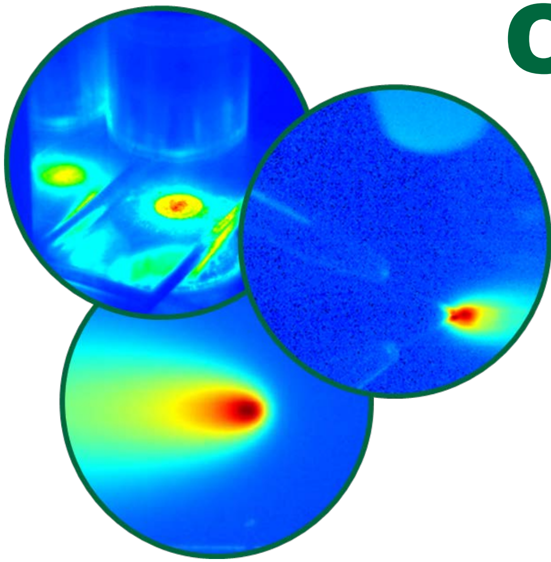
# On-Line Weld NDE with IR Thermography



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*Oak Ridge National Laboratory*

*June 16-20, 2014*

**Project ID # LM054**





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# Overview

## Timeline

- Start: June, 2008
- End:
  - Phase I: June, 2010
  - Phase II: Sept, 2014
- Percent complete:
  - Phase I: 100%
  - Phase II: 90%

## Budget

- Total project funding
  - DOE share: $1,410K
  - Industry in-kind share: $350K
- Funding for FY13: $0
- Funding for FY14: $110K

## Barriers

- Barriers addressed
  - Non-destructive techniques for the evaluation of the integrity of joints made with lightweight materials.

## Partners

- Interactions / collaborations
  - Chrysler, Ford, and GM
  - ArcelorMittal
  - AET Integration Inc.
  - AMD NDE Steering Committee
  - A/SP Joining Team
  - Cosma International - Eagle Bend Manufacturing
- Project lead
  - Oak Ridge National Laboratory

# Project Objective

- Develop a fully automated online non-destructive evaluation (NDE) technology for RSW quality monitoring based on infrared (IR) thermography that can be adopted reliably and cost-effectively in high-volume auto production environment for weld quality assessment
  - An expert system including hardware and software
  - Capable for both **post-weld** and **real-time** on-line weld quality inspection
  - **Weld quality database** covering wide range of weld configurations (materials, thickness, coatings) common in auto-body structures

# Relevance: Technology Gaps that This Project Addresses

- Today industry primarily relies on destructive testing of spot welds
  - Labor intensive, slow and expensive (rework and scraps)
  - Less effective for advanced high-strength steels, aluminum and other lightweight materials
- The destructive evaluation of weld quality is based on statistics and random sampling of small portion of as-welded auto-bodies.
  - Impossible to inspect 100% of the welds
  - No efficient method to immediately send feedback to the production lines

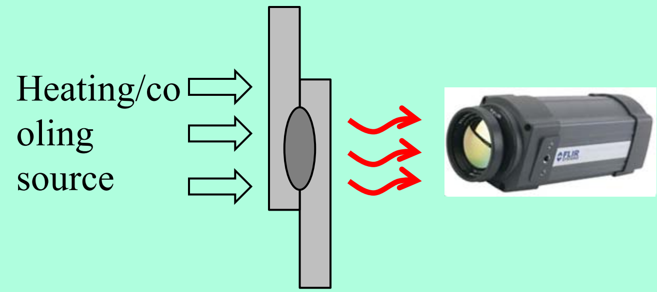
# Project Milestones

| Month/Year | Milestone or Go/No-Go Decision |
|---|---|
| Jun-10 | Demonstrate feasibility – detection of major weld quality Phase I Go/No-Go Decision (**Passed**) |
| Nov-10 | Produce additional spot welds with different weld quality attributes for different steels, coating, thickness and stack-up configurations (**Completed**) |
| Feb-11 | Modeling of post-mortem inspection to identify quantifiable IR thermal signatures and refine/optimize heating device and procedure (**Completed**) |
| Apr-11 | Confirm the capability of low-cost IR camera (**Completed**) |
| Dec-11 | Develop IR image acquisition module and analysis algorithms module for both real-time and post-weld inspection (**Completed**) |
| June-12 | Development of expert software and prototype system including image acquisition, user interface, ability to adaptive learning and decision making (**Completed**) |
| Dec-12 | Evaluate and improve system accuracy (**Completed** with expanded sets of welds) |
| June-13 | Prototype demonstration, beta test and improvements (**Completed**) |
| Sept-14 | Field tests on OEM/supplier assembly production lines (On-going) |
| Sept-14 | Technology transfer (On-going) |

# Principles and Past Attempts on IR Thermography based Weld Inspection

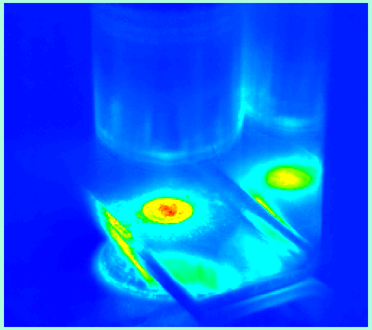
- Potential advantages of IR:
  - Non-contact, Non-intrusive,
- Past post-weld NDE work mostly limited to laboratory trials
  - Flash lamp heating source: pulsed heating in milli-seconds
  - Minimal surface temperature change (low signal-to-noise ratio)
    - Highly sensitive to surface condition and environment interference
    - Requiring painting of weld surface – impractical in auto production line
- Real-time NDE
  - Utilize the heat during welding
  - New innovation – no successful attempts in the past

*Post-weld*




Unknown & non-uniform surface condition (usually low emissivity)

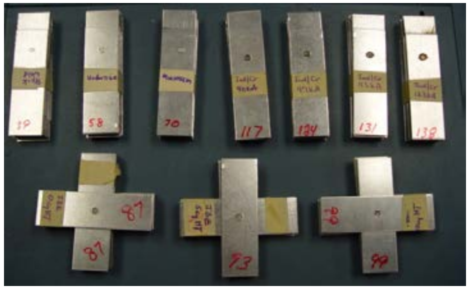
*Real-time*



Utilize the heat generated during welding

# Approach

- A large set of weld coupons and actual welded auto parts with controlled weld quality/defects attributes
  - Various welding conditions
  - Effects of electrode wear
  - Effects of part fit-up tolerance
- Destructive characterizations to determine weld quality and defects.
- Increasing signal-to-noise ratio in post-weld
- Novel IR image/signal analysis algorithms for both post-weld and real-time inspection
  - Provide quantitative measure of the quality and the level of defect (if any) of spot welds
  - No need for special surface treatment (as-welded surface condition
- Development of prototype system (software and hardware)
- Beta/field testing in production environment
- Tech transfer and commercialization



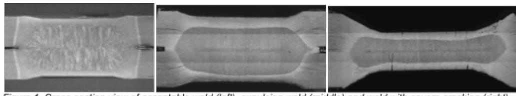



*Figure 1. Cross-section view of acceptable weld (left), expulsion weld (middle) and weld with severe cracking (right).*

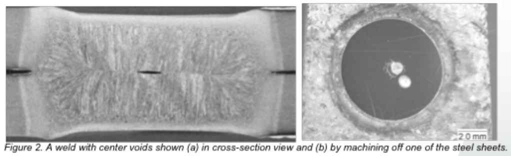



*Figure 2. A weld with center voids shown (a) in cross-section view and (b) by machining off one of the steel sheets.*

# Accomplishment

- Successfully developed an IR-based spot weld NDE inspection prototype system capable for both real-time and post-weld on-line applications.
- Reliable detection of weld size, cold weld, and surface indents with sufficient accuracy for various combination of materials, thickness, stack-up configuration, surface coating conditions and welding conditions.

| Application | Measurable weld attributes | Inspection time |
|---|---|---|
| Real-time | • Nugget size and weld shape<br>• Cold/stick weld defects<br>• Explusion | 1.5~3s |
| Post-weld | • Nugget size<br>• Cold/stick weld defects<br>• Weld thickness/indentation | ~3s |



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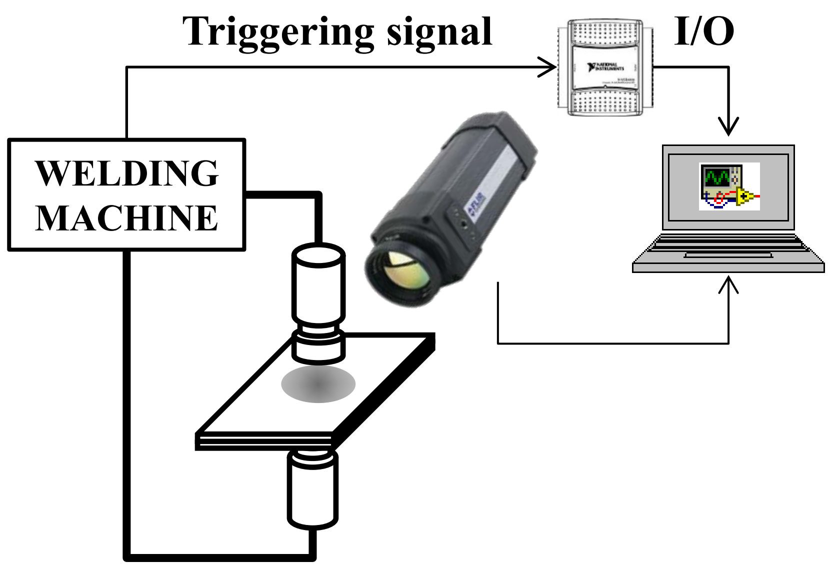
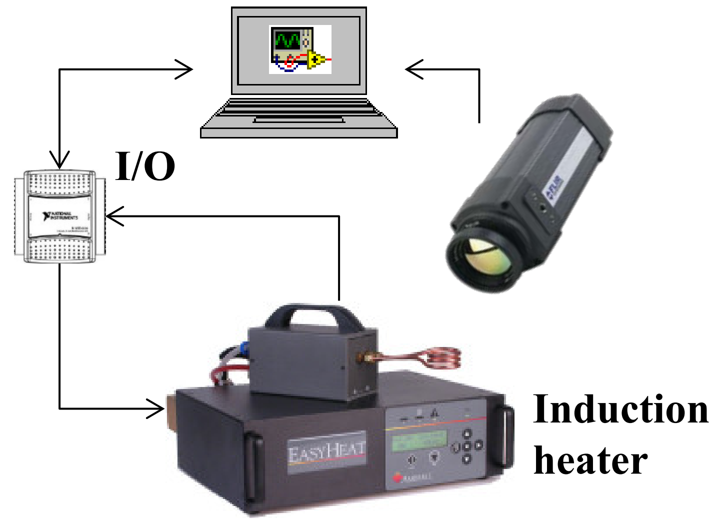
# Accomplishment: Automated Prototype System

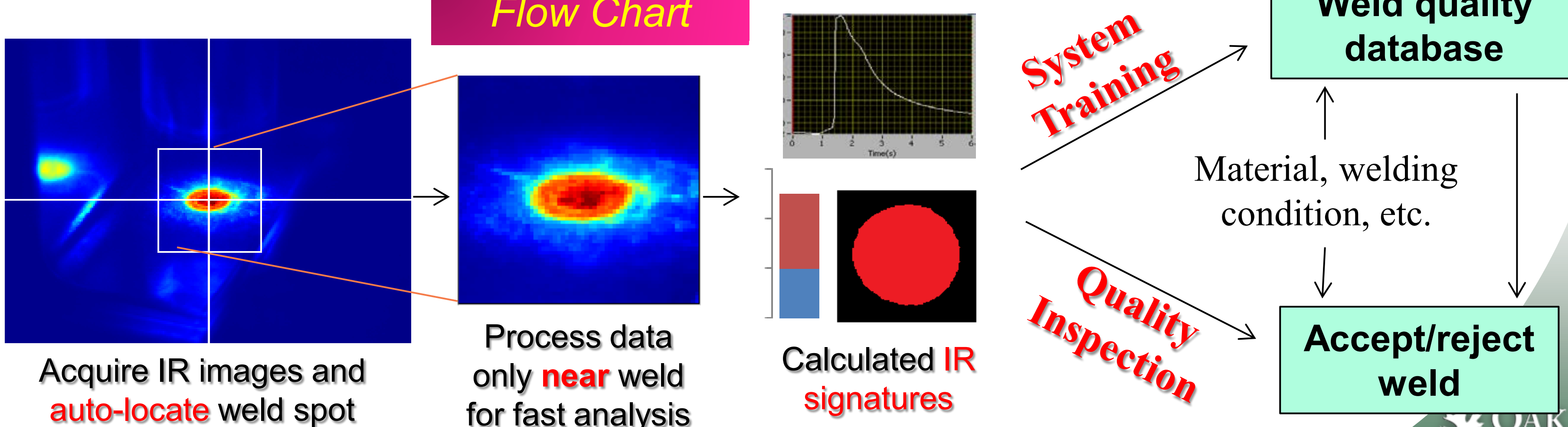
## Real-time



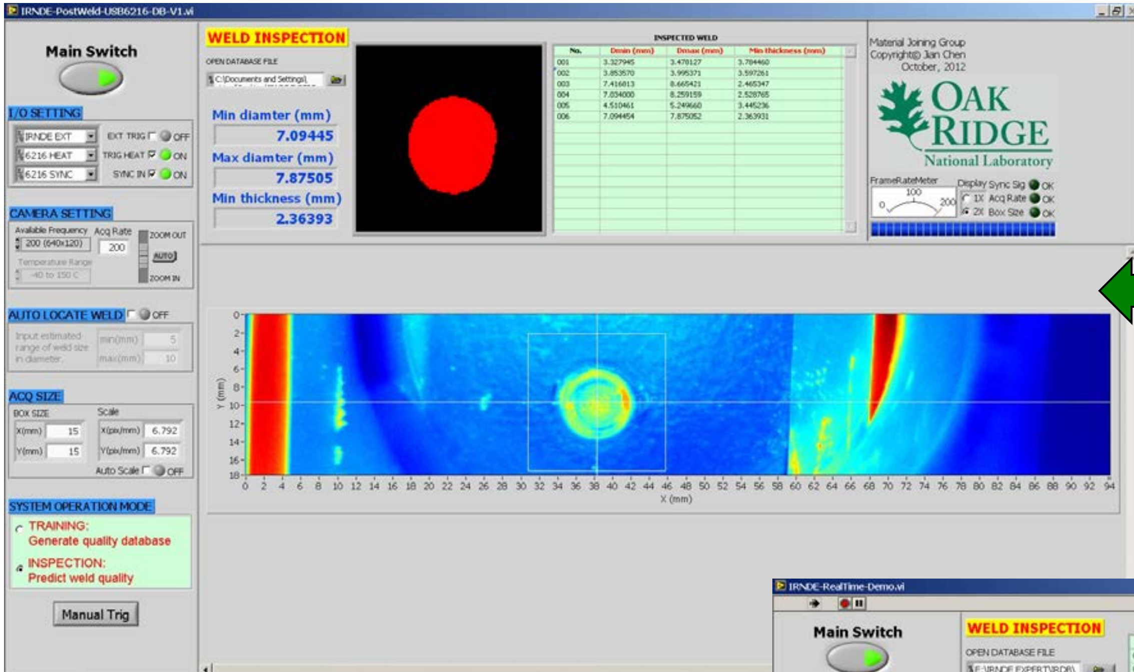

## Post-weld




## Flow Chart

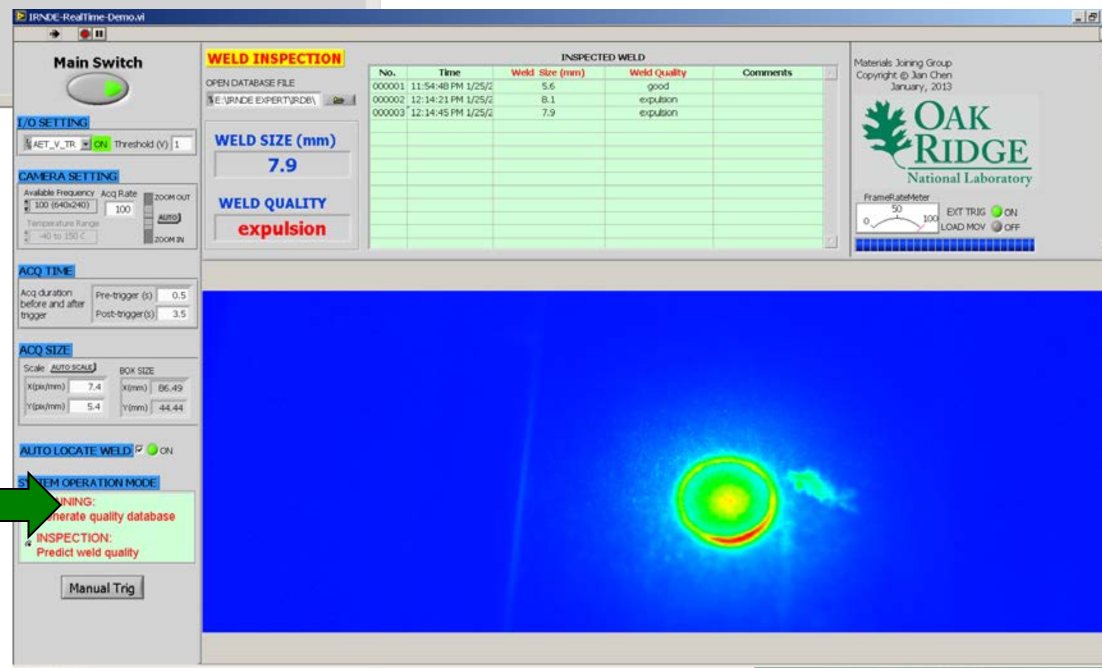


# Accomplishment: Weld Quality Analysis Software




*Post-weld*

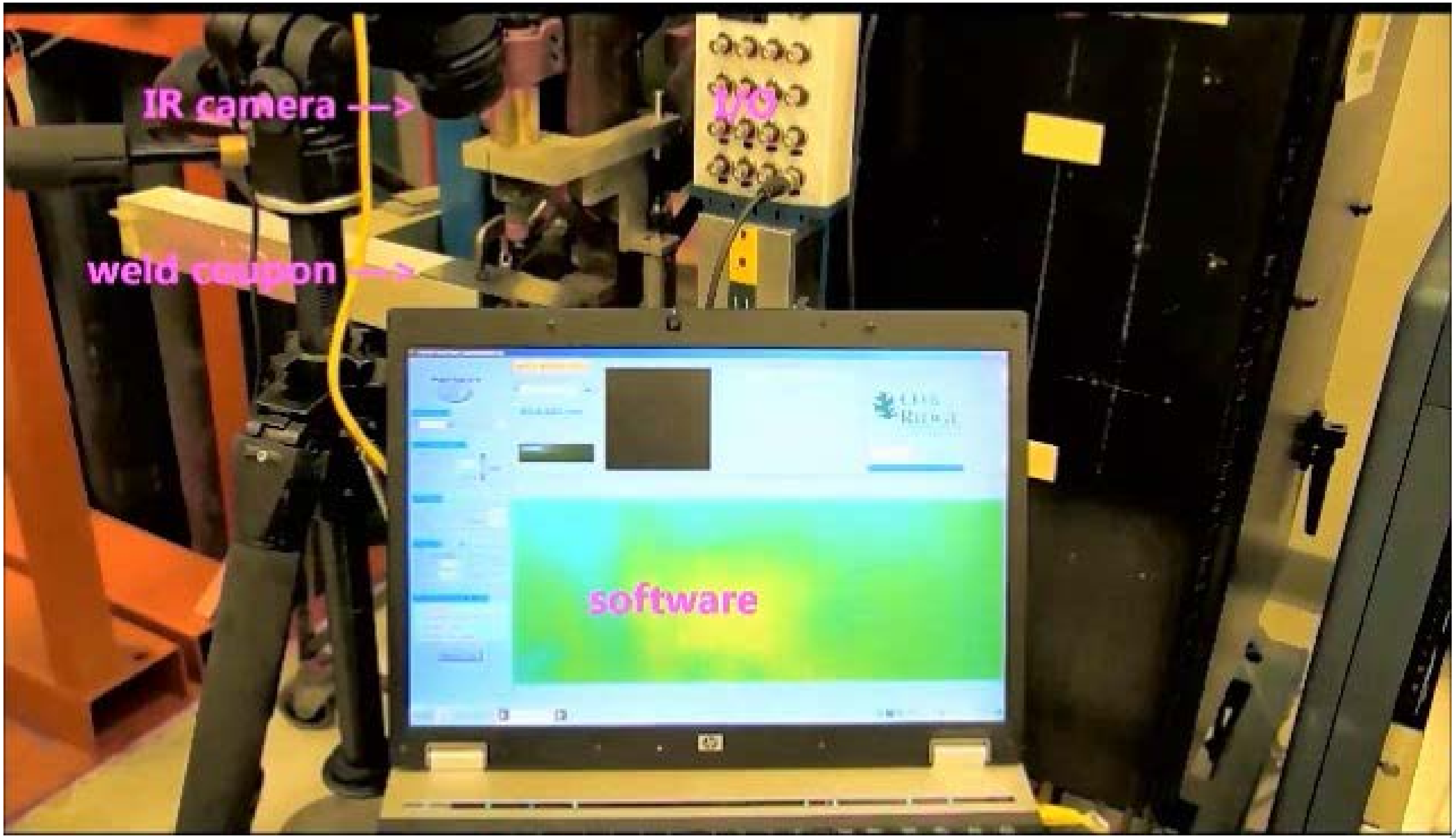
- Measurable weld attributes
  - Nugget size and shape
  - Cold/stick weld defect
  - Weld thickness/indentation



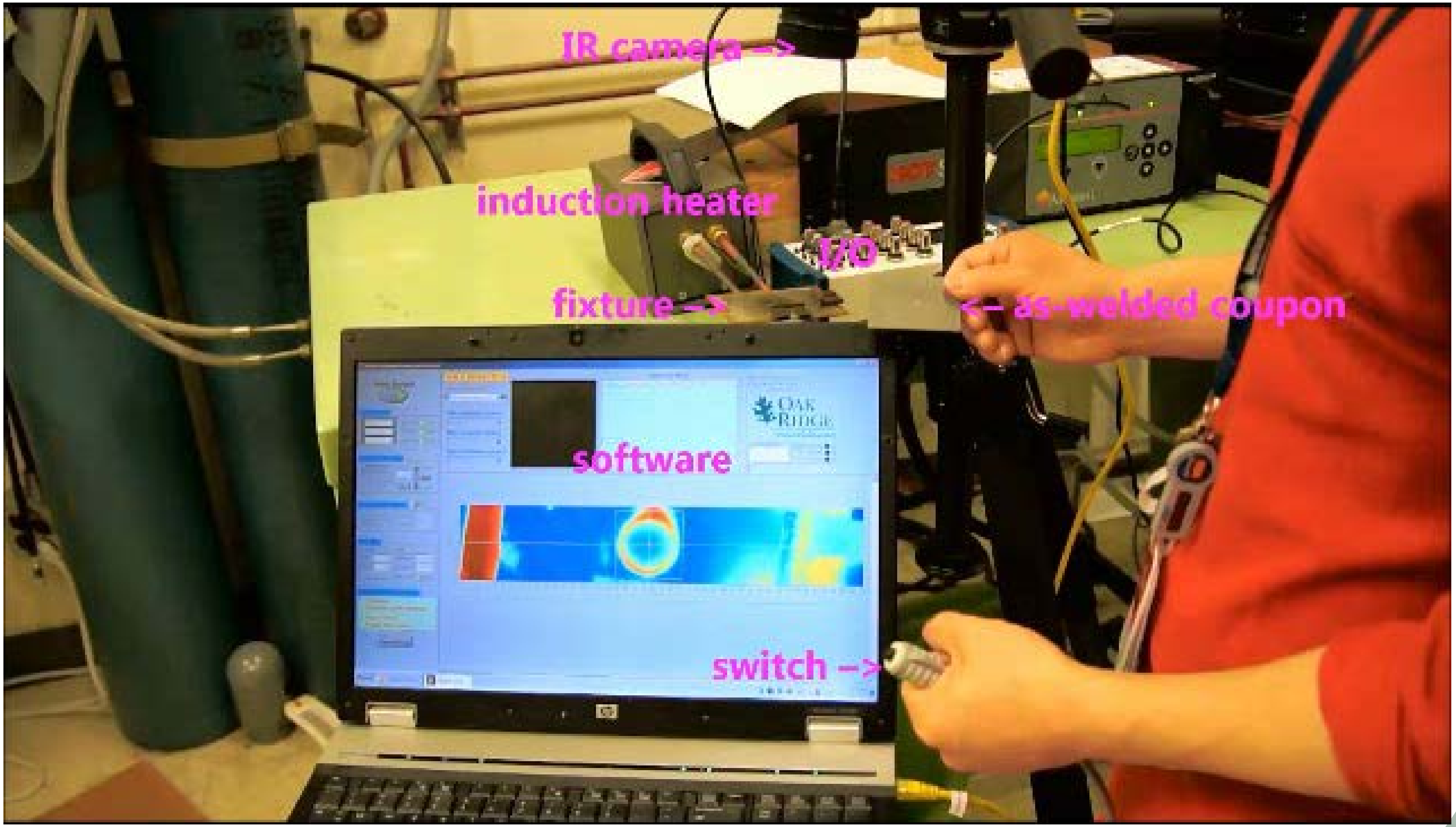

*Real-time*

- Measurable weld attributes
  - Nugget size
  - Cold/stick weld defect
  - Expulsion

# Real-time NDE System Operation Demonstration (Movie clip)



# Post-weld NDE System Operation Demonstration (Movie clip)



# Accomplishment: Prototype system tested using a large matrix of AHSS welds

| **2T stack**: Steel Grades, Coating, Thickness |
| --- |
| • Boron bare 1.0mm<br>• Boron bare 1.0mm |
| • Boron aluminized 1.0mm<br>• Boron aluminized 1.0mm |
| • Boron bare 1.0mm<br>• Boron aluminized 1.0mm |
| • Boron bare 1.0mm<br>• Boron bare 2.0mm |
| • Boron aluminized 1.0mm<br>• Boron aluminized 2.0mm |
| • Boron aluminized 1.0mm<br>• Boron bare 2.0mm |
| • Boron bare 2.0mm<br>• Boron bare 2.0mm |
| • Boron aluminized 2.0mm<br>• Boron aluminized 2.0mm |
| • Boron bare 2.0mm<br>• Boron aluminized 2.0mm |

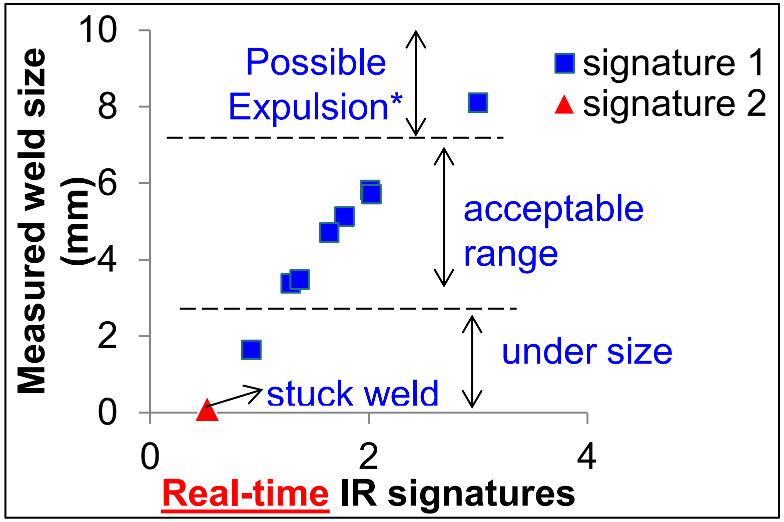
| **2T stack:** Steel Grades, Coating, Thickness |
| --- |
| • DP590 galvanized 1.2mm<br>• DP590 galvanized 1.2mm |
| • DP590 galvanized 1.8mm<br>• DP590 galvanized 1.8mm |
| • DP600 HDG 1.0mm<br>• DP600 HDG 1.0mm |
| • DP600 bare 1.0mm<br>• DP600 bare 1.0mm |
| • DP600 HDG 1.0mm<br>• DP600 HDG 2.0mm |
| • DP600 bare 2.0mm<br>• DP600 HDG 2.0mm |
| • DP980 cold rolled 1.2mm<br>• DP980 cold rolled 1.2mm |
| • DP980 cold rolled 1.2mm<br>• DP980 cold rolled 2.0mm |
| • DP980 cold rolled 2.0mm<br>• DP980 cold rolled 2.0mm |

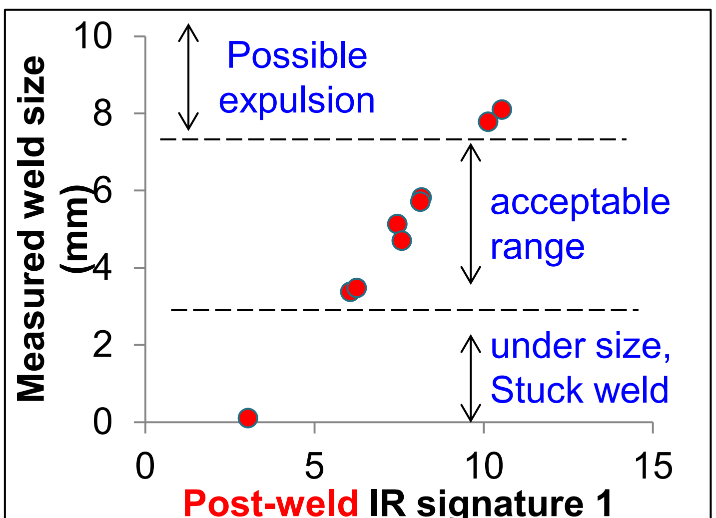
| **3T stack:** Steel Grades, Coating, Thickness |
| --- |
| • Boron bare 1.0mm<br>• Boron bare 2.0mm<br>• Boron bare 1.0mm |
| • Boron aluminized 1.0mm<br>• Boron aluminized 2.0mm<br>• Boron aluminized 1.0mm |
| • Boron bare 1.0mm<br>• Boron aluminized 2.0mm<br>• Boron bare 1.0mm |
| • Boron aluminized 1.0mm<br>• Boron bare 2.0mm<br>• Boron aluminized 1.0mm |
| • TRIP780 HDGA 1.0mm<br>• TRIP780 HDGA 1.9mm<br>• TRIP780 HDGA 1.0mm |

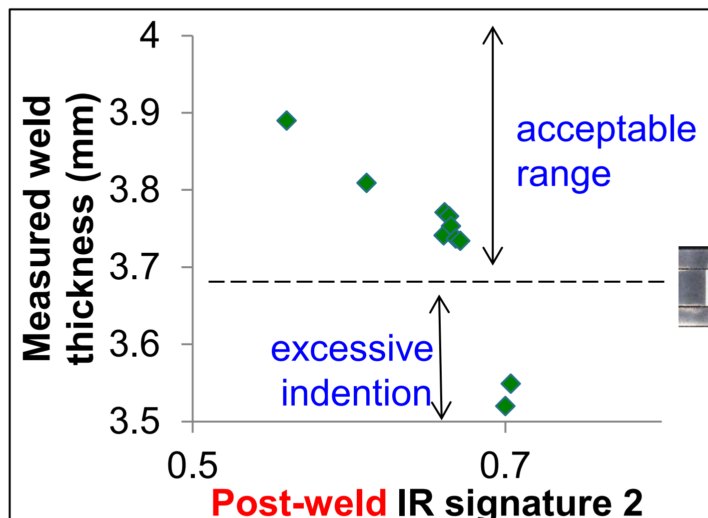
- *Welds made with different combinations of materials, thickness, stack-up configurations and coatings.*
- *Each combination includes spot welds with varying attributes (i.e., nugget size, indentation, etc.)*

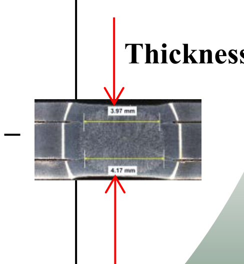
# Accomplishment: IR Signatures vs. Weld Attributes (Quality Database)

**3T welds**
- Boron bare 1.0mm
- Boron aluminized 2.0mm
- Boron bare 1.0mm



# Accomplishment: Detection of stick weld

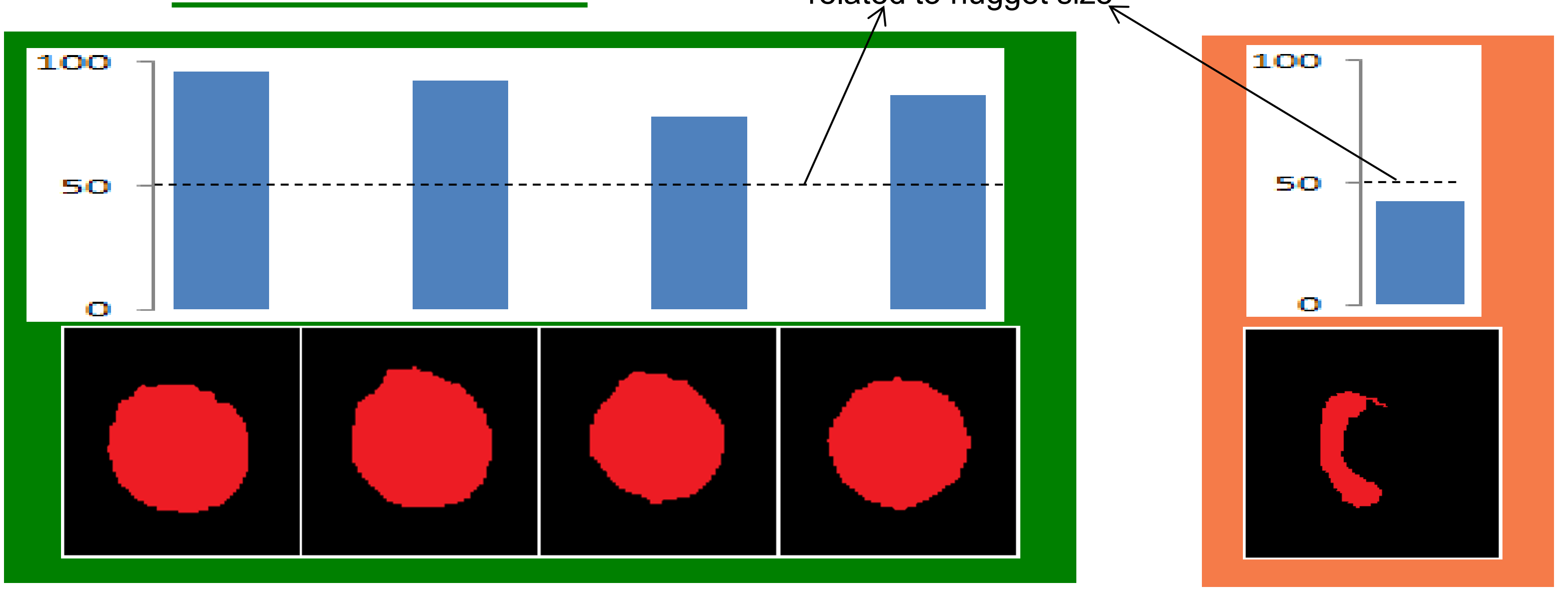
Normal-size welds

Threshold value
related to nugget size

Stick weld

Real-time signature

Post-weld signature




**Detection of stick weld**
- DP600 HDG 1.2 mm
- DP600 HDG 1.2 mm



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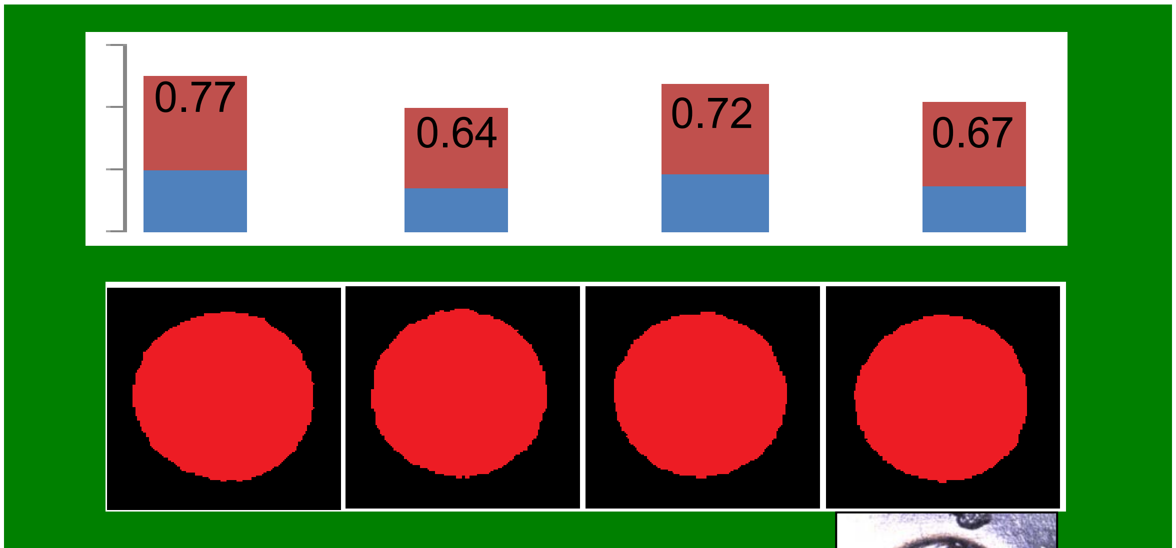
# Accomplishment: Detection of undersized welds due to part fit-up tolerance variations

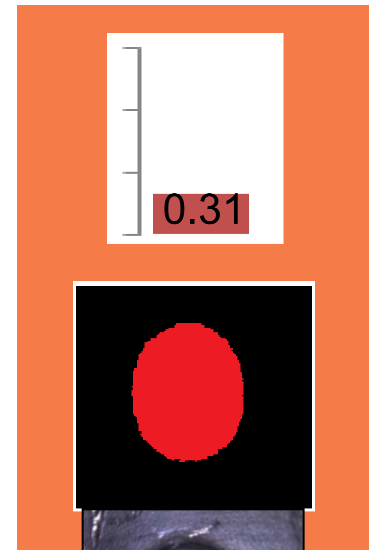
**Normal welding condition**

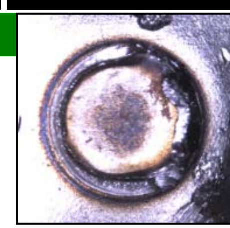
**Undersized welds due to large gap**

Real-time signature

Post-weld signature



- **DP600 bare 2.0mm**
- **DP600 HDG 2.0mm**

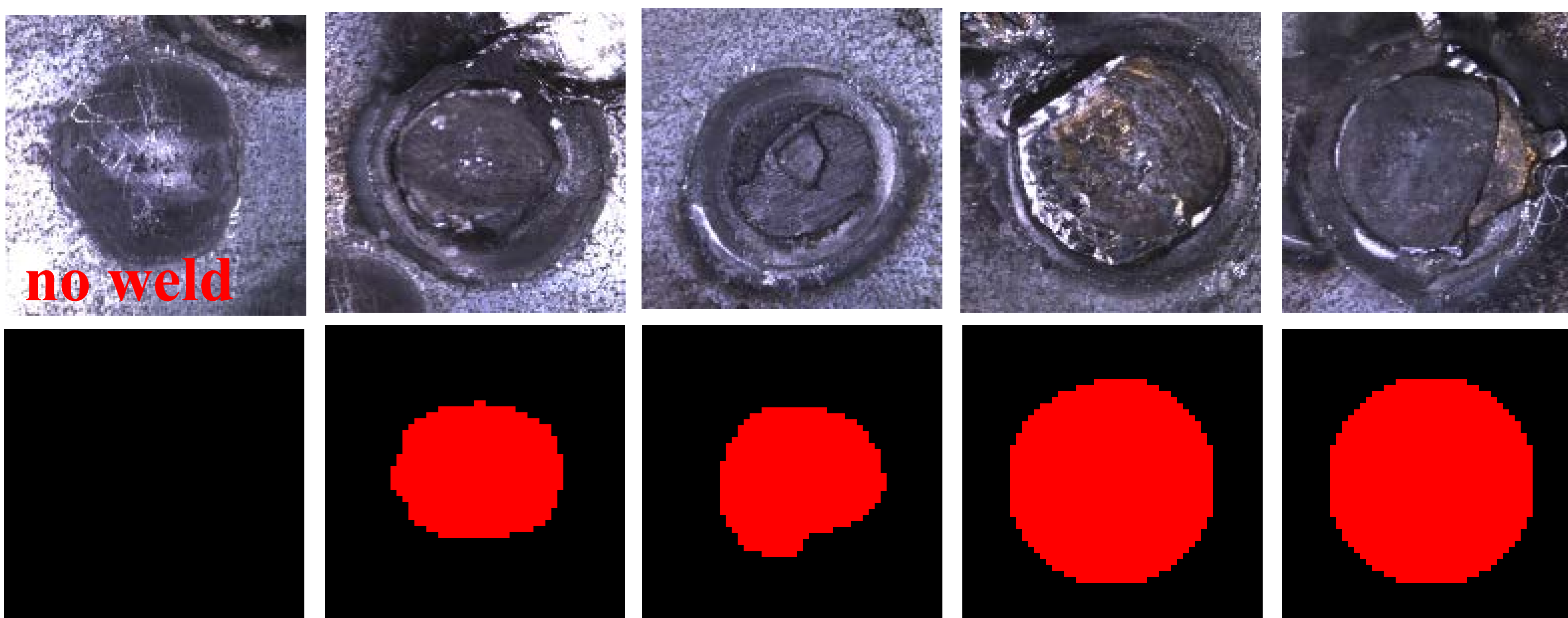
# Accomplishment: Actual Auto Body Parts

**2T auto body structures**

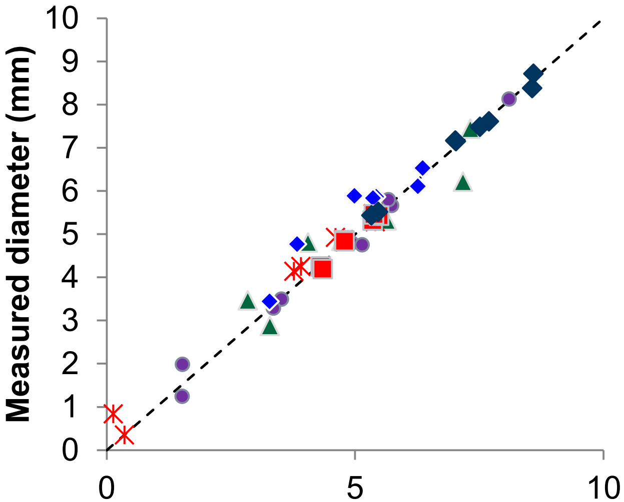


Destructive measurement

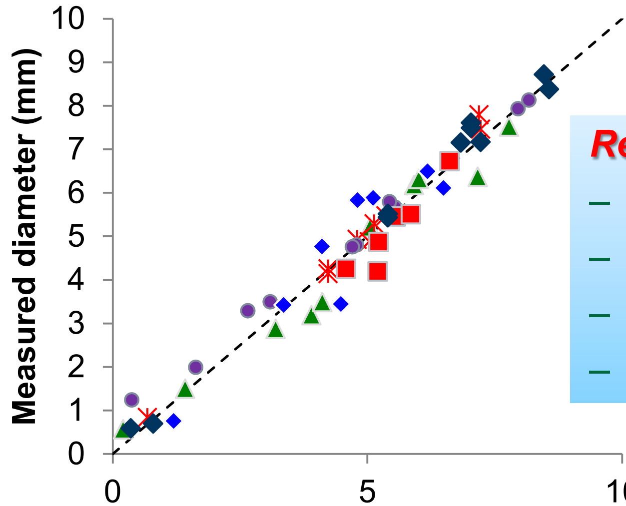
Post-weld signature



# Accomplishment: Weld Quality Prediction



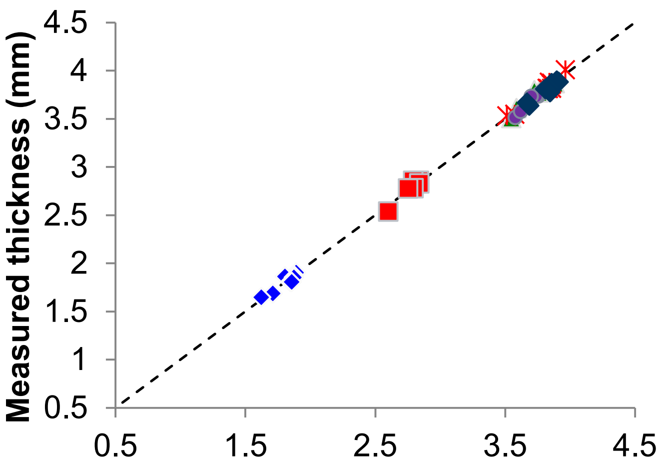

**Real-time** predicted diameter (mm)



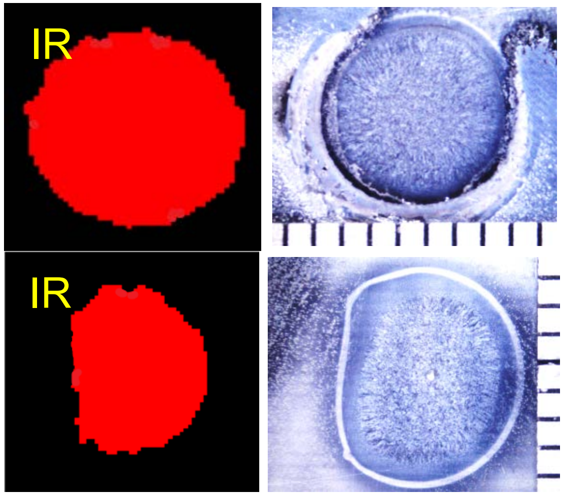

**Post-weld** predicted diameter (mm)

***Results from a combination of***

- *Materials*
- *Plate thickness*
- *Stack up configurations (2T/3T)*
- *Surface coatings*




**Post-weld** predicted thickness (mm)




**Post-weld** predicted shape



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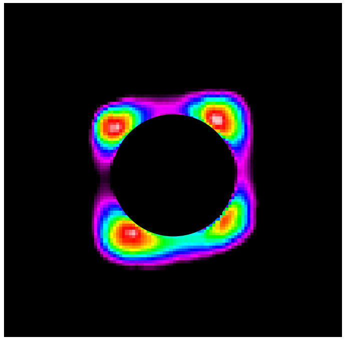
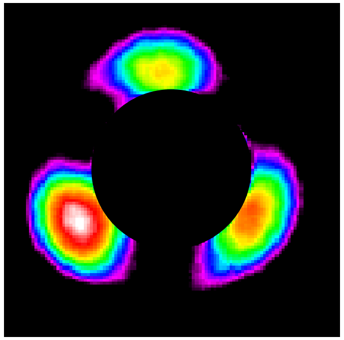
# Application to Nut Welds (Initial Results)





# Responses to reviewers' comments

- More communication and collaboration with industry partners is needed to ensure the methodology will apply in actual plant environment.
  - *A field demonstration and project review meeting was held in Detroit in June 2013 to technical representatives from four major auto OEMS. The system was further improved based on the feedbacks from OEMs to specifically addressing scenarios expected in actual plant environment (e.g. changing in electrode conditions and part fit-up tolerance).*
  - *Field testing and refinement are underway through partnership with a major tier 1 supplier on actual auto-body components under real-world plant production environment. Preliminary results are very promising*
- Further efforts can be initiated on reducing the cost of the inspection system to below the $30,000 point.
  - *We have identified IR cameras cost less $5K could be potentially used in our system. These cameras needs to be systematically evaluated.*
- The effort should be expanded to multi-material joints as well, if possible.
  - *Preliminary tests on Al alloys and other joints are promising. Thus, the technology developed in this project could be expanded to multi-material joints upon further application specific development, to address a critical needs.*

# Collaboration and Industry Participation

- Extensively and closely worked with the industry stakeholders/end-users during R&D and system prototyping and testing
  - Support and cost-share from Ford, GM, Chrysler and ArcelorMittal
  - AMD NDE Steering Committee
  - A/SP Joining Team
  - Project technical advisory committee
    - M. Jones, W. Charron, and A. Wexler, Ford Motor
    - B. Carlson, D. Simon and, D. Hutchinson, General Motors
    - C. Schondelmayer, George Harmon and D.J. Zhou, Chrysler
    - S. Kelly and B. Yan, ArcelorMittal
  - Field test at Cosma's Eagle Bend Manufacturing Plant in Clinton, TN
- Prototype online deployment and research licensing is on-going

# Plan for FY14

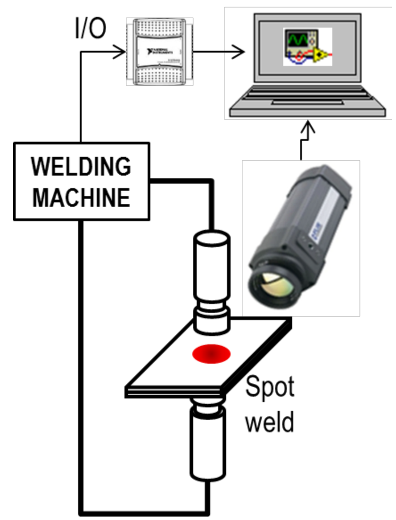
- Identify OEM testing sites
  - Cosma's Eagle Bend Manufacturing Plant, Clinton, TN (30 min drive from ORNL)
  - Other potential plants (depending on the progress at EBM and availability)
- IR NDE system field beta testing, evaluation and refinement
  - Tests on real weld parts
  - System reliability evaluation (in production line environment)
- Field demonstration of the system performance
- Technology Transfer and Commercialization (potential partner identified)

- Future opportunities (after this project)
  - Other materials and joining processes
    - Al Alloys (promising results have been obtained), and Mg alloys
    - Solid-state joining processes

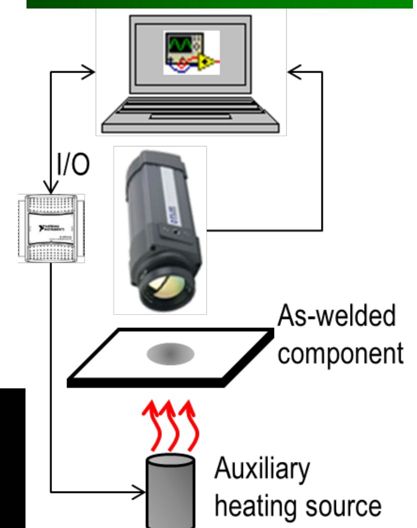
# Summary

- An innovative weld quality non-destructive evaluation (NDE) technology using infrared (IR) thermography
  - Including innovations in both hardware setup and software to correlate IR signals to quality (thermal signature)
  - Addressing a major need and significant market in auto industry
    - Capable for both *real-time* online and *post-weld* online/offline NDE
    - Applicable to high-volume mass production environment
    - Enabling increased use of high-strength lightweight materials in auto-body structures to meet the government mandates for fuel efficiency and crashworthiness
    - Affordable: $25-35K/unit
- Funded by DOE EERE Vehicle Technologies Office, with strong auto industry supports (A/SP, ArcelorMittal, Ford, GM, Cosma)

*Real-time NDE*

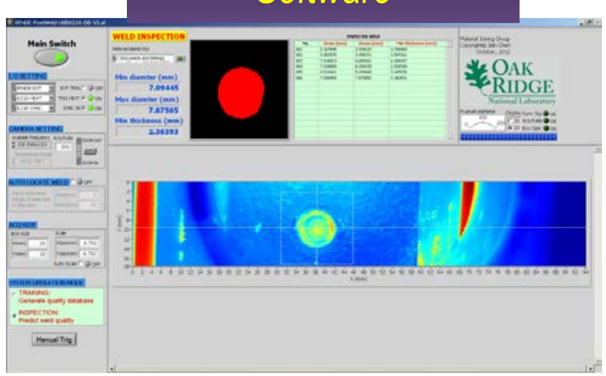


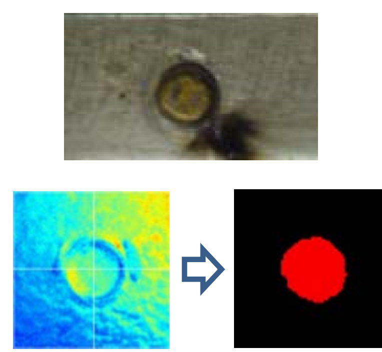

*Post-weld NDE*




*Hardware*

*Software*



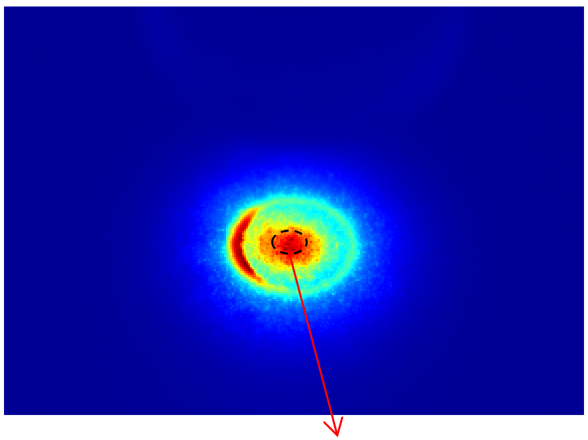



# Technical Back-Up Slides

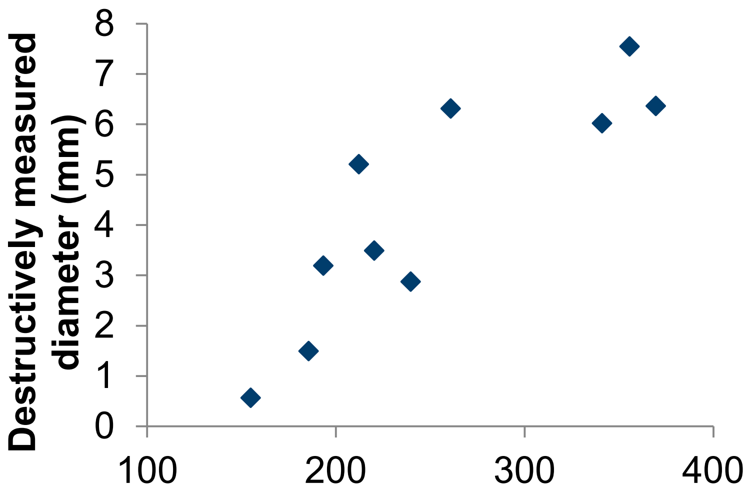
# A Major Problem in Conventional IR NDE

***IR camera measures the IR intensity. Variations in surface condition (i.e. emissivity) cause unreliable prediction of weld size by peak IR intensity.***

***We have developed novel IR image/signal analysis algorithms that effectively solved this major problem.***



**Peak IR intensity at weld center**



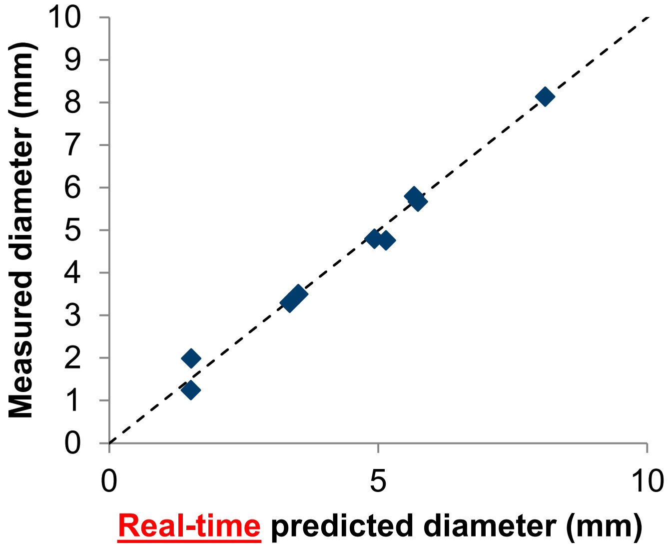

$$T \approx f(W_{tot}, \varepsilon)$$

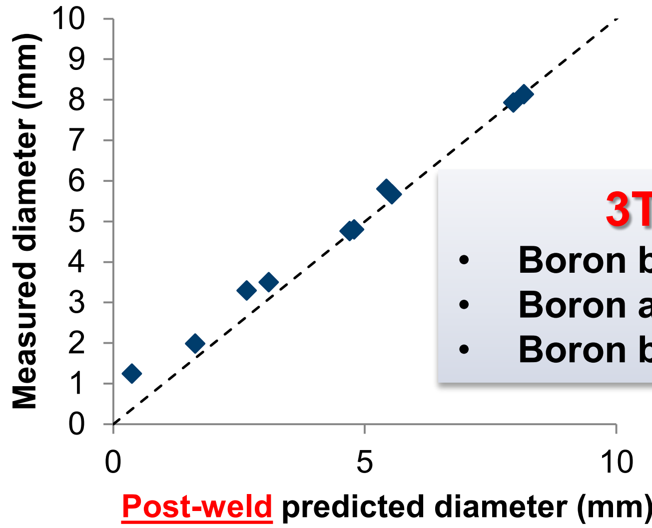
Temperature

Measured IR intensity

Surface emissivity (unknown)

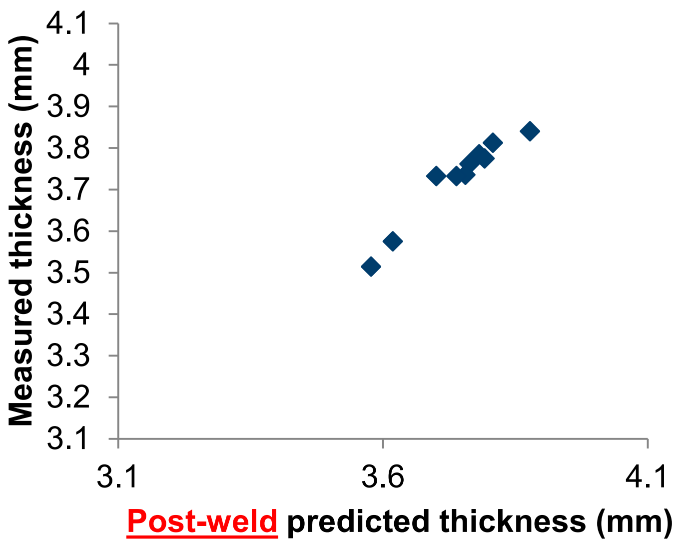
# Accomplishment: Weld Quality Prediction

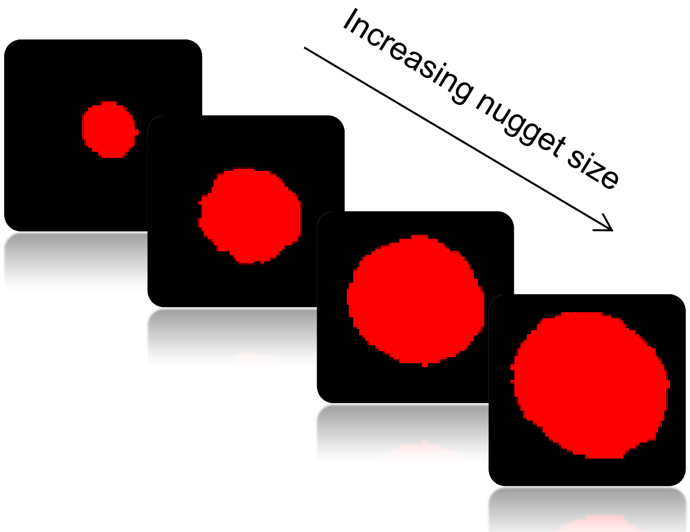



**3T flat coupons**

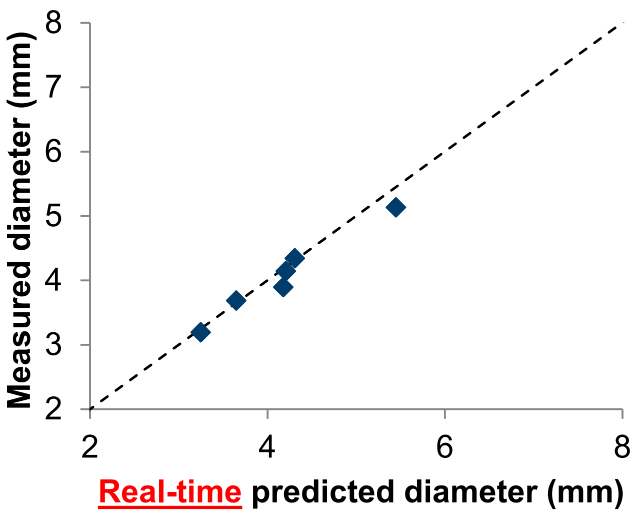
- **Boron bare 1.0mm**
- **Boron aluminized 2.0mm**
- **Boron bare 1.0mm**

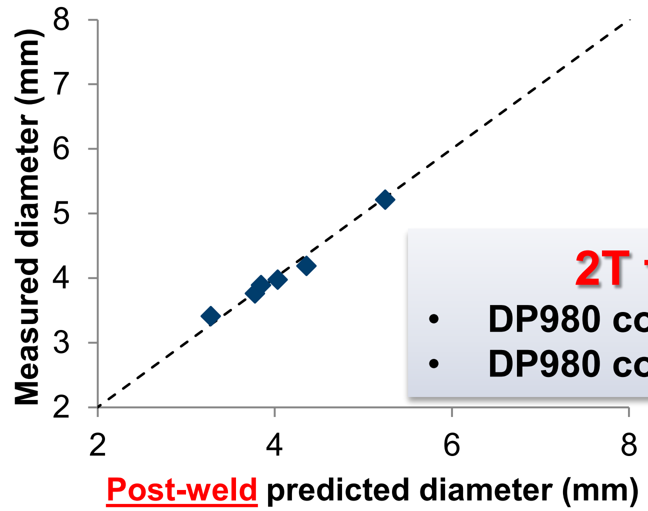



**Post-weld predicted shape**

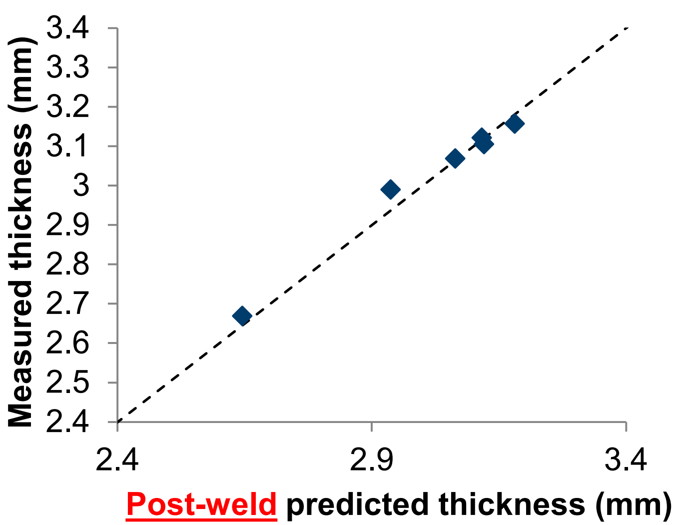
# Accomplishment: Weld Quality Prediction

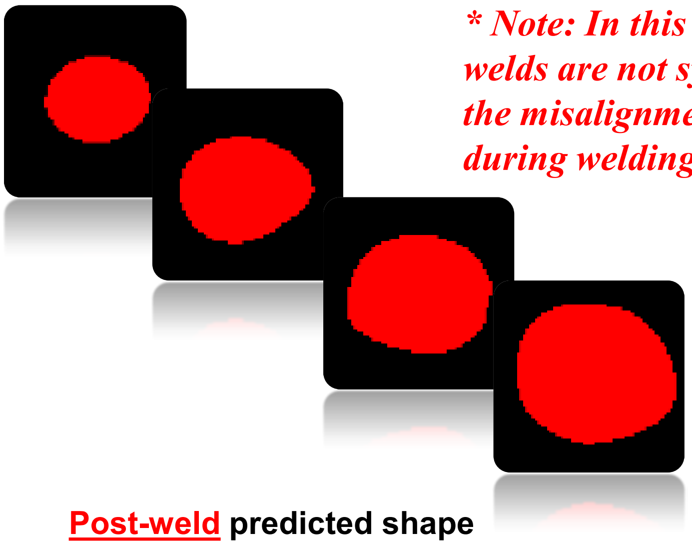



**2T flat coupons**

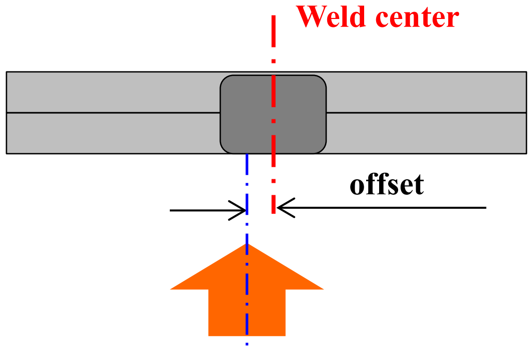
- **DP980 cold rolled 1.2mm**
- **DP980 cold rolled 2.0mm**

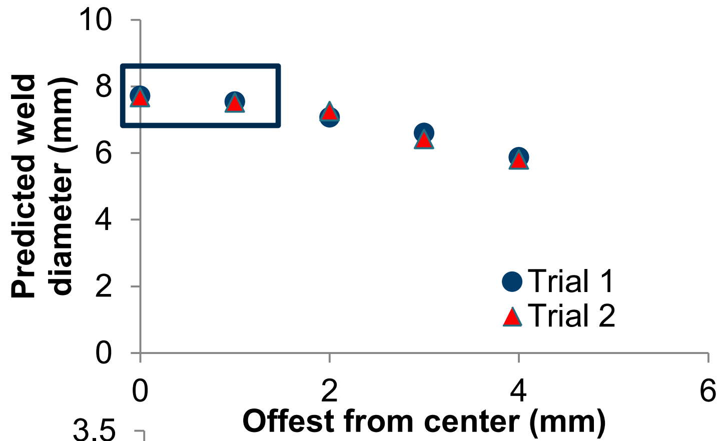


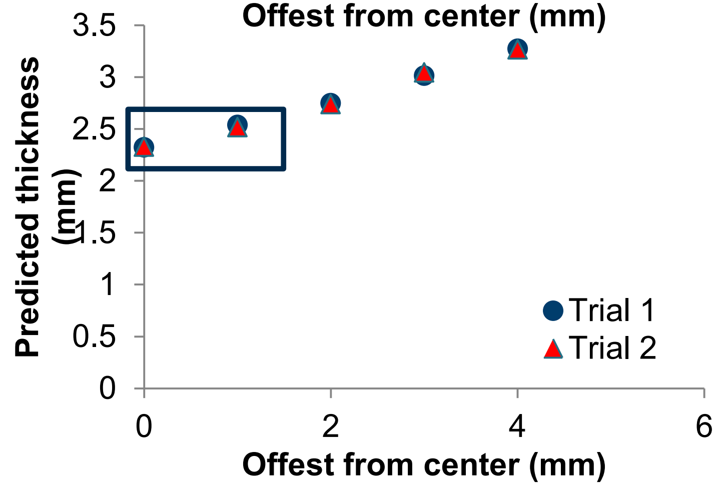




** Note: In this case, some of the welds are not symmetric due to the misalignment of electrodes during welding.*

# Accomplishment: Influence of Coil/Weld Alignment (Post-weld)




- Experiments were conducted on the same weld.
- Inspection at each offset location was *repeated twice*.

➢ **Predictions were fairly repeatable.**

➢ **1mm coil/weld alignment offset resulted in about 0.2mm error for predictions of both nugget size and weld thickness**