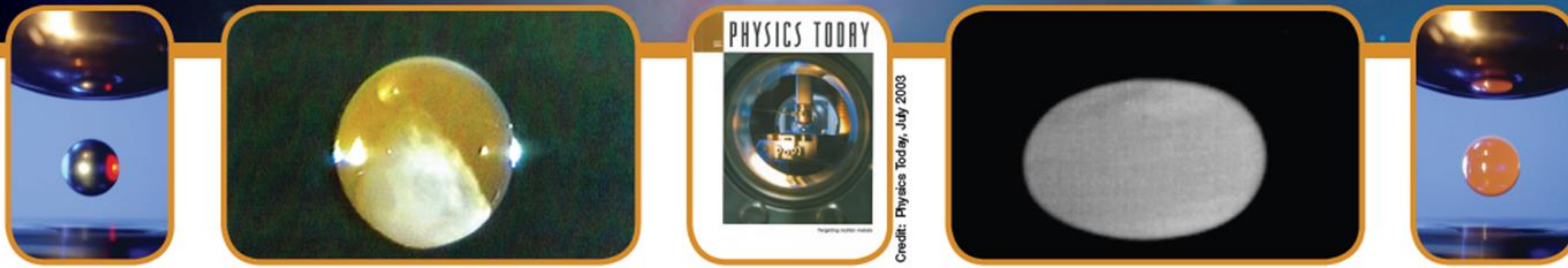
Marshall Space Flight Center

Electrostatic Levitation Laboratory



Thermophysical Properties of Nickel-Based Superalloys

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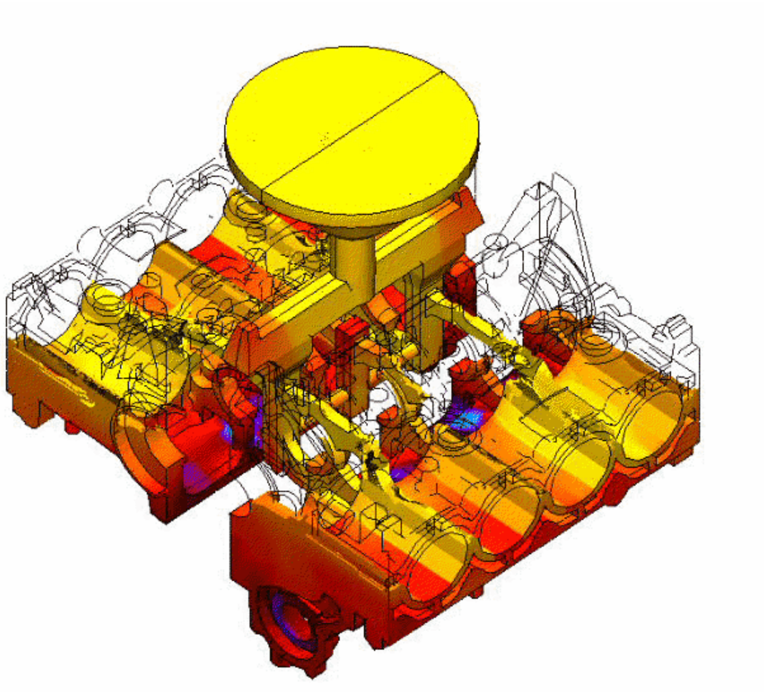
Boulder, C0
June 24-29, 2018

Motivation for the Investigation

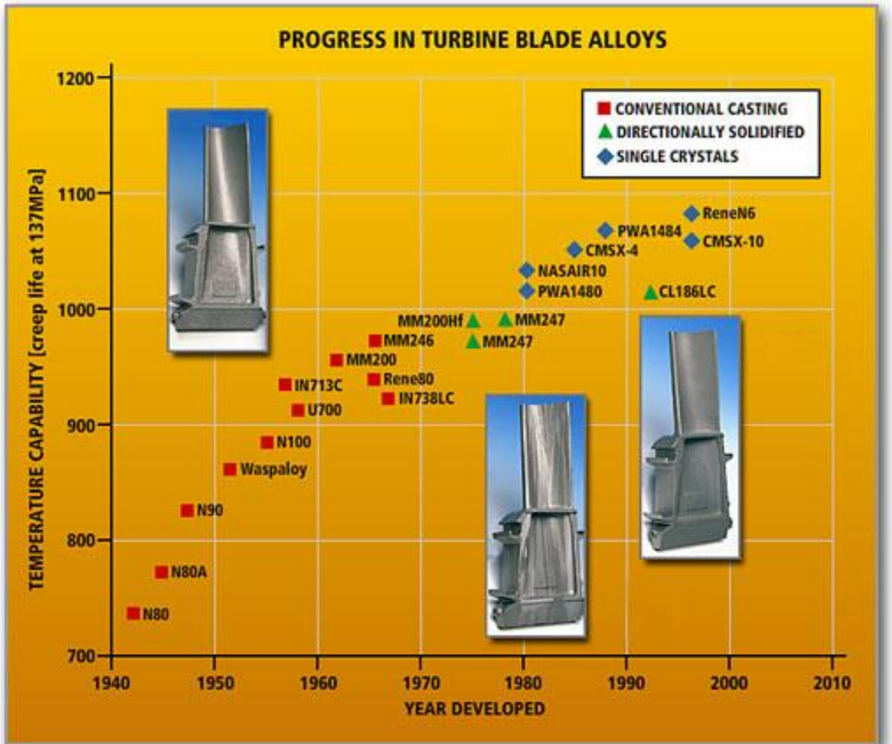


A model of a casting process[1]

- Need high quality thermophysical properties of high-temperature materials.
- These properties are critical for developing accurate models with predictive capability
  - Casting
  - Welding
  - Additive Manufacturing
- Measurements will improve manufacturing of propulsion components, leading to higher performance and higher reliability.
- More efficient and more reliable production of metallic parts for exploration, commercial, and industrial applications using these alloys.

References:
1. http://www.technalysis.com/casting_software.aspx

Nickel-Based Superalloy Overview



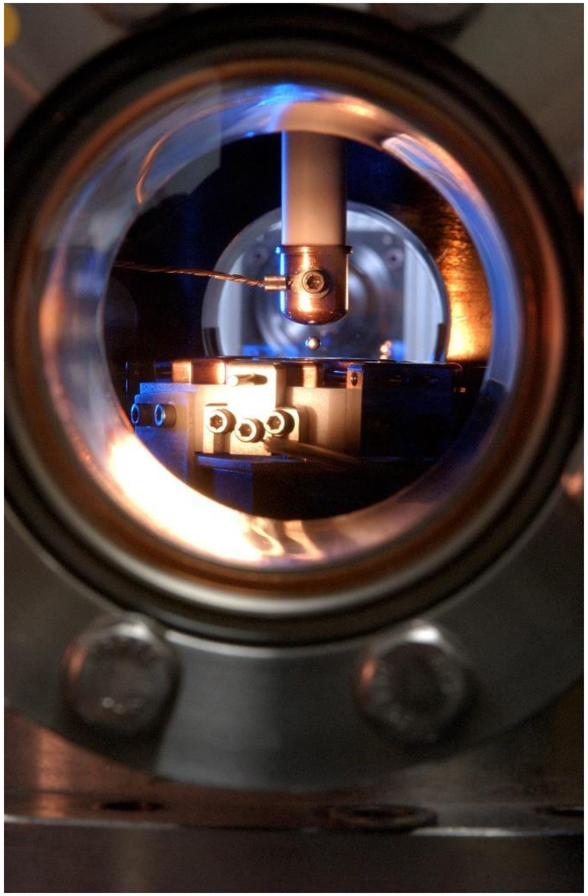
Historical improvement in blade performance[2]

- Superalloys are key materials for
  - Turbopumps in chemical rockets
  - Components in jet engines for commercial and military applications
  - Development of advanced space hardware
- Demands for higher thrust, thrust to weight ratio, and fuel efficiency
  - Push engine operating temperatures and stresses higher
  - Thermal barrier coating design optimized
- Historical development
  - The first commercial nickel-based alloy development was done by the British in the early 1940s including Nimonic-75 and Nimonic-80 alloys
  - Conventional casting alloys continued to improve in terms of temperature capability over the next several decades
  - Directional solidification and single crystal casting have allowed further improvements

References:
2. https://www.grc.nasa.gov/WWW/StructuresMaterials/AdvMet/research/turbine_blades.html
L. Langston and S. Jan, "Gems of turbine efficiency", *ASME, Mechanical Engineering; New York* **136** (9) (2014) pp 76-77.

Approach

- Samples were arc melted at MSFC
- Processed in the electrostatic levitator at MSFC
- Data was analyzed by Tufts University
  - Sample evaporation
  - Density
  - Surface Tension
  - Viscosity



A levitated sample in the MSFC electrostatic levitator.

Collaborations

Glenn working on the ESL Lab's Main Chamber

MSFC Electrostatic Levitation (ESL) Laboratory

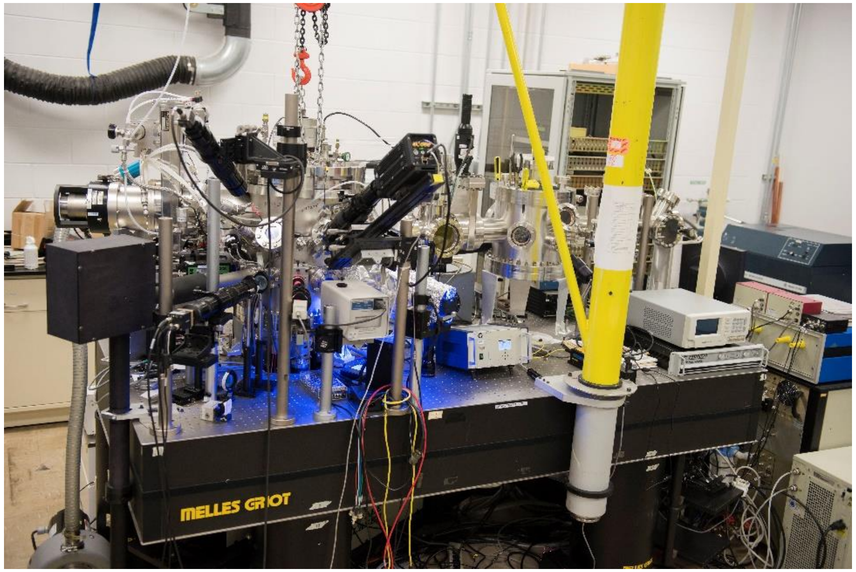
- Michael SanSoucie
- Jan Rogers
- Paul Craven
- Trudy Allen
- Glenn Fountain
- Curtis Bahr

Tufts University

- Postdoc Xiao Xiao
- PhD student Jannatun Nawer
- BS student Molly Pleskus
- Professor Douglas Matson

Professor Matson at MSFC

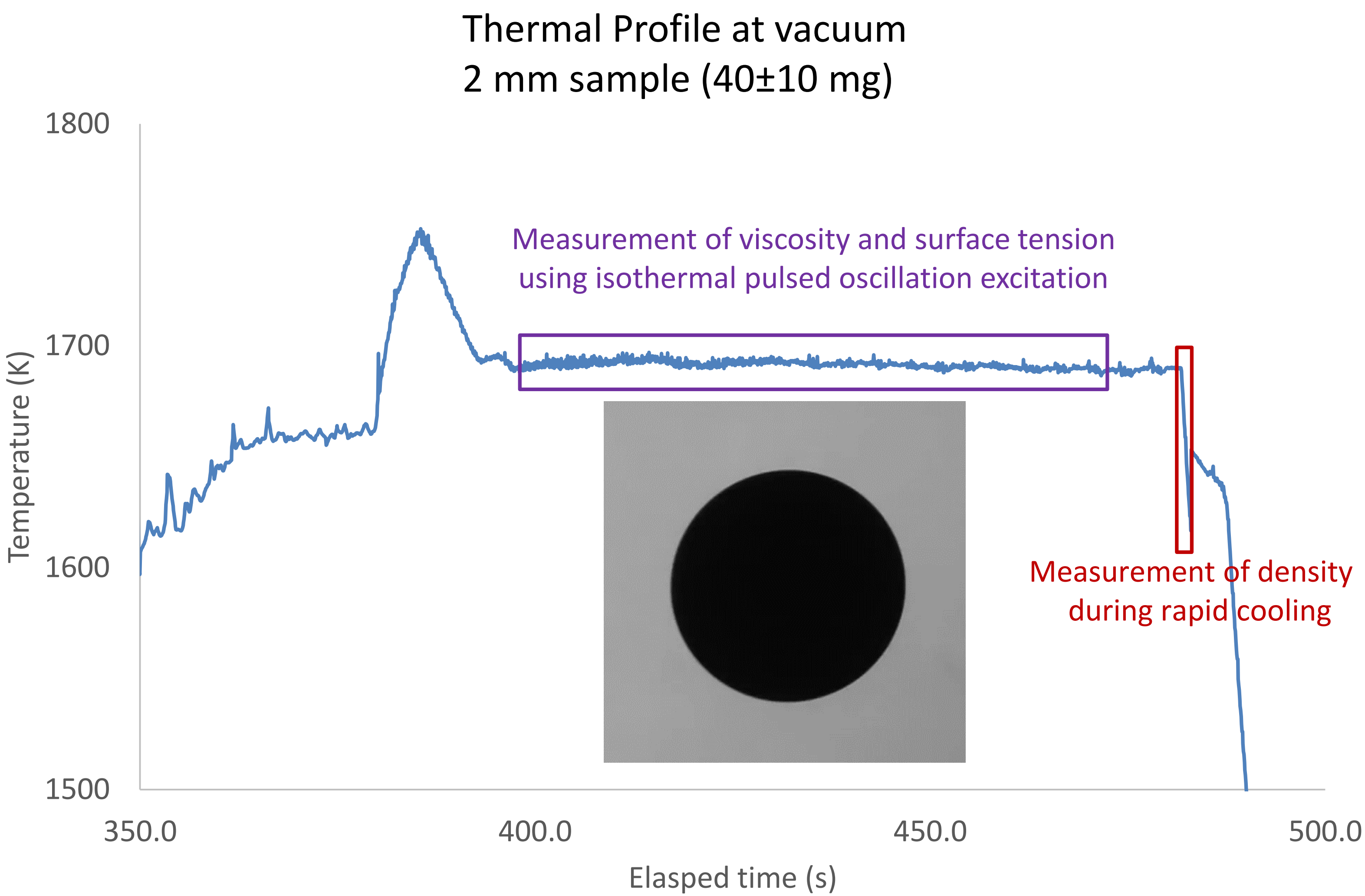
ESL Hardware



MSFC electrostatic levitator

- Electrostatic levitator
- High vacuum (~10^{-7} torr)
- 200W Nd:YAG heating laser
- Pyrometer for temperature measurement
- High-speed camera
  - 30fps @ 512x512 for density
  - 1000fps @ 512x512 for surface tension & viscosity
- Small sample size (~40 mg, ~2 mm DIA)
  - Spherical shape
  - Evaporation tracking required

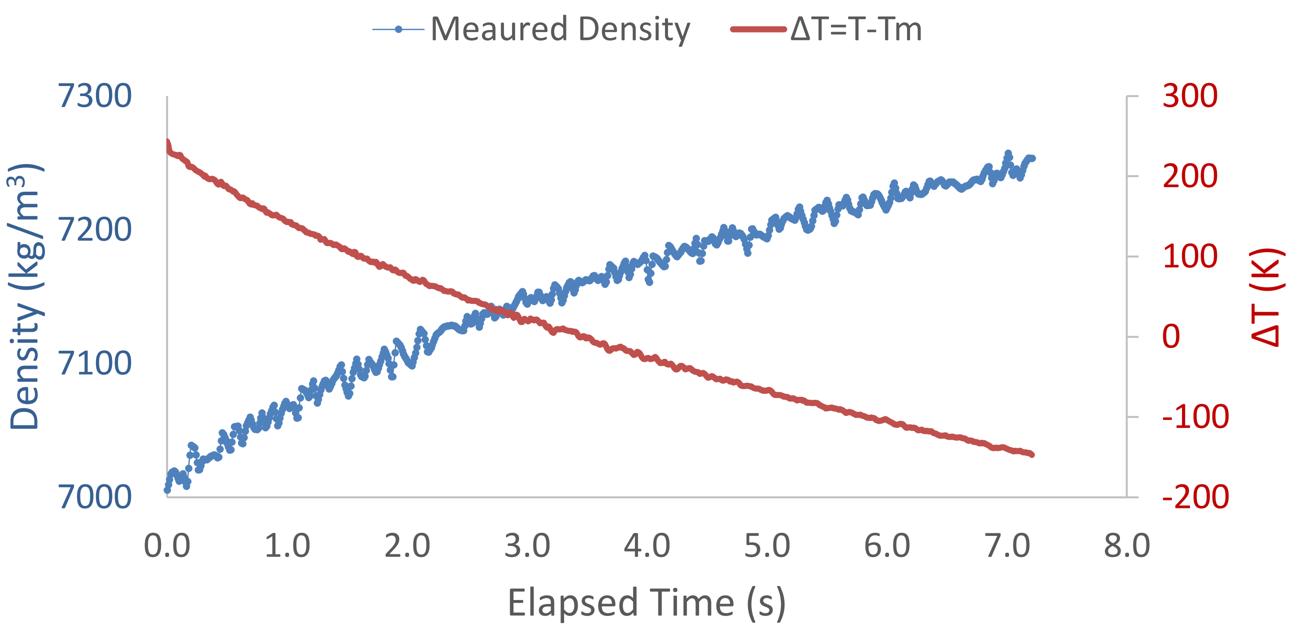
ESL Processing Conditions



Measurement of Density

Typical thermal cycle – rapid cooling after laser is turned off

- Pyrometer monitors temperature from superheated to undercooled condition
- Video monitors sample shape with 2-D image used to indicate 3D volume



$$\rho = \frac{mass}{vol}$$

$$vol = \frac{4\pi}{3}\left(\frac{A}{\pi}\right)^{\frac{3}{2}}$$

$$mass = m_o - \delta_m$$

$$\delta_m = \sum_{i=1}^{n}\left\{\int_0^t \frac{\alpha_i\left(\gamma_i\, c_i\, P_{v,i} - P_{ref}\right)A_t}{\sqrt{2\,\pi\, M_i\, R\, T}}\, dt\right\}$$

Key points to verify

- Does overall mass change? (yes, impacts density)
- Does this cause a composition shift? (no)

Total Evaporation

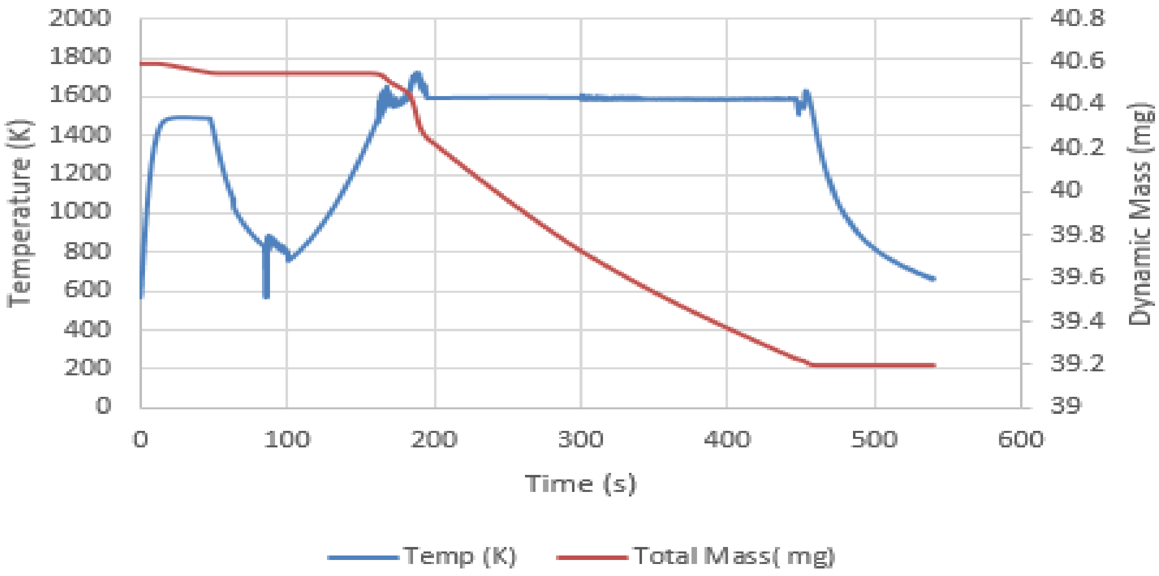
Langmuir Equation

$$\delta_m = \sum_{i=1}^{n} \left\{ \int_0^t \frac{\alpha_i \left(\gamma_i \, c_i \, P_{v,i} - \mathrm{P}_{\mathrm{ref}} \right) A_t}{\sqrt{2 \, \pi \, M_i \, R \, T}} \, dt \right\}$$

Total loss in ESL
δ_m = 3.4% overall

all constituents
$\delta_{m,i}$ < 1% in ESL

negligible
shift in
composition



Predicted total mass loss as a function of time at temperature

- At high temperature, mass is lost faster
- Analysis requires tracking of each chemical species

Observed composition shift negligible

ASTM E 1097-12 Direct current plasma emission spectroscopy
Luvak Inc., Boyleston MA 01505

Element	Initial Composition (%)	MAT-1254 Arc melted (%)	Mat 1256 Processed in ESL (%)	Mat 1257 Processed in ESL (%)
Al	5.69	6.31	5.98	6.04
Co	10	10.2	9.82	9.04
Cr	6.5	3.72	2.34	2.88
Ti	0.86	0.77	0.75	0.69

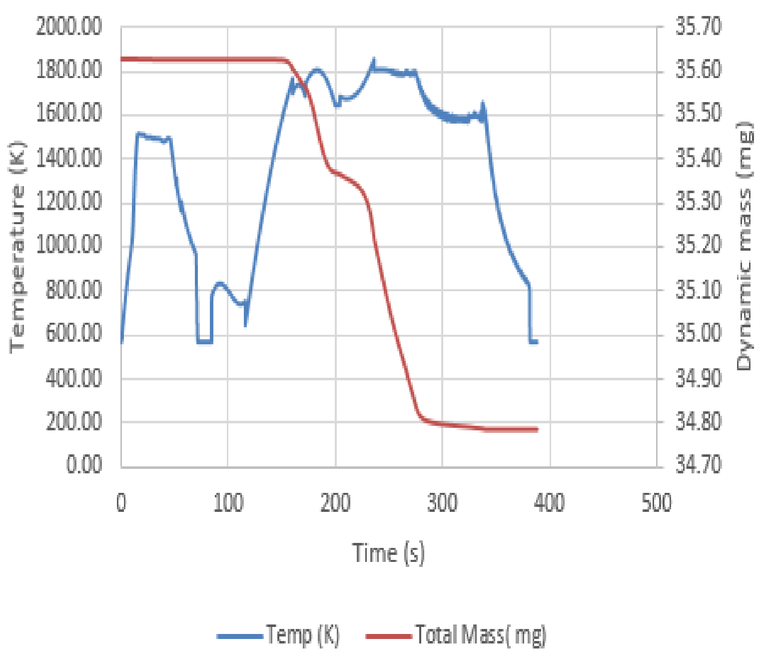
Model Results Tracking Each Constituent

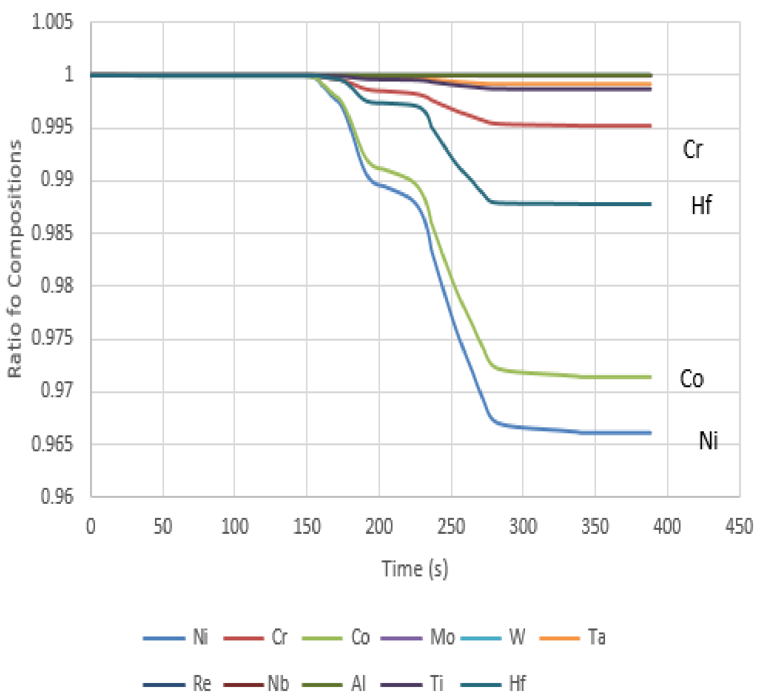
Pre arc melting: 35.69 mg
Post arc melt mass: 35.63 mg
Post ESL mass: 34.48 mg

Observed Evaporation: 1.15 mg
Predicted Evaporation: 0.84 mg

All constituents vary by less than 1% from their initial composition

Aluminum does not evaporate!

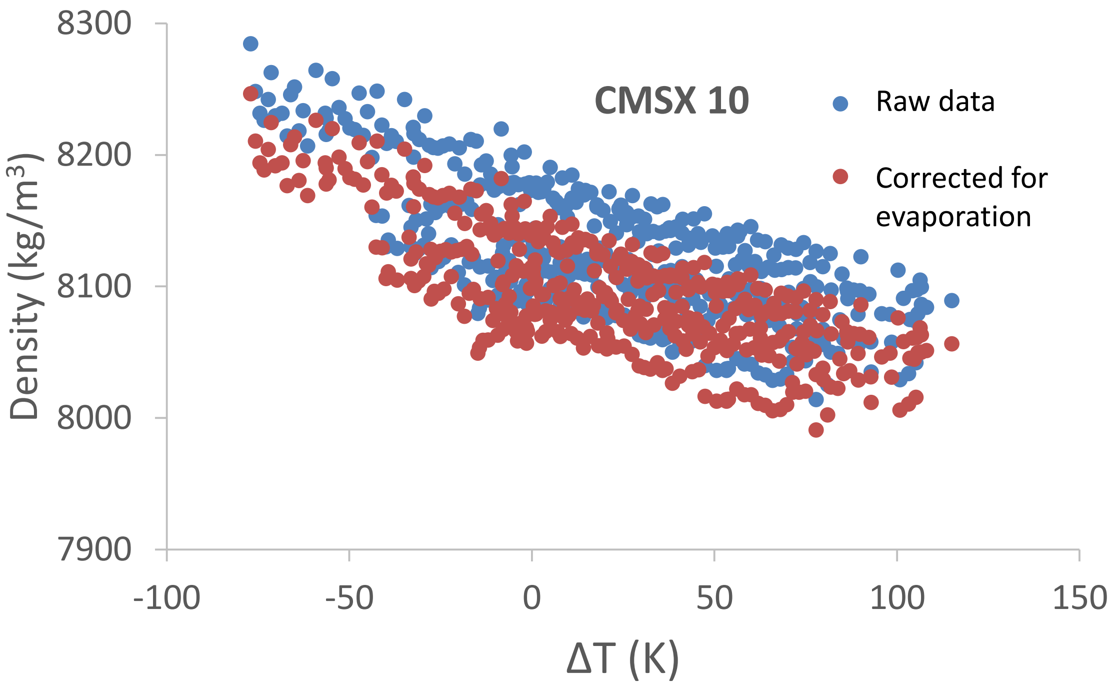




Correction for Evaporation

Langmuir Equation

$$\delta_m = \sum_{i=1}^{n} \left\{ \int_0^t \frac{\alpha_i \left(\gamma_i \, c_i \, P_{v,i} - \mathrm{P}_{\mathrm{ref}} \right) A_t}{\sqrt{2 \, \pi \, M_i \, R \, T}} \, dt \right\}$$



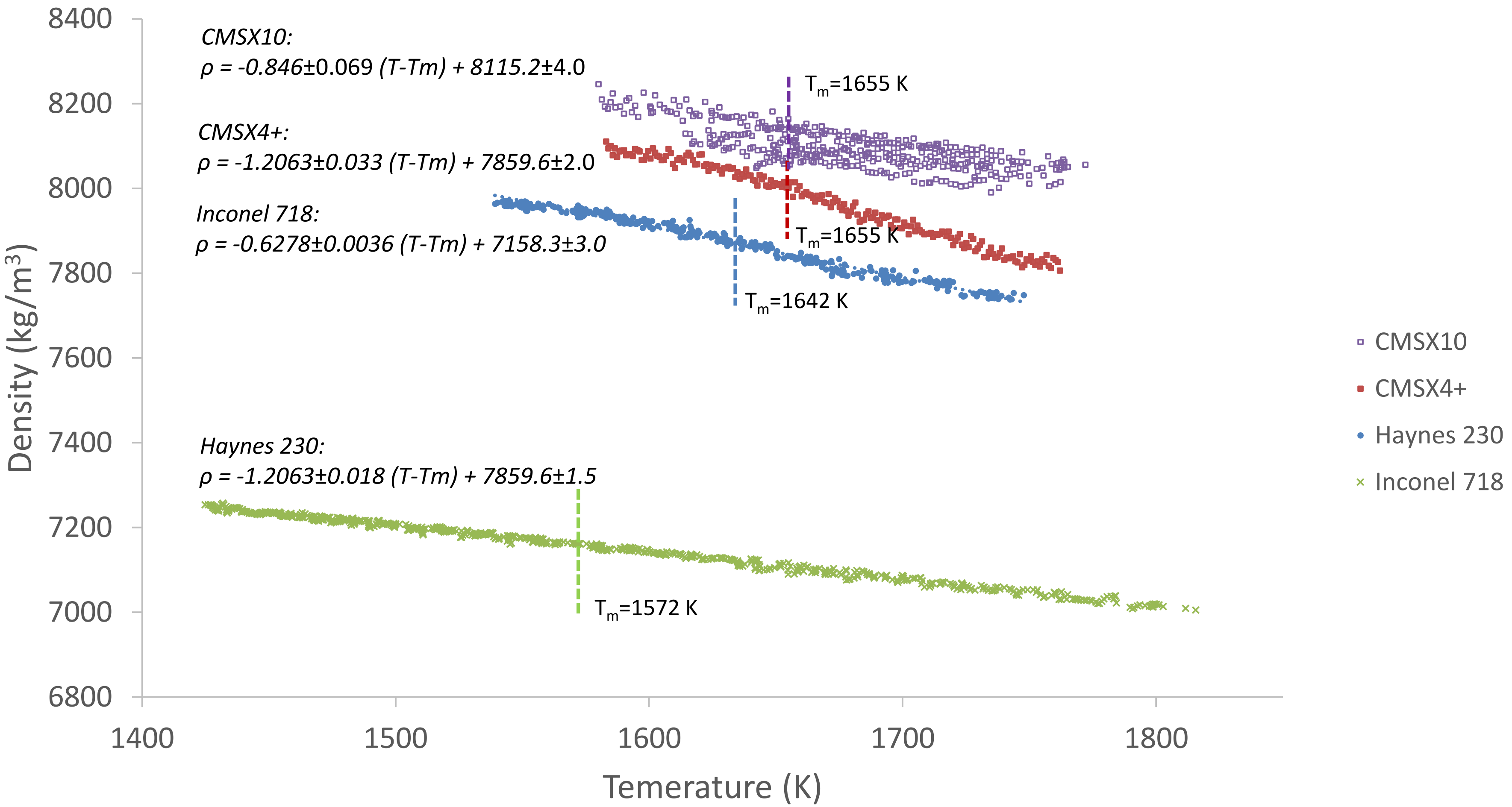
Evaporation has a significant influence on the accuracy of the measurement but only a small influence on precision.

This is because much of the evaporation occurs before the test is run during pre-melt processing.

$\rho_{uncorrected}$ = *-0.8707*±0.0798 *(T-Tm) + 8146.1*±4.0

$\rho_{corrected}$ = *-0.8460*±0.0690 *(T-T_m) + 8115.2*±4.0

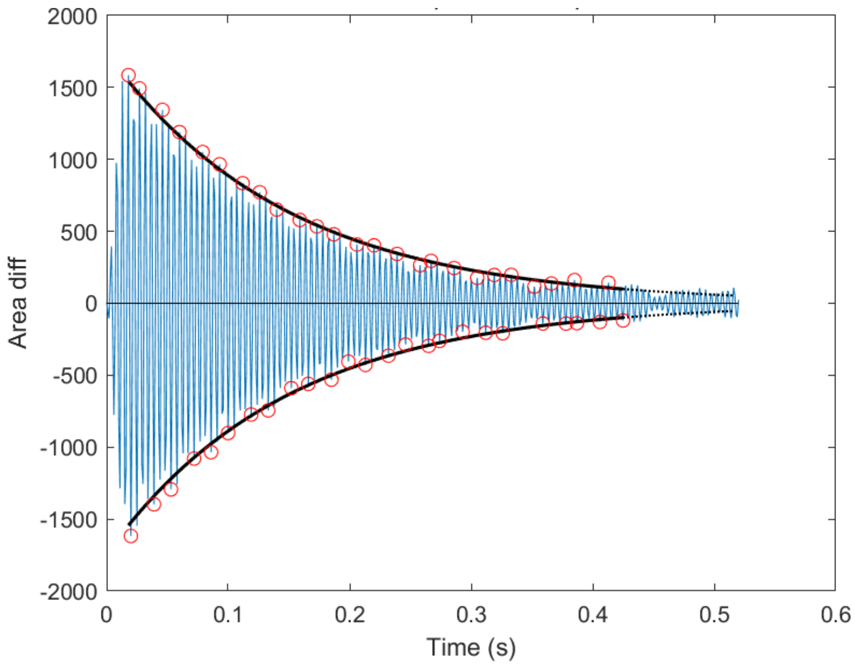
Density



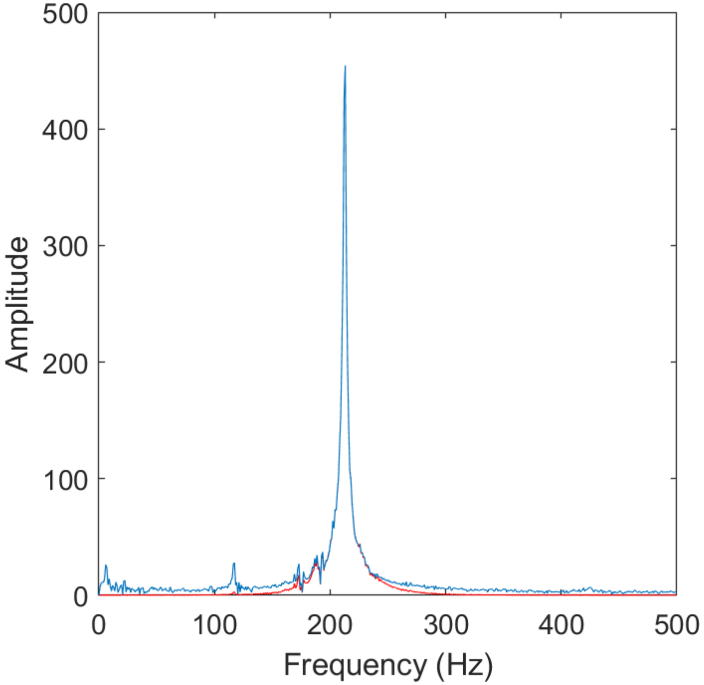
CMSX10:
ρ = -0.846±0.069 (T-Tm) + 8115.2±4.0
CMSX4+:
ρ = -1.2063±0.033 (T-Tm) + 7859.6±2.0
Inconel 718:
ρ = -0.6278±0.0036 (T-Tm) + 7158.3±3.0
Haynes 230:
ρ = -1.2063±0.018 (T-Tm) + 7859.6±1.5
T_m=1655 K
T_m=1655 K
T_m=1642 K
T_m=1572 K
8400
8200
8000
7800
7600
7400
7200
7000
6800
Density (kg/m^3)
1400
1500
1600
1700
1800
Temerature (K)
CMSX10
CMSX4+
Haynes 230
Inconel 718

Pulsed Oscillation Testing

Damping Analysis



FFT Analysis



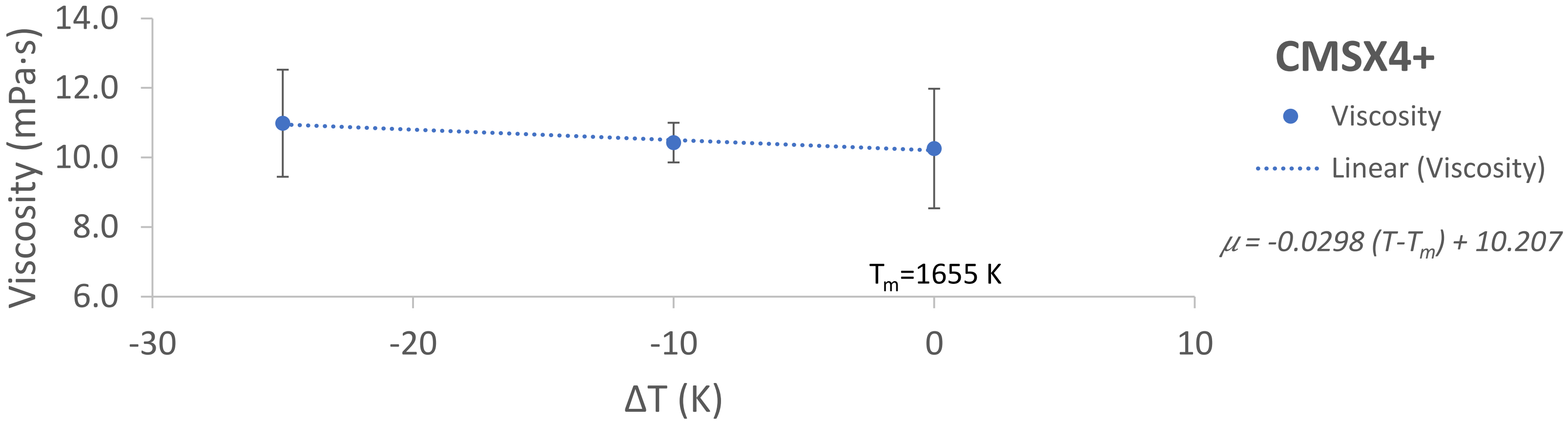
Viscosity

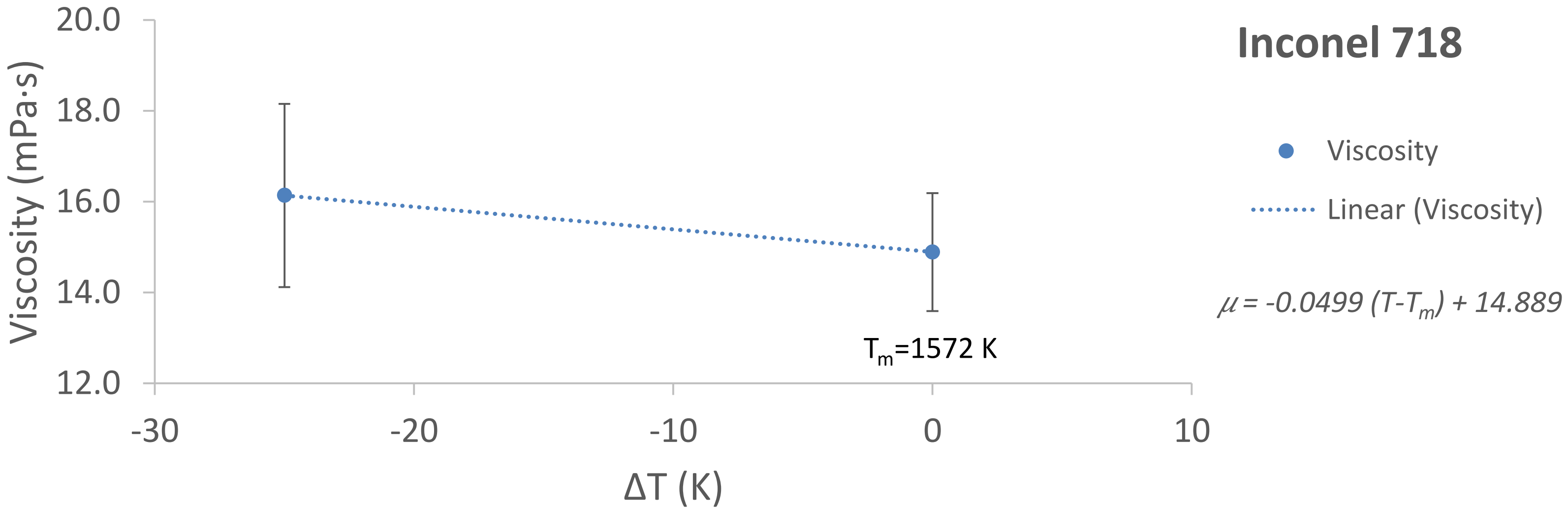
$$\mu = \frac{\rho R_0^2}{5\tau}$$

Surface Tension

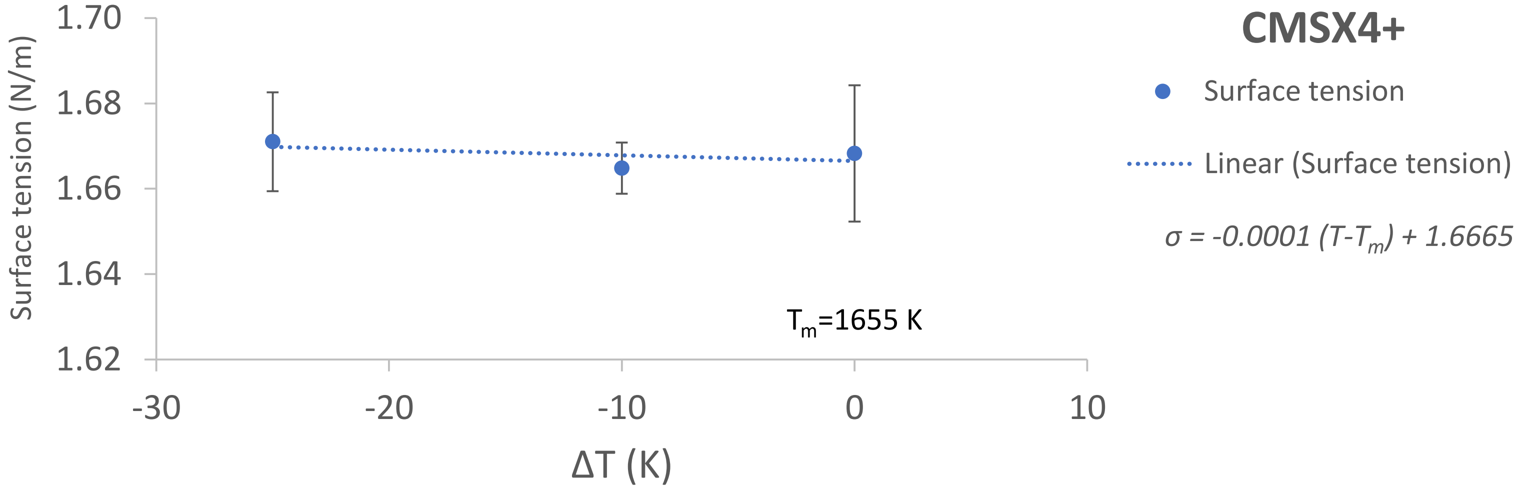
$$\sigma = \frac{3}{8}\pi m f^2$$

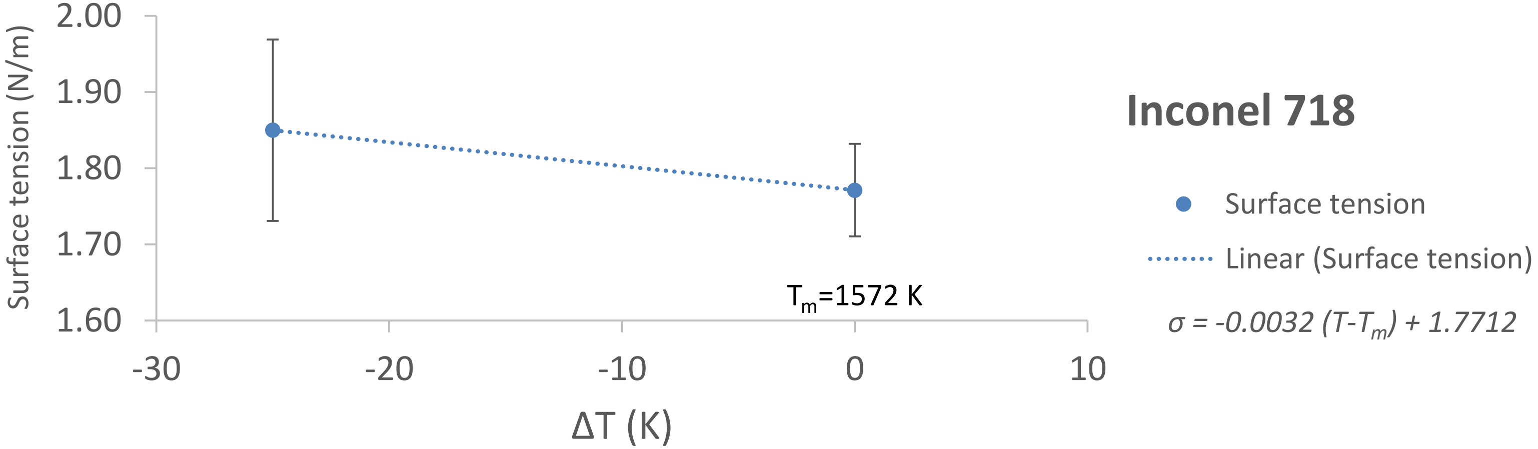
Viscosity Results





Surface Tension Results





Conclusions

- Due to small sample sizes
  - Samples are nearly spherical for better quality raw data.
  - Evaporation must be tracked since sample size changes
    - this impacts density, surface tension and viscosity measurement.
  - Tracking of individual species shows composition shifts during testing are insignificant.
- Density evaluations show high technique accuracy when corrected for evaporative losses during pre-processing; precision is only slightly improved.
- More work is required to obtain an understanding of the statistics for reporting surface tension and viscosity results as a function of temperature.

Future Work

- Expand the range of alloys investigated by initiating study of *Additive Manufacturing* alloys.
- Experiments on the Japan Aerospace eXploration Agency (JAXA) Electrostatic Levitation Furnace (ELF) to investigate and manage statistical error to improve both accuracy and precision of each measurement.
- Continue to develop new techniques to track evaporation to minimize and control the potential for composition shifts during processing.

Acknowledgments

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