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An Experimental Investigation of Residual Stress Development in Selective Laser Melting of Ti-6Al-4V

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Outline

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- **Motivation and background**
- **Materials and procedures**
- **Results**
- **Conclusions**
- **Future Work**

Motivation

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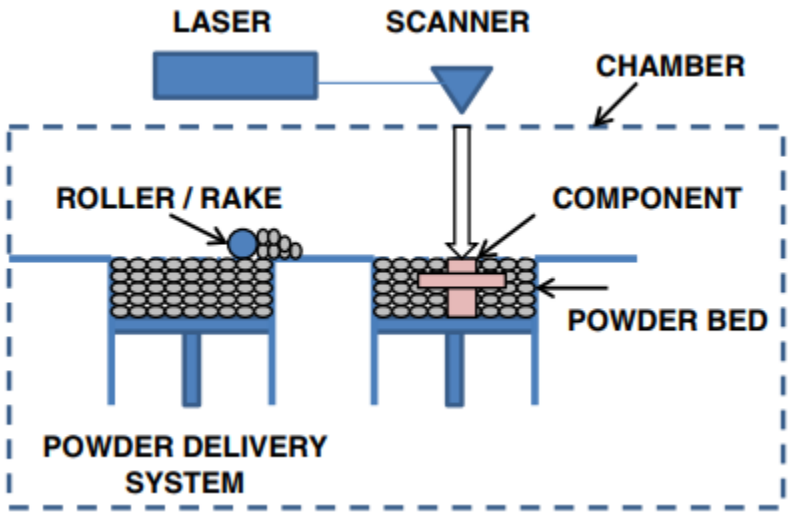
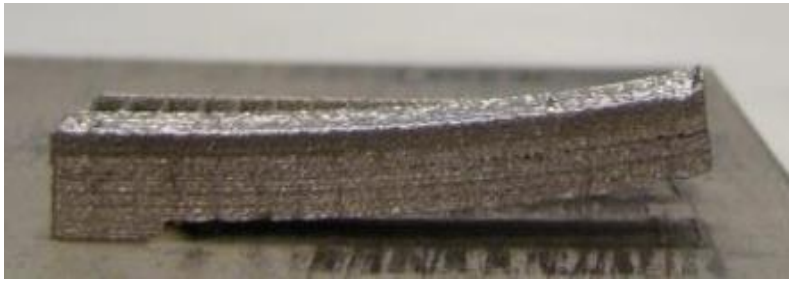
- **Advantages of Selective Laser Melting (SLM) Additive Manufacturing (AM) Compared to Other Processes:**
  - Produces high resolution
  - Complex internal passages
  - Dimensional control
- **SLM Disadvantages:**
  - Produces large thermal gradients that produce undesirable residual stress
  - Residual stress (RS) causes thermal cracking and build distortion in AM which results in build failure

Objective: Develop methods to measure and control residual stress in SLM builds



Frazier et al. (2014)



Ti64 AM build distortion

Background: Residual Stresses in SLM

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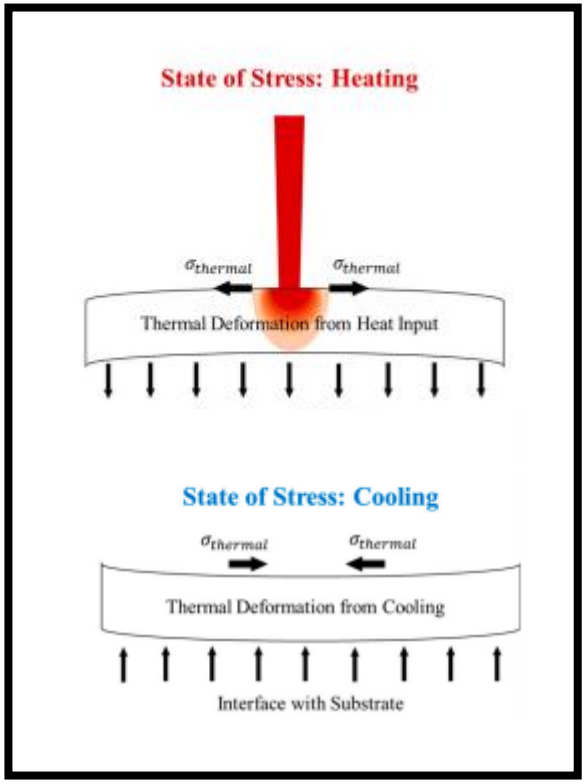
- **Prior Literature Observations:**
  - **Melt pool cooling rate can be tailored to reduce residual stress**
  - **Process parameters (e.g. laser power, scan speed, hatch spacing, dwell time, and scan strategy) can affect the evolution of residual stress**
  - **Substrate preheating and support structure can reduce residual stress**
- **Previous work fails to establish:**
  - **The effect of substrate geometry, thickness, confinement, and overhang on residual stress**
  - **The effect of process parameters on residual stress**
  - **The effect of prior build-plate condition on AM residual stress**
  - **Effect of measurement method (e.g. XRD, Hole Drilling, Contour Method, and Layer removal method) on residual stress**



Farrington et. al (2017)

Program Material & AM System

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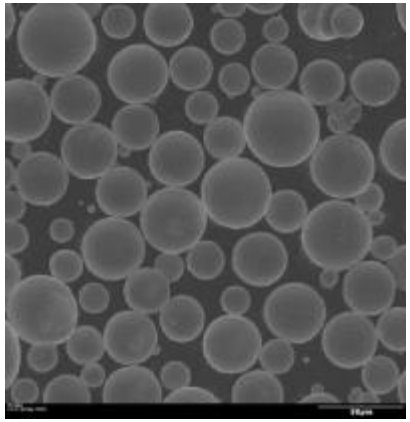
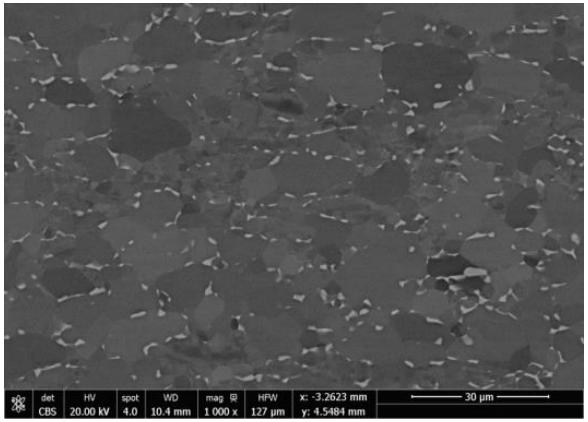
Program Material

- Ti-6Al-4V substrate and Ti-6Al-4V AM powder
- Average diameter of Ti64 powder particles: 23.4 µm
- As-received substrate microstructure: 93% alpha and 7% beta by area fraction
  - Substrates cut from a 28” x 24” plate that had a thickness of 5/16”
  - Substrates dimensions were 76.2 mm x 76.2 mm x 7.93 mm and 25.4 mm x 25.4 mm x 7.93 mm



As-Received powder



Microstructure of as-received Ti64 substrate

SLM System

- IPG 500 W Laser with a spotsize of 50 µm
- F-theta lens with 6 inch focal length
- AM system enables customized process design

UTC SLM AM system

Initial Substrate Heat Treatments to Eliminate Residual Stresses

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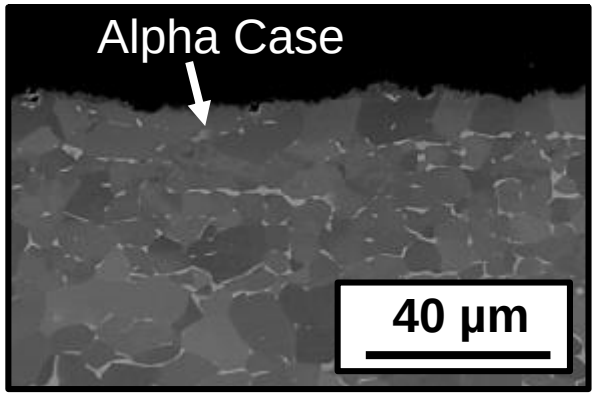
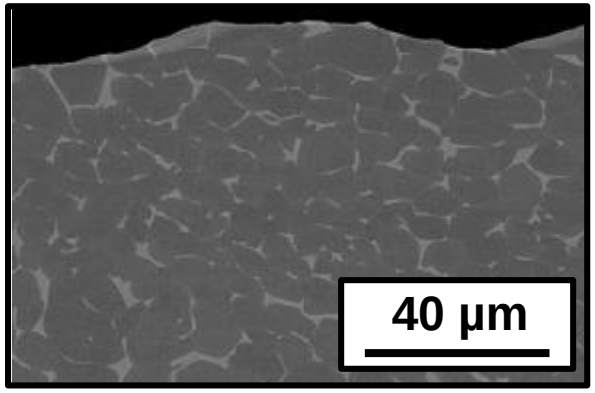
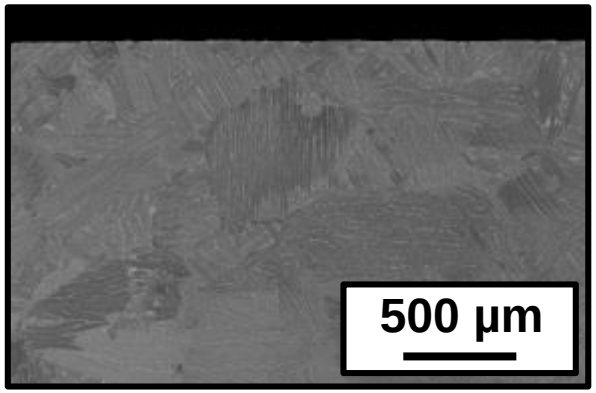


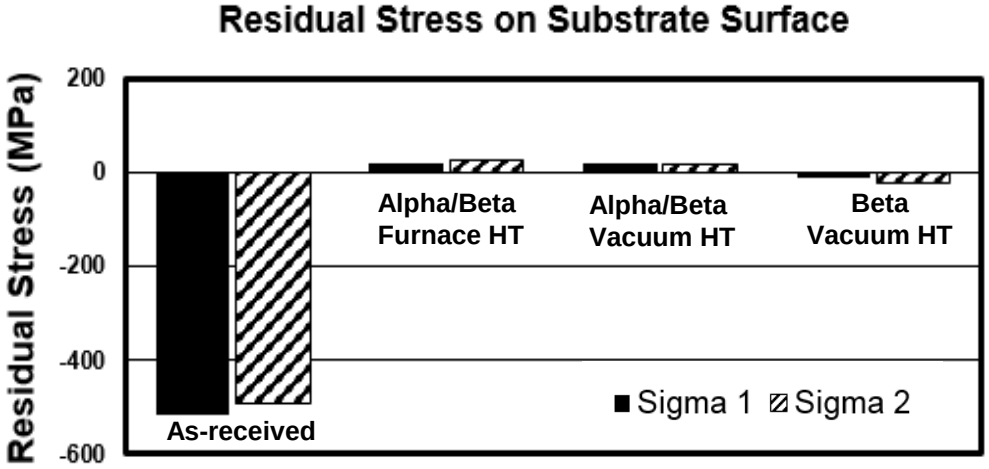
Alpha/Beta Furnace HT



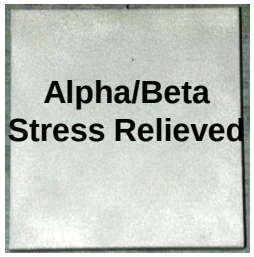
Alpha/Beta Vacuumed HT



Beta Vacuum HT



Furnace Heat Treatment:
954°C/1hr + furnace cool
Vacuum Heat Treatment:
927°C/1hr + cool at 100 °F/hr



DoE for Laser Glaze, Substrate Condition, and Build Volume AM Builds

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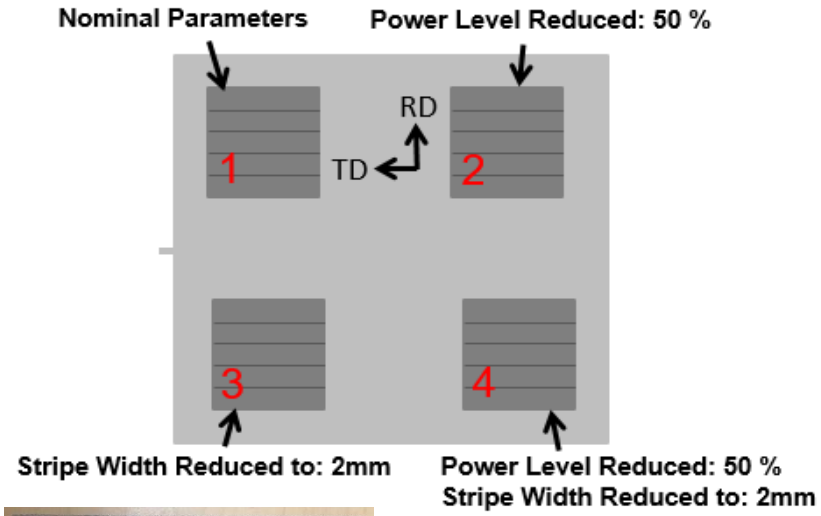
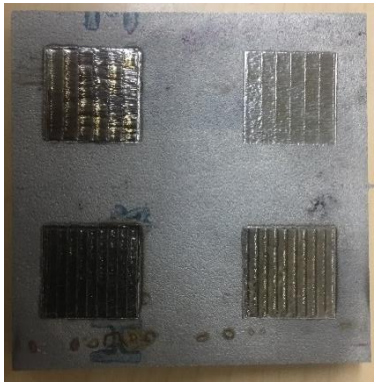
Build plan for Laser Glazes on 76.2 mm x 76.2 mm substrates





Substrate Conditions:
- Alpha/Beta Vacuum HT
- Beta Vacuum HT
- Alpha/Beta Furnace HT
- As-received

Build Plan for Various Build Volumes on 76.2 mm x 76.2 mm

- AM Build Size: 76.2 mm x 76.2 mm x 1.6 mm
- AM Build Size: 50.8 mm x 50.8 mm x 1.6 mm
- AM Build Size: 25.4 mm x 25.4 mm x 1.6 mm

DoE for (25.4 x 25.4 x *h*)mm AM Builds

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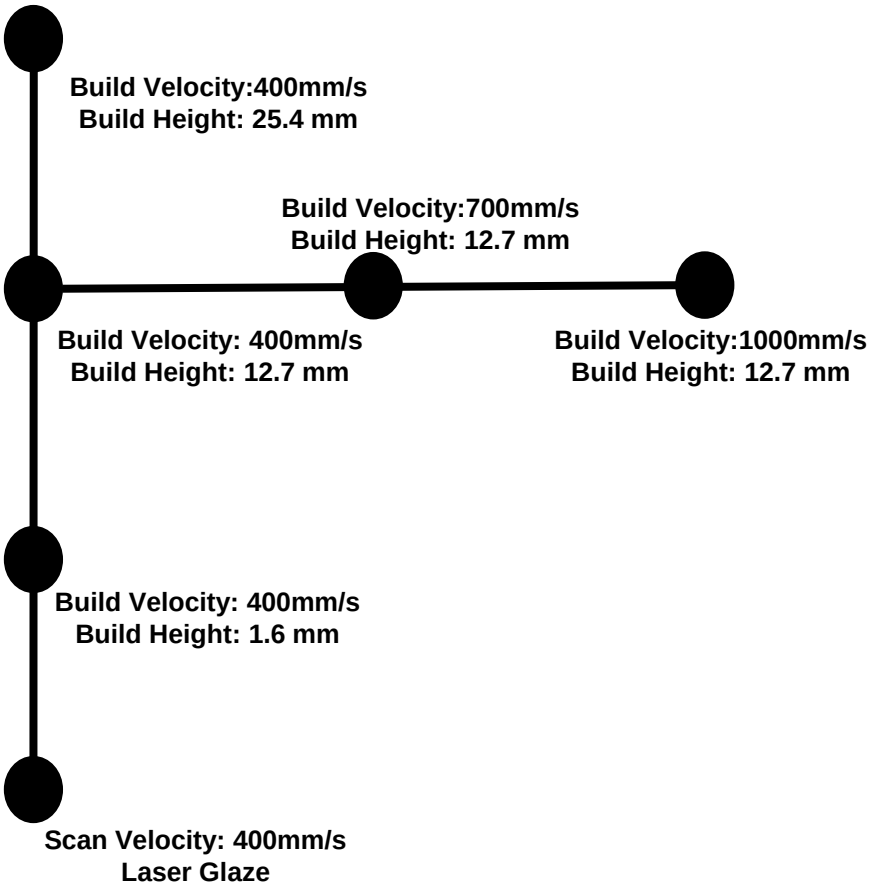
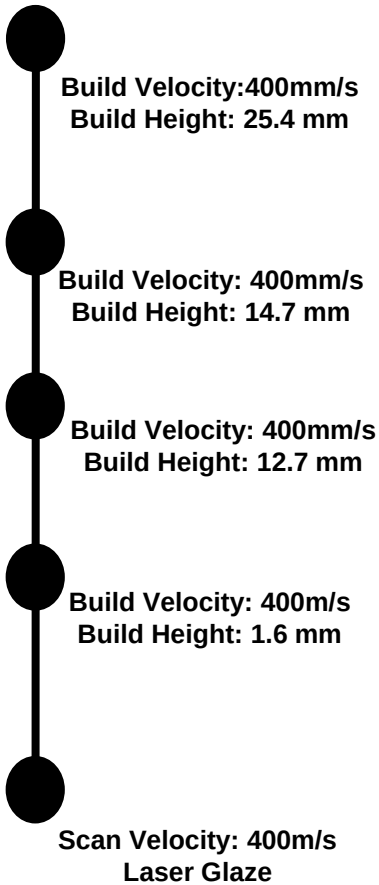
Build plan for AM samples on 76.2 mm x 76.2 mm substrates



Build plan for AM samples on 25.4 mm x 25.4 mm substrates



Results

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Surface RS Measurements

- XRD Measurements
- Hole Drilling Measurements
- XRD vs. Hole Drilling Measurements

Subsurface RS Measurements

- Layer Removal Method

Effect of Substrate Condition on XRD RS

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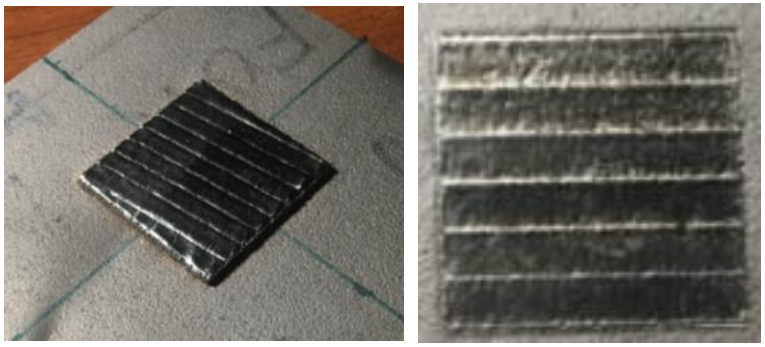
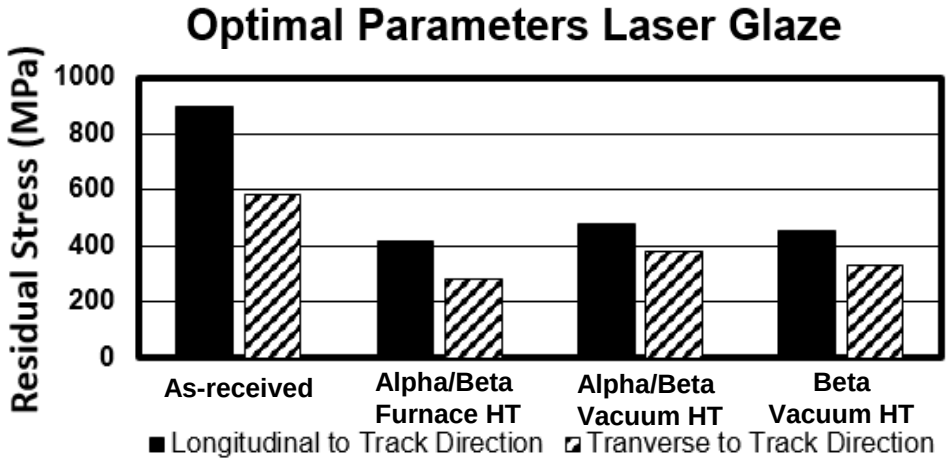
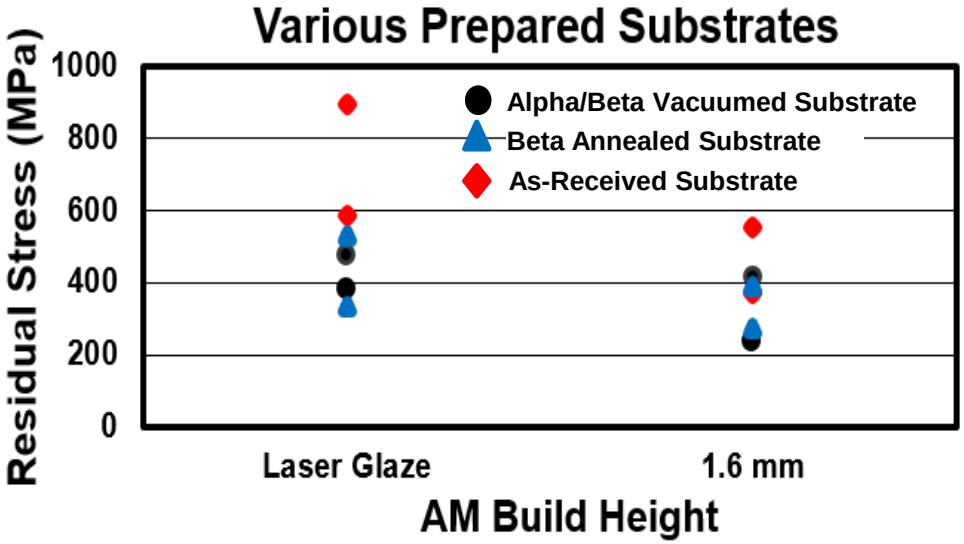
- **Largest measured stresses were always parallel to the laser track direction**
- **Initial substrate stress does affect AM build surface residual stress**
- **Higher laser power and smaller stripe width decreased surface residual stress**



1.6 mm AM build and laser glaze





Effect of AM Build Plan Area on XRD RS

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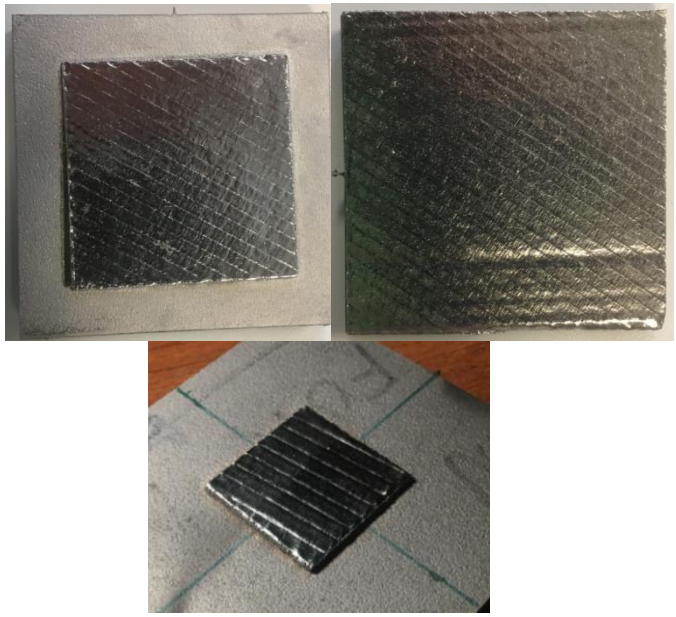
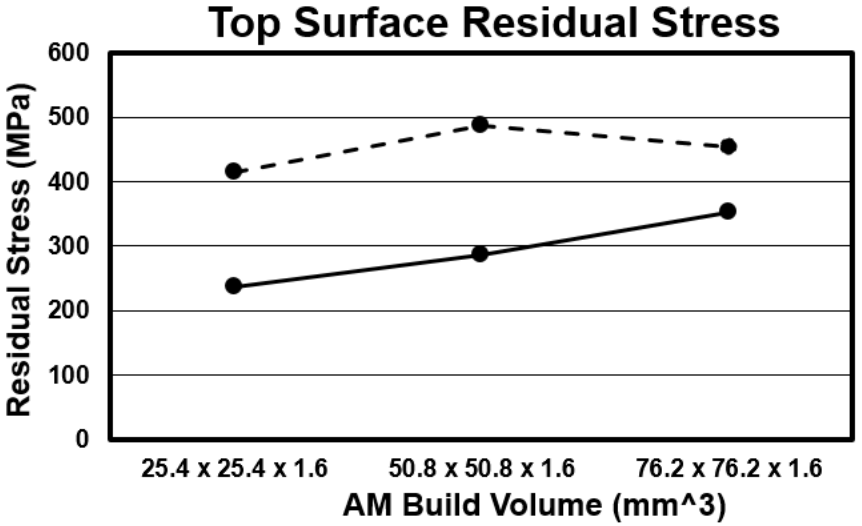
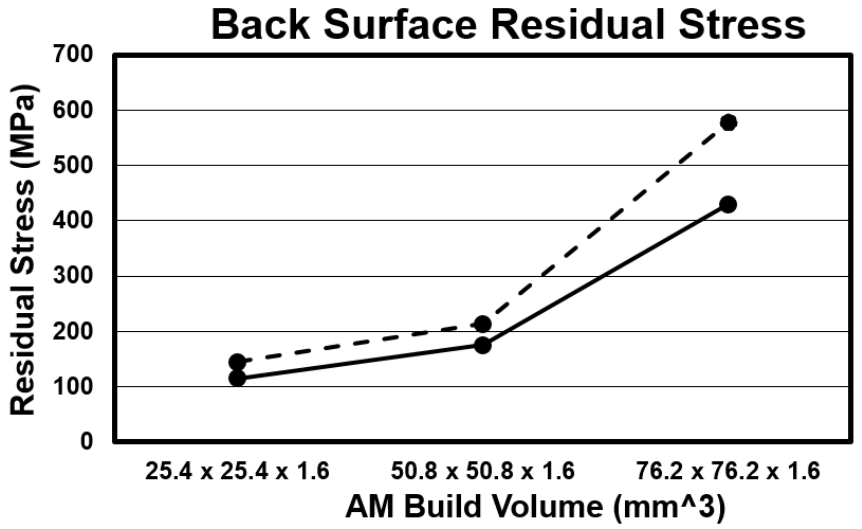
- **Largest measured stresses were always parallel to laser track direction**
- **Back surface residual stress increased as AM build volume increased**
- **Substrate distortion increased as AM build volume increased**







Effect of Substrate with no Overhang on XRD RS

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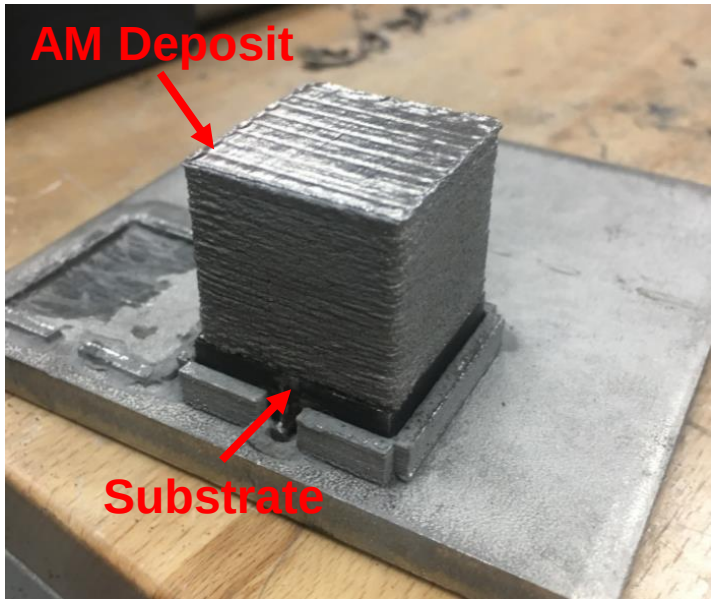
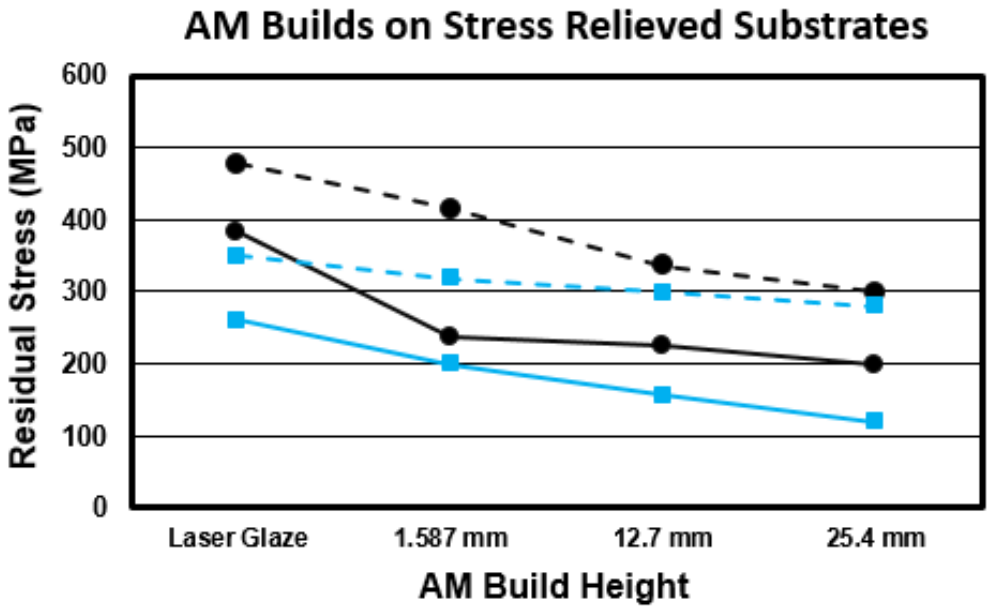
- **Principal stresses were parallel and perpendicular to the laser track direction with respect to the *final* deposited layer**
- **AM builds fabricated on substrates with no overhang exhibited lower top surface and substrate backside residual stress compared to substrate with overhang**



AM build with no substrate overhang



Effect of Scan Speed on XRD RS

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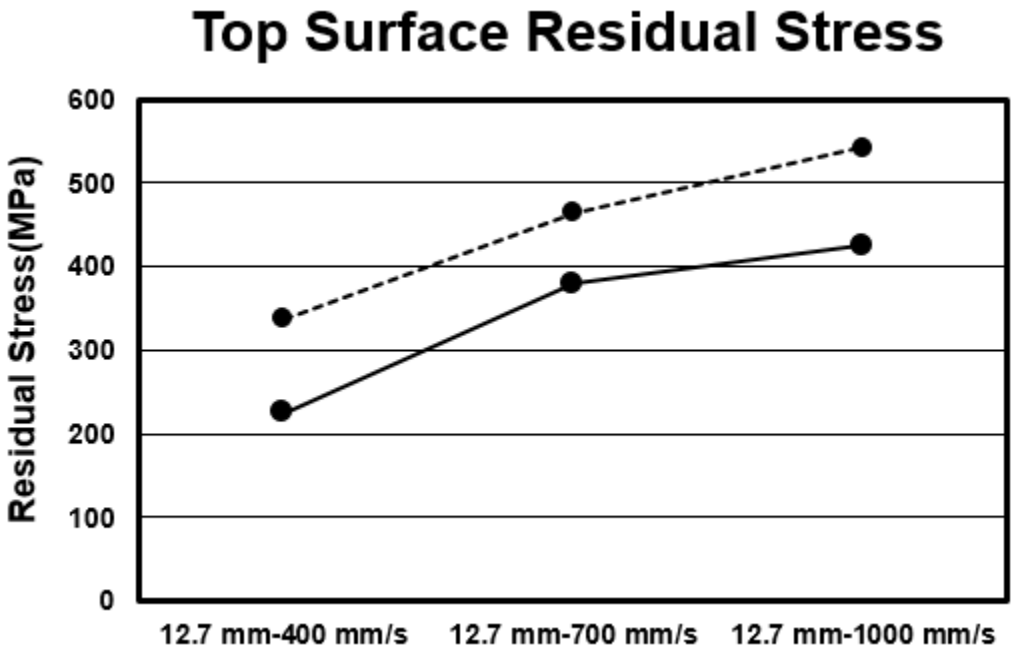

Top surface residual stress increased as scan speed increased

Hole Drilling RS Measurements

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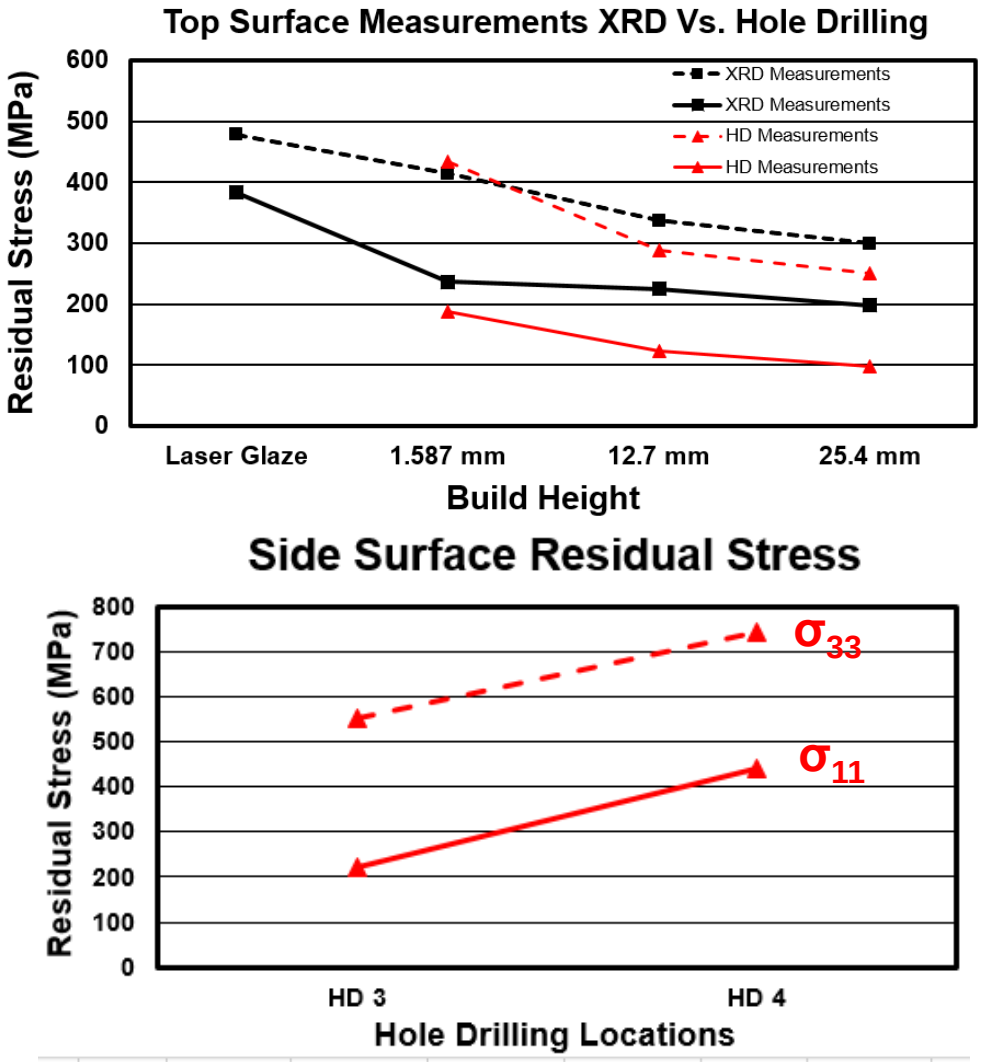

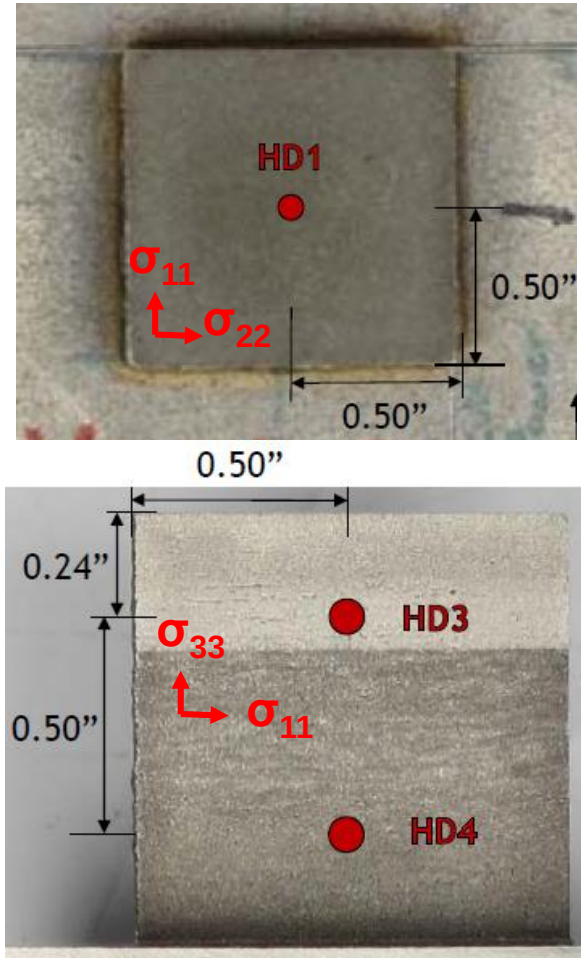

Hole Drilling Locations on AM Deposits

Hole Drilling RS Measurements

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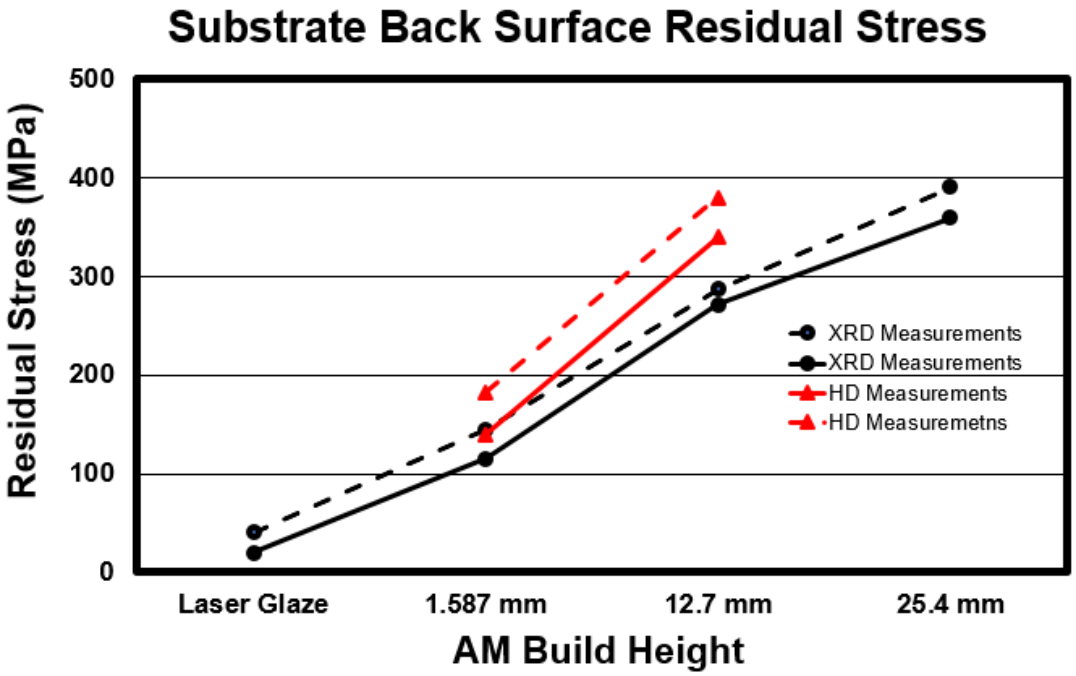

Hole Drilling Location on Substrate Back Surface

Hole Drilling RS Measurements

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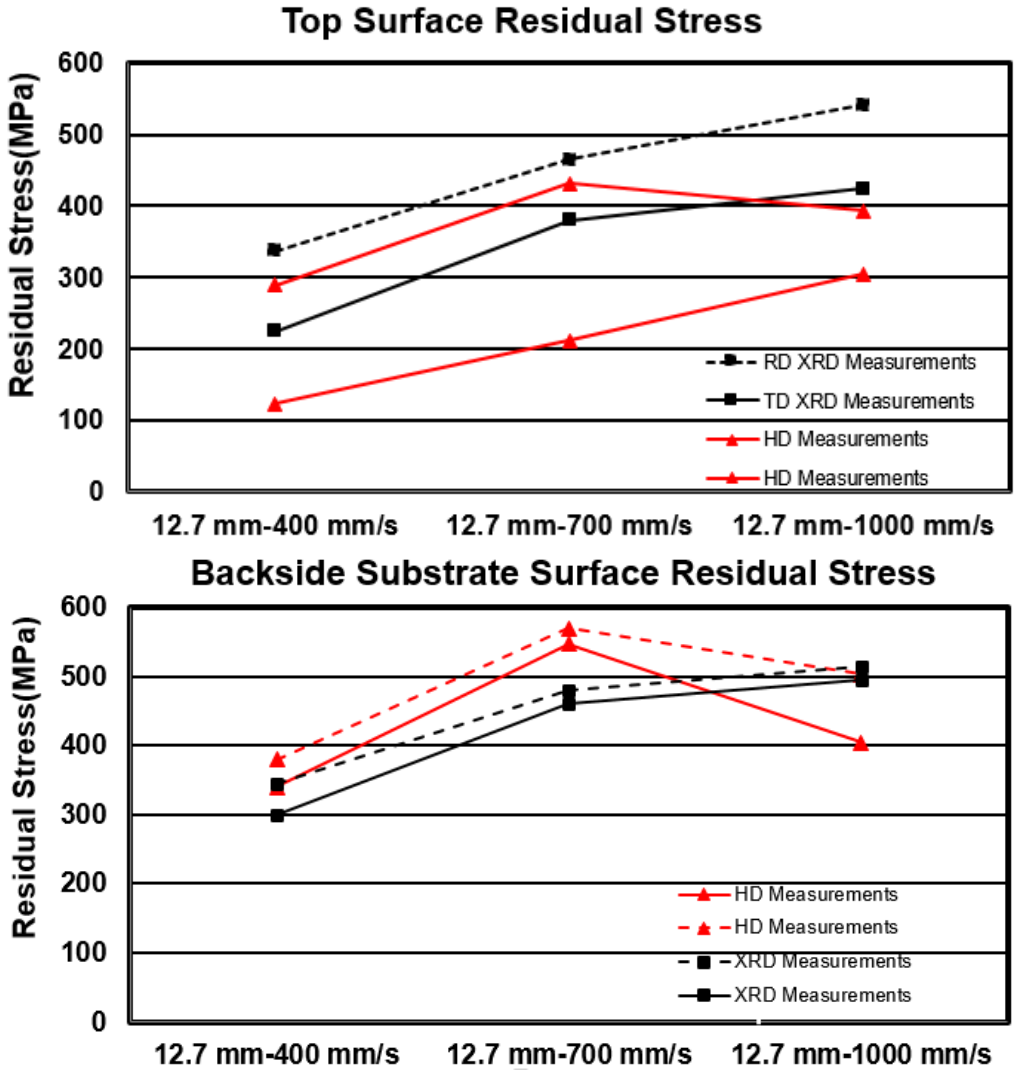

Hole Drilling Locations on AM Deposits

Results

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Surface RS Measurements

- XRD Measurements
- Hole Drilling Measurements
- XRD vs. Hole Drilling Measurements

Subsurface RS Measurements

- Layer Removal Method

Layer Removal Method

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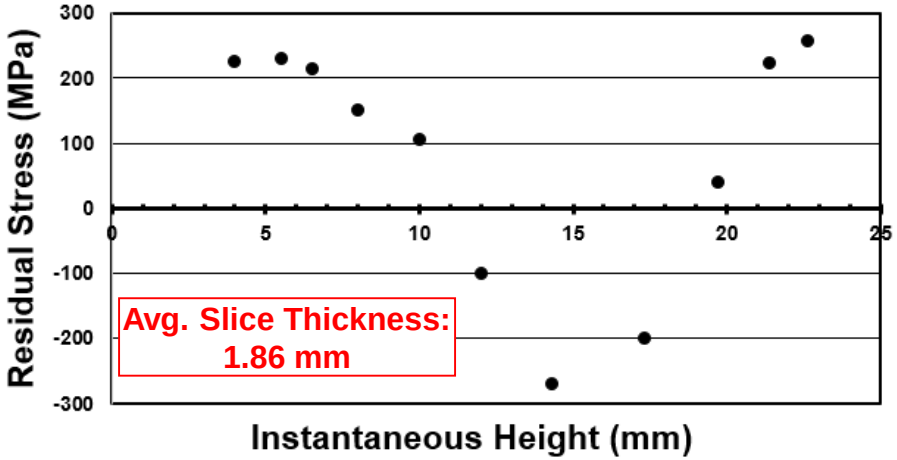
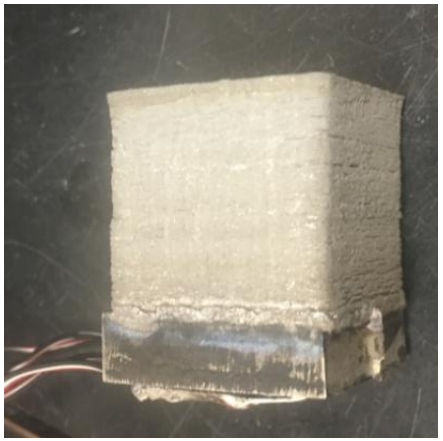
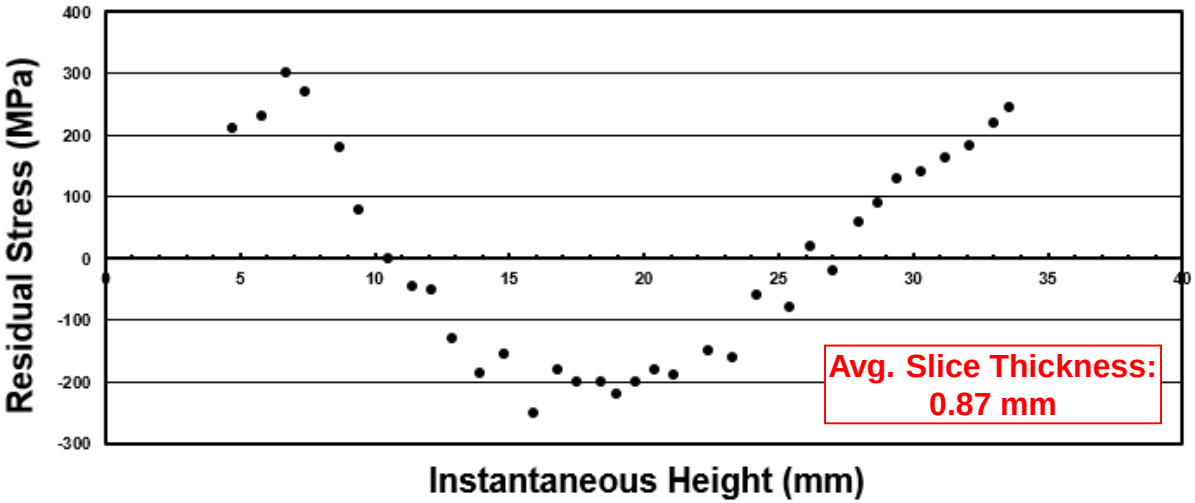
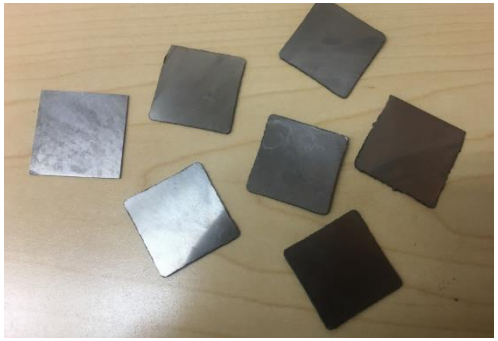
14.7 mm AM Build





25.4 mm AM Build





Layer-removal-method sample

Conclusions

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- **Higher laser power, lower scan speed, smaller stripe width, reduction in substrate overhang, reduction in plan area all decrease top-surface residual stress**
- **There are similarities and differences among the different measurement techniques**

Future Work

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- **Determine x-ray elastic constants for Ti64 substrates and additively manufactured Ti64**
- **Determine texture of AM builds (EBSD)**
- **Determine Knoop hardness yield loci to assess plastic anisotropy**

Questions?

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