Metal Freeform Additive Manufacturing through Extrusion of Semisolid Alloy Slurries

5th WMRIF International Workshop for Young Scientists

November 8, 2016

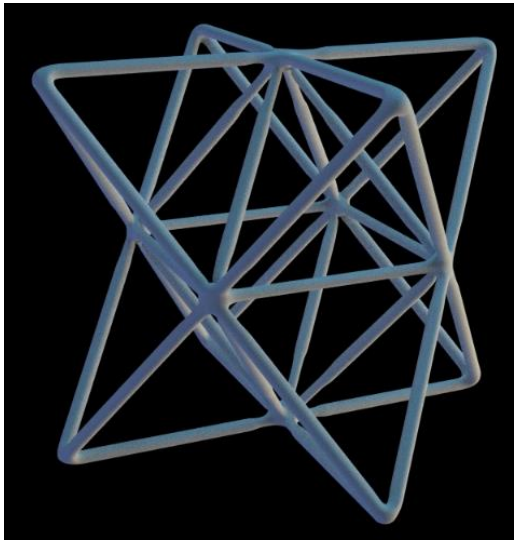
Andrew Pascall

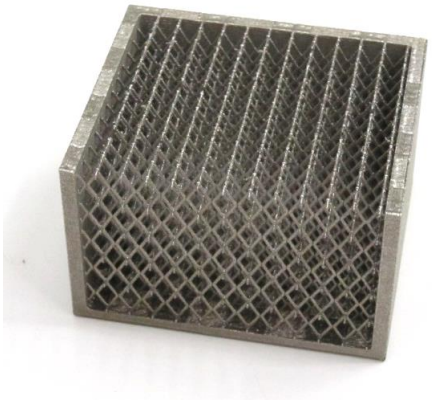
LLNL-PRES-707921

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Additive manufacturing (AM) allows you to go directly from design to a part



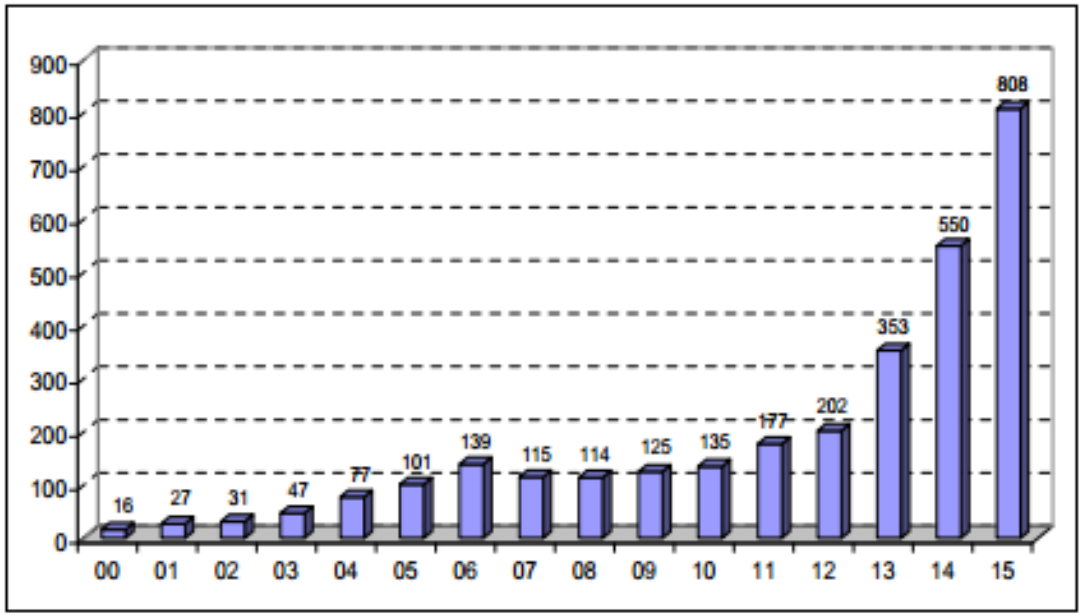


Advantages:

- Can produce complex parts
- Eliminate tooling & fixturing
- Simplify supply chain
- Reduce innovation time
- Part-to-part customization
- Smaller factory footprint

Interest in Metal AM is increasing

Metal AM machine unit sales

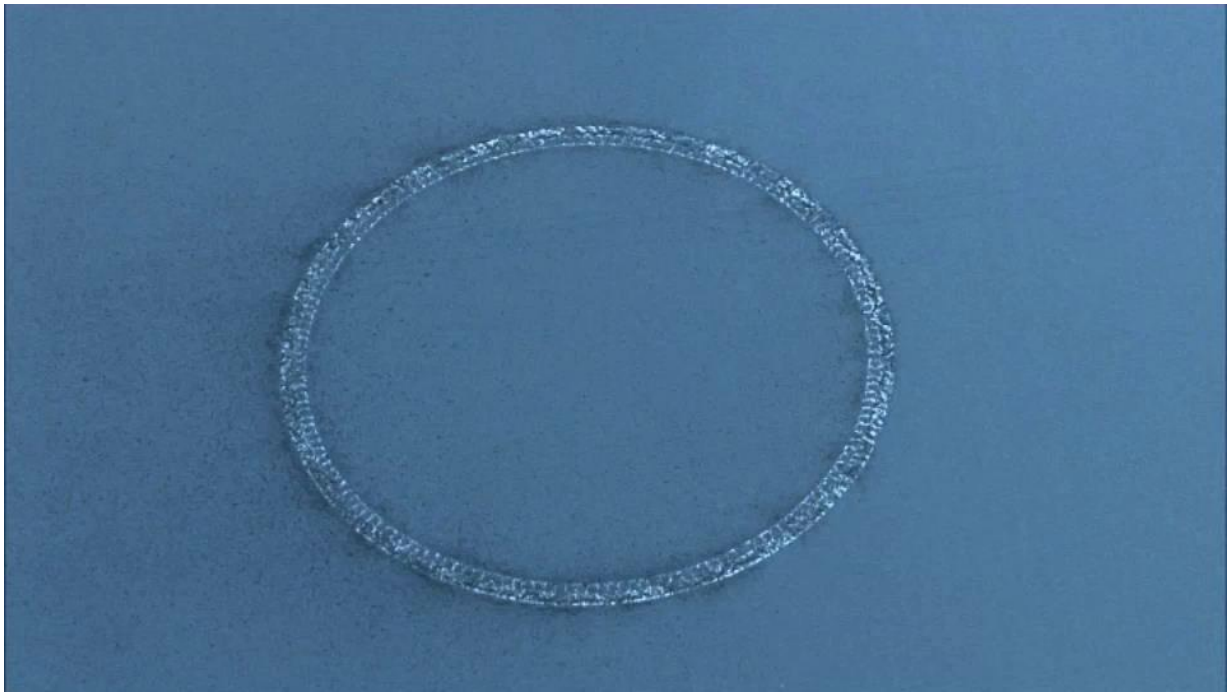


Source: Wohlers Associates, Inc.

- General Electric hopes to make 100K AM parts/yr by 2020.
- Already have printers producing FAA approved fuel injectors

Selective Laser Melting is the Leading Metal AM Technique

Selective Laser Melting (SLM) uses a rastered laser beam to locally melt metal powder

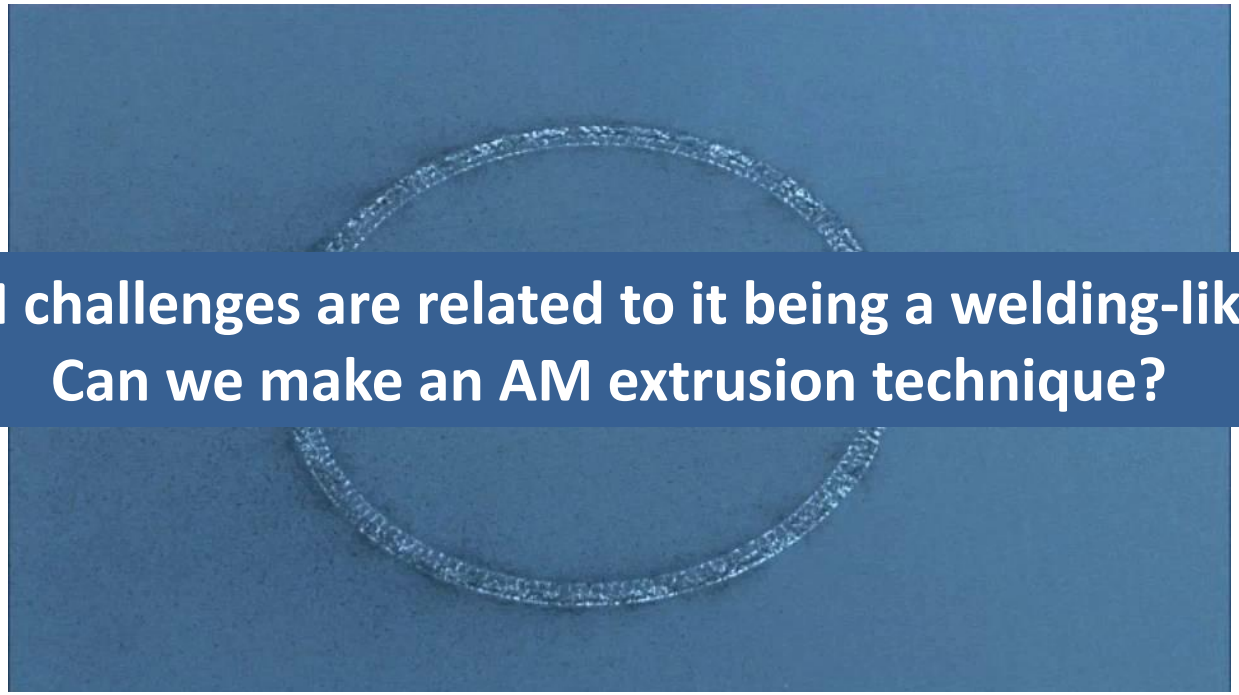


Challenges:

- Residual stresses
- Voids and pores
- Oxide Inclusions
- Surface finish
- Geometric tolerances

Selective Laser Melting is the Leading Metal AM Technique

Selective Laser Melting (SLM) uses a rastered laser beam to locally melt metal powder

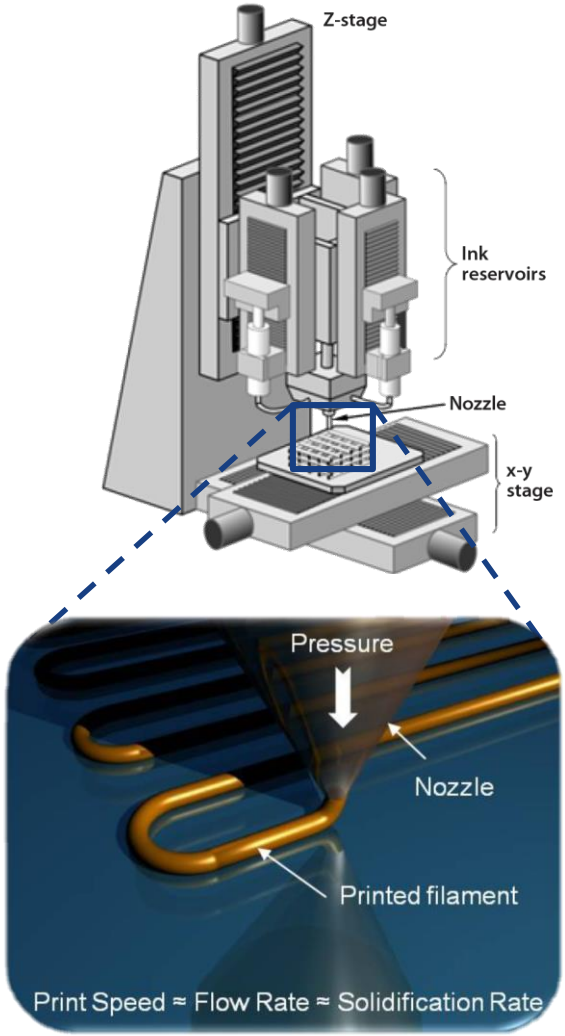


Many SLM challenges are related to it being a welding-like process
Can we make an AM extrusion technique?

Challenges:

- Residual stresses
- Voids and pores
- Oxide Inclusions
- Surface finish
- Geometric tolerances

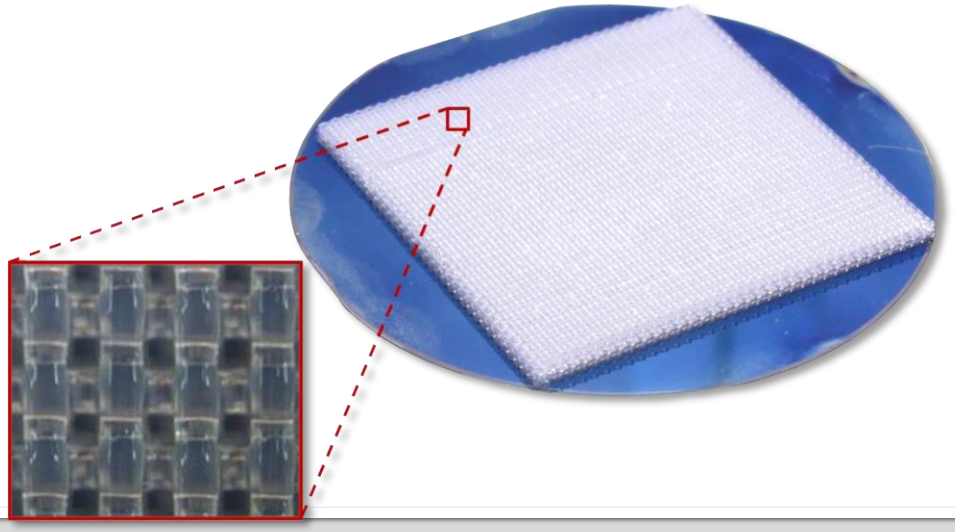
LLNL has experience with "Direct Ink Writing" casting techniques



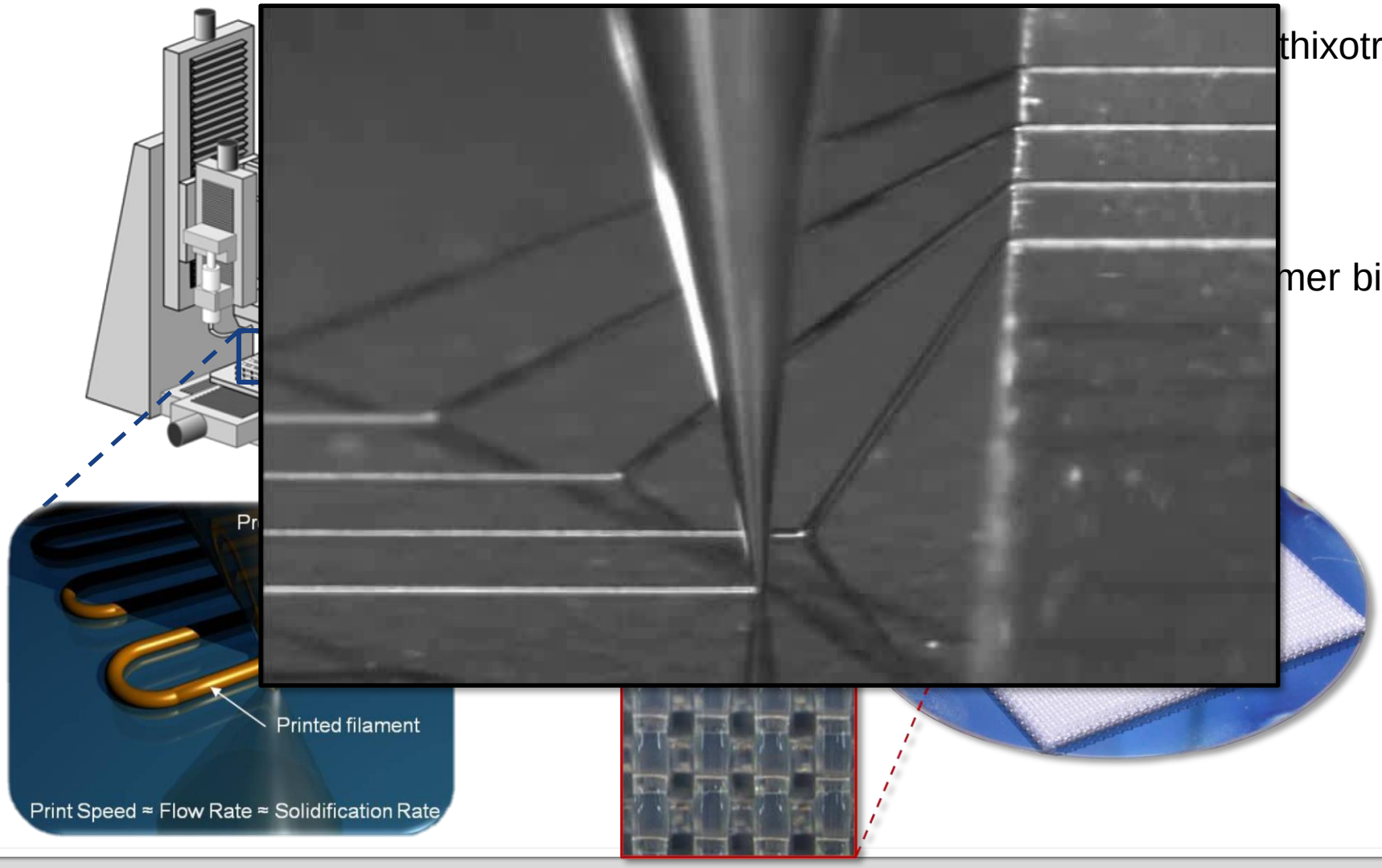
Direct Ink Writing extrudes a shear-thinning, thixotropic ink into a filament from a nozzle

Limitations:

- Low temperature
- Inks are generally particles mixed with polymer binders
- Ink must have correct rheology



We have experience with “Direct Ink Writing” extrusion techniques

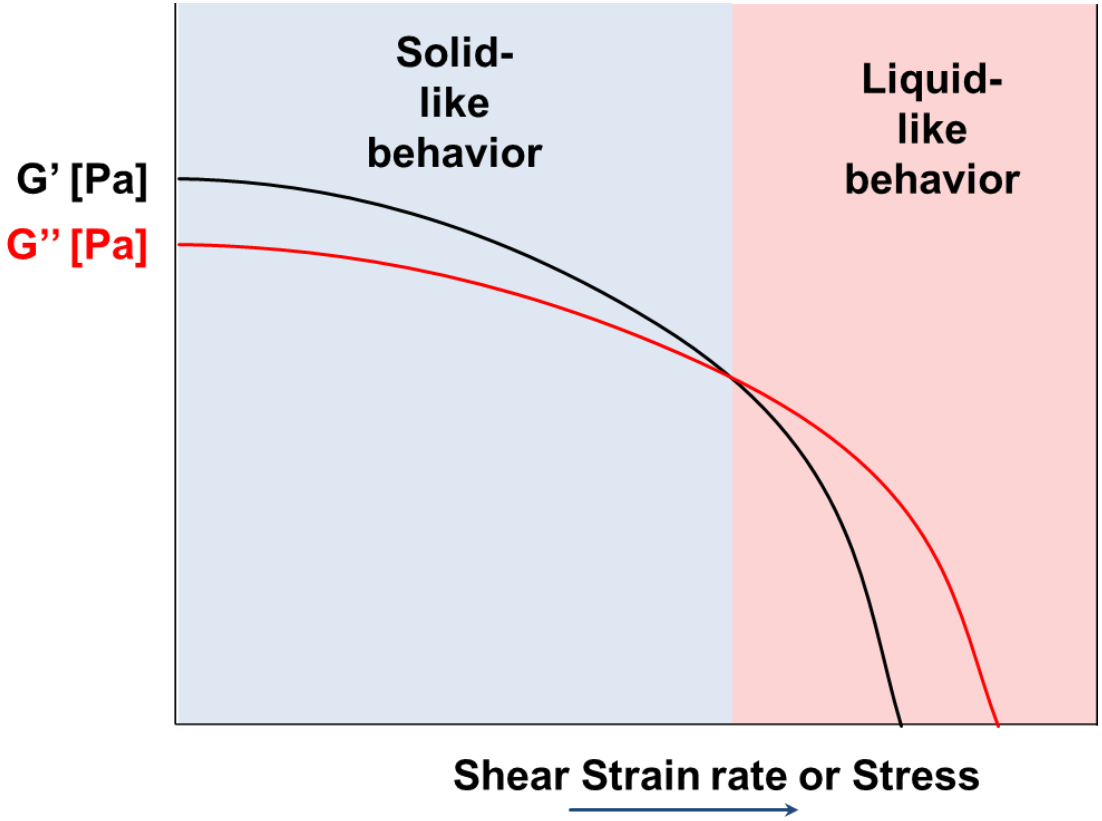


thixotropic

mer binders

Increasing shear stress in some fluids changes the flow behavior from solid-like to liquid-like

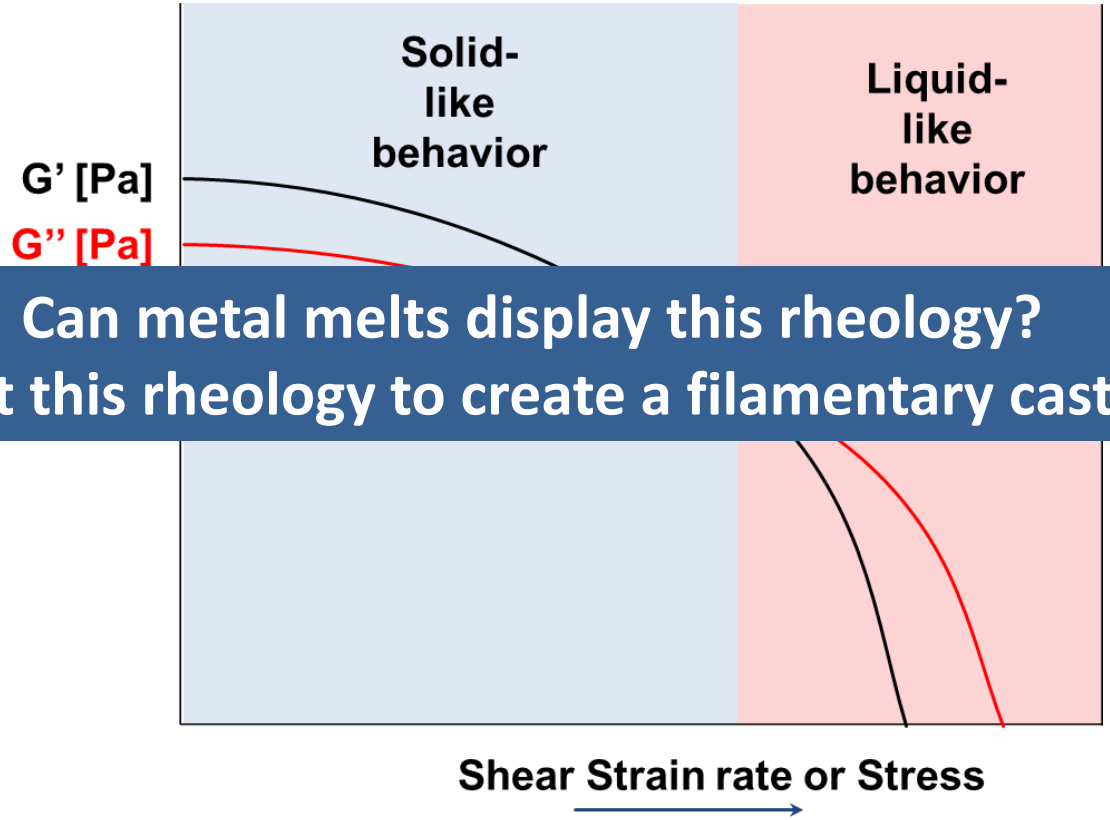
G': Elastic or Storage Shear Modulus
G": Viscous or Loss Shear Modulus



This rheology can be associated with particle loaded liquids

Increasing shear stress in some fluids changes the flow behavior from solid-like to liquid-like

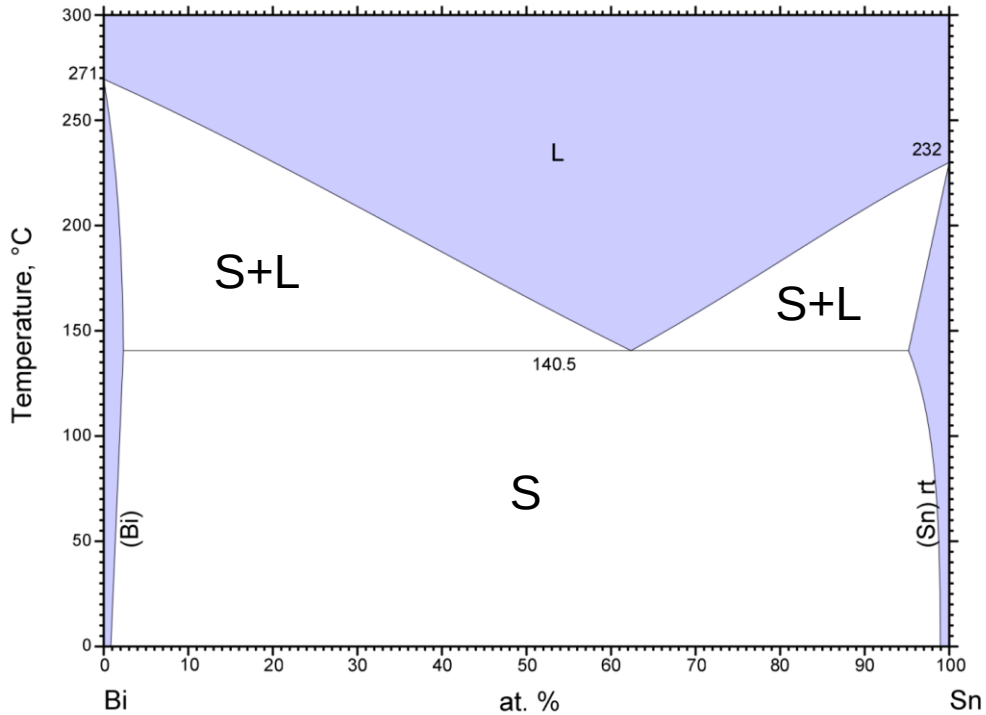
G': Elastic or Storage Shear Modulus
G": Viscous or Loss Shear Modulus



Can metal melts display this rheology?
Can we exploit this rheology to create a filamentary casting process?

This rheology can be associated with particle loaded liquids

Bismuth-tin alloy as a model system



We chose Bi-Sn as a model system:

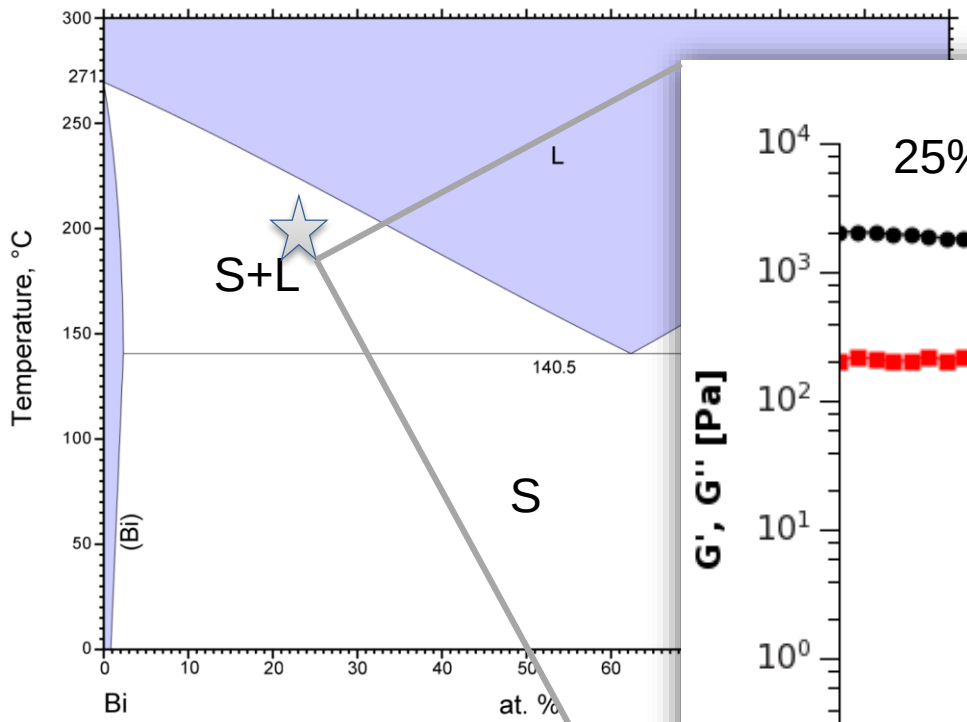
- Non-toxic
- Simple eutectic
- Low melting

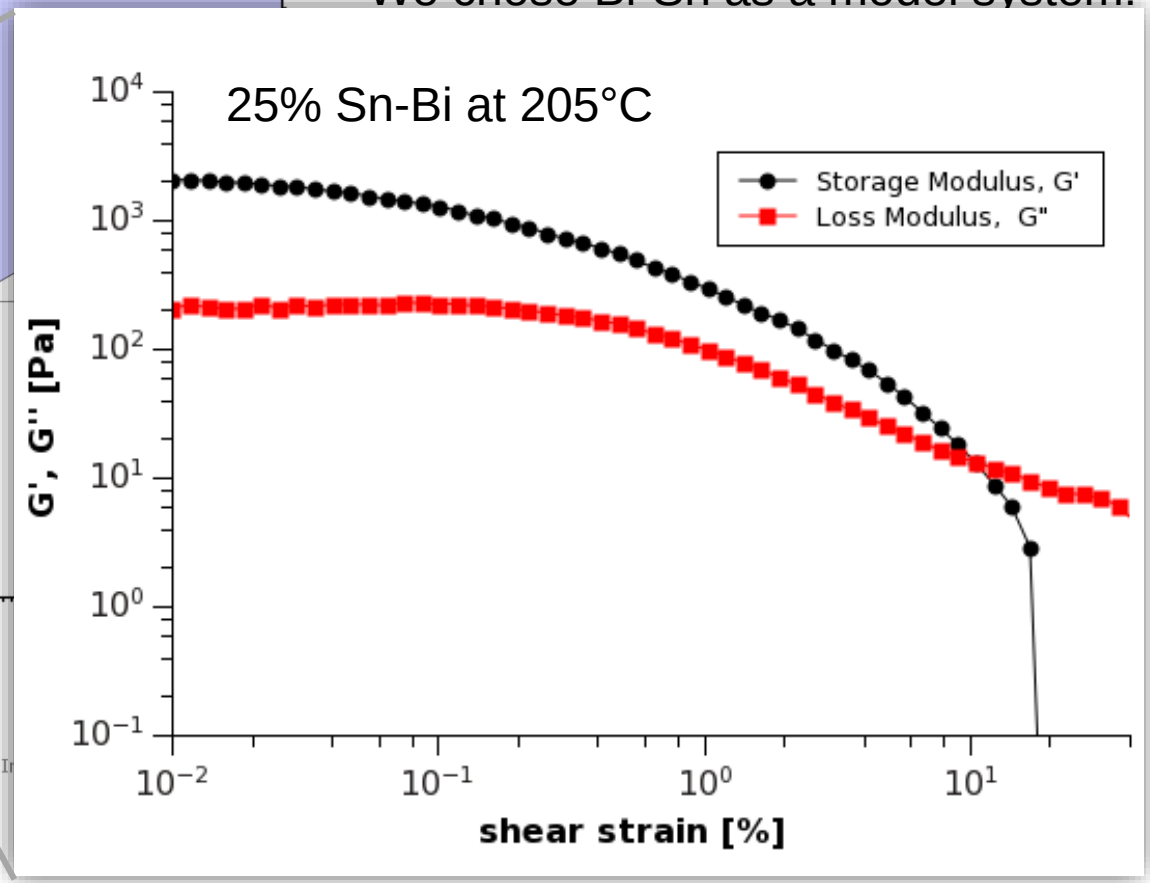
Hypothesis:
The semisolid region might have the right rheology

To our knowledge, no one has explored the oscillatory rheology of metals.

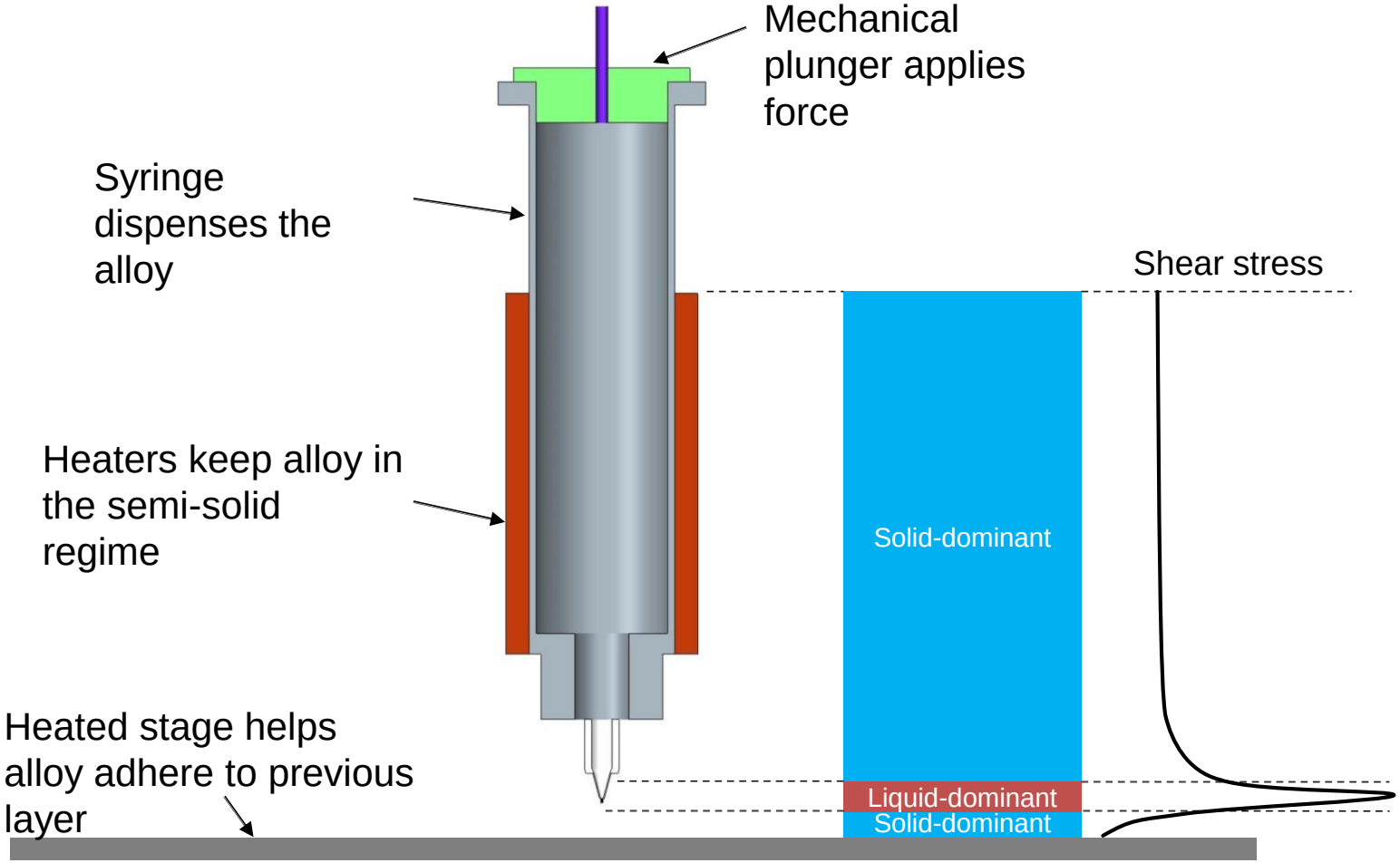
Bismuth-tin alloy as a model system

We chose Bi-Sn as a model system:

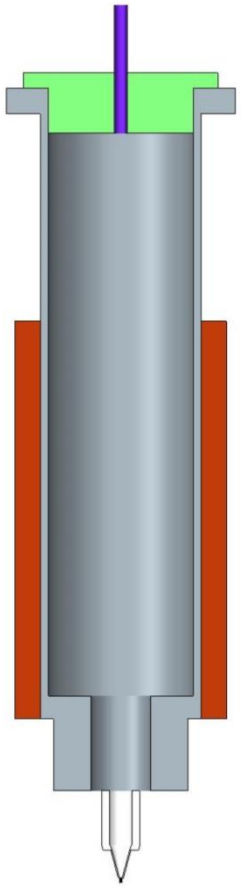




Initial dispenser design

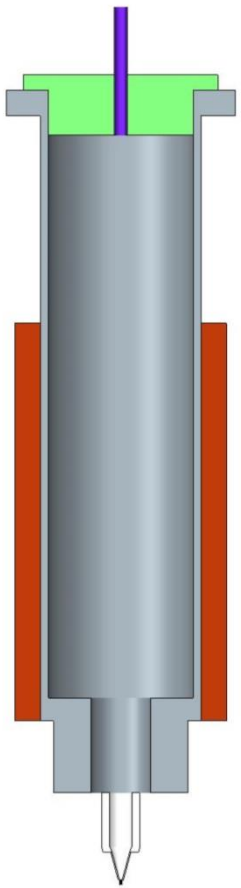


Simple design is not adequate

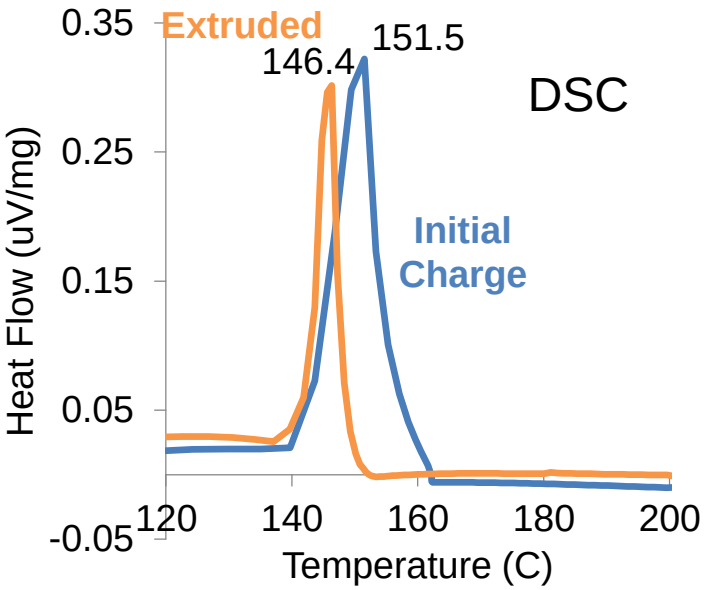


- Without stirring, only liquid drops would extrude from 500 µm nozzle
- Drops are a different composition
- **Hypothesis**: Dendrites forming in nozzle, filtering liquid

Simple design is not adequate



- Without stirring, only liquid drops would extrude from 500 µm nozzle
- Drops are a different composition
- **Hypothesis**: Dendrites forming in nozzle, filtering liquid

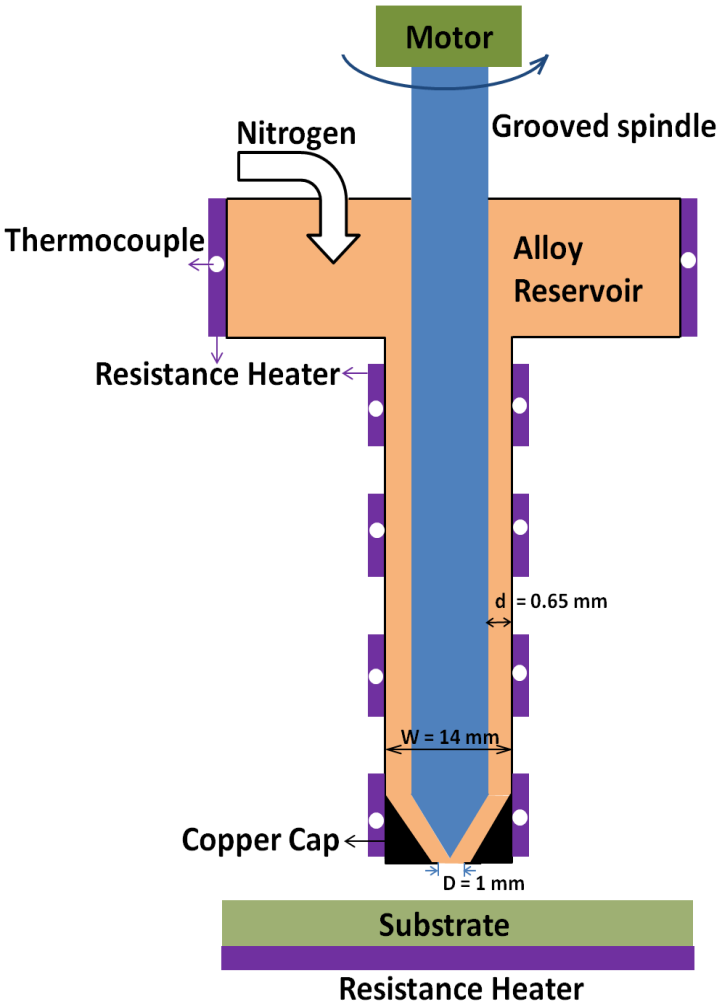


Liquidus temp shifted after printing

Dendrites are 100s of microns long!

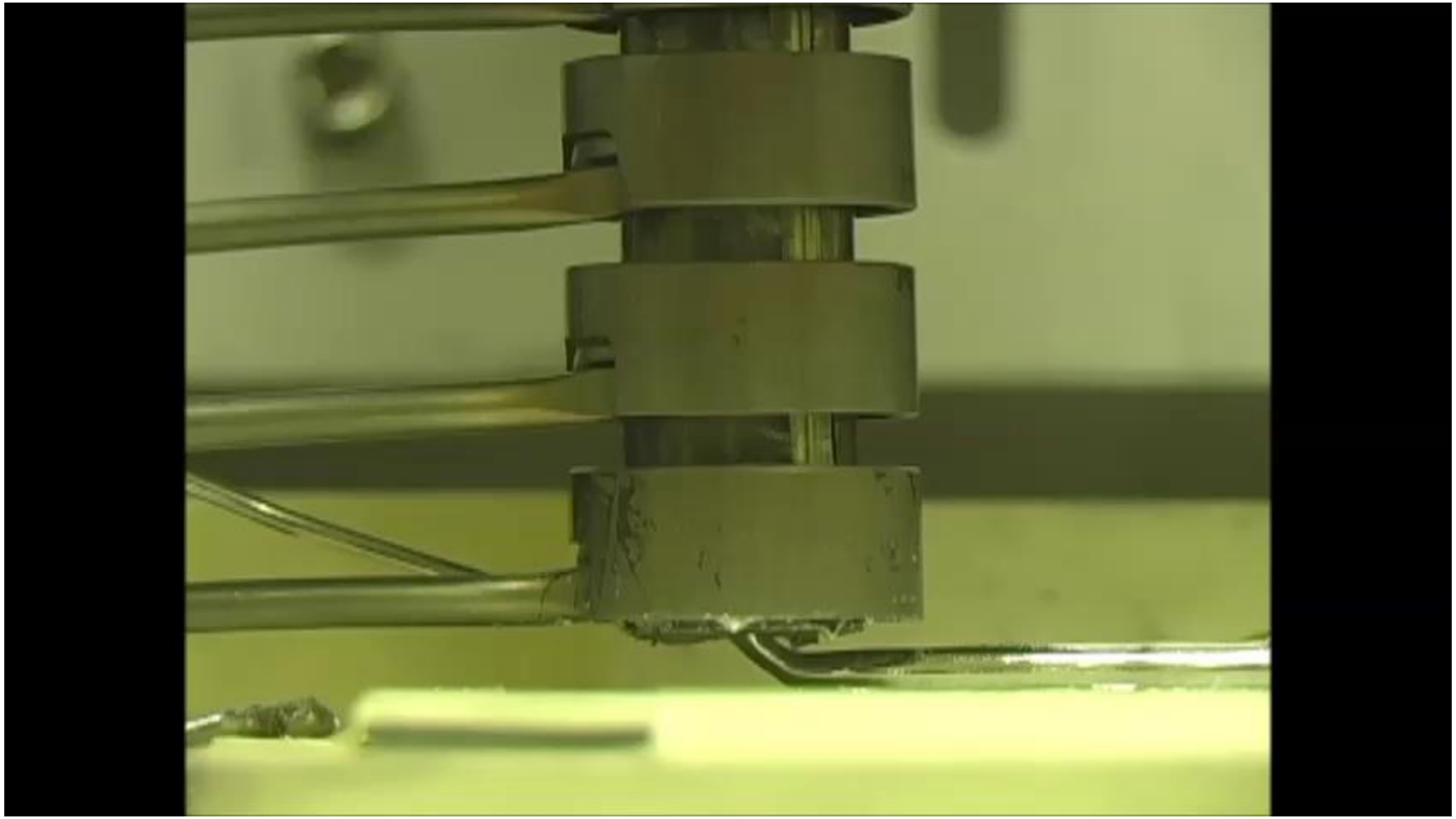
BiSn 75at% Bi - Filament 1 - Thin Section ~5mm from Thick - 50x

Next generation dispenser allows stirring

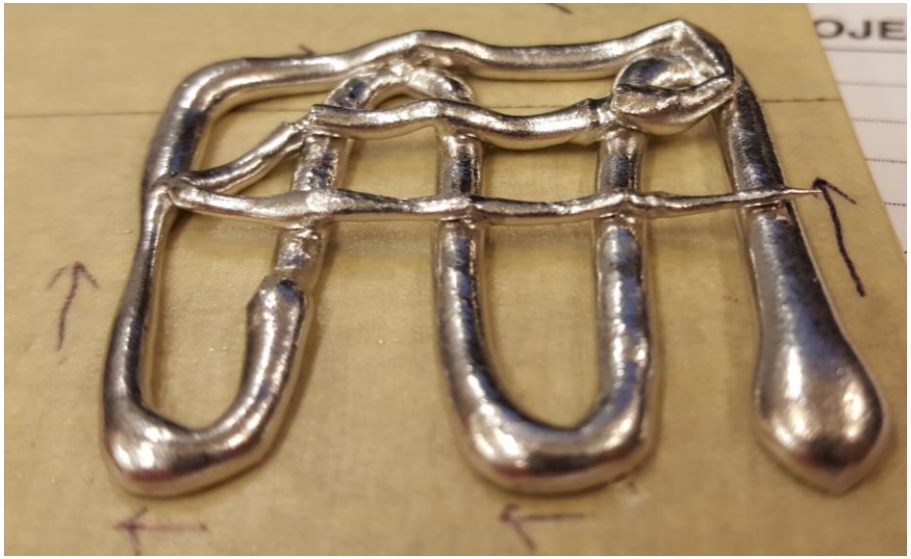


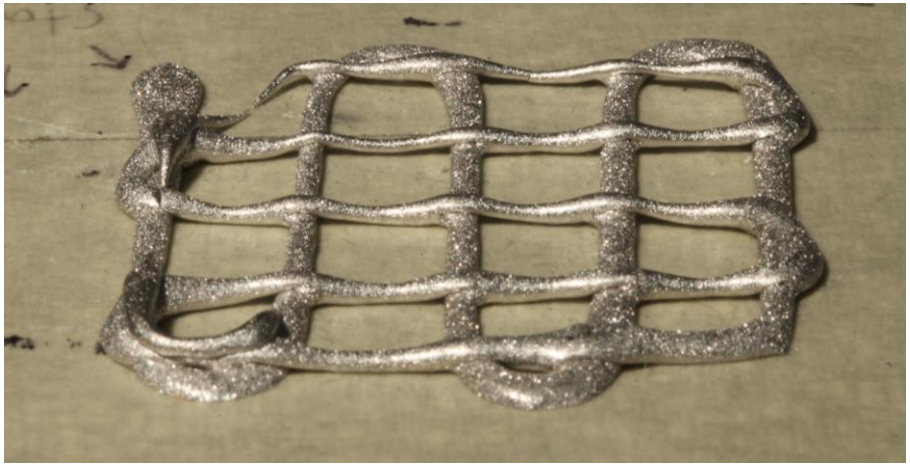
Based off similar design by Rice, et al. (2000)

Direct Metal Writing of Bi-Sn filaments



Extruded filaments show ability to self-support over a range of temperatures



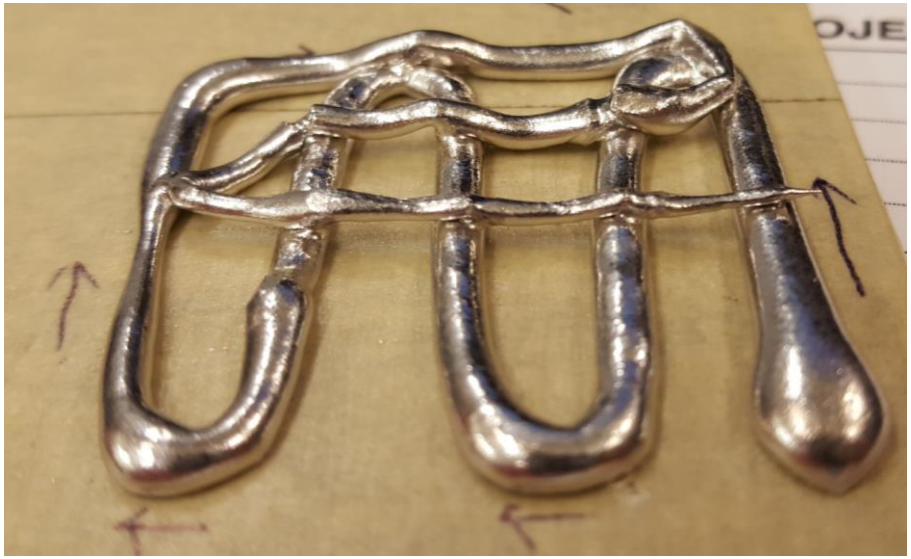


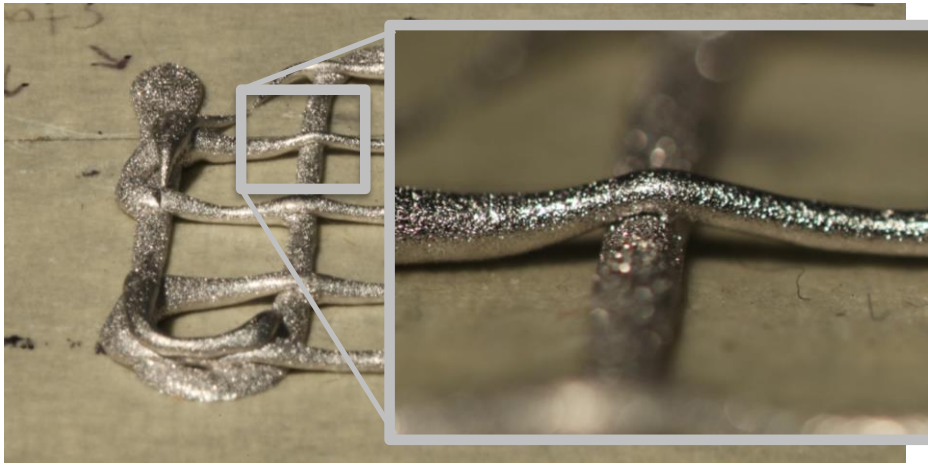
Printed at 210°C
14% solids

Printed at 200°C
28% solids

At 220°C, drops extrude.
At 190°C, filament does not extrude.

Extruded filaments show ability to self-support over a range of temperatures



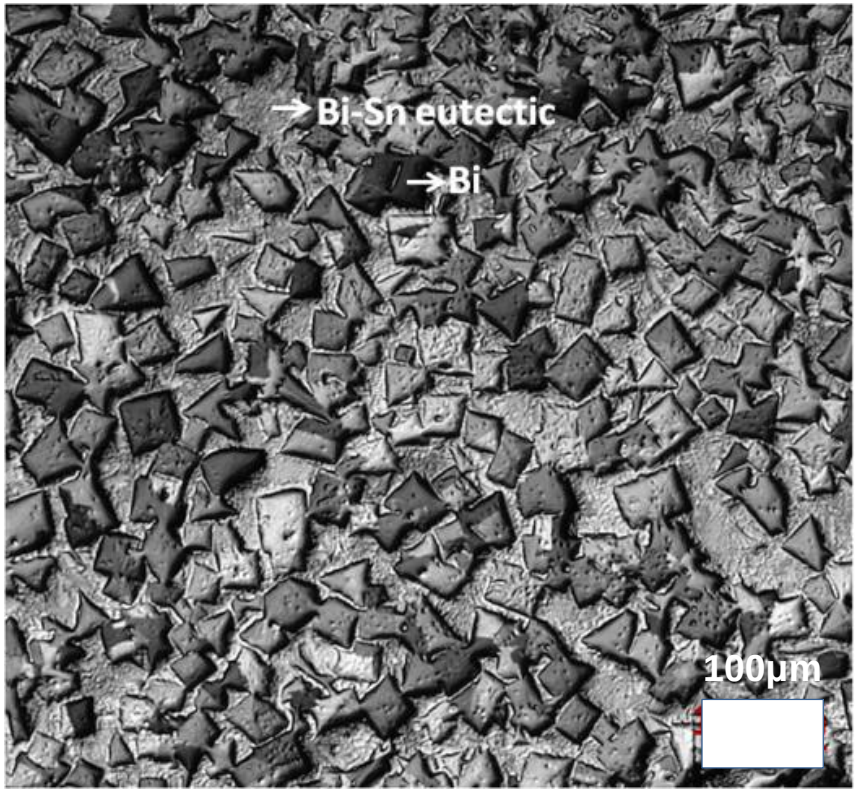


Printed at 210°C
14% solids

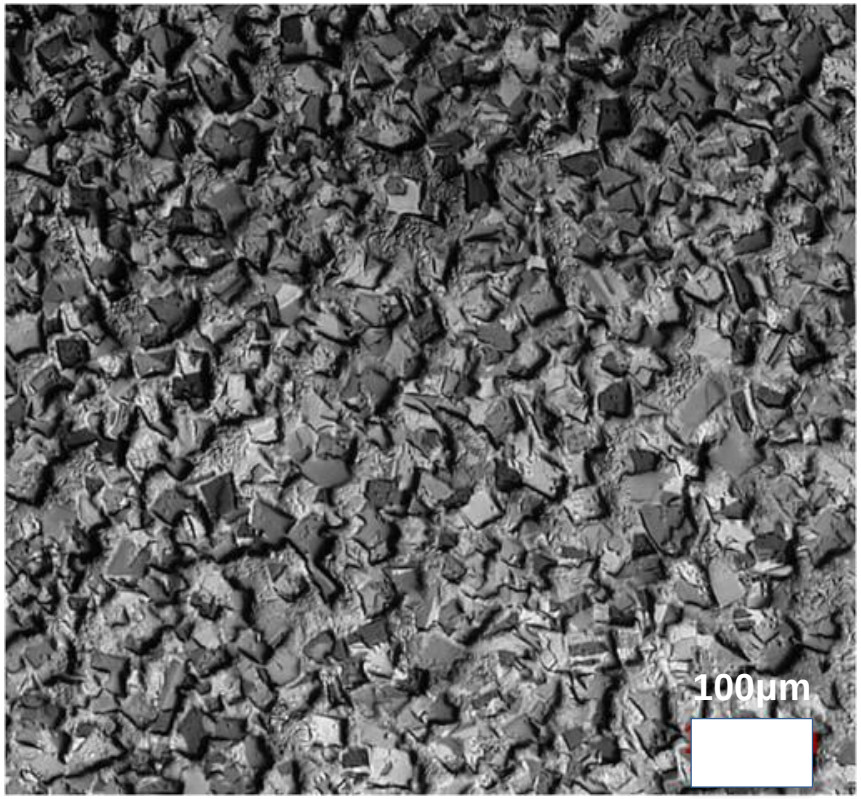
Printed at 200°C
28% solids

At 220°C, drops extrude.
At 190°C, filament does not extrude.

Extruded filaments show ability to self-support



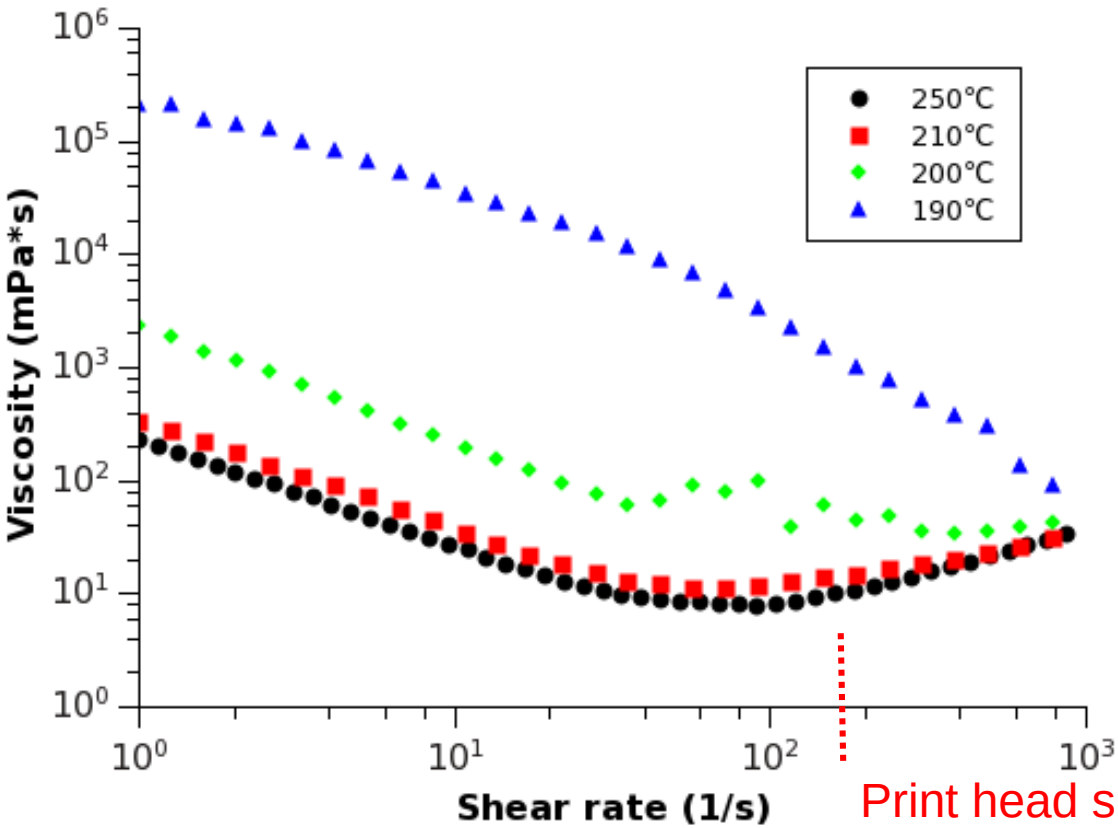
Printed at 210°C
14% solids



Printed at 200°C
28% solids

High solids, fine grained microstructure key to self-supporting behavior

Viscosity jumps 100x over 10°C



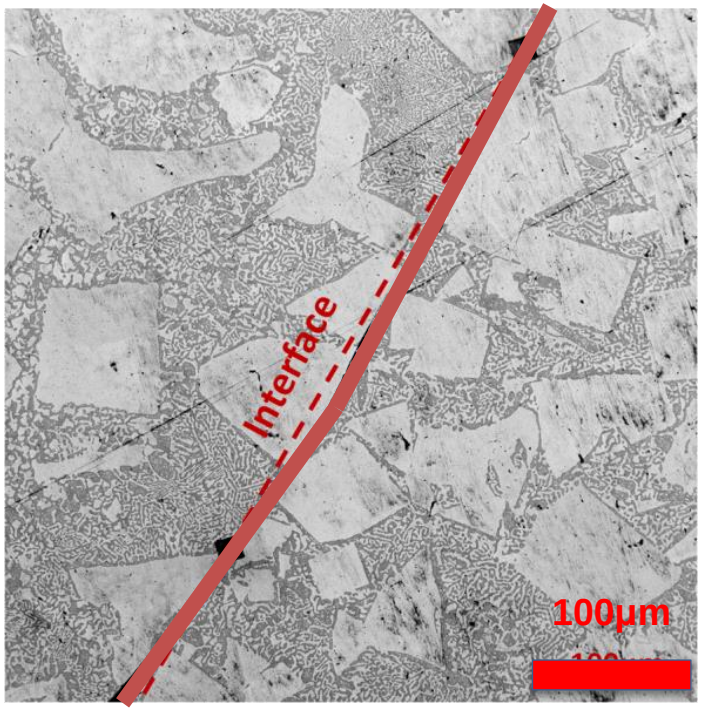
25at%Sn-Bi alloy

Temperature (°C)	Equilibrium Solid Fraction
250	0
210	0.14
200	0.28
190	0.33

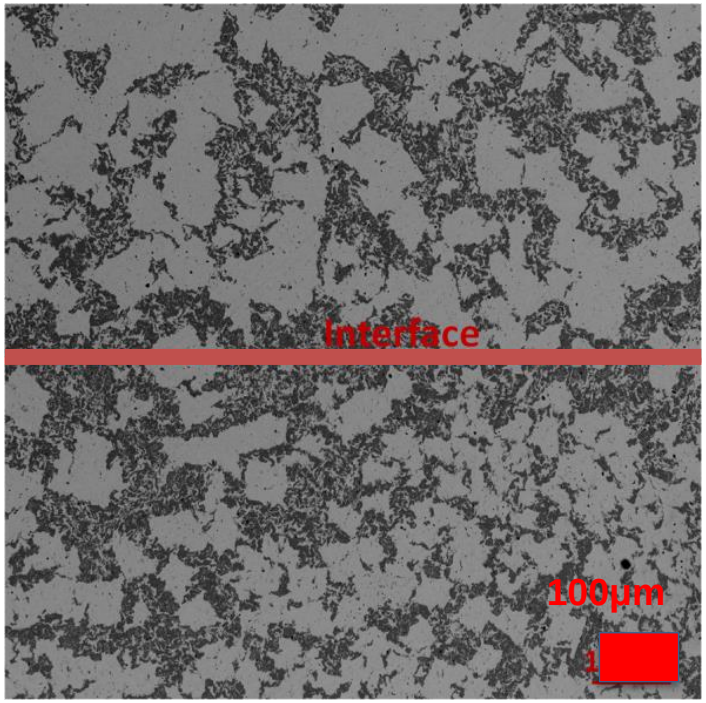
Liquidus Temperature: 220°C
Solidus Temperature : 140°C

The right microstructure is critical for printing
Microstructure is highly temperature dependent

Heating the build platform is important for interlayer bonding

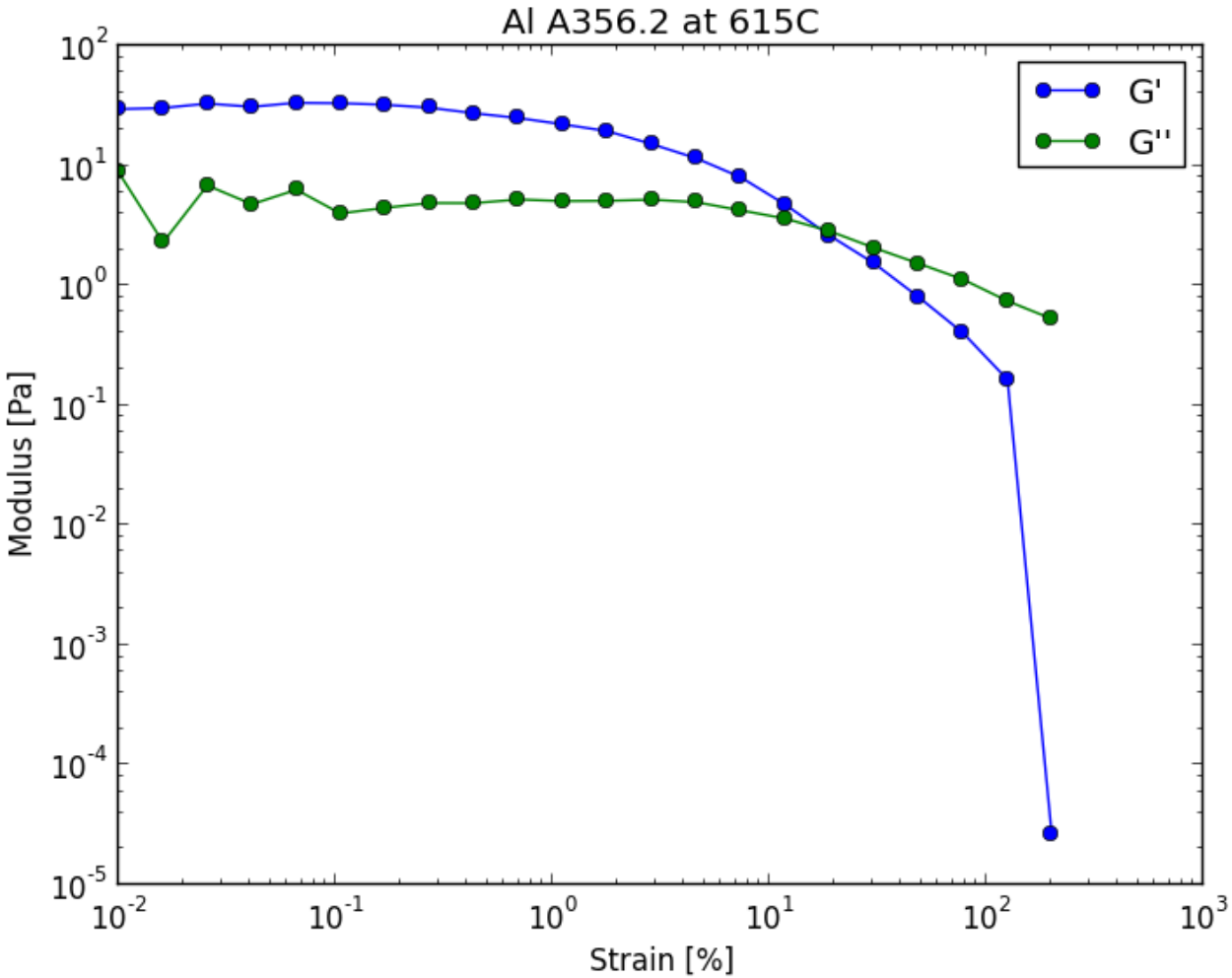


Printing at 200°C
No stage heating

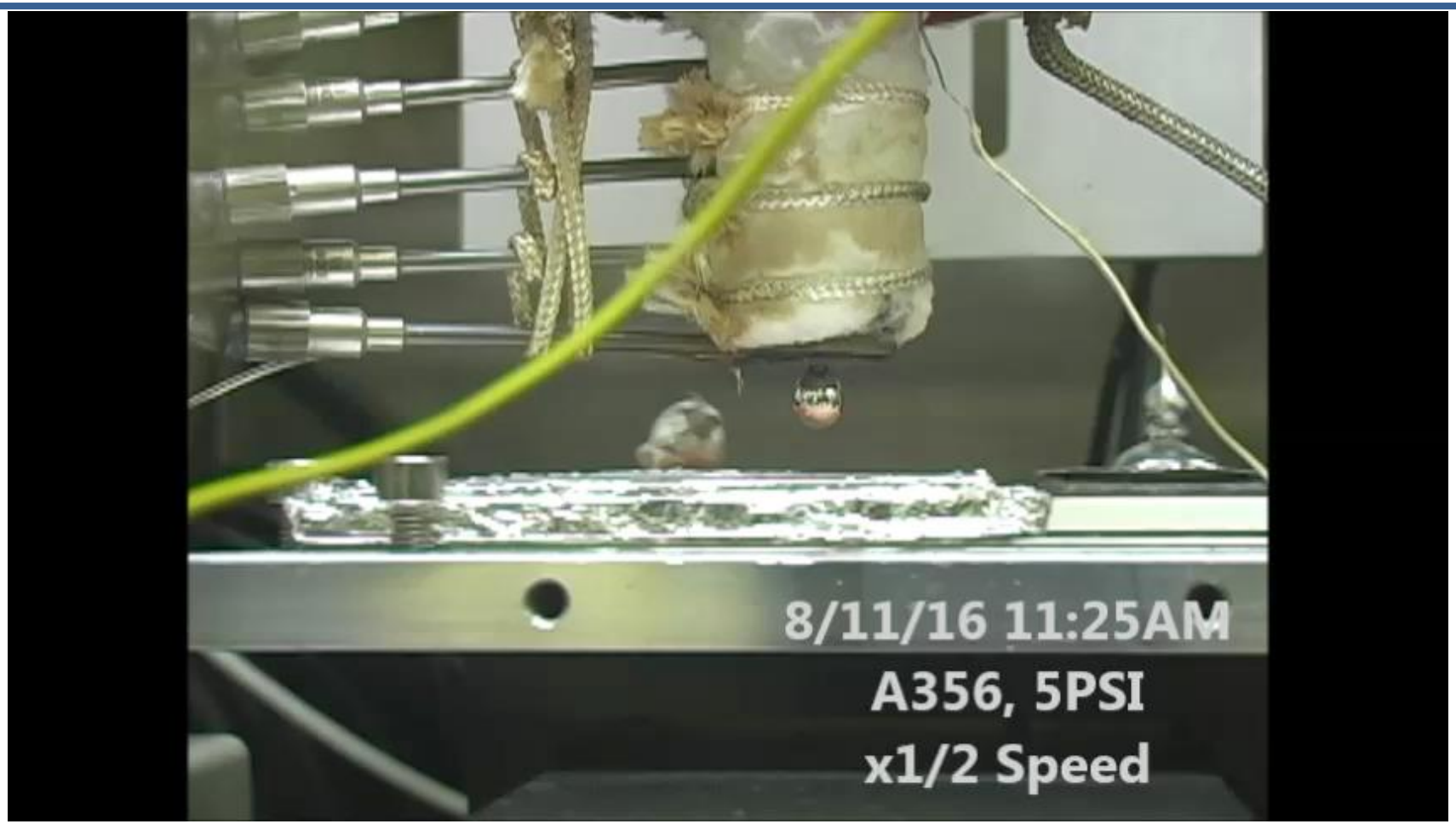


Printing at 200°C
Stage heating to 100°C

Al A356.2 casting alloy (Al-Si) rheology appears printable



Al alloy shows promise, but thermal control is challenging—semisolid region over only Δ60°C



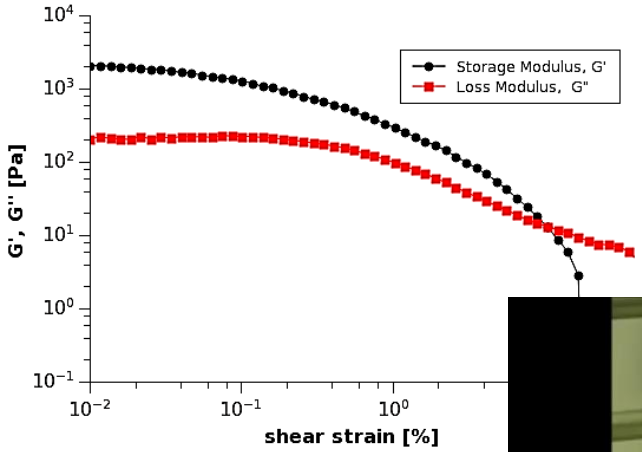
Lessons learned from semisolid extrusion

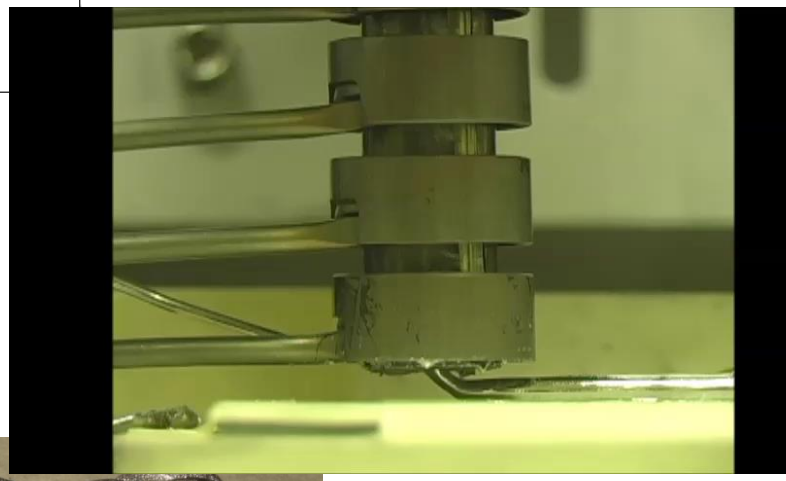
- Semisolid alloys demonstrate printable rheology over a narrow range of temperatures
- Stirring the semisolid alloy is key to forming correct microstructure
- Printing on a heated stage is critical to forming metallurgical bonds between layers
- Precise thermal control is required. Δ20°C is the difference between printable/unprintable for Bi-Sn system.

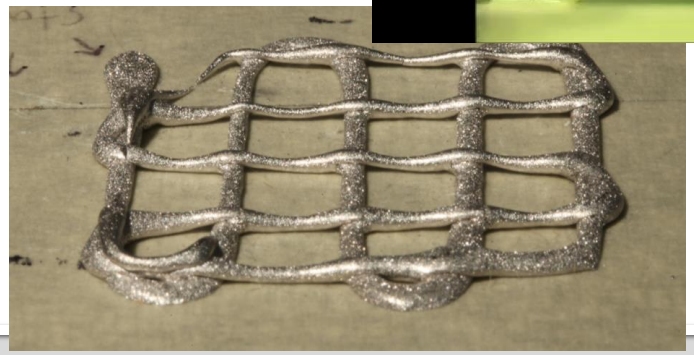
Acknowledgements

Contributors

Dr. Wen Chen
Luke Thornley
Hannah Coe
Michael Wight
Prof. Diran Apelian (WPI)
Dr. Ryan Hunt
Dr. Eric Duoss
Dr. Joshua Kuntz
Dr. Christopher Spadaccini



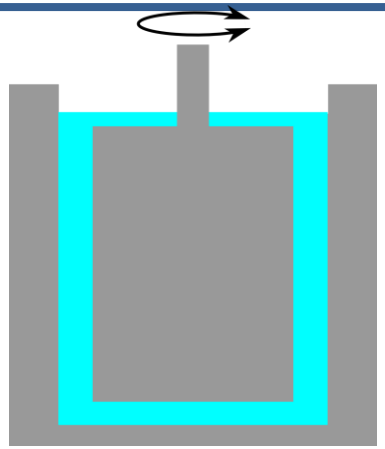


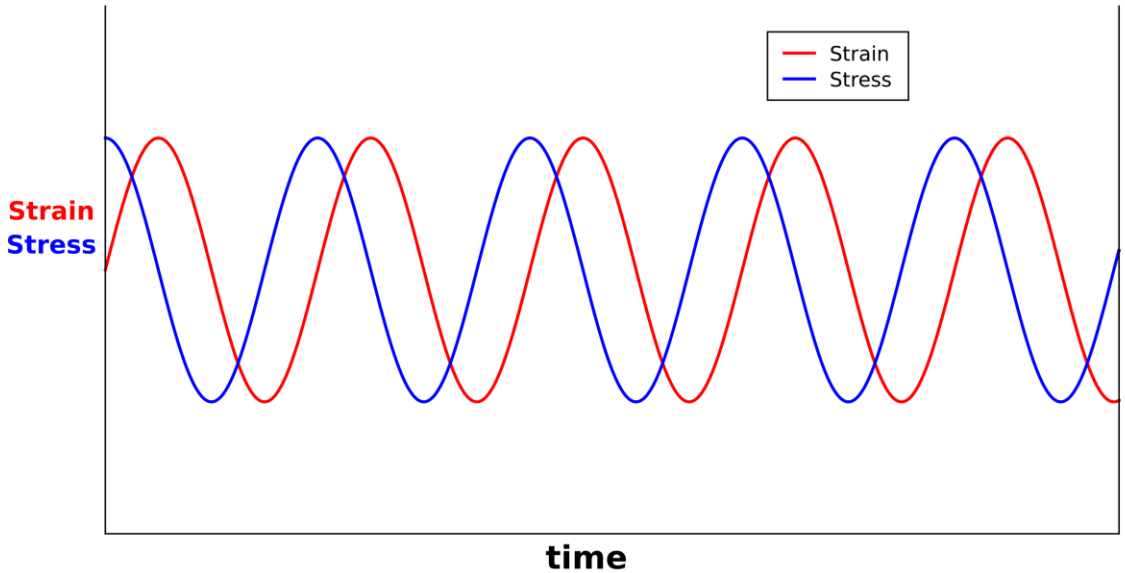


Laboratory Directed Research and Development

Backup slides

Oscillatory Rheometry





Imposed shear strain: $\gamma = \gamma_0 \ \sin \omega t$

For Elastic solids: $\sigma = G\gamma$

For Viscous fluids: $\sigma = \eta\dot{\gamma}$

Generally for viscoelastic fluids:

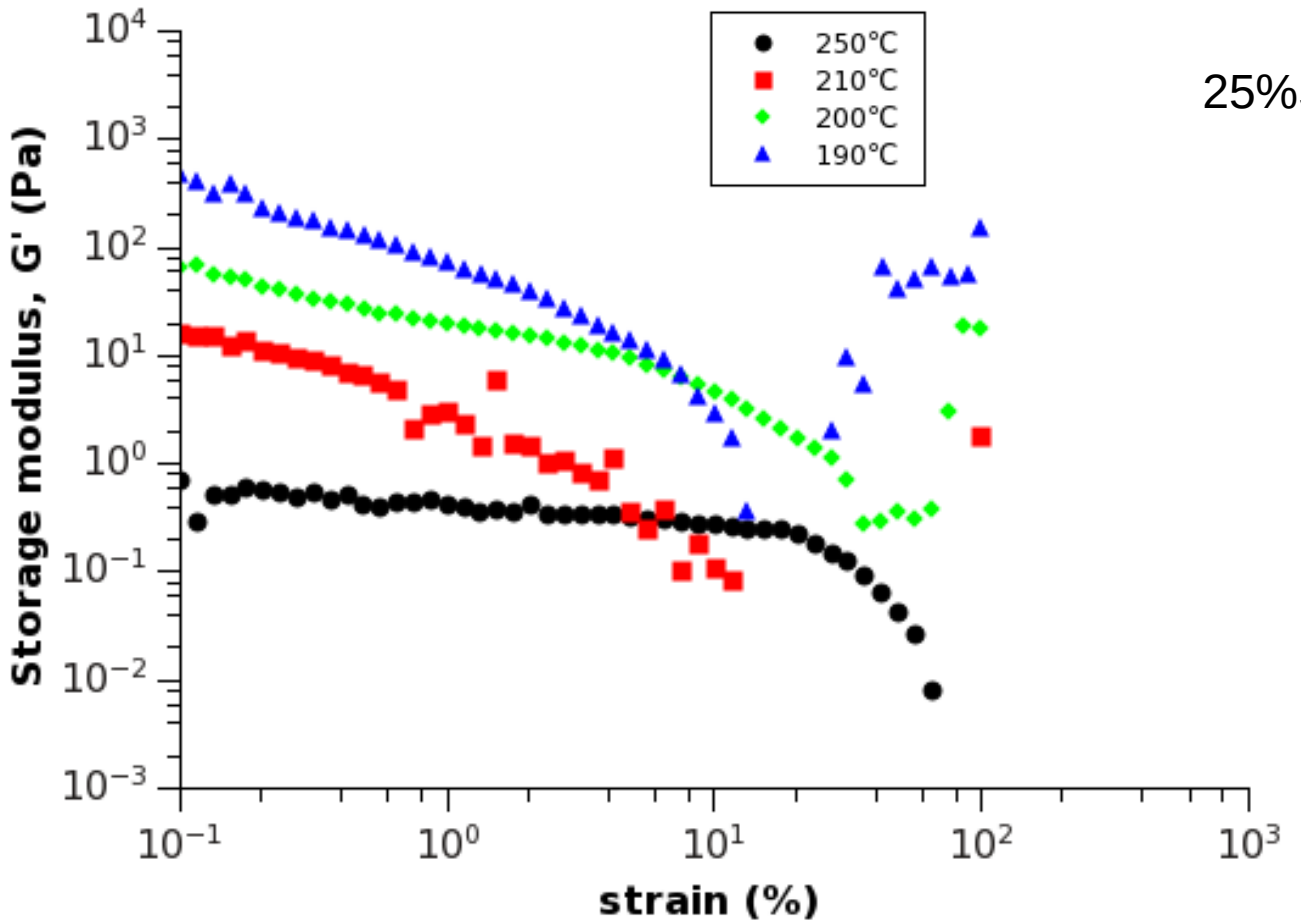
$$\sigma = G'\gamma_0 \sin \omega t + G''\gamma_0 \cos \omega t$$

Rheometry up to 1000°C

Anton-Paar MCR 502 with CTD-1000

- Capable of oscillatory rheometry up to 1000°C
- Run under an inert atmosphere (Ar or N_2)

Yields stress of fluid increase with decreasing temperature



25%Sn-Bi

Al phase diagram