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ACC 2019 Workshop

Robot Assisted Manufacturing: Challenges and Opportunities

Manufacturing Automation in Industrial Processes

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Outline

- Motivation
- Technical Capabilities & Accomplishments
- Technical Detail
  - Welding
  - Deburring
- Conclusions, Next Steps

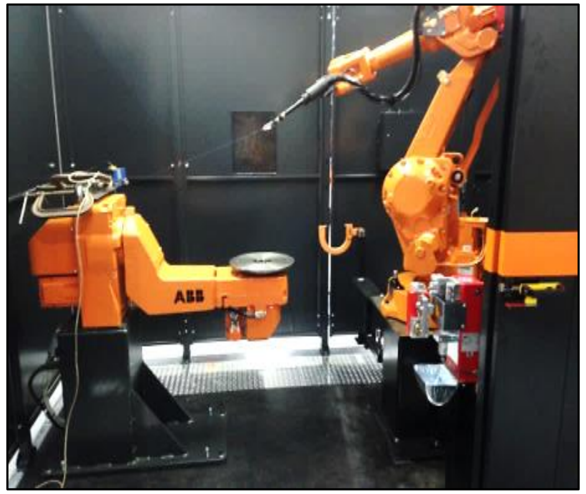
Robotics for Manufacturing - Overview

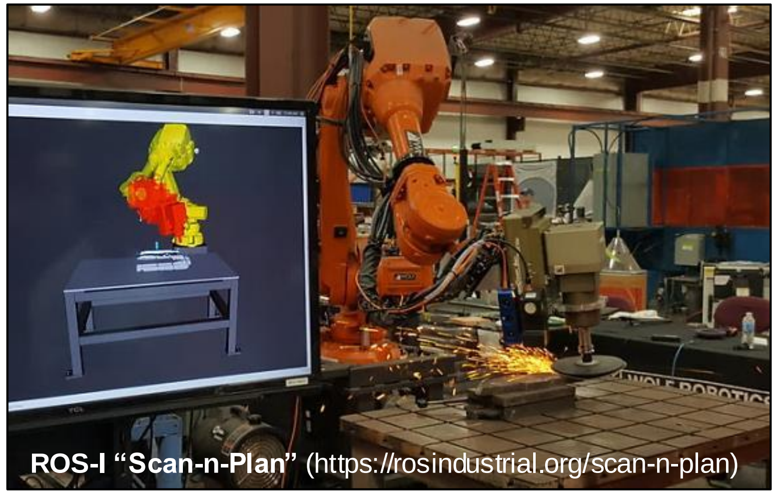
- Robotic technologies applied to manufacturing have potential to reduce operating costs, increase production rates, and decrease EH&S concerns
- Flexible programming methods are required to replace current industrial robot implementation, which is often restricted due to difficult setup
- Adaptive manufacturing techniques can accommodate part variation, thereby reducing scrap and downtime due to reprogramming/retooling

Challenges

- **Programming complexity**
- **High-mix, low volume**
- **Part to part variability**
- **Toolpath accuracy**


GOM 3D scanner system (www.gom.com)




ROS-I "Scan-n-Plan" (https://rosindustrial.org/scan-n-plan)

Robotics for Manufacturing Goals:

- *Develop technologies toward a more adaptive industrial robot*
  (more in-process, automated decision making, monitoring, and control)
- *Leverage process models & monitoring, closed loop control, flexible software framework*

Motivation – Manufacturing Examples

Smart automation supports repeatable, reliable, and safe manufacturing processes

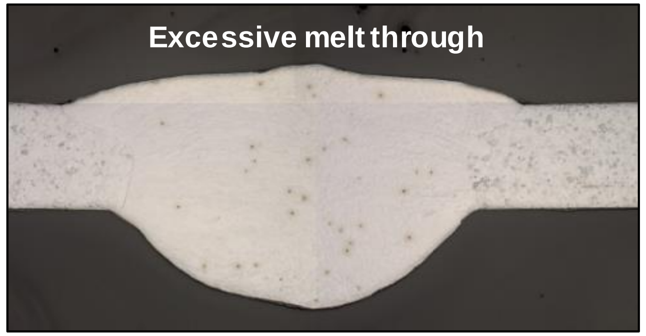
Welding

Problem:

- Manual assembly and variable fit during tack-welding. Extensive manual welding.
- Material & part variability increases errors/defects, requiring rework or resulting in scrap
- Parts often not repeatable/reliable enough for standard offline robot programming methods

Challenges:

- Joints between variable thickness sections, including joints between castings and rolled/forged sections
- Varying heat-sink effect, combined with variable fit-up



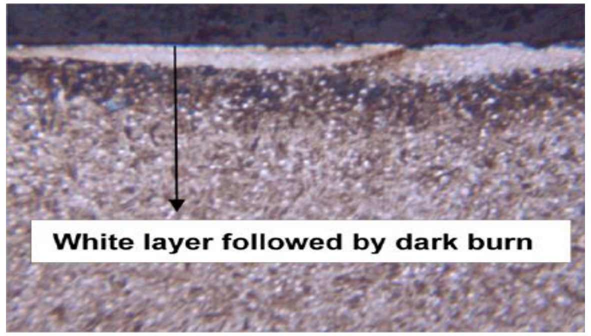
Deburring/Blending

Problem:

- Manual deburring and blending produce uncontrolled material removal rates, depends on user skill and fatigue
- Material changes due to excessive heat input (too much force, clogged media, slow travel speeds).
- Deburring – small contact zone, fast heat buildup
- EH&S concerns with vibration, noise, dust

Challenges:

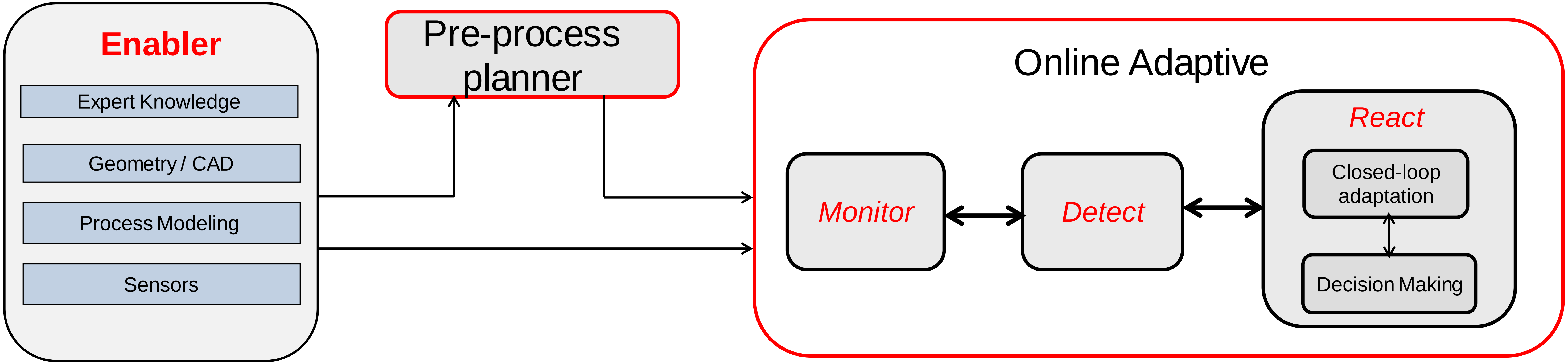
- Compliant tooling is the norm, but reduces accuracy
- Fine feature deburring requires high accuracy motion platform.

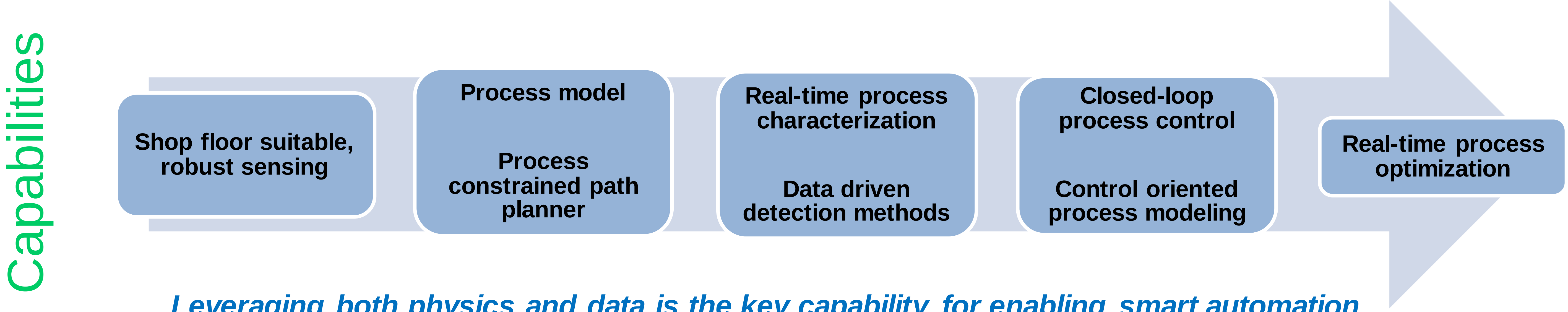


Reduce defects, rework, and scrap rates while improving safety

Capabilities

Focusing on process monitoring & control techniques to make off-the shelf industrial robots smarter and adaptive





Leveraging both physics and data is the key capability for enabling smart automation

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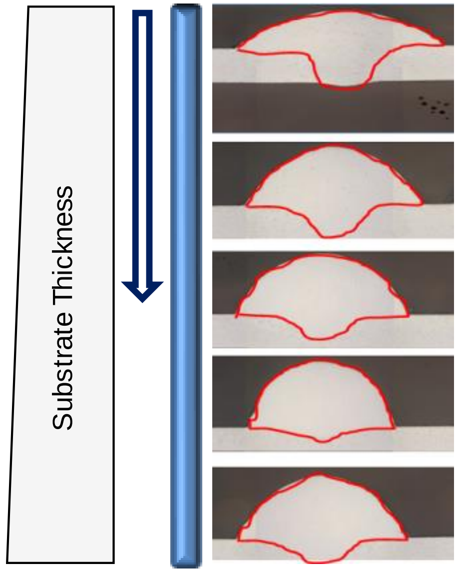
Automated Welding and Process Monitoring

Implementation of pre-planning & in-situ adaptation strategy to achieve optimized & robust weld process

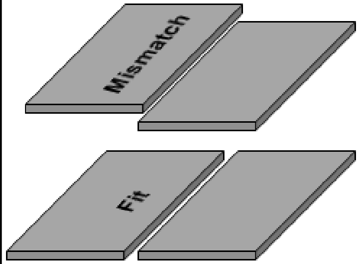
Pre-planned process schedule

Goal: Achieve optimal weld penetration for varying substrate thickness (varying heat sink effect) and varying fit-up (gap & mismatch)

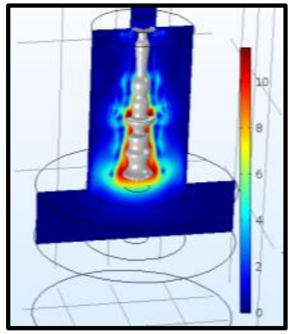
- Desired weld penetration depth depends on the welding application, joint geometry, and material properties
- Process modeling and experimental verification shows the melt depth as the substrate thickness varies
- Demonstrate optimized robotic weld parameter selection for variable fit-up, thin sheet metal joints



Scan joint



Identify fit and mismatch



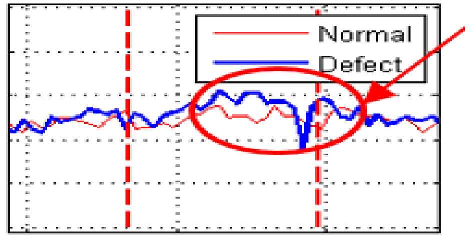
Assign weld schedule from FEA and experimental testing

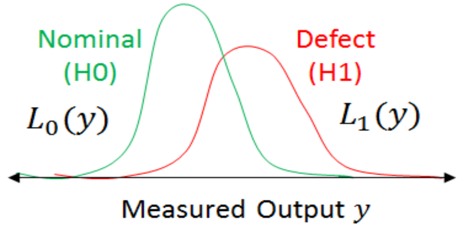
Execute optimized robotic weld

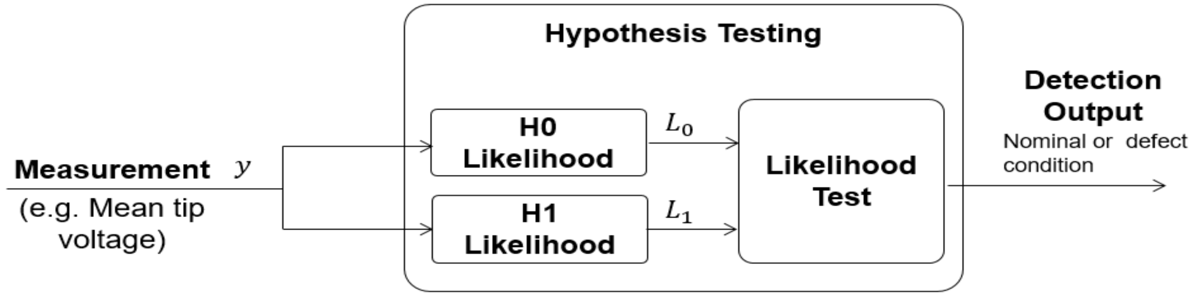
Online adaptive process

Goal: Predict and react to process defects *in-situ* for non-uniform gap or varying thickness

- Traditionally, automated weld joints with fixed/uniform gap are handled with pre-defined weld parameters
- Due to manual assembly, the gap between the plates can vary and often results in challenging welds, defects, rework
- Goal is to predict when defects are likely to occur and react by halting the process or adjusting weld conditions on-the-fly to accommodate part variations







Data-driven weld monitoring process, utilizing weld process measurements to identify and react to potential defects

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LIFT Joining R3-1

Robotic GTAW of Thin Components with Variable Fit-Up

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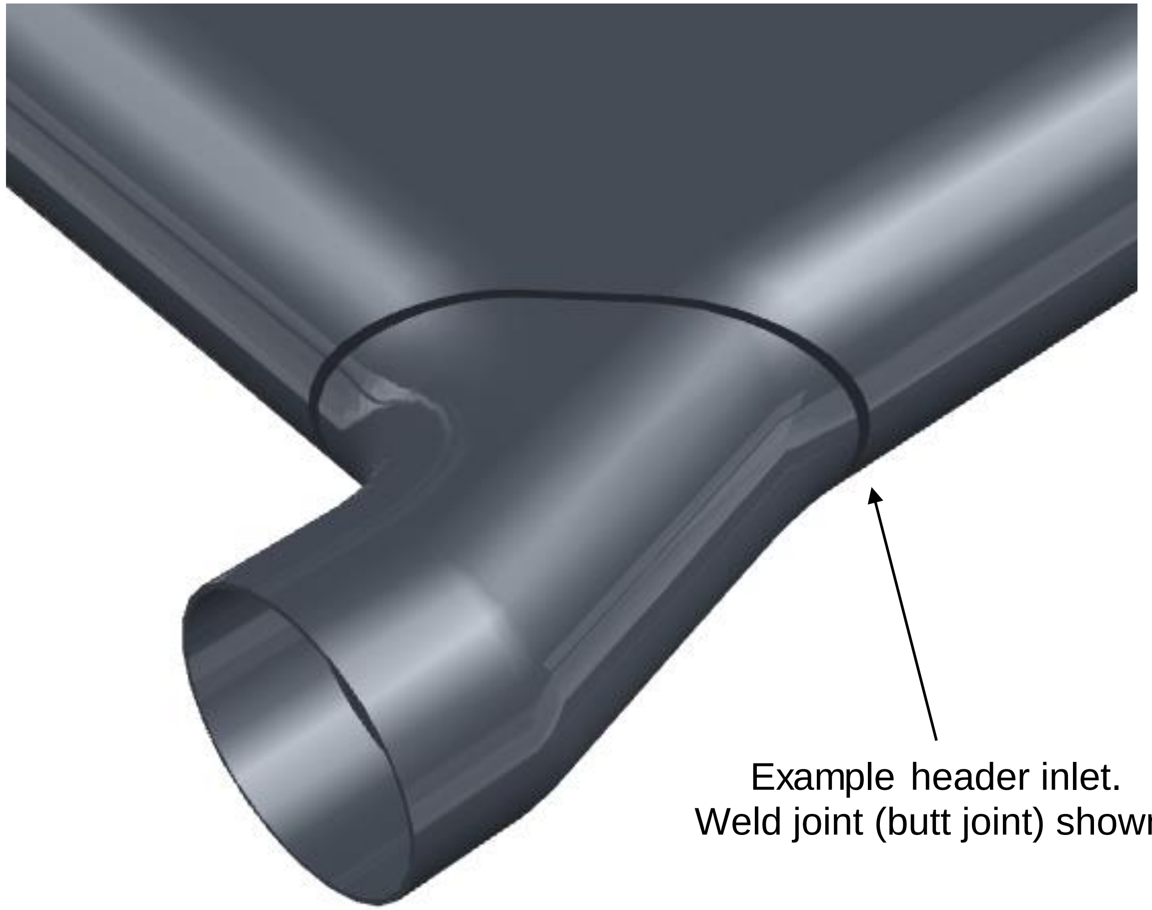
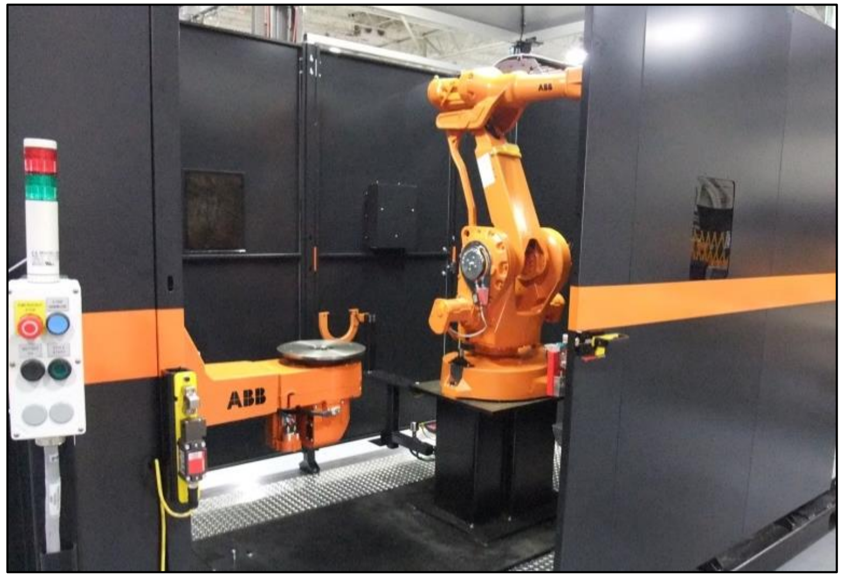
Header inlet geometry example

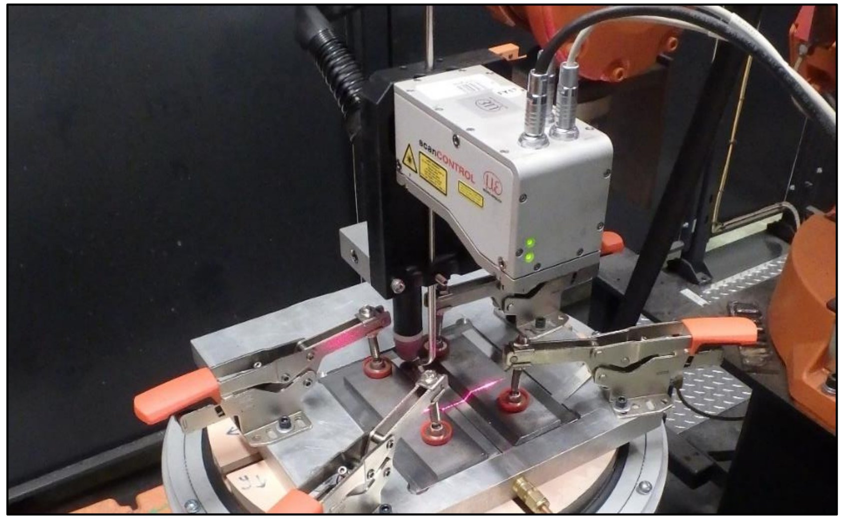
- Challenge weld joint selected based on difficult production part. Geometry, material, and thickness were used in selection of test coupons.
- Butt-joint configuration, nickel alloy, thin material
- Difficult welds due to variable fit-up
    - Current production pieces are formed, hand assembled, fixtured, and tacked
- Part to part, batch to batch variation, plus variation between users and assembly
- Current parts are fixtured and welded manually



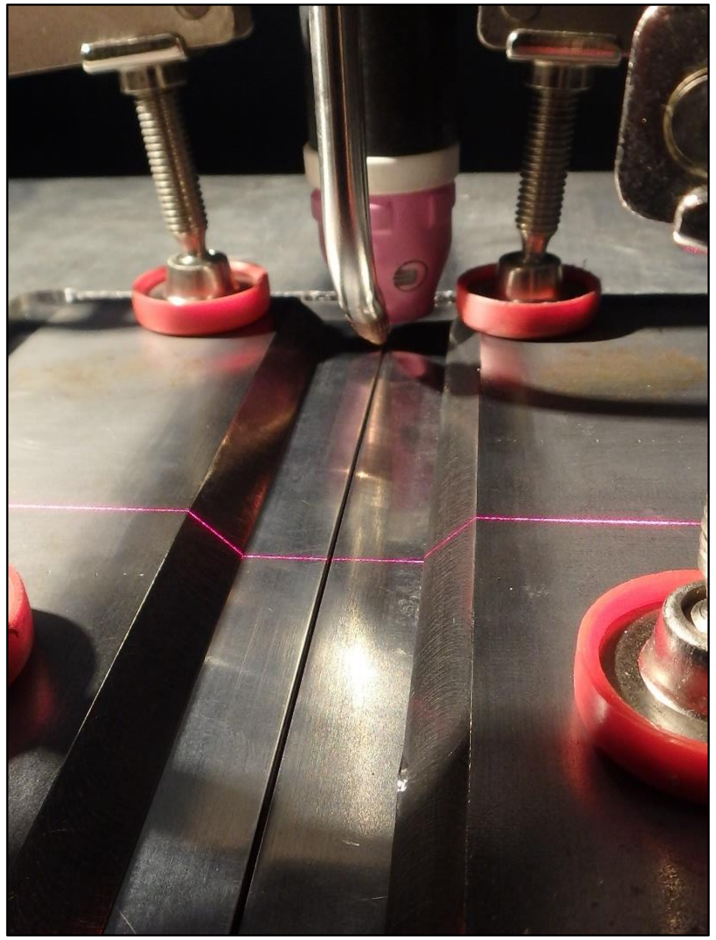
Example header inlet.
Weld joint (butt joint) shown.

UTRC Welding Cell + Scanner

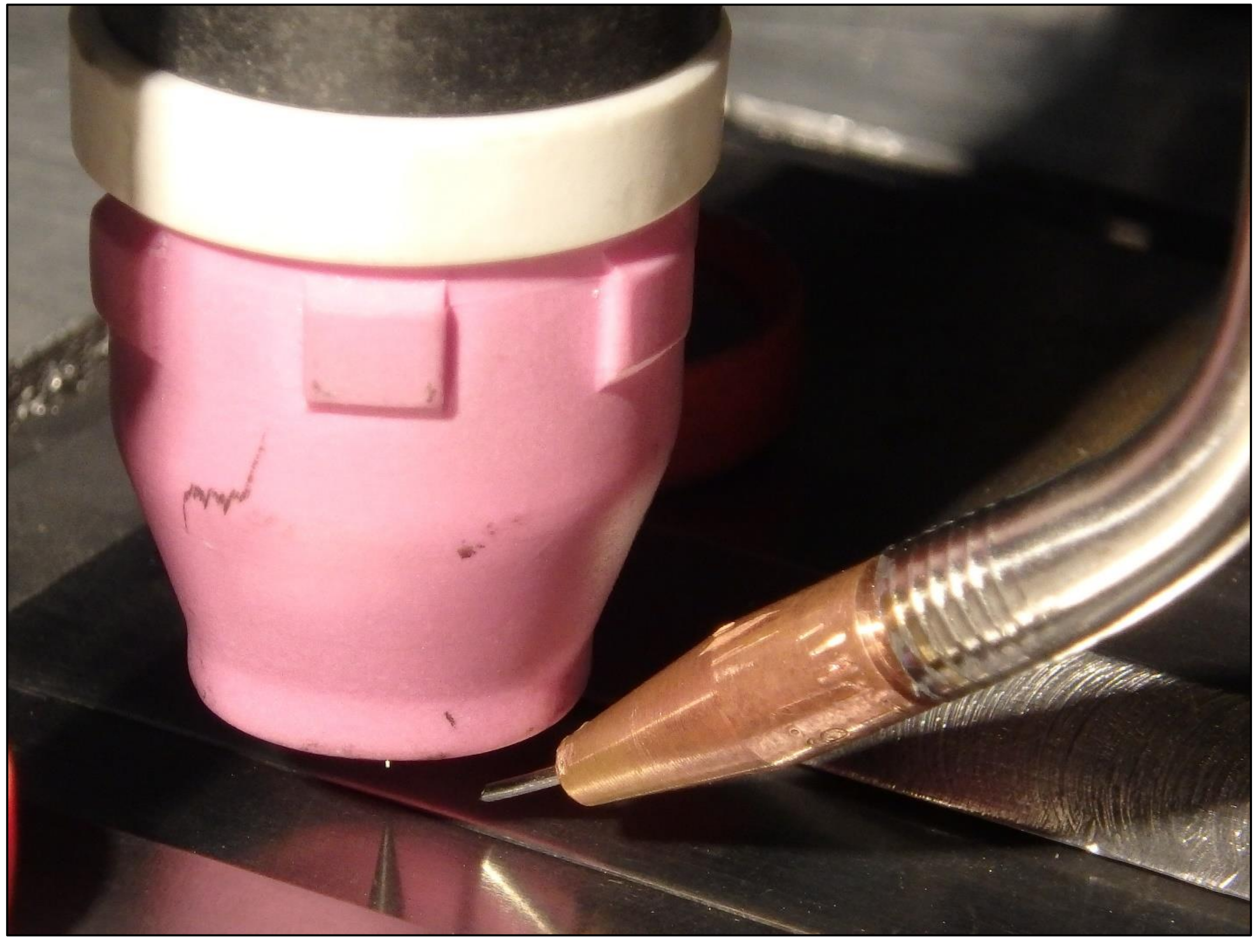




Laser scanner ahead of torch

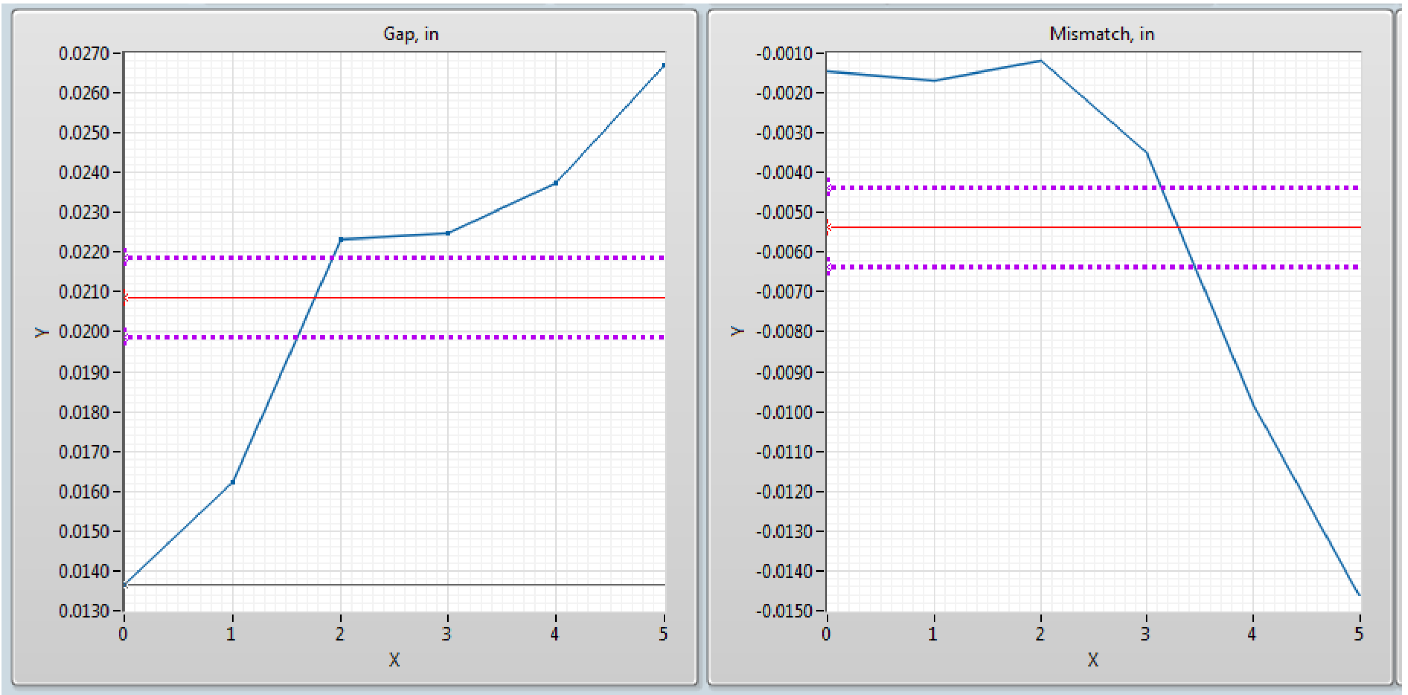


Test fixture for butt-joint, scanner measuring gap+mismatch



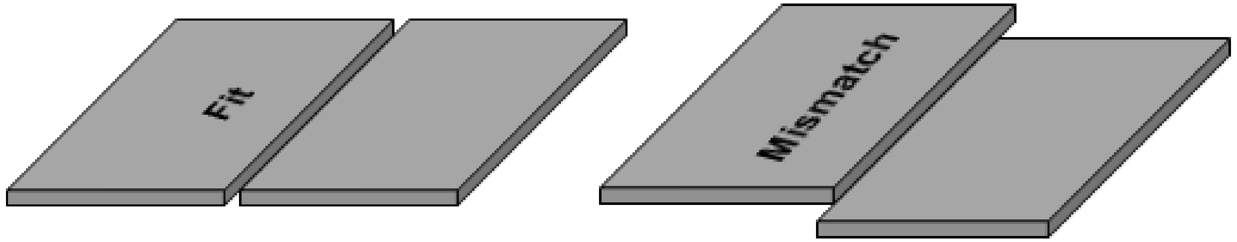
Ready to weld

UTRC: Scanning & Welding



Laser scanner captures joint gap & mismatch

References database of optimized weld schedules, or other experimentally developed weld conditions



Variable mismatch with changing weave plane
0.015” gap, 0.015” → 0.0” → –0.015” mismatch,

Challenge coupon: 0.0” gap, 0.032” mismatch
Successful weld

UTRC: Test coupons – Non flat (split tube)

Split tube test article:
Variable gap + mismatch
Utilize turntable + coordinated robot motion
Continuously variable gap & mismatch

Successful welds on tube sections with variable gap+mismatch

Turntable with coordinated motion, maintains prescribed travel speed and weave on non-flat parts

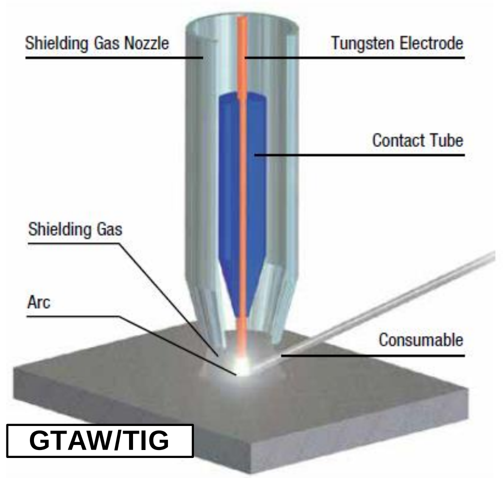
Overview of Weld Modeling

Purpose:

- Development of a physics based model for GTAW
- Support future needs for process modeling and process optimization
- Accelerate future GTAW efforts with new materials and weld joint configurations
- Reduce experimental requirements needed to arrive at optimal weld conditions
- Understanding of defects, constraints, and process window
- Commercially available code (COMSOL) leveraged

Physics Based Modeling of Welding

Welding modeling efforts aim to enhance process understanding and accelerate experiments



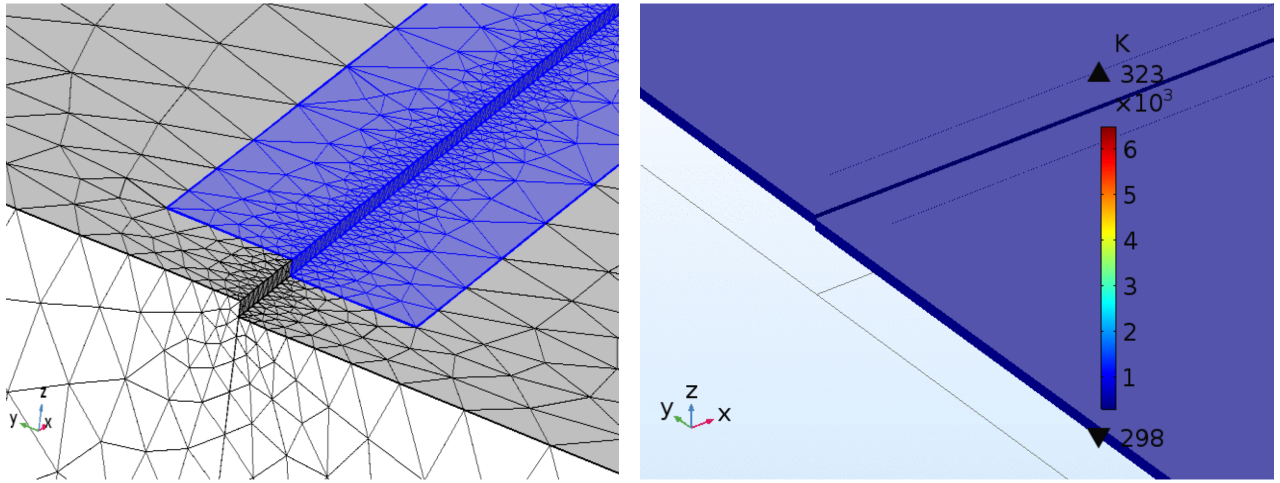
Models to reduce future DoE requirements for new materials and weld joint configurations

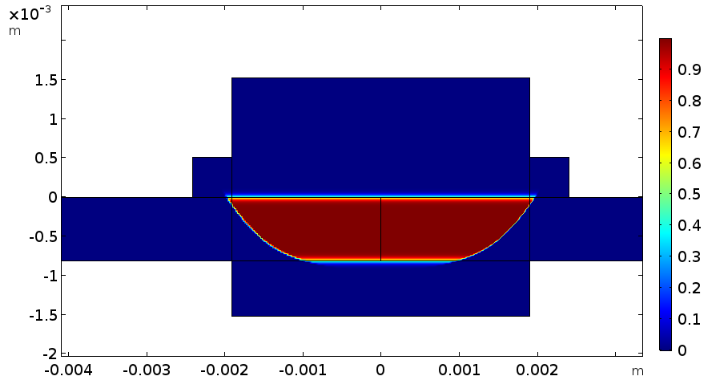
Leverage multiple modeling tools to capture multi-physics:

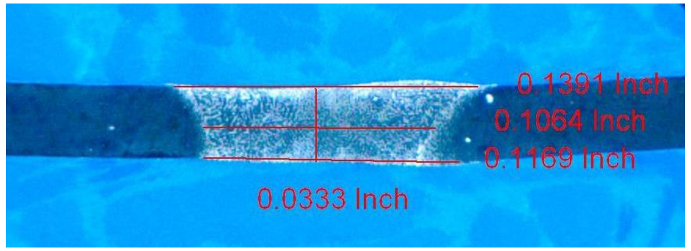
- Electromagnetic (2D)
  - Identify arc stability & heat input due to poor joint fit/mismatch
- Level-set model (2D)
  - Phase interfaces, liquid/plasma
- Flow thermal model (2D)
- Thermal model (3D)

Modeling weld joint domain with gap and mismatch

- Thermal conduction to the substrate is modeled
- Fraction of heat source into the substrate and the loss to surroundings:
  - Can be determined from experimental melt pool cross section
- Thermal data/melt-pool dimension can further be used to calibrate absorptivity

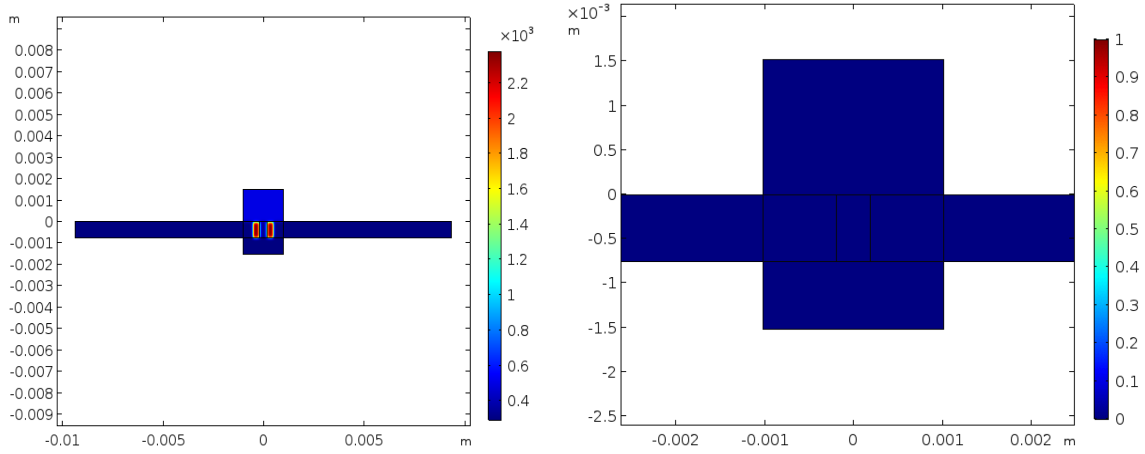






Calibration with experimental coupons:

Example GTAW butt-joint configuration



Coupled heat transfer, level set and CFD model

- 2D domain and can provide insight to formation of defects (e.g., melt through)
- Evolution of melt pool:
  - a) Initial stage with blue indicating solid substrate
  - b) Temperature map showing melting at both sides
  - c) Mass fraction with level set algorithm showing how the plates are joined

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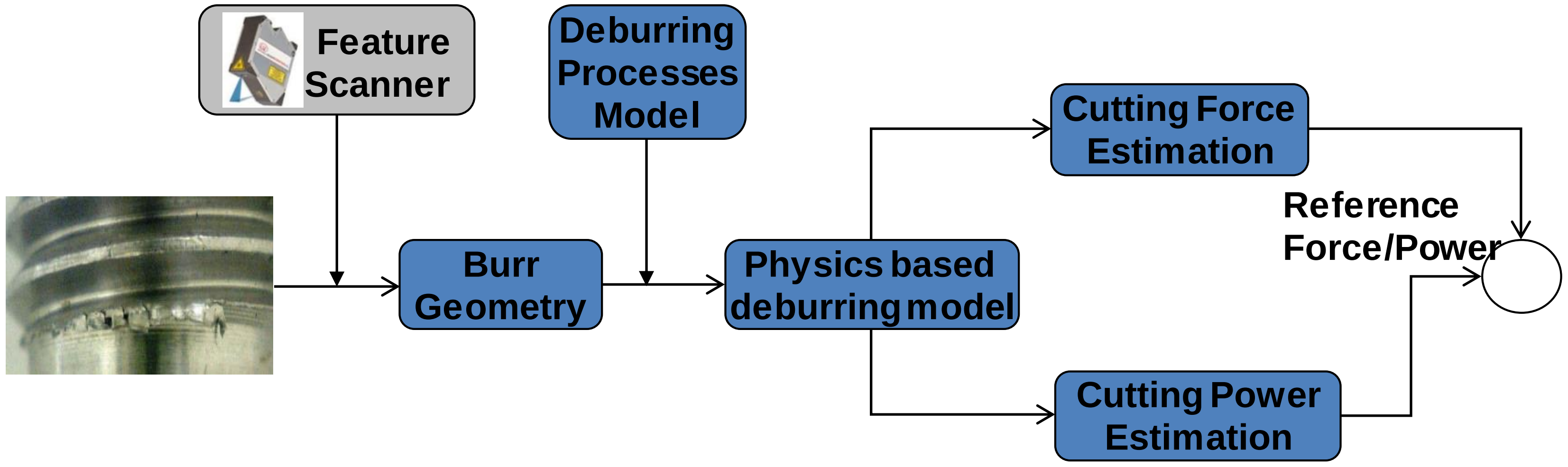
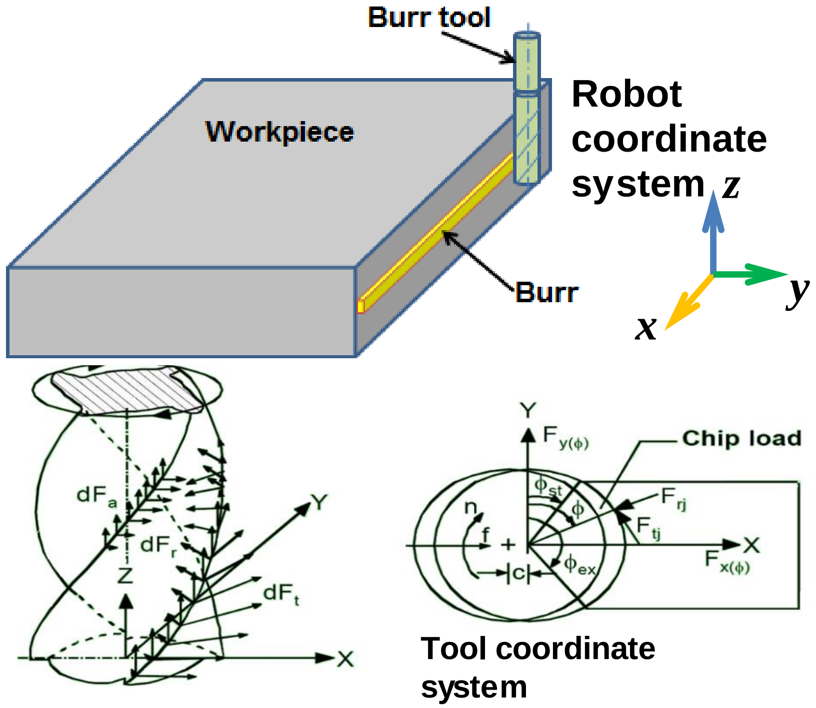
Adaptive Deburring and Blending

Sensor-aided identification of optimum material removal parameters to achieve robust deburring process



- Deburring/blending problem can be approached from either a pre-planning (e.g., scan-and-plan) method, and/or online monitoring approach (e.g., force control)
- Pre-planning relies on information of burr size, informed by scanner/vision system
- Online monitoring can be tuned with information from physics based models of material removal process

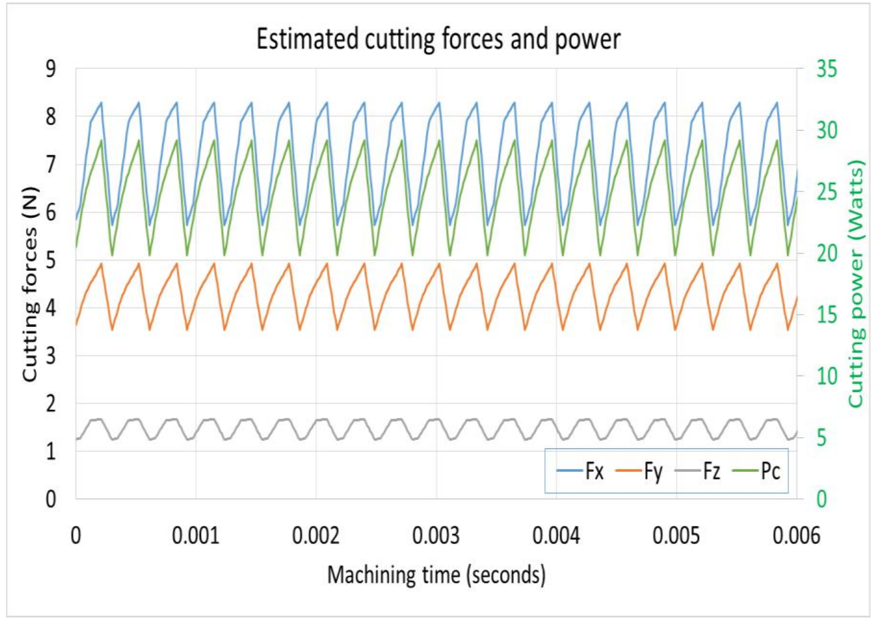
First-principle based model of deburring forces (power) is a key enabler of adaptive deburring process



- **Force component along cutting edge**
- **Resultant force in tool coordinate system**
- **Cutting power**

$$P_c = \sum_{j=1}^{m} F_{tj} v_c$$

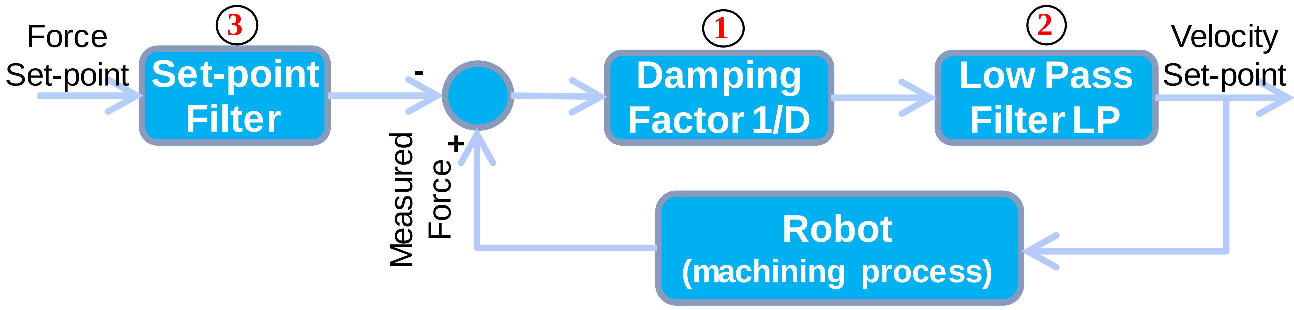
$$\begin{cases} F_x = \sum_{j=1}^{m} \left(F_{tj}\cos\phi_j - F_{rj}\cos\beta\sin\phi_j\right) \\ F_y = \sum_{j=1}^{m} \left(F_{tj}\sin\phi_j - F_{rj}\cos\beta\cos\phi_j\right) \\ F_z = \sum_{j=1}^{m} F_{rj}\sin\beta \end{cases}$$



Control Approaches for Robotic Deburring

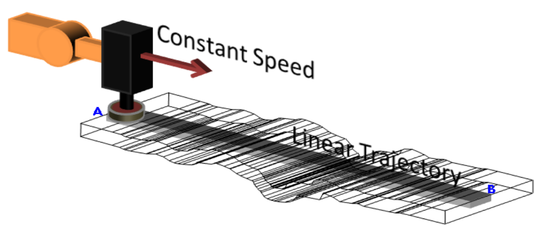
Control methodologies utilizing two different sensors: (a) force sensor (b) spindle load

Force Control Implementation (Robot Built-In Functionality)

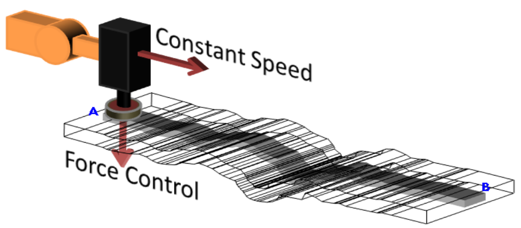


Force Control "Pressure" – For a given force reference, the controller will strive to maintain the reference force.

Robot may deviate from programmed tool path in order to maintain contact with surface and maintain prescribed load.



Without Force Control

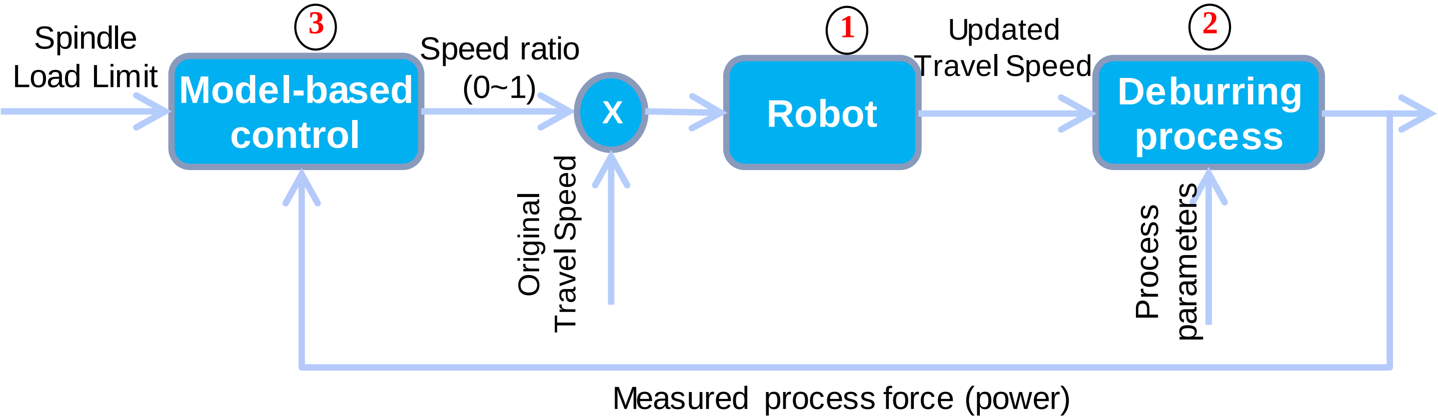


With applied Force Control

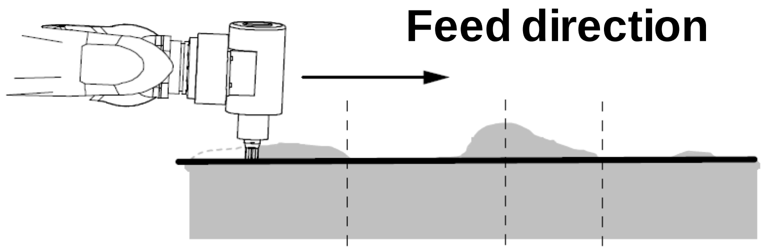
By maintaining constant applied forces, a force controlled robot offers the possibility of gaining a higher stiffness of the robot without compromising the six degrees of freedom motion.

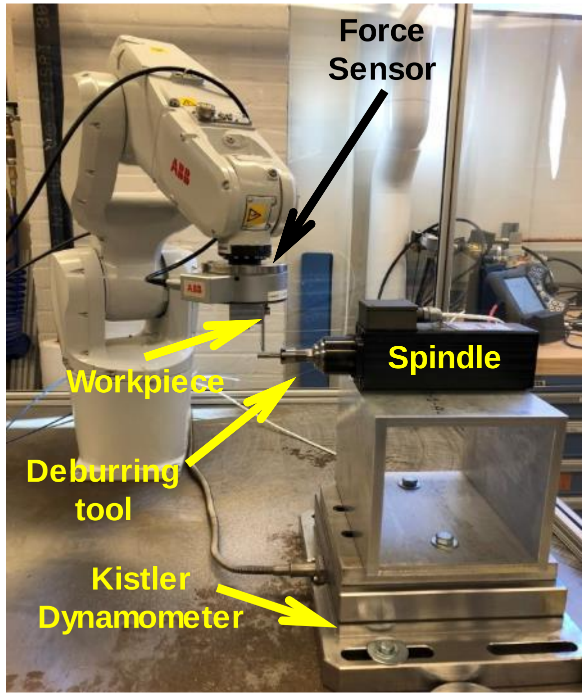
Application: Polishing, Grinding, Assembly

Spindle Load Control (Leveraging Deburring Load Model)



"Speed Change" – Enable the deburring process to control travel speed (feed rate), i.e., slow down when encountering excessive burrs or speed up when no burrs exist.

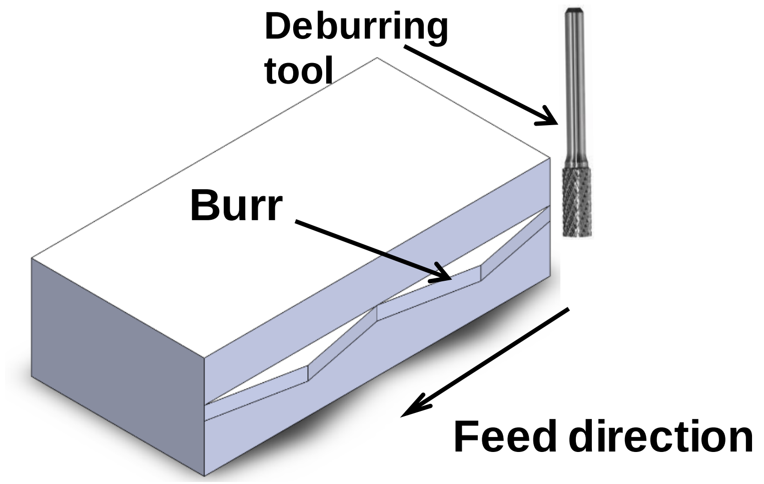


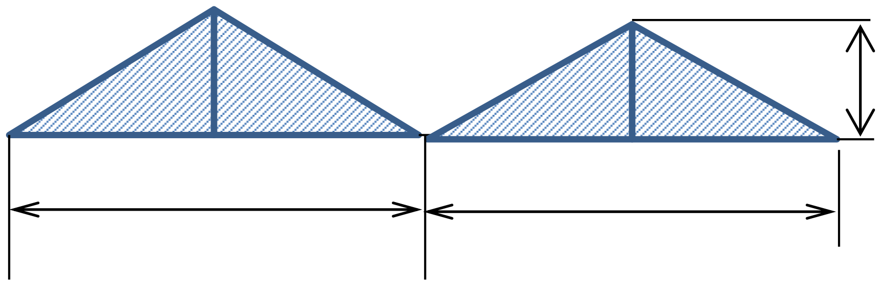


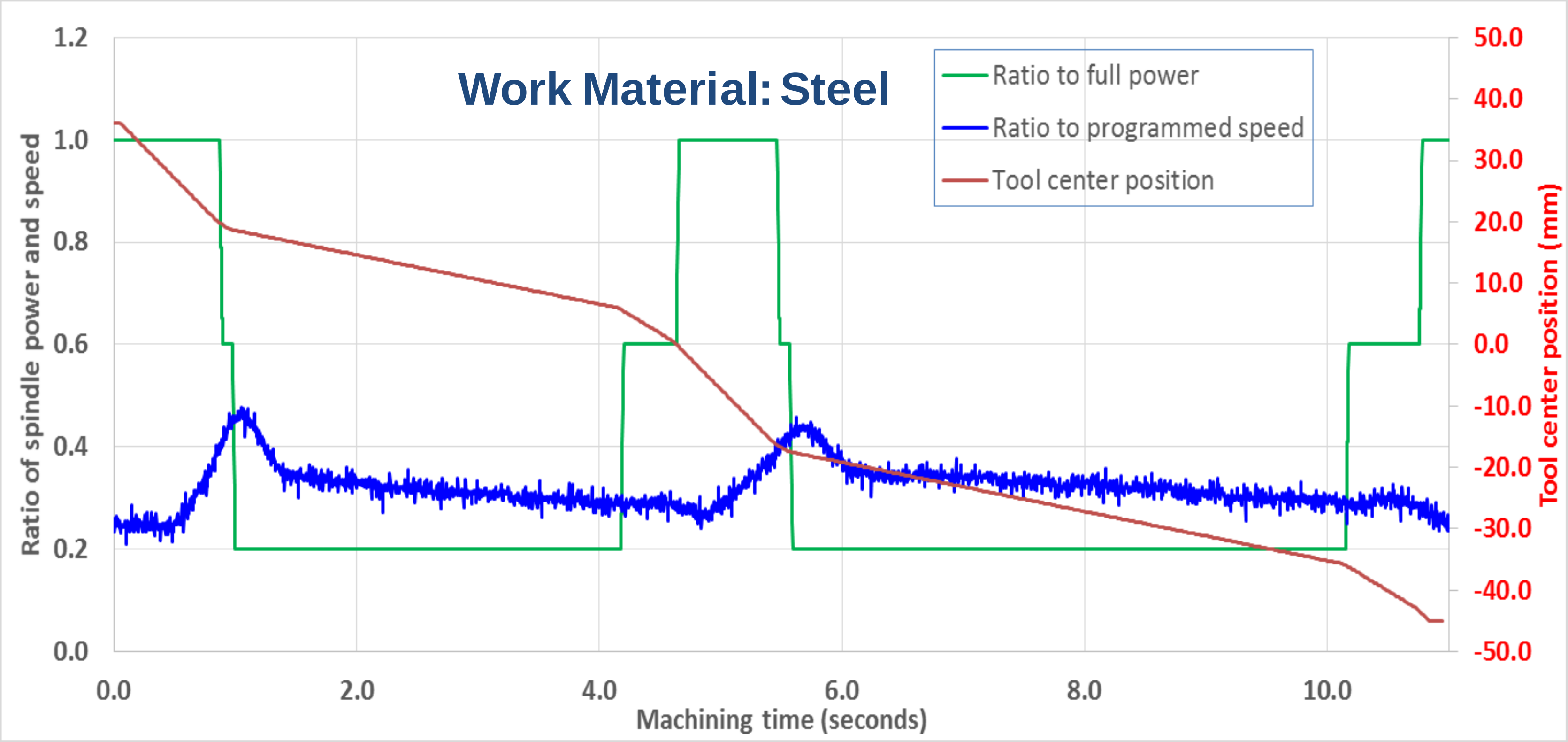
Application: Deburring, Grinding, etc.

Control Approach for Robotic Deburring

Experimental verification of adaptive feed rate control







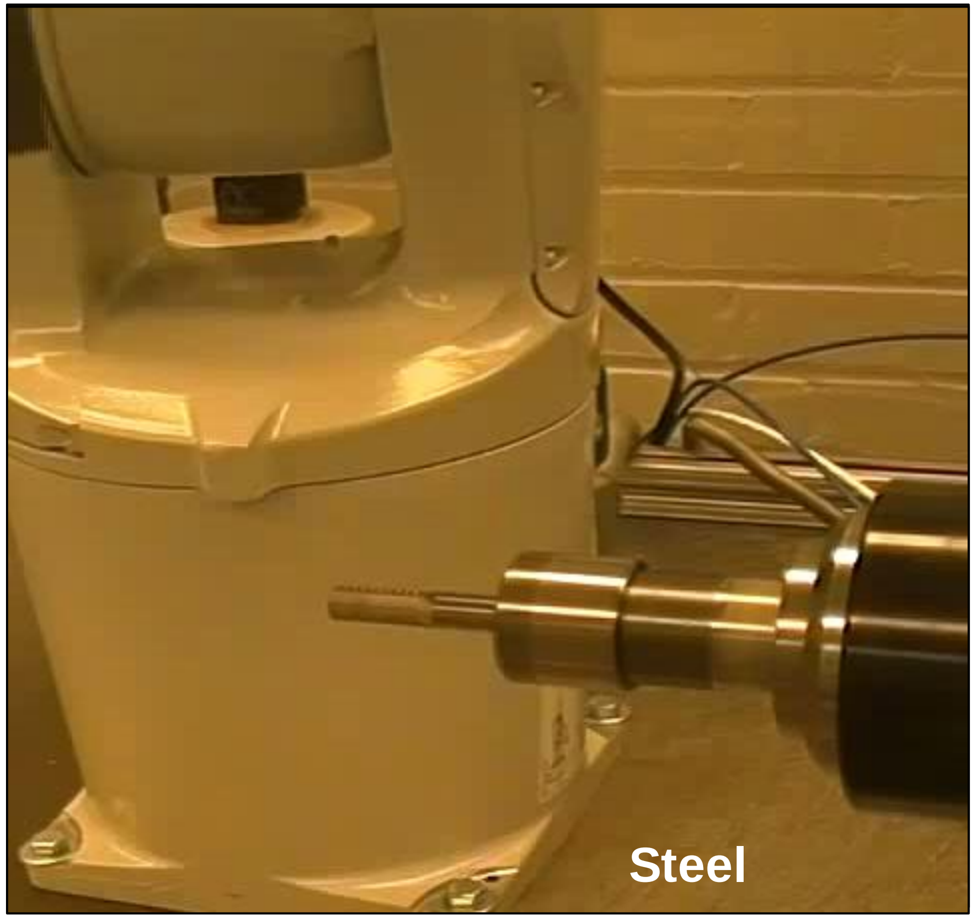
Workflow for model based control rule

Step 1: Calibrate the power / load at spindle idle condition

Step 2: Estimate and prescribe the spindle load change for speed / feed rate control as per estimated load from physics based model

Step 3: Tune controller parameters for spindle load / power signals and feed back the signal to robot for real-time control

Deburring tests



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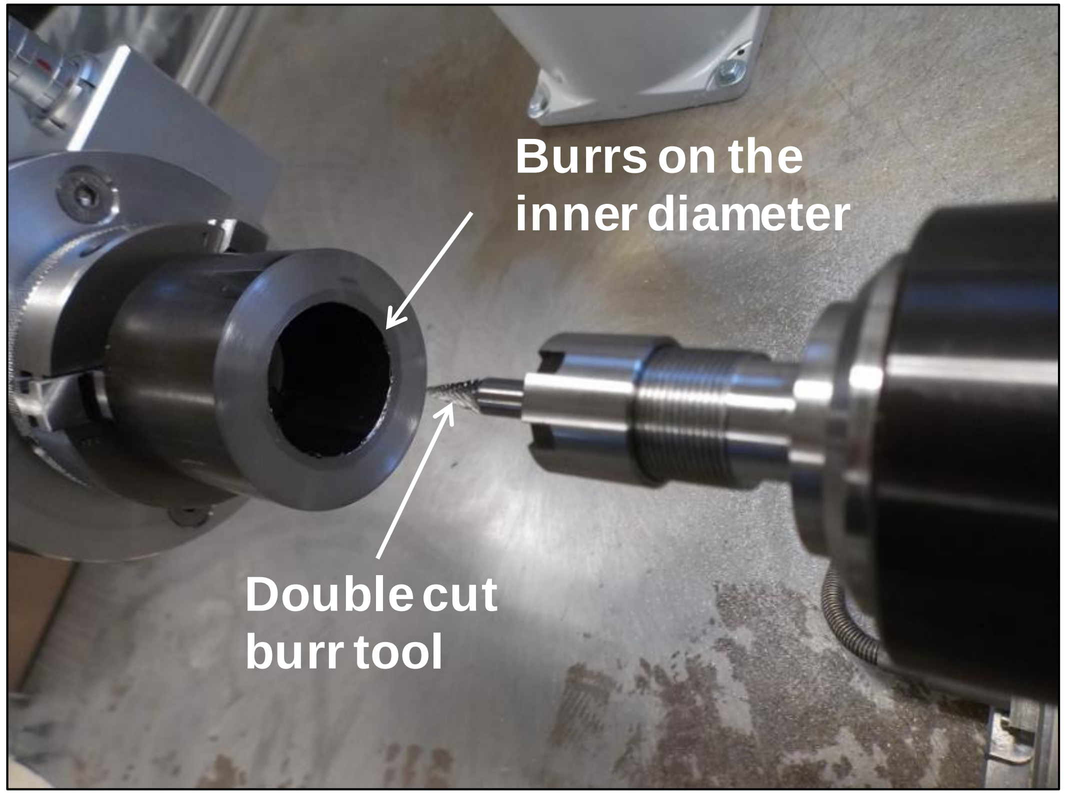
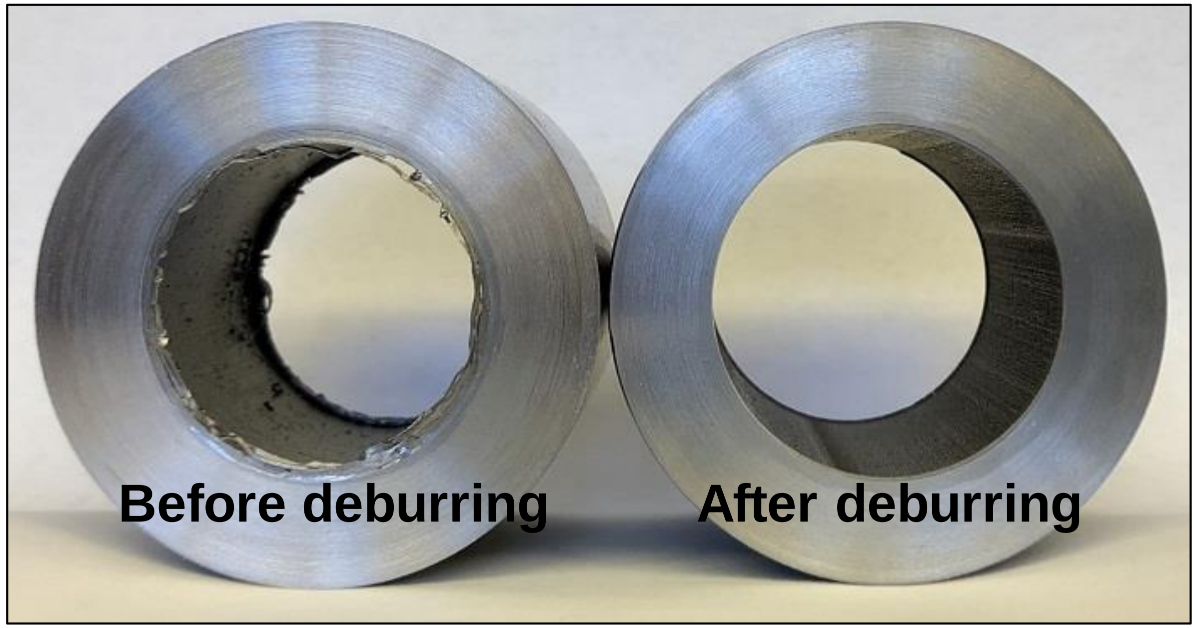
Additional deburring test on a steel tube





- **Cone shaped burr tool was used to remove the burrs on the edges.**
- **Burrs on both inner and outer diameter have been removed.**

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THANK YOU