Developing Modeling Capabilities for Electron and Laser Beam Welding to Enable In-Space Manufacturing and Repair

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Overview:

In-Space Manufacturing
- In-space manufacturing can be used to assemble and repair complex structures
- Not limited by launch requirements:
  - Volume
  - Mass
  - Forces
- Likely a requirement for future space exploration

Electron/Laser Beam Welding
- Use high energy density electron/laser beam
- Melts/vaporizes base material to produce a weld

Benefits
- Functions well in vacuum
- Minimal consumable mass reduces launch costs
- High precision welds

Challenges
- Require high confidence and understanding to utilize for in-space manufacturing
- Processes and properties behave differently in space vs. terrestrial environments
- Limited in-space welding experience
- Expensive and challenging to conduct in-space testing

It is important to develop robust, accurate models of in-space electron and laser beam welding to improve understanding of these processes, enable more efficient testing, and develop in-space manufacturing capabilities.

Skylab Welding Model:

Background:
- 1972 electron beam welding (EBW) study conducted on Skylab
- First U.S. in-space welding experiment
- Three disks (Aluminum 2219, 304 Stainless Steel, Tantalum) with gradually changing thicknesses

Challenges:
- Skylab is one of few in-space welding experiments
- Important for informing future in-space welding modeling efforts
- Not modeled sufficiently with modern technology

Objectives:
- Conduct thermal and hardness modeling of heat affected zone
- Compare model to data to ensure accuracy
- Expand to further cases to better understand in-space EBW

Project Work:

Setup

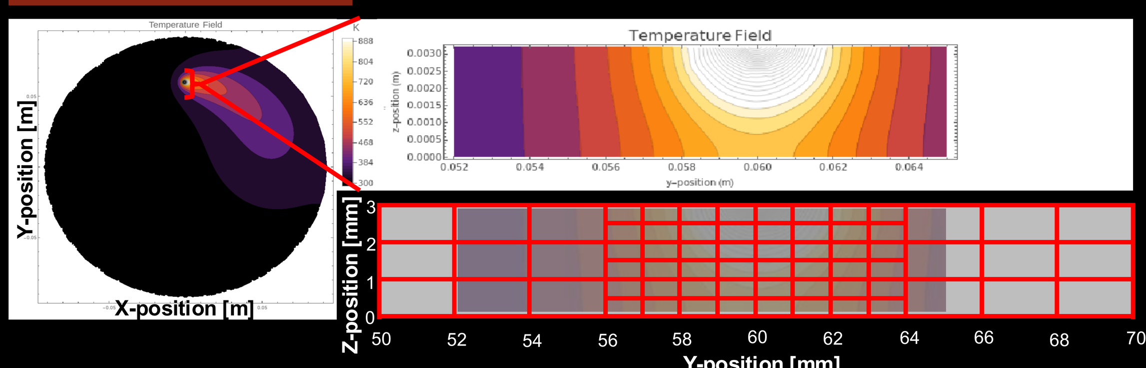


Figure 1 (left): Temperature field model of plate
Figure 2 (top right): Temperature field model of selected cross section
Figure 3 (bottom right): Cross section with overlayed mesh grid

Note: Setup work conducted by MSFC Skylab model team prior to internship start

- Mathematica to model temperature field on plate
- Cross section of plate selected
- Mesh created within cross section defines points for hardness model
- Aluminum 2219 at three initial temperatures (100K, 293K, 400K)

Temperature Profiles

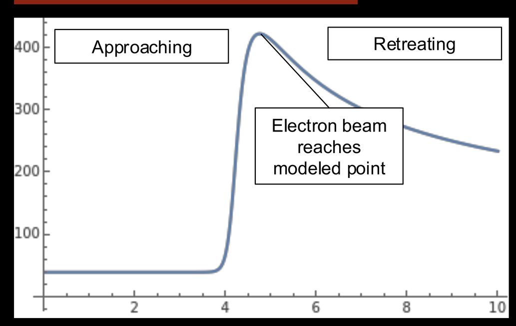


Figure 4: Temperature profile of example mesh point produced with Mathematica code

Note: Temperature profile work conducted by Dr. Ellis Crabtree (internship mentor).

- Temperature profile with moving heat source
- Repeated for all mesh points
- Exclude fully melted points

Thermo-Calc

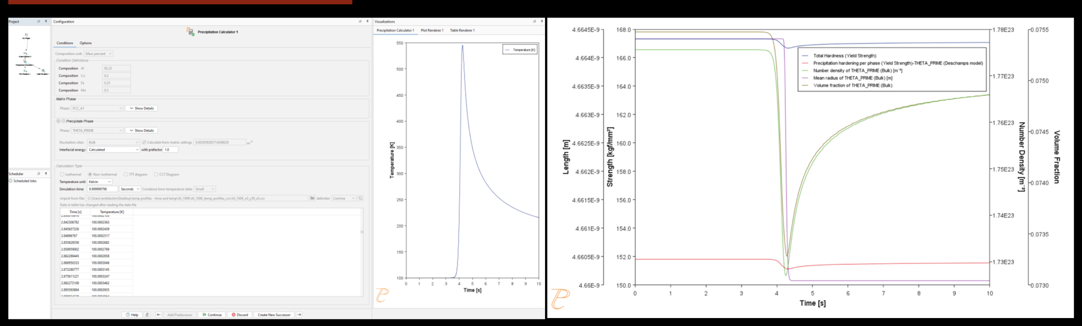


Figure 5 (left): Thermo-Calc PRISMA set-up
Figure 6 (right): Material property plot for example modeling case. Plotted values include total hardness, precipitation hardening per phase, number density of θ', mean radius of θ', and volume fraction of θ'.

- Thermo-Calc PRISMA precipitation modeling for 234 points
- Temperature profiles converted to csv files
- Simulation time of 10 seconds
- Resulting plot of material properties over time

Results

Figure 7 (left): Thermo-Calc table depicting time and hardness points for example case
Figure 8 (right): Excel sheet tracking hardness results for all cases

- Total hardness table to obtain final hardness at each point
- Tracked results in Excel
- Noted model inputs and incomplete simulations (predicted in weld pool)

Hardness Plots

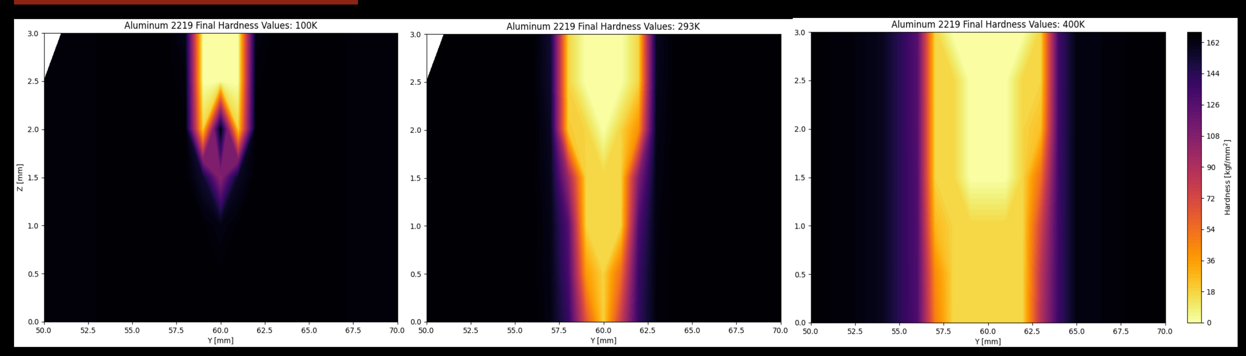


Figure 9: Mesh plots of cross sections depicting final hardness values
Figure 9a (left): Initial temperature of 100K
Figure 9b (center): Initial temperature of 293K
Figure 9c (left): Initial temperature of 400K

- Used Python to produce mesh plots of final hardness values
- Have results that can be compared with data
- Clear variation in heat affected zones indicates necessity of modeling in-space welding environments

Future Work
- **Compare** to Skylab data and other modeling techniques
- Repeat for **other materials**
- **Expand model** to be applicable to further cases and **inform** in-space welding experimentation

Laser Keyhole Depth Model:

Background:
- Laser beam welding (LBW) can create a keyhole
- Keyhole depth changes with atmospheric pressure

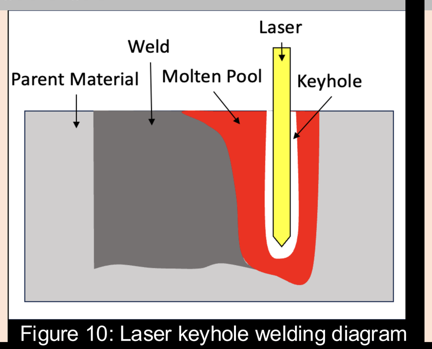


Figure 10: Laser keyhole welding diagram

Challenges:
- Different keyhole formation mechanisms in space: pressure, gravity, convection, buoyancy, etc.
- Many current models are not necessarily applicable to in-space applications
  - Earth-based assumptions
  - Use terrestrial data

Objectives:
- Develop a purely physics-based model of keyhole depth
- Apply model to in-space LBW applications

Project Work:

Literature Review
- Initial understanding of LBW
- Understanding of parameters that impact keyhole depth
- Implications of space environments on relevant parameters

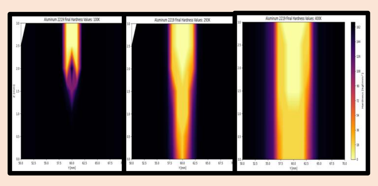
Analyzing Previous Models
- Fabbro et al. (2016) model: keyhole depth in reduced ambient pressure
  - Identified data-based coefficients
  - Compared to prior MSFC model iterations to identify inaccuracies
- MSFC model iterations
  - Re-derived equations to gain understanding and identify errors

Model Development
- Modeled keyhole as a nozzle with force and energy balance
- Incorporated pipe flow equations to include pressure drop
- Defined relevant equations, known vs. unknown values
- Identified variables requiring further research and model incorporation

Future Work
- Continue integrating physics components to **create full model**
- **Compare** results to existing models and experimental data
- Use work to **set depth** in keyhole FEA analysis
- Use model to **inform** in-space welding experimentation

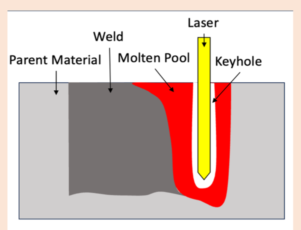
Future Goals:

Skylab



Material properties in heat affected zone

Keyhole



Keyhole geometry

Additional Models
Additional weld properties and variables

In-Space Welding Simulations
- Develop Skylab and keyhole models and combine, along with other models, into more complete welding simulations
- Keyhole geometry to better understand heat affected zone geometry
- Material properties in heat affected zone to better understand properties around a keyhole
- Will allow for more complete understanding of in-space welding properties, and thus capabilities

Impacts:
- Improves understanding of in-space welding
- Supports more tailored in-space testing
- Facilitates faster, cheaper, and more effective development of in-space manufacturing processes
- Production and repair capabilities for complex in-space structures
- Enables future scientific discovery and human space exploration

Conclusion:

Future long distance and long duration human spaceflight relies on developed in-space manufacturing and repair processes.

Current modeling work is necessary to enable this development.

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