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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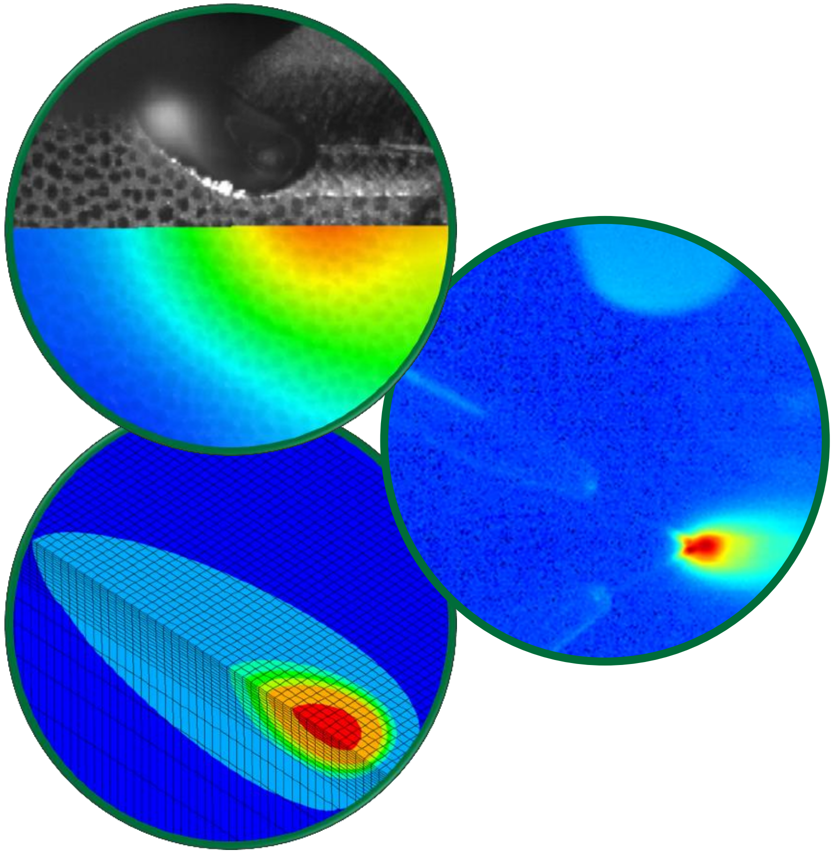

U.S. DEPARTMENT OF ENERGY

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Overview

- NEET1- Advanced Methods for Manufacturing
- Time line
  - Start: October, 2014
  - End: September, 2017
- 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

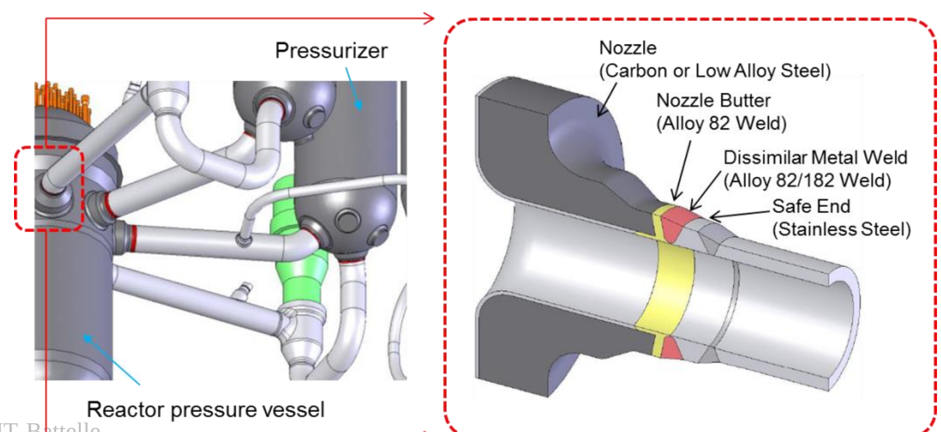
Issue Date: October 31, 2013

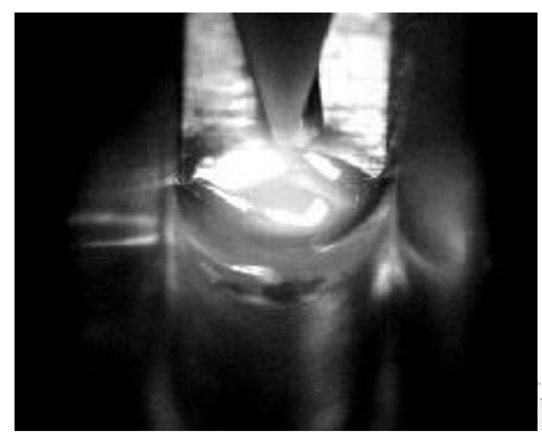
Pre-Application (Mandatory) Due Date: December 2, 2013 at 8:00 PM ET

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

Objective

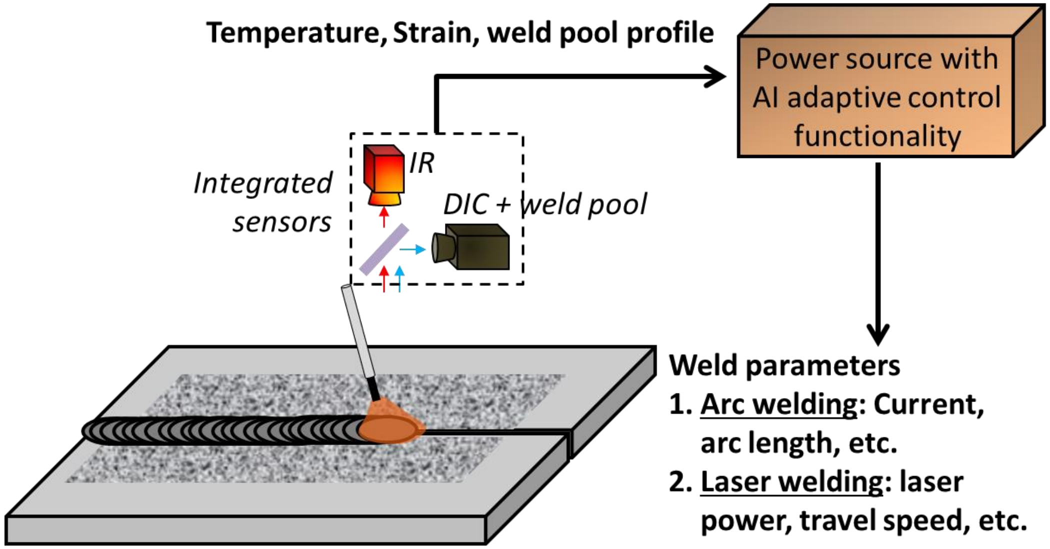
- This project aims at developing a welding quality monitoring and control system based upon *multiple optical sensors*.
  - Enables real-time weld defect detection and adaptive adjustment to the welding process conditions to eliminate or minimize the formation of major weld defects.
  - Addresses the 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

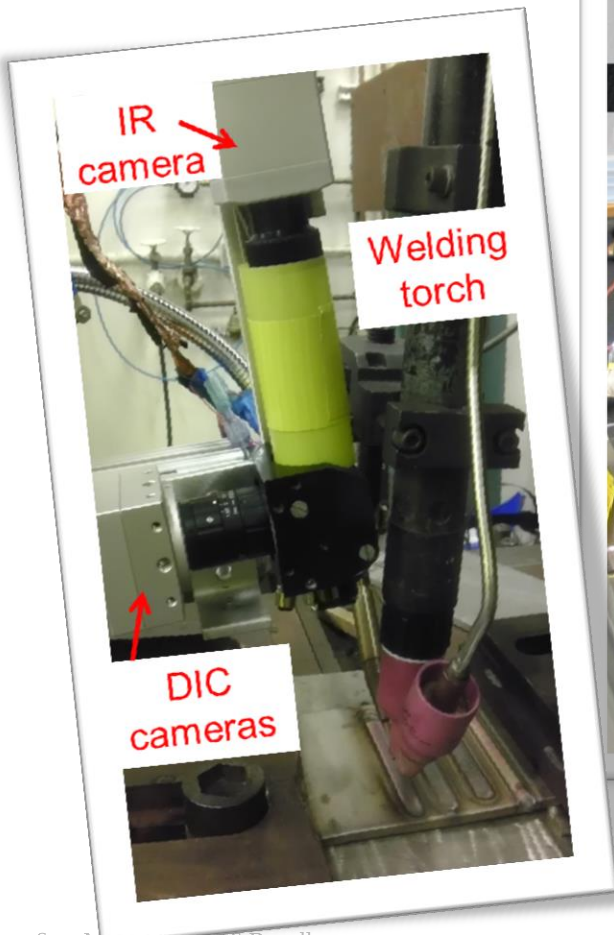
- ***Non-contact*** optical monitoring system for inspecting each weld pass
- Building a foundation of signal/knowledge database from past experiences to detect certain types of weld defects
  - Temperature field
  - Strain/stress field (related to residual stress, distortion, cracks, etc.)
  - Weld 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

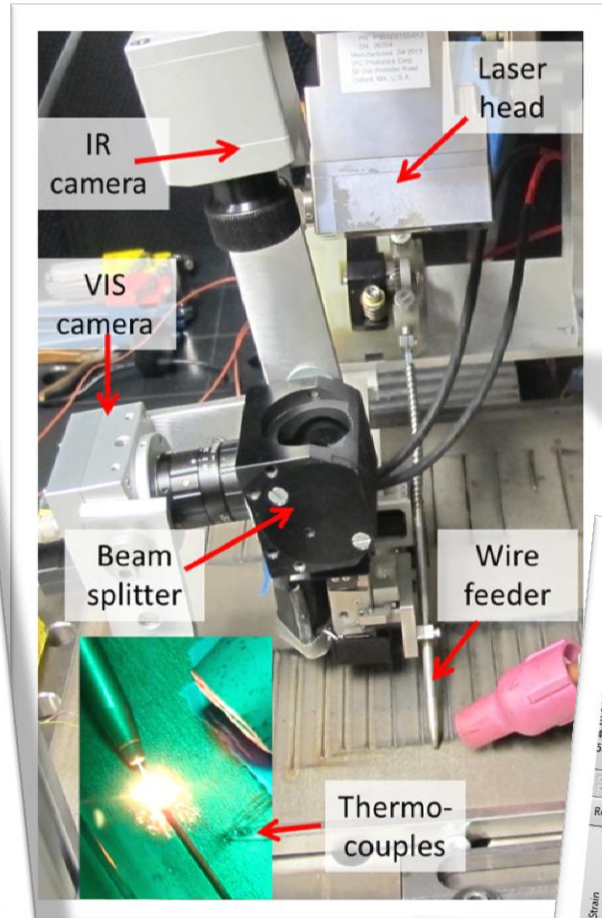


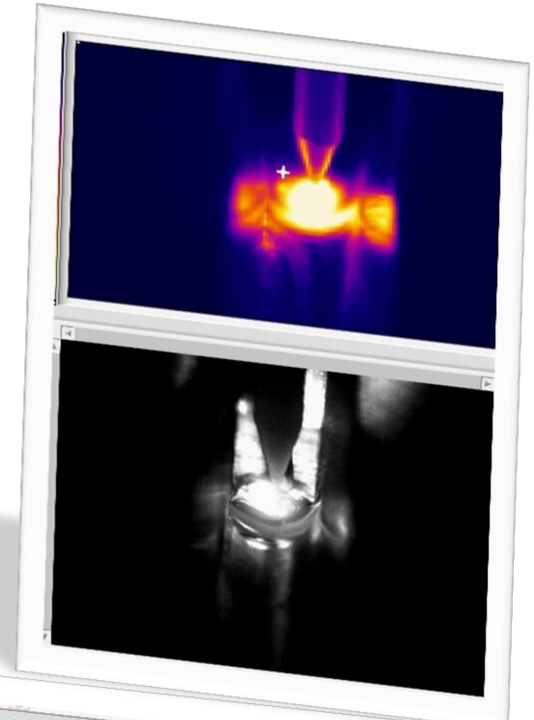
Current accomplishments

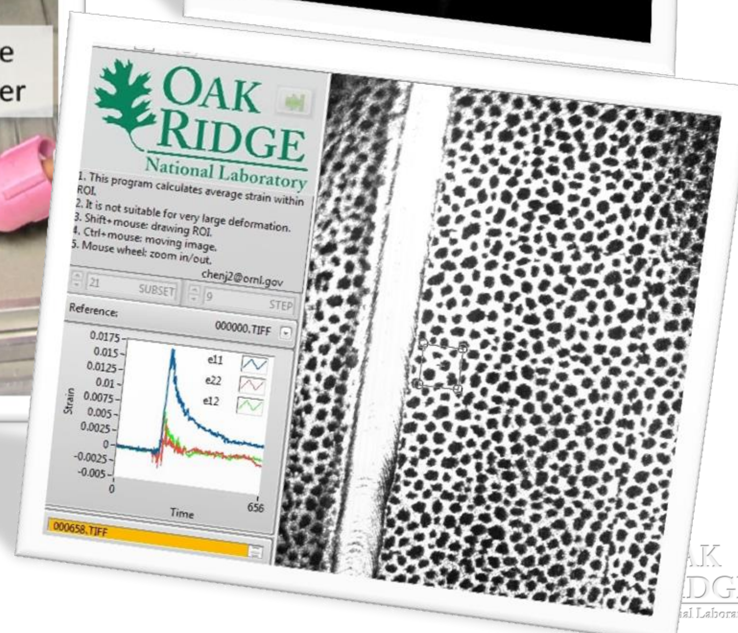
- System development
  - Hardware: cameras, optical illumination and filtering systems, I/O connections, etc.
  - Software: hardware control, data acquisition and analysis
- Development of new sensing methods and algorithms
  - Novel high-temperature DIC method and algorithm
    - Real-time temperature, strain and stress monitoring in HAZ
  - Weld pool visualization and surface dynamics
    - Defects identification and penetration control

Hardware integration and software development









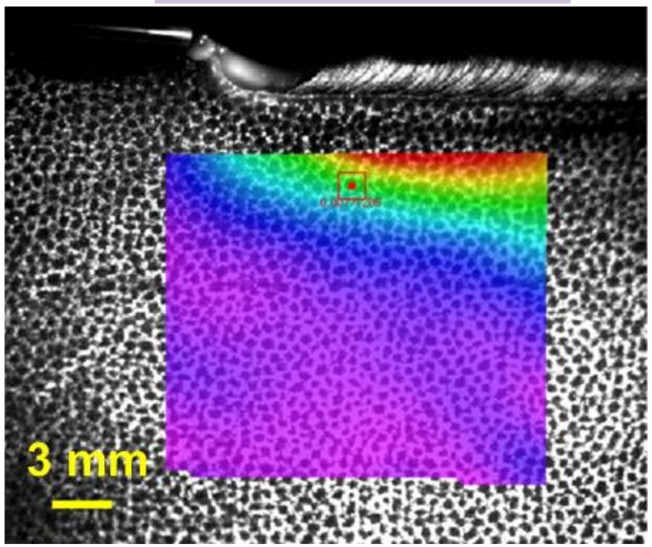
Novel high-temperature DIC for strain measurement

- DIC is a noncontact optical method to measure surface strain.
- The application in in-situ *welding monitoring* has been very challenging

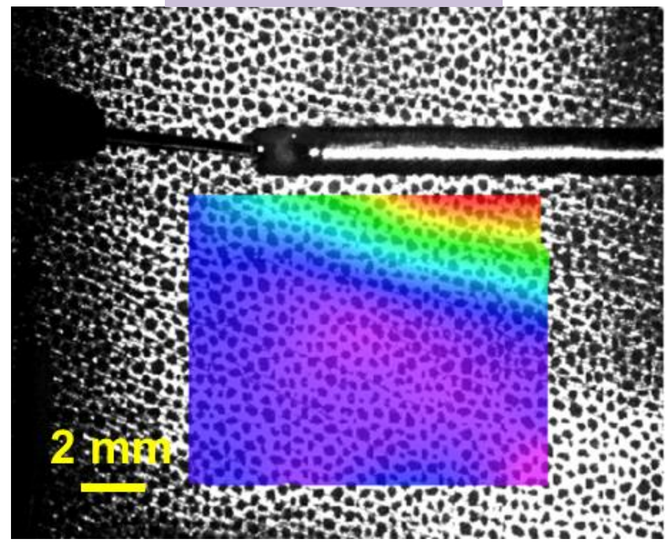
Challenges	Solutions
Intense arc light	Special optical illumination and filtering system
Damage/burning of speckle pattern	Novel speckle patterns survived at temperature up to the melting point
Specular reflection on metal surface	Novel stereo (3D) DIC algorithm
Real-time data processing	In-house software

Special optical system and high-temperature speckle*

Arc welding (TIG)



Laser welding

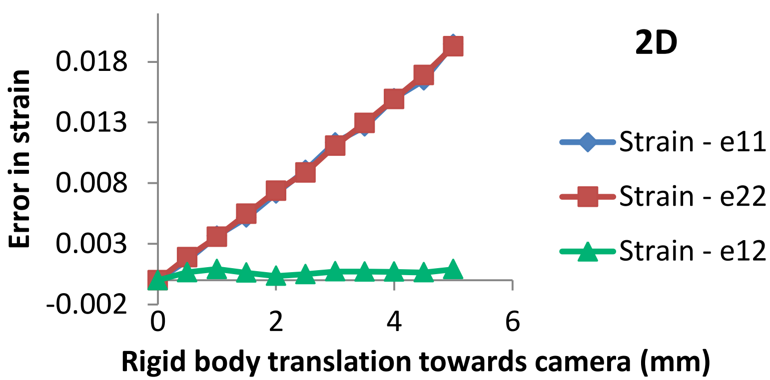


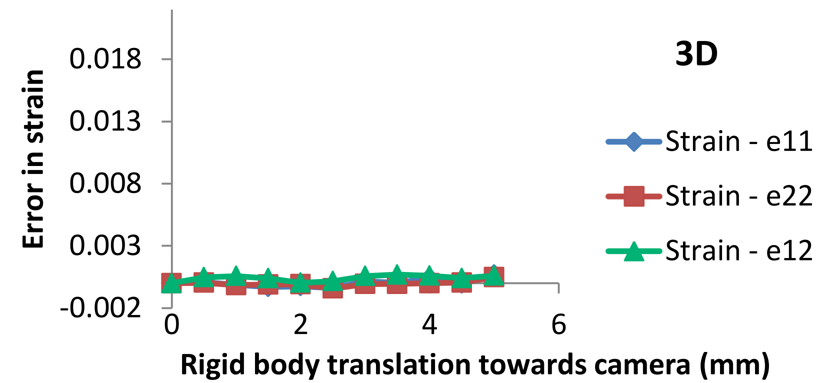
- Basic requirements of DIC algorithm: stable illumination and stable speckle pattern
  - Special illumination and filtering system to greatly suppress the intense welding arc or laser plume
  - Novel speckle pattern survived at temperatures up to the melting point

** J Chen, X Yu, R G Miller, Z Feng, "In-situ Strain and Temperature Measurement and Modeling during Arc Welding", Science and Technology of Welding and Joining, Volume 20, Issue 3 (March 2015), pp. 181-188*

Novel 3D DIC method on specular surface

- Why 3D DIC (stereo camera setup)?
  - Large error is expected for 2D DIC (one single camera) setup when out-of-plane displacement occurs





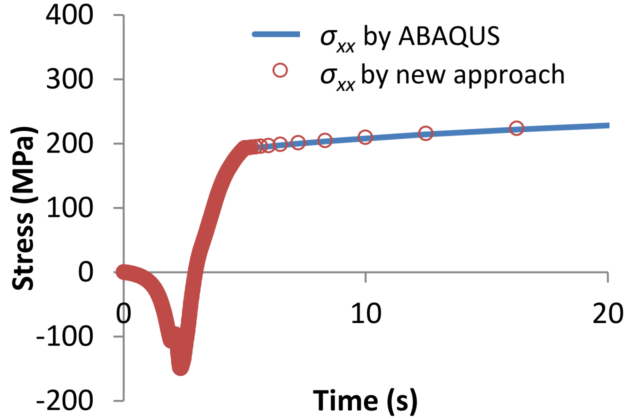
- Conventional (commercial) 3D DIC codes does NOT work on specular metal surface
  - Projected speckle pattern to both cameras can be totally different causing issues in pattern matching
- Novel 3D DIC algorithm and procedure has been developed
  - Works for both specular and diffuse surfaces

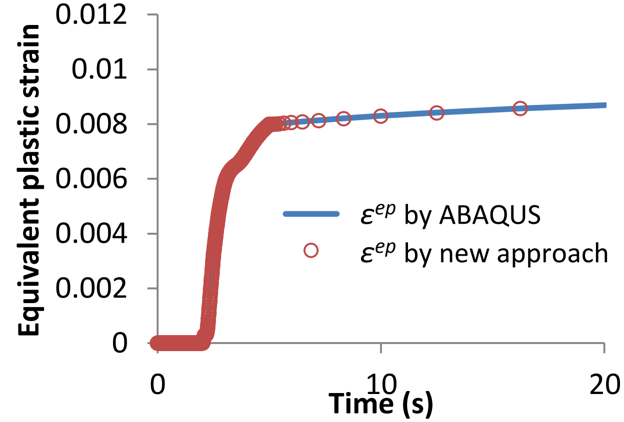
Beyond strain: real-time ***stress*** calculation

- The evolution of stress is directly correlated to certain weld attributes/defects (distortion, residual stress, etc.)
- A new algorithm has been integrated to calculate stress in real time based on in-situ strain and temperature measurements
  - Works for both elastic and plastic deformation
  - without the complication of numerical models
- The new algorithm is under patent application. Details are not disclosed herein

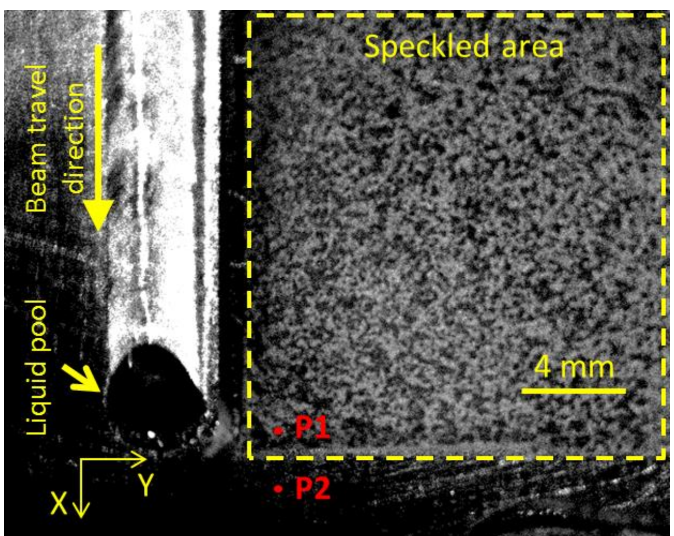
Stress calculation

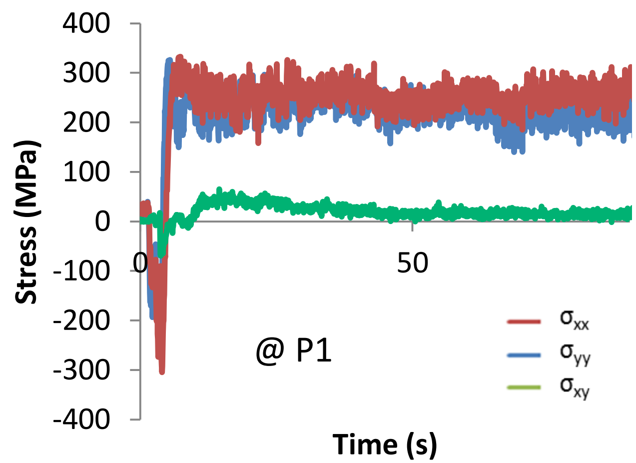
- Algorithm is validated by a simulated welding process





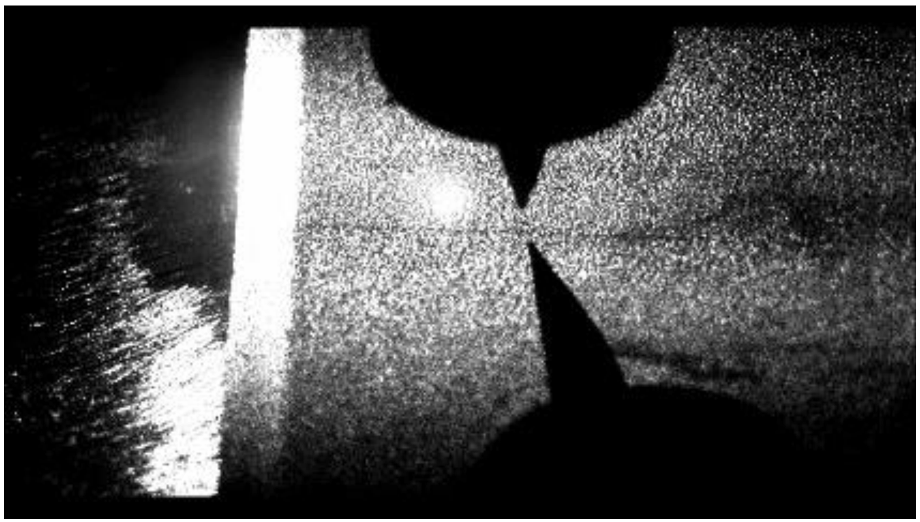
- Real-time stress monitoring during laser welding

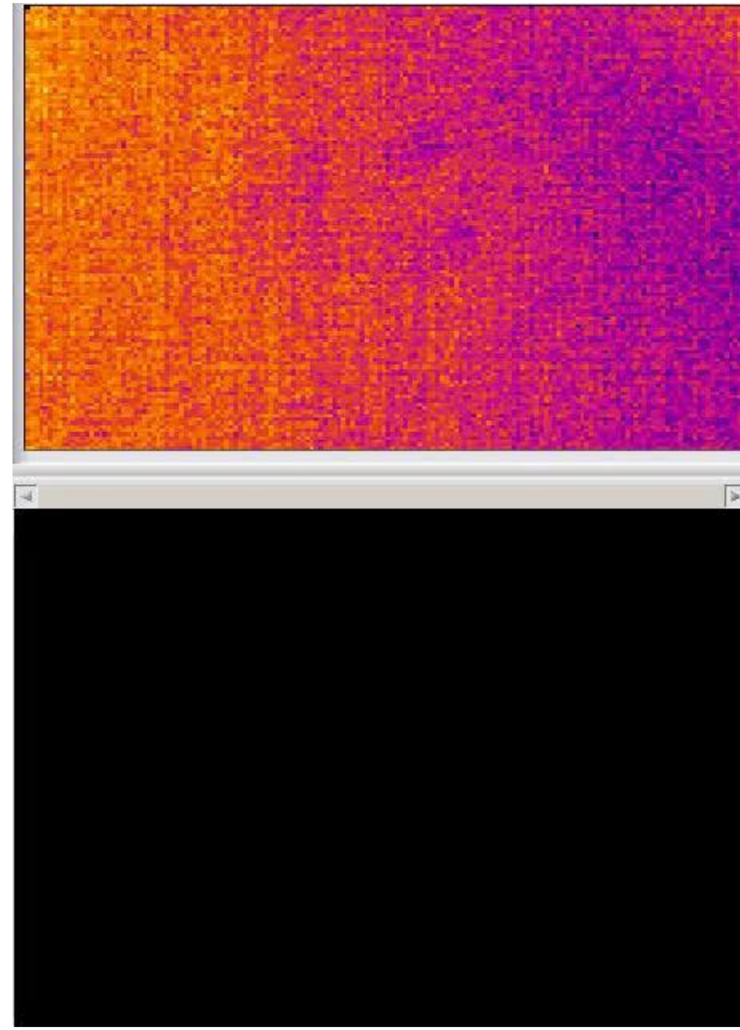




XRD measured residual stress @ P2:
σ_{xx}=221 MPa
σ_{yy}=324 MPa

Weld pool visualization





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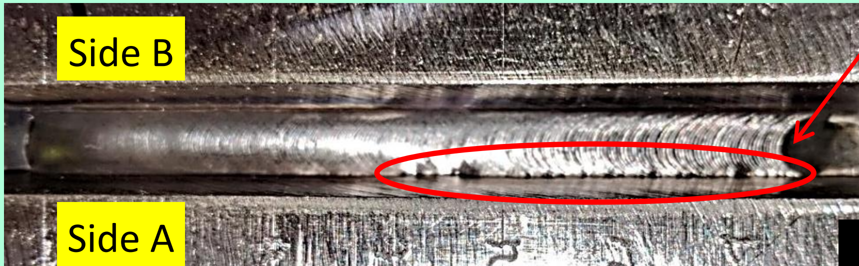
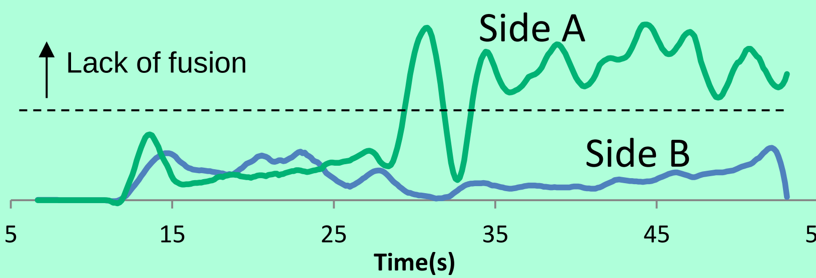
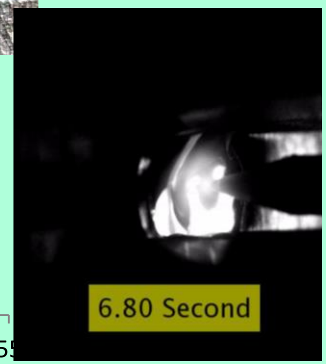
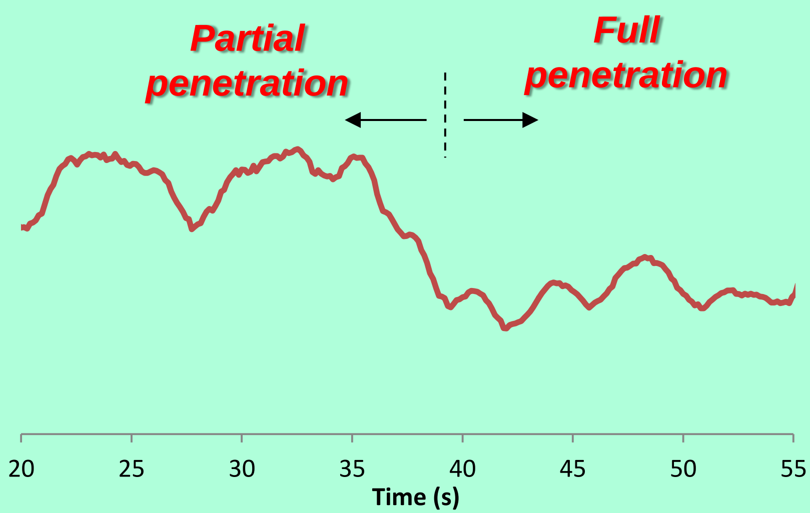
Defects detection

Lack of fusion

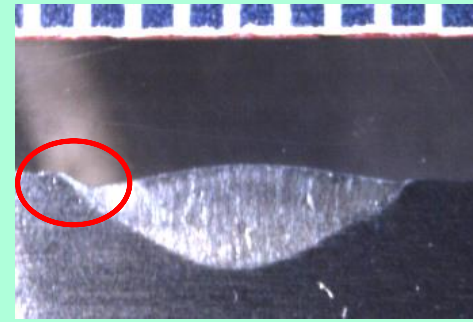


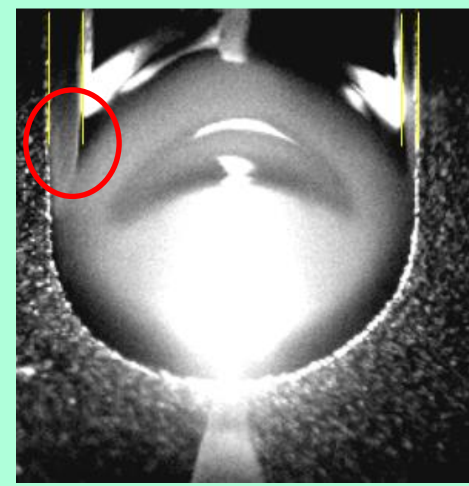




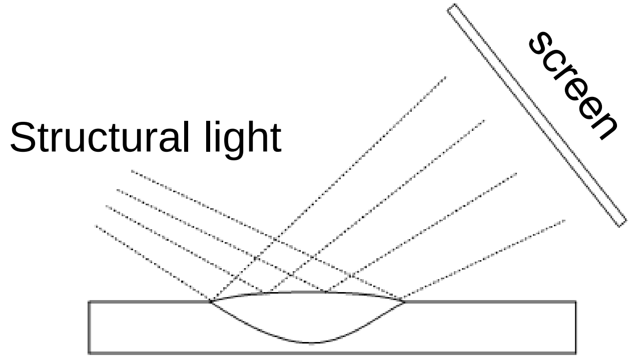


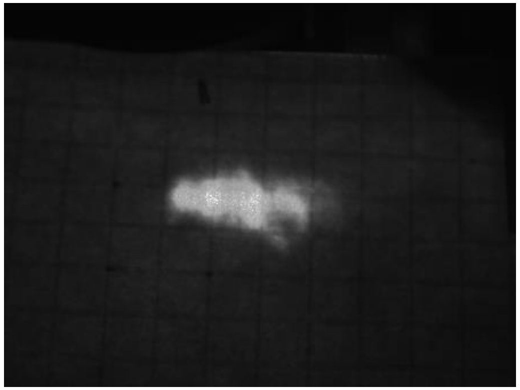
Undercutting



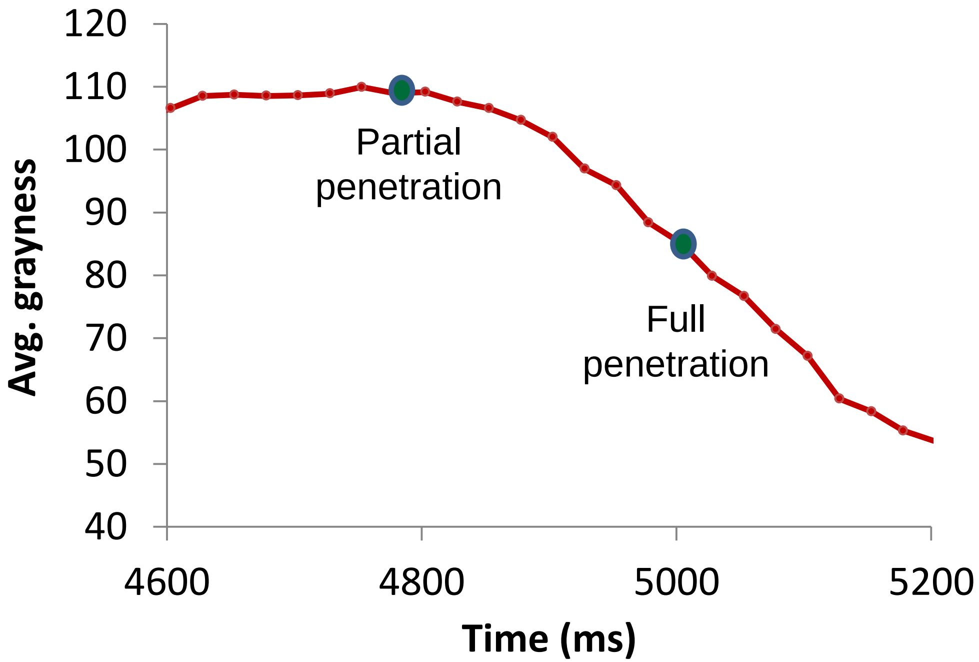


Penetration depth by light reflection





Average grayness varies due to the transition of surface vibration from partial to full penetration.



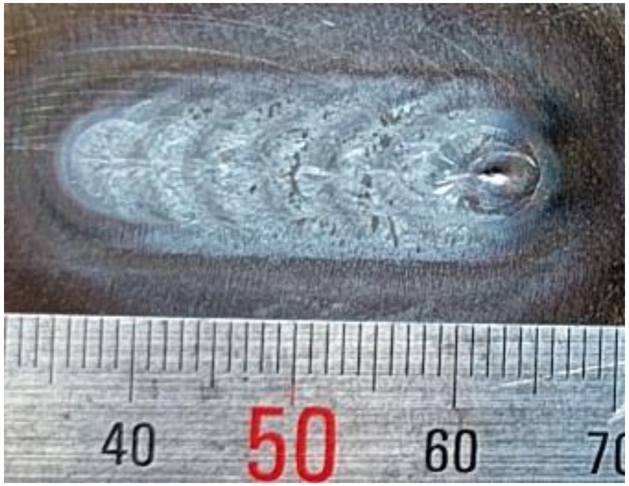
Weld pool dynamic model and full penetration control

$$Y(k+1) = 1.06 * Y(k) - 0.098 * u(k)$$

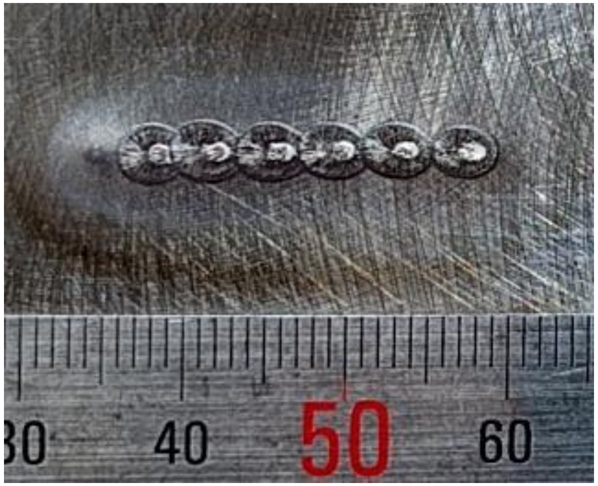
Y - image grayness

u - welding current

Front side



Back side



Summary

- A multi-optical sensing system was 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.
- Defects such as lack of fusion and undercutting were positively identified.
- Penetration depth was correlated to the grayness of the reflected structural light, based on which a full-penetration control algorithm was developed.

Next Steps

- Continue to refine and optimize the multi-optical system (hardware and software).
  – To get more reliable signals
  – To detect more types of weld defects
- Further develop control algorithms to minimize or avoid the formation of the detectable defects.
- Build a working prototype system for demonstration.

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Thank you!

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