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
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
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

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- **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.

ORNL’s unique high-temperature in-situ DIC

Conventional DIC measured from the reverse side

Regularly painted speckles

Disbonding and burning of the paint

High-temperature speckles

Conventional DIC measurement far away from welding torch

ORNL’s high-temperature DIC adjacent to weld pool
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)

\((x, y + dy)\) \[ \rightarrow \] \((x + dx, y + 2dy)\)

\((x, y)\) \[ \rightarrow \] \((x + dx, y)\)

\((x + u, y + v)\)

Deformation

\((x + u + \frac{\partial u}{\partial y} dy, y + v + \frac{\partial v}{\partial y} dy)\)

\((x + u + dx + \frac{\partial u}{\partial x} dx, y + v + \frac{\partial v}{\partial x} dx)\)

\(\varepsilon_{xx} = \frac{L2 - L1}{L1} = \frac{\partial u}{\partial x}\)

\(\varepsilon_{yy} = \frac{L4 - L3}{L3} = \frac{\partial v}{\partial y}\)

\(\varepsilon_{zz} = \frac{L2' - L1'}{L1'} = 1 - \frac{(1 + \varepsilon_{xx}) \cdot \partial \xi(x + u, y + v) / \partial x}{\partial \xi(x, y) / \partial x} - 1\)

Coordinates (\(\xi, \eta\)) in non-distorted domain

\((\xi(x, y + dy), \eta(x, y + dy))\) \[ \rightarrow \] \((\xi(x + dx, y + 2dy), \eta(x + dx, y + 2dy))\)

\((\xi(x, y), \eta(x, y))\) \[ \rightarrow \] \((\xi(x + dx, y), \eta(x + dx, y))\)

\((\xi(x + u, y + v), \eta(x + u, y + v))\)

\(\varepsilon_{\xi\xi} = \frac{L2' - L1'}{L1'}\)

\(\varepsilon_{\eta\eta} = \frac{L4' - L3'}{L3'}\)

\(\varepsilon_{\xi\eta} = \frac{(1 + \varepsilon_{yy}) \cdot \partial \eta(x + u, y + v) / \partial y}{\partial \eta(x, y) / \partial y} - 1\)
Real-time Strain and Weld Pool (bead-on-plate autogenous GTAW)

Two pairs of virtual strain gauges

Weld pool

(movie clip)
Weld Pool Image Processing

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

\[ gPb(x, y, \theta) = \sum \sum \beta_{i,s} G_{i,\sigma(i,s)}(x, y, \theta) + \gamma \cdot sPb(x, y, \theta) \]
Strain and Thermal Evolution

TIG welding

Strain map

Collimated IR image

Laser welding

Infrared signal

DIC strain

Time (s)

Weld 1

Weld 2

TIG Weld 1

TIG Weld 2

TIG welding

Laser welding

Weld 1

1/16 inch

Weld 2

1/16 inch
Movie clips
Numerical Modeling

1mm-thick Stainless steel 304

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