National Science Foundation's
Hybrid Autonomous Manufacturing – Moving from Evolution to Revolution
Engineering Research Center

HAMMER Overview

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Note: Unless otherwise specified, all images are from HAMMER.

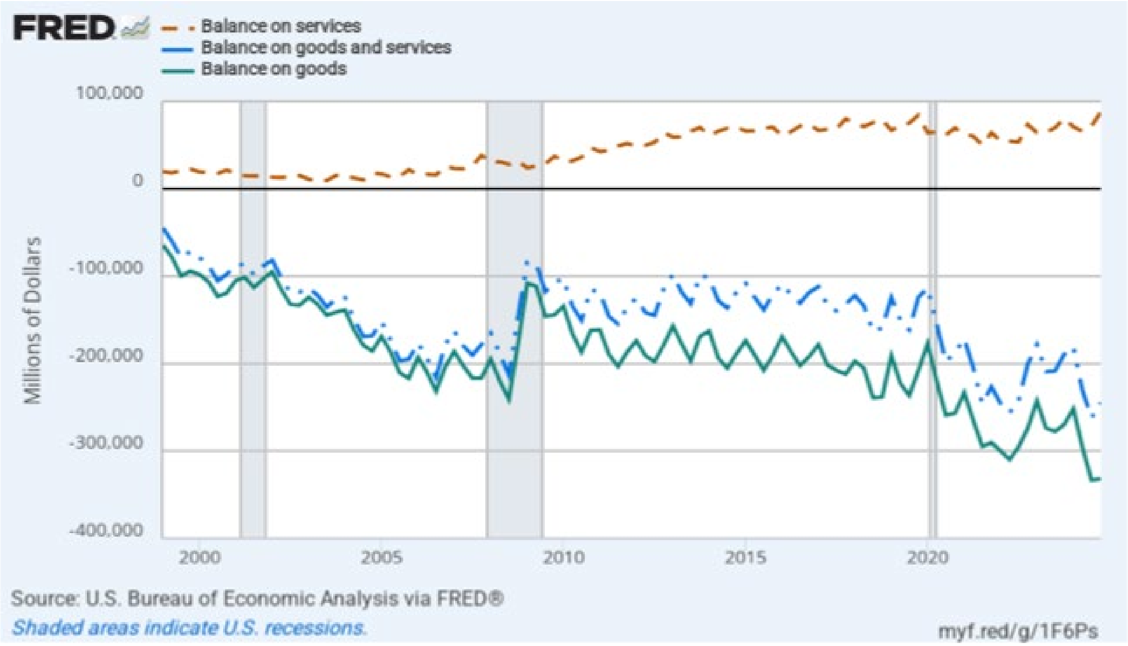
Bottom Line Upfront: Opportunities

1. Metal forming is an area of huge opportunity.
    - It's how we make the best stuff (critical aircraft parts).
    - It's how we make the most stuff (cans, cars, cutlery, etc.).
    - No serious innovation in 50 years.
    - Reshoring as a tailwind.

2. Partner with academic institutions.
    - Workforce
    - Innovation
    - Scale
    - Change is coming. Please help shape it!

Some Applied History

- The United States has developed world-leading industries.
  - Machine Tools, CNC
  - Microelectronics
  - Aerospace
  - Nuclear Power
- These industries were all developed by the U.S. Department of Defense (DoD) in private-public partnerships.
- All but aerospace were largely offshored since 1990s.
- This is causing issues that are now broadly being noticed.
  - Can't innovate next generation unless at state of the art. Issues are with:
    - Facilities
    - Talent
    - Supply chain
  - Supply chain fragility.
  - The United States can't make what is needed for defense.



THE WALL STREET JOURNAL.

President Trump visited the Fincantieri shipyard in Wisconsin in 2020, before construction began on the Constellation. SCOTT OLSON/GETTY IMAGES

POLITICS | NATIONAL SECURITY

The Warship That Shows Why the U.S. Navy Is Falling Behind China

A blizzard of design changes by the military have put production of the USS Constellation years behind schedule and millions over budget. Labor shortages, old equipment and rising steel costs aren't helping the industry.

444 Gift unlocked article Listen (14 min)

By *Alistair MacDonald* Follow and *Gordon Lubold* Follow

March 20, 2025 at 9:00 pm ET

U.S. Department *of* Defense

Fact Sheet: National Defense Industrial Strategy

The 2022 National Defense Strategy (NDS) states that the Department of Defense will prioritize coordinated efforts with the full range of domestic and international partners in the defense ecosystem to fortify the defense industrial base, our logistical systems, and relevant global supply chains against subversion, compromise, and theft.

The National Defense Industrial Strategy (NDIS) offers a strategic vision to coordinate and prioritize actions to build a **modernized defense industrial ecosystem** that is fully aligned with the NDS. It also calls for sustained collaboration and cooperation between the entire U.S. government, private industry, and our Allies and partners abroad.

The NDIS lays out four long-term strategic priorities to serve as guiding beacons for industrial action and resource prioritization in support of the development of this modernized defense industrial ecosystem.

1) Resilient supply chains that can securely produce the products, services, and technologies needed now and in the future at speed, scale, and cost.

   a) To address this priority, the DoD will incentivize industry to improve resilience by investing in extra capacity; manage inventory and stockpile planning to decrease near term risk; continue and expand support for domestic production; drive investment in the organic industrial base and production accelerators; diversify the supplier base and invest in new production methods; leverage data analytics to improve sub-tier visibility to identify and minimize strategic supply chain risks and to manage disruptions proactively; engage allies and partners to expand global defense production and increase supply chain resilience; and improve the Foreign Military Sales process.

   b) The risks of not achieving resilient supply chains include supply and materiel shortfalls; diminished surge capacity; supply chain vulnerability; and falling behind pacing challenges identified in the NDS.

2) Workforce readiness will provide for a sufficiently skilled, and staffed workforce that is diverse and representative of America.

How Can Academia Help?

Research & Development

- Work in areas of impact (e.g., metal forming).
- Little innovation since 1970, despite many new tools.
- 1968 study suggested several areas not properly explored: high energy rate, incremental, vibratory, etc.

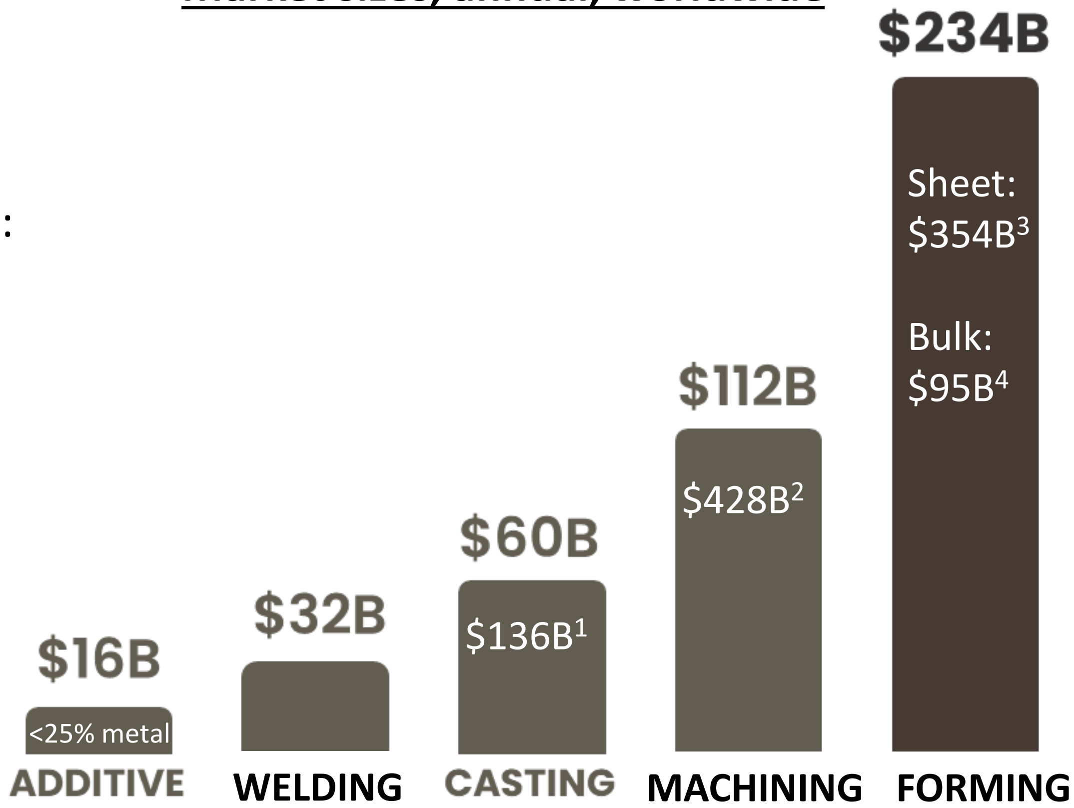
Educate

- Teach knowledge, skills, and abilities.
- More emphasis on innovation to engineers.
- Expand the pipeline for re-shoring.

Partner with Industry

- Use resources to de-risk new technology.
- Provide base for innovation.
- Cement new tech in the U.S. supply chain.
- Require new business models.

Market sizes, annual, worldwide



Mehr (Feb. 2023) NAE Smart Manufacturing Workshop

Mordor Intelligence Market Analysis Report

Inset: other credible estimates:

1, 3, & 4: Grand View Research

2: Precedence Research

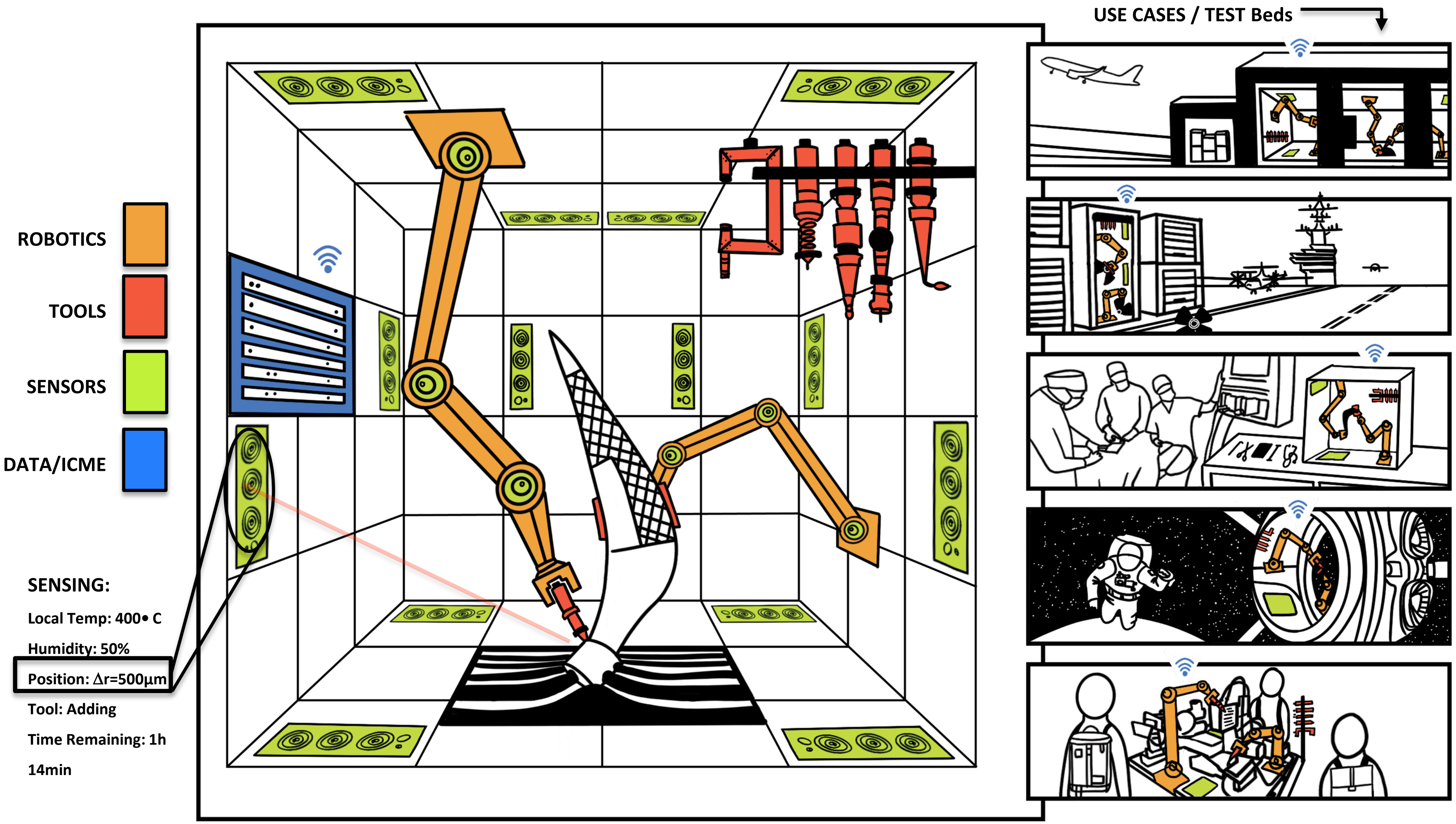
HAMMER – Hybrid Autonomous Mfg. Moving From Evolution to Revolution (an NSF Engineering Research Center [ERC])

- 10-Year Cooperative Agreement +
- ~$5M/Year Federal Funds
- Foundational Components:
  - Convergent Research
  - Engineering Workforce Development
  - Innovation Ecosystem
- Tech Foci:
  - Deformation
  - Advanced Control
  - Industry 4.0/Artificial Intelligence (AI)
  - New Processes
- Innovation Ecosystem
  - Federal Program
  - 501c3
  - Venture Studio

Diverse 5 Institution Team: Manufacturing, Metallurgy, Machine Learning (ML), Controls, Education, Social, and Policy.

HAMMER ERC · The Ohio State University College of Engineering · Case Western Reserve University Est. 1826 · North Carolina Agricultural and Technical State University · Northwestern University · The University of Tennessee Knoxville

NSF HAMMER-ERC Approach



Research Thrusts

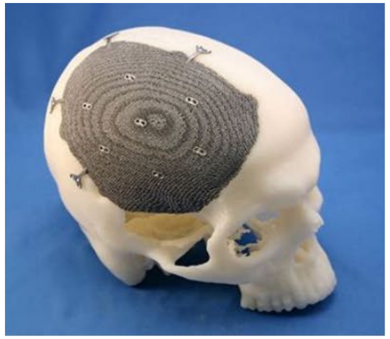
T1: Design: product and process.

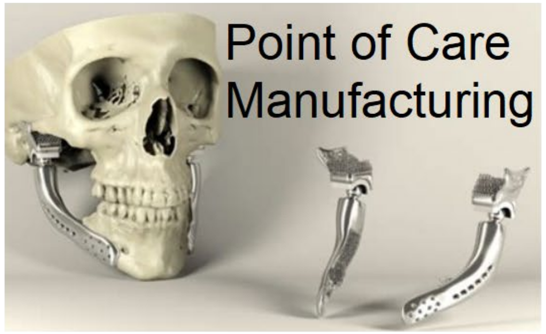
T2: Tools and Process Convergence: new tools and processes.

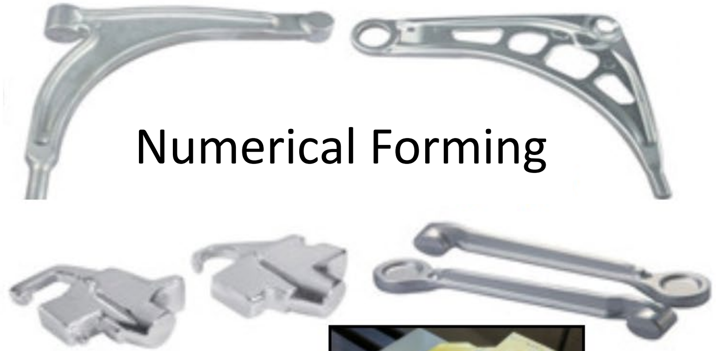
T3: Materials State Awareness: Enabling process- and model-based quality certification.

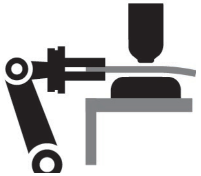
T4: Control, Intelligence, and Autonomy: Leveraging AI to control processes learn.

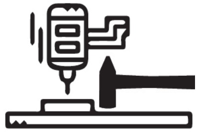
HAMMER Testbeds

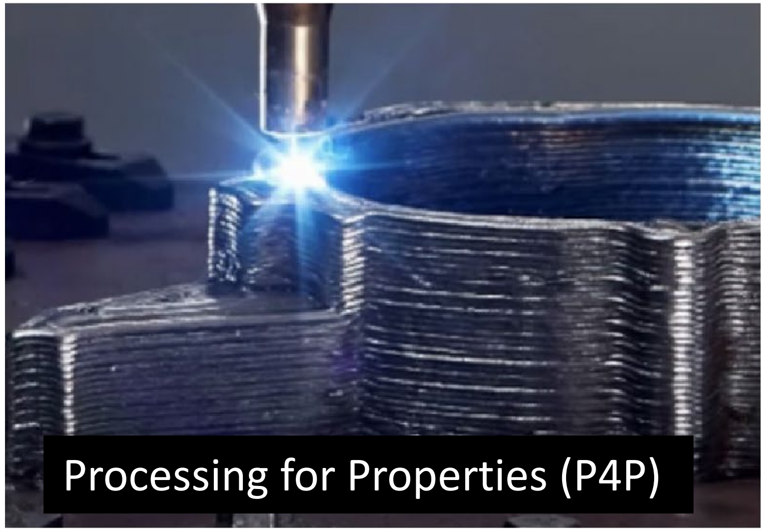


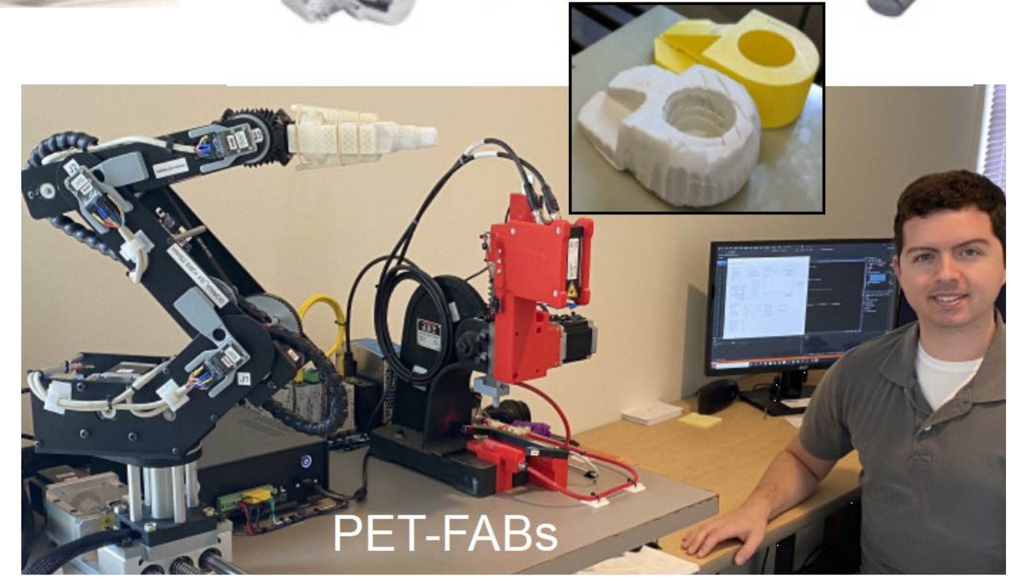










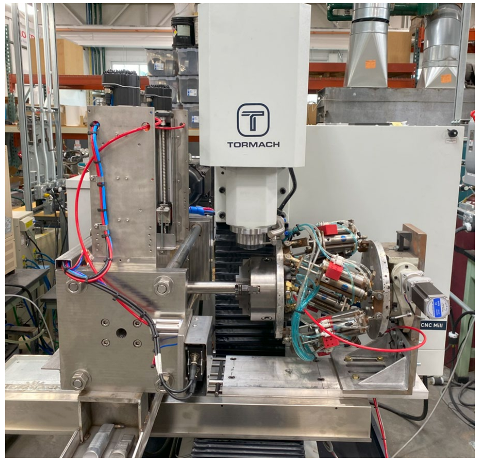


Physical Exploration & Training – Factory/Artisan Boxes

Our CNC Deformation Tools

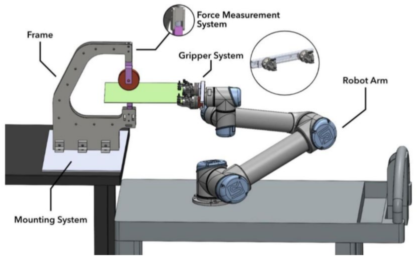
Machina Labs

Agility Forge

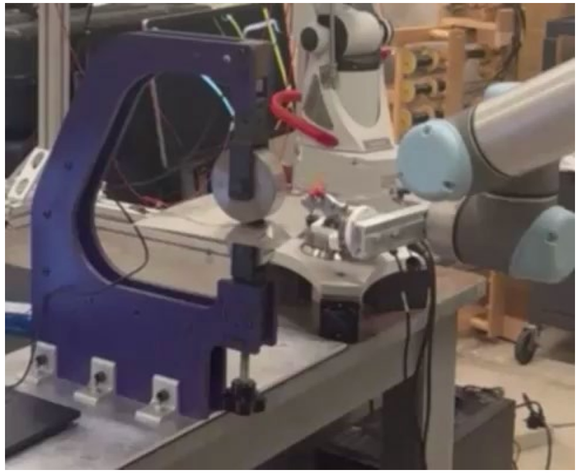


Robotic English Wheel

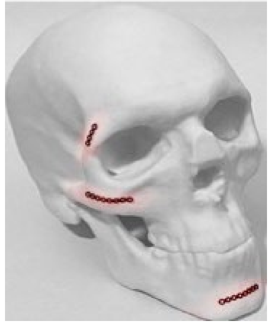
PET-FAB TESTBED: Miniature version of the wheeling set-up with compliant grippers and load cell integration

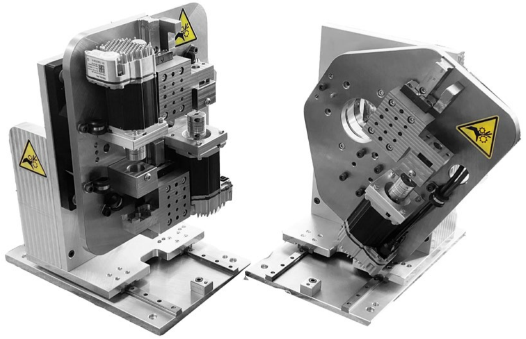


CAD of table-top mini-English wheel set-up developed by **NU undergraduate capstone team**.



Robotic Fixation Plate Bending

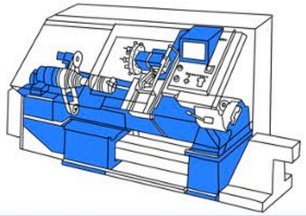
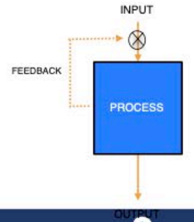


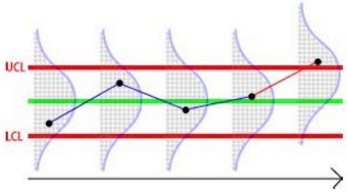


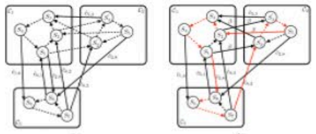
Wire Arc Additive + Forming

American Pin Bed

Levels of Manufacturing Autonomy






0	1	2	3	4	5
No Automation	**Open-loop motion**	**Closed Loop Control**	**Process simulation & in-situ correction**	**Automated Hybrid Process Execution**	**Automated Design & Negotiation**
Zero autonomy. Operator controls motion and settings.	Computer Numerical Control (CNC) of motion for primary operation.	Key component metrics are sensed during process and control algorithms minimize errors.	Experience or physics-based simulation gives expected outcomes and process strategy may be modified.	Multiple fully-automated processes are used with automated hand-offs between.	System considers multiple process paths & tradeoffs: performance, price, tolerances and lead time.

Commercial & Unitary process

Multi-process ERC vision

Additive + GE, Markforged, others…
Machining + Protolabs
Welding + Path Robotics
Deformation + Machina Labs

Requires concurrent hardware and computational development

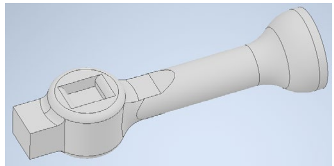
Agility Forge, a Leading Example

Robotic blacksmith involving all HAMMER thrusts

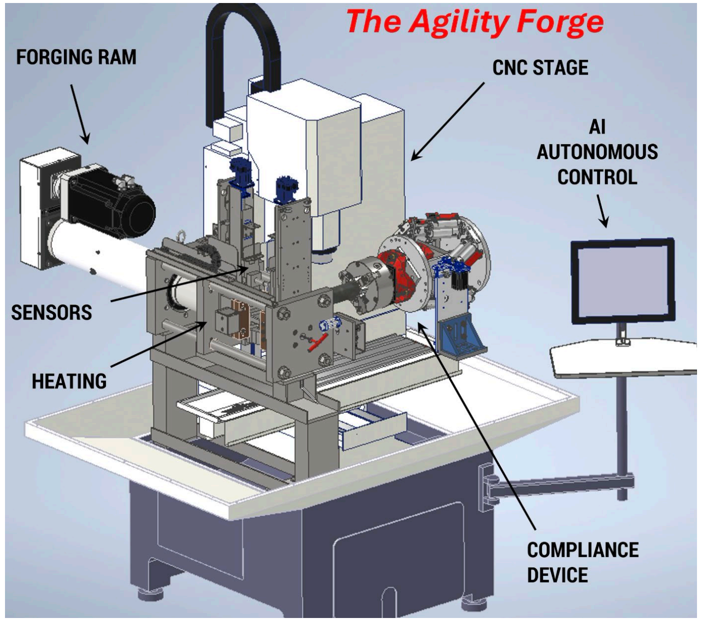
Ideas predate ERC, impact should persist

Why:

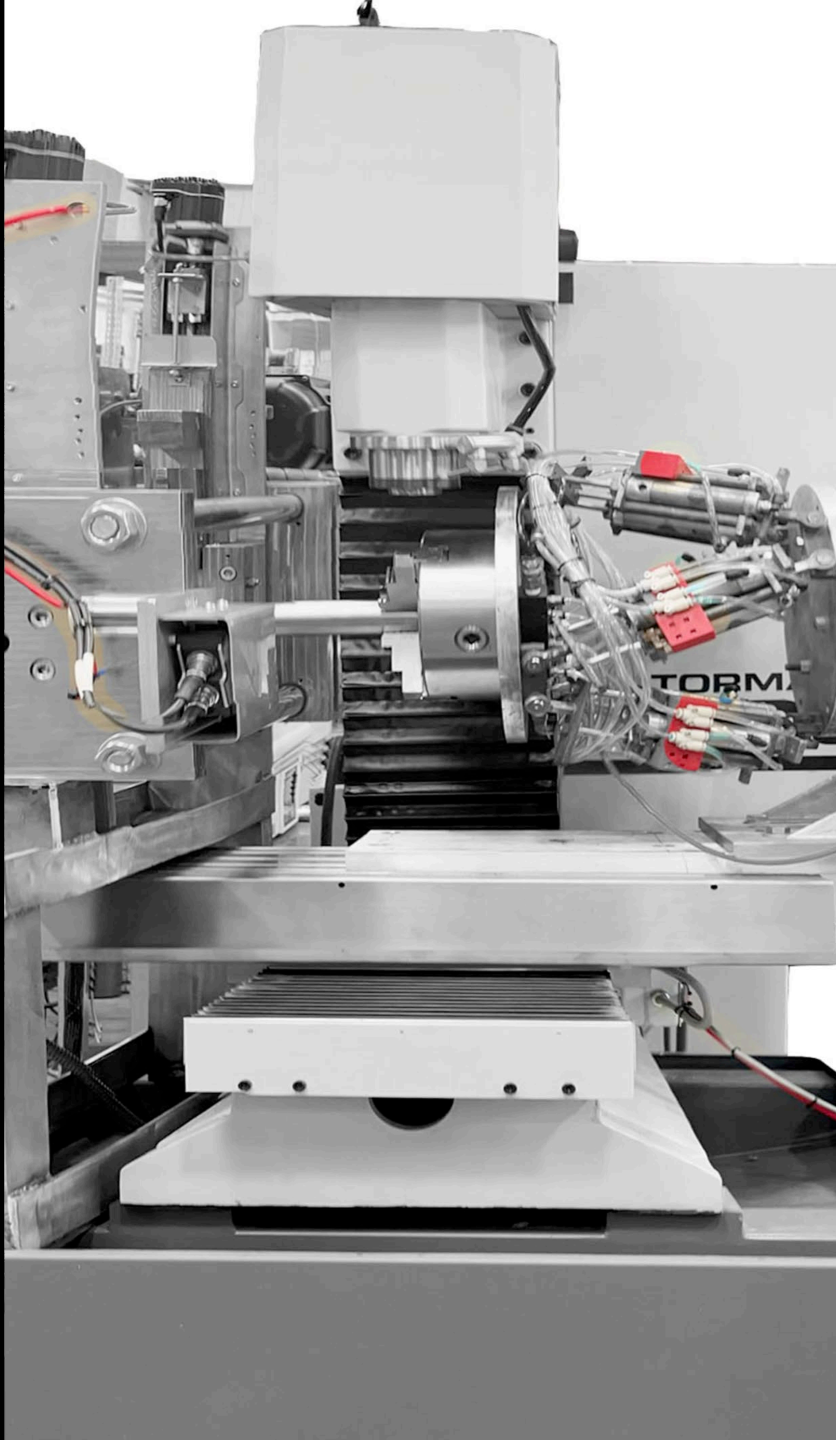
- Faster than machining
- Better materials utilization than machining
- Real forgings
- Builds on decades of metal processing
- Measures materials properties in-situ
- Demonstrates commercial need
- Machine AI learning and control platform
- Inexpensive addition to CNC mill



Result



THE AGILITY FORGE IS



Design Flexibility With the Agility Forge (STARC)

Core system

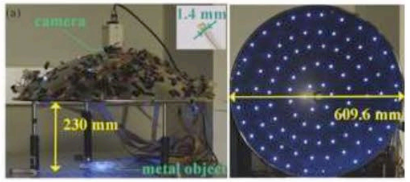
Options

Sensors

Core system

Proximity sensors
Thermocouples
Force & displacement

Options



Shape
Local hardness
Temperature fields
Microstructure
Think beam-lines…

Thermal

Core system

Induction heating

Options

Gas Forge
Flame
Lasers
Electric Furnaces, etc.

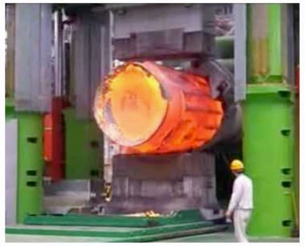
Actuators

Core system

Servoelectic press

Changeable tools

Options



Servoelectric pressses
English Wheel
American Pin Bed
Laser-Impulse
Power Hammers
Electromagnetic Hammers
Integrated systems
(like BendyBot)

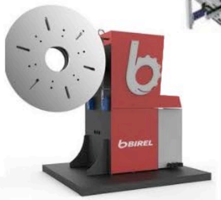
Robotics

Core system

Adapted CNC machining center offers high dimensional control and strength.

Options

Robots of varied size & shape



Computation

Core system

Open-source algorithms
- C#
- Unity
- Python
- Linux CNC
- Unity

Focus on data storage & interoperability
Similar to FDM printers

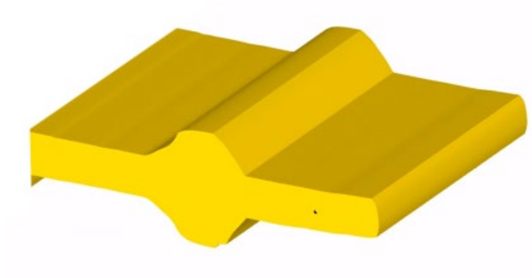
Options

ROS
Rockwell
Siemens
Competitions
Modules
GUI - access
Proprietary
Open Source

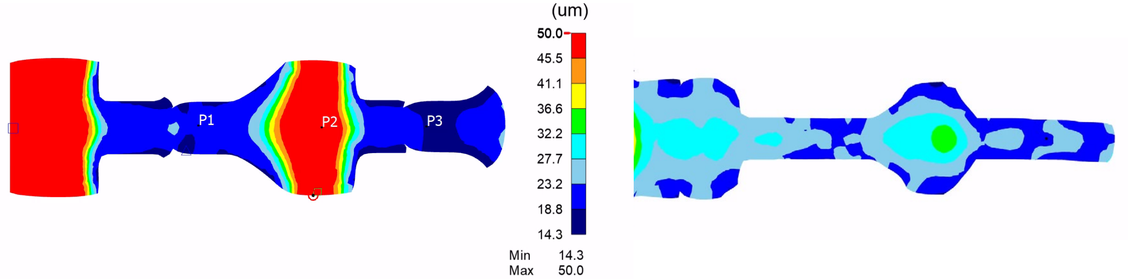
Focus on training data
Modular, interoperable
Data standards

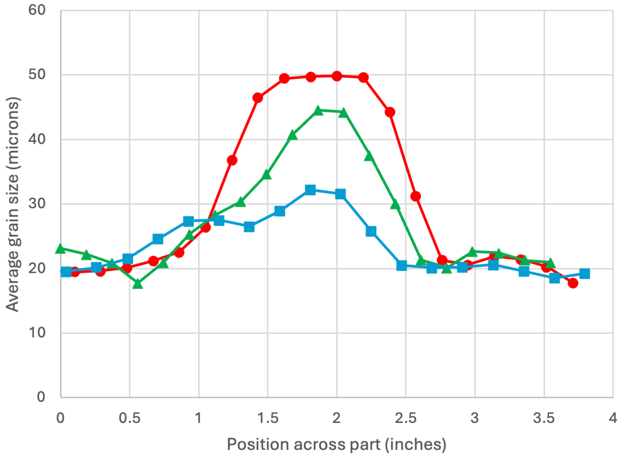
Controlling Shape and Microstructure

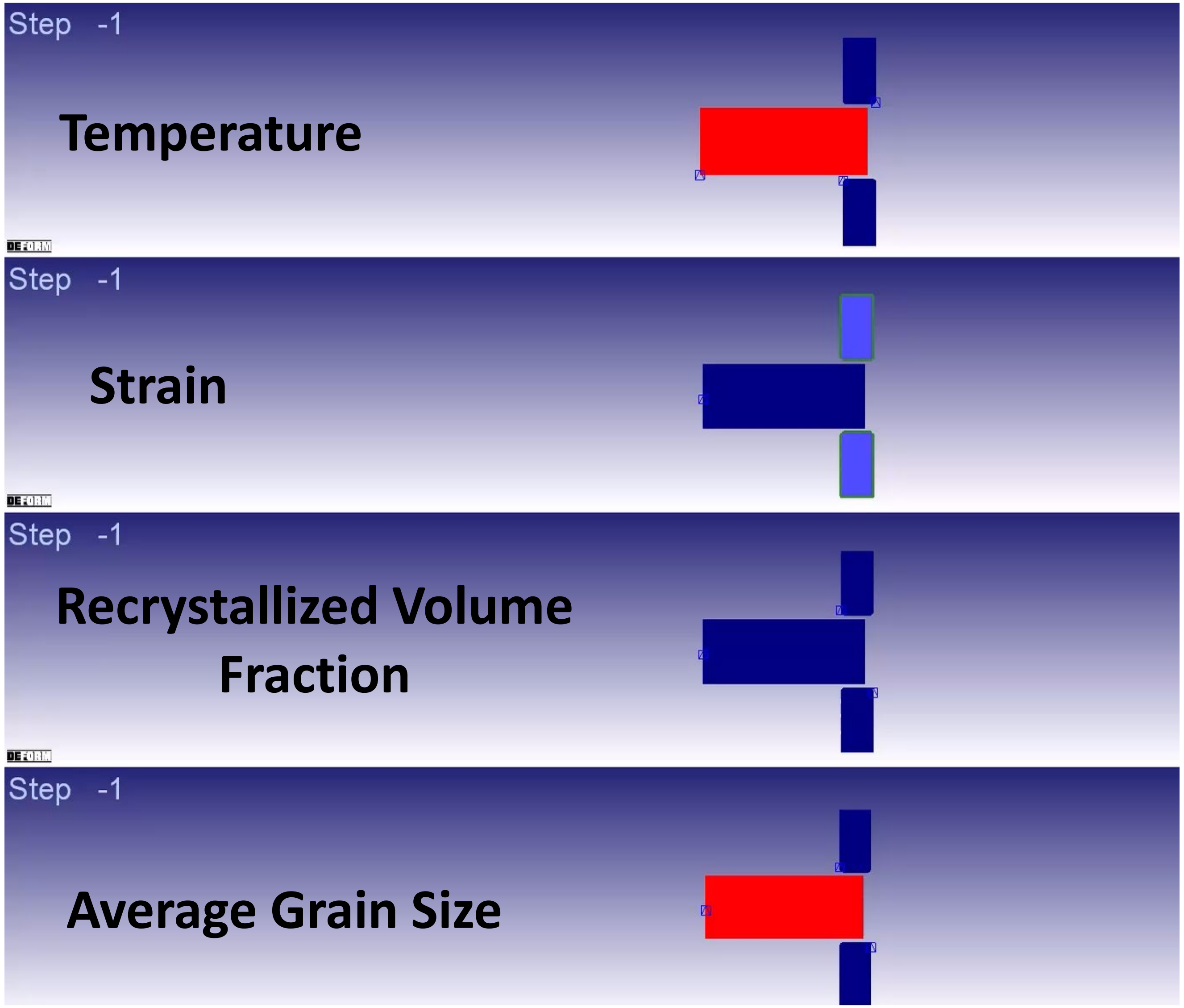
Example part geometry



Resulting grain size dist. from three paths



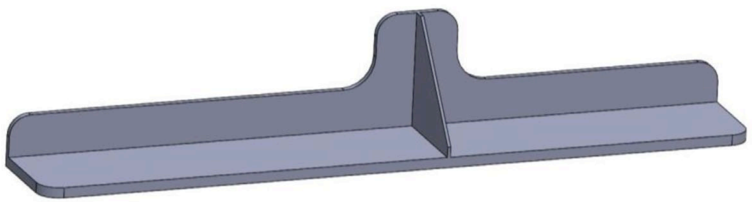




Agility Forge Video

MM Advantage vs. **M**achining **A**dditive or **C**asting

Scales to large sizes (A)



Caiazzo et al. *Metals, 2017*

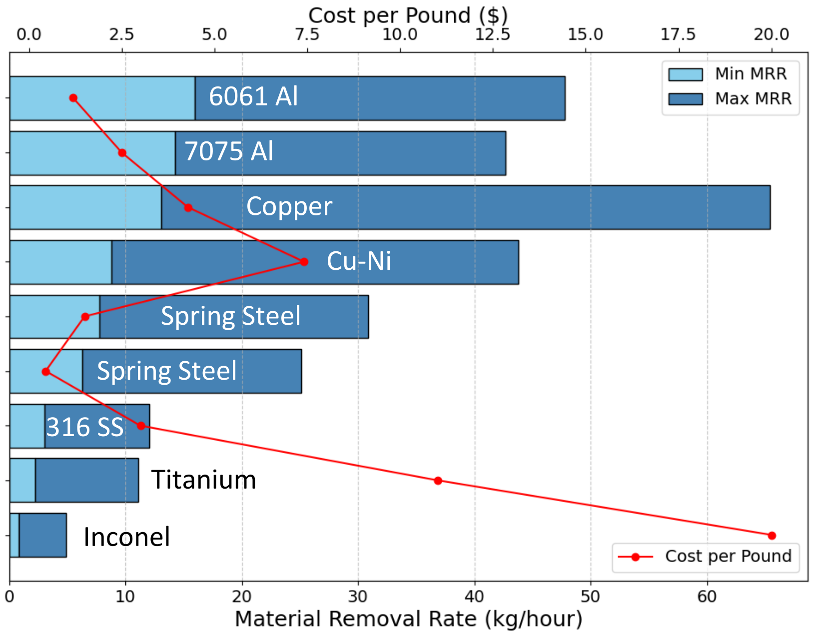
Improved buy/fly (M)

- hard-to-machine
- high-cost alloys

Improved microstructure (A, C)

Ease of Certification (A)

Embodied energy (M, A)

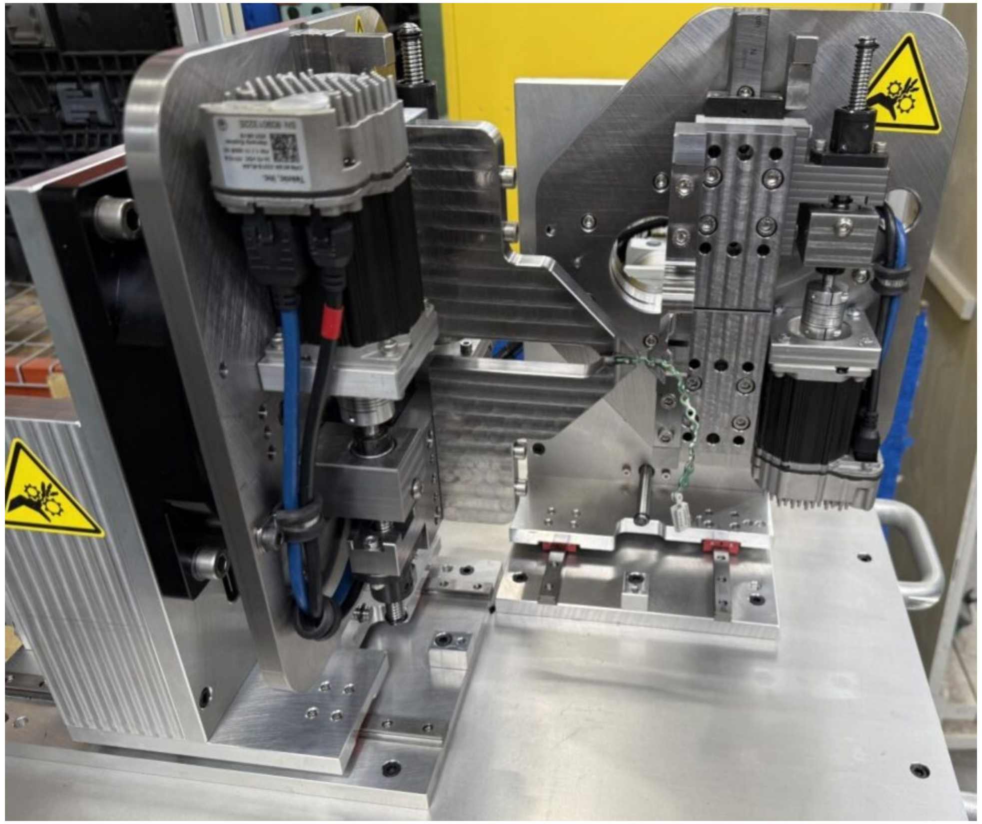


Boeing 737 Pickle Forks

Fixation Plate Bender (Bendy Bot)

Fixation Plate Bender 1.0 (years 1 - 2)

Fixation Plate Bender 2.0 (years 2 - 3)

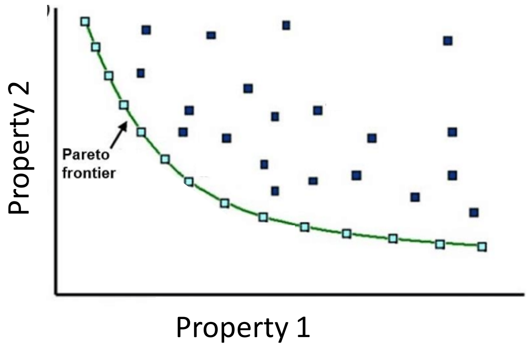


Fixation Plate Bender 1.0 → 2.0 Video

The HAMMER-ERC Strategic Process

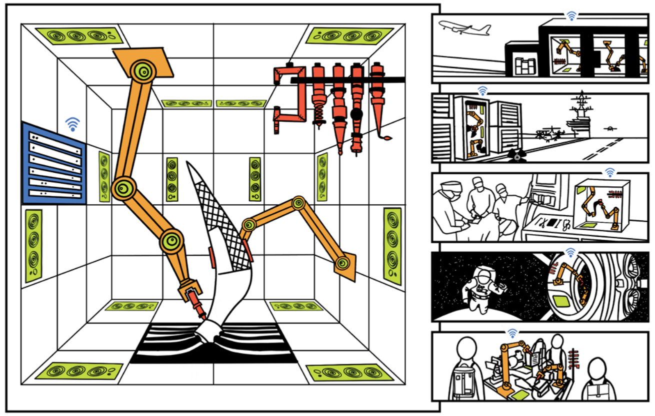
Learn

Design attributes predicted for many components and paths



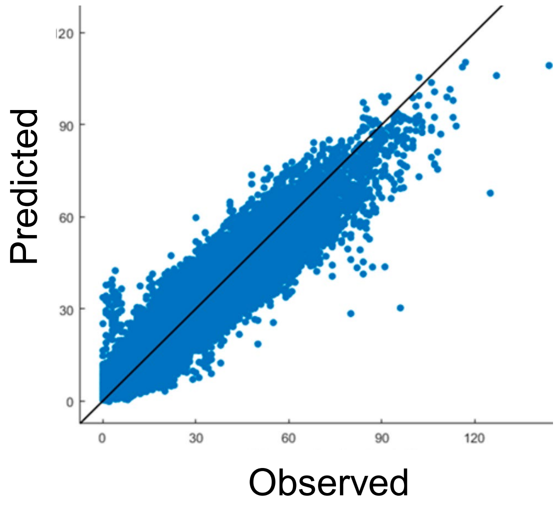
Concurrent & generative

Execute manufacturing & collect in-process data



Toward autonomous control

Measure properties/attributes



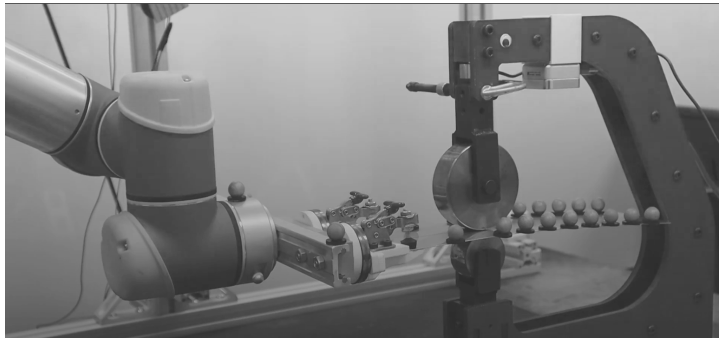
Model-based qualification

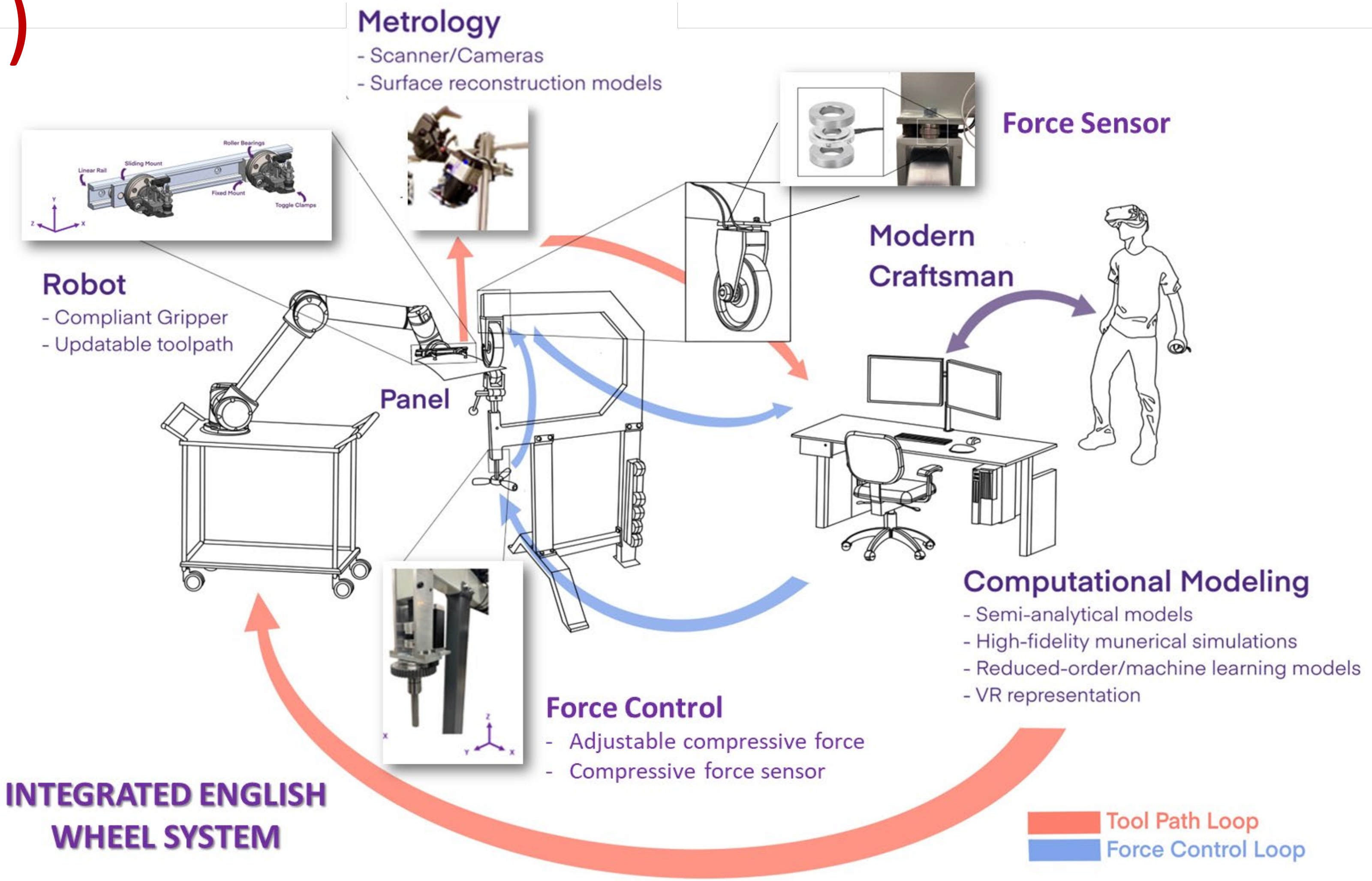
Needs: • Research • Education • Talent (diverse and at scale) •Commercial engagement

Approach: Small, informed, and diverse partner set; sponsors who support the vision, not distract; listen.

NSF ERC HAMMER ERC The Ohio State University College of Engineering Case Western Reserve University Est. 1826 North Carolina Agricultural and Technical State University Northwestern University The University of Tennessee Knoxville

Robot-Assisted Automation of English Wheel Forming (T103, T201, T202)





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Digital Twin (T103)

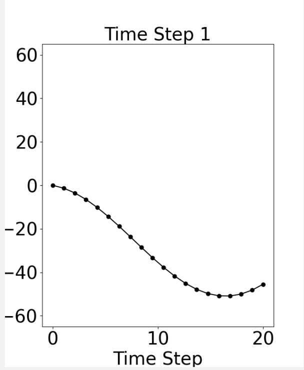
❖ O2: Real-time state-space ML model and MPC for toolpath optimization in robot forming

Physical System

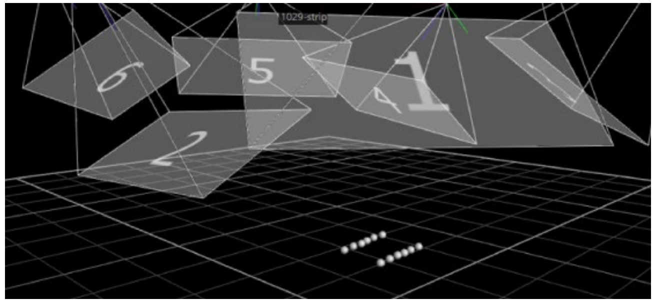
Design of Experiments on Toolpaths

Experimental Setup

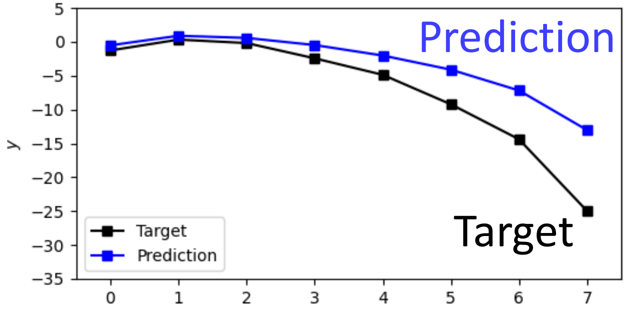
Optimal Tool Path Profile



Physical to **Virtual**



Deformation Metrology through Vicon Tracking



Model Predictive Control (MPC) for Real-Time Decision-Making

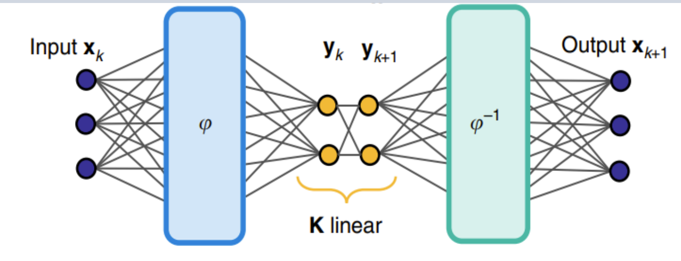
Virtual to **Physical**

Virtual System

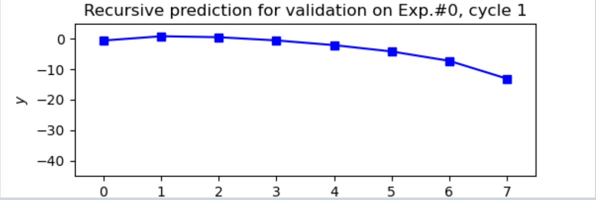
Surrogate Modeling

State Space Representation for Sheet Deformation

$$\mathbf{z}_{k+1} = \mathbf{A}\mathbf{z}_k + \mathbf{B}\mathbf{u}_k$$



Nonlinear System Identification via Deep Koopman Operator



State Prediction

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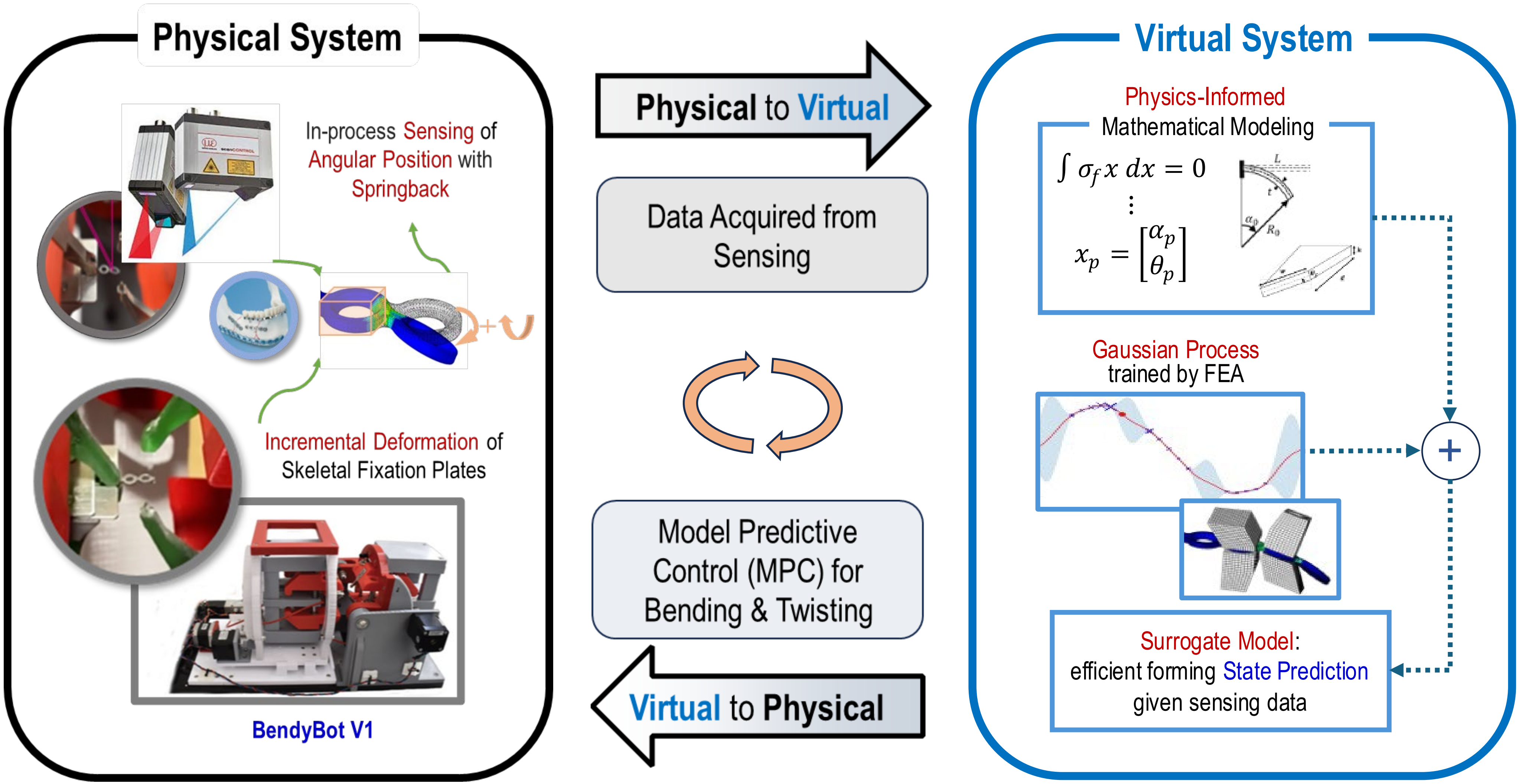
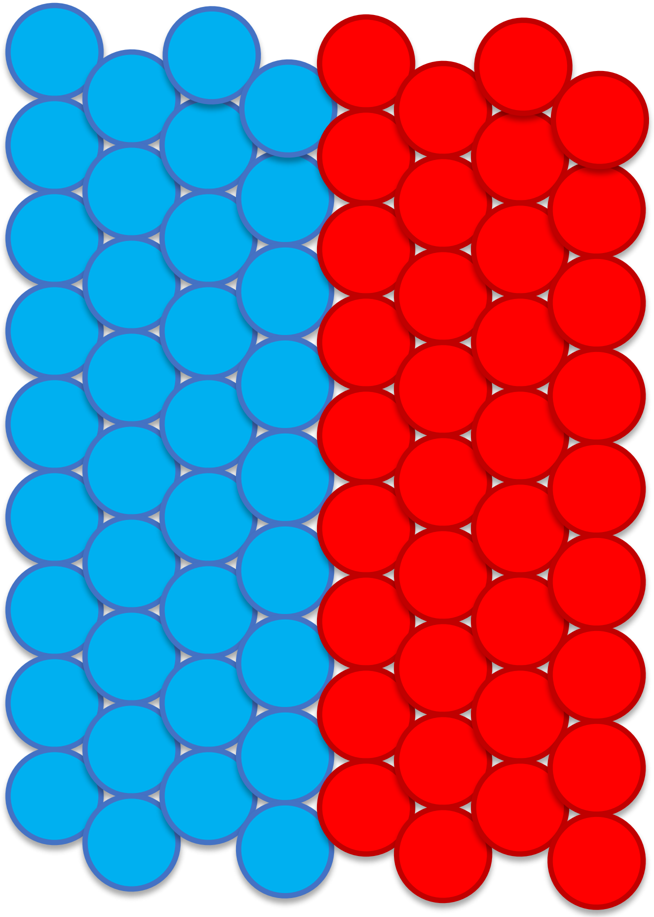
Digital Twin: Hybrid Physics-Informed & ML-Enhanced



An *Ideal* Dissimilar Metal Weld?

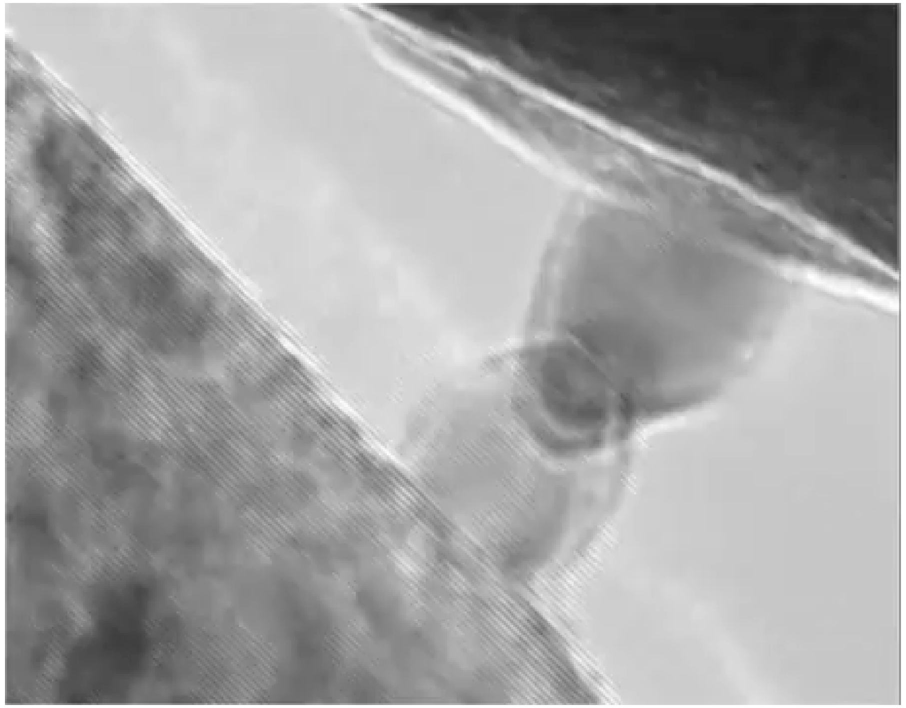


Transition metals share electrons…

Atomically clean, flat surfaces would bond.

Can conventional methods do this?

What kind of process can?



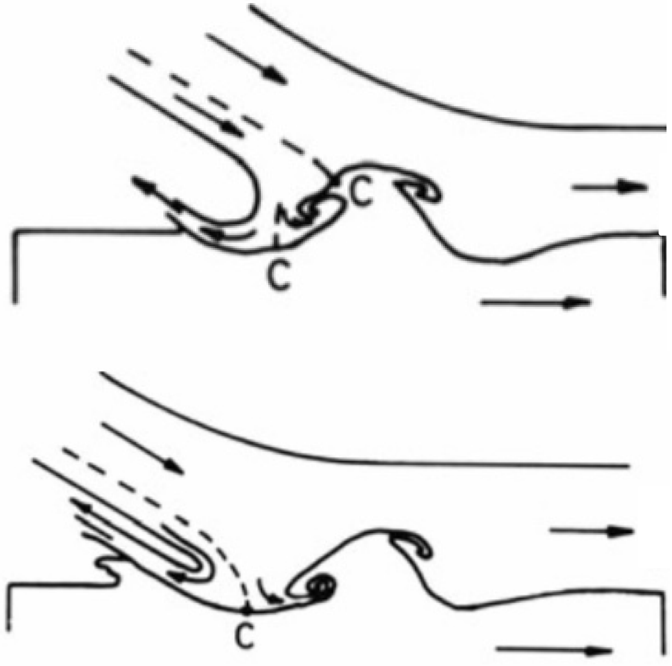
ARTICLES
PUBLISHED ONLINE: 14 FEBRUARY 2010 | DOI: 10.1038/NNANO.2010.4
nature nanotechnology

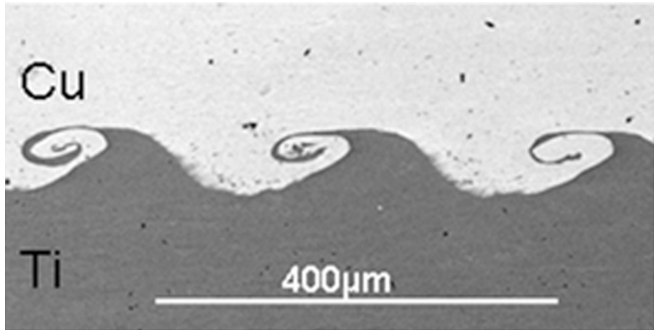
Cold welding of ultrathin gold nanowires

Yang Lu[1], Jian Yu Huang[2], Chao Wang[3], Shouheng Sun[3] and Jun Lou[1]*

Impact Welding

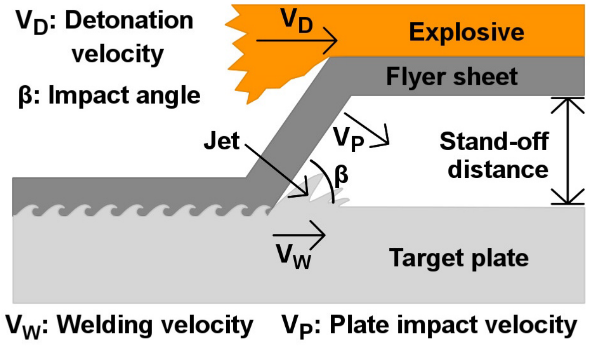
- *Jetting* cleans surfaces
- Ultrahigh pressures for atomic contact
- Large plastic strains
- Adiabatic heating: deformation, friction, gas
- Local heterogeneity
- Very rapid cooling
- Reflected stress waves

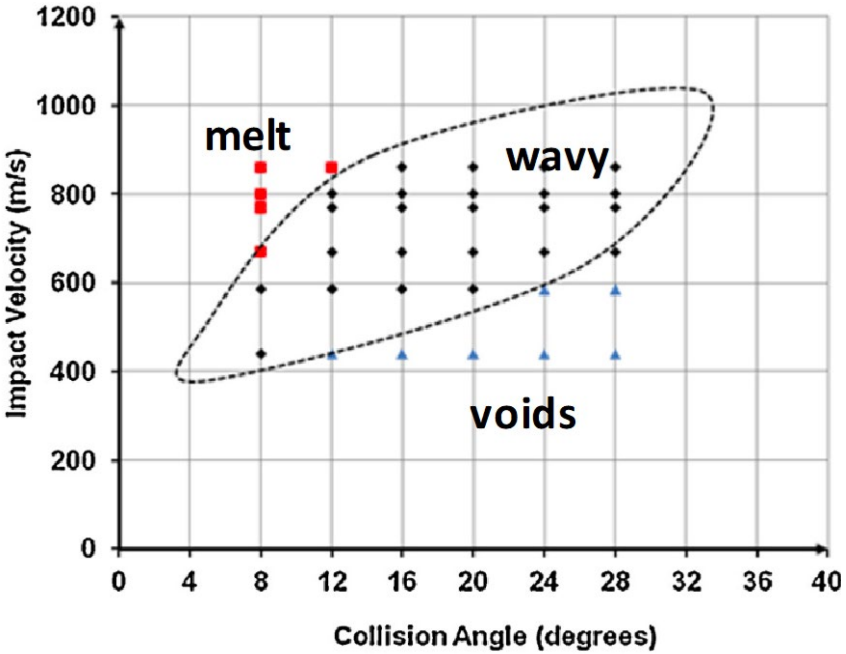


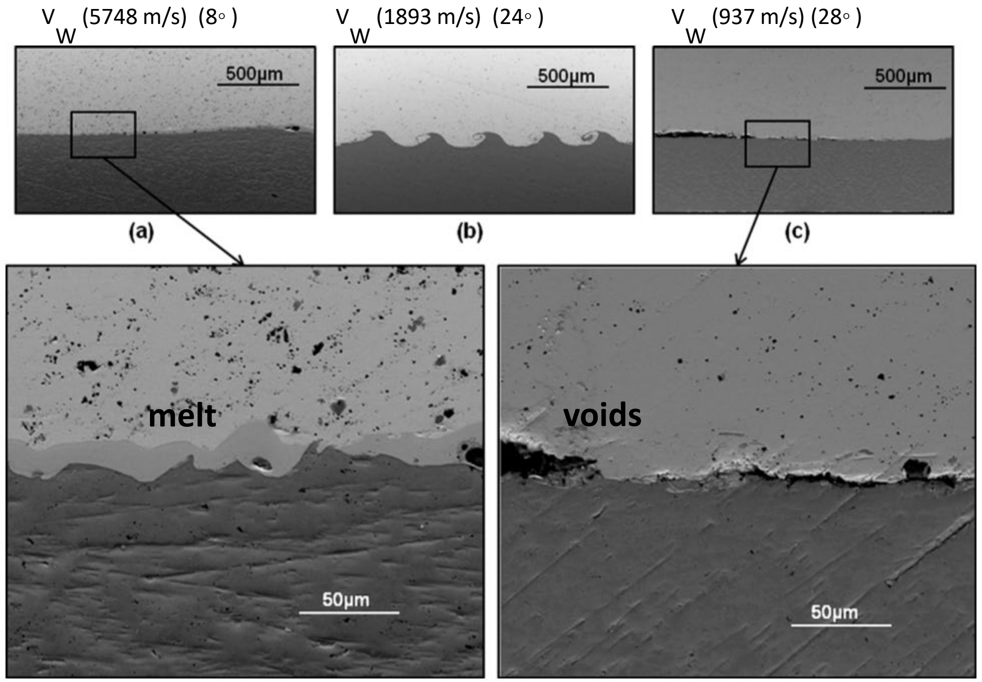


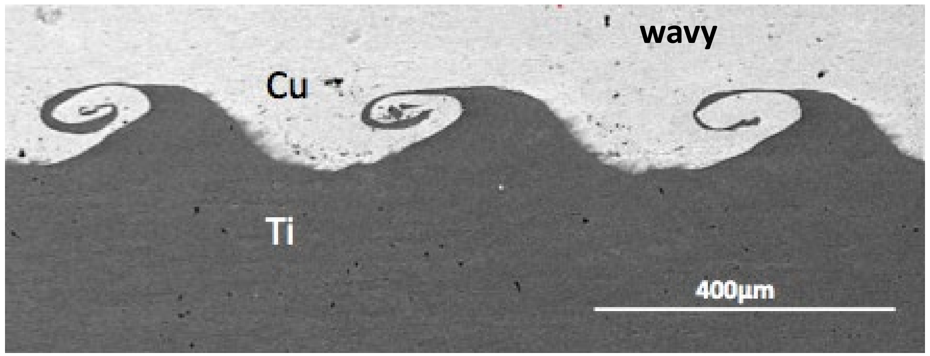
(Top) Mechanism of Bahrani, Black and Corssland, *Proc. Roy. Soc.*, (1967).

Processing → Structure → Properties





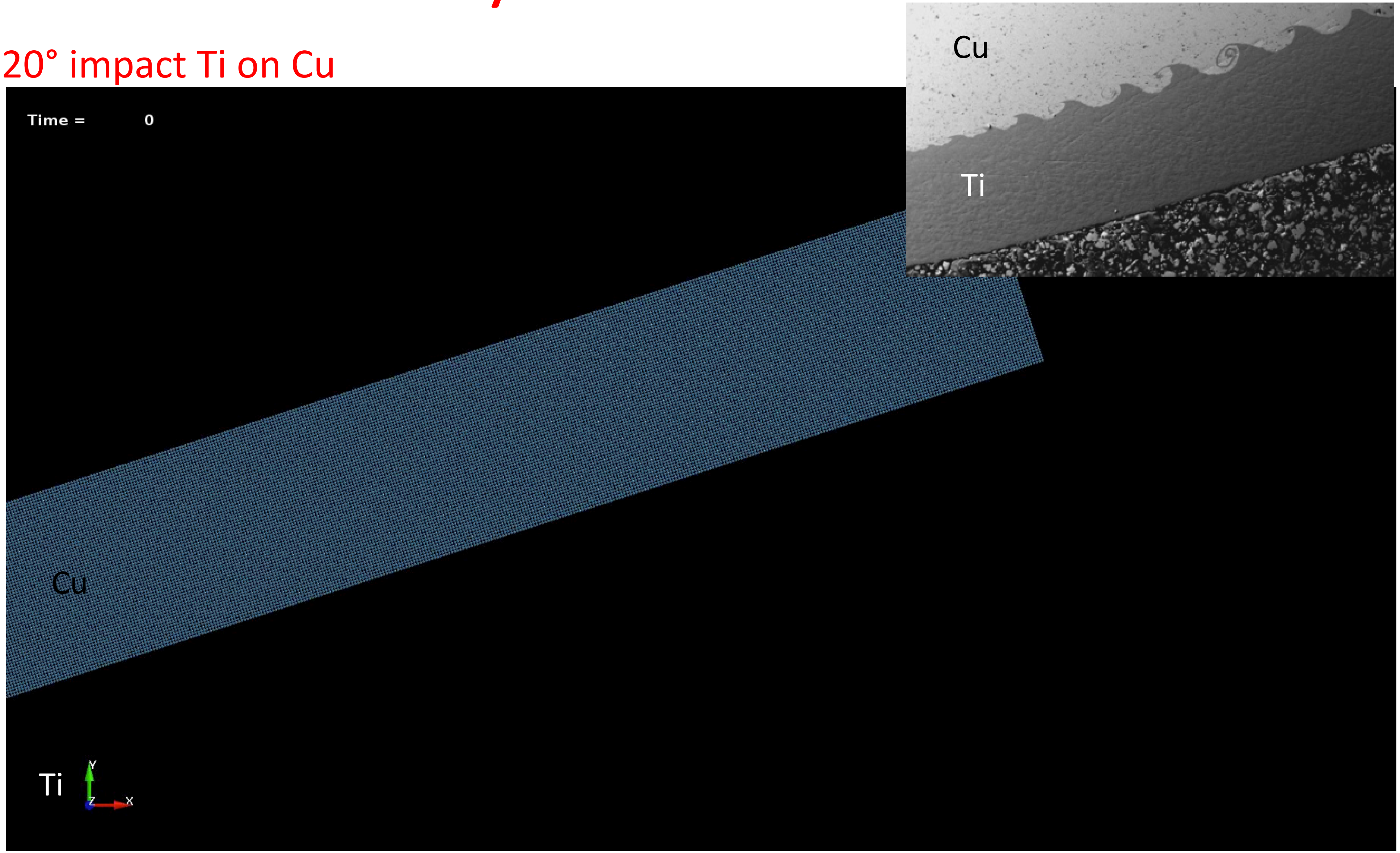




Vivek, Liu, Hansen, and Daehn, *J. Mater Proc.*, 2014

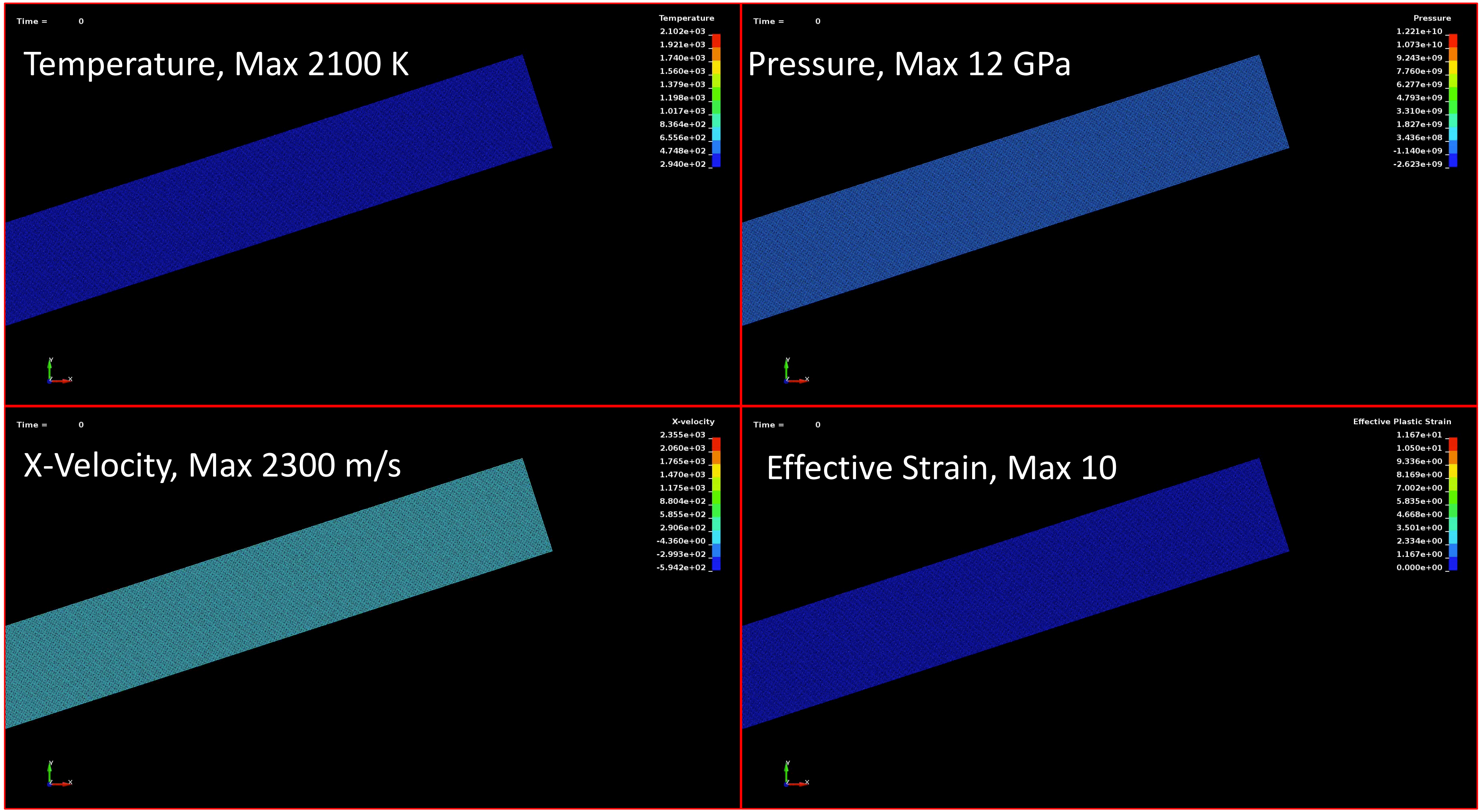
Smoothed Particle Hydrocode Simulation

800 m/s, 20° impact Ti on Cu



Nassiri, *Appl. Phys. Let.*, 2017 – LS DYNA SPH

Design Parameters



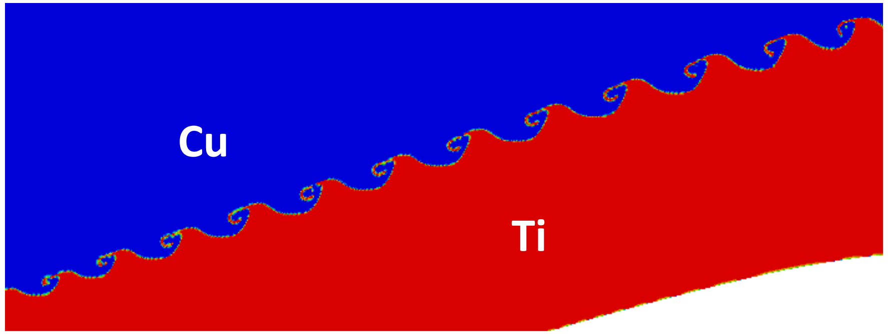
Nassiri et al., *Appl. Phys. Let.*, 2017

Varied Systems

Cu-Ti

Impact angle, $\beta = 20°$

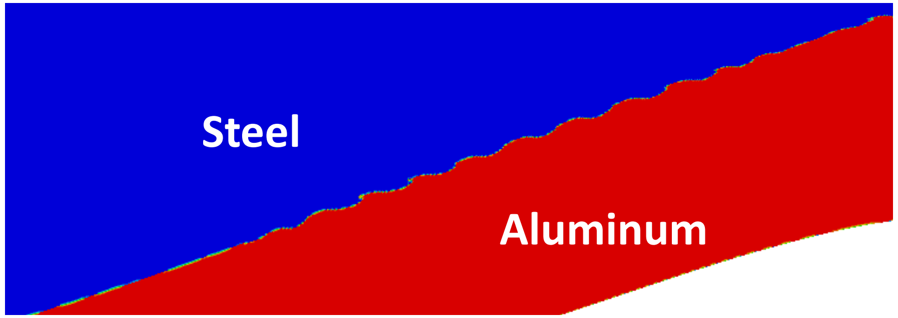
Impact velocity, V_p = 770 m/s

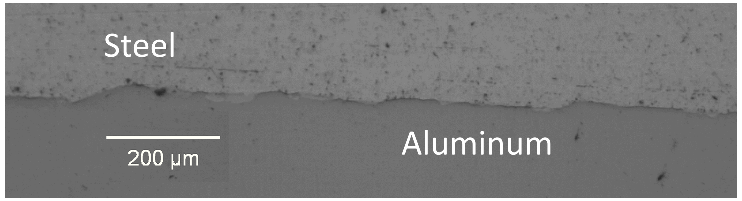


Fe-Al

Steel-Aluminum

Steel-Al
Steel 4130
Al 6061

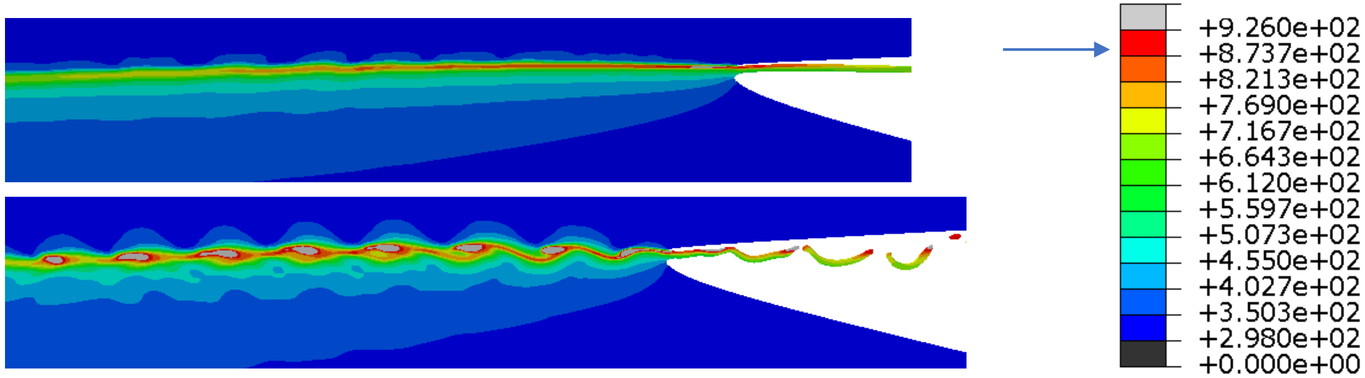




Melting point of Al 6061

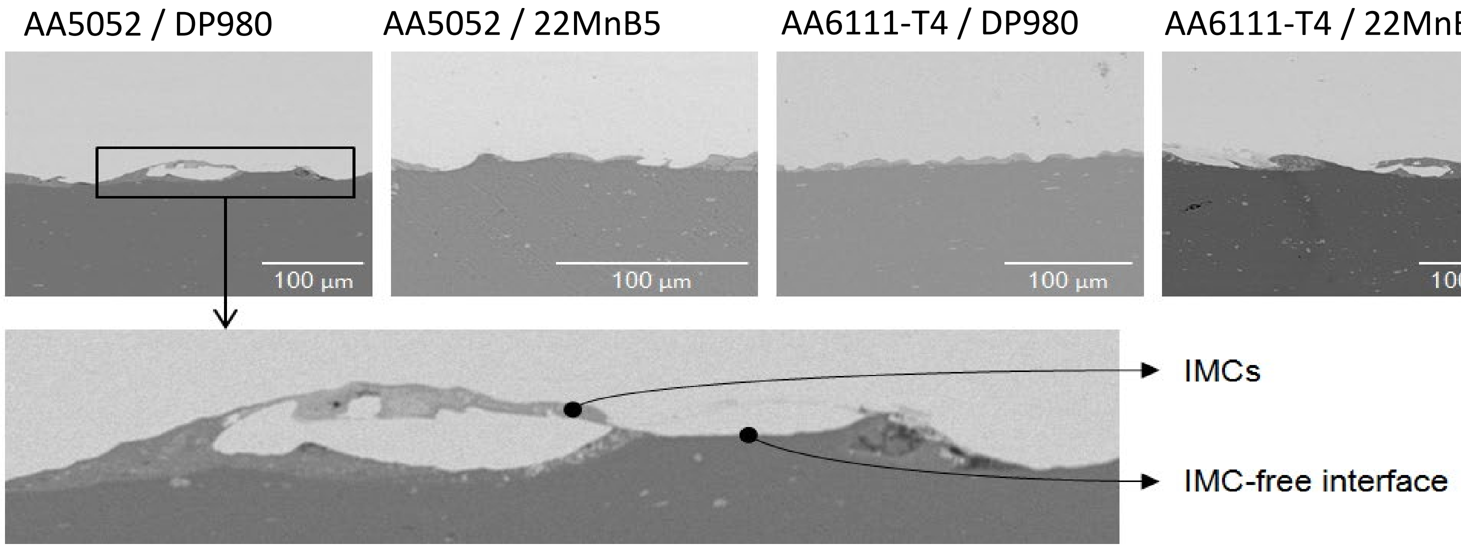
670 m/s

860 m/s

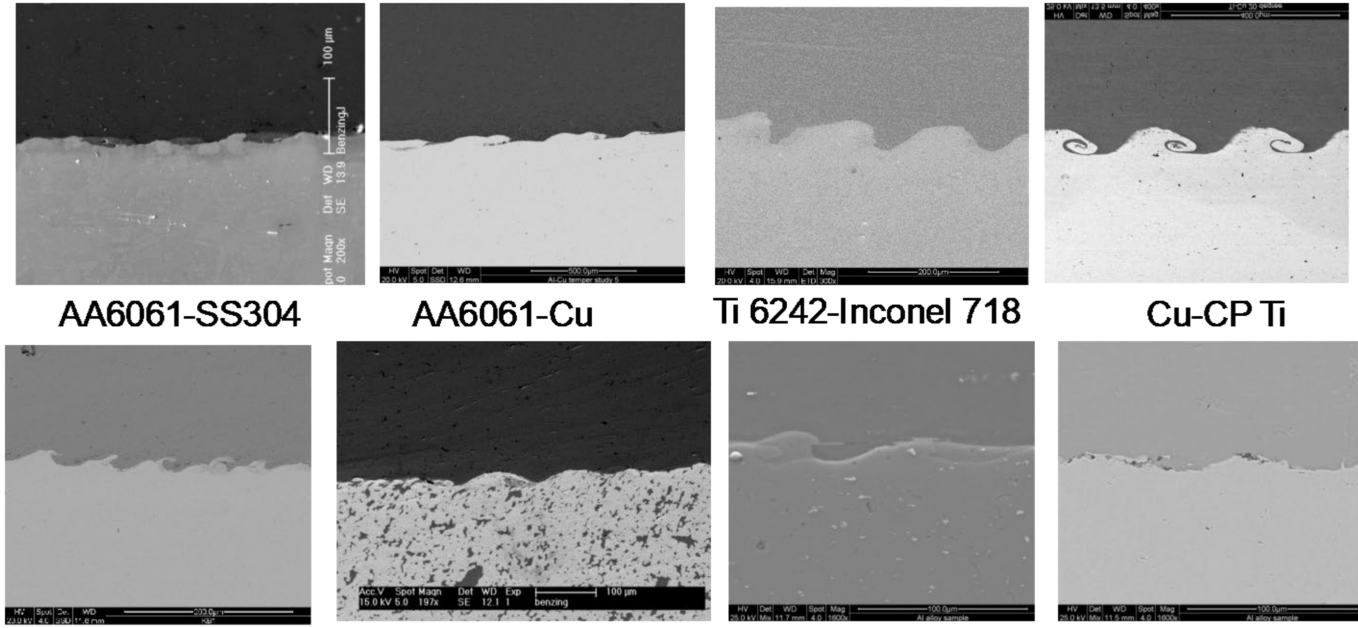


(Pacific Northwest National Lab, Varun Gupta and Collaborators)

Advanced/Dissimilar Metal Welding



- **Solid-State**
- No heat
- No distortion
- No heat-affected zones
- Parent metal strength
- Joins strong alloys
- Joins dissimilar alloys
- <20% energy of fusion
- Simple equipment

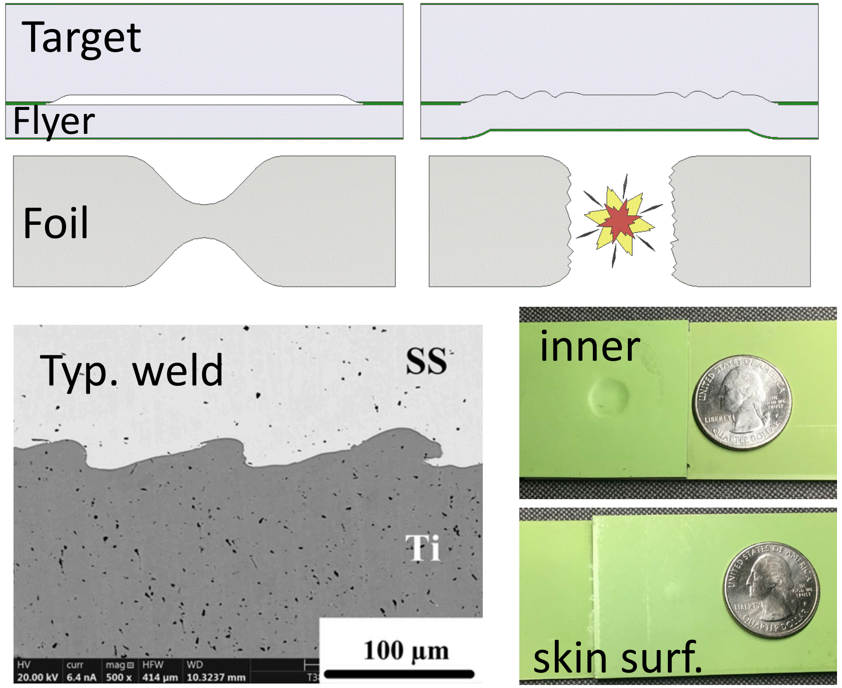


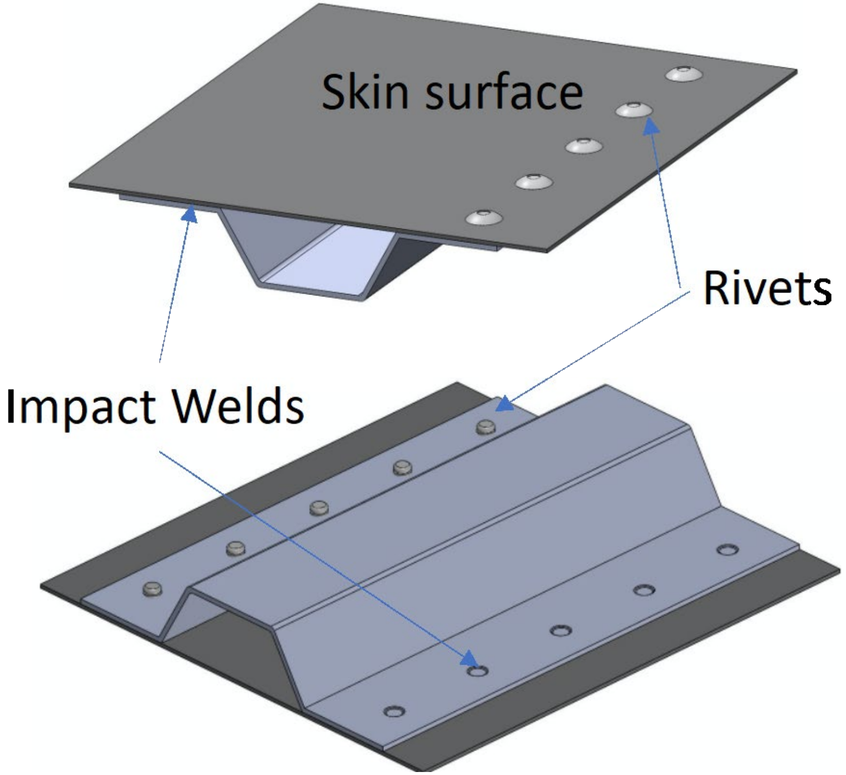
AA6061-SS304 | AA6061-Cu | Ti 6242-Inconel 718 | Cu-CP Ti

Cu- Zr BMG | Cu-17F W alloy | AA6061-AZ91D | CP Ti-1018 steel

Aerospace Joining

- Prototypical structure – stiffened skin, usually joined by riveting. Local impact welding provides much better structure.





How It Is Done

Evolving Weld Schedules

Aluminum 2024-T3 to Aluminum 6061-T6 Weld Schedule

Strong impact welds can be formed by the Vaporizing Foil Actuator Welding (VFAW) process between aluminum alloys 2024-T3 and 6061-T6. Here a weld schedule for joining 1mm 2024-T3 to 1.6mm 6061-T6 is presented. The faying surfaces must be bare metal free of grease or oils. This weld type typically fails at the weld interface at loads above 6,500N. An oval shaped unwelded region due to flat impact is typical. This is a consequence of the foil detonation characteristics.

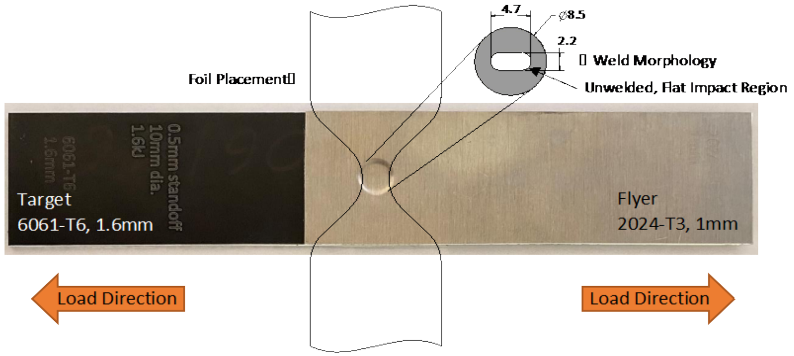


Figure 2: An example weld is shown with the foil orientation, typical weld morphology, and standard tensile test loading direction indicated. A dimple is left in the flyer sheet at the weld site. This dimple takes on the approximate shape of the machined standoff cut in the target sheet.

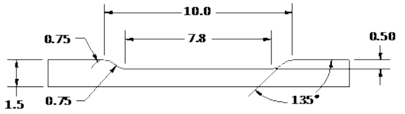


Figure 4: A cross sectional view of the machined pocket used to generate a standoff gap. This feature is machined into the target coupon at the intended weld site.

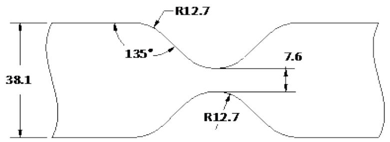


Figure 4: Geometry of the foil actuator.

Weld Parameters

Flyer	2024-T3 1mm
Target	6061-T6 1.6mm thick
Faying Surfaces	Bare metal free of contaminants
Energy	1.6kJ
Current Rise Time	12μs
Typical Max Current	75kA
Foil	7.6mm wide 0.051mm thick
Standoff	0.5mm
Pocket Diameter	10mm
Weld Diameter	8.5mm
Weld Area	47.2mm^2

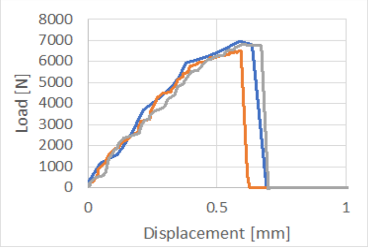


Figure 1: Typical weld tensile test curves. The loading direction is indicated in Figure 1.

Aluminum 2024-T3 to Aluminum 7075-T6 Weld Schedule

Strong impact welds can be formed by the Vaporizing Foil Actuator Welding (VFAW) process between aluminum alloys 2024-T3 and 7075-T6. Here a weld schedule for joining 1mm 2024-T3 to 3mm 7075-T6 is presented. The faying surfaces must be bare metal free of grease or oils. This weld type typically fails outside the weld at loads above 8,700N. An oval shaped unwelded region due to flat impact is typical. This is a consequence of the foil detonation characteristics.

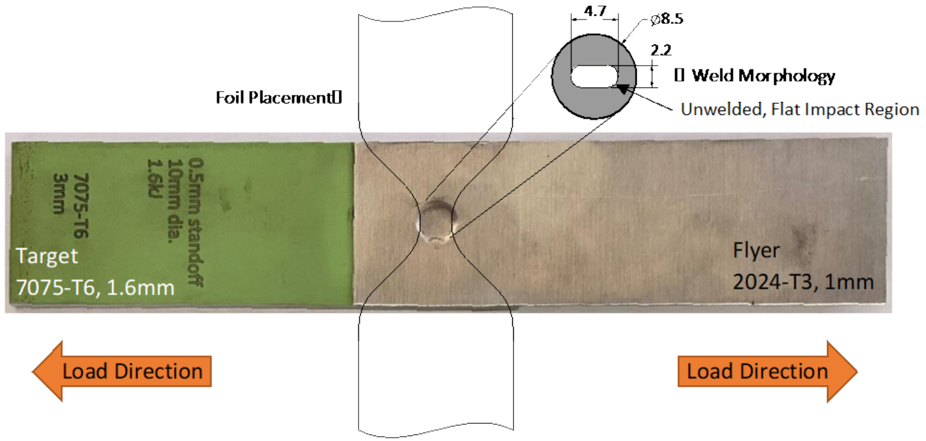


Figure 1: An example weld is shown with the foil orientation, typical weld morphology, and standard tensile test loading direction indicated. A dimple is left in the flyer sheet at the weld site. This dimple takes on the approximate shape of the machined standoff cut in the target sheet.

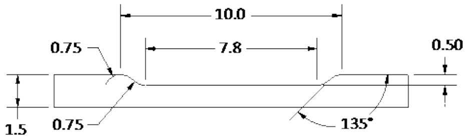


Figure 4: A cross sectional view of the machined pocket used to generate a standoff gap. This feature is machined into the target coupon at the intended weld site.

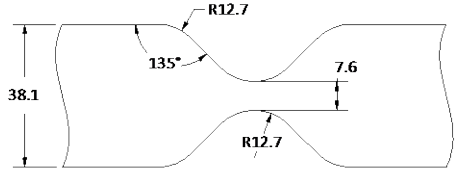


Figure 4: Geometry of the foil actuator.

Weld Parameters

Flyer	2024-T3 1mm
Target	7075-T6 3mm thick
Faying Surfaces	Bare metal free of contaminants
Energy	1.6kJ
Current Rise Time	12μs
Typical Max Current	75kA
Foil	7.6mm wide 0.051mm thick
Standoff	0.5mm
Pocket Diameter	10mm
Weld Diameter	8.5mm
Weld Area	47.2mm^2

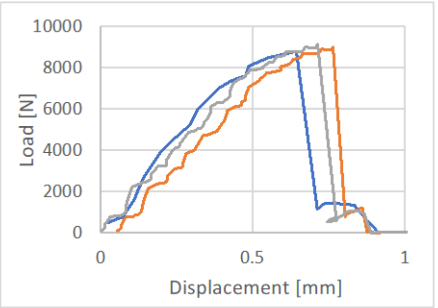


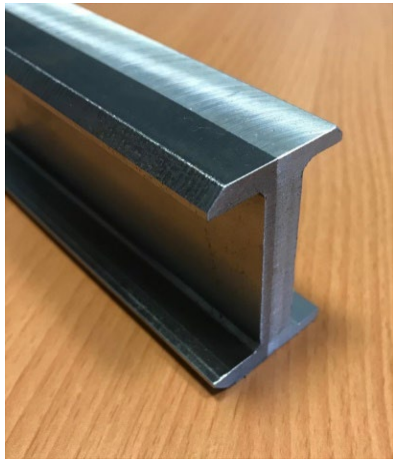
Figure 2: Typical weld tensile test curves. The loading direction is indicated in Figure 1.

Compact Impulse System for Impulse Processing

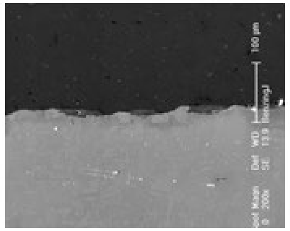
- Electronics by Welding Technology Corporation
- Capacitance of 100 μF
- Charge capability of 6 kJ
- Short-circuit current rise time of 7 μs
- Equipped with a welding head, work platform, and a chamber
- Accomplishes easy operation, good portability, and great noise control magnitude (<80 dB)

Impact Welding

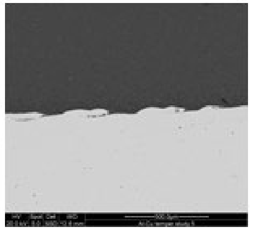
- Welding of dissimilar pairs
- Parent metal strengths and properties retained after welding
- Welding of “un-weldable” alloys
- Limited thermal distortion
- We have developed impact welding tools that can be used in indoor settings, unlike explosive



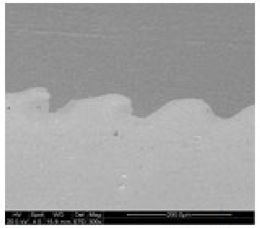
Explosively welded transition joints for ship building, rail cabs, etc.



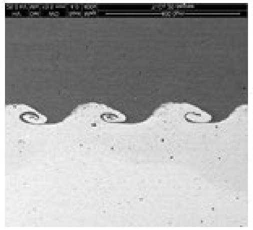
AA6061-SS304



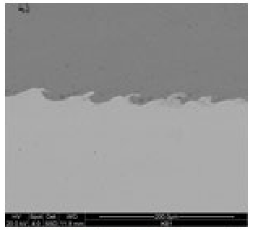
AA6061-Cu



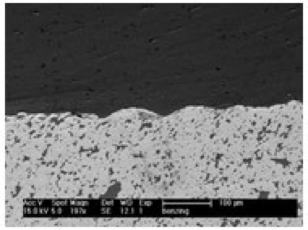
Ti 6242-Inconel 718



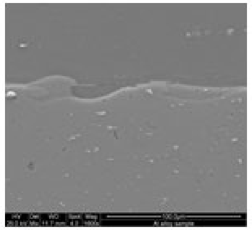
Cu-CP Ti



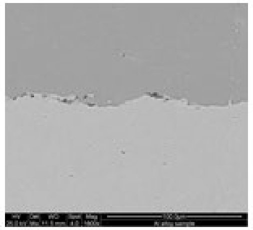
Cu- Zr BMG



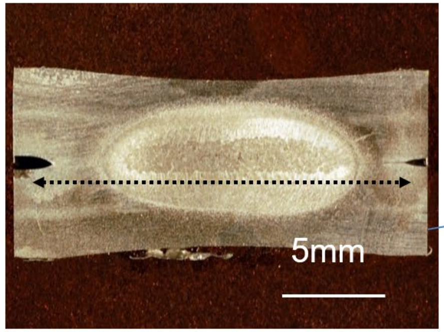
Cu-17F W alloy



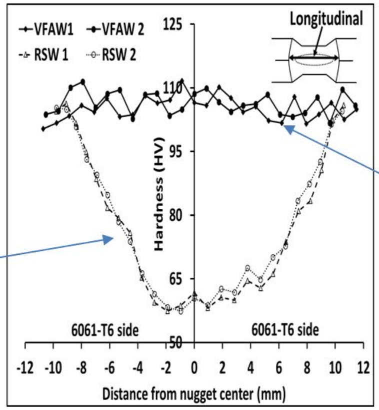
AA6061-AZ91D

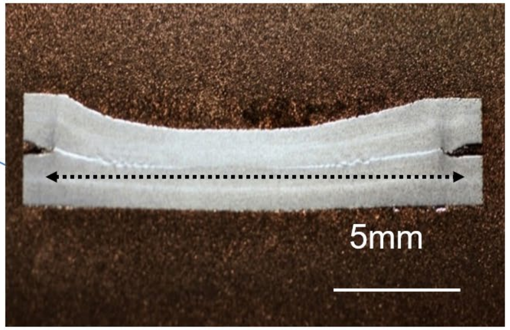


CP Ti-1018 steel



RSW (AA6061-T6) with 50kJ energy

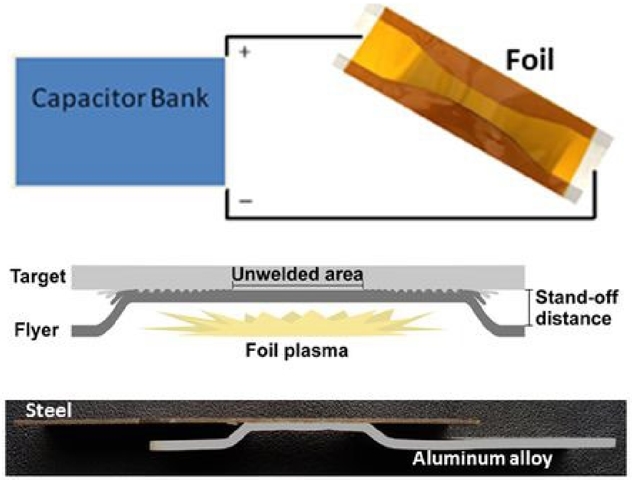




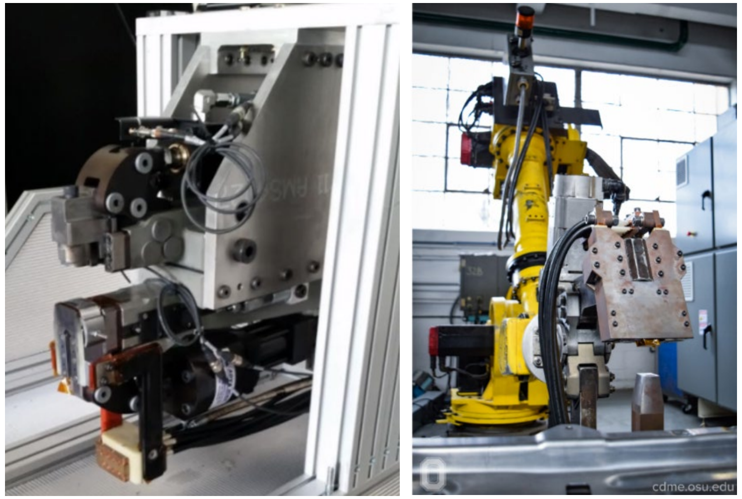
VFAW (AA6061-T6) with 4kJ energy

Tools for Impulse Manufacturing

- Vaporizing foil actuator (VFA)
- Electrically driven rapid vaporization of thin metallic conductor to generate explosive-like pressures in a controlled area
- Used for impact welding but also for springback removal in forming, adiabatic cutting, and powder compaction



Principle of VFA welding



Automated VFA weld heads

10% lighter multi-material engine cradle

Sponsor:

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

Key Accomplishments

Research and Development

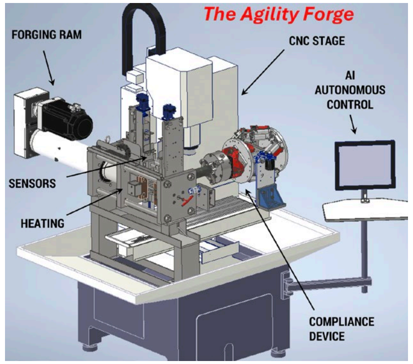
Papers 66 (37 peer reviewed)

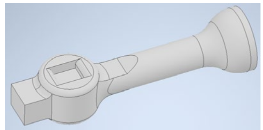
Multiple awards

Patents (15 disclosures to date)

9 engineered systems

2 drawn to commercialization





Result

Innovation Ecosystem

New model: provides shared culture; links to authentic problems; unifies research, student development, and commercialization

Provides new long-term funding mechanism

Education/Outreach

Leading in metal forming education; developing content, sharing across universities. Developing standalone credentials

Strong engagement with K-14 educators through Research Experiences for Teachers (RET) and teachers' camps

Multiple student engagement events, leading to recruitment