Improving Weld Productivity and Quality by means of Intelligent Real-Time Close-Looped Adaptive Welding Process Control through Integrated Optical Sensors

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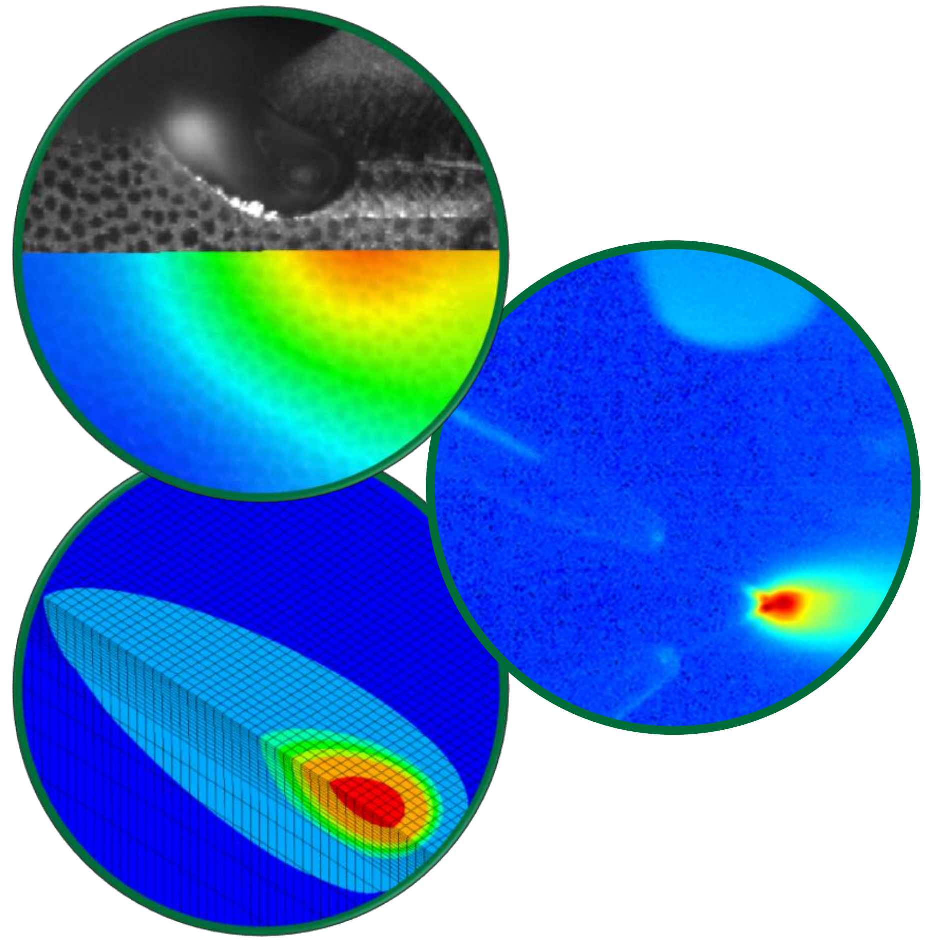

U.S. DEPARTMENT OF ENERGY

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Overview

- NEET1- Advanced Methods for Manufacturing
- Time line
  - Start: October 2014
  - End: June 2018
- Total project funding from DOE: $800K
- Technical barrier to address
  - Advanced, high-speed and high-quality welding technologies

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy

Idaho Operations Office

Fiscal Year 2014 Consolidated Innovative Nuclear Research

Funding Opportunity Announcement:
DE-FOA-0000998

Announcement Type: Initial

CFDA Number: 81.121

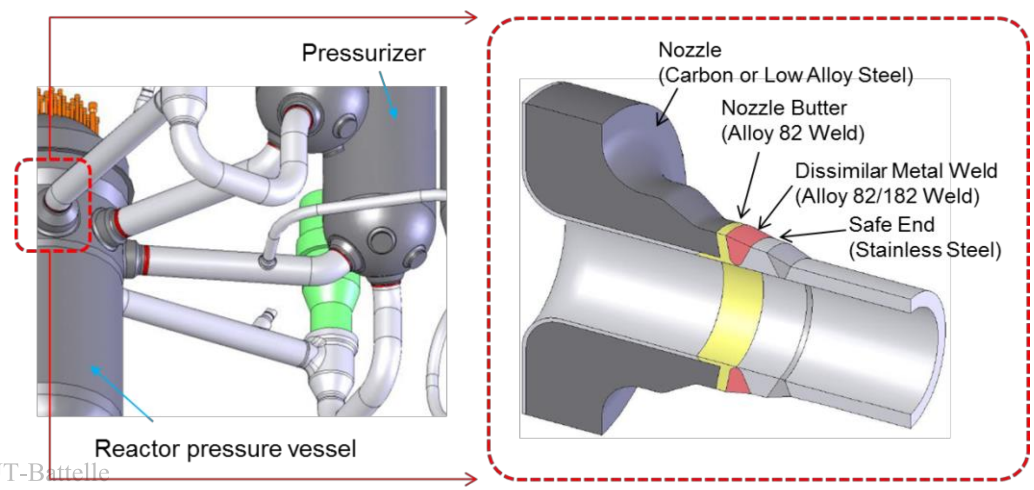
Issue Date: October 31, 2013

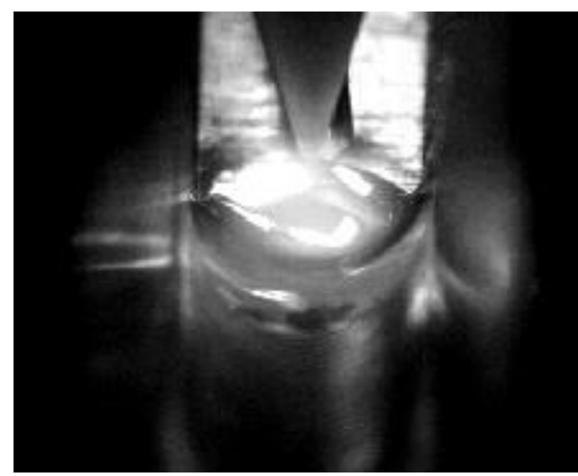
Pre-Application (Mandatory) Due Date: December 2, 2013 at 8:00 PM ET

Application Due Date: April 3, 2014 at 8:00 PM ET

Objective

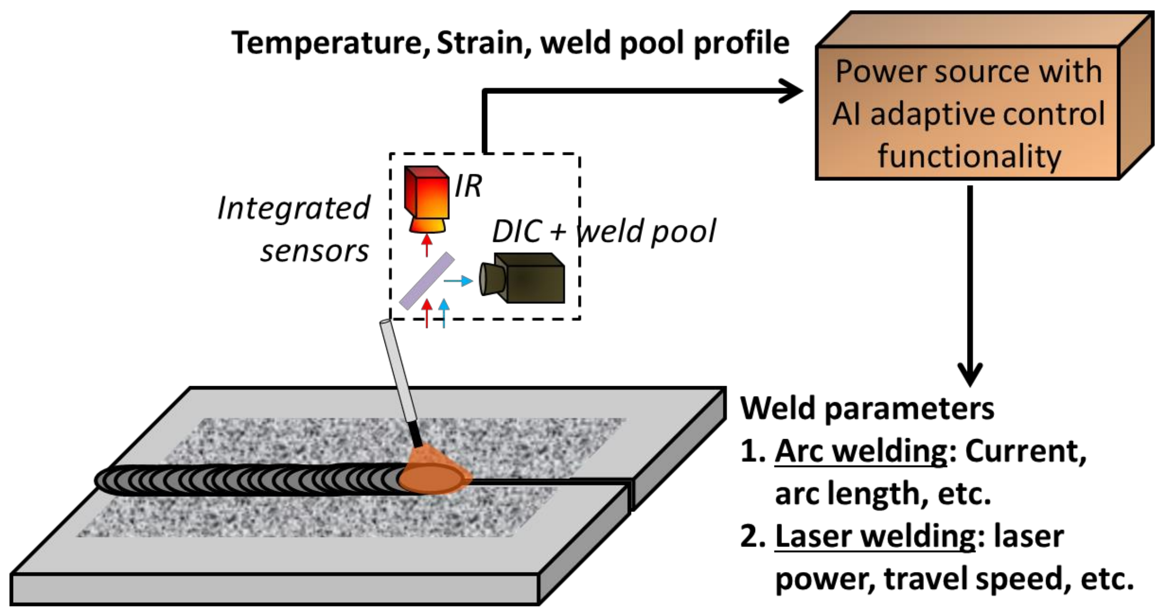
- This project aims at developing a welding quality monitoring and control system based upon *multiple optical sensors*.
  - Enables real-time weld defect detection and adaptive adjustment to the welding process conditions to eliminate or minimize the formation of major weld defects.
  - Addresses the needs to develop “advanced (high-speed, high quality) welding technologies” for factory and field fabrication to significantly reduce the cost and schedule of new nuclear plant construction.





Principal

- ***Non-contact*** optical monitoring system for inspecting each weld pass
- Building a foundation of signal/knowledge database from past experiences to detect certain types of weld defects
  - Temperature field
  - Strain/stress field (related to residual stress, distortion, cracks, etc.)
  - Weld pool surface profile (related to bead shape, lack of penetration, etc.)
- Close-looped adaptive welding control algorithm will correlate the above measurement signals to the weld quality and provide feedback control signals in real time

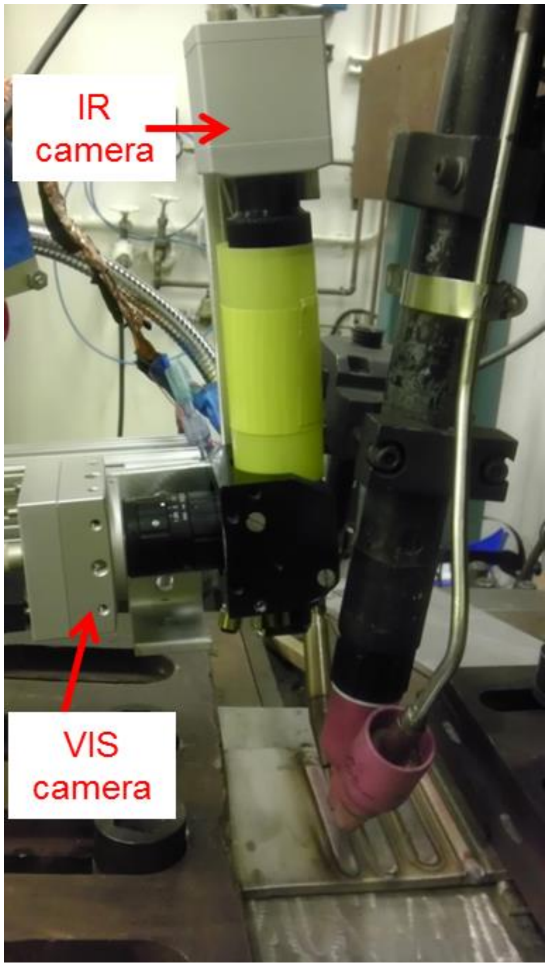


Accomplishments

- Optical sensors
  - System integration
- In-line process monitoring and control
  - Real-time strain, stress and distortion monitoring
    - High-temperature DIC
    - In-house DIC code
    - Stress calculation procedure
  - Penetration control and lack-of-fusion mitigation
    - Weld pool monitoring
    - Adaptive welding process control

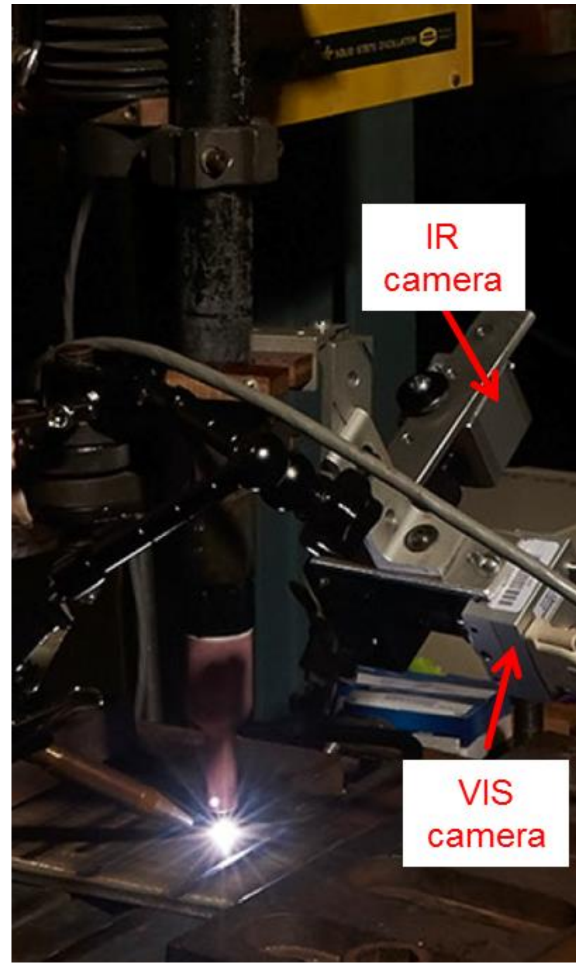
System setup

Part 1: Strain, stress monitoring



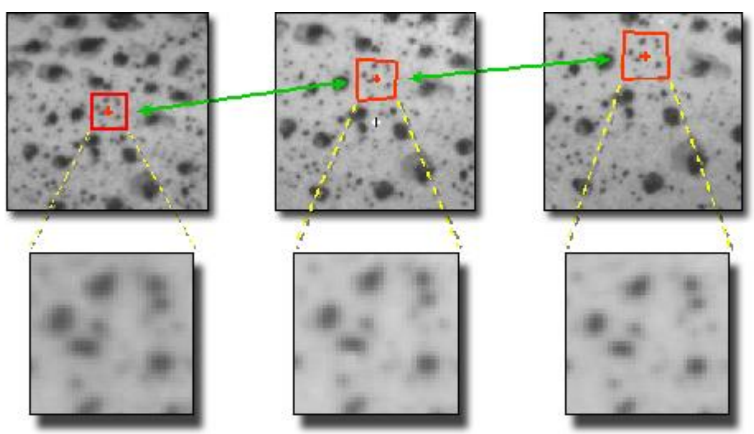
Camera is stationary

Part 2: Weld pool monitoring and process control



Camera moves with welding torch

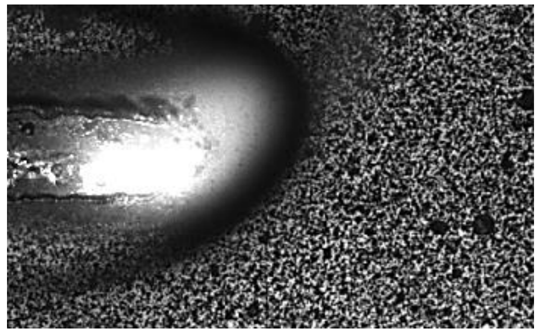
Part 1: Strain, stress and distortion monitoring by ORNL's high-temperature DIC



tracking the displacement of each subset.

Technical challenges

- Conventionally spray-painted speckle pattern is venerable to high temperature.



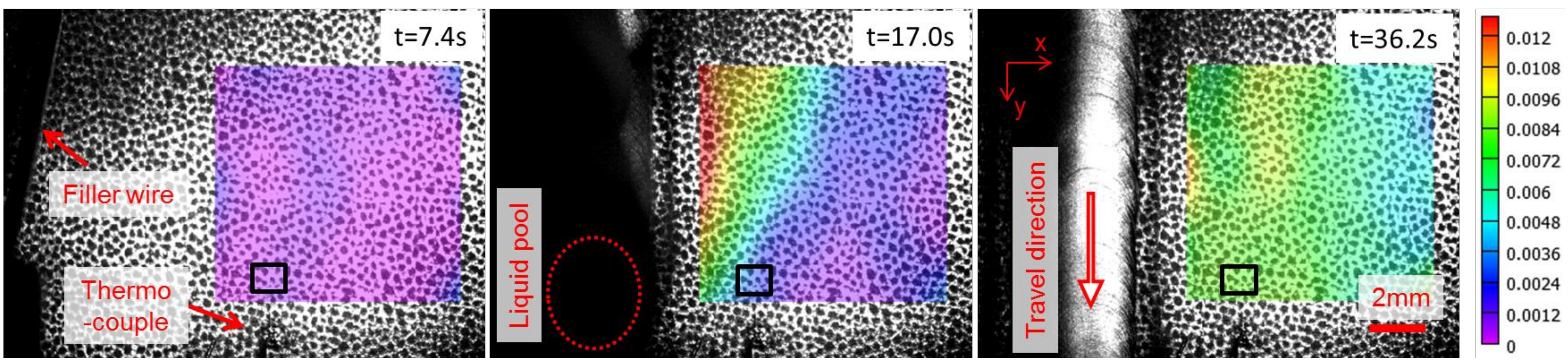
Burning and disbanding of the spray paint.

- Intense arc light acts as an unstable light source that deteriorates the quality of images for correlation analysis.

ORNL’s high-temperature DIC approach

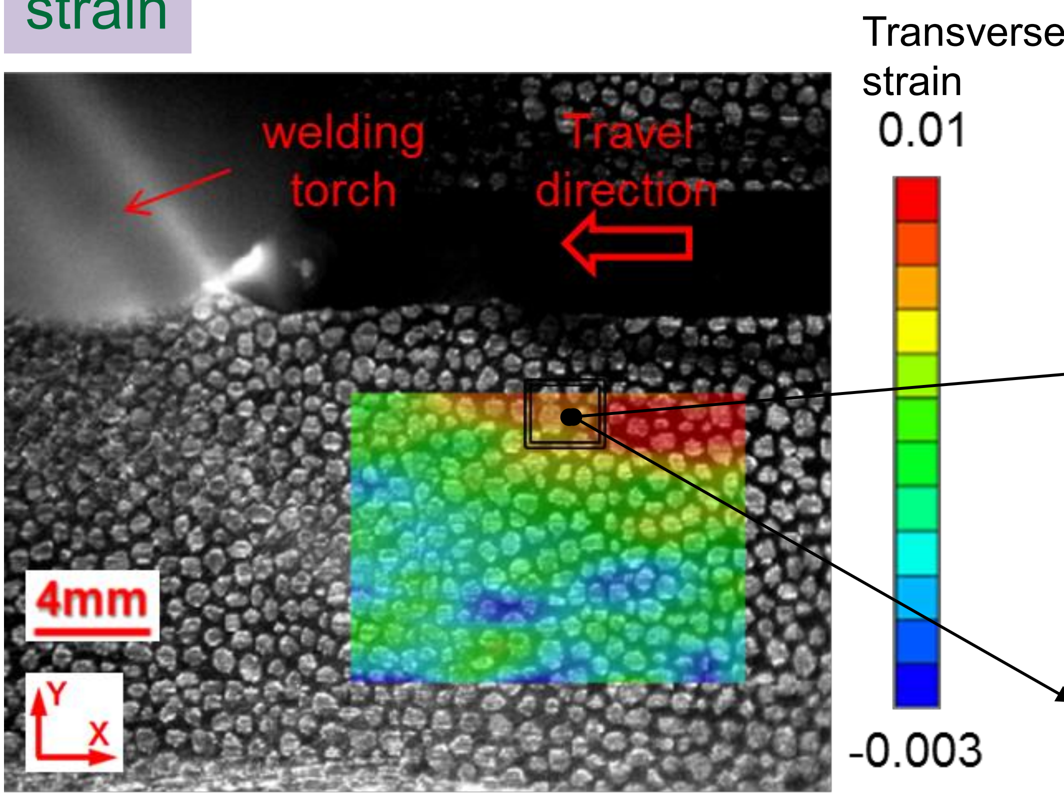
- Special surface speckle preparation method that can be used at the temperature up to material’s melting point
- Pulsed laser illumination synchronized with camera shutter to overcome arc light
- In house software to achieve real-time 3D distortion, strain and stress monitoring

Evolution of transverse strain

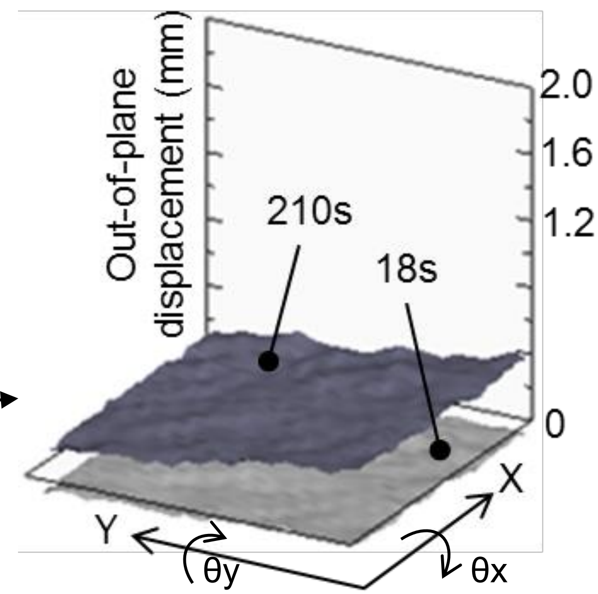


3D distortion and strain monitoring in HAZ through novel high-temperature DIC

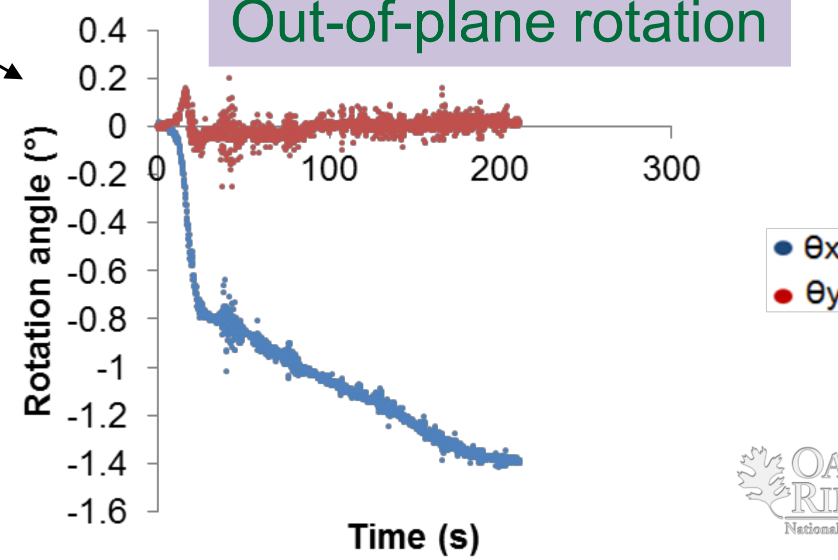
strain



Out-of-plane displacement

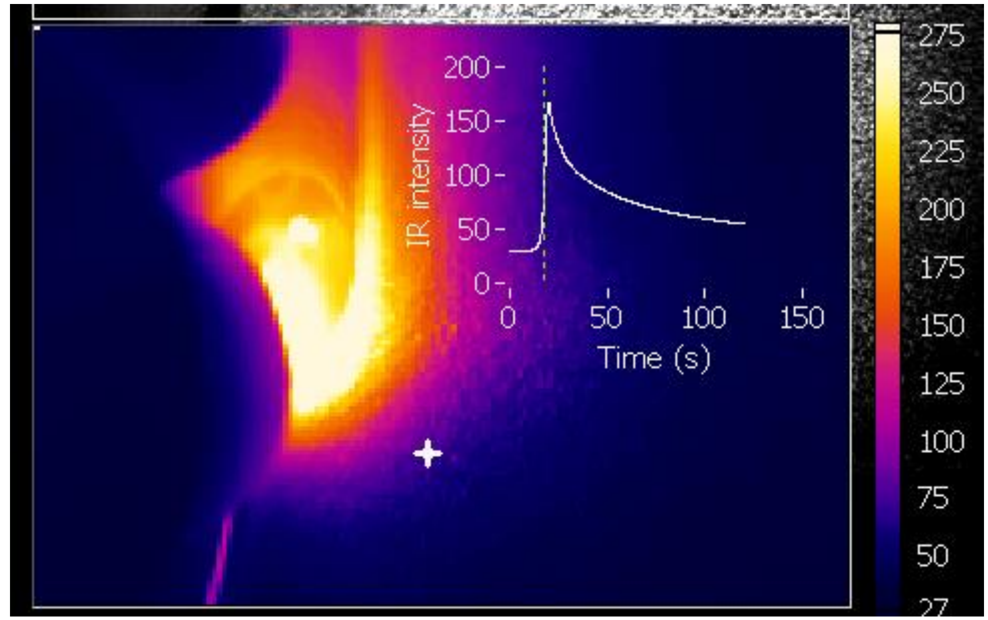


Out-of-plane rotation

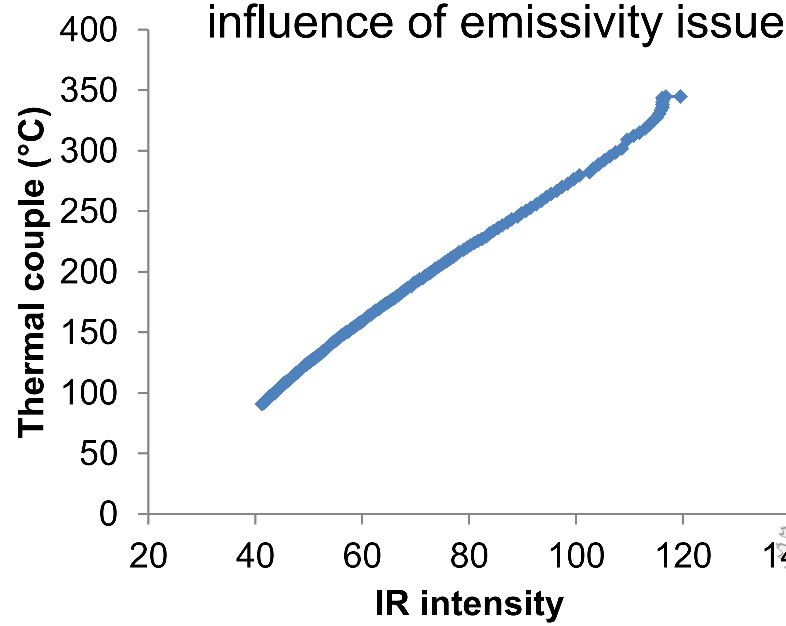


Temperature/thermal measurements

- Both thermal couples and infrared (IR) cameras are used for temperature measurements.
  - Thermal couple
    - Pros: accurate
    - Cons: contact, single point
  - IR camera:
    - Pros: non-contact, full field
    - Cons: affected by emissivity

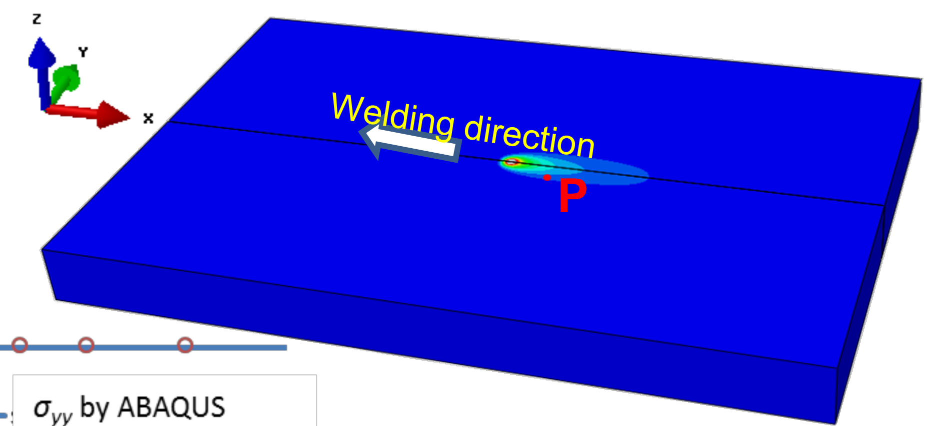


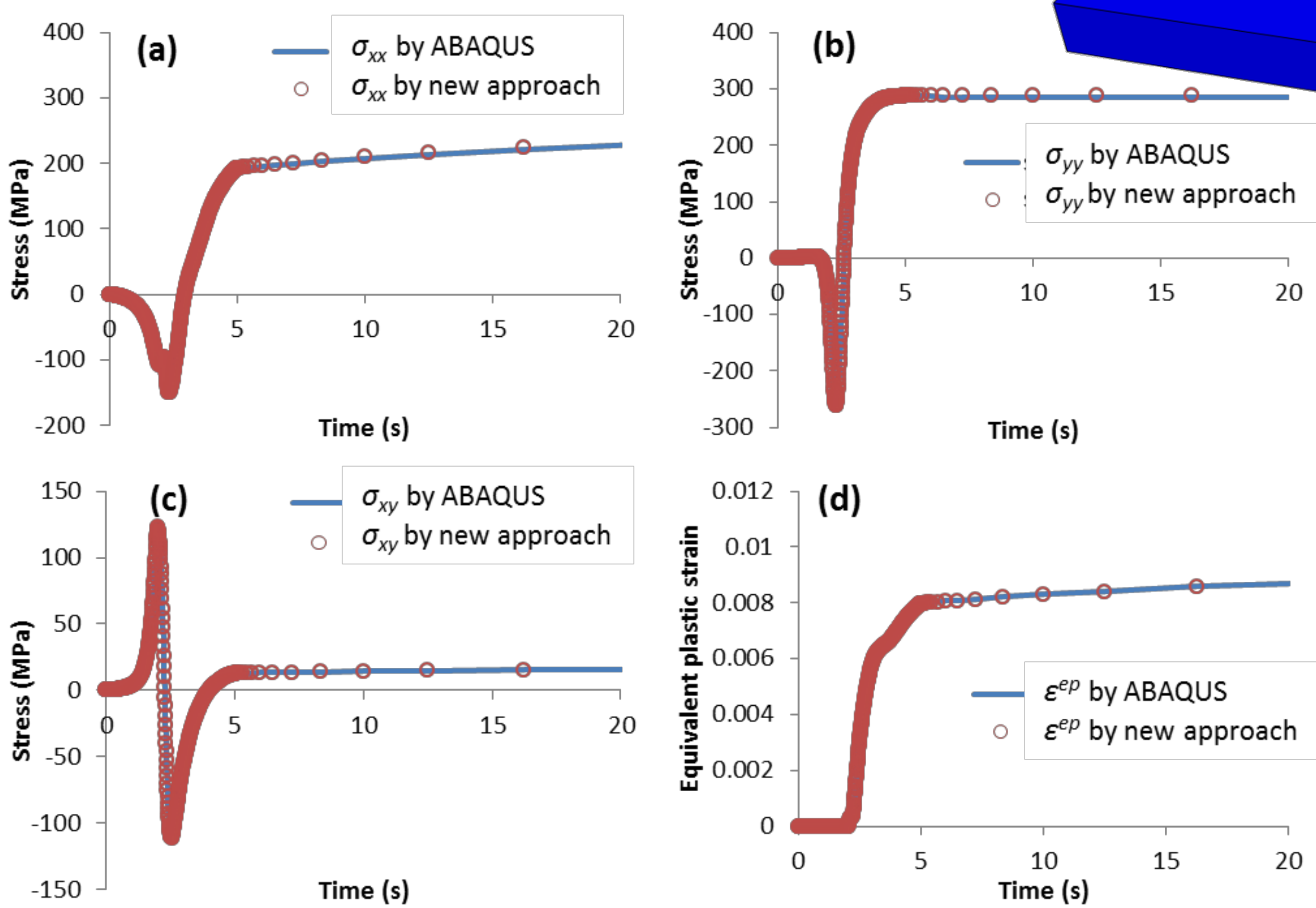
Calibration to minimize the influence of emissivity issue.



Novel procedure to calculate stress in real time

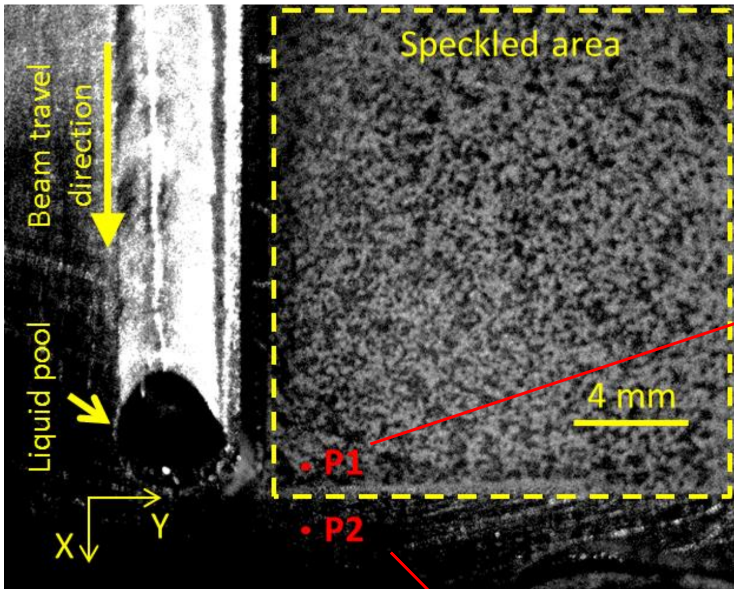
Algorithm is validated by numerical models



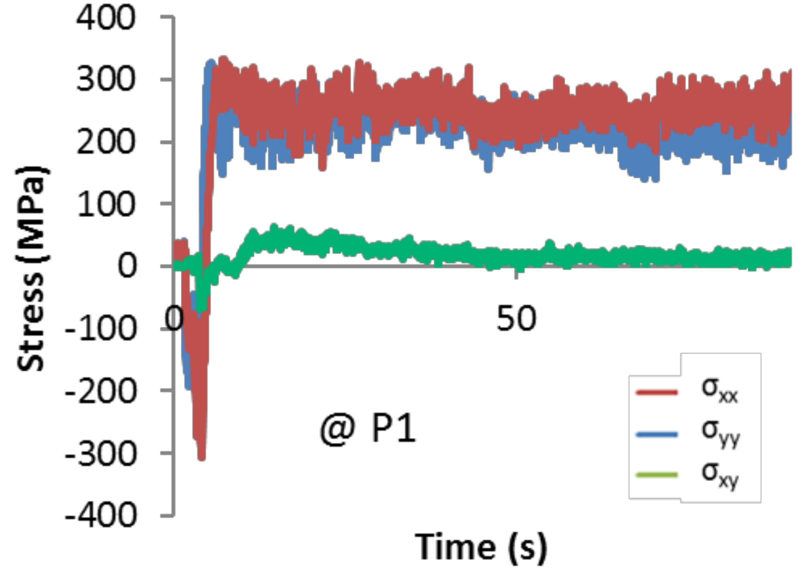


Experimental demonstration

Laser welding



In-line stress calculation

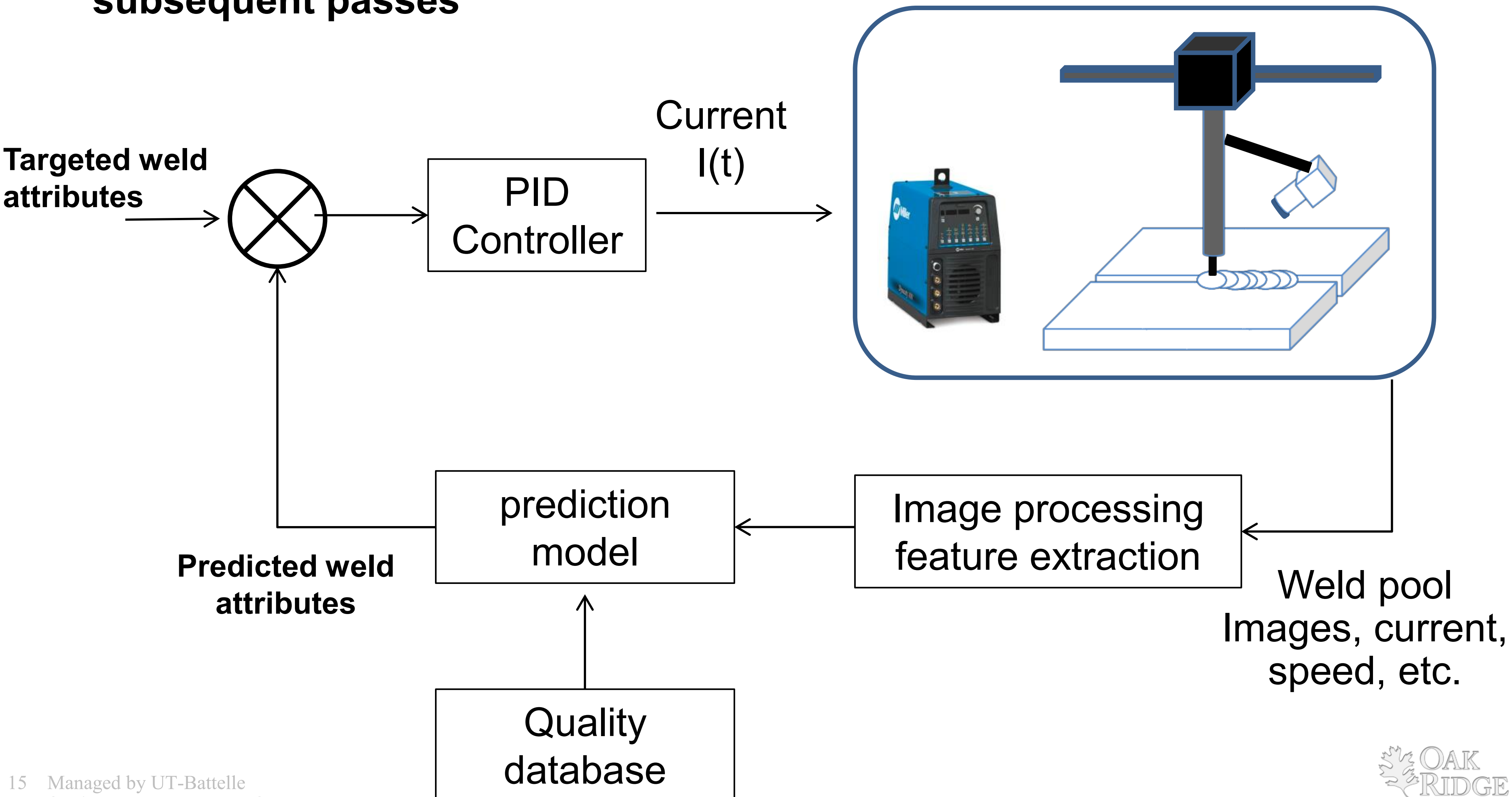


Post-weld residual stress by XRD
σ_{xx}=221 MPa
σ_{yy}=324 MPa

Part 2: Weld pool monitoring and welding process control

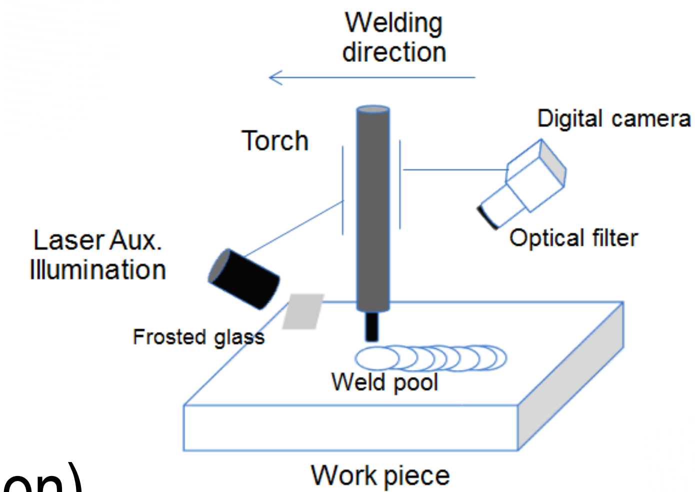
Feedback control

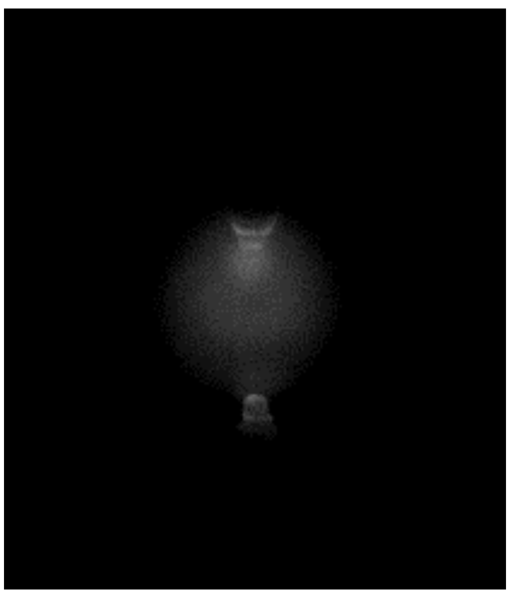
Weld attributes to control:
- **Root pass full-penetration**
- **Lack-of-fusion mitigation in the subsequent passes**

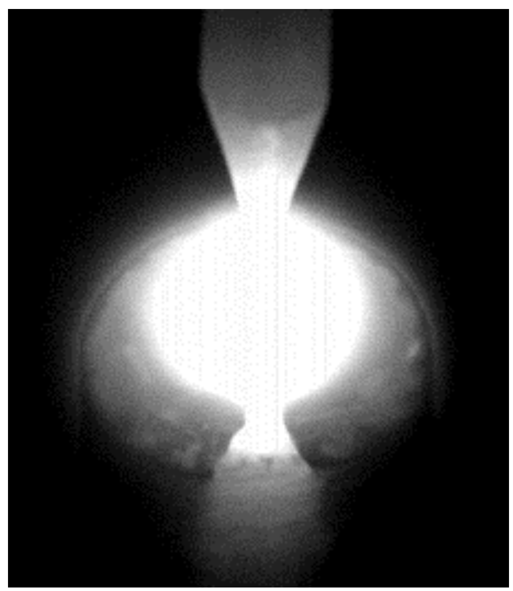


Weld pool visualization

- Challenges: intense arc light
- Solutions: optical filters, camera shutter control and auxiliary illumination source
- Two types of image sources
  - Passive vision images (arc light as illumination)
  - Active vision images (pulsed laser as illumination)





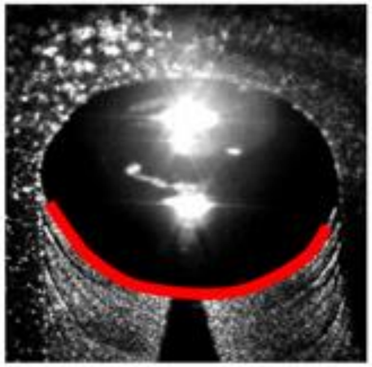


Passive vision images with adaptative exposure control

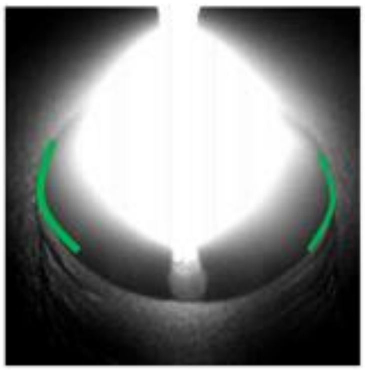
Active vision image

3D weld pool information

Active vision



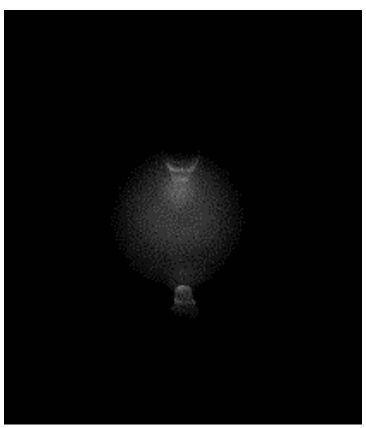
Passive vision w/ long exposure

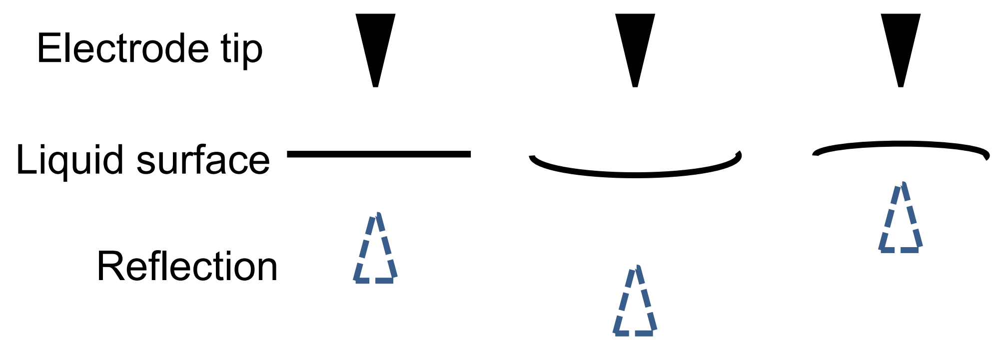


Weld pool length and width

Weld pool surface height

Passive vision w/ short exposure

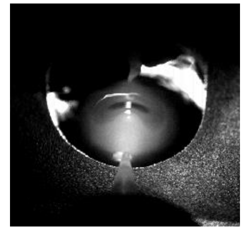


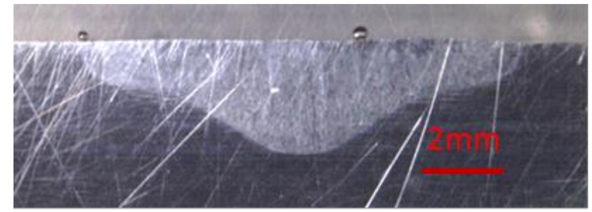


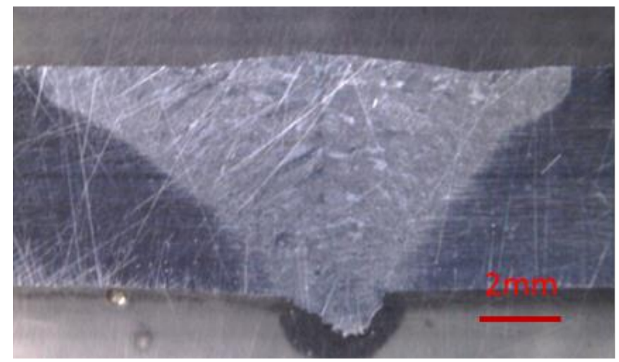
Part 2.1 Penetration control

Testing conditions to establish penetration database (bead on plate)

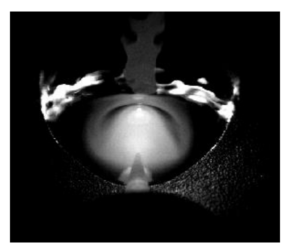
Thickness (mm)	Welding speed (mm/s)	Current (A)
2mm	1mm/s	45~70
	2mm/s	50~100
3mm	1mm/s	80~120
	2mm/s	100~145

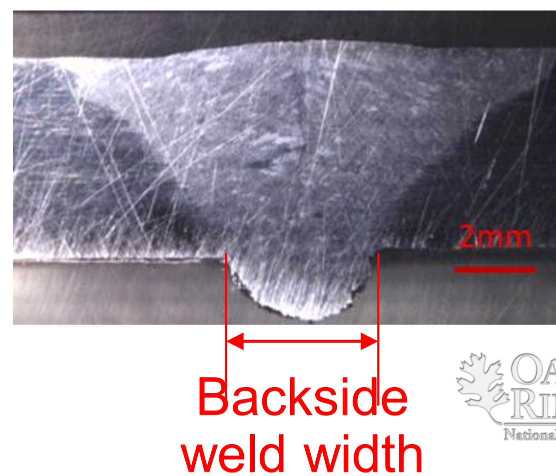






1000+ image frames were analyzed and compared to the post-weld characterization.





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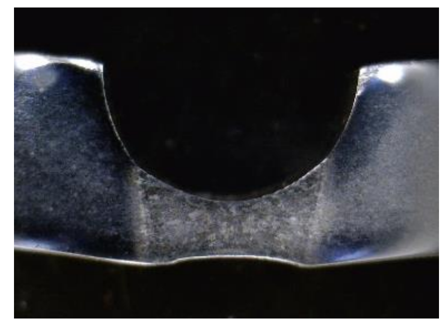
Testing conditions to establish penetration database (U groove)

No	Root face thickness (mm)	Current (A)	Speed (mm/s)
1	1	100	1
2	1.5	100	1
3	2	100	1
4	1	120	1
5	1.5	120	1.5
6	2	120	1
7	1.5	90	1
8	1.5	100	1.5
9	1.5	120	1
10	1.5	130	1
11	1.5	140	1
12	1.5	150	1
13	1	150	1

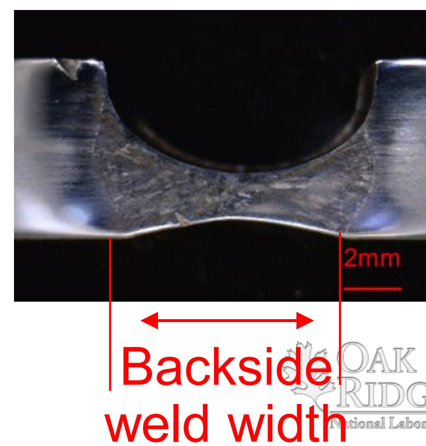
1000+ image frames were analyzed and compared to the post-weld characterization.

Partial penetration

Full penetration



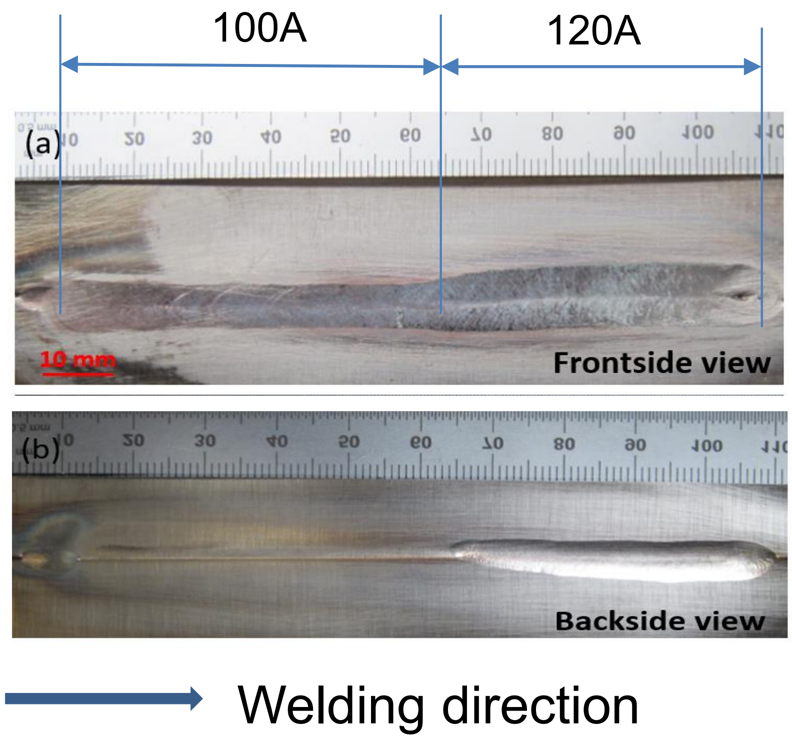
over penetration

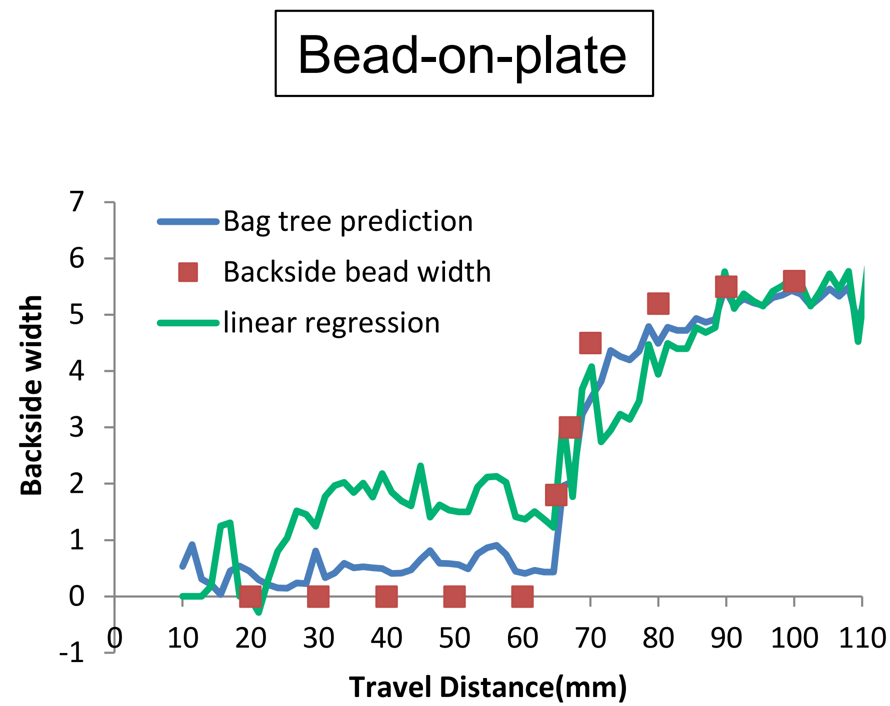


Tools used to establishment the database

- Artificial neural network (ANN)
- Linear regression
- Support vector machine (SVM)
- Bag tree

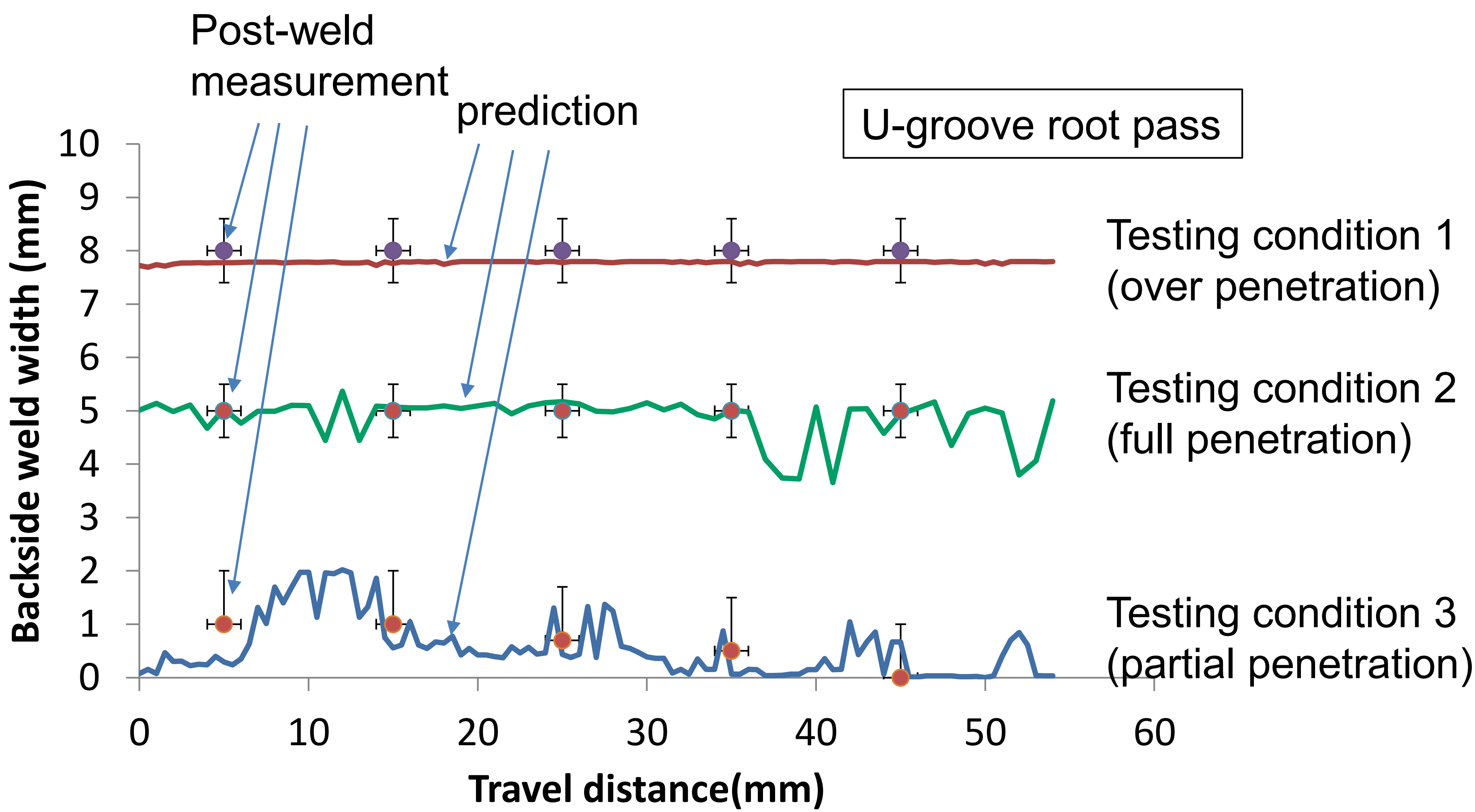
Error comparison



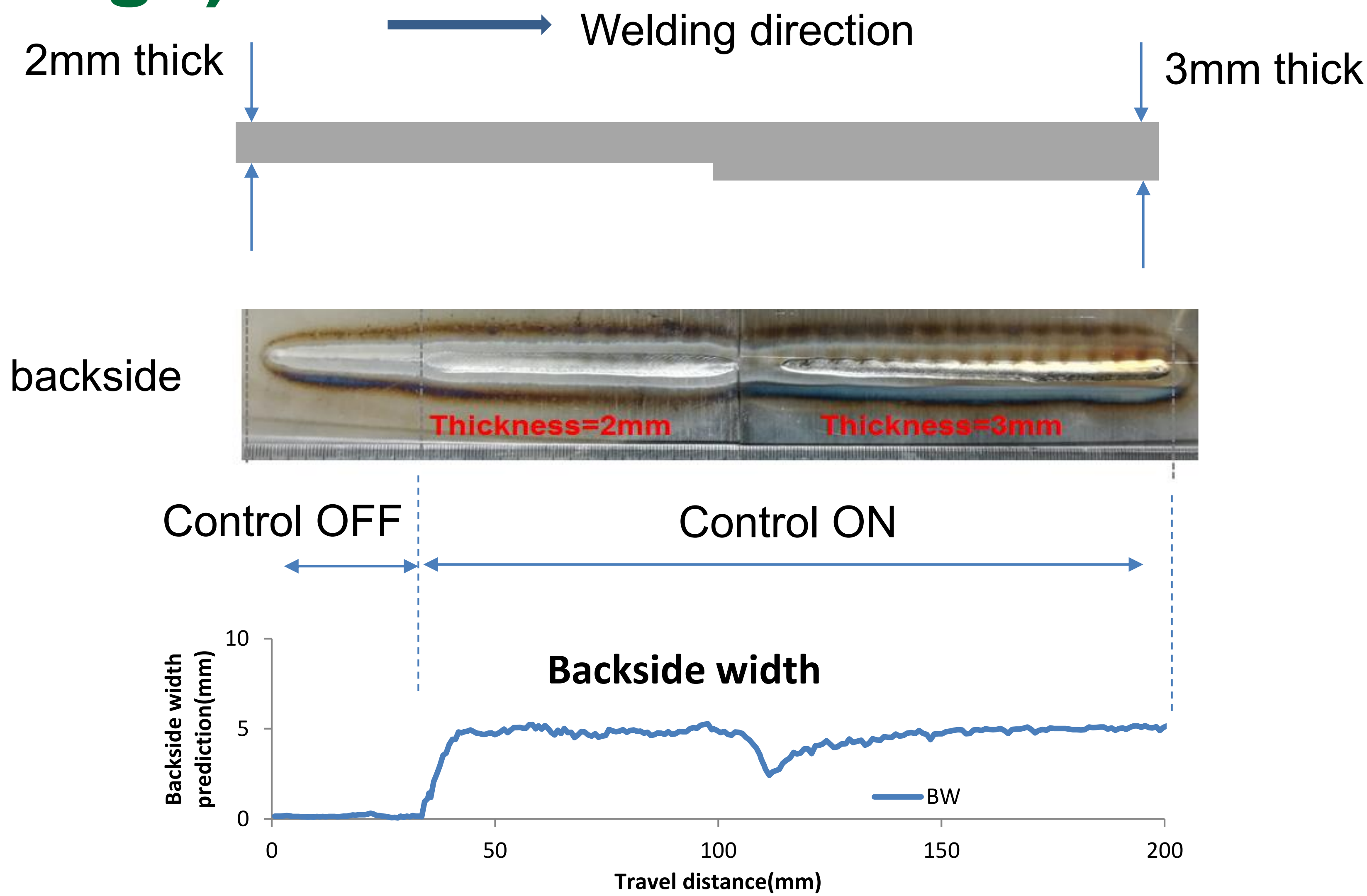


Method	RSME
Linear regression	1.83 mm
Bag tree	0.86 mm
SVM	0.99 mm
ANN	1.07 mm

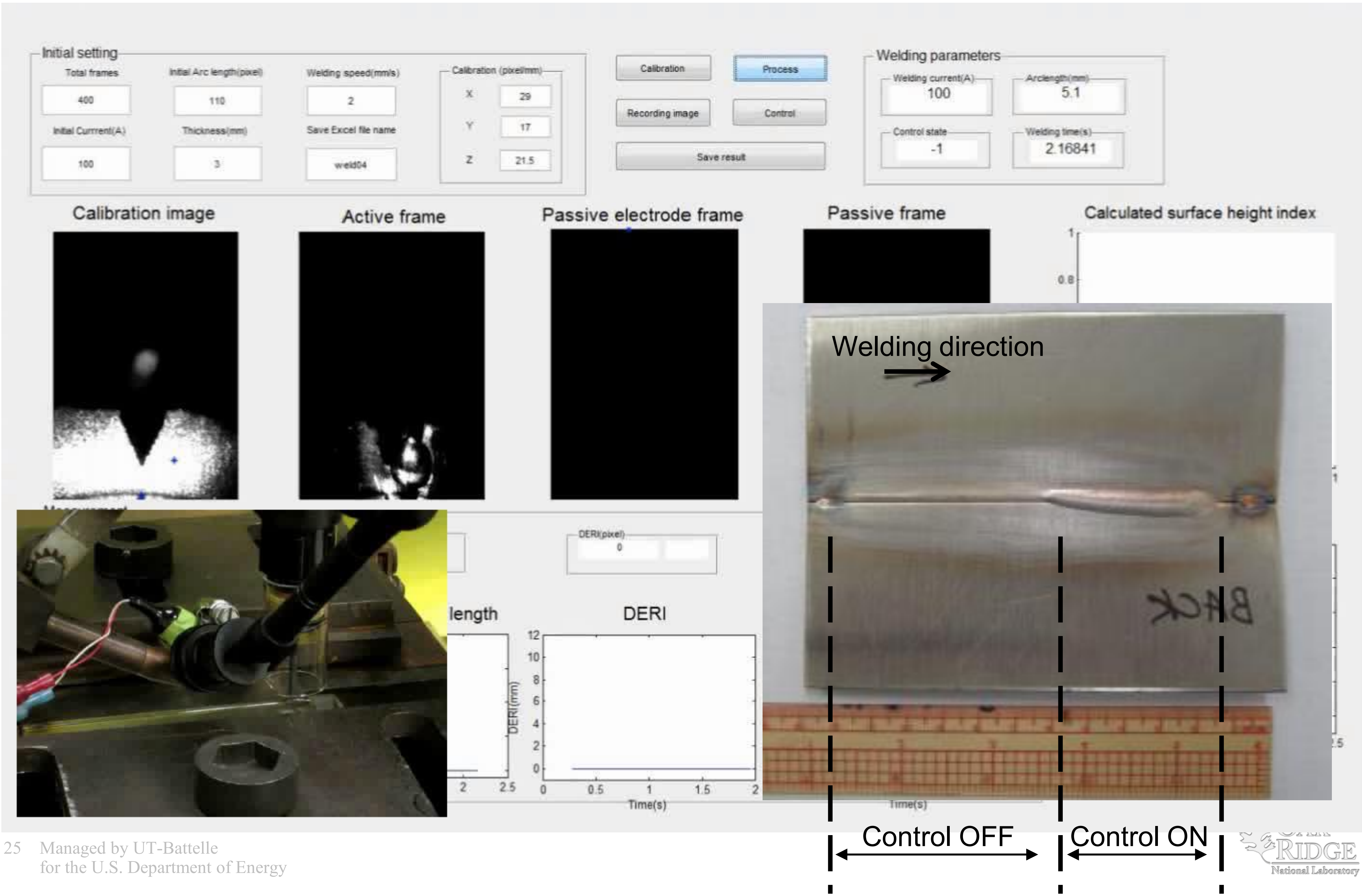
Validation of penetration prediction



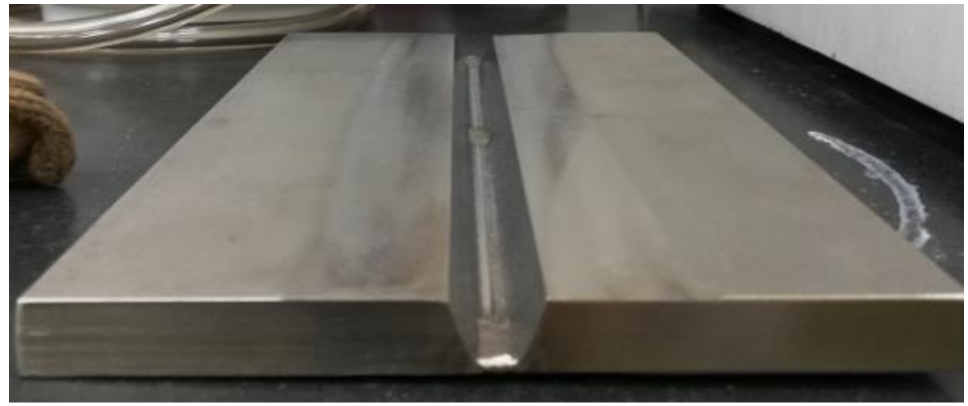
Demonstration of penetration control (Case 1: bead-on-plate & thickness change)



Demonstration of penetration control (Case 2: butt joint)



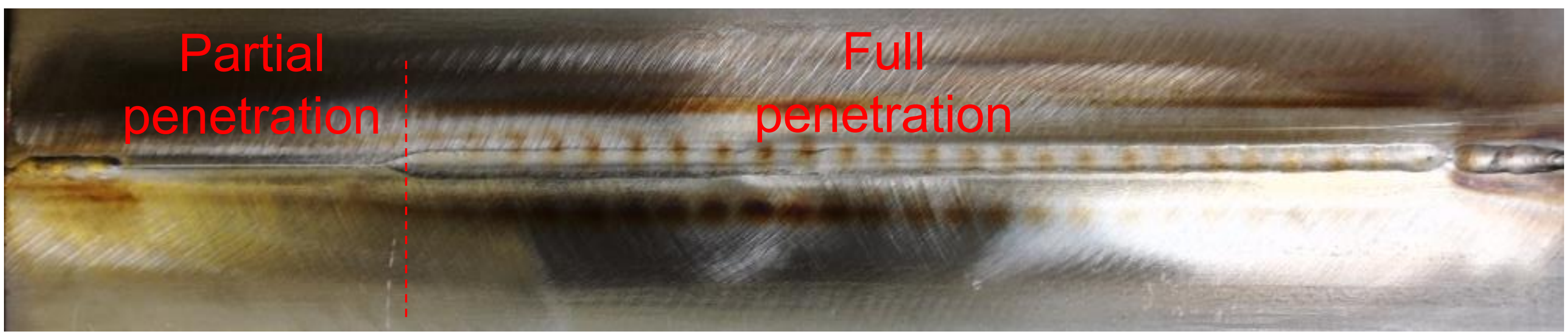
Demonstration of penetration control (Case 3: U-groove root pass)



Travel direction

Root pass

Bottom view



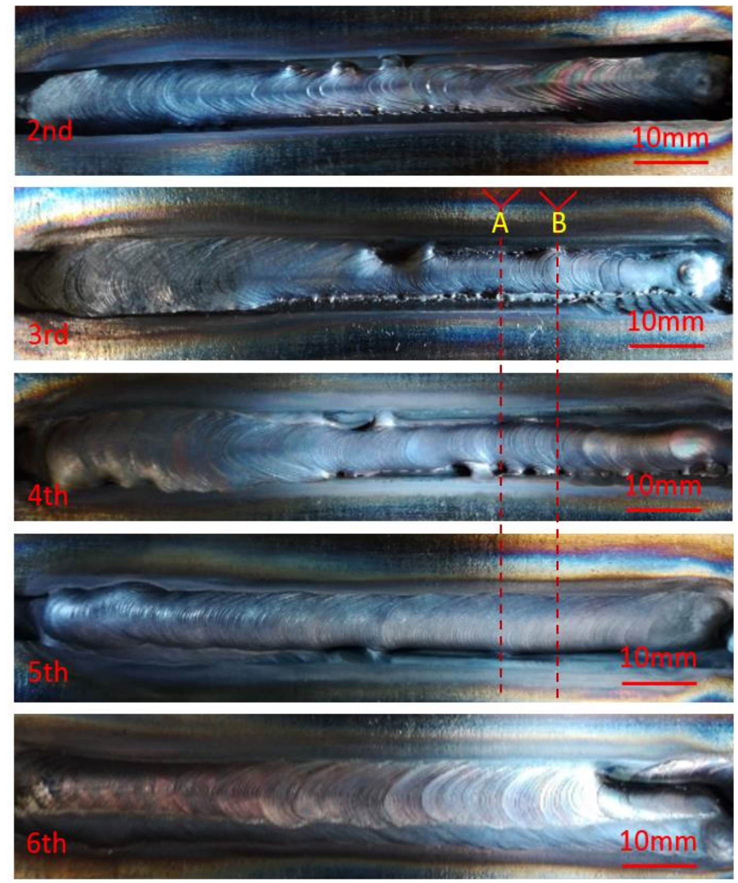
Control OFF

Control ON

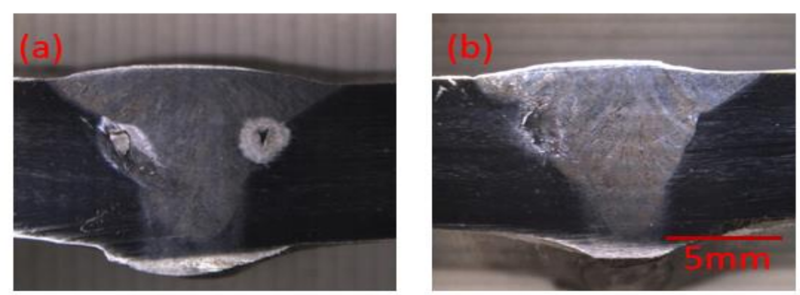
Part 2.2 lack-of-fusion mitigation

Testing conditions to establish quality database (lack of fusion)

	Layer number	Current (A)	Travel speed (mm/s)	Wire feeding speed(inch/min)
Sample 1 (6mm thick)	I	150	1->2	25
	II	150	1->2	30
	III	150	1->2	30
	IV	150	2	25
	V	150	2	20
Sample 2 (12 mm thick)	I	150	1->2	25
	II	200	1->2	40
	III	200	1.8->2	40
	IV	200	1->2	40
	V	220	1	40
	VI	220	1->2	40
	VII	220	1	50



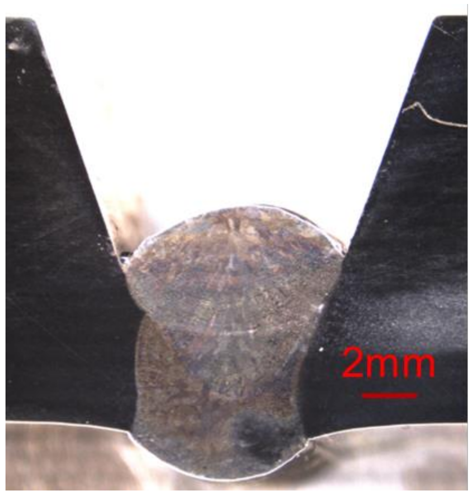
A total of **<u>1434</u>** image frames were analyzed and labeled based on post-weld observation/cross-section.

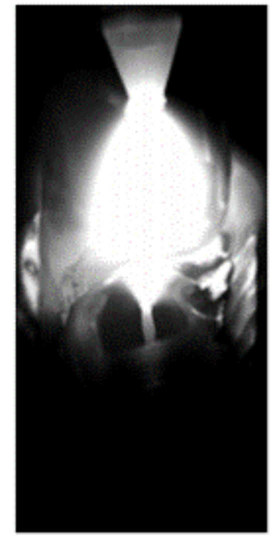


Weld pool feature vs. fusion status

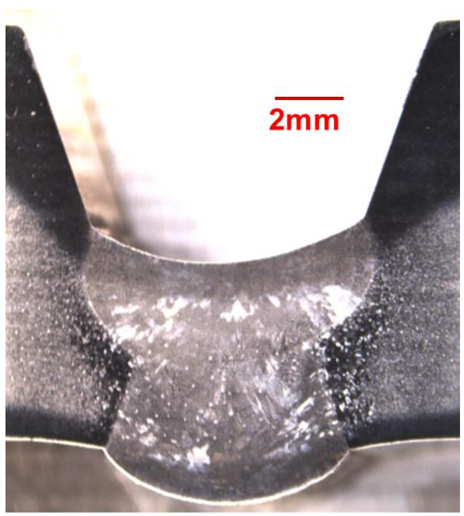
Short exposure | Long exposure

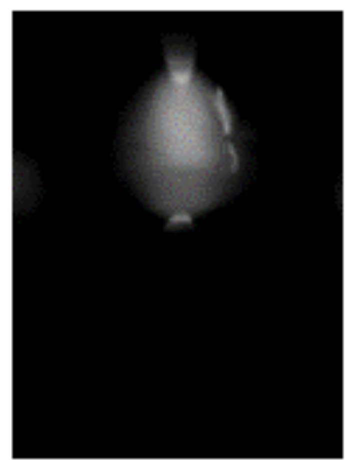
Lack of fusion

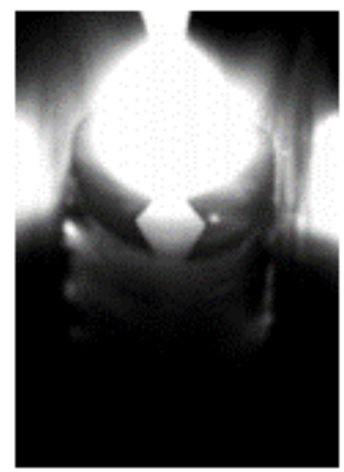




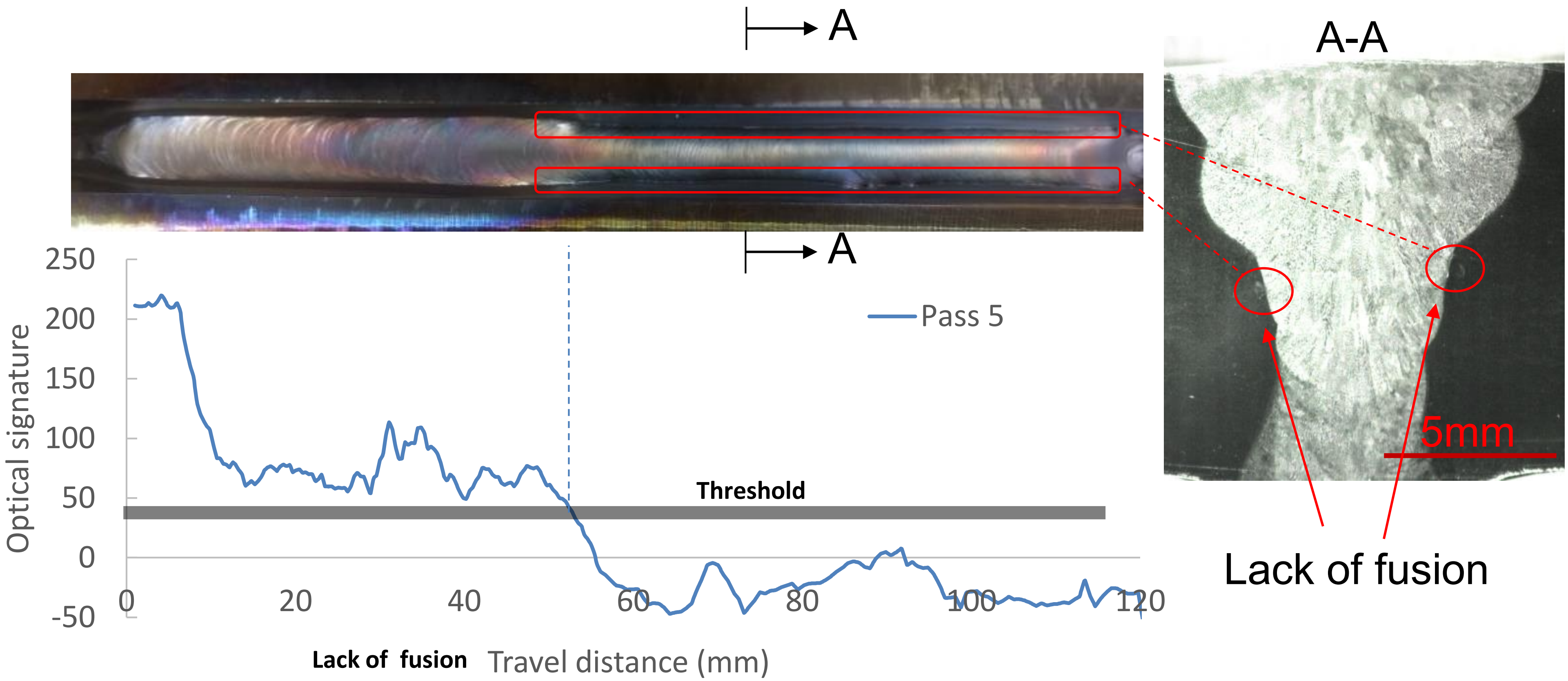
Complete fusion







Optical signature vs. lack-of-fusion



Data training and testing

Datasets

	Layer number	Current (A)	Travel speed (mm/s)	Wire feeding speed(inch/min)
Dataset 1: Sample 1 (6mm thick)	I	150	1->2	25
	II	150	1->2	30
	III	150	1->2	30
	IV	150	2	25
	V	150	2	20
Dataset 2: Sample 2 (12 mm thick)	I	150	1->2	25
	II	200	1->2	40
	III	200	1.8->2	40
	IV	200	1->2	40
	V	220	1	40
	VI	220	1->2	40
	VII	220	1	50

Performance of lack-of-fusion prediction with bagging tree model

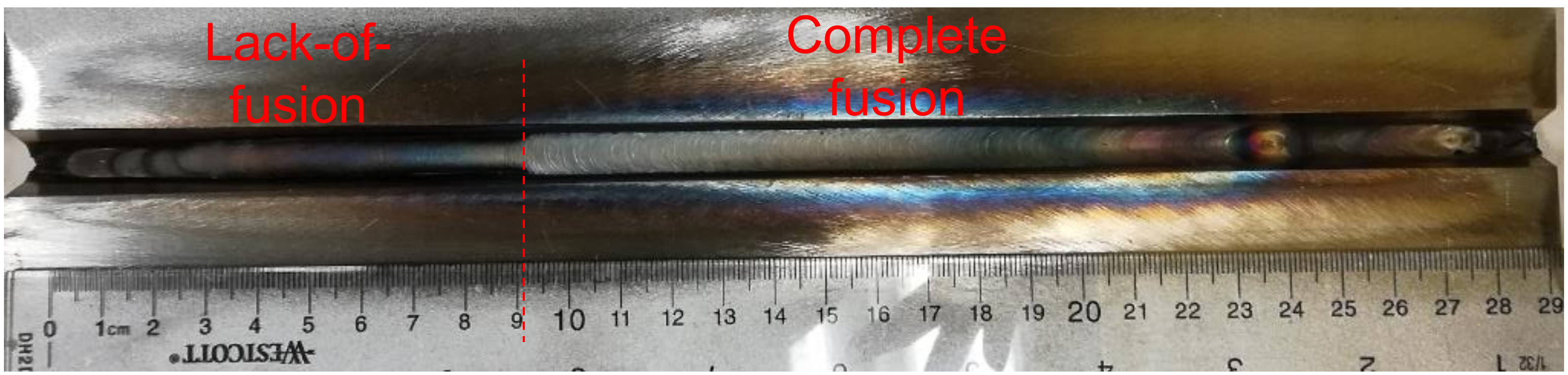
Number of Model	Training data	Testing data	Accuracy（%）
I	70% dataset I	30% dataset I	**97.58**
II	100% dataset I	100% dataset II	**95.79**
III	70% dataset I&II	30% dataset I&II	**95.49**

Demonstration of lack-of-fusion mitigation (2^{nd} pass in U-groove)

Pass 2

Travel direction

Top view



Control OFF

Control ON

Summary

- A multi-optical sensing system is integrated and tested for monitoring arc welding and laser welding processes.
- Novel methods and algorithms were developed for real-time strain and stress monitoring in HAZ.
- Weld pool surface feature can be correlated to penetration states and lack-of-fusion defects
- The system can adaptively control the welding process to achieve full penetration and mitigate the formation of lack-of-fusion defects

Journal publications

- J Chen and Z Feng, “Strain and Distortion Monitoring during Arc Welding by 3D Digital Image Correlation”, Science and Technology of Welding and Joining, 23(6), 2018, 536-542.
- S. A. David, J. Chen, B.G. Brian and Z. Feng, “Intelligent Weld Manufacturing: Role of Integrated Computational Welding Engineering”, Transactions on Intelligent Welding Manufacturing, Volume 1, Issue 2 (2017), 3-30.
- JS Chen, J Chen, et al., “Dynamic Reflection Behaviors of Weld Pool Surface in Pulsed GTAW”, Welding Journal 97 (6), 2018, 191S-206S.
- Z Chen, J Chen and Z Feng, “Monitoring Weld Pool Surface and Penetration from Reversed Electrode Image”, Welding Journal, Volume: 96 Issue: 10 Pages: 367S-375S.
- Z Chen, J Chen and Z Feng. “Welding penetration prediction with passive vision system." Journal of Manufacturing Processes 36 (2018): 224-230.

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Thank you!

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