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

Jian Chen, Roger Miller, Zhili Feng

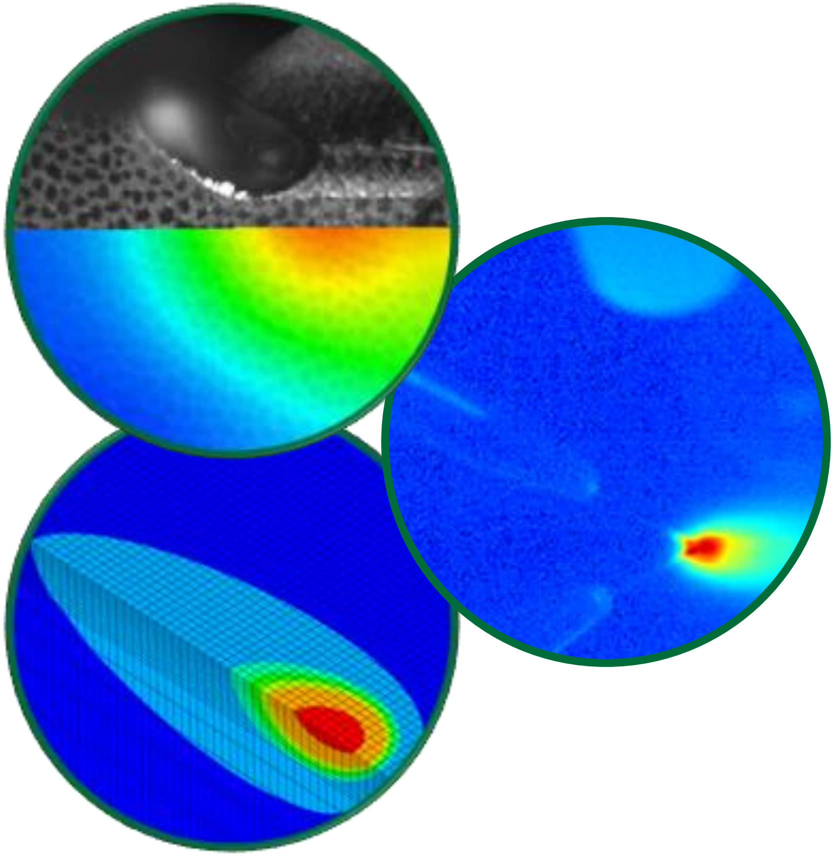
Oak Ridge National Laboratory

Yu-Ming Zhang

University of Kentucky

Robert Dana Couch

Electric Power Research Institute



U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

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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

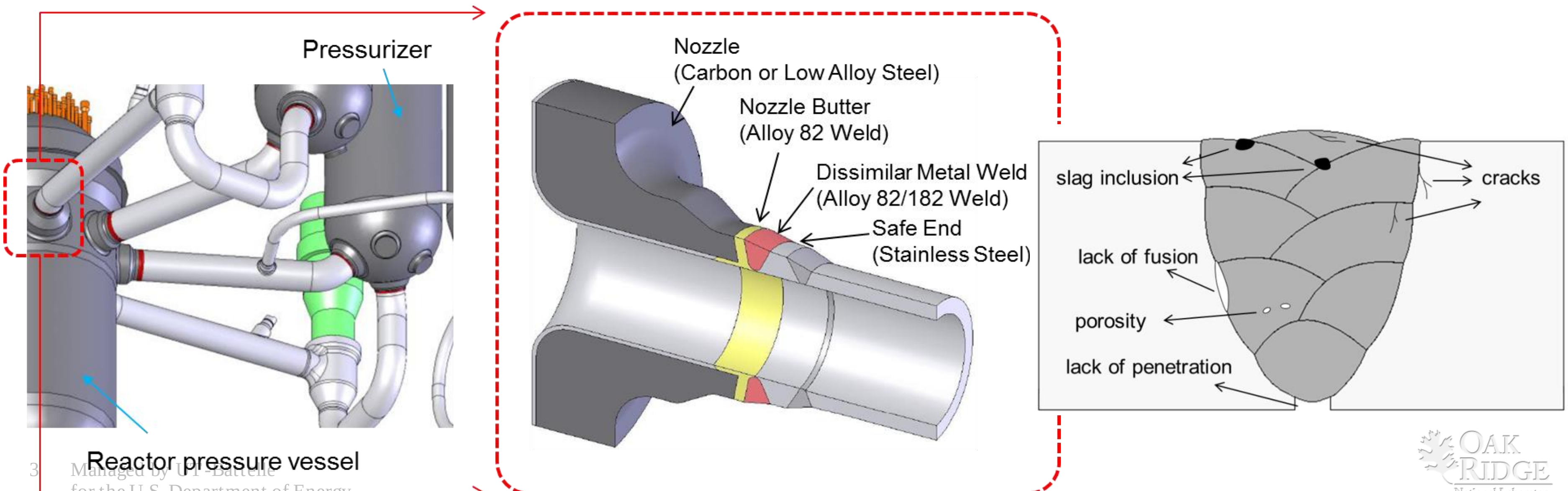
Issue Date: October 31, 2013

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

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

Introduction

- Welding is one of the most important manufacturing technologies for fabricating nuclear reactors.
- Eliminating weld defects is crucial due to the detrimental effects on the component integrity and safety.
- It is difficult to proactively adjust in real time the welding conditions to compensate unexpected variations in real-world welding causing the formation of welding defects.

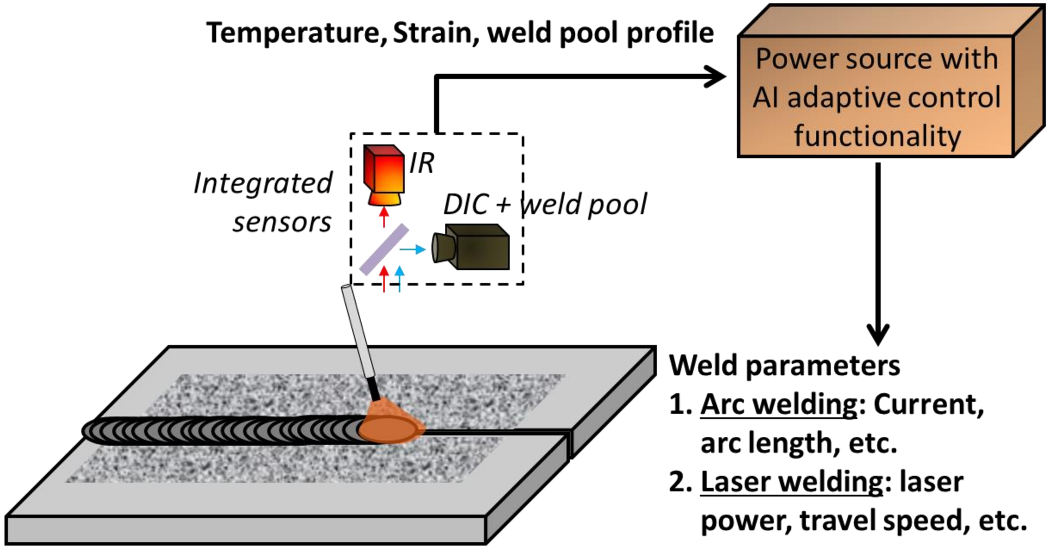


Objective

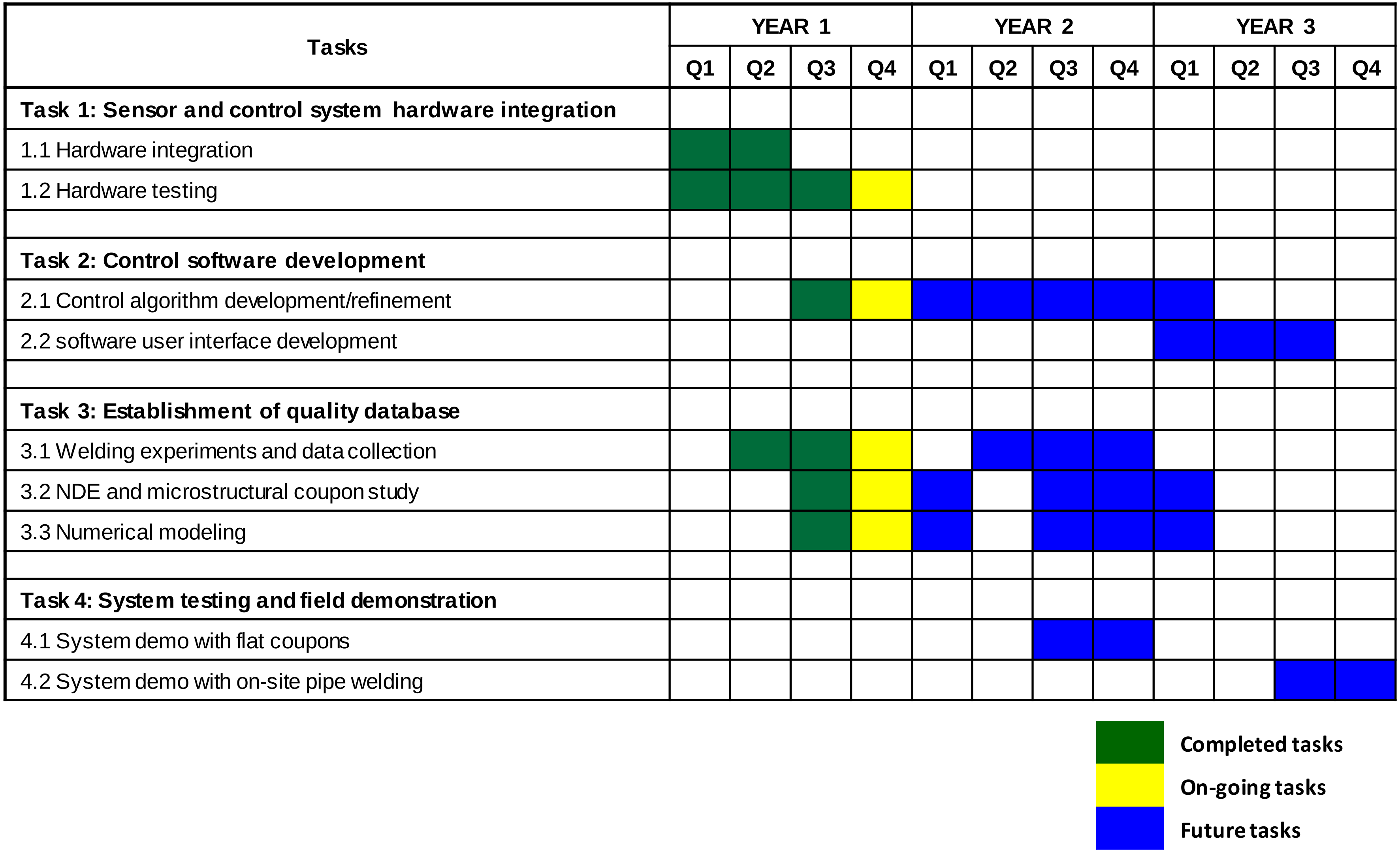
- This project aims at developing a novel close-looped adaptive welding quality control system based upon *multiple optical sensors*.
  - Enables real-time weld defect detection and adaptive adjustment to the welding process conditions to eliminate or minimize the formation of major weld defects.
  -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



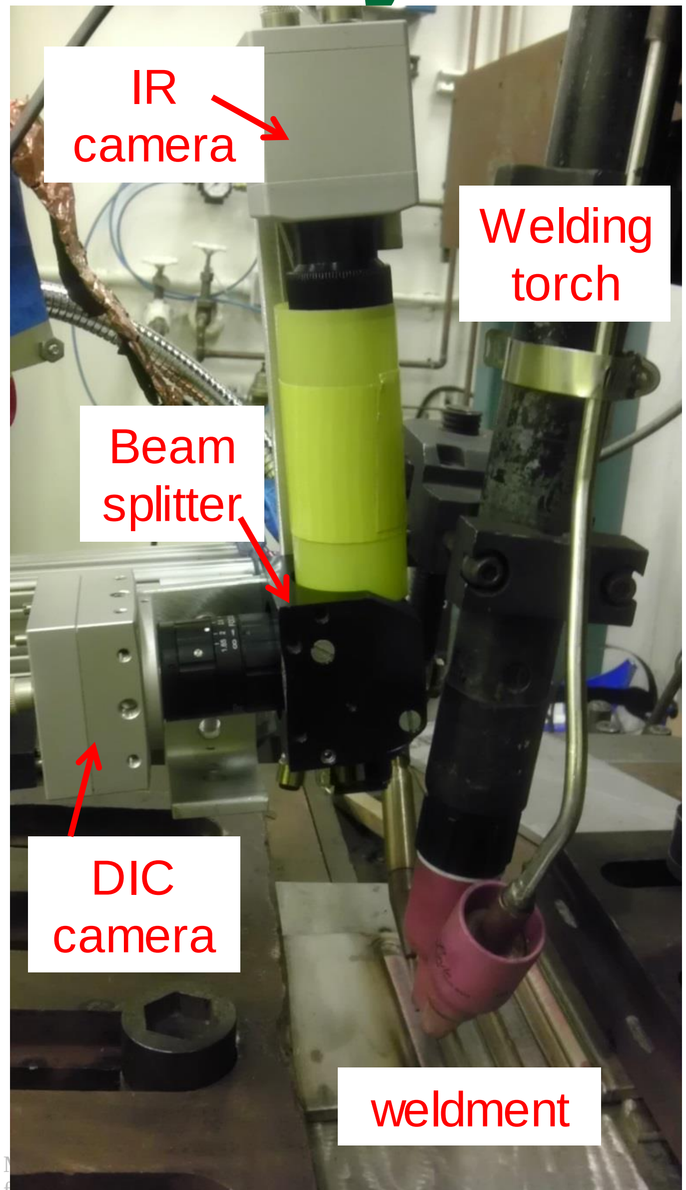
Milestones


Tasks
YEAR 1
YEAR 2
YEAR 3
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Task 1: Sensor and control system hardware integration
1.1 Hardware integration
1.2 Hardware testing
Task 2: Control software development
2.1 Control algorithm development/refinement
2.2 software user interface development
Task 3: Establishment of quality database
3.1 Welding experiments and data collection
3.2 NDE and microstructural coupon study
3.3 Numerical modeling
Task 4: System testing and field demonstration
4.1 System demo with flat coupons
4.2 System demo with on-site pipe welding
Completed tasks
On-going tasks
Future tasks

Current accomplishments

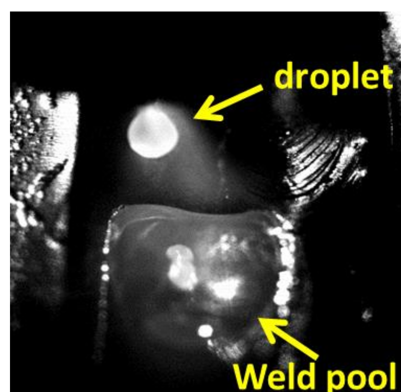
- Integrated a novel optical illumination and camera system for DIC strain measurement adjacent to weld pool and for weld pool visualization
  - Solved critical technical challenges encountered in high-temperature DIC strain measurement
  - The intense welding arc light can be effectively suppressed
  - Developed a special surface speckle preparation method that can be used at the temperature up to materials melting point
- Developed a high-accuracy DIC strain method by considering the influence of lens optical distortion
- Performed real-time liquid pool and DIC measurement for arc welding and laser welding

Laser-Based Optical Illumination and camera System Setup



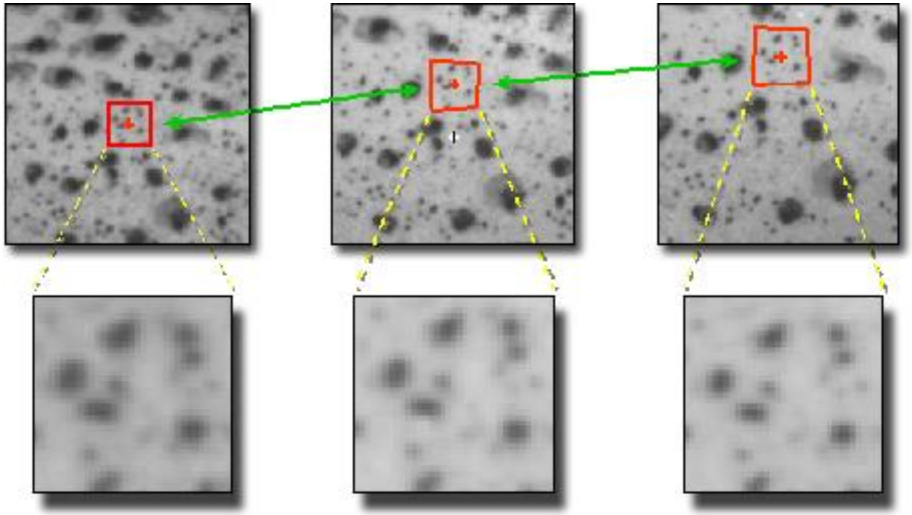
Through conventional camera (or high-speed camera) system

Through ORNL's new camera and laser-based optical system



Surface Strain measurement using Digital Image Correlation (DIC)

- DIC is a non-contact optical method.
- The surface is painted with a speckle (random) pattern.
- It tracks subsets of neighboring pixels (indicated in red in the figure) during deformation to calculate the displacements and strains.



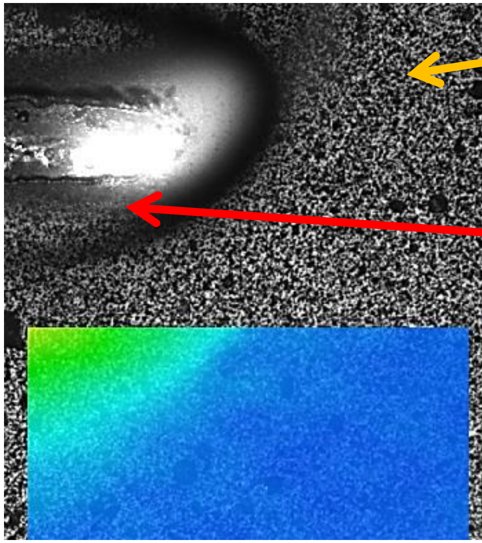
Conventional method to prepare speckle pattern

1. A layer of white paint is uniformly coated on the steel surface as the background.
2. Black paint is sprayed to form randomly distributed speckle patterns on the white background

http://www.correlatedsolutions.com/index.php/principle-of-digital-image-correlation

ORNL's unique high-temperature in-situ DIC

Conventional DIC measured from the reverse side

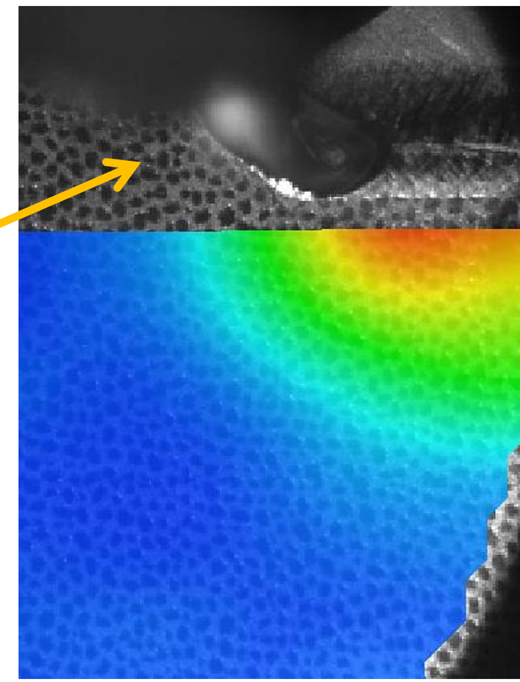


Regularly painted speckles

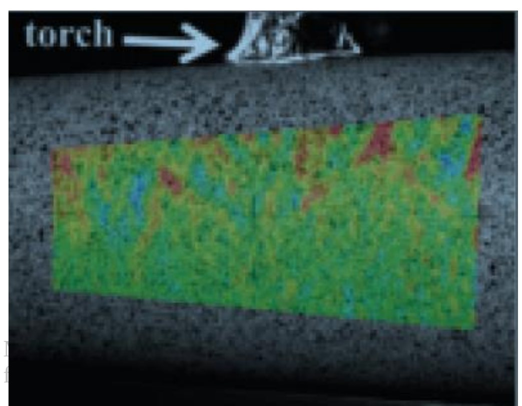
Disbonding and burning of the paint

ORNL's high-temperature DIC adjacent to weld pool

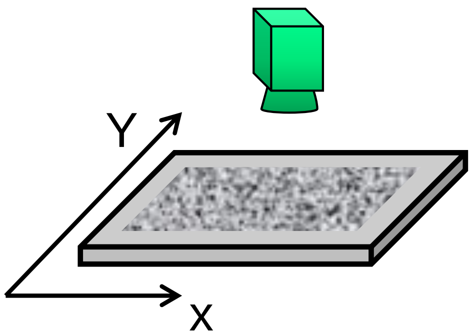
High-temperature speckles

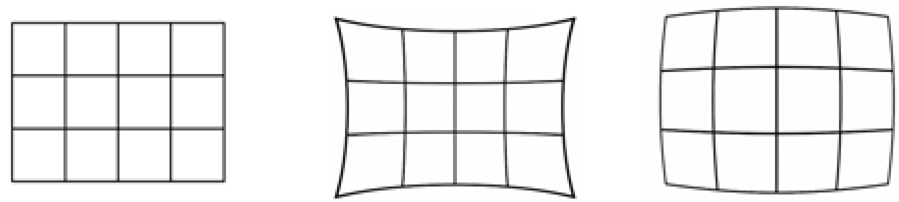


Conventional DIC measurement far away from welding torch

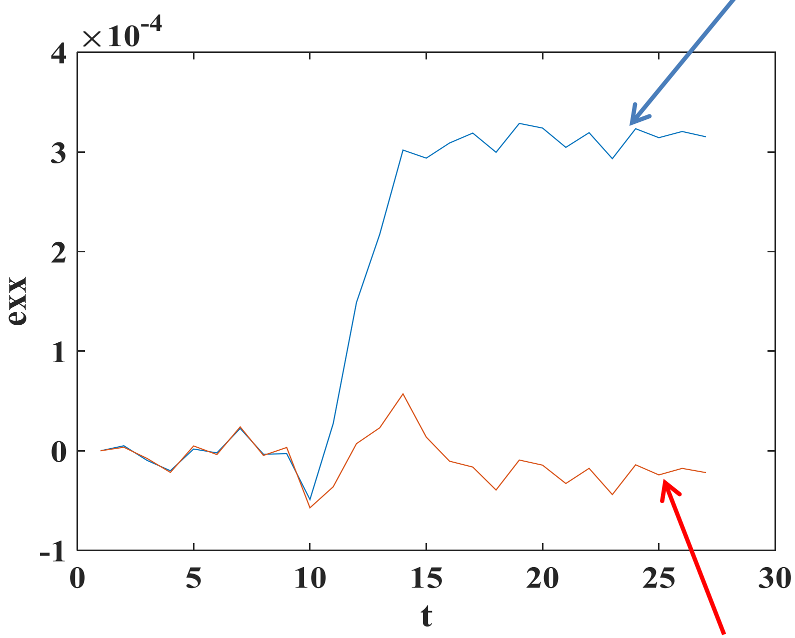


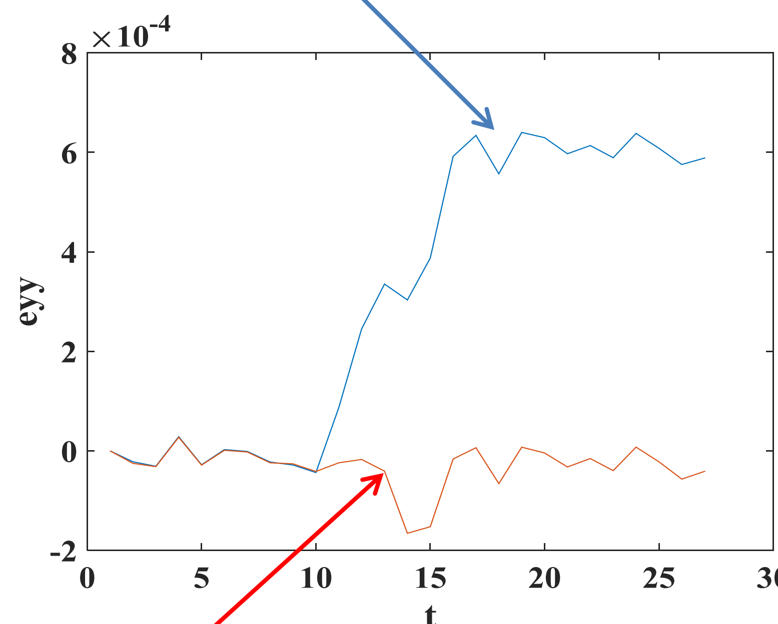
Influence of Lens Distortion on DIC Strain Measurement





Error due to lens distortion

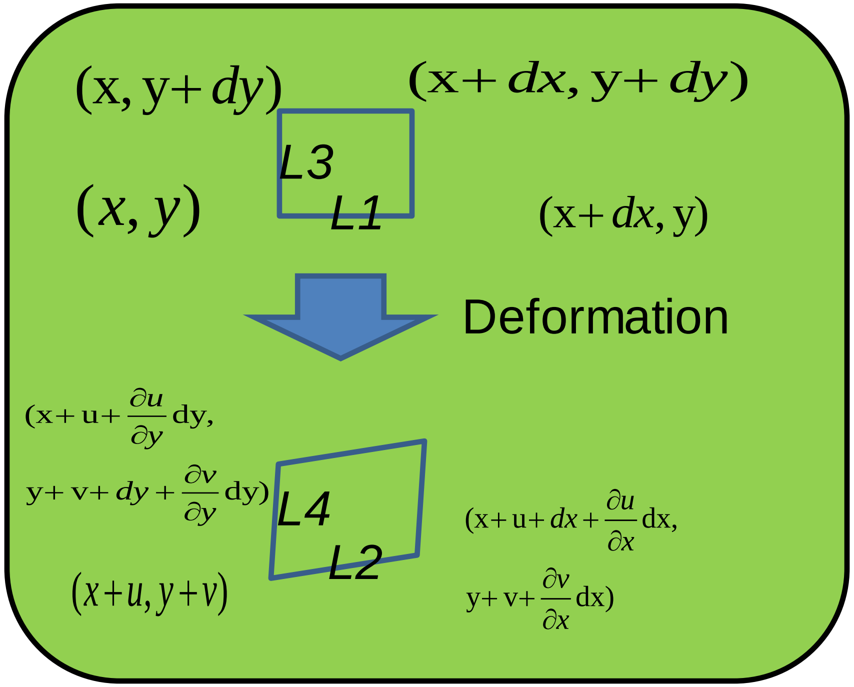




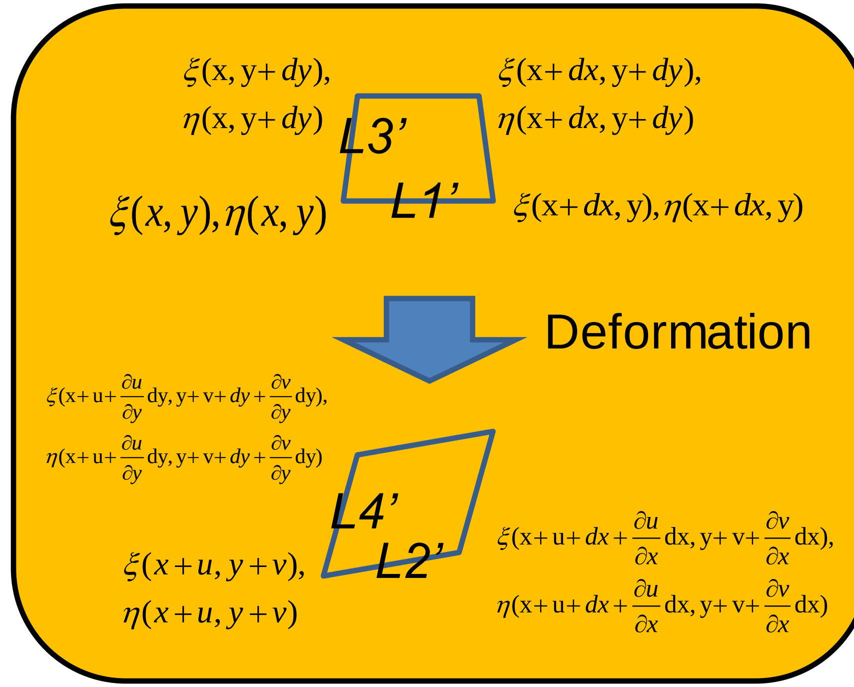
Corrected strain by ORNL's distortion-compensation algorithm and calibration procedure.

Optical Distortion Compensation Algorithm

Coordinates (x,y) in original DIC images (with distortion)



Coordinates (ξ,η) in non-distorted domain

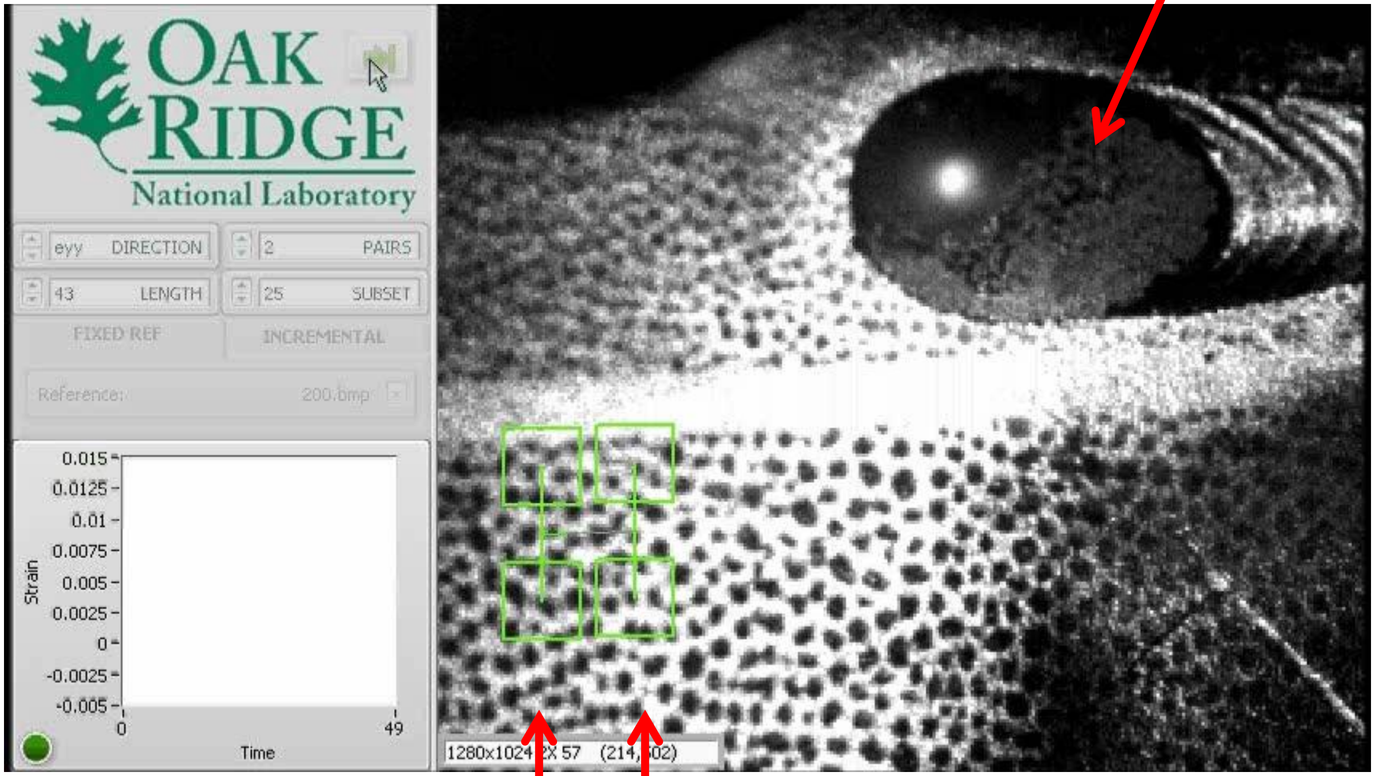


$$\varepsilon_{xx} = \frac{L2 - L1}{L1} = \frac{\partial u}{\partial x} \qquad \varepsilon_{yy} = \frac{L4 - L3}{L3} = \frac{\partial v}{\partial y}$$

$$\varepsilon_{\xi\xi} = \frac{L2' - L1'}{L1'} \qquad \varepsilon_{\eta\eta} = \frac{L4' - L3'}{L3'}$$

$$\varepsilon_{\xi\xi} = \frac{L_2'}{L_1'} - 1 = \frac{(1+\varepsilon_{xx}) \cdot \partial\xi(x+u, y+v) / \partial x}{\partial\xi(x, y) / \partial x} - 1 \qquad \varepsilon_{\eta\eta} = \frac{(1+\varepsilon_{yy}) \cdot \partial\eta(x+u, y+v) / \partial y}{\partial\eta(x, y) / \partial y} - 1$$

Real-time Strain and Weld Pool (bead-on-plate autogenous GTAW)



Weld pool

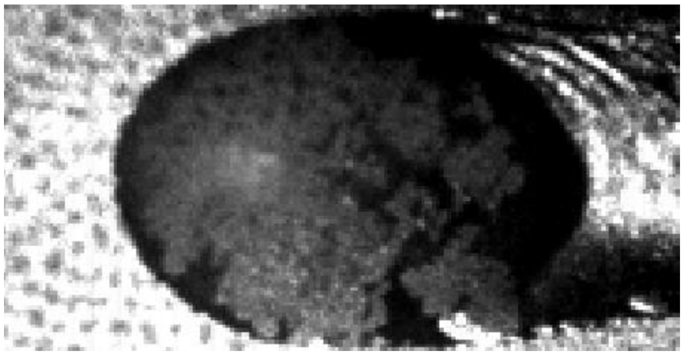
Two pairs of virtual strain gauges

(movie clip)

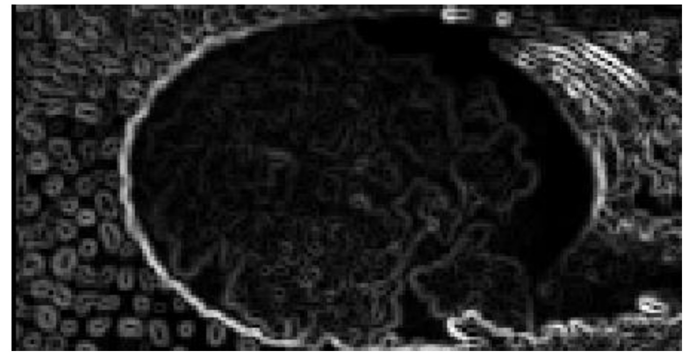
Weld Pool Image Processing

gPb function is written as a weighted sum of local and spectral signals:

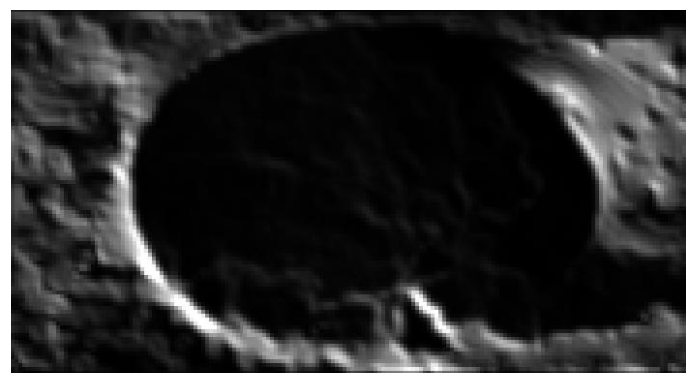
$$gPb(x, y, \theta) = \sum \sum \beta_{i,s} G_{i,\sigma(i,s)}(x, y, \theta) + \gamma \cdot sPb(x, y, \theta)$$



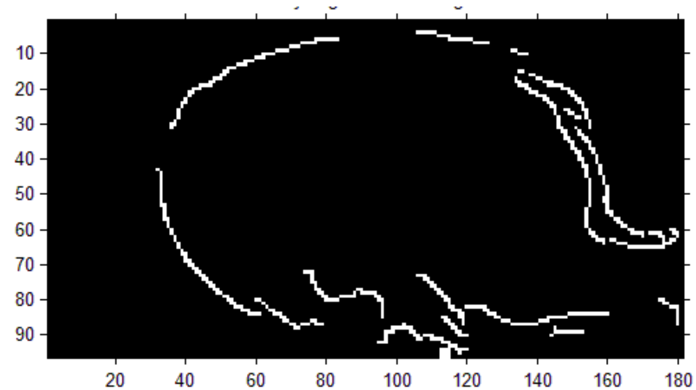
Original Image



Sobel filtered image



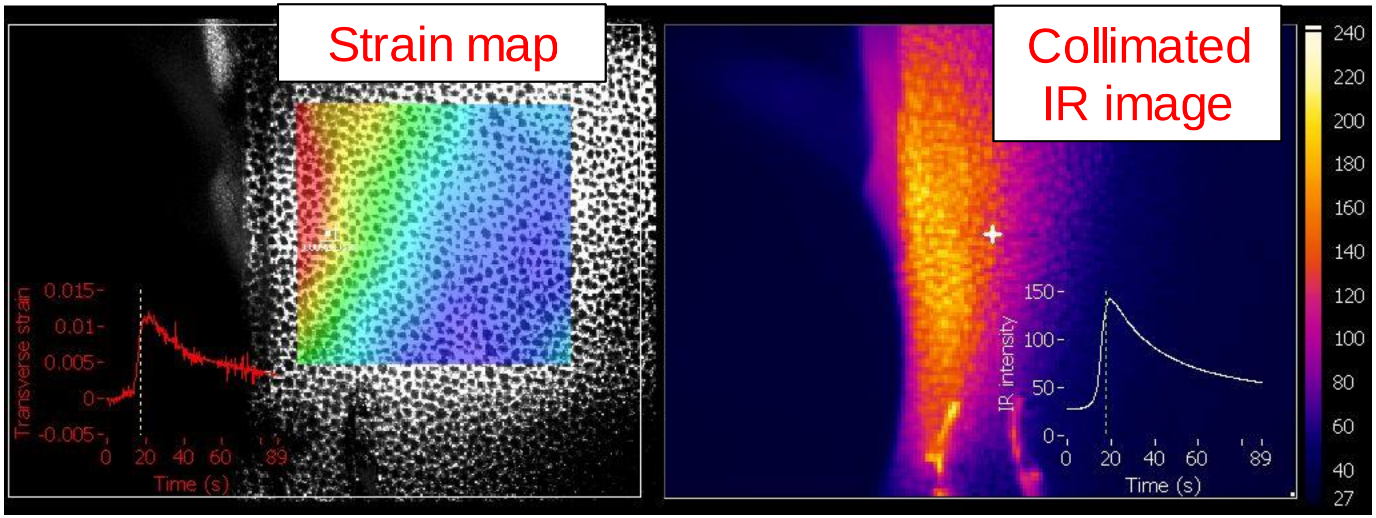
Global Pb algorithm filtered

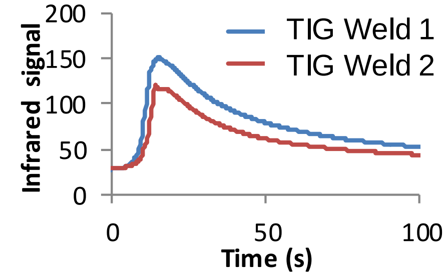


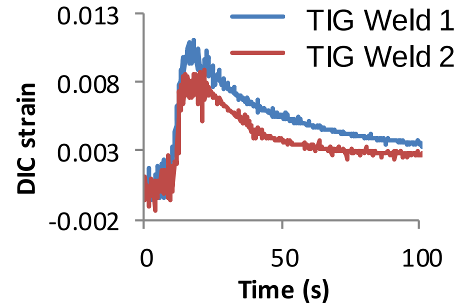
Edge detection

Strain and Thermal Evolution

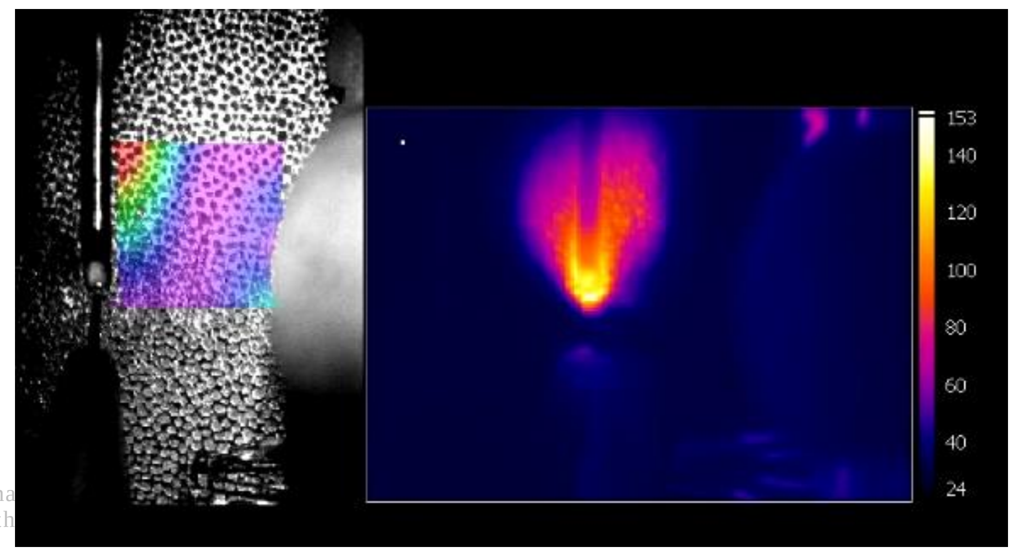
TIG welding

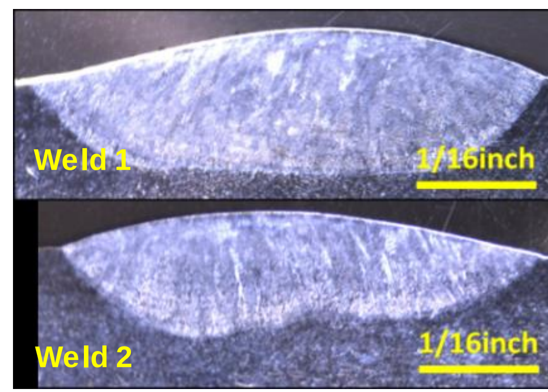




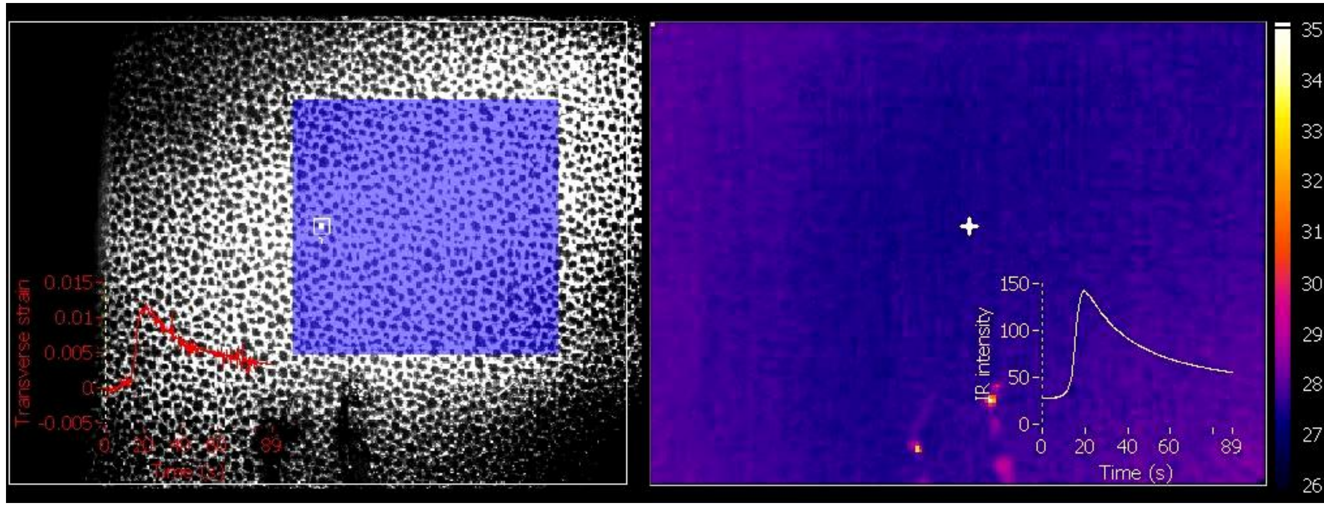


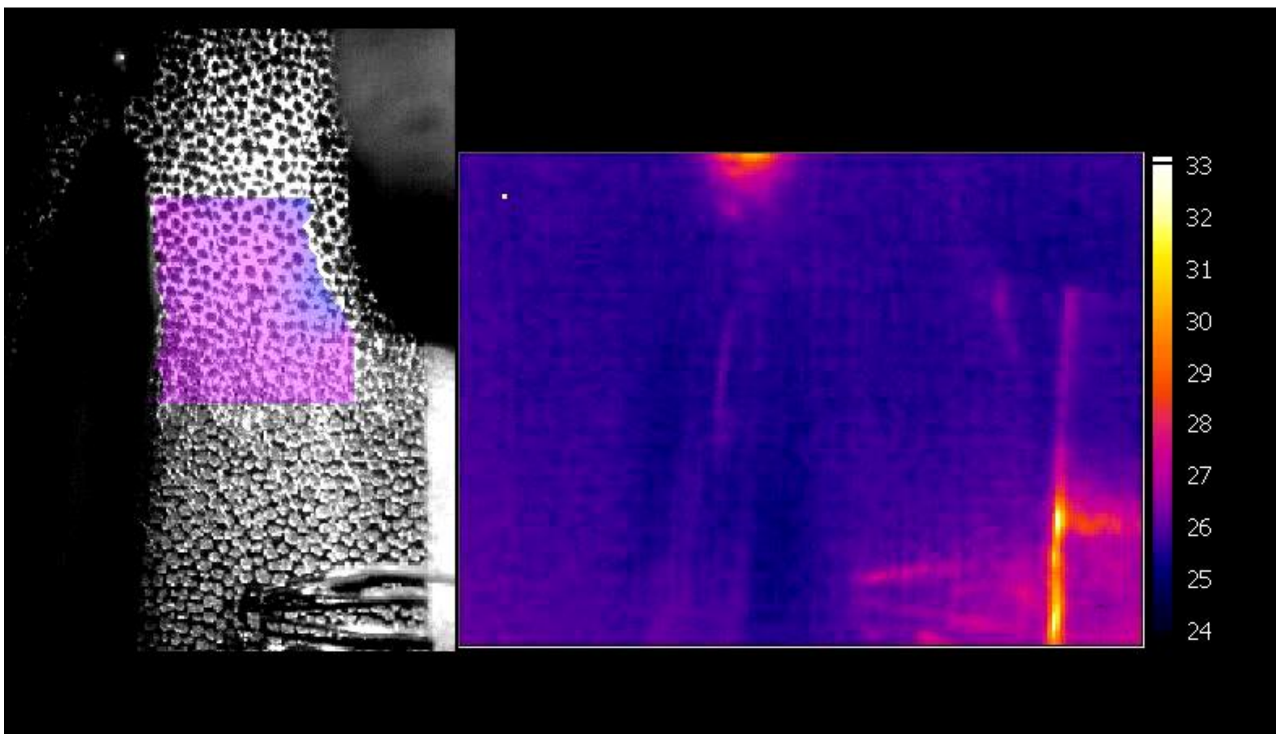
Laser welding





Movie clips


Transverse strain
0.015
0.01
0.005
0
-0.005
0 20 40 60 89
Time (s)
IR intensity
150
100
50
0
0 20 40 60 89
Time (s)
35
34
33
32
31
30
29
28
27
26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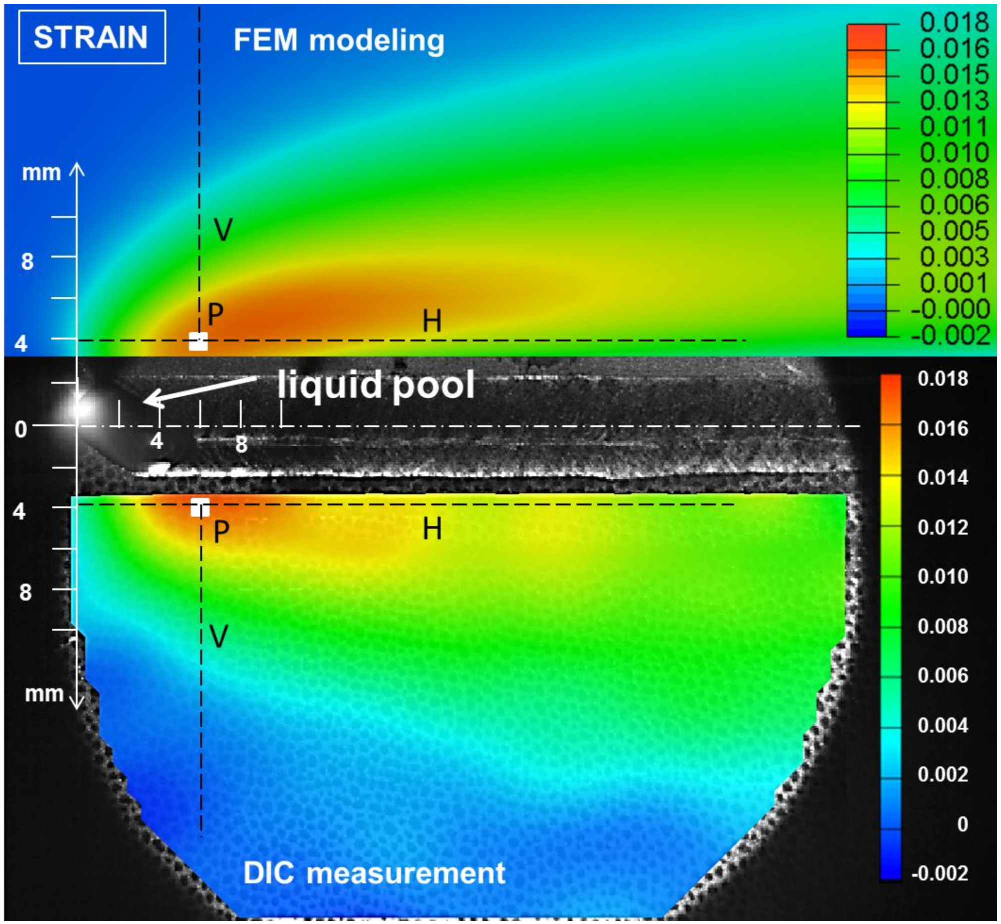
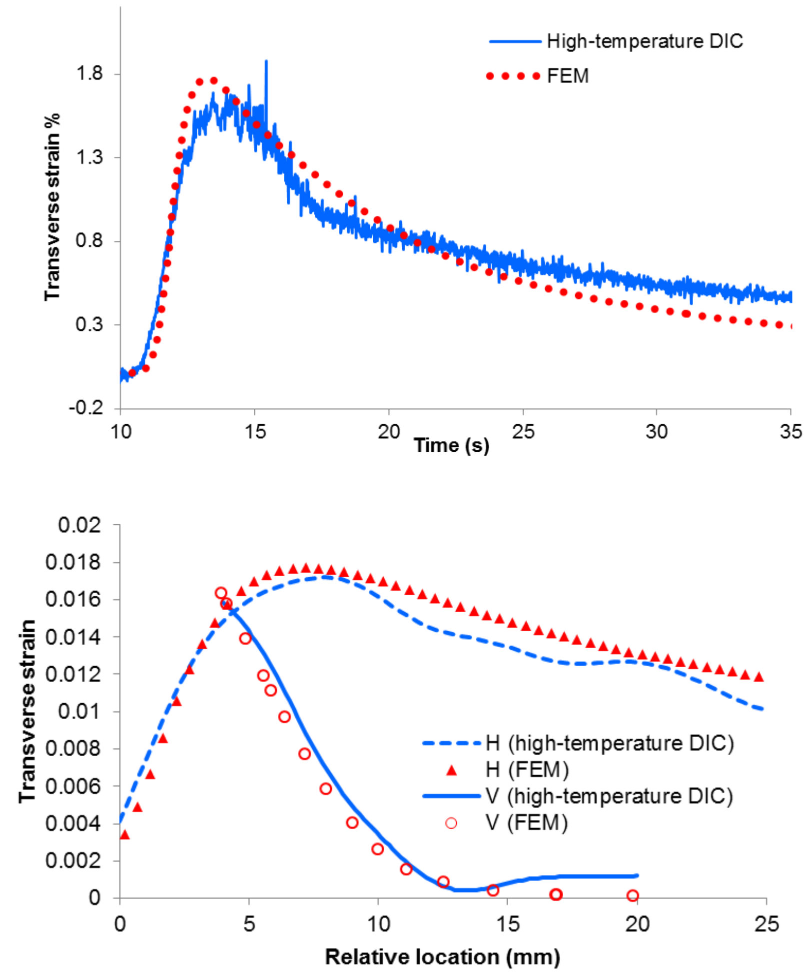
Numerical Modeling

1mm-thick Stainless steel 304





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

Summary

- Laser-based optical illumination and camera system effectively suppresses intense weld arc light
  - Ready for clearly visualizing weld pool and DIC images
- Novel high-temperature surface speckles survive at temperatures up to the melting point of the metal.
  - Capable of measuring DIC strain adjacent to weld fusion line
- Optical-distortion-compensation algorithm is developed and applied for high-accuracy DIC strain measurement.
- Current system setup can be used for various welding processes (arc welding and laser welding).

Next Steps

- Further refine the multi-optical system (hardware and software).
- Perform more welding experiments and numerical modeling to correlate measured signals to weld quality/defects.
- Develop welding control algorithms.

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Thank you!

Jian Chen
☎ (865) 241-4905
zcj@ornl.gov