AWS Professional Program: Chicago IL, USA

In-Space Laser Forming Under Thermal Vacuum (TVAC) Conditions

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NASA Marshall Space Flight Center, Presenting

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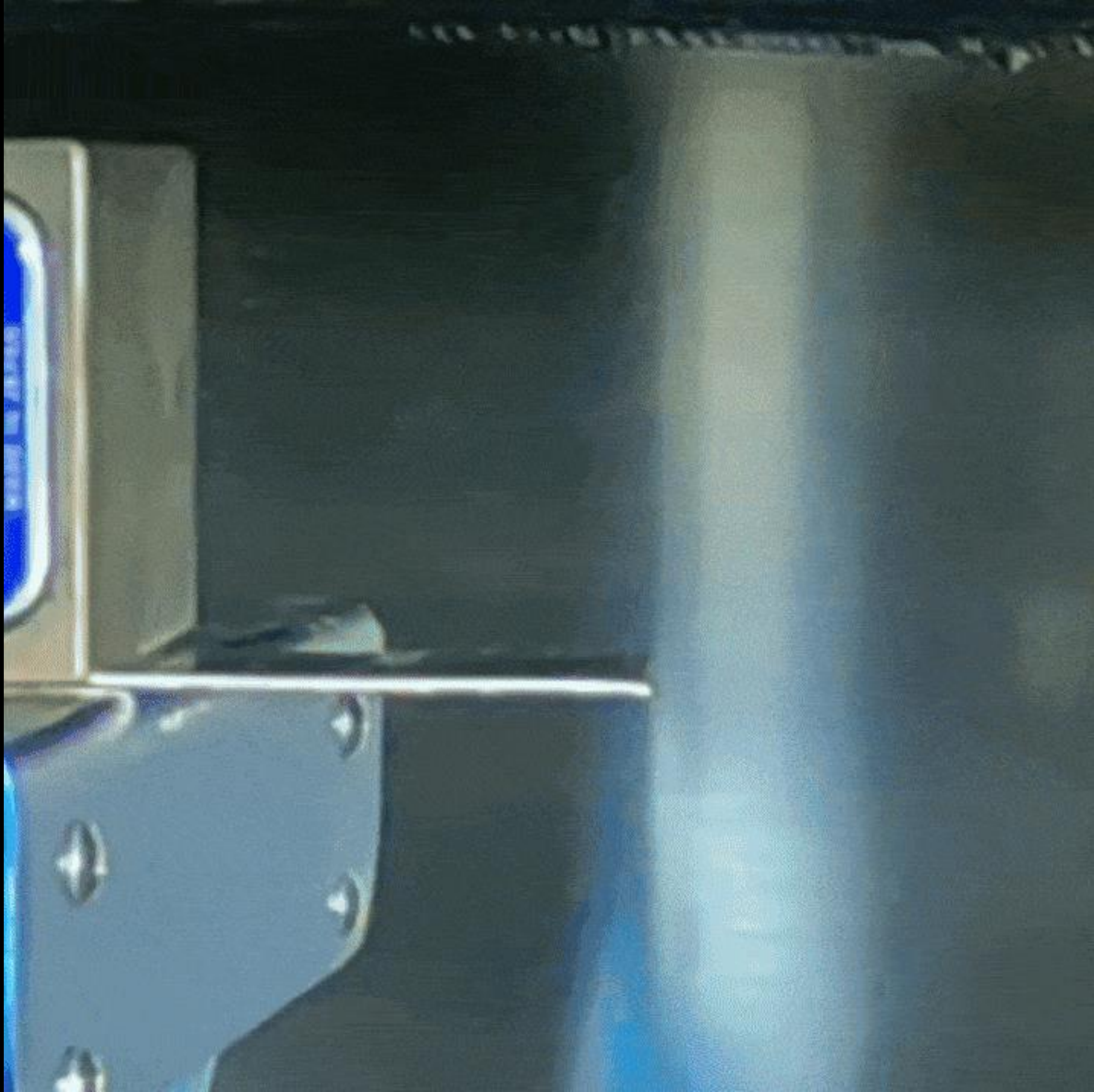
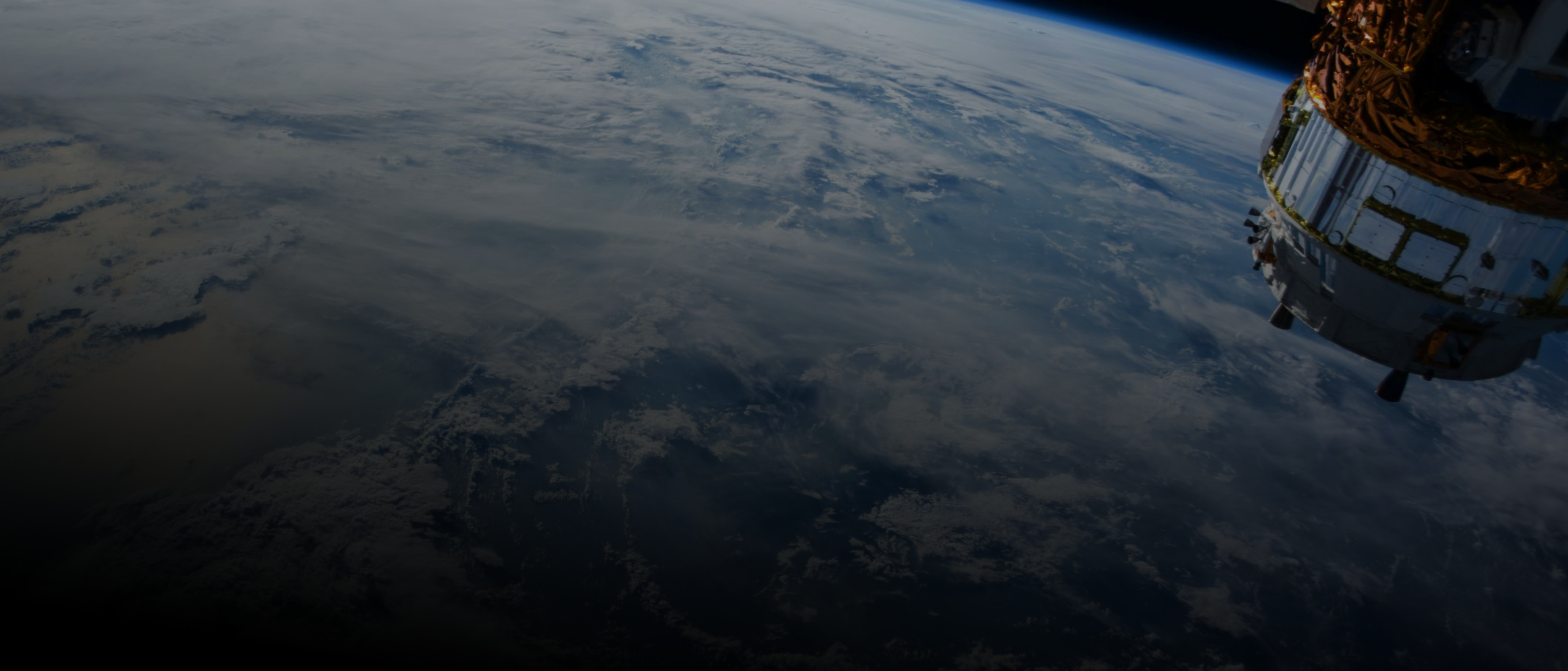




Laser Forming of Metals

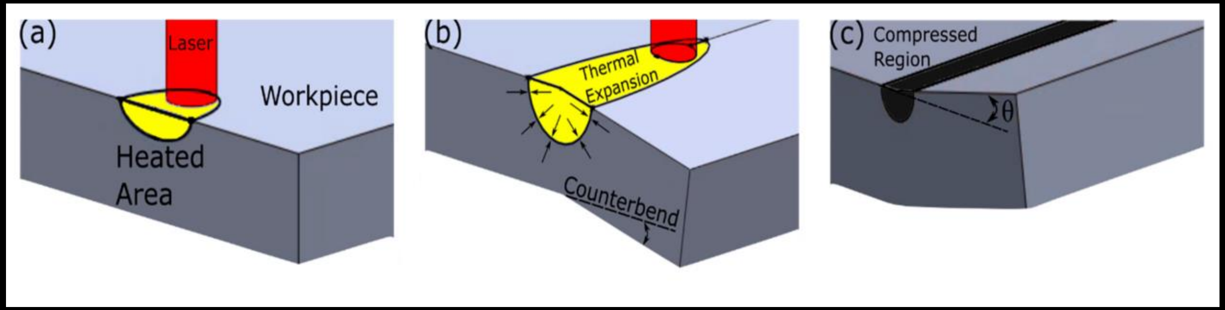
Background

Background

Laser Forming for Space

DARPA Novel Orbital and Moon Manufacturing, Materials, and Mass-efficient Design (NOM4D) – TVAC laser forming (LF)

- University of Florida (UF) demonstrating LF (bending of sheet metal) under vacuum
- MSFC extending LF to thermal vacuum (TVAC)
- Excellent synergy with in-space welding (ISW), especially laser beam welding (LBW)



Thermal Gradient Mechanism (TGM) enables bending towards laser beam

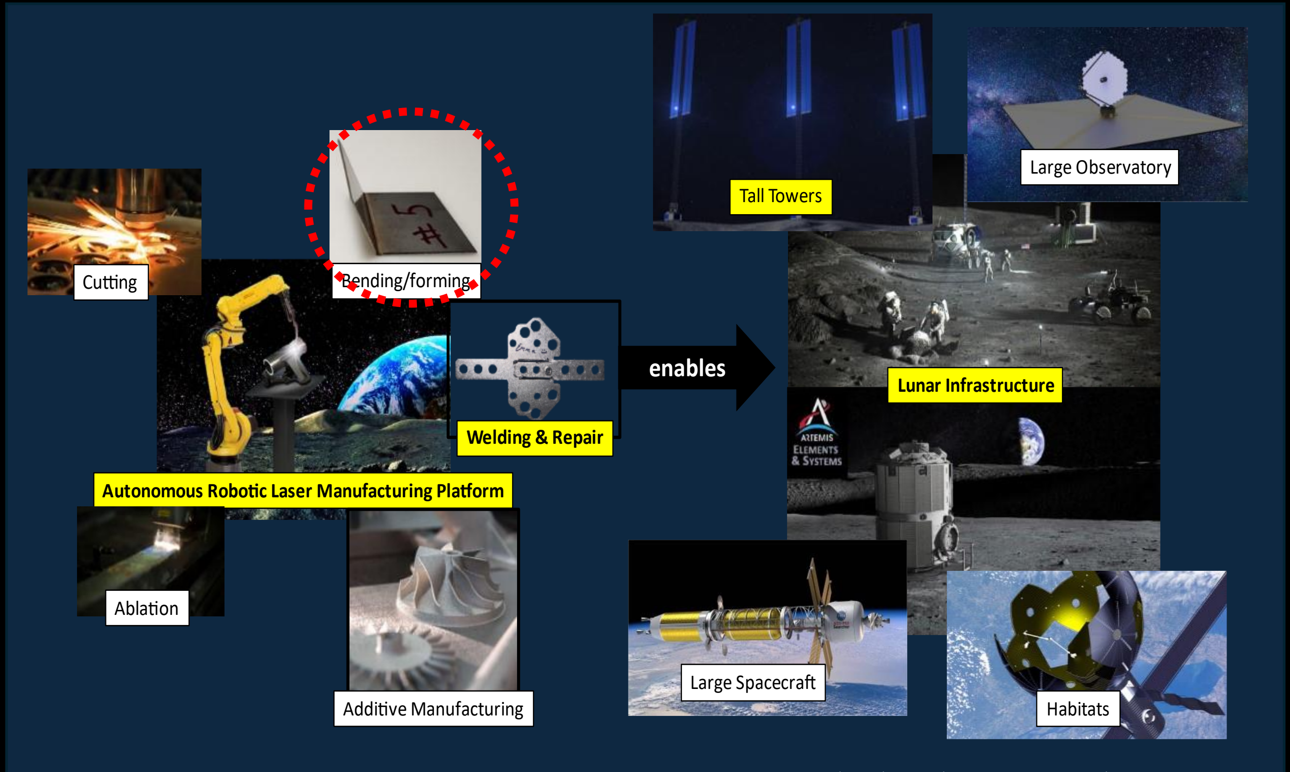
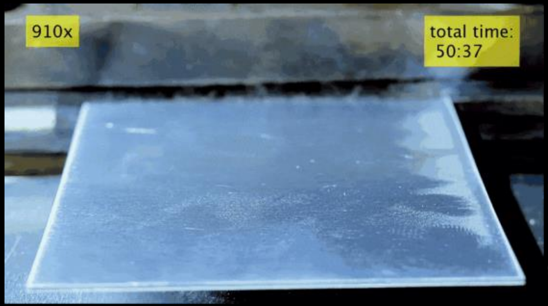
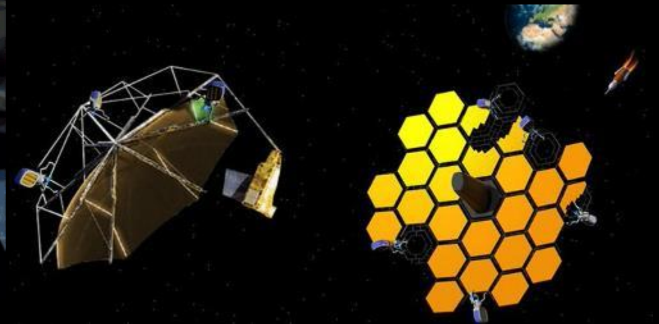


Image credit: ThinkOrbital, www.mechanicalcaveman.com



Form complex geometries with minimal pre/post-processing or workpiece setup

Credit: University of Florida

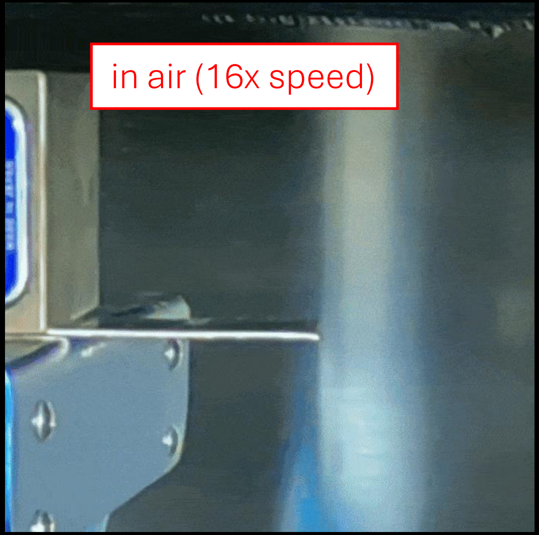


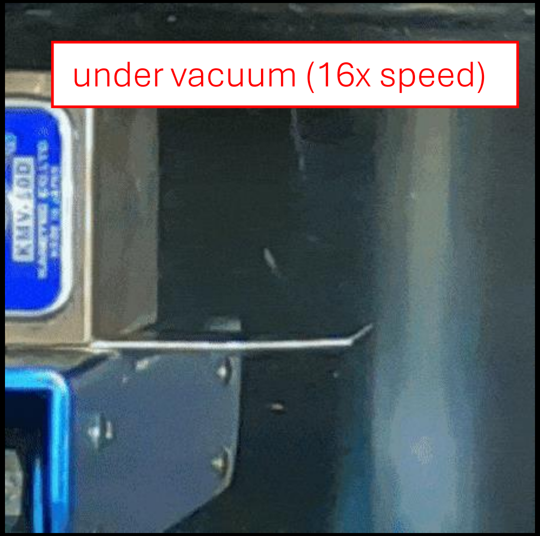
Credit: DARPA

Background

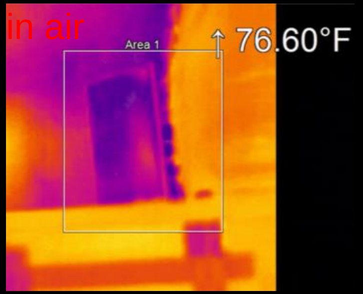
Laser Forming at MSFC

Less than two weeks from authority to proceed to initial demonstration of laser forming in air and under vacuum

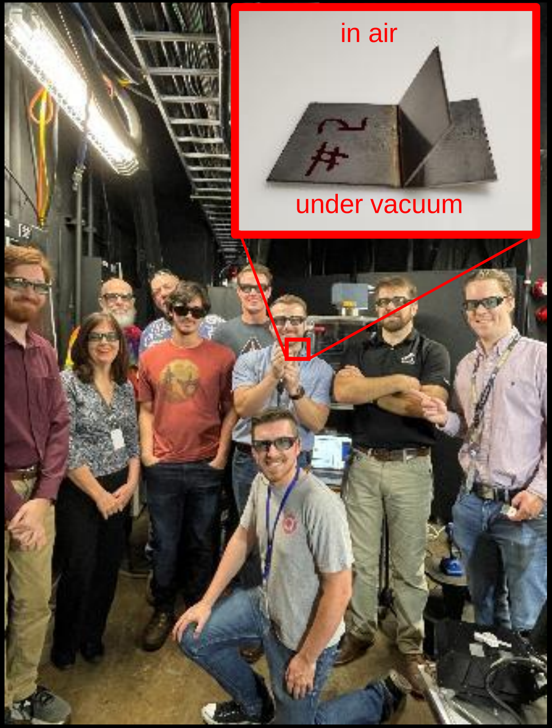




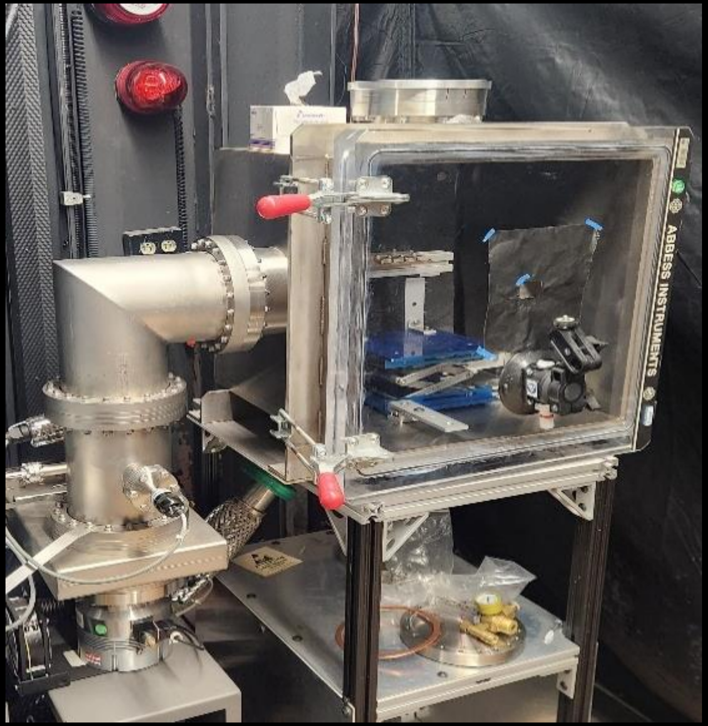
Laser bent AISI 304 stainless steel, 0.6 mm thick



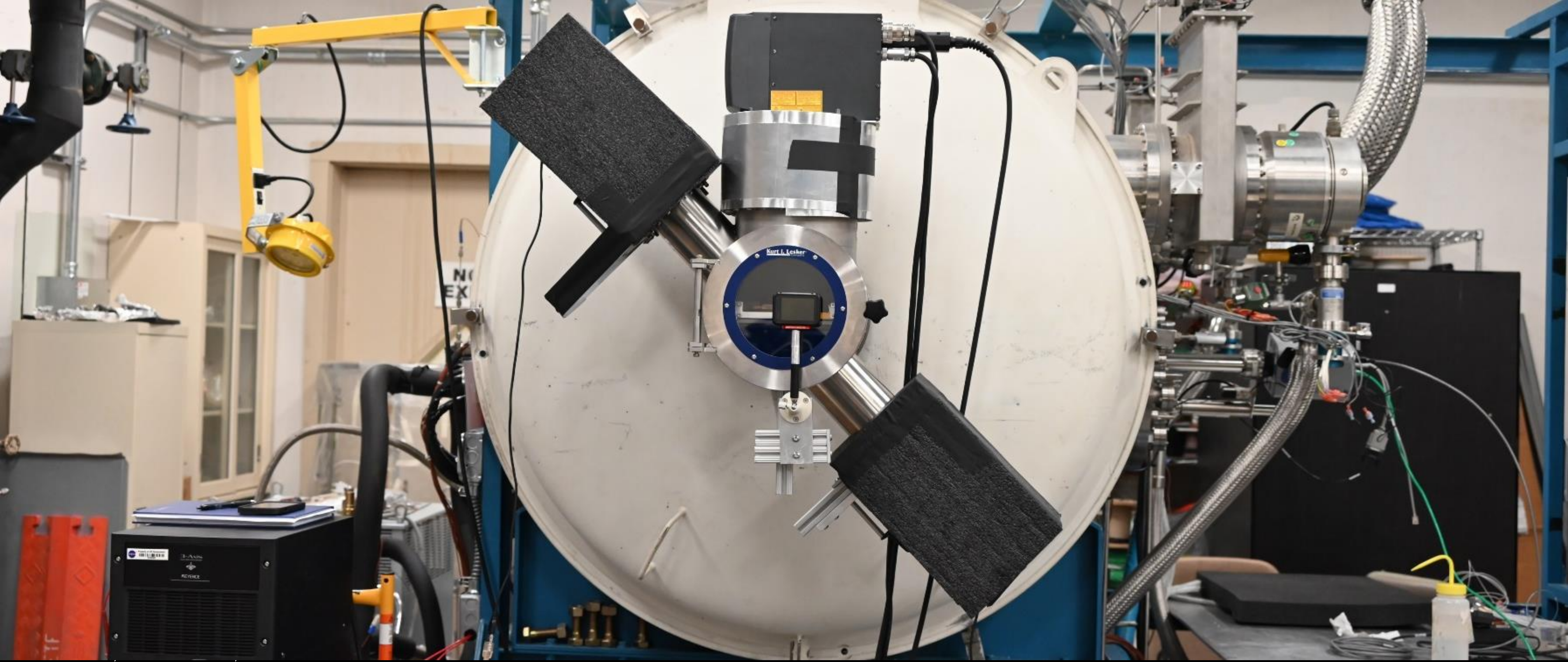
Long-wave infrared thermography



Initial laser bending demonstration team



Developmental vacuum chamber for rapid parameter development



Aluminum, Stainless Steel, and Titanium

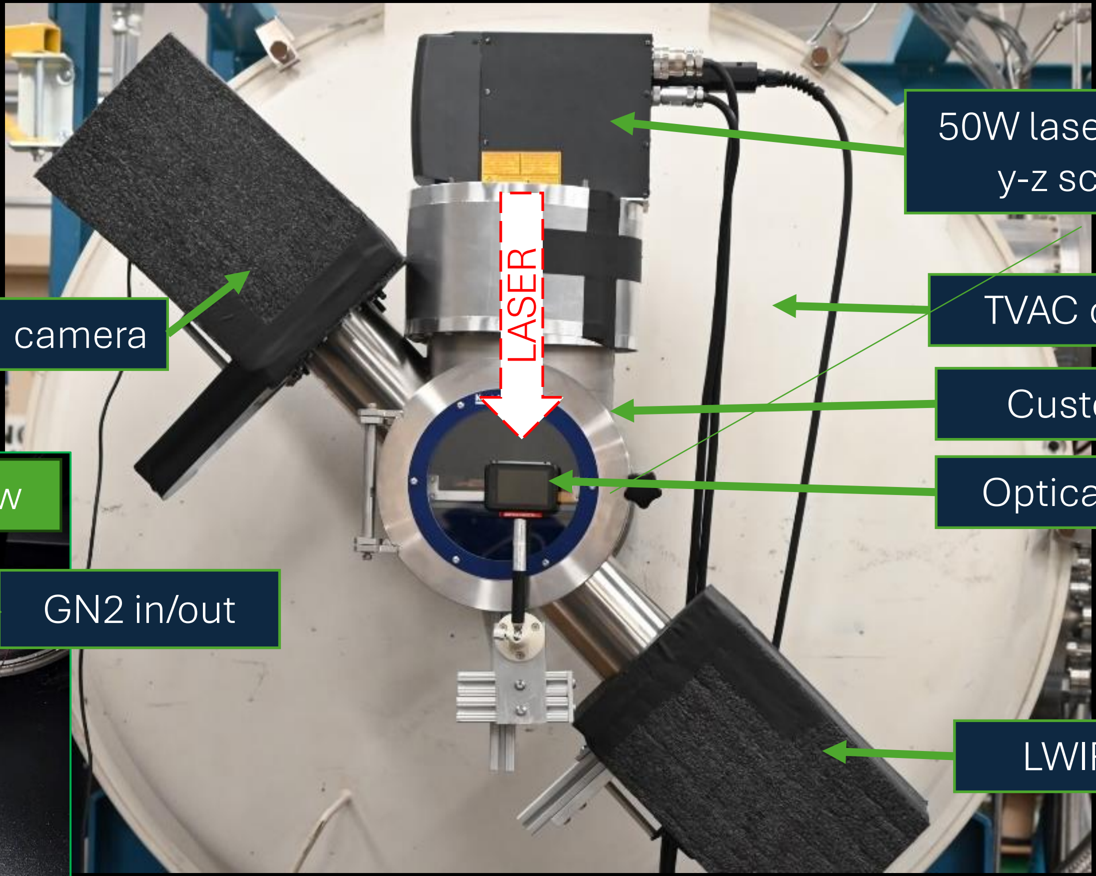
TVAC Trials

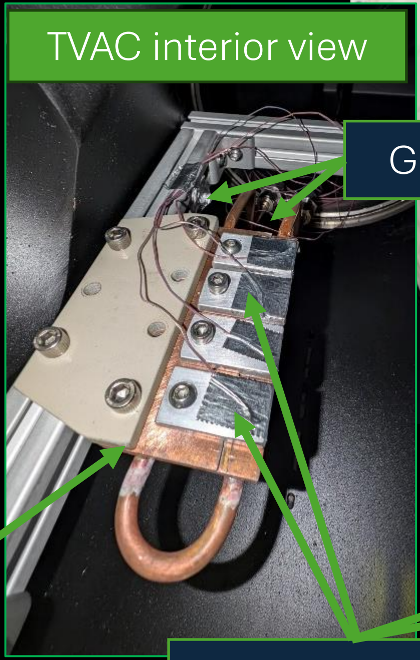
Thermal Vacuum Trials

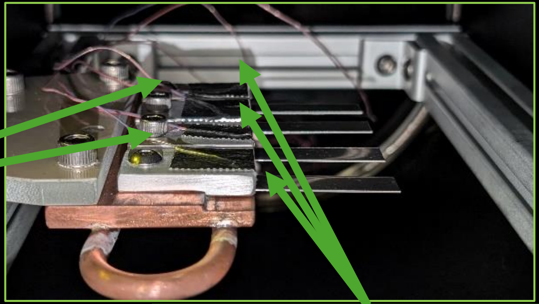
TVAC Setup at MSFC

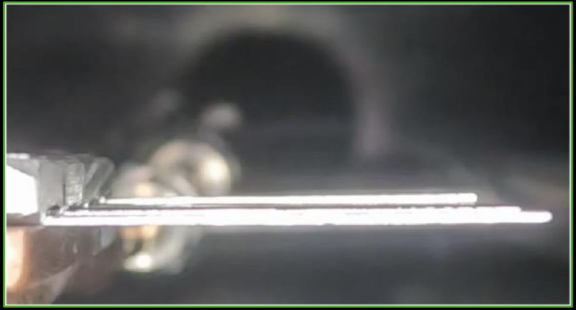
V-9 TVAC with custom "Tee":

- Vacuum down to ~10^{-5} Pa (10^{-7} Torr): convective heat transfer suppressed
- Temperature held from ~150 to 330 K (-120 to +60 °C): active thermal control of fixturing/specimens







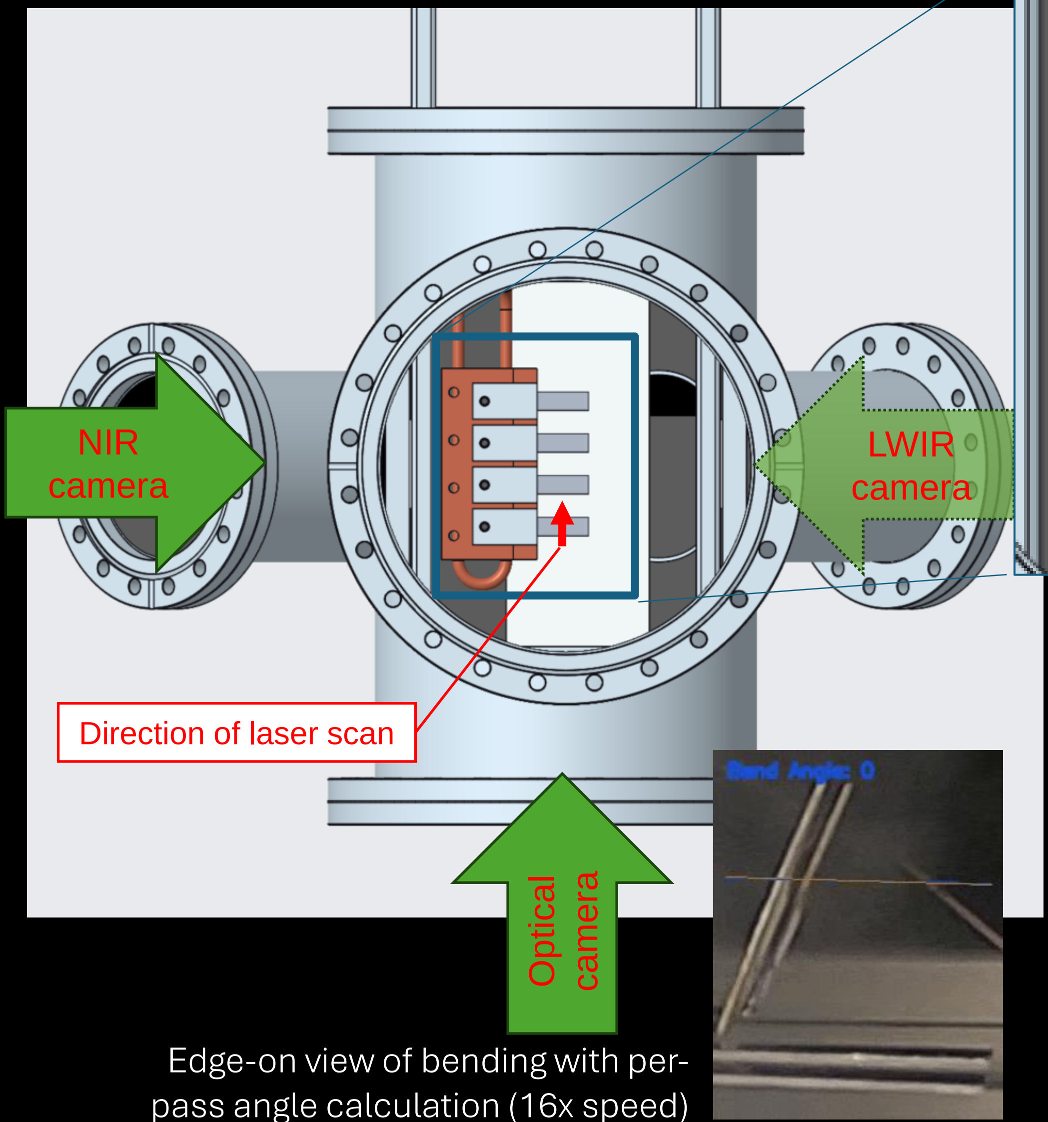


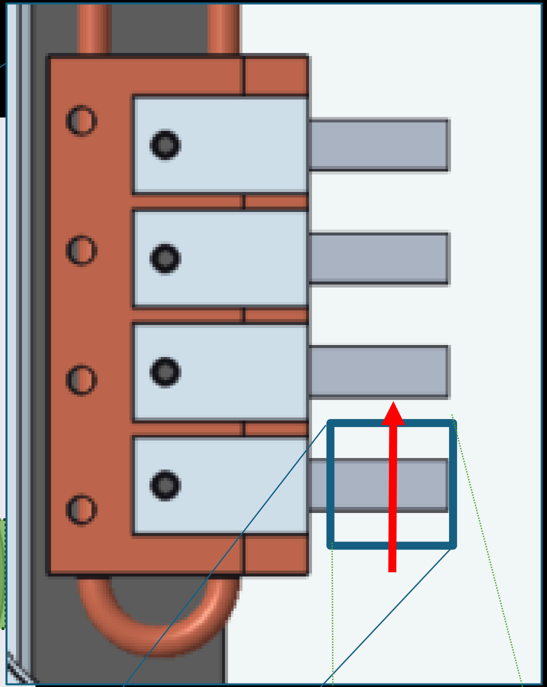
Side-on view during bending

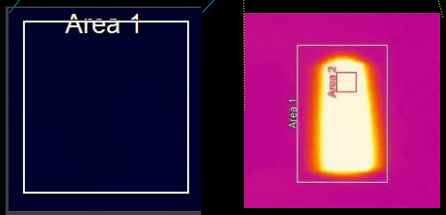
Thermal Vacuum Trials

Thermography and Videography

- Correlating bend-per-pass measurements with thermography to reveal underlying mechanism and accelerate technology maturation
- IR thermography not calibrated, cannot give absolute values but suitable for trends analysis;
- ~ 600°C is lower limit of NIR thermal camera (Optris PI 08M)
- ~ 250°C is upper limit of LWIR thermal camera (Optris PI 640i)







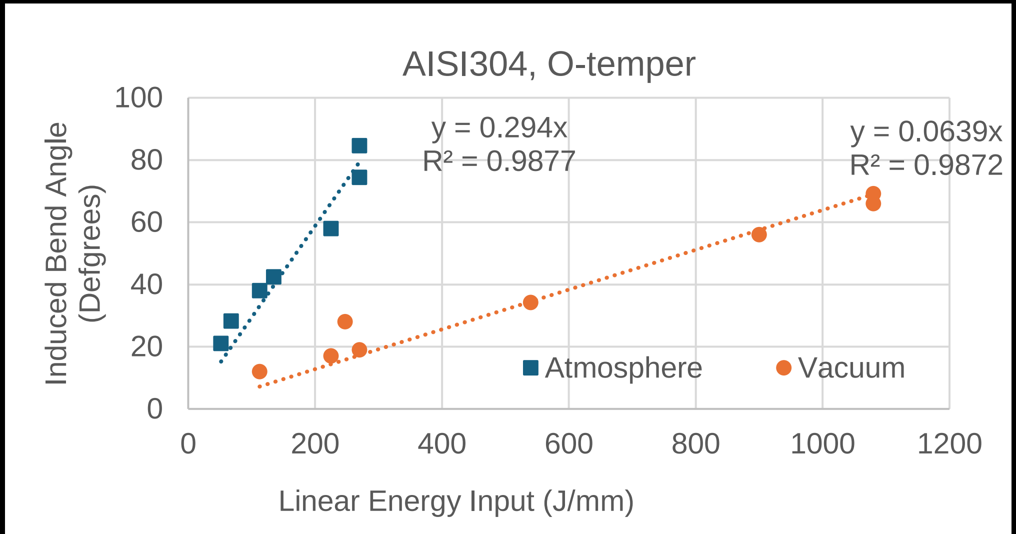
Thermographs of bend region: NIR (obverse) and LWIR (reverse)

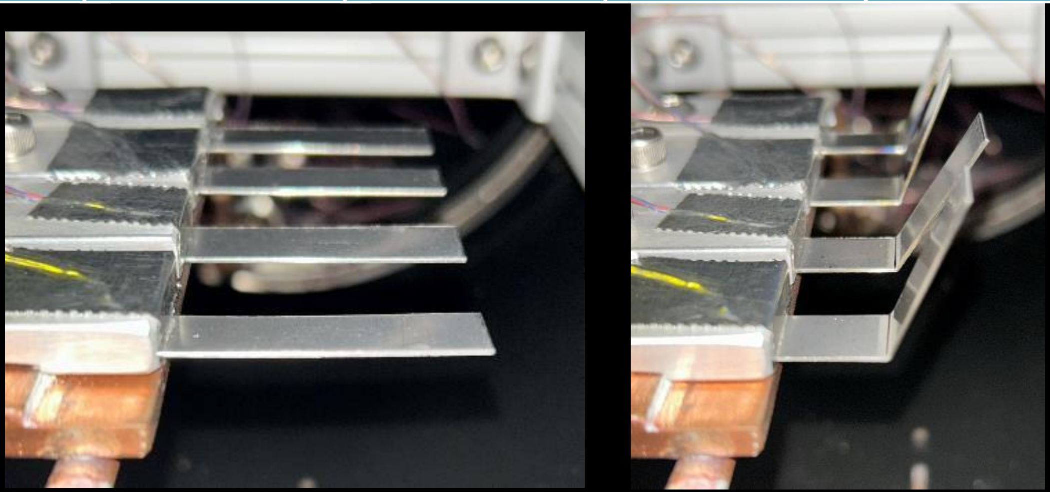
Edge-on view of bending with per-pass angle calculation (16x speed)

Thermal Vacuum Trials

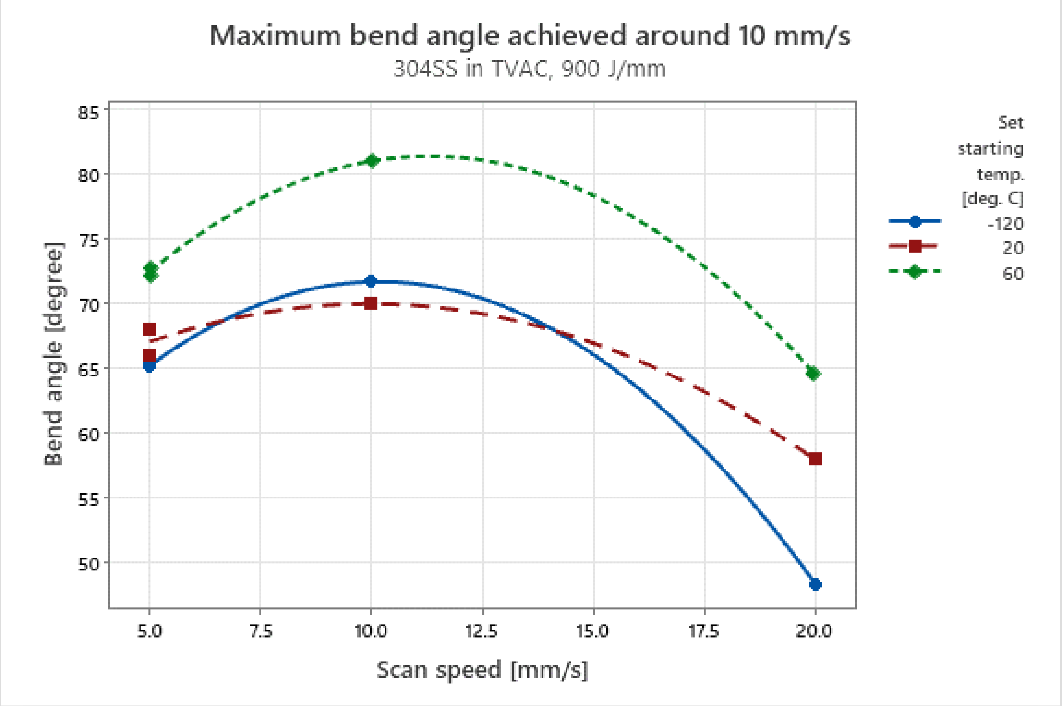
AISI 304 Stainless

- Linear regression for AISI304 on linear energy density gave confidence to proceed to TVAC trials
- Remarkably consistent bending in TVAC at same linear energy density for AISI304
- Relative insensitivity to process parameters points towards domination by thermophysical properties for AISI304 (low thermal diffusivity)





AISI304 strips bent at -120°C workpiece initial temperature under vacuum

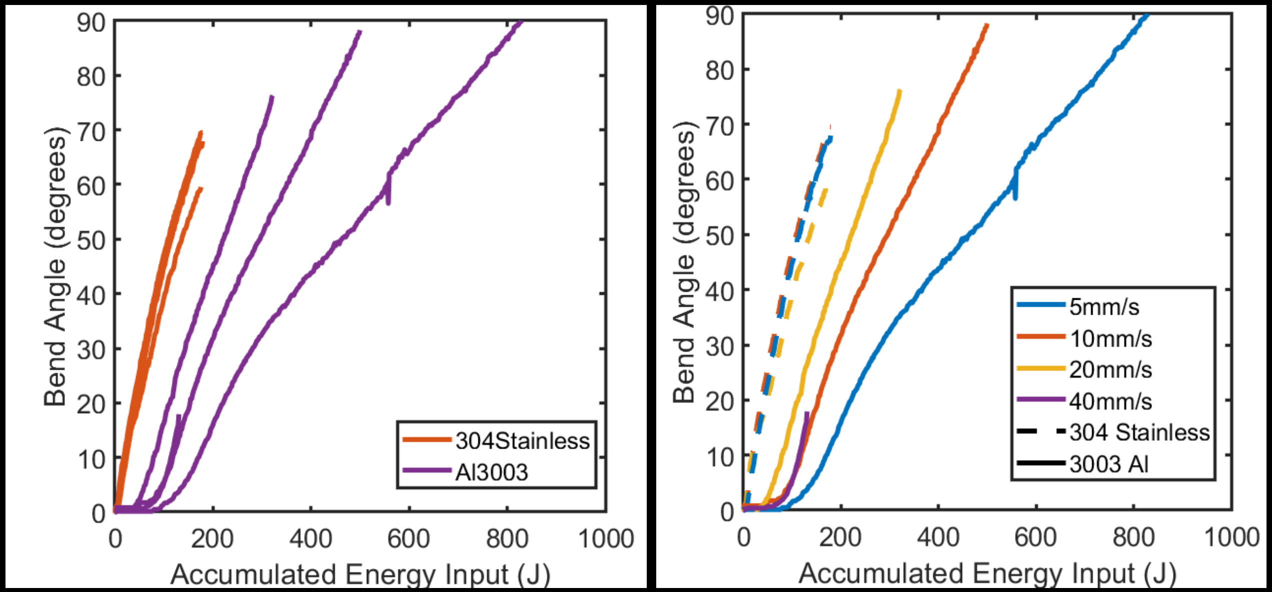


Higher process temperatures demonstrated more bending

Thermal Vacuum Trials

Aluminum 3003

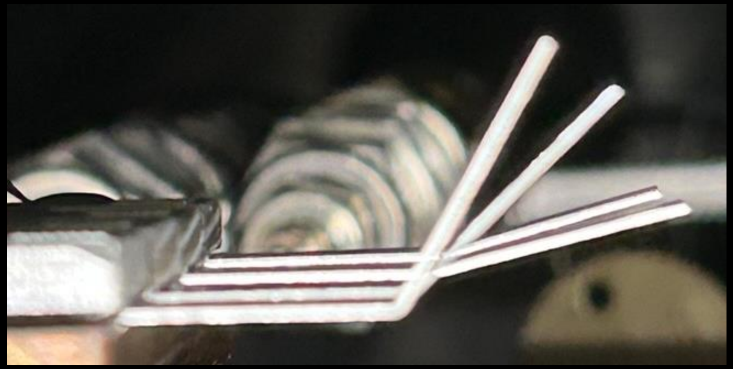
- Aluminum comparisons from trials:
  - More variable to scan speed than steel
  - Requires more energy due to reflectivity
  - More sensitive to focus and workpiece displacement
- AA3003 far more sensitive than AISI304 in general for LF
  - Smaller process window for input energy: lower melting point and higher reflectivity
  - Higher thermal diffusivity requires better control of energy input rates
  - Smaller windows for energy input and rate require tighter control of focus and laser spot size



Vacuum Ambient: TVAC ~300 K; 20 °C

AA3003 (TVAC ~150 K ; -120 °C)

AA3003 exhibits reduction in bend angle at lower process temperatures



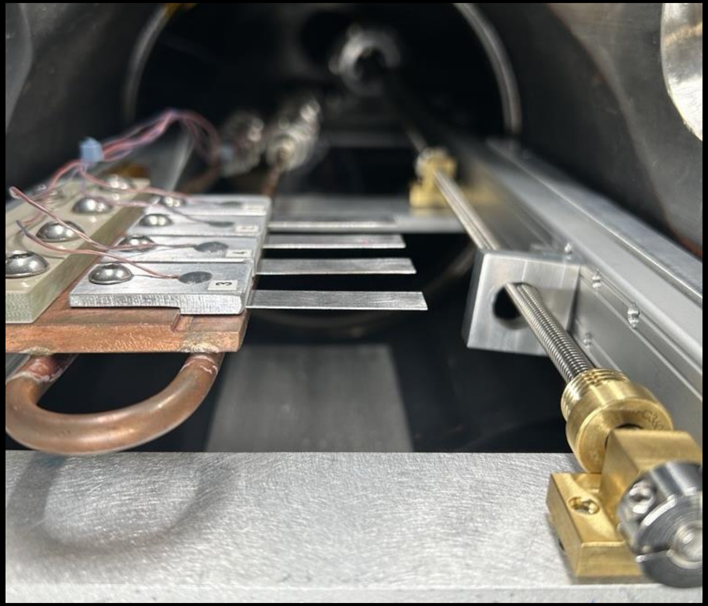
AA3003 (TVAC ~300 K ; 20 °C)

Large discrepancies in bend angle traced to slight variance in focus and/or workpiece displacement

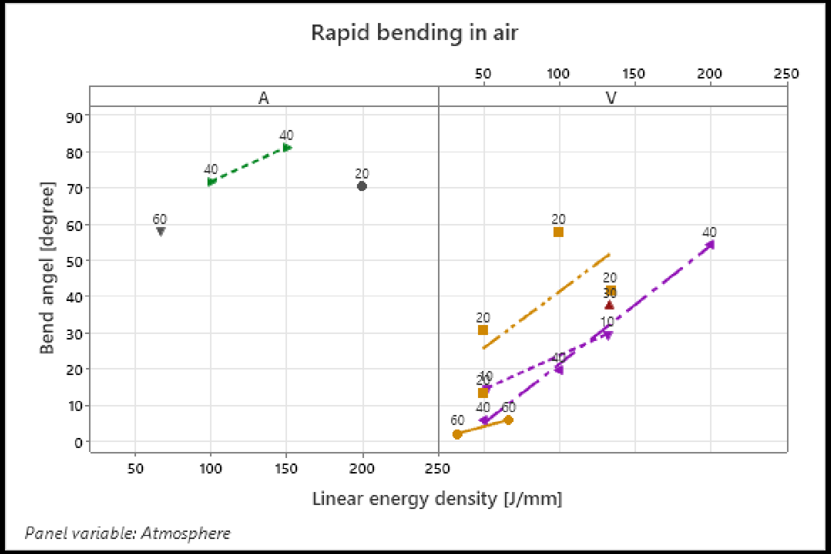
Thermal Vacuum Trials

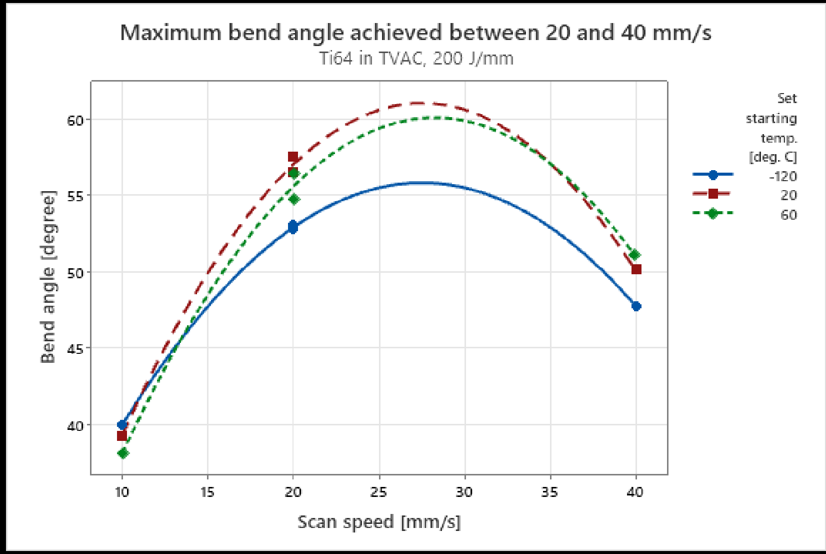
Grade 5 Titanium

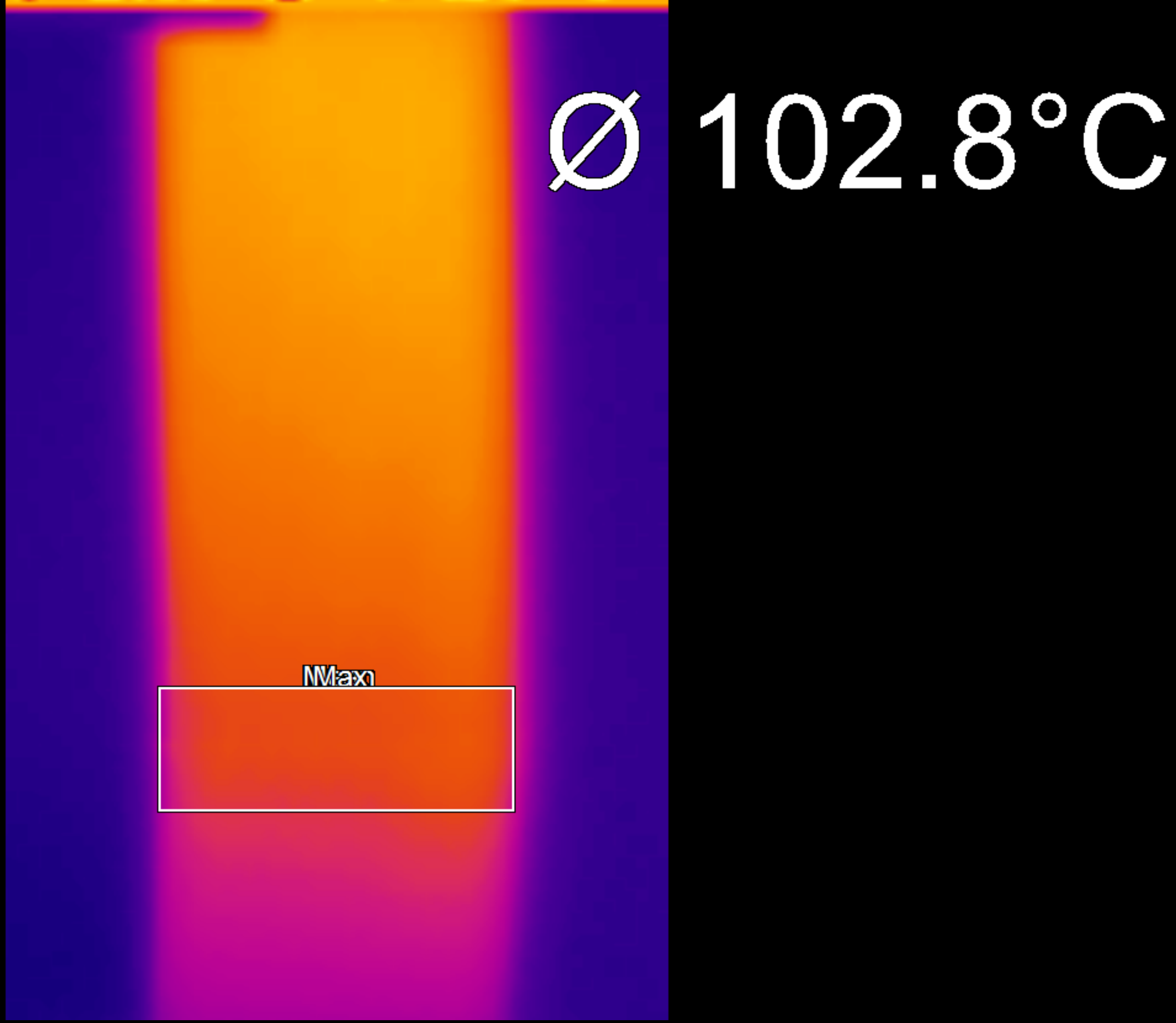
- Lessons learned from aluminum led to the incorporation of translation mechanism to maintain laser distance and focus (Skylab Solar Array Deployment EDU)
- Titanium appears less sensitive to process temperature than scan speed
  - Note: titanium's thermal diffusivity and reflectivity are lower than both stainless steel's and aluminum's
- Process models to consider thermomechanics

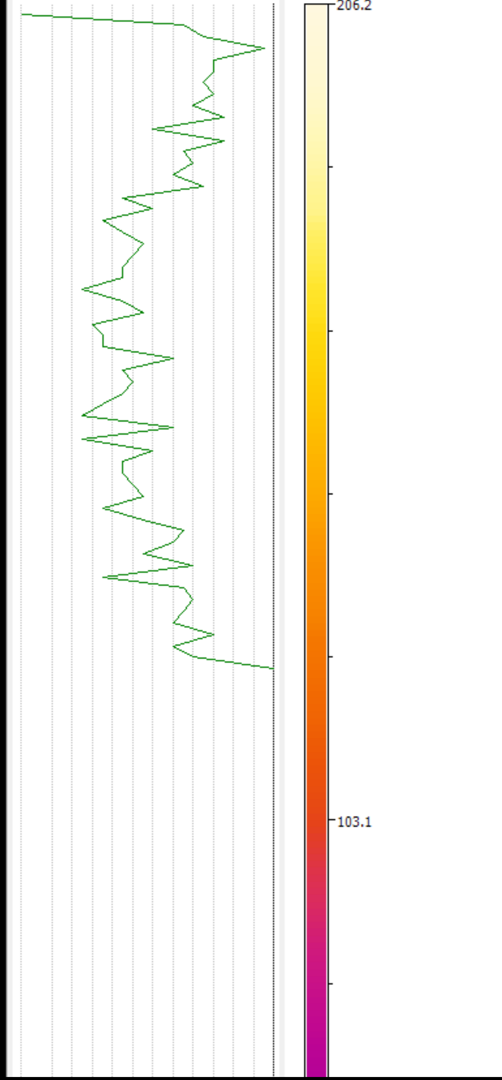


Ti64 in TVAC ~150 K; -120 °C









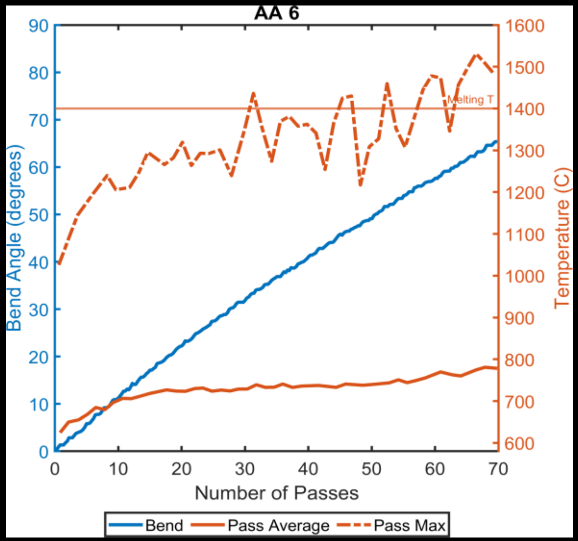
In-Situ Monitoring Analysis

Thermography

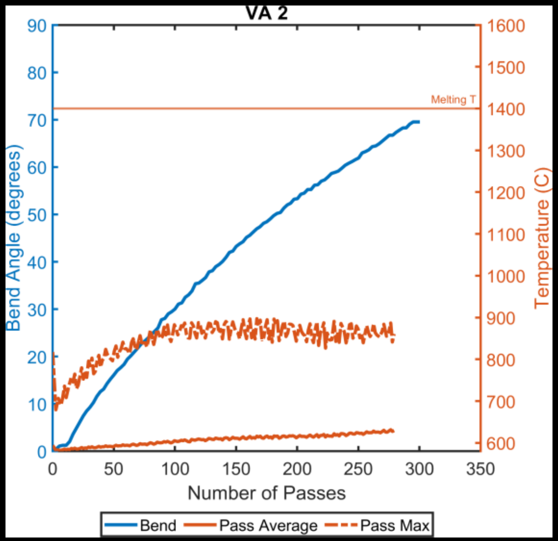
Thermography: AISI 304

Typical Trends

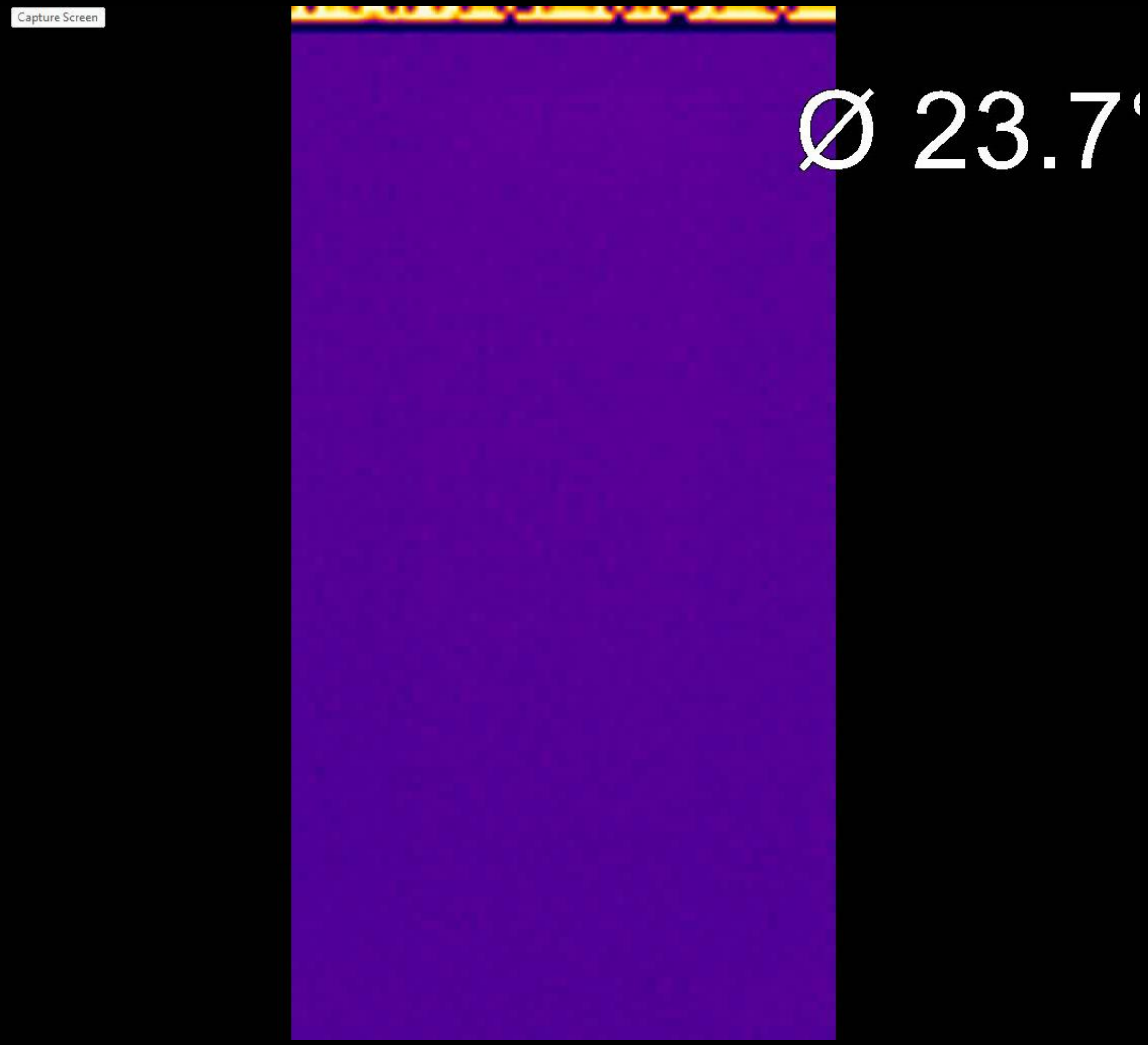
- Full thermal analysis of all TVAC trials still in process
    - AISI 304 is described here to demonstrate response in air vs. vacuum
- In atmosphere, laser spot hits AISI304 liquidus; in vacuum, laser spot remains well below liquidus
- Current hypothesis is that oxidation provides both additional energy and better coupling with laser, increasing the efficiency of energy input drastically



Atmosphere Ambient



Vacuum Ambient



Reverse side thermography of AISI304

Steel, Titanium, Aluminum

Metallography

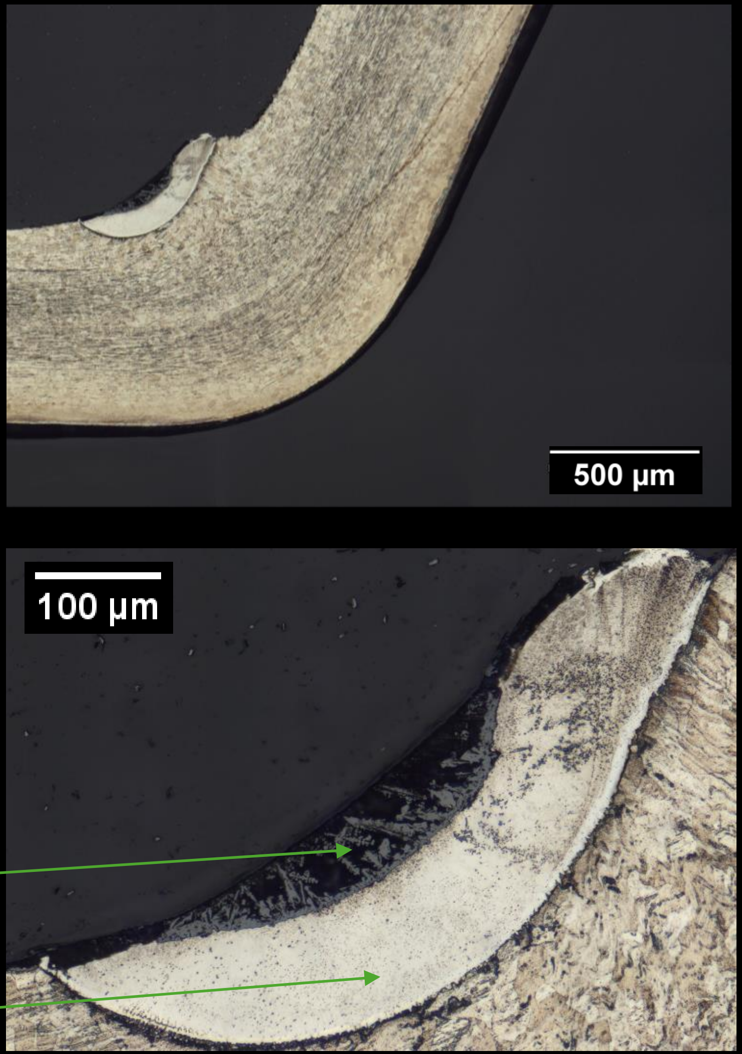
Metallography

AISI 304 Stainless

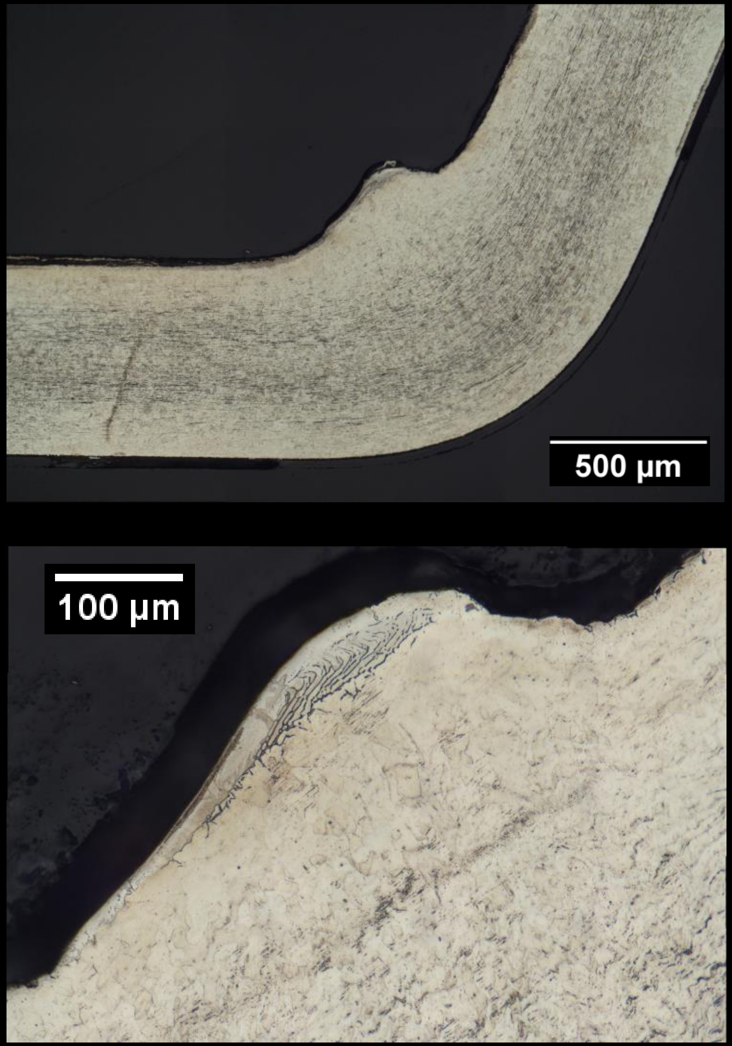
- Both conditions evidence geometry distortion to accommodate bending
- Evidence of melting only in exists in air
  - Lends credence to thermography measurements
  - Evidences different laser-material interaction under vacuum
- Postulated mechanisms:
  - Growth of oxide layer
  - Ablation of oxide layer
  - Generation of plasma

Re-solidified region, including dendrites

Restructured region



Atmosphere Ambient

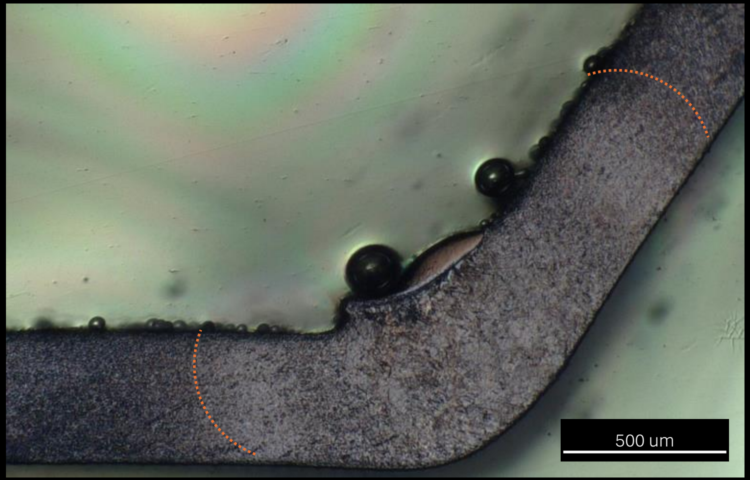


Vacuum Ambient

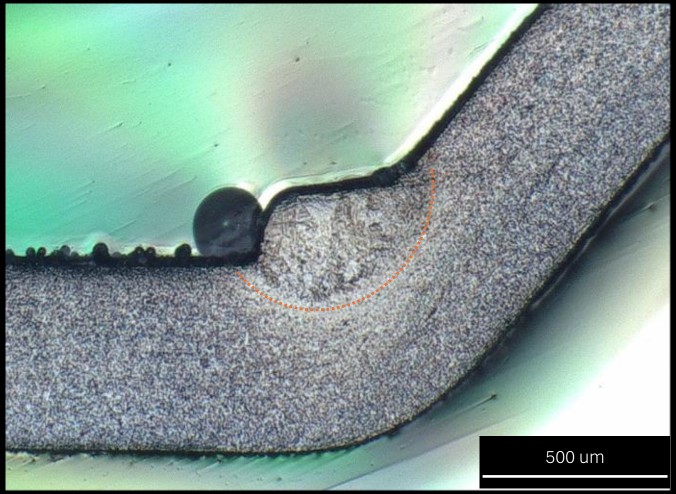
Metallography

Grade 5 Titanium

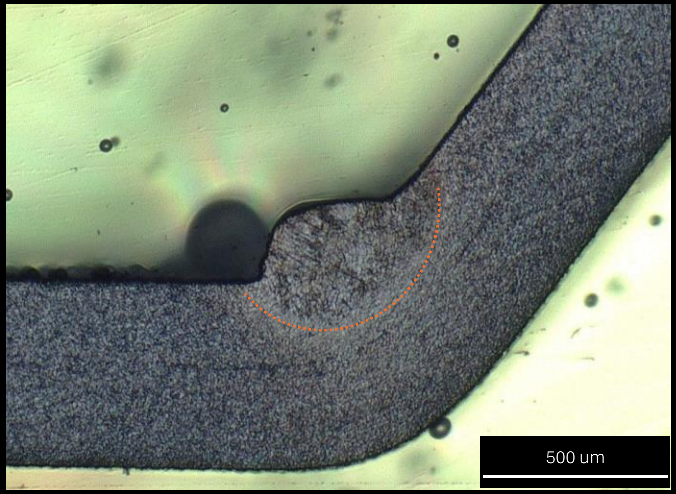
- Heat-affected/transformed area larger and more noticeable in atmosphere
  - Expected alpha case present
- In vacuum, volume of heat affected region relatively unchanged with respect to process temperature
  - Somewhat against expectations from effects of workpiece temperature on melt pool in welding



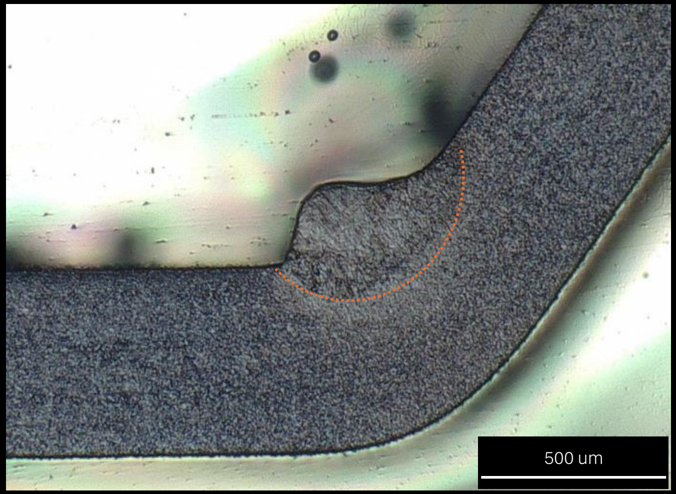
Atmosphere Ambient



Vacuum Cold



Vacuum Ambient

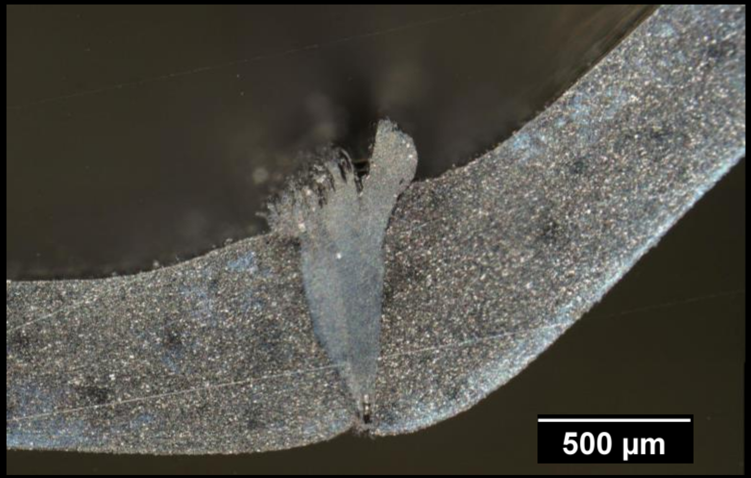


Vacuum Hot

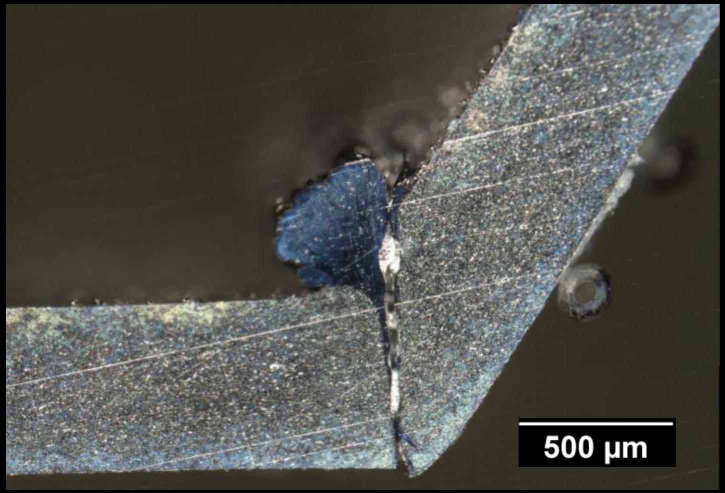
Metallography

3003 Aluminum

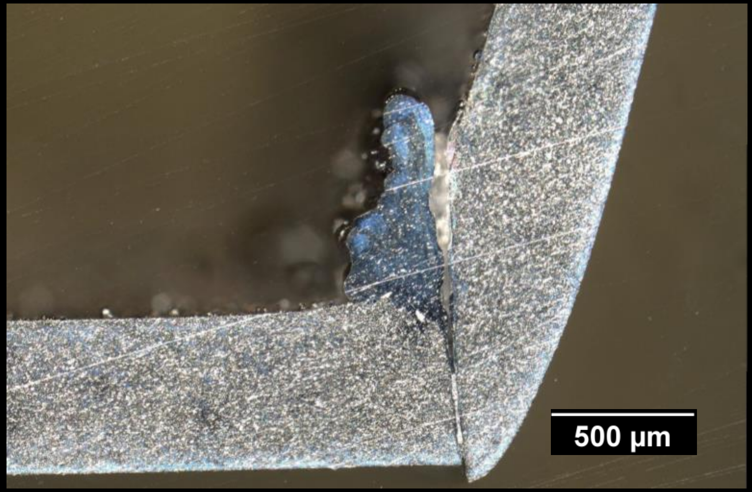
- Highly energetic operation for aluminum; melting observed in many, if not all cases
  - Negative impacts on bend region strength are likely
- Note: Metallography performed on most recent trials of aluminum TVAC testing in which laser was highly focused; process optimization is expected to modify this result



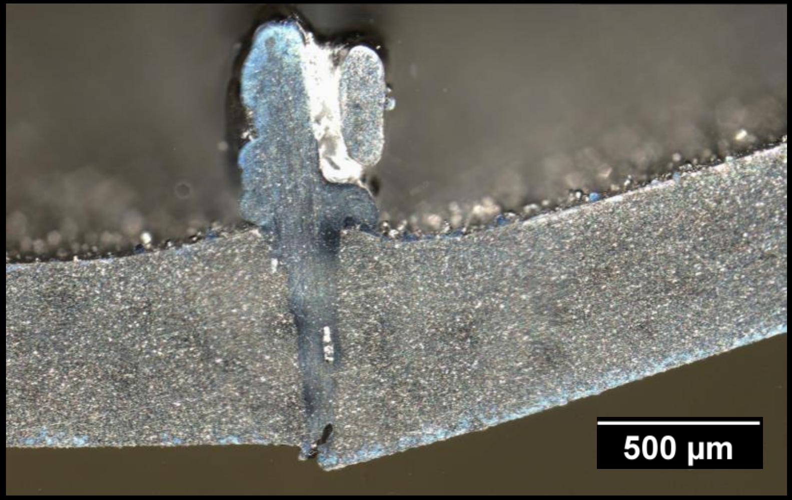
Atmosphere Ambient



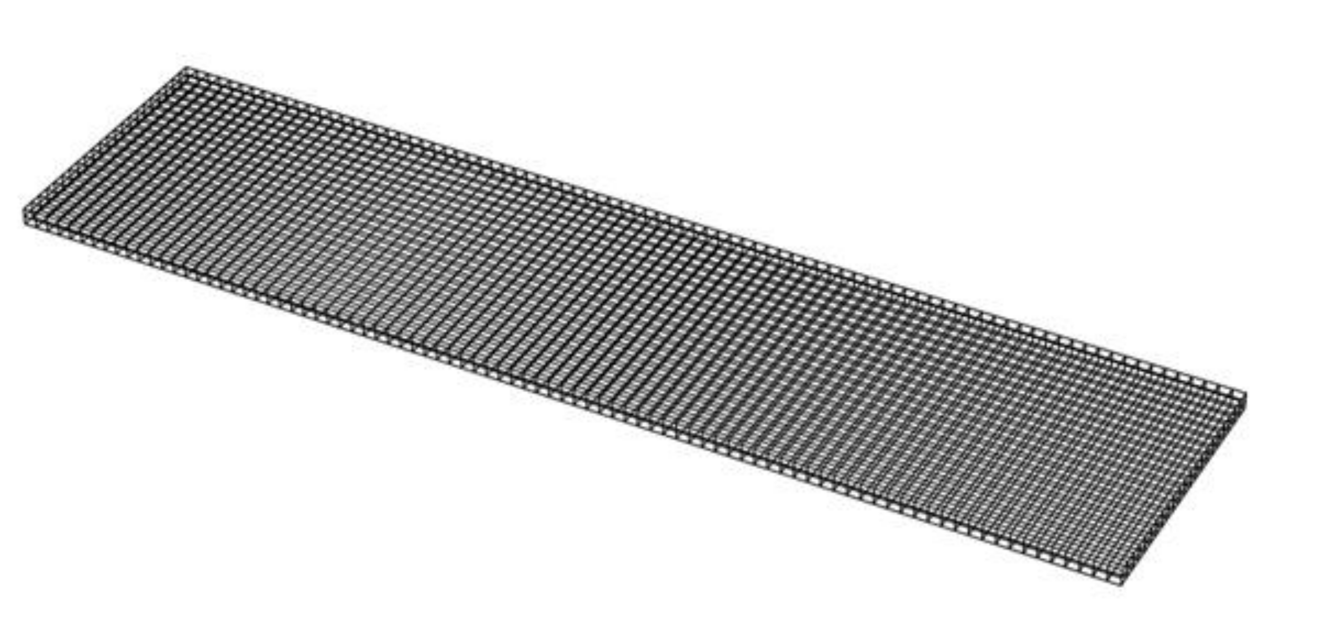
Vacuum Cold

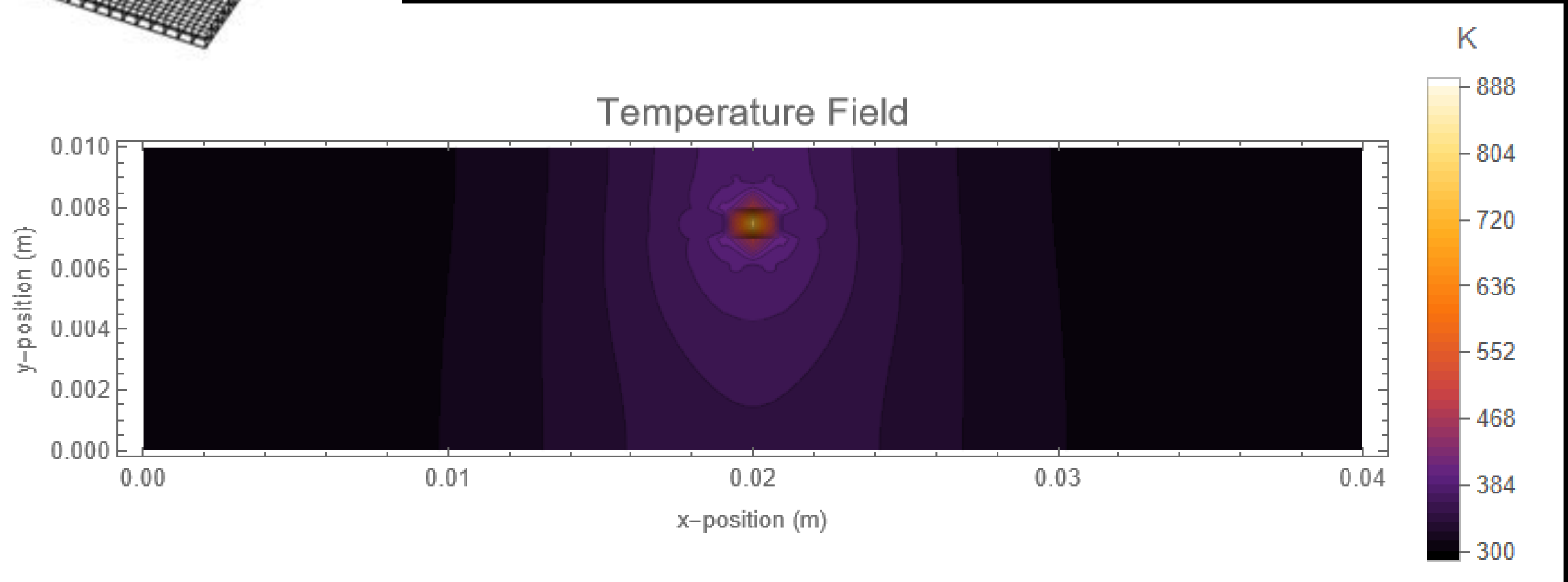


Vacuum Ambient



Vacuum Hot





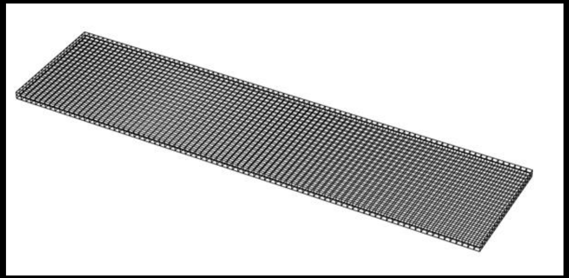
Thermophysical Properties Integration

Digital Twin & Modeling

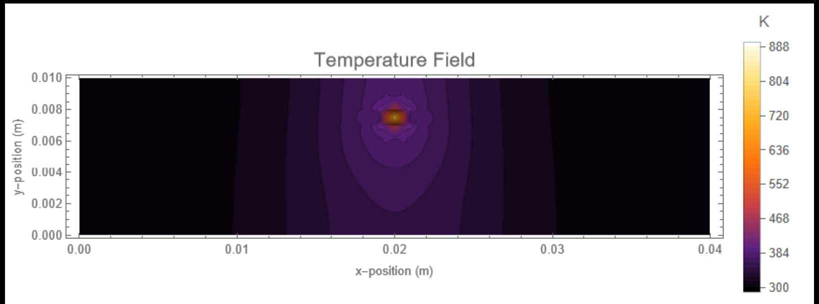
Digital Twin

Thermal Modeling

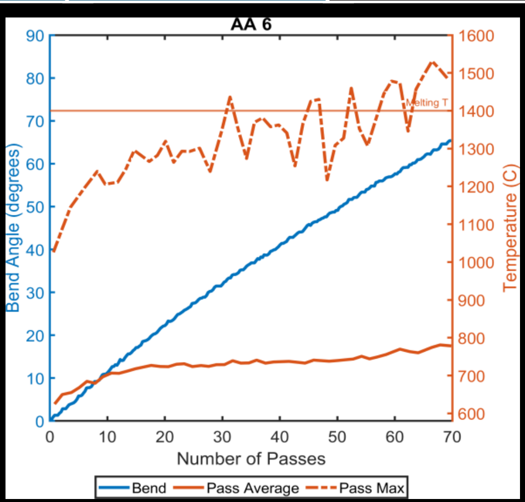
- FEA thermal model beginning to reveal air/vacuum behavior
- Initial evaluation of thermal model shows general agreement with NIR obverse (top-side, under laser spot) measurements
- Hints that oxidized vs bare (ablated) surface may explain differences in bending in air vs vacuum

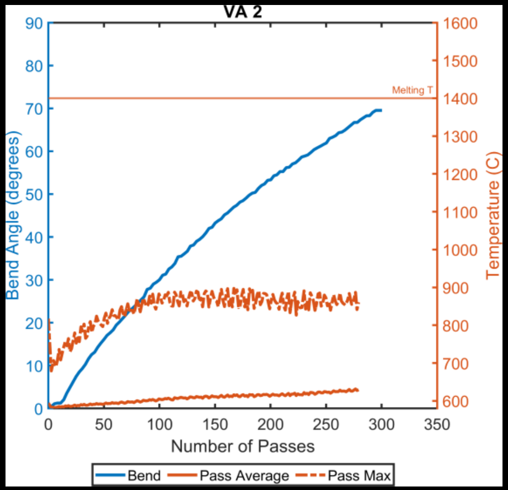


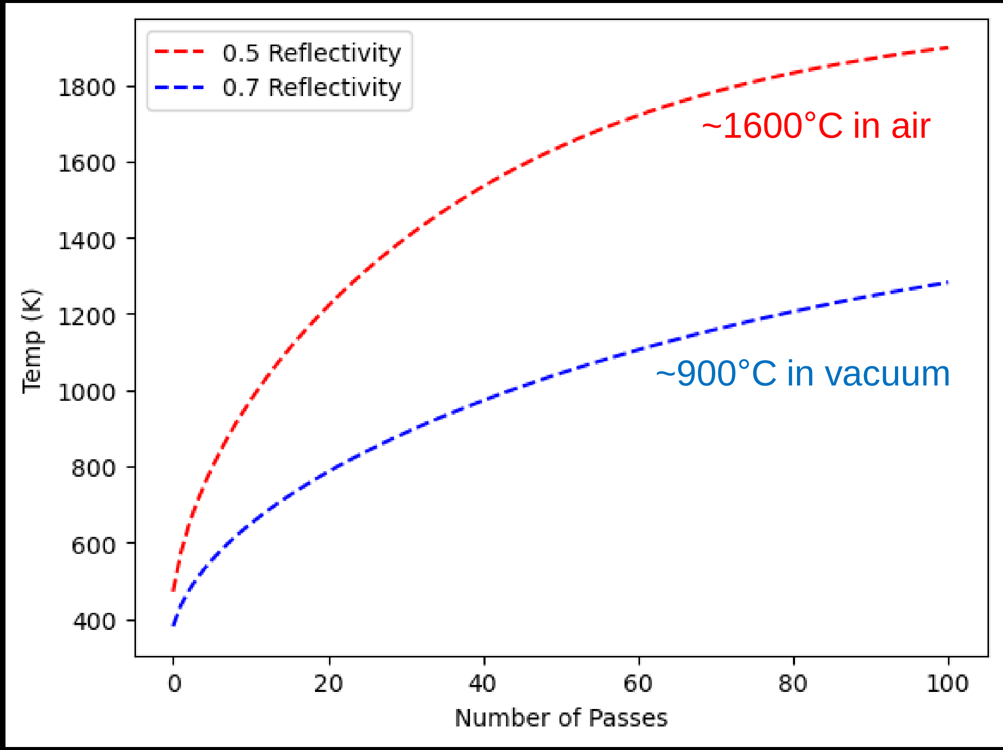
FEA model depicting a thin LF specimen



Preliminary thermal model depicting temperature field of Al LF specimen





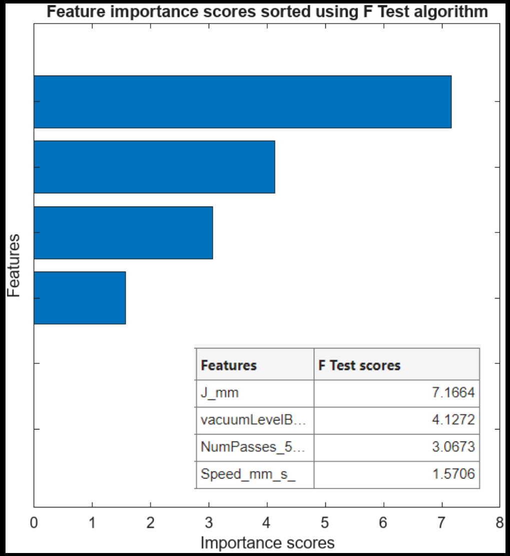


Thermography measurements compared to thermal modeling results

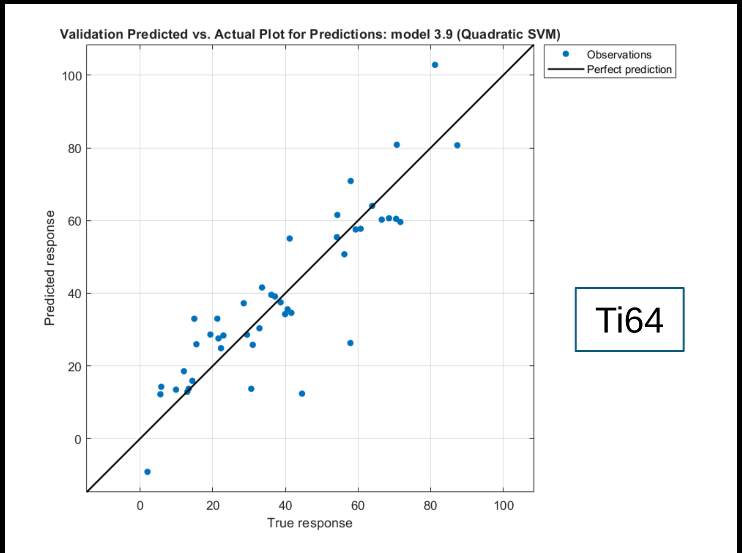
Digital Twin

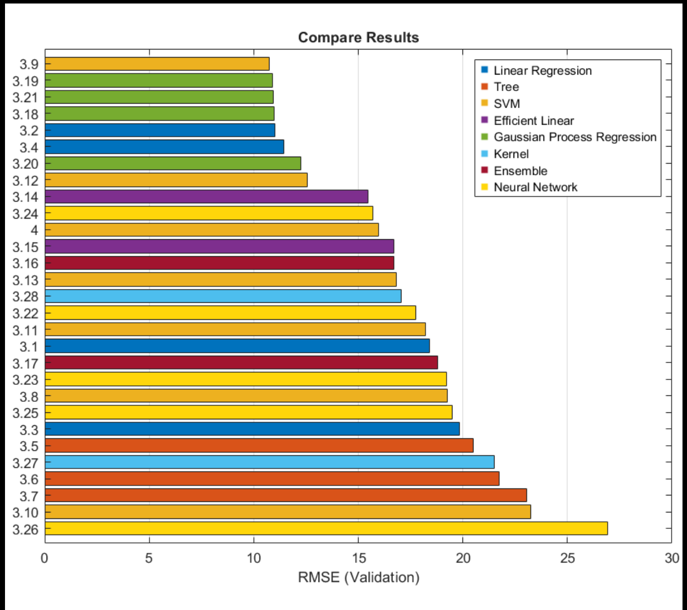
Bend Angle Prediction

- Using ML on datasets to assign weight to factors and fit regressions to bend angle results
- Actively collecting more data to improve confidence in results
- Energy density and vacuum level most influential positive factors
- Temperature an influential negative factor, but one-half intensity

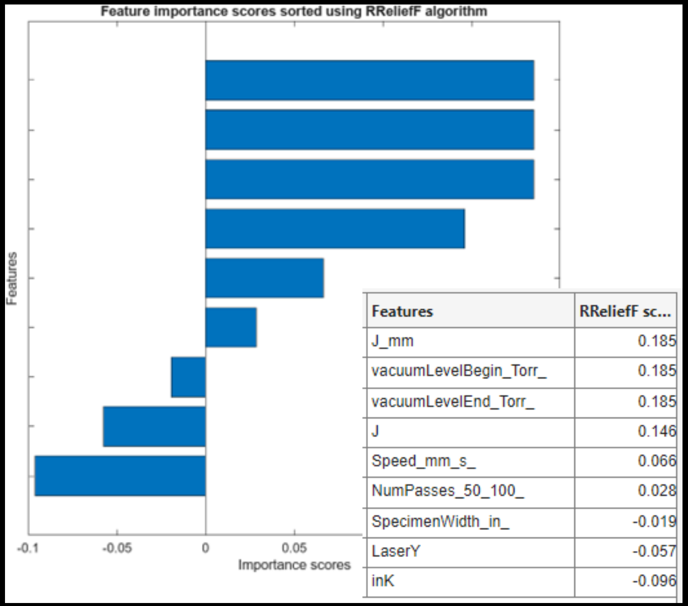


Features	F Test scores
J_mm	7.1664
vacuumLevelB...	4.1272
NumPasses_5...	3.0673
Speed_mm_s_	1.5706



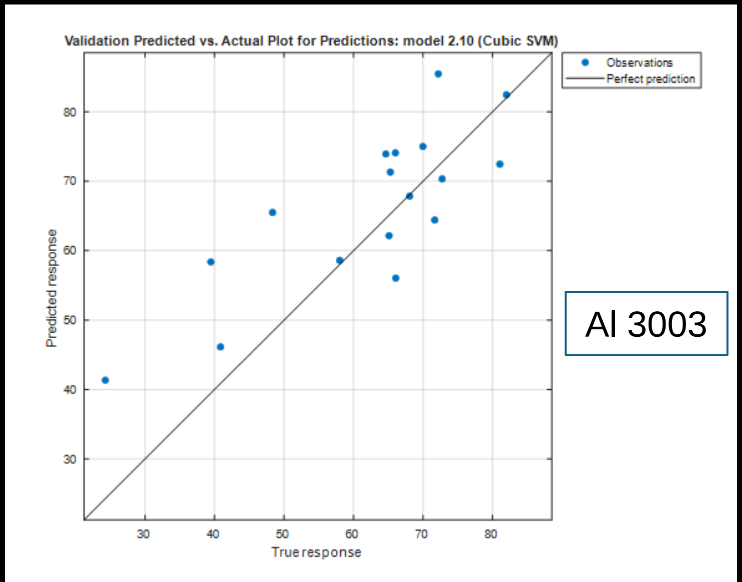


Evaluation of various ML model types for laser forming

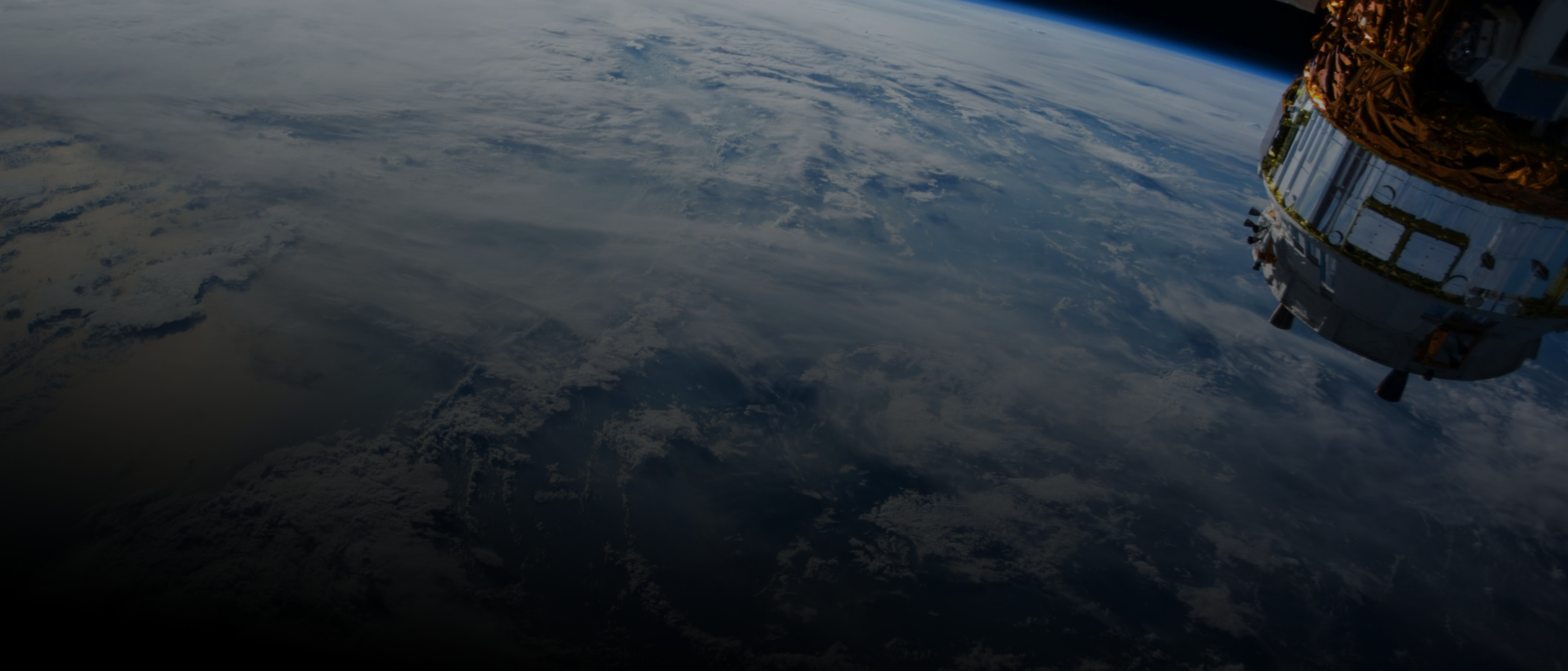


Features	RReliefF sc...
J_mm	0.185
vacuumLevelBegin_Torr_	0.185
vacuumLevelEnd_Torr_	0.185
J	0.146
Speed_mm_s_	0.066
NumPasses_50_100_	0.028
SpecimenWidth_in_	-0.019
LaserY	-0.057
inK	-0.096

Ranking features by importance using RReliefF



Regression output via cubic support vector machine (SVM)



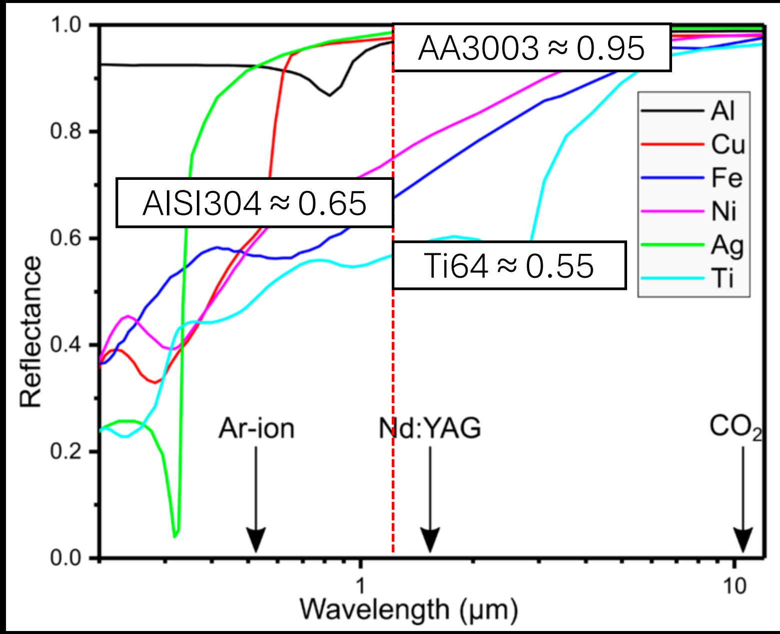
Summary Work To-Date

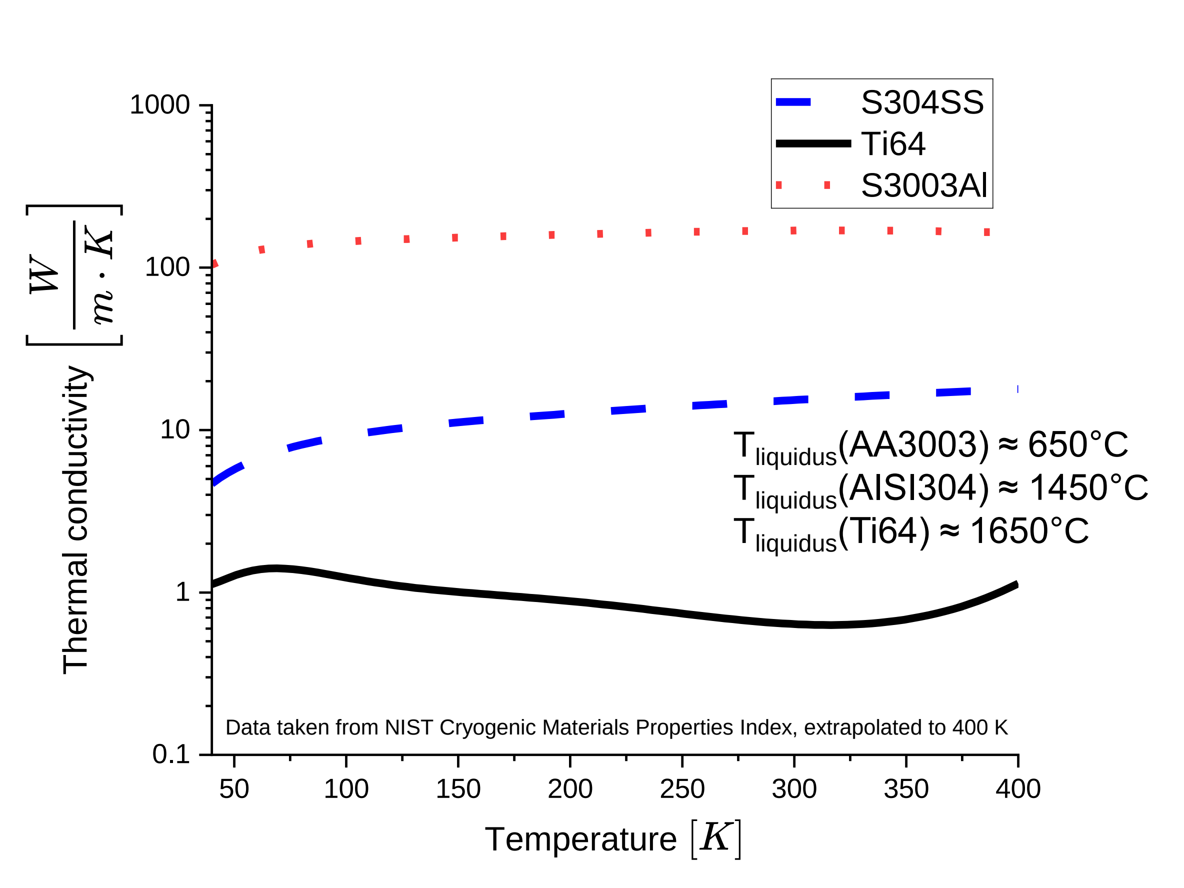
Discussion

Discussion

Material Property Effects

- AA3003 proved to have a noticeably tighter process window:
  - Higher power and tighter control to induce bending due to slower thermal build-up from order-of-magnitude higher thermal conductivity and laser reflectivity
  - Much lower liquidus leads to spatter and other deleterious over-power conditions
- Process windows will be highly dependent on material and physical properties.

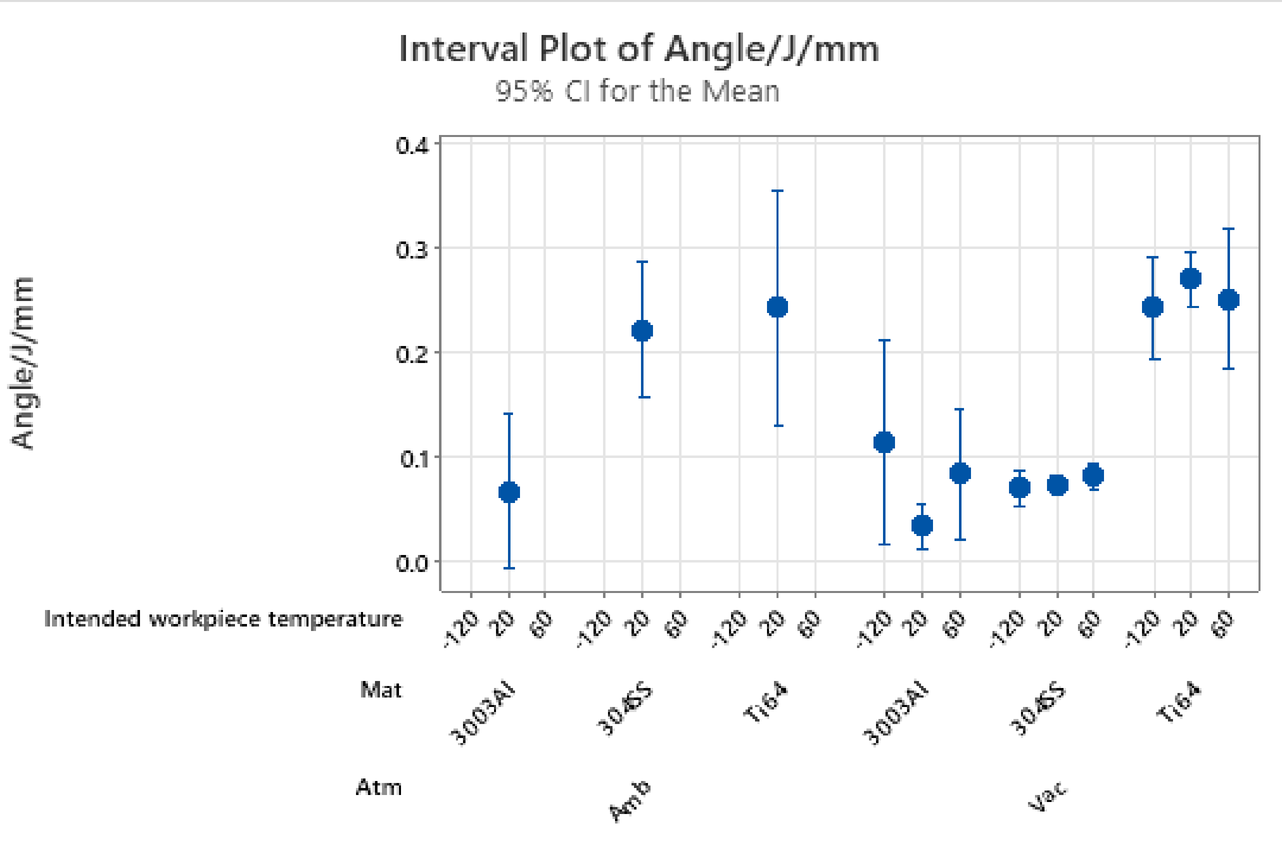




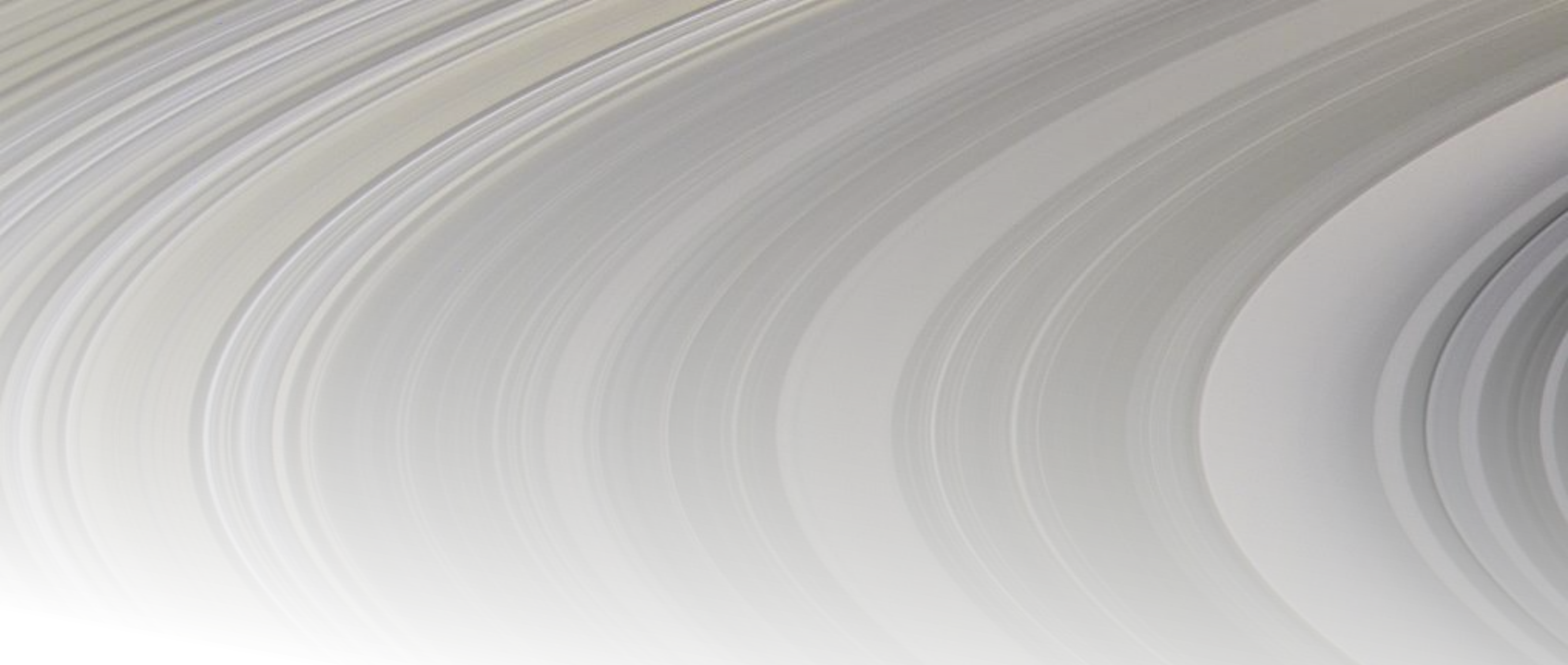
Discussion

Results Summary

- Change in angle of bend per linear density used as comparison across materials, energy input, scan speeds, etc.
- 3003 Al proved to require the most energy to bend in atmosphere, as well as be the most variable under vacuum
  - Lower melting point, higher reflectivity, and higher thermal conductivity suspected to be contributing factors to this observation
- NASA and partners are maturing in-space laser processes, including laser forming
  - Laser forming works in TVAC, imbuing confidence in its relevance for in-space manufacturing
- Building ecosystem of data, hardware, expertise, and partnering opportunities
  - TVAC experience and instrumentation expertise along with unique equipment & facilities
  - Computational models anchored by collected data
  - Network of academic (Univ. of Fla.), government (DARPA), and industrial collaborators/partners
  - Open to collaborations and partnerships, technology transfer, etc. with existing and new entities



Interval plot of all TVAC trials: intervals determined by individual standard deviations



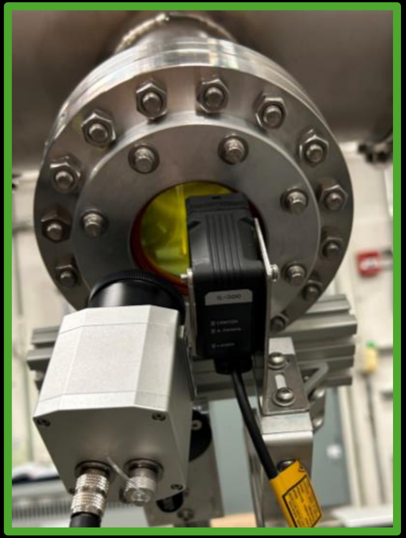
Ongoing and Planned

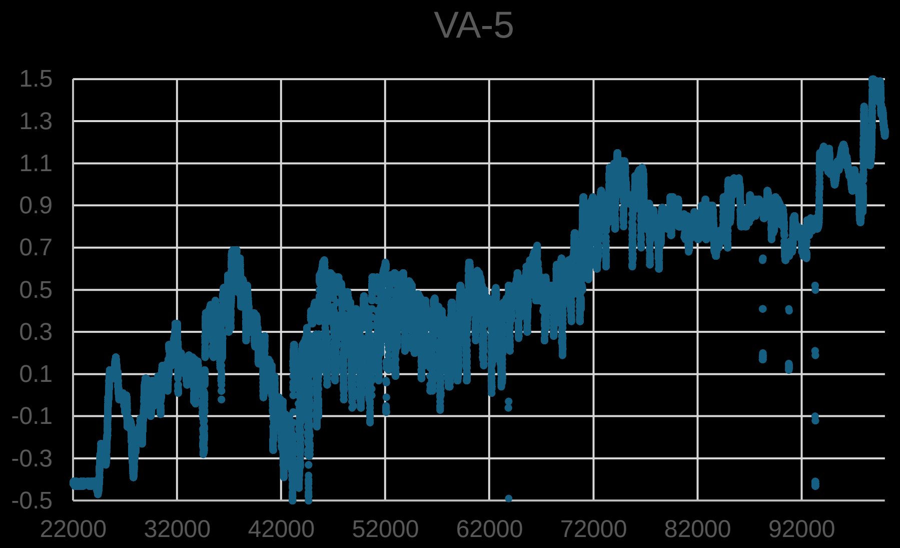
Future Work

Future Work

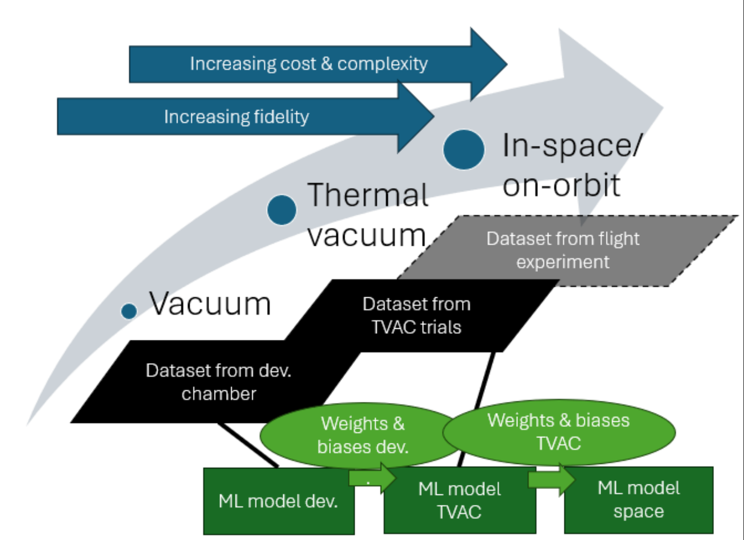
Ongoing Developments

- Developing laser displacement sensing for focusing & bend-per-pass measurement
  - Require ruggedized, in-vacuum sensor for future work (and space)
  - Allows faster, higher resolution, and more reliable bend-per-pass measurements
- Continued Materials Diagnostics:
  - Optical, SEM-EDS, XPS
  - Hardness Testing, Bend, & Tensile Testing
- Additional Data Collection for Machine Learning Models
  - Continue building Digital Twin via ICME
  - Pioneer ML transfer learning for laser forming
- Investigate influence of oxide layer thickness and laser etching
- Explore melting/oxidation differences that speed bending process in air
- Spectroscopy – determining if plasma present in air/vacuum





Laser displacement sensor added to lower viewport (left) and raw data collected during ongoing calibration (right)

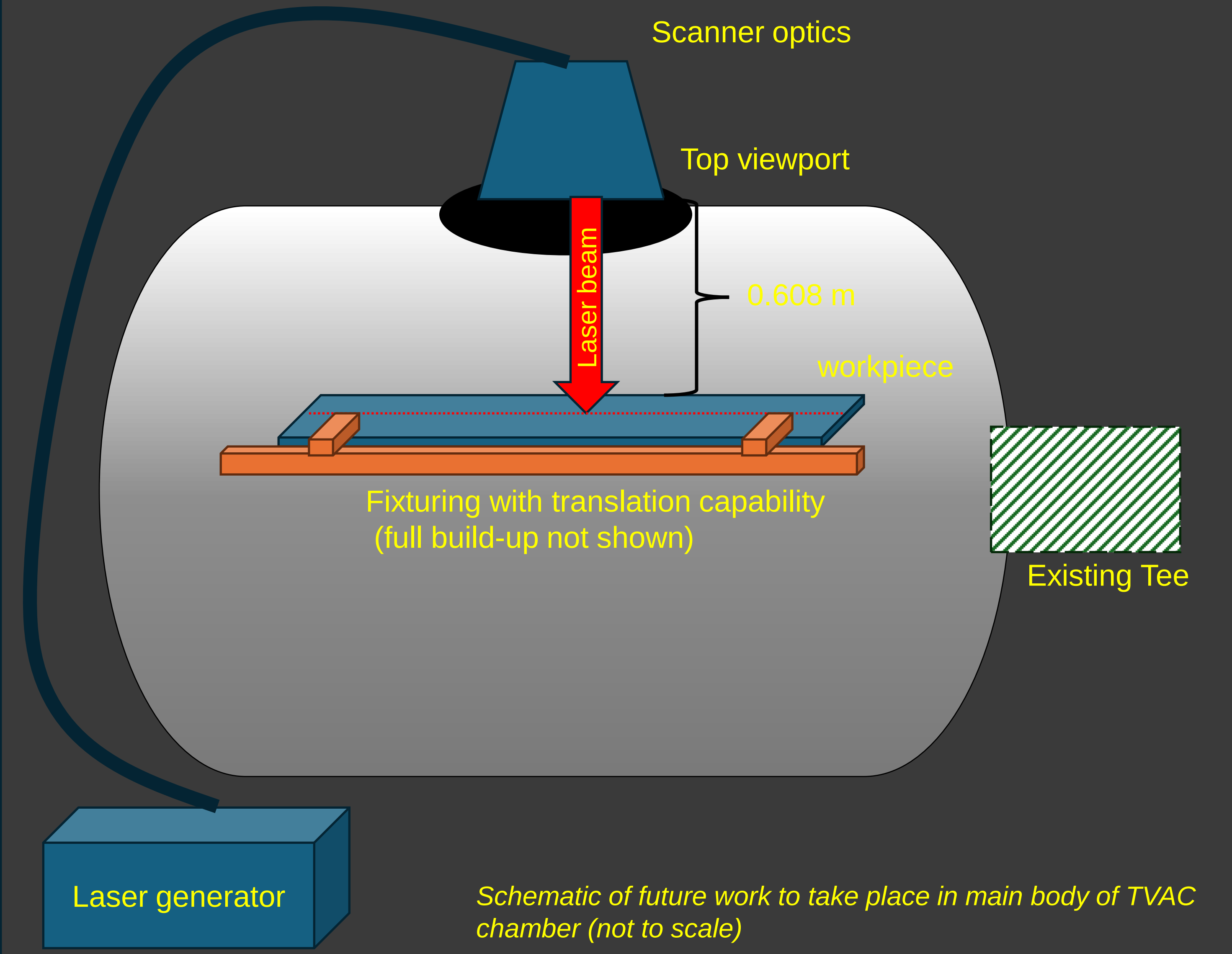


Transfer learning: train model on more extensive dataset, transfer weights & biases to model for rarefied dataset

Future Work

Scaling Up

- Next steps in process development will require scale-up to a higher-power laser scanner on V-9 TVAC main cavity
- Laser generator and electronics still in ambient
- Test pieces and fixtures will allow cutting, forming and welding processes on the meter-scale
- Will require translation/manipulation capability of the test pieces within the vacuum chamber



Schematic of future work to take place in main body of TVAC chamber (not to scale)

Q&A

Exploring the secrets of the universe for the benefit of all.

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