Experimental Development for Thermal Measurements of Rapid AM Solidification

The Ohio State University
Welding Engineering

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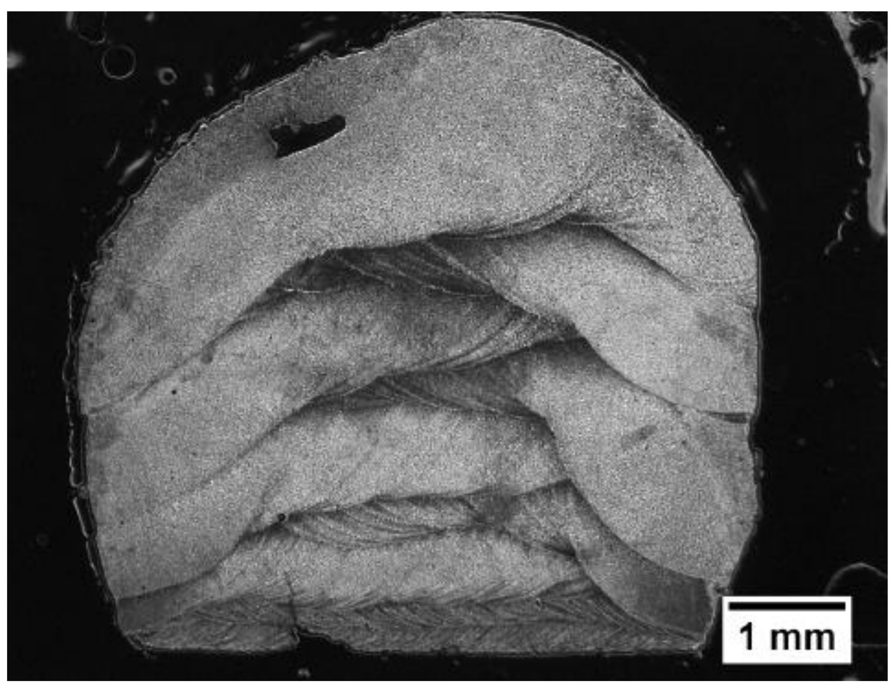
Background



As-deposited Heusler alloy using laser metal deposition, showcasing multiple layer build (Source: Chmielus, M., University of Pittsburgh)

Laser additive manufacturing (L-AM) is a process that uses a laser source to rapidly melt and solidify usually powder-fed material, repeatedly layering material according to its 3D computer-aided design model. The physical processes are very similar to laser beam welding. L-AM enables complex geometries and cuts down on machining, making it more efficient compared to traditional manufacturing processes (i.e. casting). However, the associated reheating cycles **create complex thermal histories** in the deposited material that greatly affect the microstructure, and therefore the properties.

The overall objective of this research is the **physical simulation of rapid solidification and cooling** under lab conditions in order to develop a three part map, correlating: *cooling rate-microstructure-properties*.

Based on this advanced understanding, L-AM processing parameters can then be adjusted to achieve desirable cooling rate, and therefore end-application material properties in the deposited component.


Example of real-world application of laser-based additive manufacturing (Henry Royce Institute, 2020)

Objectives

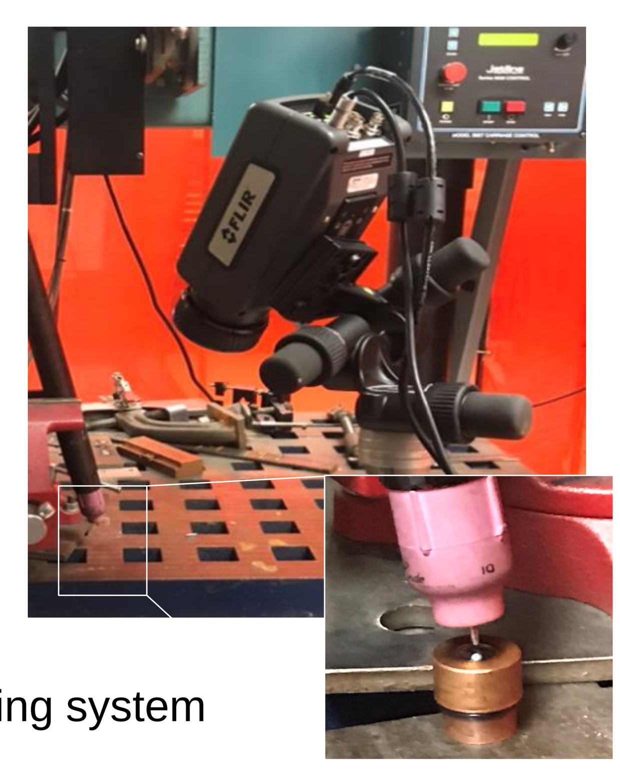
- Simulate rapid solidification (target: 10^2 - 10^4 K/s) via arc melting of nickel-base alloy Ni-625, as a function of weight to vary cooling rate.
- Develop experimental set-up, and determine reliability of infrared camera and thermocouple readings in measuring cooling rates for small samples (weight: 0.02 - 2 gram).
- Conduct secondary dendrite arm-spacing (SDAS) measurements to indirectly estimate cooling rate of arc melted samples.

Experimental Method

- Three different sample weights (0.02, 0.2 and 2 gram) were melted to vary cooling rate using electrode arc melting in Argon atmosphere.
- Procedure: Cut and weigh Ni-625 wire; melt samples on copper-base (Goal: minimize melt time, just enough to form button.)

Infrared (IR) Camera Set-Up

- Copper crucible acts as cooling substrate, tungsten electrode, ~170A, argon gas, standoff ~3mm, 1-5 sec melt time. Image of set-up on right.
- FLIR Camera, image sizing 320x256, super-frame rate 95.65 Hz, high temperature lens.

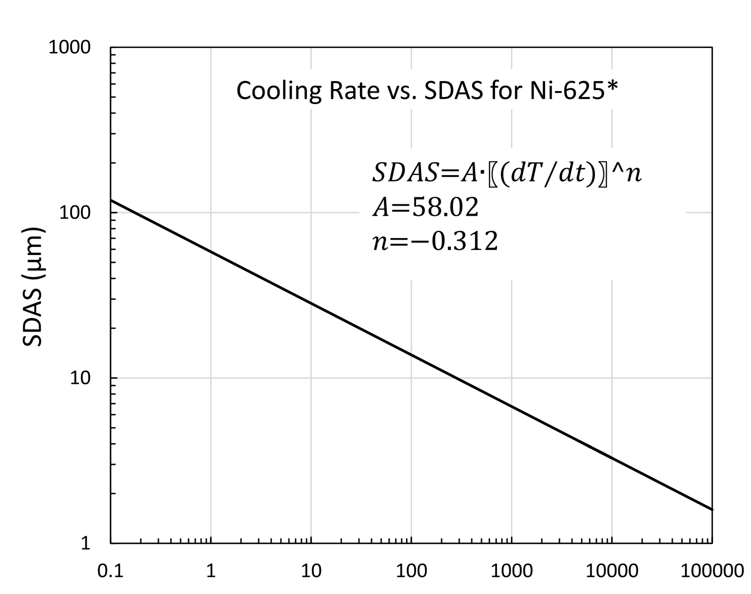


Thermocouple (TC) Set-up

- Thermocouple measurement in arc melting system with water-cooled copper crucible.
- LabView program, direct reading of temperature vs time.
- Arc ignited directly above the sample, held for ~1-10 sec.

SDAS Measurements

- Arc melted samples mounted, polished, etched. Numerous micrographs taken of dendrite arms throughout microstructure.
- ImageJ was used to measure spacing (microns) between dendrite arms.
- Average SDAS correlated to cooling rate via equation from literature (shown in graph).



(Adapted from: J. Tinoco and H. Fredriksson, 2004)

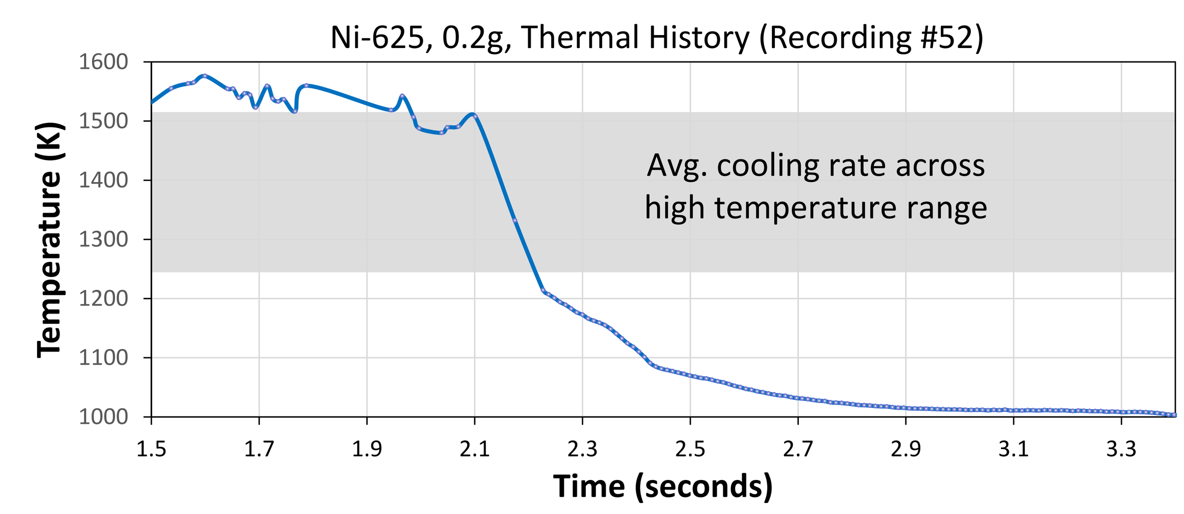
Conclusions

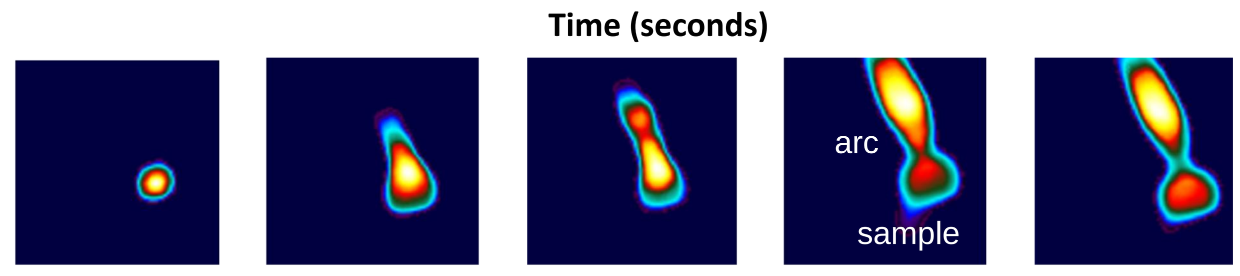
- SDAS measurements on Ni-625 samples indicated cooling rates of up to 10,000 K/s for 0.2 g samples, in line with target range for laser additive process.
- SDAS measurements were simple to execute and produced consistent results.
- Cooling rates varied for different sample weights.
- IR data had substantial variability, determined to be unreliable for cooling rate measurements.
- Proof of concept was achieved for thermocouple (TC) setup in arc melting system, promising for future research.

Results and Discussion

Estimating Cooling Rate for Rapid Solidification via …

Infrared (IR) Camera





t=1sec. T=1400K | t=1.5sec. T=1560K | t=2sec. T=1490K | t=2.5sec. T=1070K | t=3sec T=1010K

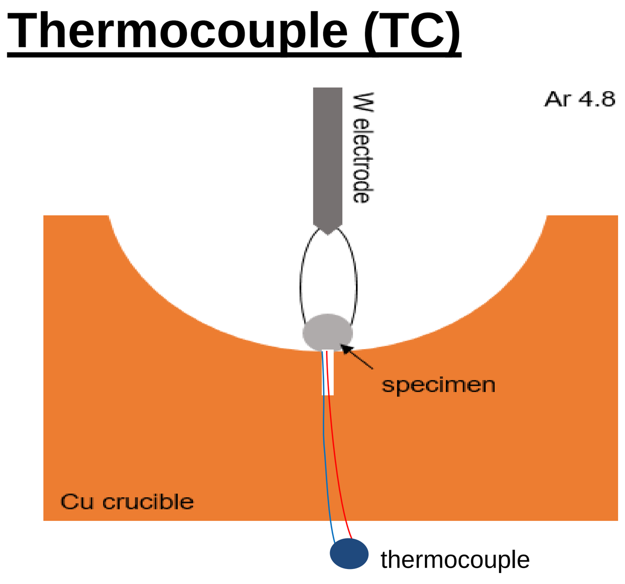
Voltage	Current	Weld Time (s)
15	100	2

Rec-#	Peak Temp (K)	Cooling Rate (K/s)
25	1580	1800
43	1560	1600
49	1630	2300
51	1580	2200
52	1580	2500
53	1580	1900

Average: ***2050 K/s***
Standard Deviation: ***340 K/s***

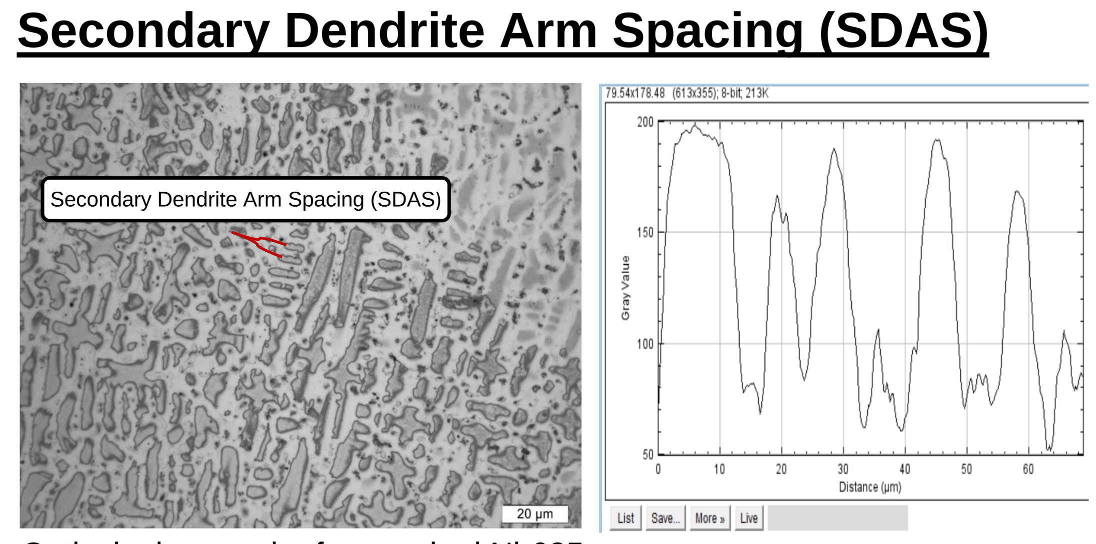
- Graph shows recording of sample surface temperature on cooling as a function of time.
- Average cooling rate was 2050 K/s with a standard deviation of 340 K/s.
- Thermal readings did not always reach melting temperature (~1600K), even though samples were verified to have melted via visual observation.

Thermocouple (TC)



Thermocouple was successfully set-up in Cu crucible of arc melting system and initial measurements were taken. No results yet.

Secondary Dendrite Arm Spacing (SDAS)



Optical micrograph of arc melted Ni-625

SDAS measurements on arc melted Ni-625 indicated cooling rates of up to 10,000 K/s for 0.2 g samples when correlated with empirical data from literature.

Future Work

- Continue thermocouple measurements in arc melting system for all samples weights, compare results to IR camera measurements.
- Compare experimental cooling rate measurements (TC, IR) to results from secondary dendrite arm spacing (SDAS) measurements.
- Conduct rapid solidification simulation for shape memory alloy (NiMnGa), subject of NSF-sponsored project to develop cooling rate-microstructure-property map. Overall goal of this project is to print functional components of NiMnGa.
- Extend experiment to other AM materials of interest (e.g. 304L).

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