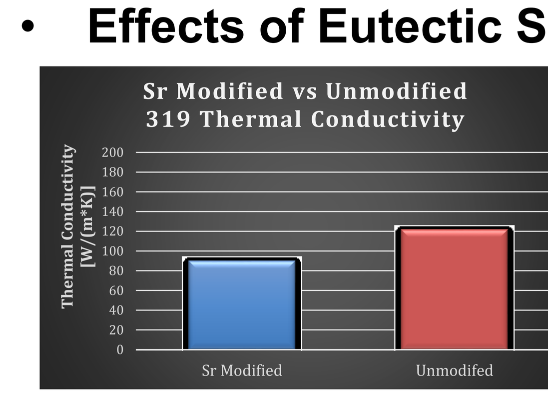
- **Effects of Aging Time on Thermal and Electrical Conductivities**

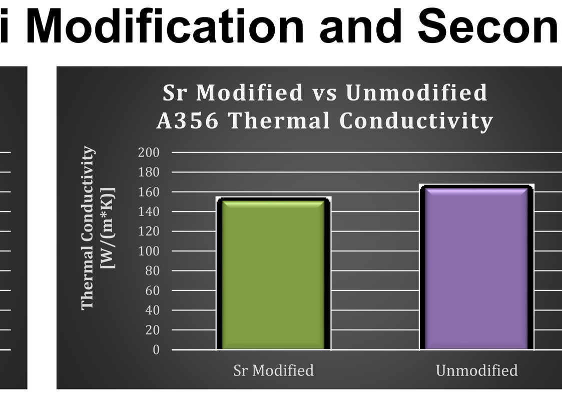


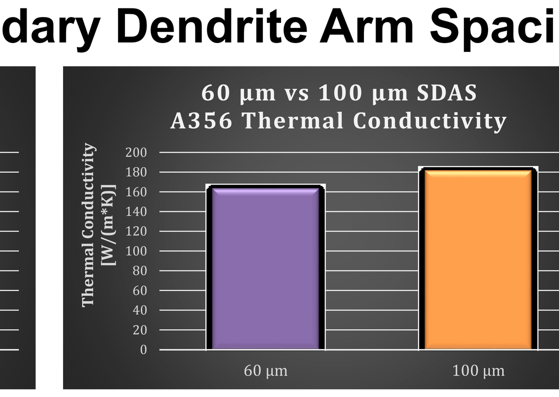


  - Thermal conductivity of 6061 increases with the increase in aging time from 0 hours (T4) to 16 hours (T6) *(i.e., from 141 to 191 W/(m*K); due to the formation of precipitates, which leaves the α-Al matrix "leaner" in alloying elements such as Mg and Cu)*
  - Thermal conductivities of 319 alloys are lower than those of 6061 and A356 alloys *(due to the additional presence of Cu in the α-Al matrix of these alloys – in solutionized-only state)*
  - Electrical conductivity increases with aging time *(the same trend is expected for 319 and A356 cast alloys given that the α-Al matrix is the dominant contributor to transport properties)*

- **Effects of Eutectic Si Modification and Secondary Dendrite Arm Spacing**







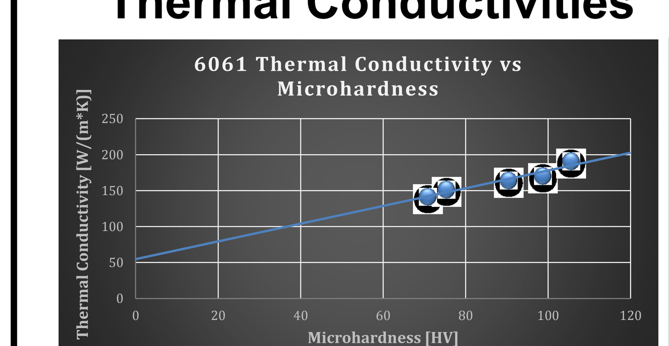
  - Both 319 and A356 Sr modified alloys show a lower thermal conductivity than the unmodified ones *(modification is associated with finer and closer spaced distributions of Si particles in the eutectic regions)*
  - Higher SDAS alloys have higher thermal conductivity *(larger SDAS are associated with larger α-Al regions and coarser spacing of the Si particles in the eutectic areas)*

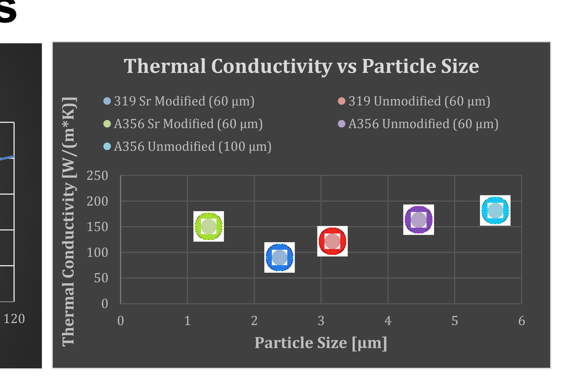
$$Eq.Dia. = \sqrt{\frac{4 \cdot Area}{\pi}}$$

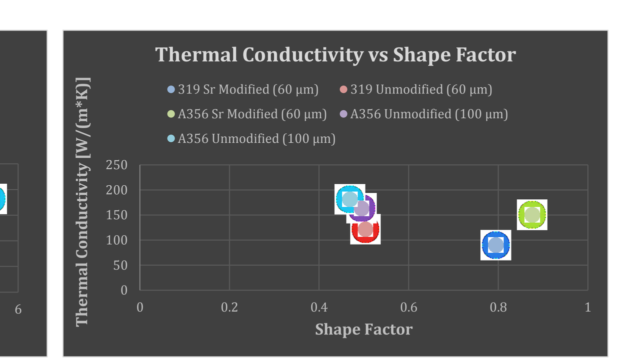
$$Shape\ Factor = \frac{4 \cdot \pi \cdot Area}{(Convex\ hull\ perimeter)^2}$$

Eutectic Si particle		319 Unmodified (60 µm SDAS)	319 Sr Modified (60 µm SDAS)	A356 Unmodified (60 µm SDAS)	A356 Unmodified (100 µm SDAS)	A356 Sr Modified (60 µm SDAS)
Diameter [µm]		3.17	2.38	4.46	5.61	1.32
Shape Factor		0.504	0.795	0.495	0.468	0.876

- **Correlations Between Microhardness & Eutectic Si Morphology and Thermal Conductivities**







  - Both thermal conductivity and microhardness of 6061 increase with aging time
  - Thermal conductivity increases are associated with larger eutectic Si particle size and smaller shape factor *(modification produces smaller Si particles with higher shape factor, and also produces a finer and more uniform distribution within the eutectic regions themselves)*

Recommendations & Future Work

- Apply the developed testing methodology to other Al and metal alloys and heat treatments to further understand transport phenomena
- Improve thermal measurement apparatus by providing better thermal insulation and more uniform contact between plates and samples
- Study and compare thermal measurements done at room and high temperatures & in-situ aging of the materials inside the test apparatus