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

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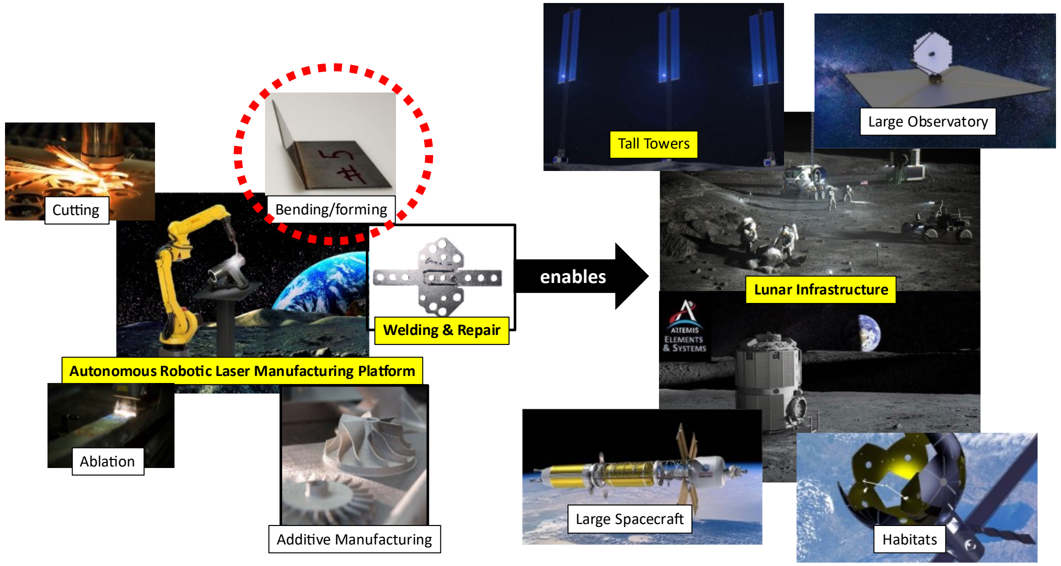
Presented on 2026-03-18 at TMS2026 in San Diego, CA

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



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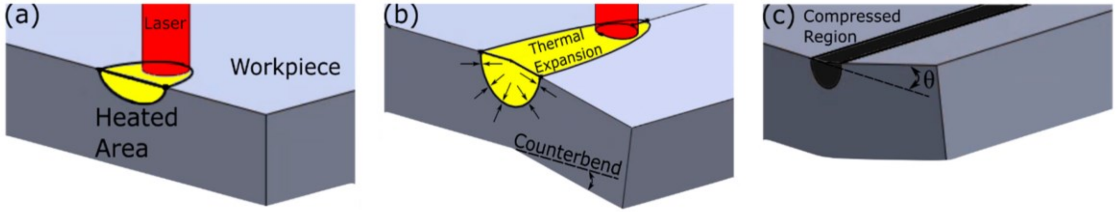
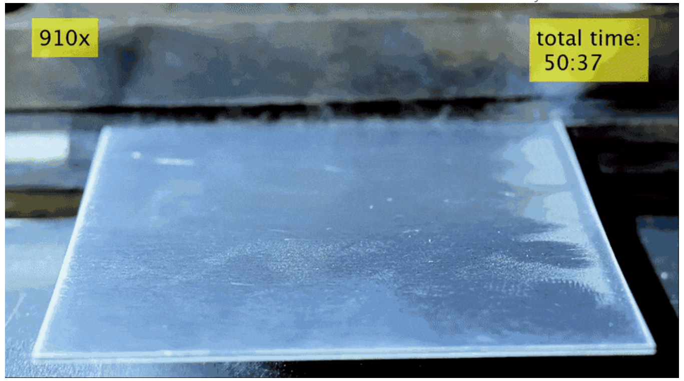
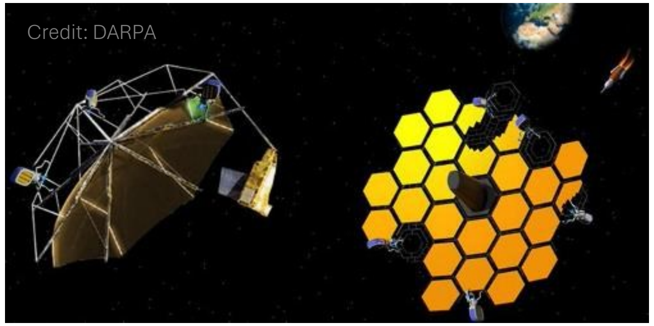


Thermal Gradient Mechanism (TGM) enables bending towards laser beam

Credit: University of Florida

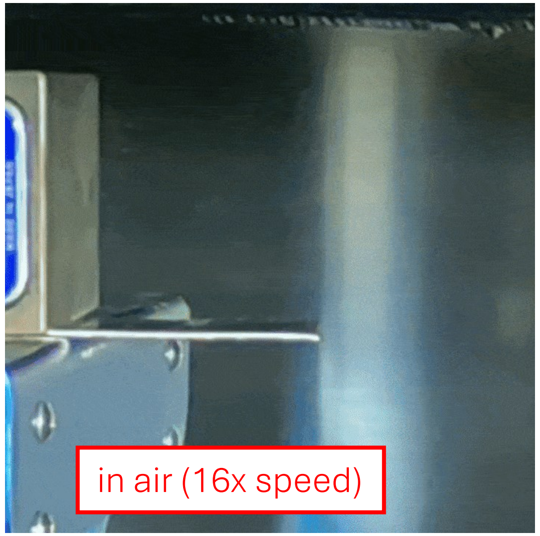


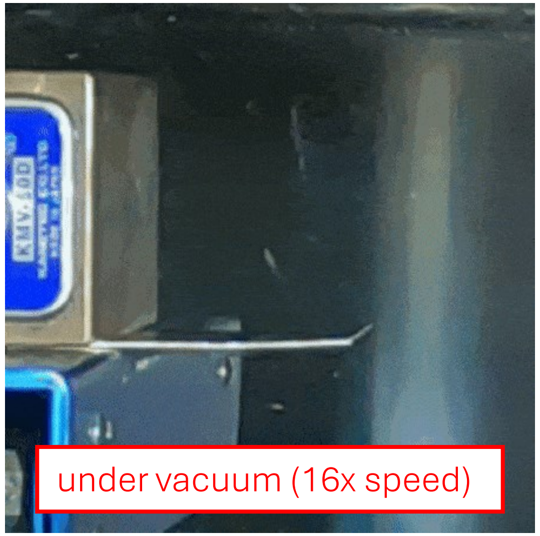
Form complex geometries with minimal pre/post-processing or workpiece setup

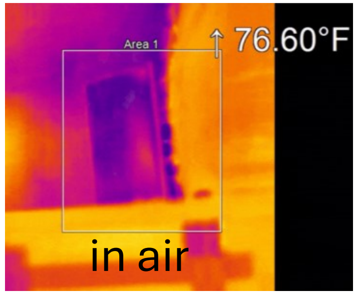


- University of Florida (UF) demonstrating LF (bending of sheet metal) under vacuum
- MSFC extending LF to thermal vacuum (TVAC)
- Excellent synergy with in-space welding (ISW), especially laser beam welding (LBW)

Rapid advancement in state-of-art for LF under vacuum



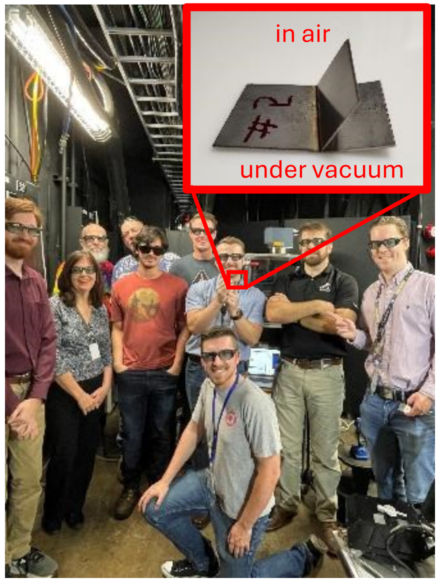


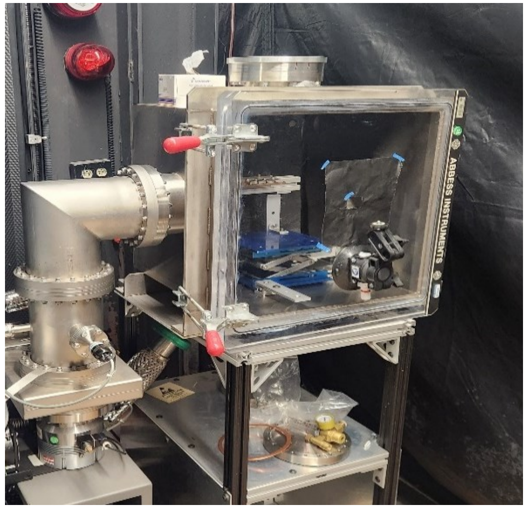


Long-wave infrared thermography

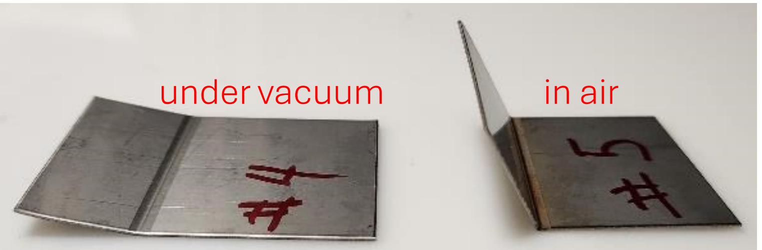
Less than two weeks from authority to proceed to initial demonstration of laser forming in air and under vacuum

Initial laser bending demonstration team





Developmental vacuum chamber for rapid parameter development



Laser bent AISI 304 stainless steel, 0.6 mm thick

New state-of-the-art: Vacuum (~10^{-3} Pa/10^{-5} Torr) greater than achieved previously

Versatile TVAC facilities at MSFC

V-9 TVAC with custom Tee:
Vacuum down to ~10^{-5} Pa (10^{-7} Torr);
<u>convective heat transfer suppressed</u>
Temperature held from ~150 to 330 K (-120 to +60 °C);
<u>active thermal control</u> of fixturing/specimens

50W laser head with x-y-z scanning optics

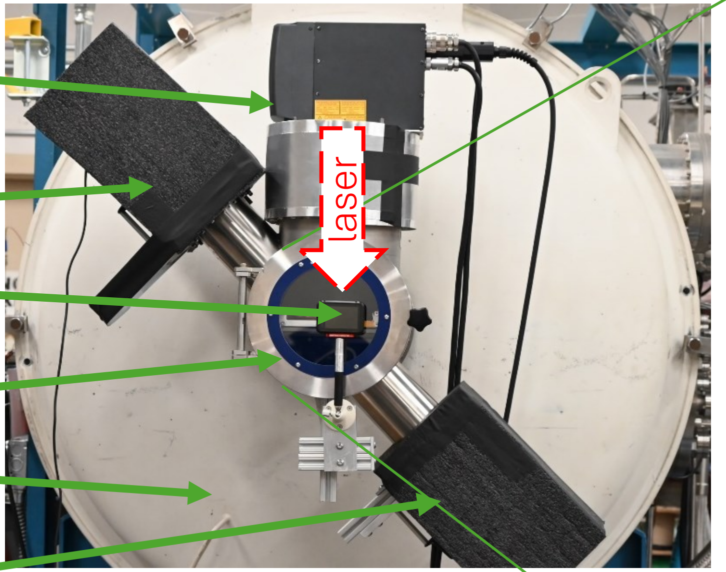
NIR (high-temp.) camera

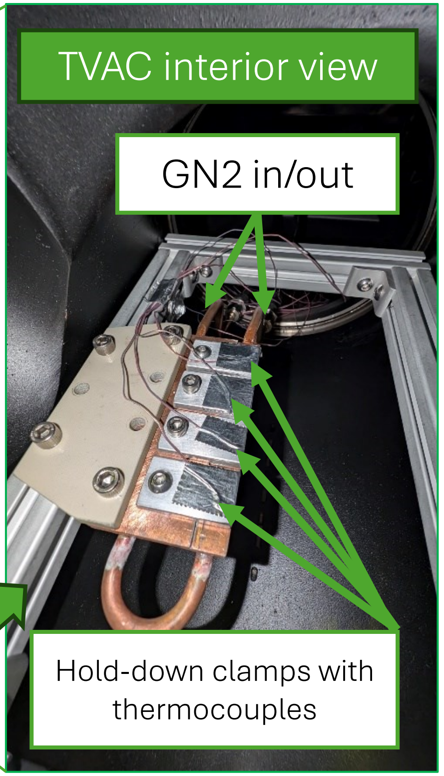
Optical camera

Custom Tee with fixturing

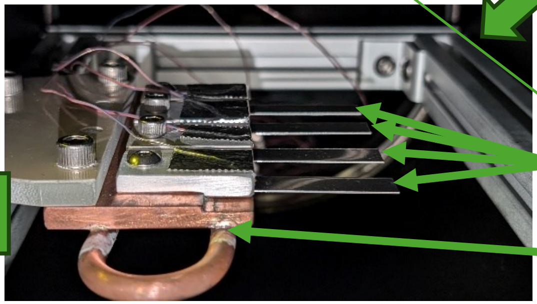
TVAC chamber

LWIR (low-temp.) camera





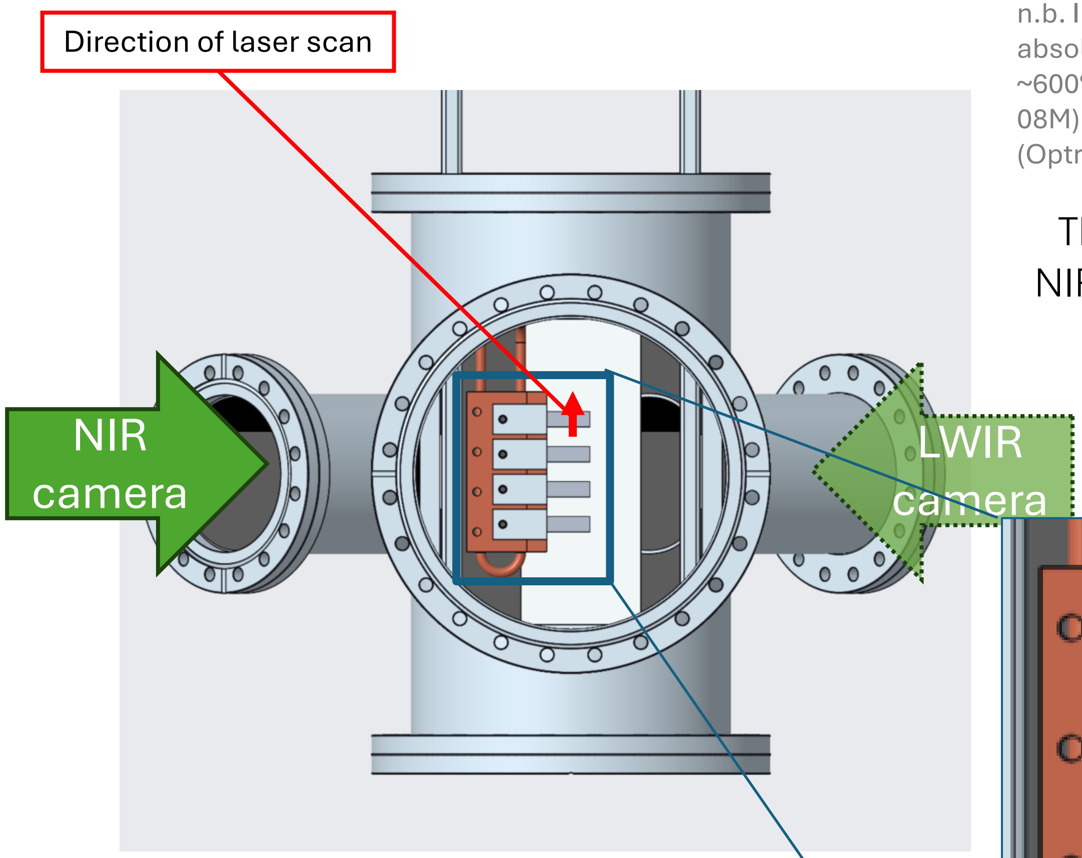
Side-on view during bending



Bending specimens

Thermal backplane with GN2 loop

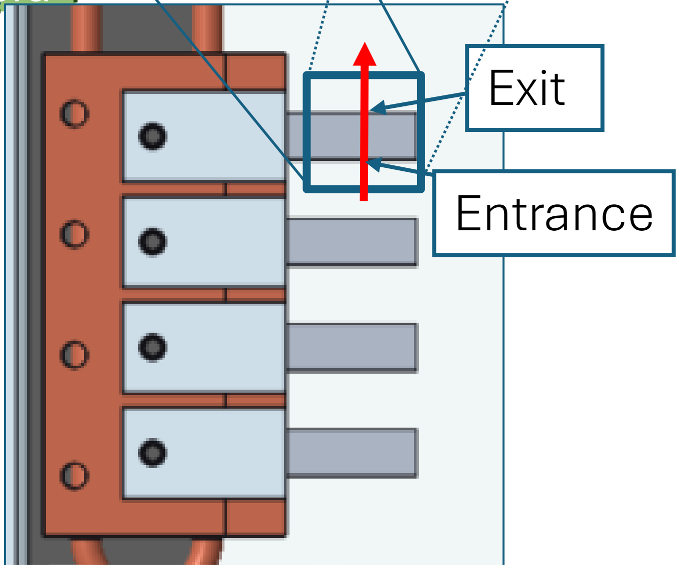
In operando thermography and videography



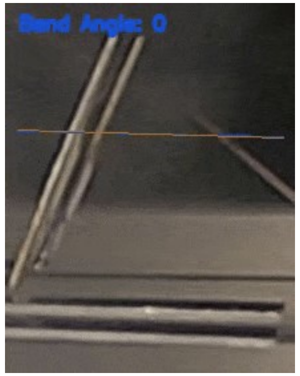
Top-down render of custom Tee on TVAC, indicating bend region

n.b. 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) and ~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)



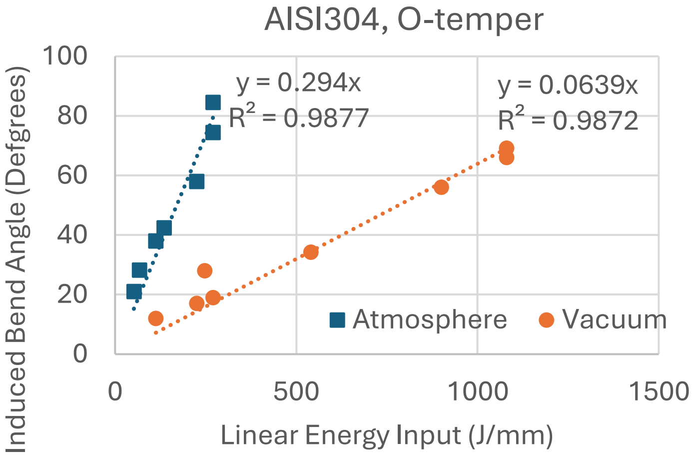
Correlating bend-per-pass measurements with thermography to reveal underlying mechanism and accelerate technology maturation

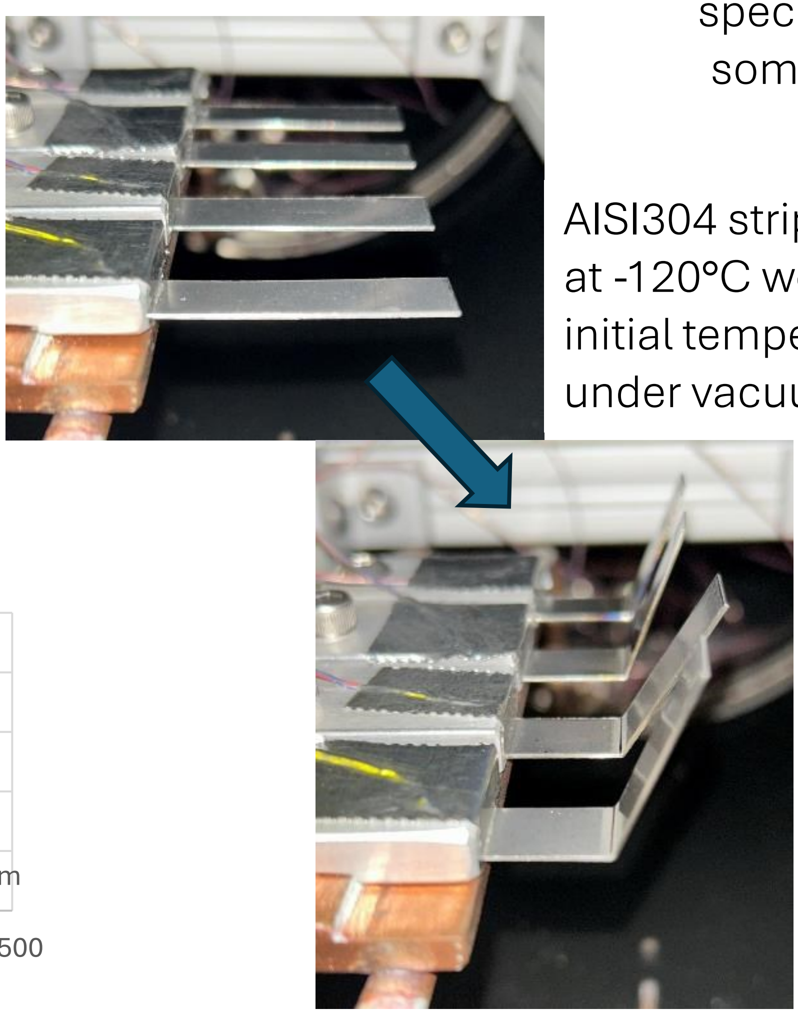
AISI304 stainless steel

First known demonstration of LF in TVAC

Remarkably consistent bending in TVAC at same linear energy density for AISI304

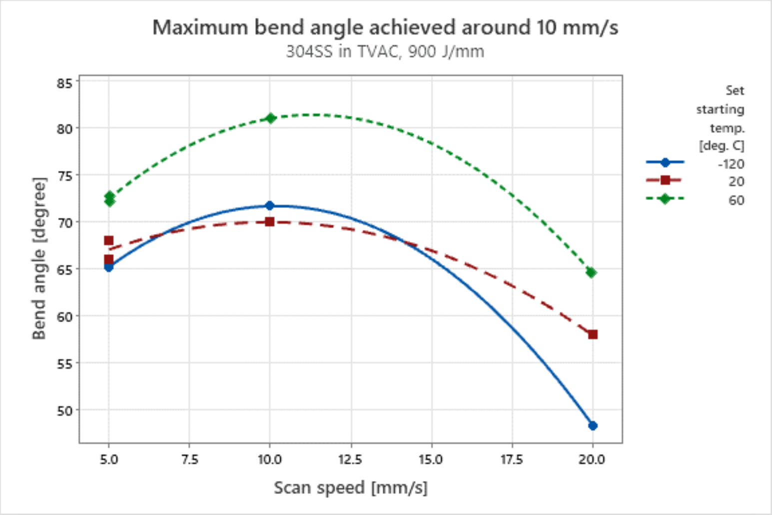
Linear regression for AISI304 on linear energy density gave confidence to proceed to TVAC trials; optimized for constant defocus and 45 W laser power





Preheated specimens show somewhat more bending

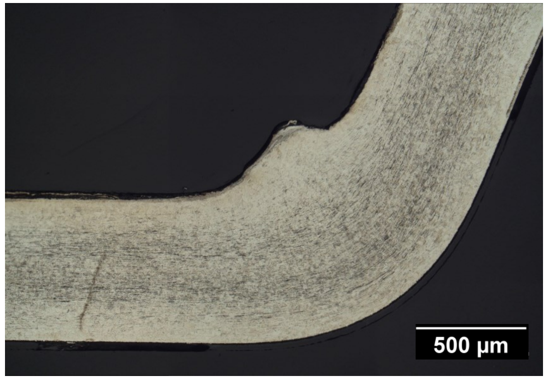
AISI304 strips bent at -120°C workpiece initial temperature under vacuum



Relative insensitivity to process parameters points towards domination by thermophysical properties for AISI304 (low thermal diffusivity)

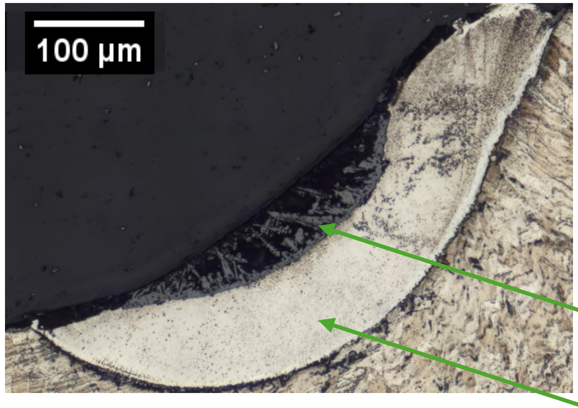
Evidence of melting/re-solidification present only in air

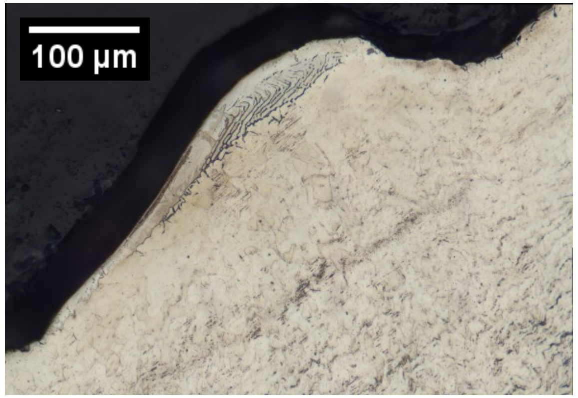
Both conditions evidence geometry distortion to accommodate bending



Atmosphere

Vacuum



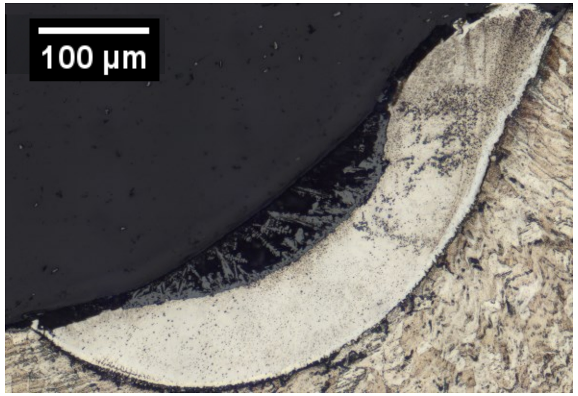


Re-solidified region, including dendrites

Restructured region

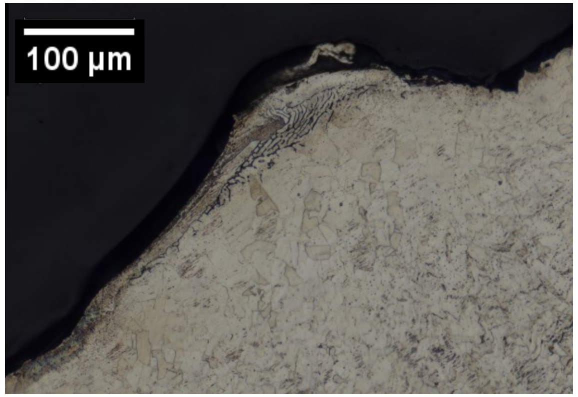
Some restructuring evident in vacuum at all temperatures

Evidences completely different laser-material interaction under vacuum

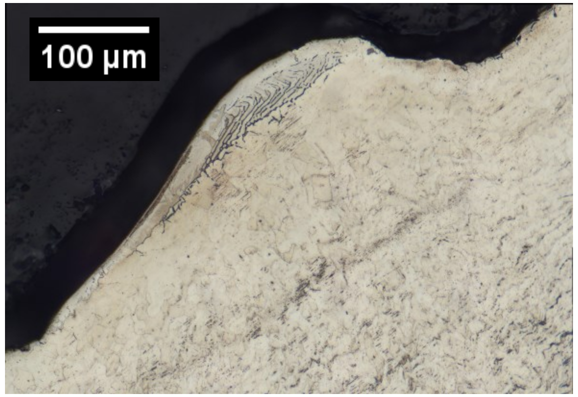


Atmosphere Ambient (20°C)

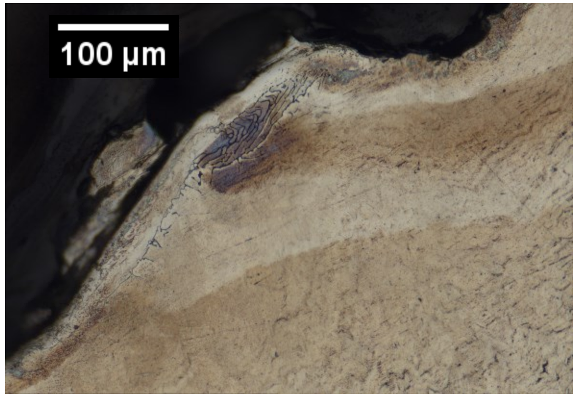
Postulated mechanisms:
Growth of oxide layer?
Ablation of oxide layer?
Generation of plasma?



Vacuum Cold (-120 °C)

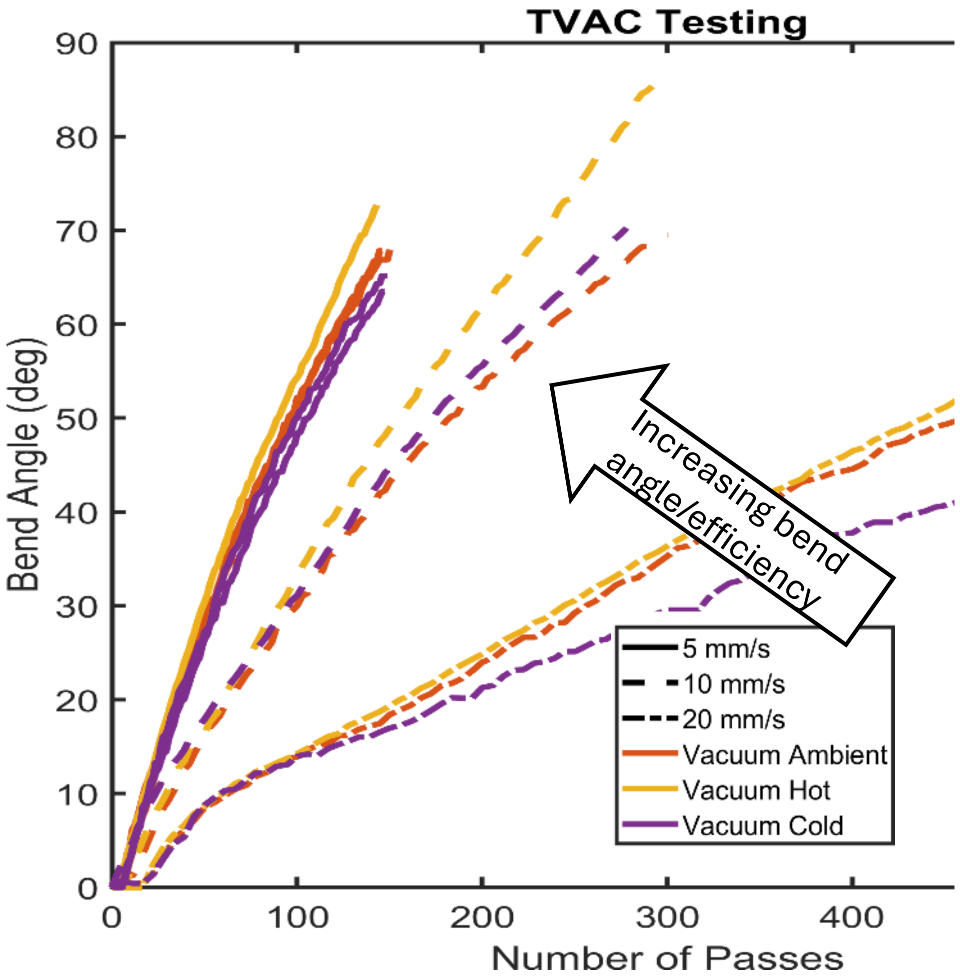


Vacuum Ambient (20°C)



Vacuum Hot (60°C)

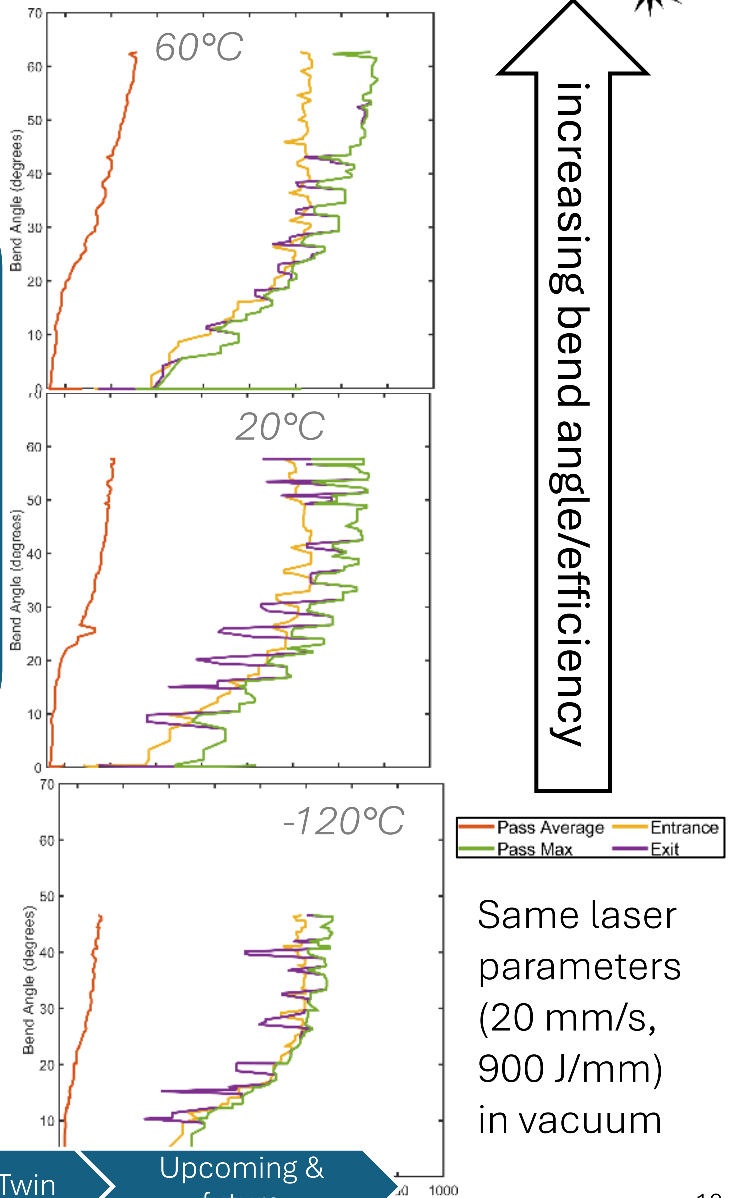
Workpiece initial temperature and bend angle linked to thermography



Weakly increasing bend angle with increasing workpiece initial temperature (at left) linked to lower saturation temperatures at colder starting temperatures from thermography (at right)

Lower saturation temperature leads to reduced bending (?)

Points towards domination by thermophysical properties for AISI304 (low thermal diffusivity)



Same laser parameters (20 mm/s, 900 J/mm) in vacuum

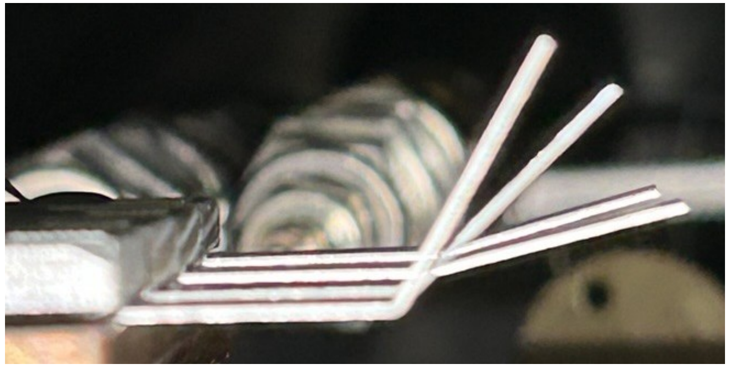
AA3003 aluminum

Many complications to the LF in TVAC story

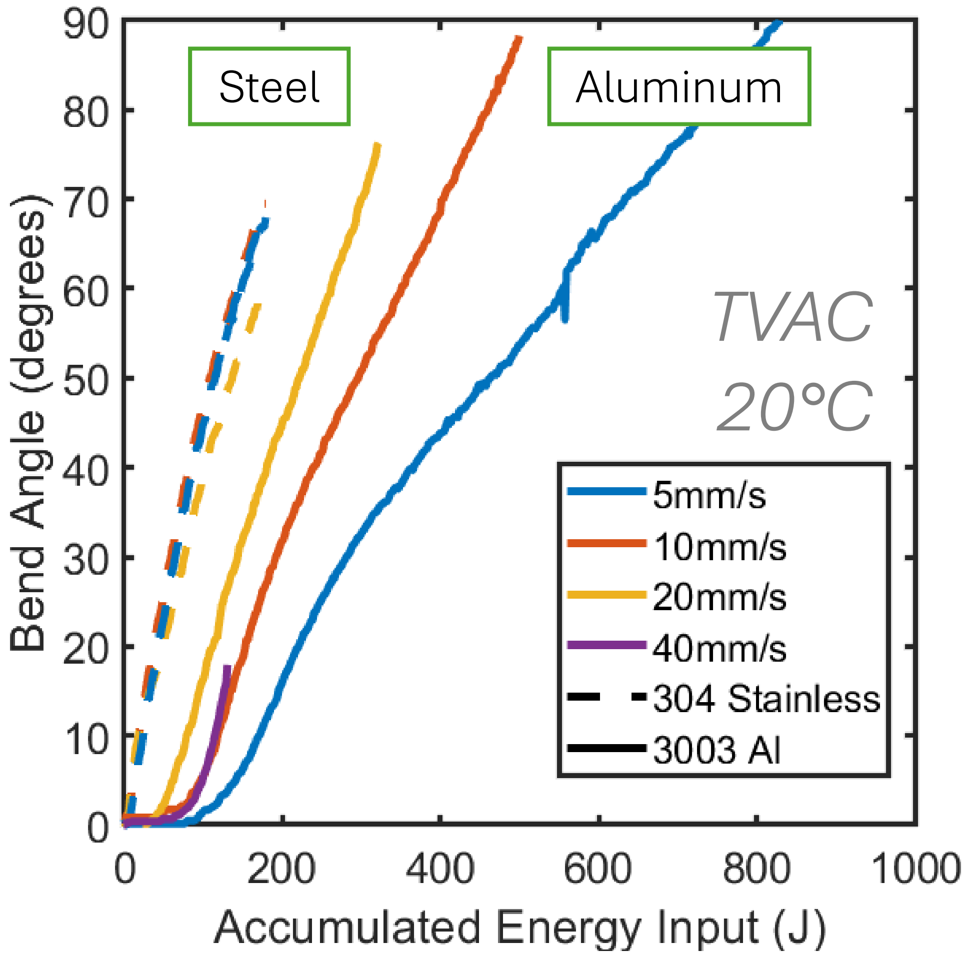
AA3003 requires more energy to bend than AISI304 and is more sensitive to process parameters

Tighter focus and higher laser power (50 W) required to bend AA3003

AA3003 more affected by cold temperatures (~150 K; -120 °C); exhibits reduction in bend angle



Slight changes in focus/workpiece displacement radically alter bending in AA3003 (~300 K ; 20 °C)

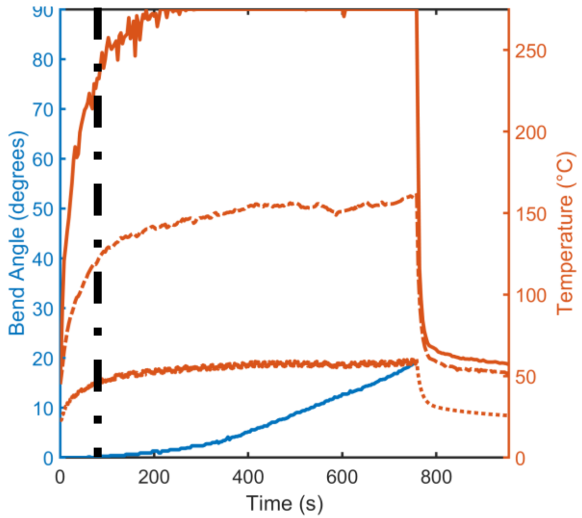


Aluminum requires critical temperature for bending; affected by workpiece temperature

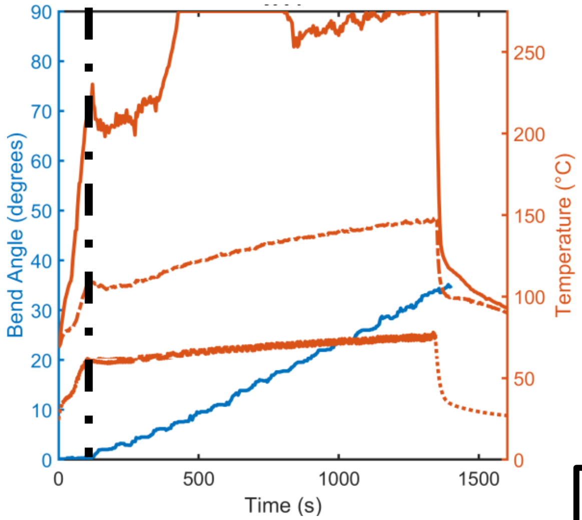
IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

AA3003
TVAC
50W, 5mm/s

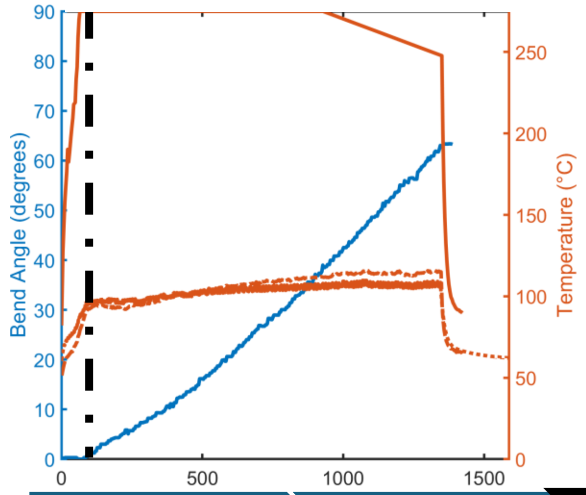
Atmosphere Ambient (20°C)



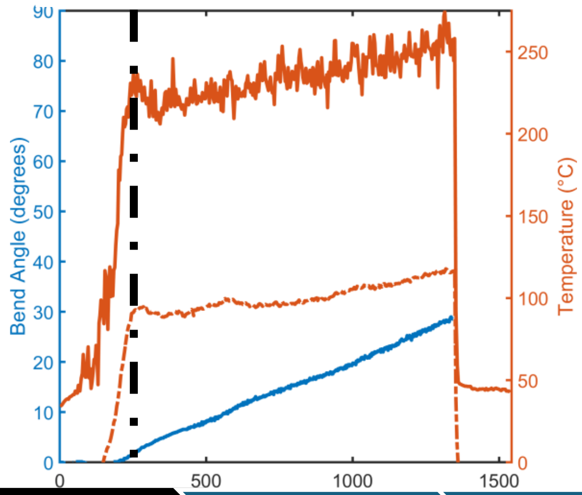
Vacuum Ambient (20°C)

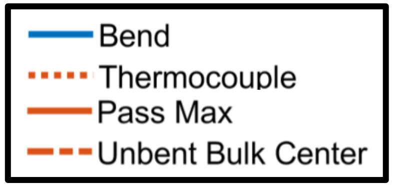


Vacuum Hot (60°C)



Vacuum Cold (-120 °C)





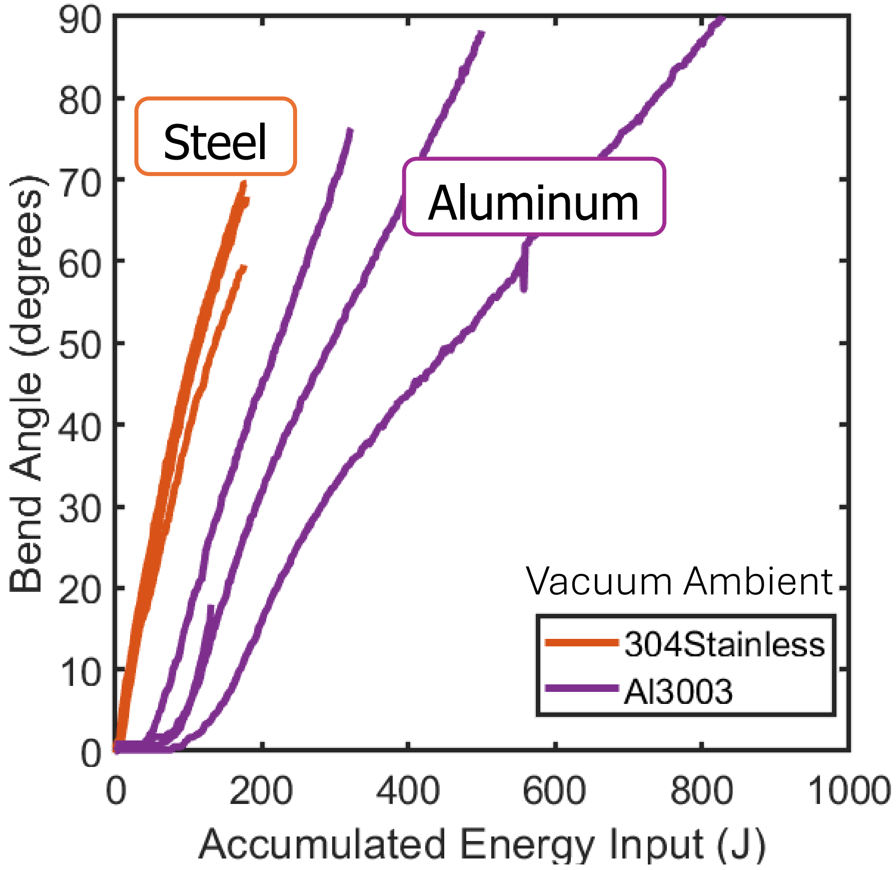
Critical temperature: ~100°C from thermocouple, ~200°C on reverse

<u>Not</u> direct temperature measurements in bending region

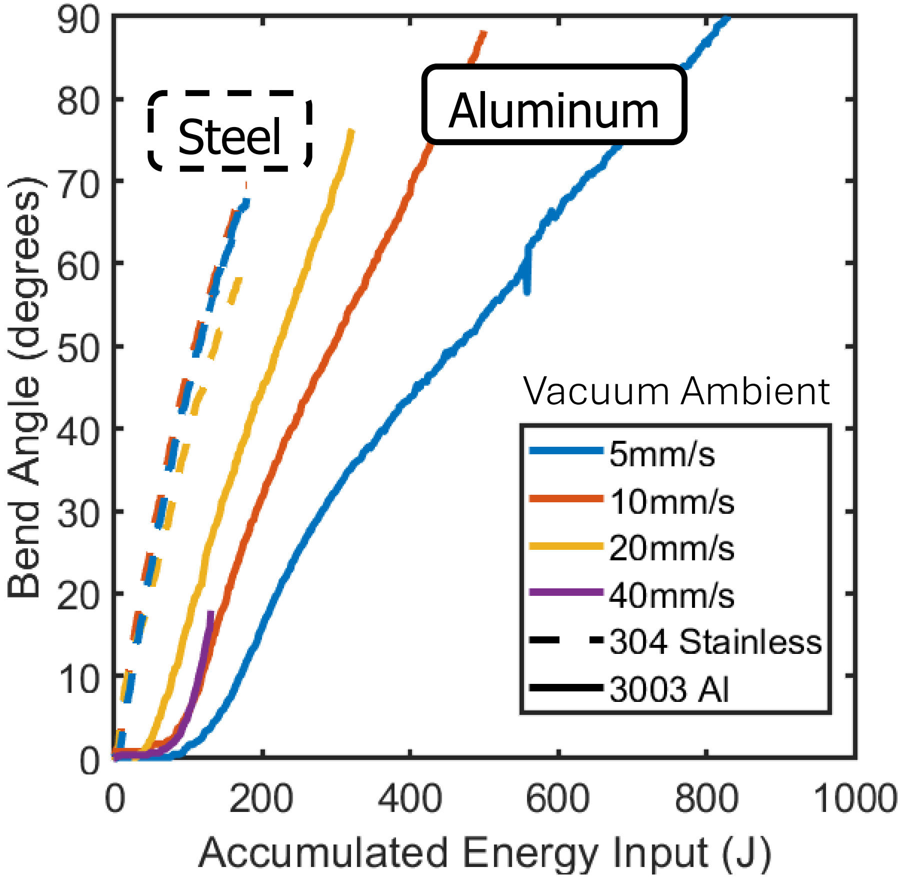
Employ thermal modeling to reconstruct bend region temperature profile and elucidate laser-workpiece interactions

AA3003 far more sensitive than AISI304 for LF

Aluminum requires more energy to bend than steel

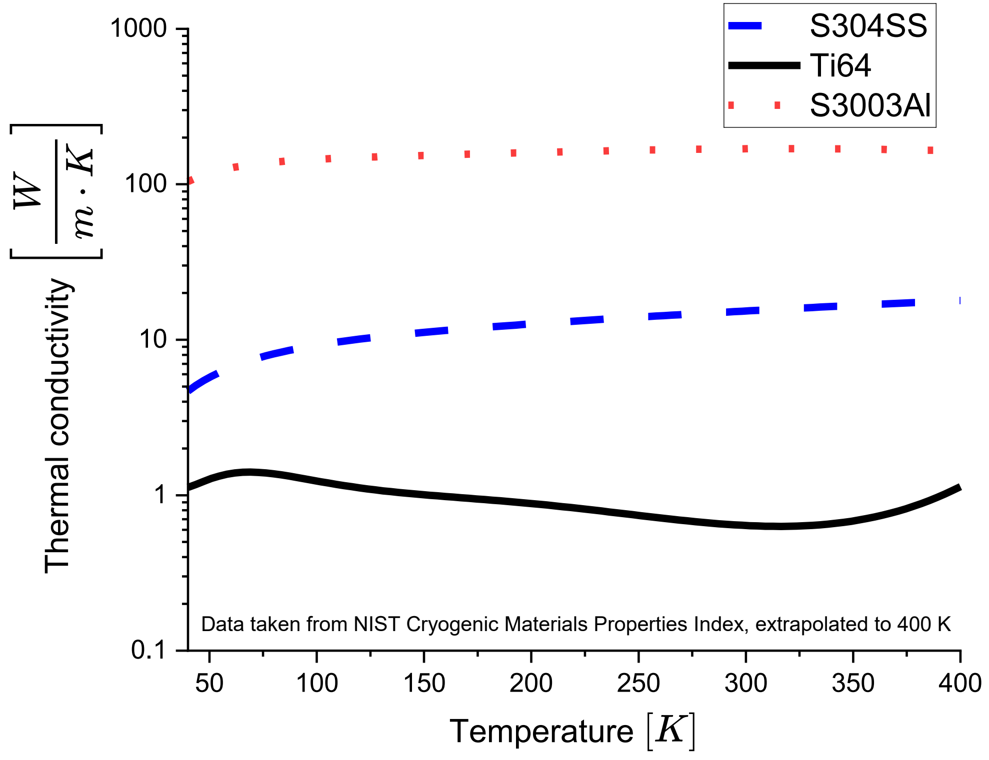


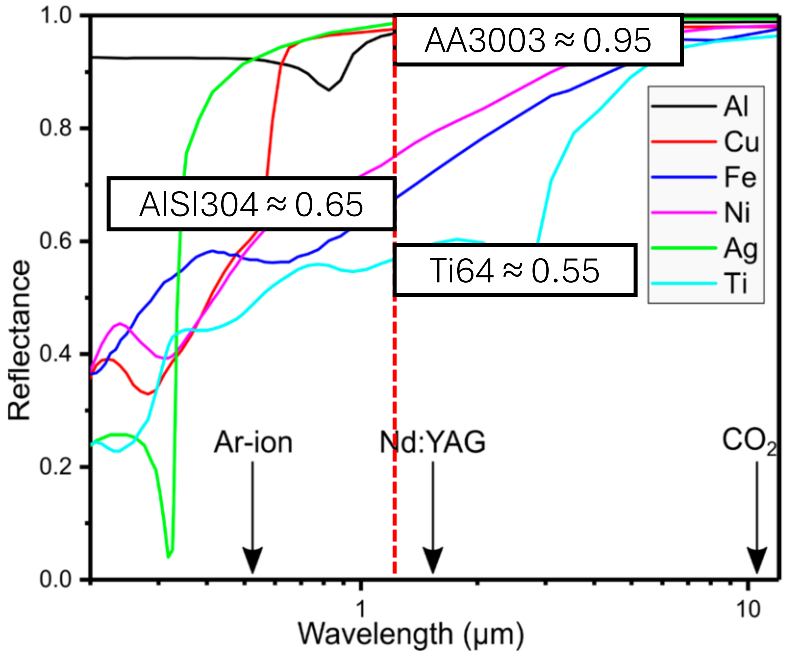
Aluminum is more variable to speed than steel



Smaller process window for AA3003 stymies development

AA3003 required <u>higher power and tighter focus</u> than AISI304 to induce bending due to slower thermal build-up from order-of-magnitude <u>higher thermal conductivity and laser reflectivity</u>





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$T_{liquidus}$(AISI304) ≈ 1450°C
$T_{liquidus}$(AA3003) ≈ 650°C
$T_{liquidus}$(Ti64) ≈ 1650°C

AA3003 has much lower liquidus → leading to spatter and other deleterious over-power conditions

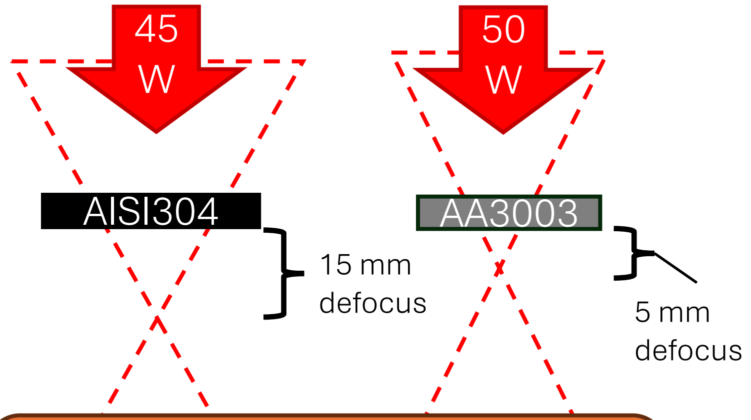
Facilities & capabilities | AISI304 | AA3003 | Ti64 | Testing | Digital Twin | Upcoming & future

Mitigating focusing risk by displacement sensor

AA3003 more sensitive than AISI304 to changes in spot size from displacement variation

Material	%Δ in spot diameter	%Δ in spot area/power density
AISI304	2	3
AA3003	4	8

For a mere 250 μm displacement variation



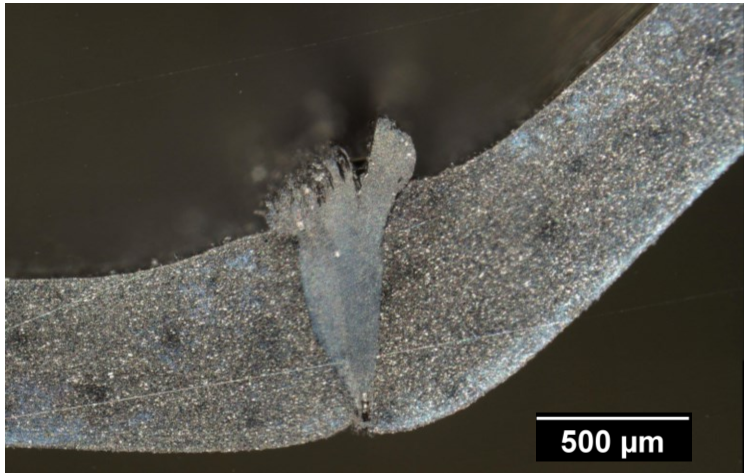
Mitigating laser focus risk with 30 μm-resolution displacement sensor

Thus, processing window for AA3003 is vexingly narrow
between inadequate power density (no bending) and excessive power density (spatter, melting)

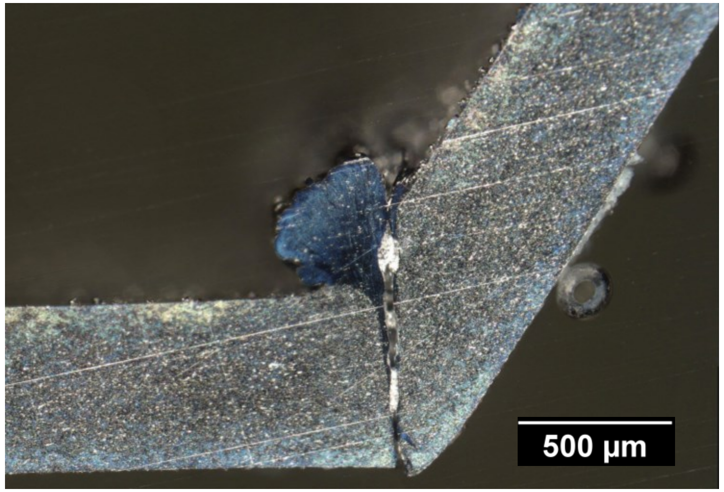
Initial trials of displacement sensor (during subsequent Ti64) trials indicated provisional resolution of focus risk

Narrow process window for aluminum hinders structural use

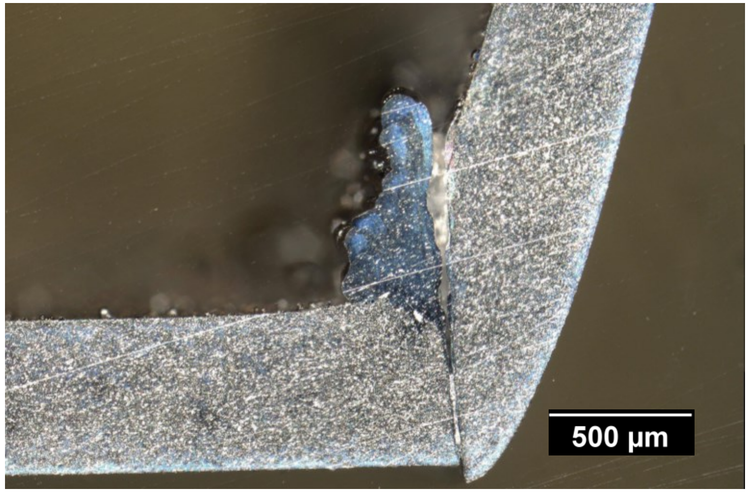
- Narrow process window for aluminum:
  - Here: Highly energetic (overfocused?) led to melting; complicates structural use
  - Less energy or defocus previously: able to bend without melting, but at extremely reduced rate (approaching half hour instead of minutes)



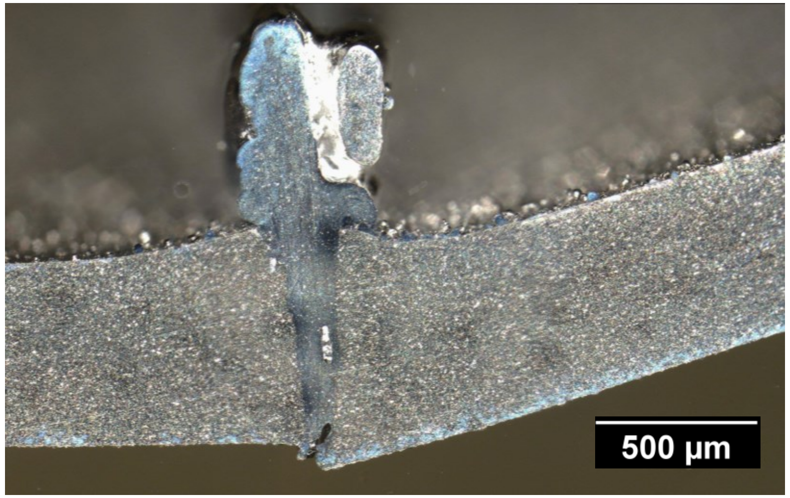
Atmosphere Ambient (20°C)



Vacuum Cold (-120 °C)



Vacuum Ambient (20°C)

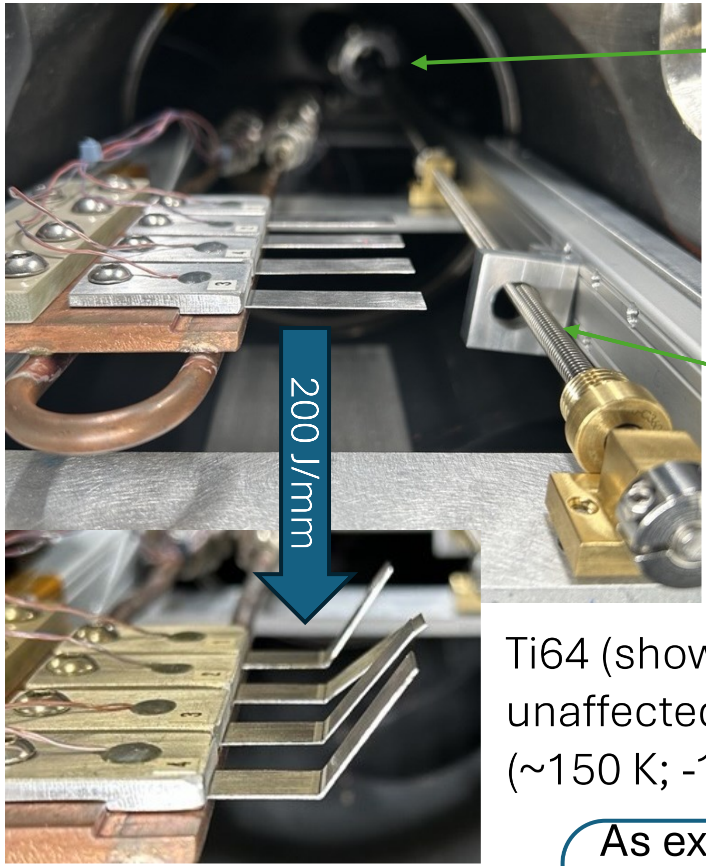


Vacuum Hot (60°C)

Ti64 titanium

A return to relatively expected LF in TVAC behaviors

Titanium insensitive to temperature but sensitive to scan speed

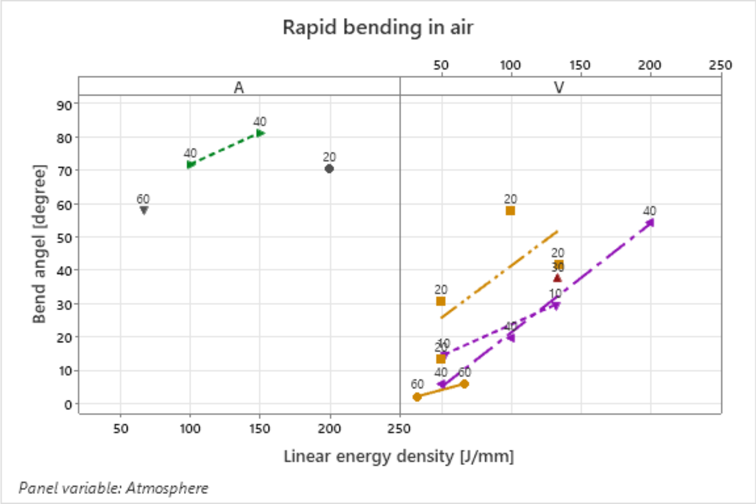


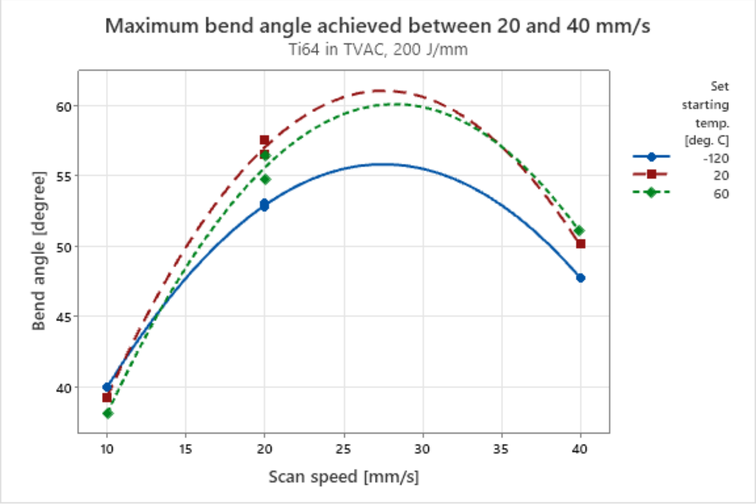
Re-used Skylab solar array deployment motor EDU (TVAC-rated)

Translating mechanism allows more precise alignment of workpiece with laser

Ti64 (shown here) almost unaffected by temperature (~150 K; -120 °C)

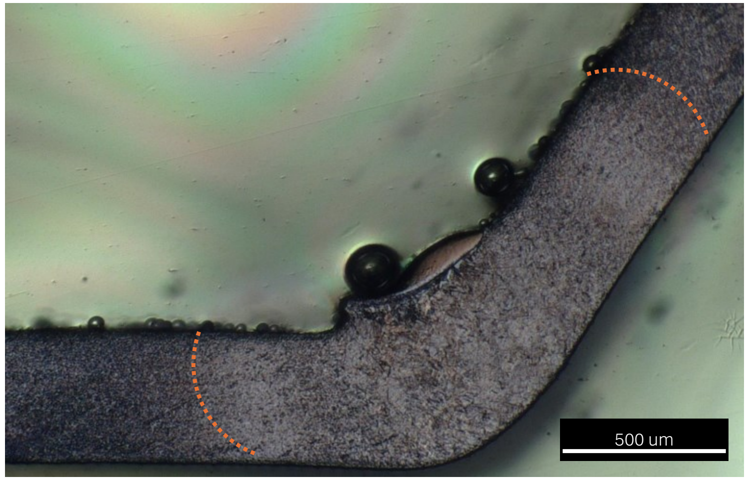
As expected, lower laser power (40 W) and larger spot size (20 mm defocus) for Ti64; But more sensitive to speed than AISI304 (complicates lower thermal diffusivity argument for reduced process parameter sensitivity)



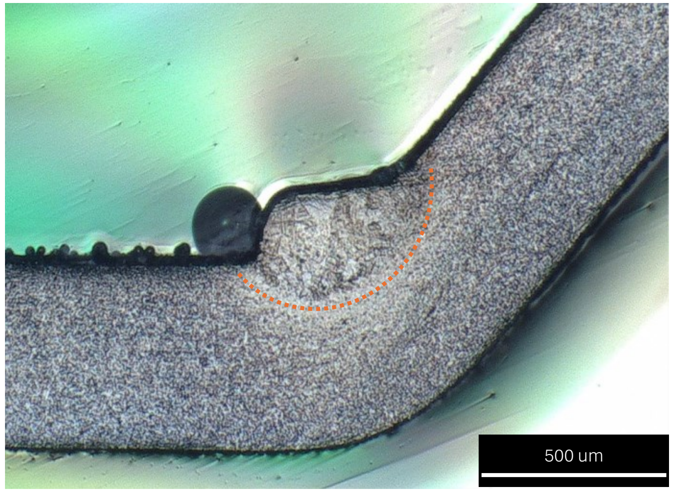


Ti64 metallography unexpectedly consistent

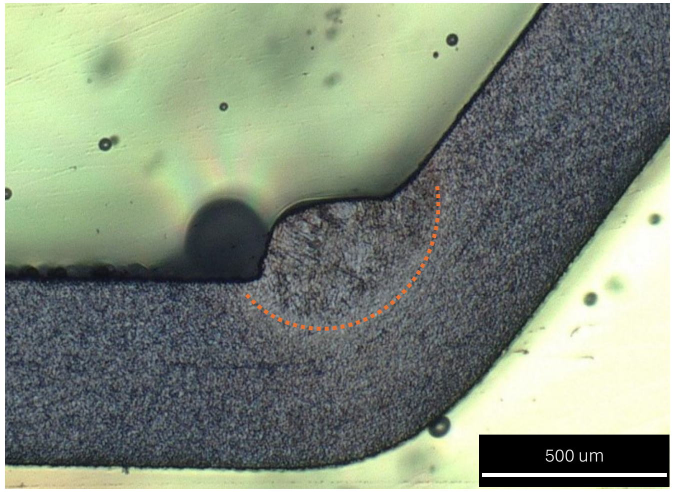
- Heat-affected/transformed area larger and more noticeable in atmosphere
  - Expected alpha case present
- In vacuum, volume of heat affected region relatively unchanged with process temperature
  - Somewhat against expectations from effects of workpiece temperature on melt pool in welding



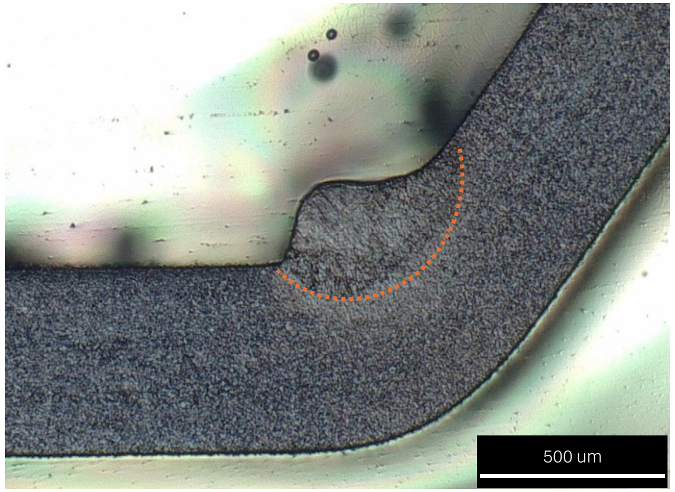
Atmosphere Ambient (20°C)



Vacuum Cold (-120 °C)



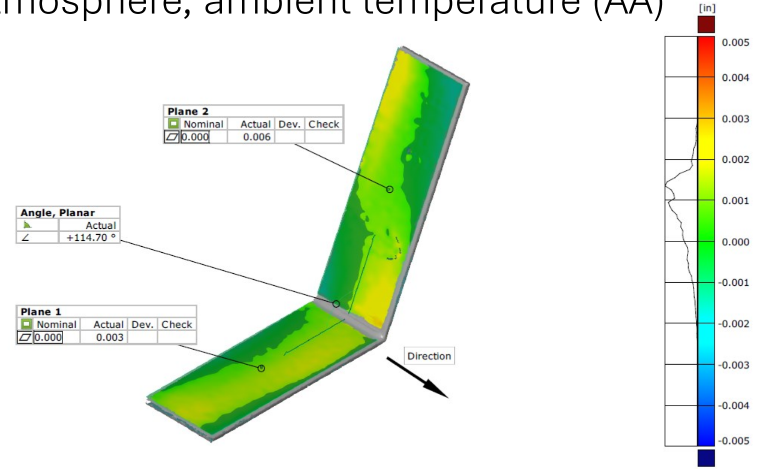
Vacuum Ambient (20°C)



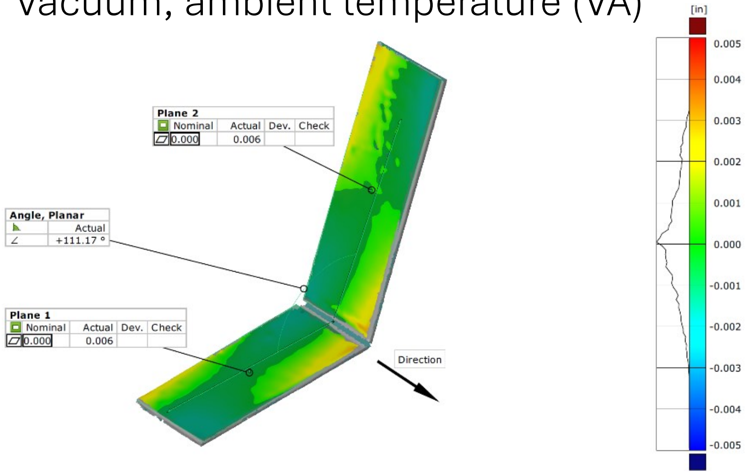
Vacuum Hot (60°C)

Structured light scans reveal distortion

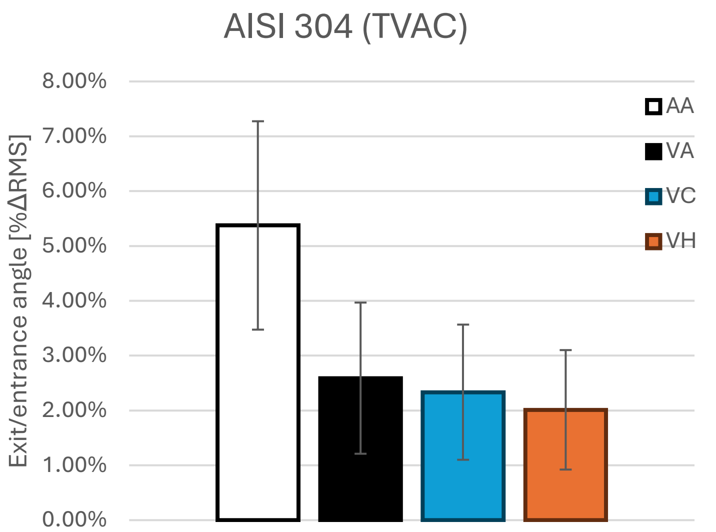
Atmosphere, ambient temperature (AA)

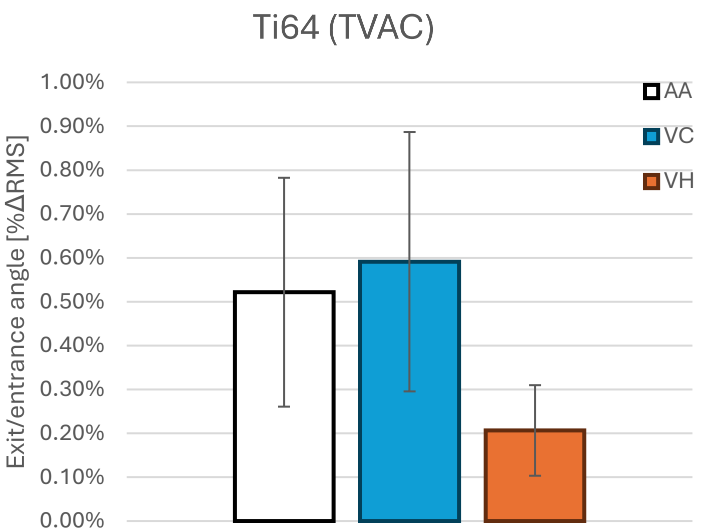


Vacuum, ambient temperature (VA)



n.b. direction here is labelled opposite to actual



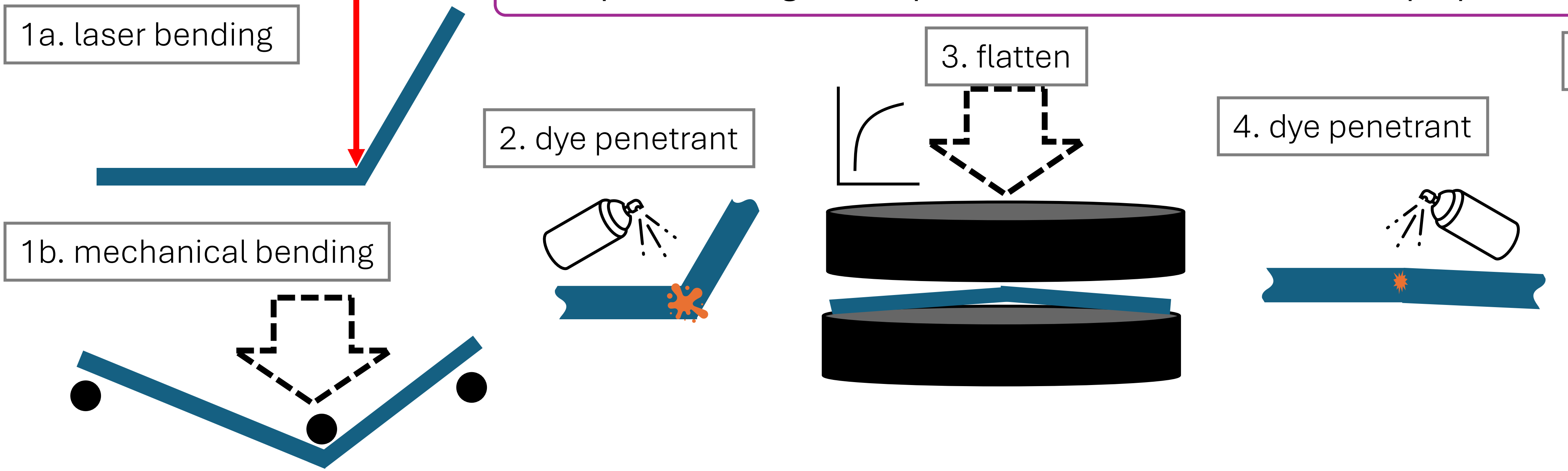


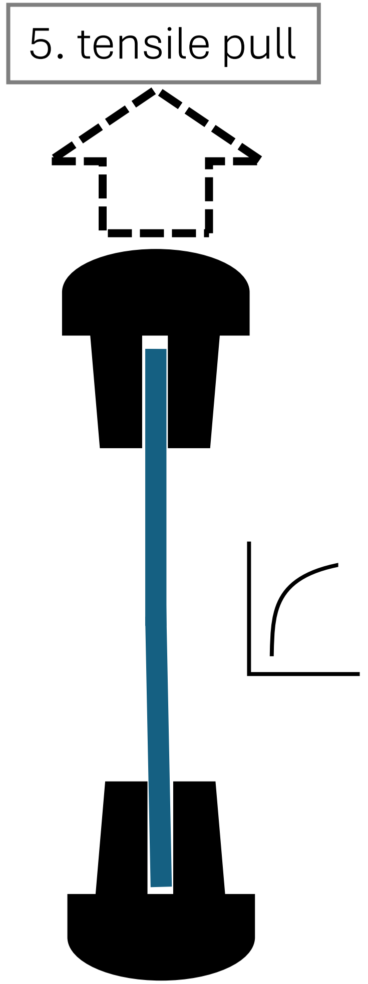
AISI 304: trending towards lower distortion under vacuum
Ti64: unclear

Sparse data hampers statistics

Planned mechanical testing methodology

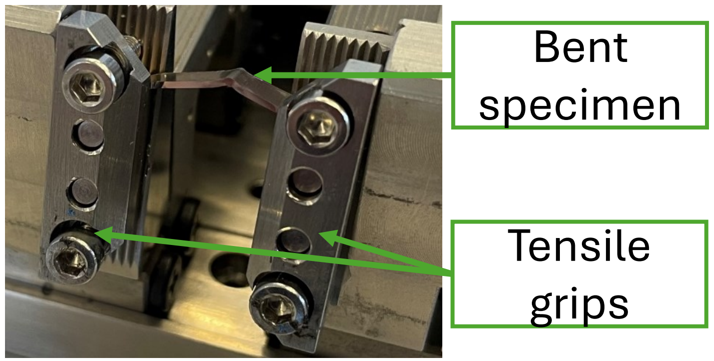
Compare bending techniques via defects and mechanical properties



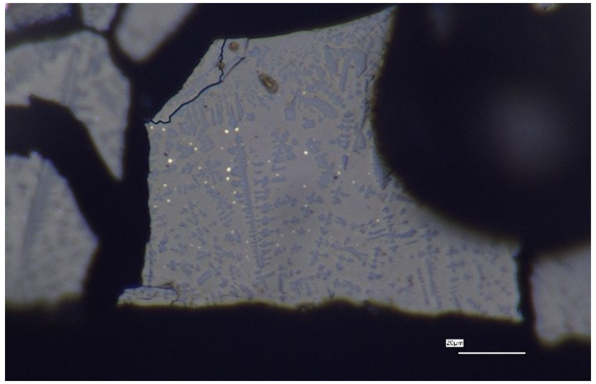


First-of-a-kind capability for *in situ* tensile pull of bent specimens during EBSD:

- reveals how microstructure deforms during loading after laser forming
- **informs performance (fatigue, etc.) predictions**



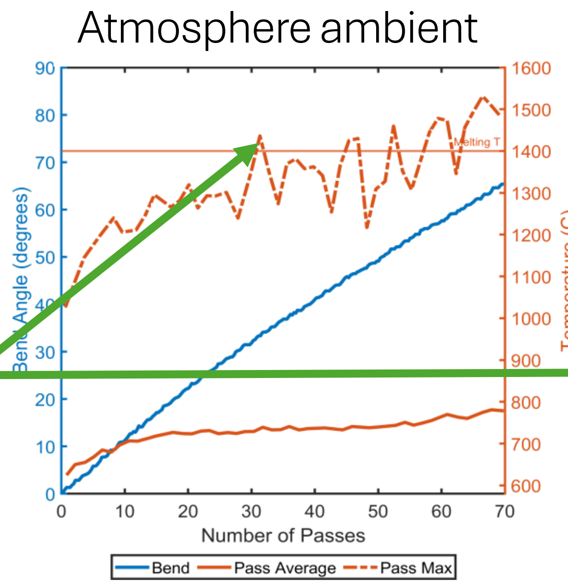
Exploring explanations for faster bending in air

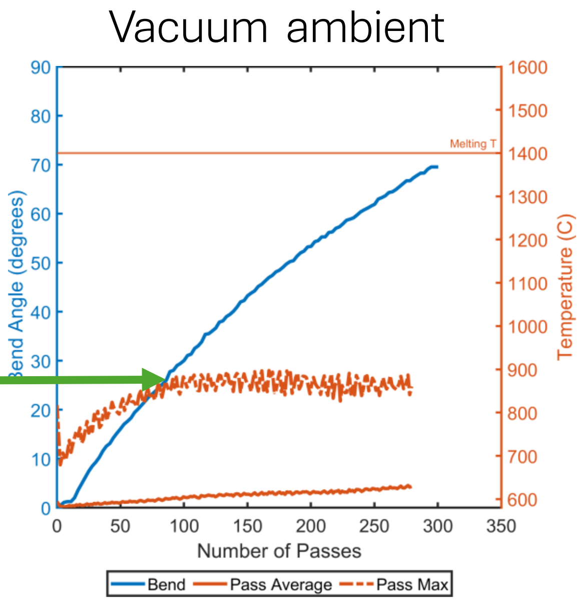


Solidification structure indicating localized melting under laser in AISI304

In atmosphere, laser spot hits AISI304 liquidus; in vacuum, laser spot remains well below liquidus

Note > 4x reduction in number of passes for bending in air!



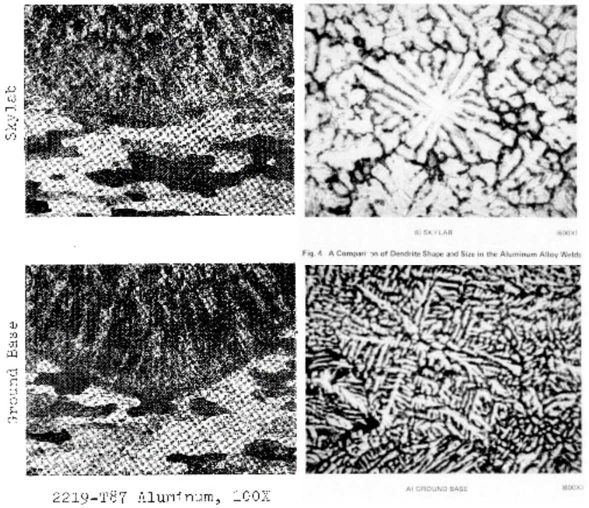


Emerging theory: Difference in oxidation evolution enhances thermal build-up and thus bending rate in atmosphere

Alternative theory: Enhanced laser coupling to plasma induced in air above bend region provides more heat and thus bending

How to collect evidence for each?
XPS and IR reflectivity measurements for oxide
Spectroscopy for plasma
Thermal modeling for both

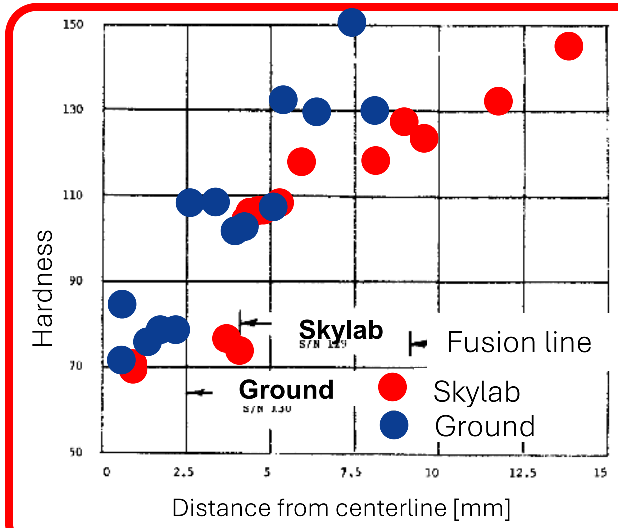
Skylab electron beam weld thermal modeling



- In the ground-based samples, the dendrites are much larger at the root region than at the crown region. For Skylab samples, reduced difference in size.
- Concluded some unknown combination of ***G*** *(temperature gradient)* and ***R*** *(solidification range)* varied between ground and flight

G. Busch. Grumman Report (1976). https://ntrs.nasa.gov/citations/19770024270

Structure

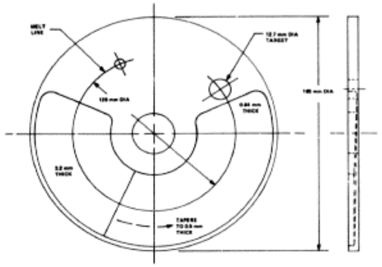


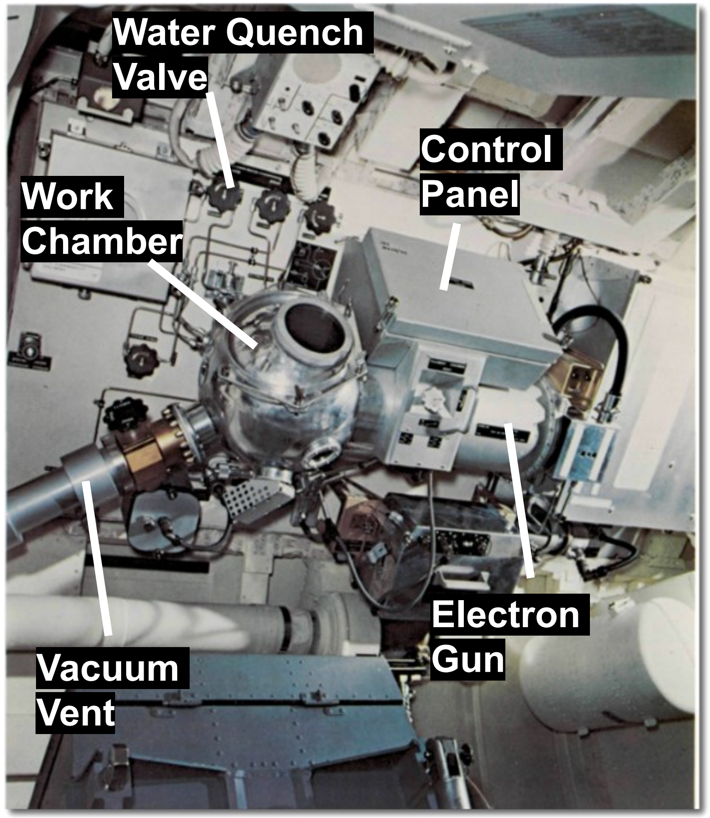
R.E. Monroe. NASA CR-129041 (1974). https://ntrs.nasa.gov/citations/19750002046

Properties

- Monroe (1974) produced hardness plots for full penetration Skylab and Ground welds.
- Li et al. (1976) concluded that no significant differences in hardness were observed between the ground-based and Skylab samples of 2219. Tantalum discs did show a significant difference, but no explanation was provided.

Processing





Travel speed = 1.61 cm/s, E = 20 kV, I = 50-80 mA

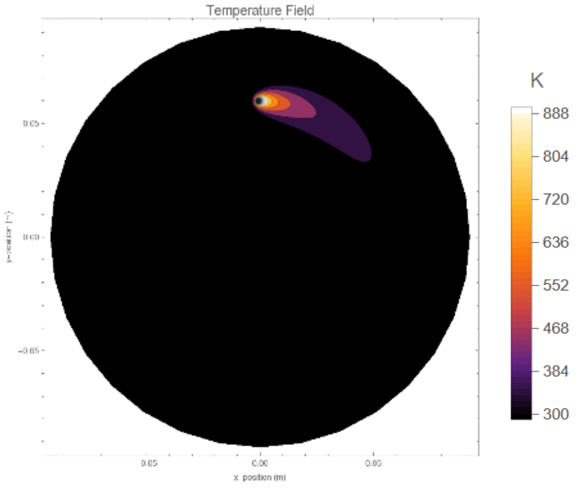
Alloys: Stainless Steel (304), Aluminum (2219-T87), CP Tantalum.

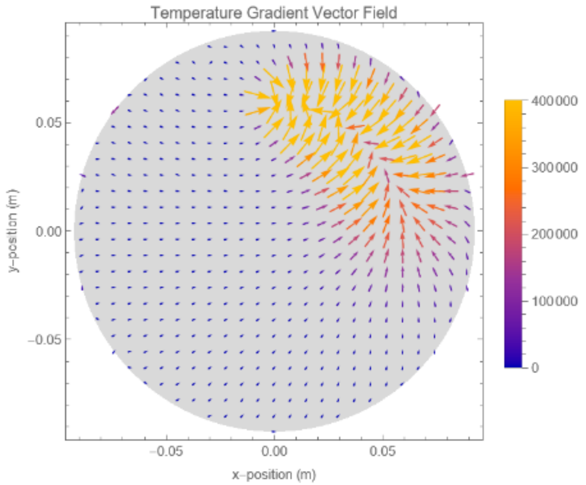
After 2 hr space vent, Vacuum = 10^{-4} Torr (~10^{-2} Pa)

[Computational and Physics-Based Modeling for the Development of in-Space Welding Technology - NASA Technical Reports Server (NTRS)]

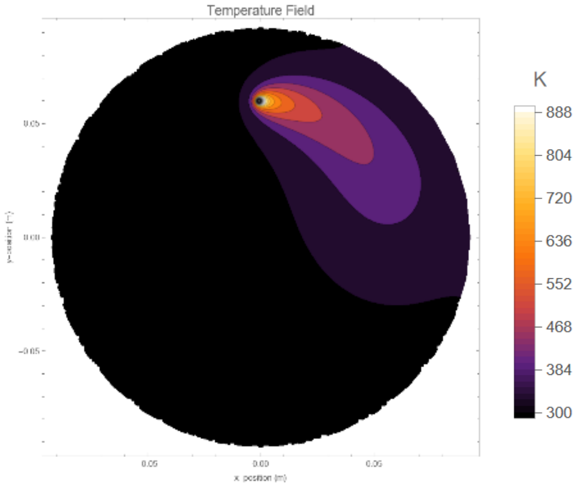
Temperature & gradient maps of Skylab AA2219-T87 disc

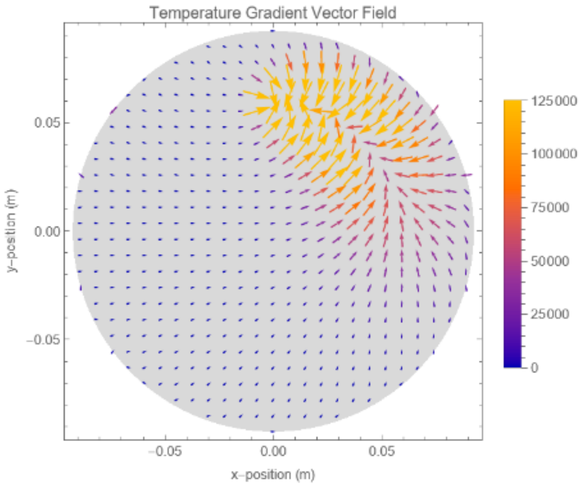
T_0 = 100 K



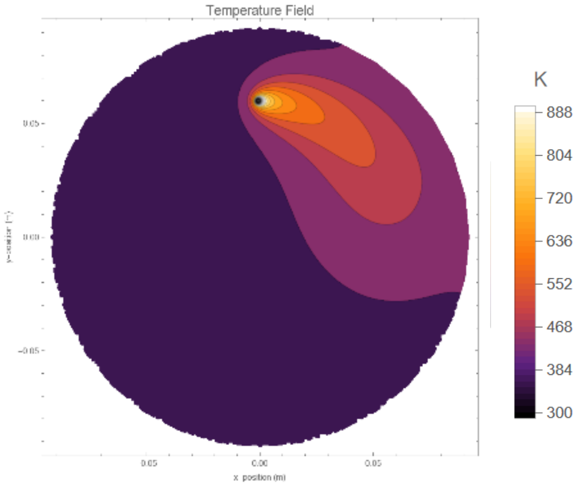


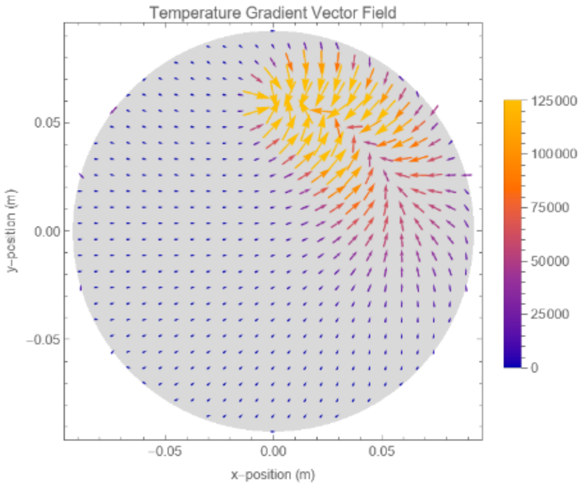
T_0 = 293 K



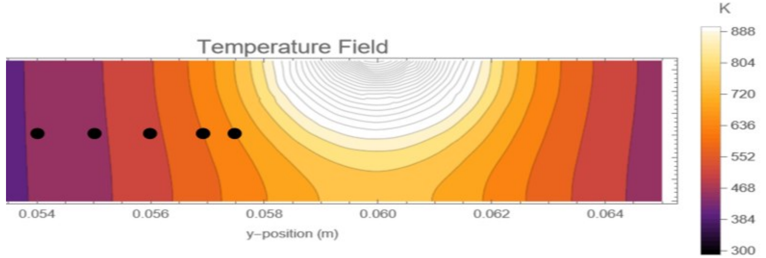


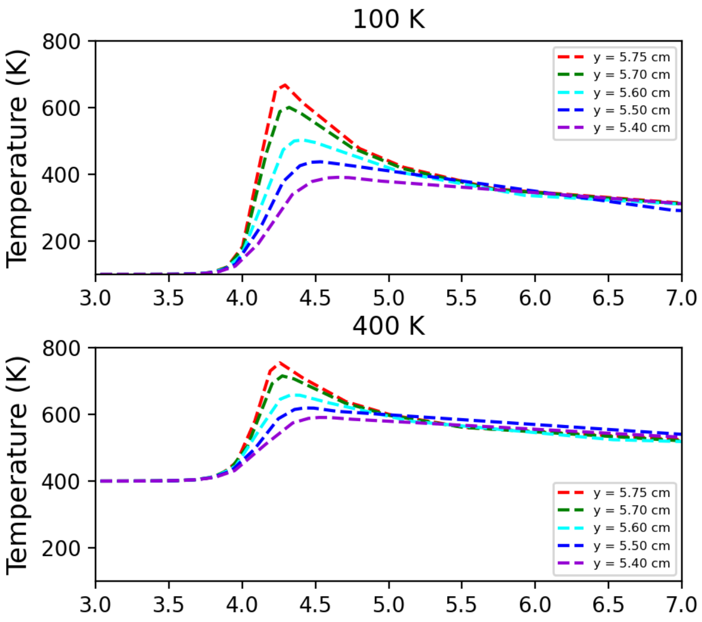
T_0 = 400 K



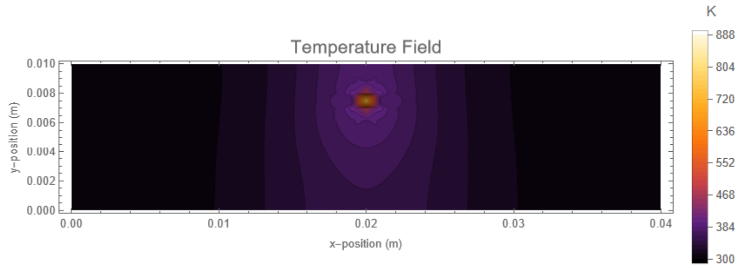


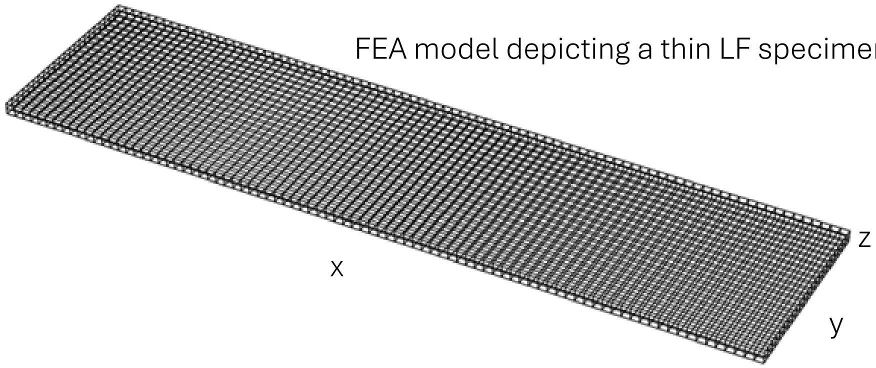
Leveraging ICME modeling to link laser absorptivity, thermophysical properties of material, laser parameters, etc.



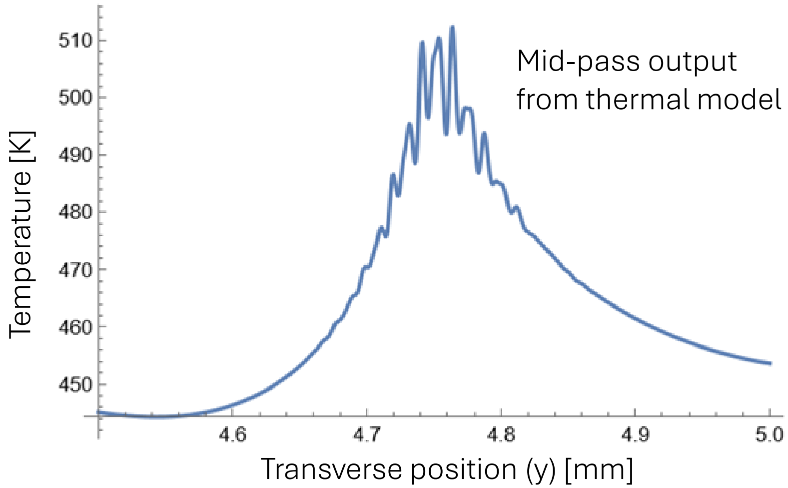


Preliminary thermal model (in-house finite element analysis code) depicting temperature field of aluminum LF coupon from obverse





FEA model depicting a thin LF specimen

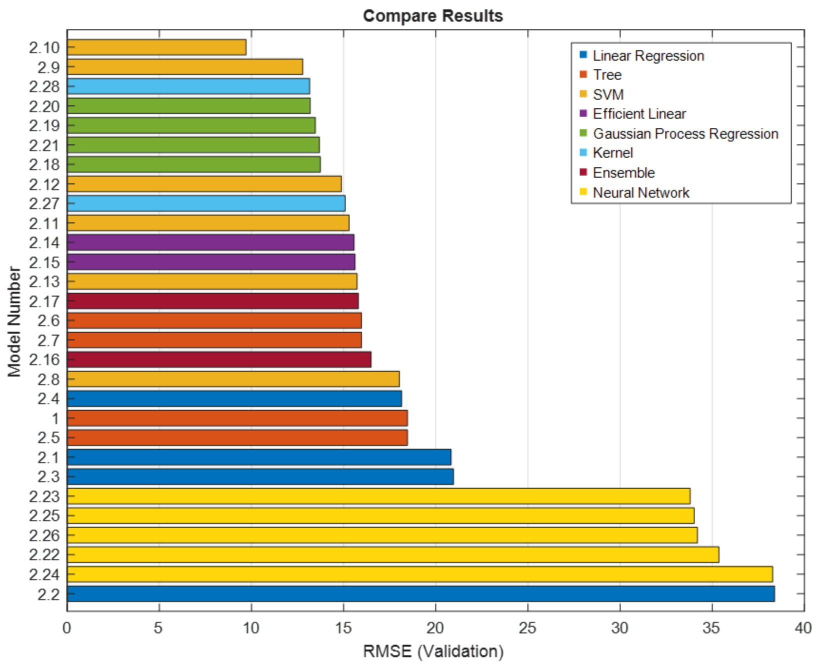


Mid-pass output from thermal model

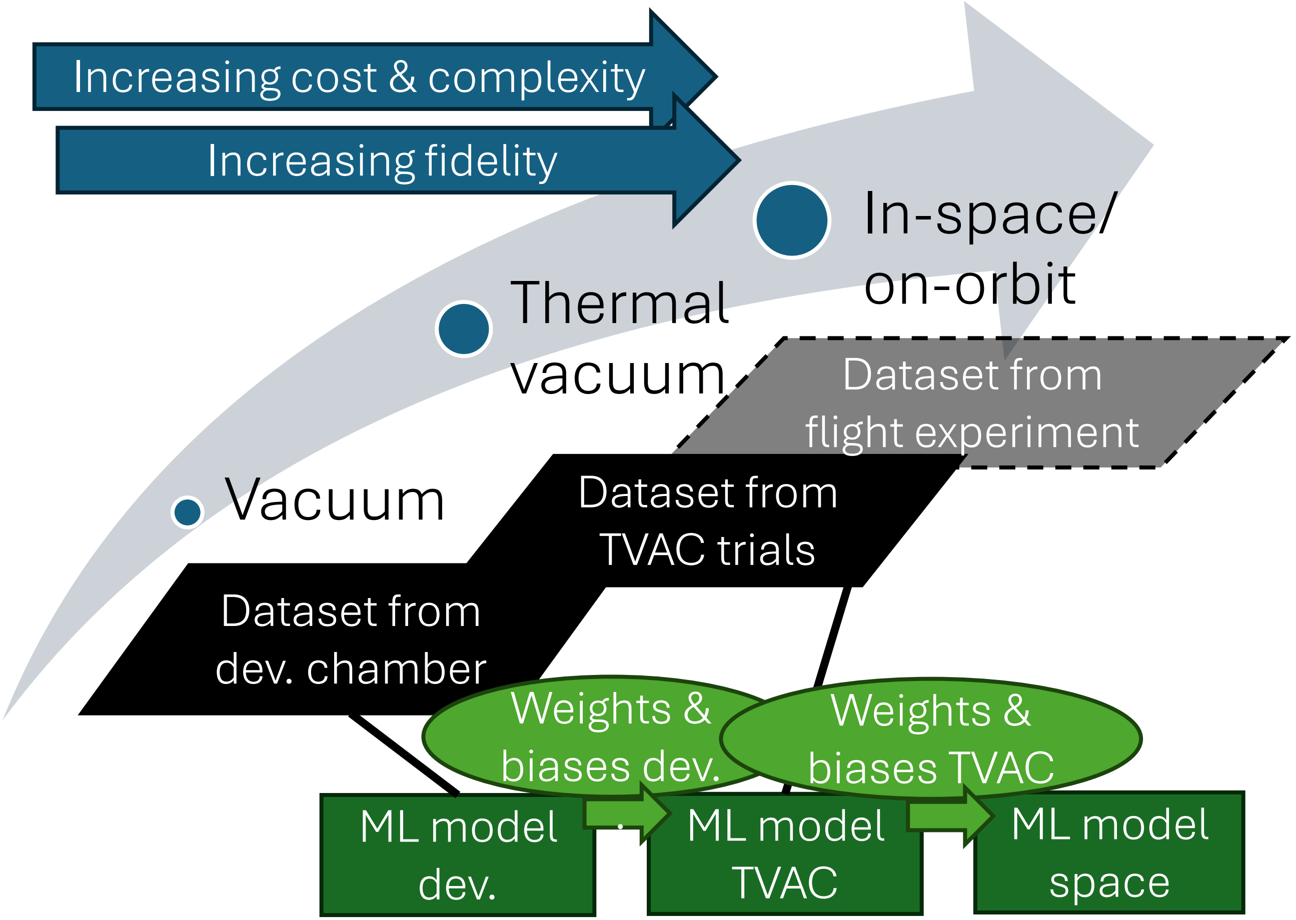
Validating thermal model with thermocouples and thermography

Leveraging AI/ML to reduce experimental burden

ML models to be trained on large developmental dataset linked to limited TVAC/flight datasets while considering delta in gravity, thermals, etc.

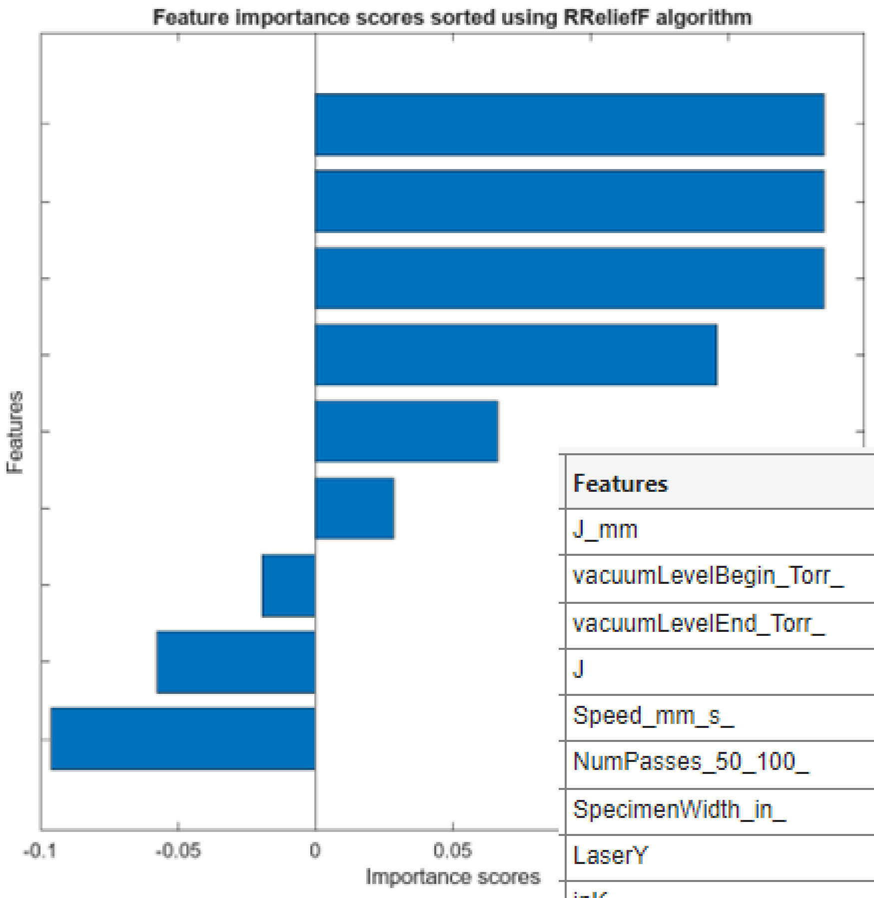


Evaluation of various ML model types for laser forming



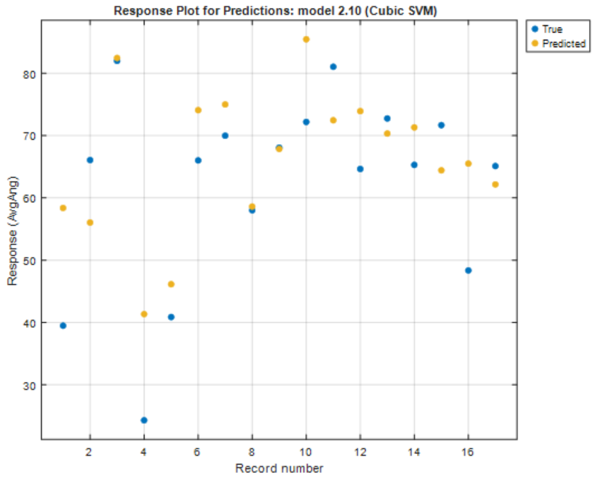
Transfer learning: train model on more extensive dataset, transfer weights & biases to model for rarefied dataset

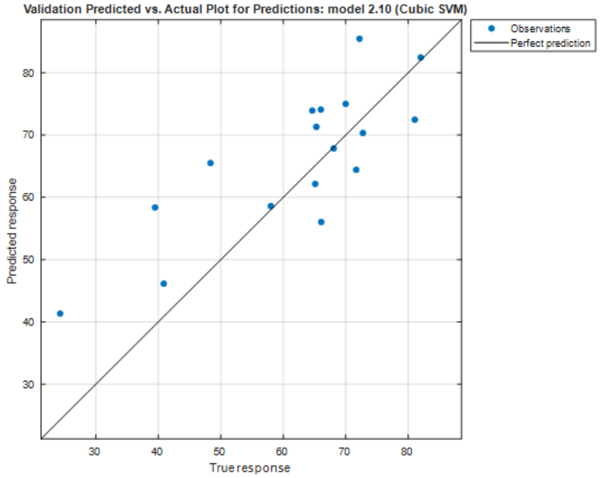
Bend angle prediction of AA3003



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





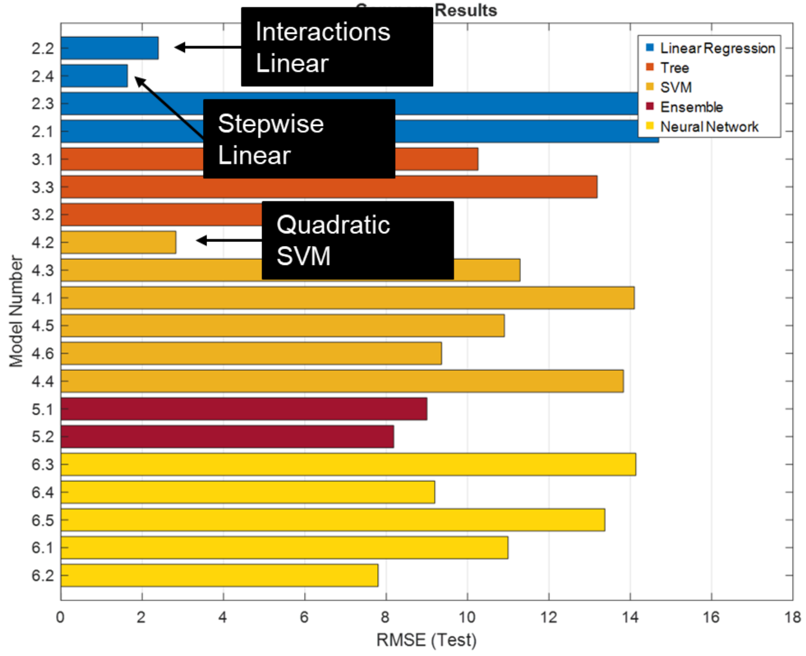
Regression output via cubic support vector machine (SVM)

Energy density and vacuum level most influential positive factors
Temperature an influential negative factor, but one half intensity

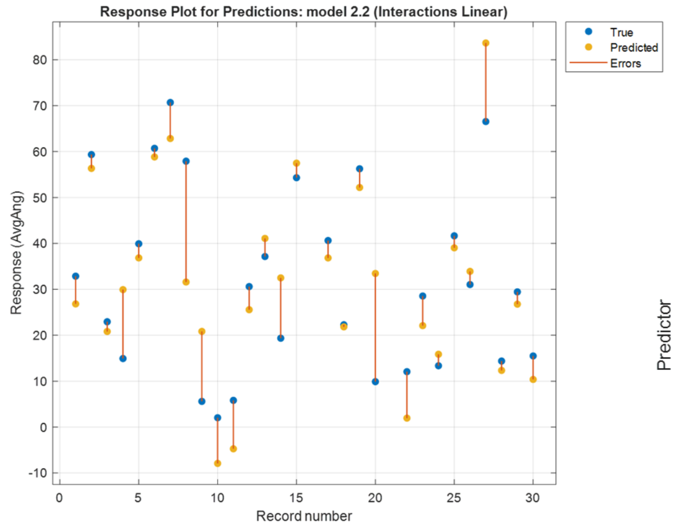
Bend angle prediction of Ti64

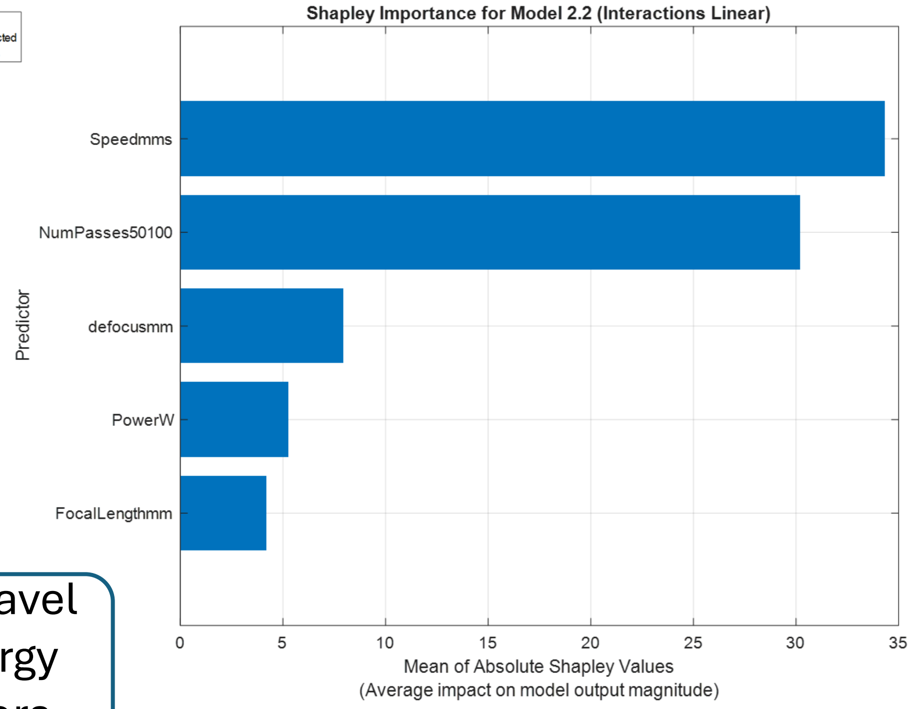
Model performances evaluated as best: linear, SVM

RMSE << SD



Regression output via linear interactions



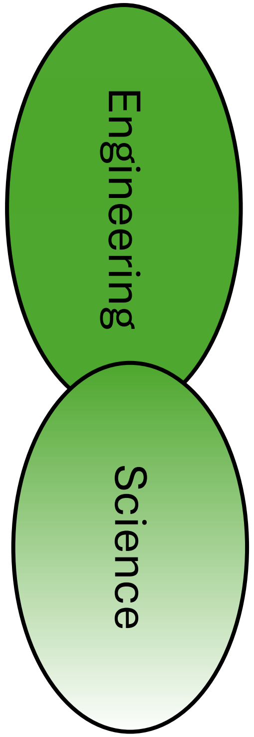


Neglecting vacuum level, travel speed and cumulative energy input most important factors

Including more factors (vacuum, temperature) in model iterations

Upcoming and future work for fundamental understanding

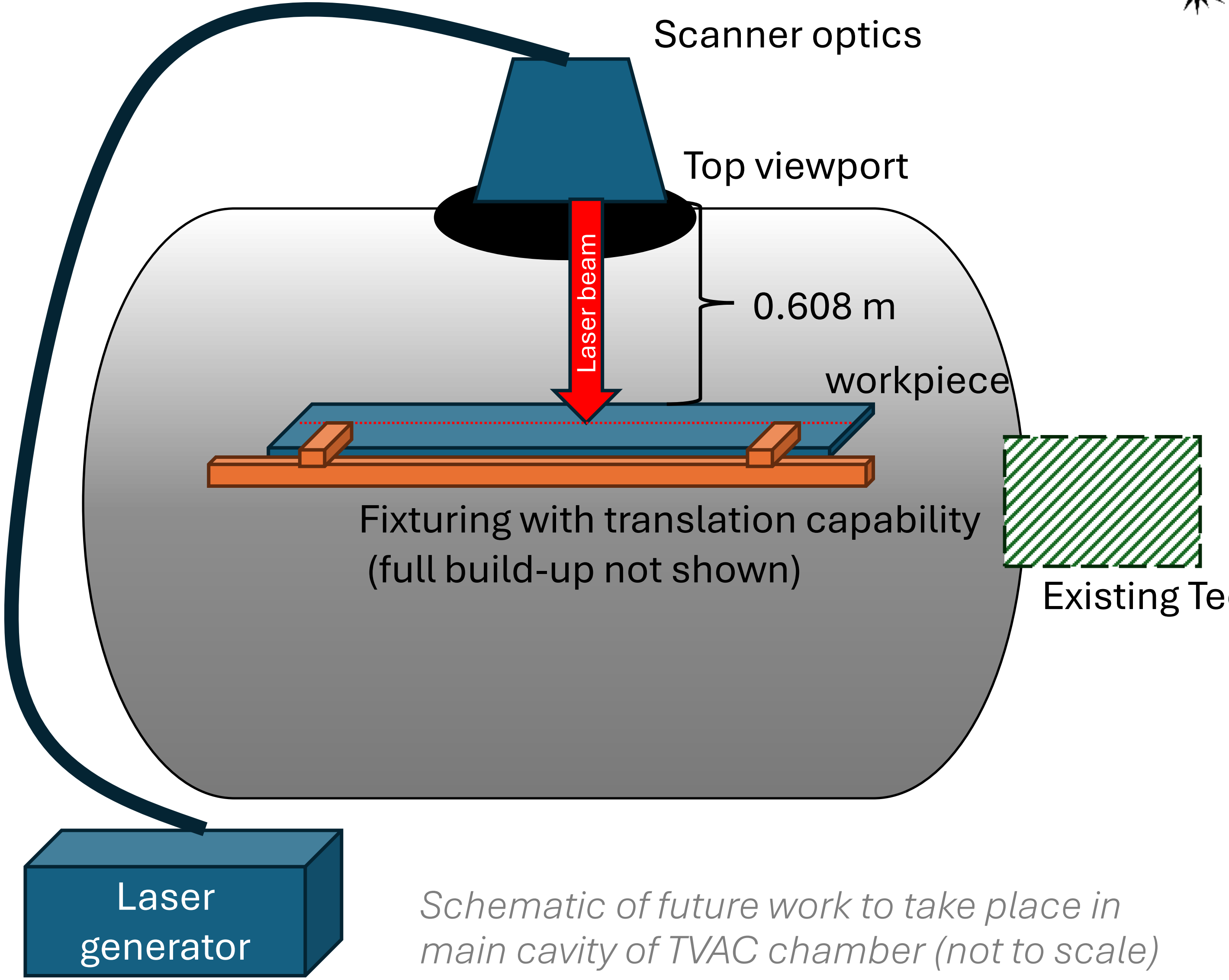
- Substantial work in materials diagnostics and property testing
  - *e.g.* what is mechanical performance of laser formed specimens?
- Continue building Digital Twin via ICME
- Pioneer ML transfer learning for laser forming
- Investigate influence of oxide layer thickness (and etching) on aluminum
- Explore melting/oxidation differences that speed bending process in air



We have shown that AISI304, AA3003, and Ti64 bend in TVAC
Now: understanding the fundamental mechanisms <u>and</u>
maturing the technology for practical application in space

Scaling up within main TVAC cavity

- Next steps in process development will require scale-up to a higher-power laser scanner on 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
- Demonstration planned by June 2026



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

Conclusions

- NASA and partners are maturing in-space laser processes, including laser forming
  - Laser forming does work in TVAC, imbuing confidence in its relevance for in-space manufacturing
- Demonstrated laser forming in space-like environments to:
  - Understand combined effects of reduced pressure and extreme temperatures
  - Provide validation datasets to anchor computational models
  - Mature technology to enable manufacturing structures in space, including scale up
- 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
    - Numerous opportunities: Announcement of Collaboration Opportunity, Cooperative Agreement Notice, Small Business Innovative Research, Space Act Agreements, etc.
    - Internships, fellowships, etc.

Acknowledgements

- This project was funded by DARPA via their NOM4D program (MIPR #HR0011470876).