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Nondestructive Inspection of Al-Steel Weld Bond

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Materials Science and Technology Division

Nondestructive Inspection of Al-Steel Weld Bond

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1. ABSTRACT

In this project, in-line and off-line infrared (IR) thermographic techniques were explored to non-destructively evaluate/predict the nugget size of welds made with different material combinations (steel to steel, aluminum to aluminum and steel to aluminum) and welding conditions. The in-line approach analyzed the relative change of the heat flow pattern generated during welding process and the off-line approach utilized an auxiliary heat source to locally heat up the welds to be inspected. Two types of auxiliary heating methods were applied. One was multi-pulsed induction heating and the other was single-pulse flash lamp heating. Algorithms were developed associated with each approach. It is demonstrated that the predicted nugget size had a positive correlation to the experimental measurements. Overall, in-line and off-line induction heating methods yielded better prediction, while the off-line flash lamp heating method has a relatively scattered prediction, which is due to the low signal to noise ratio resulting from the very small temperature changes induced by the flash lamp method.

2. BACKGROUND

Material joining or welding is the primary assembly method in the automotive industry. The quality of the welds is critical to the crash resistance and performance of vehicles. All US automakers today perform mandatory destructive teardown evaluation. The very nature of the destructive test means only a few selected joints will be sampled for quality. There are significant costs and risks associated with reworking and scrapping defectively joined parts made between the teardown tests.

The auto industry demands effective and reliable non-destructive evaluation (NDE) methods to inspect each critical joint. It is even more important for dissimilar material joining. The lack of effective and reliable NDE tools suitable to the mass production environment is a barrier to the adoption of lightweight materials and suitable dissimilar material joining technologies by the automotive industry.

As the auto industry increasingly relies on a multi-material strategy to balance the performance, fuel efficiency and cost of auto body structures, joining of dissimilar materials by means of spot welds and adhesives has become an integral part of a dissimilar materials joining solution as exemplified by the introduction of resistance spot welding of aluminum to steel process joints in the seatback of the Cadillac CT6. There is a critical need for reliable and cost-effective NDE technologies that can be used in high volume auto structure manufacturing environment to inspect adhesively bonded joints or joints with rough and complex surface patterns. Conventional NDE tools such as ultrasound have been difficult to use for such applications. Ultrasound typically requires physical contact between the transducer and the material surface through use of a gel or fluid couplant at the interface. The patterned surface topography of the resistance spot weld makes it difficult to obtain good coupling conditions for ultrasonic transmission. While use of a fluid or gel can mitigate these poor coupling conditions, scattering of the ultrasonic signal from the surface also decreases the signal to noise ratio, reducing signal quality. Furthermore, for use on highly automated high-volume auto assembly lines, the use of a fluid or gel is very difficult, if not impossible. It is therefore the goal of this project to introduce and develop an NDE method which is insensitive to the complex surface topography.

Sponsored by DOE VTO and with close collaboration with automotive industry OEMs, and Tier One suppliers, ORNL in the past few years has successfully developed a non-contact online weld NDE technology for inspecting resistance spot welds based on infrared thermography (IR NDE). This R&D 100 award winning technology has received considerable interest for licensing and technology commercialization. However, ORNL's IR NDE development was primarily limited to advanced high-strength steels, although limited testing trials suggested feasibility for Al RSW.

Independently, GM has created a novel approach to reduce the glare inherent in IR imaging of highly reflective Al surfaces which we feel is an enabler for the application of ORNL's IR NDE method to Al-Steel resistance spot welds. While the initial scoping tests exhibit promising results, the application of IR NDE to inspect Al-Steel spot welds needs to be further developed.

In this work, ORNL, in partnership with GM, proposes to develop an IR NDE method that can effectively and reliably inspect dissimilar material joints with complex surface patterns in a highly automated manufacturing environment. This method will be built upon our extensive experience in IR NDE. We plan to evaluate options to address critical bottlenecks hindering the use of IR NDE for resistance spot weld and adhesive bond inspection.

3. STATEMENT OF OBJECTIVES

The objective of this research is to extend ORNL's award winning infrared thermography based NDE technique to weld bonding of Al to advanced high-strength steels, to address an immediate and critical NDE need identified by auto OEM. To achieve this goal, ORNL and GM performed in-line and off-line IR NDE measurements on seven different sets of spot welds (including steel-steel welds, Al-Al welds and Al-steels welds), explored the complicated relationship between the joint quality and the NDE measurement results and the joint quality, and developed candidate data analysis algorithms.

4. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

The proposed IR NDE method addresses a major technology need and a significant market in the automotive industry. The new technique can ensure quality and integrity of Al-steel spot welds and drastically reduce the vehicle manufacturing cost by eliminating the material waste and labor cost associated with the periodic destructive weld quality inspections, hence, encouraging the U.S. auto industry to adopt more advanced lightweight materials to reduce vehicle's weight and meet the legislated greenhouse gas emission targets.

5. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

Resistance Spot Welding Experimental Design

Experimental Test Matrix

Seven weld variations were evaluated in this study that include steel welded to itself, aluminum welded to itself, and stack-ups with dissimilar metals, thicknesses, and welding electrodes, refer to Table 1. All steel materials were hot-dip galvanize (HDG) coated and the aluminum alloys were uncoated. No cleaning or other surface preparation was used on either material prior to welding the sheet stack-ups.

Table 1. Experimental Test Matrix with Weld Sizes

Stack-Up	Electrodes	Min (mm)	Low (mm)	Target (mm)	High (mm)	Max (mm)
1.0mm HDG LCS – 1.0mm HDG LCS	6006 Ballnose	3.0	4.0	5.0	Mid	IX
1.0mm HDG LCS – 1.0mm HDG LCS	6006 MRD	3.0	4.0	5.0	Mid	IX
2.0mm HDG LCS – 2.0mm HDG LCS	6148 MRD	5.0	6.0	7.0	Mid	IX
0.8mm x626 Al – 0.8mm x626 Al	6006 MRD	2.5	3.5	4.5	Mid	IX
1.2mm 6022 Al – 1.0mm x610 Al	6148 MRD	3.5	4.5	5.5	Mid	IX
0.8mm x626 Al – 1.0mm HDG LCS	6006 Hybrid (MRD/Ballnose)	3.5	4.5	5.5	Mid	IX
1.2mm 6022 Al – 2.0mm HDG LCS	6148 MRD	4.5	5.5	6.5	Mid	IX

Welding was performed using a medium frequency direct current (MFDC) welding machine designed for spot welding aluminum alloys. The system used an inverter weld control from WTC (Welding Technology Corp, Farmington Hills, MI,) with MFDC transformers (RoMan Manuf., Grand Rapids, MI). Pneumatic actuators were used to apply weld force. Distilled water at ambient temperature was used to cool the welding electrodes at a flow rate of 1.5 to 2.0 gpm.

Material stack-ups were welded with either 6006 (16mm diameter) or 6148 (19mm diameter) CuZr C15000 copper alloy electrodes. Ballnose electrodes were machined to include a ~5mm face. MRD electrode geometry is per GM's patented Multi-Ring Domed (MRD) electrode. All weld tests were performed with the aluminum alloy sheet contacting the positive welding electrode. Electrodes were chosen for each stack-up based on the size and type of electrode that would be used in a production body shop environment.

Weld sizes were chosen based upon GM's specifications for minimum and acceptable weld sizes in a production teardown situation. Weld currents were adjusted to produce the desired weld size in a hand peel sample. The maximum weld size was chosen when the weld schedule consistently produced internal expulsion (IX). The "High" weld size was the midpoint between the "Target" and "Max" weld sizes.

Sample Configurations

Samples were welded in a non-conductive Garolite fixture such that the welds were produced in the same location on every test specimen. A total of 3 hand peel and a single metallurgical test specimen were welded for each stack-up and weld size, refer to Table 1. To simulate the paint-bake thermal treatment that vehicles undergo in production, all samples were baked in an oven at 175°C for 35 minutes.

Sample Analysis

Metallographic specimens were sectioned and polished to a surface finish of 0.04μm using silica polishing media. Samples were examined in the unetched state to evaluate the weld nugget size. ImageJ image analysis software (U.S. National Institutes of Health, Bethesda, MD) was used to measure nugget diameter at the faying interface (straight line tool. Three welds per weld condition were measured using ImageJ.

Hand peel specimens were clamped in a static vise and manually pulled with pliers until complete failure of all 4 welds.

Nondestructive Evaluation Scenarios

In-line imaging

Thermal images were taken during and immediately after welding. For this setup a FLIR A655sc was positioned at an angle with a view of the spot weld which was unobstructed after the weld electrode raised as shown in Figure 1. The camera was automatically triggered to record as the welder started and captured at least 3 seconds of data at a rate of 200 Hz.

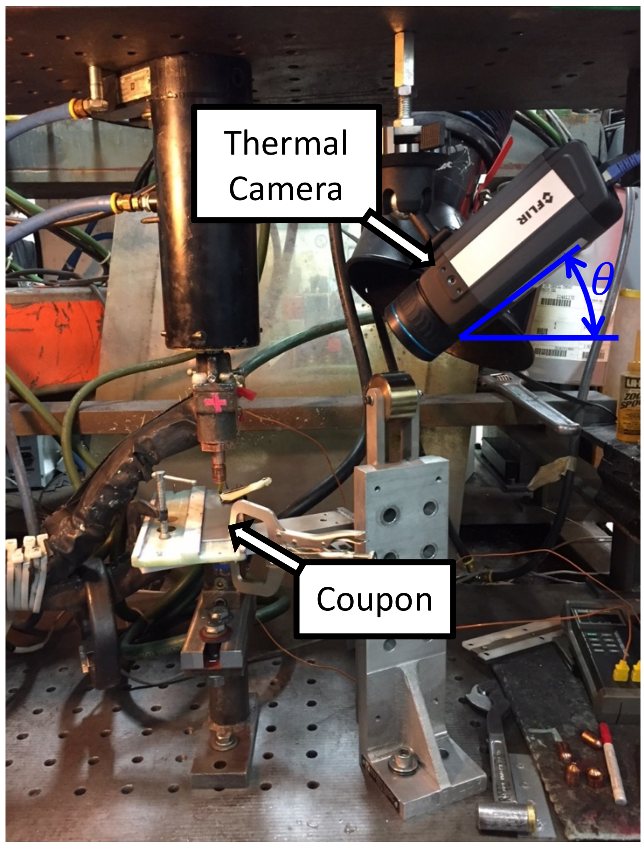


Figure 1. Weld setup with thermal camera for in-line imaging

Post Weld Imaging (Flash)

Post-Weld through-transmission thermography imaging was conducted after welding using two methods for excitation. The first method used a flash lamp as the excitation in a through-transmission configuration. Refer to Figure 2 for a schematic of this testing set-up.

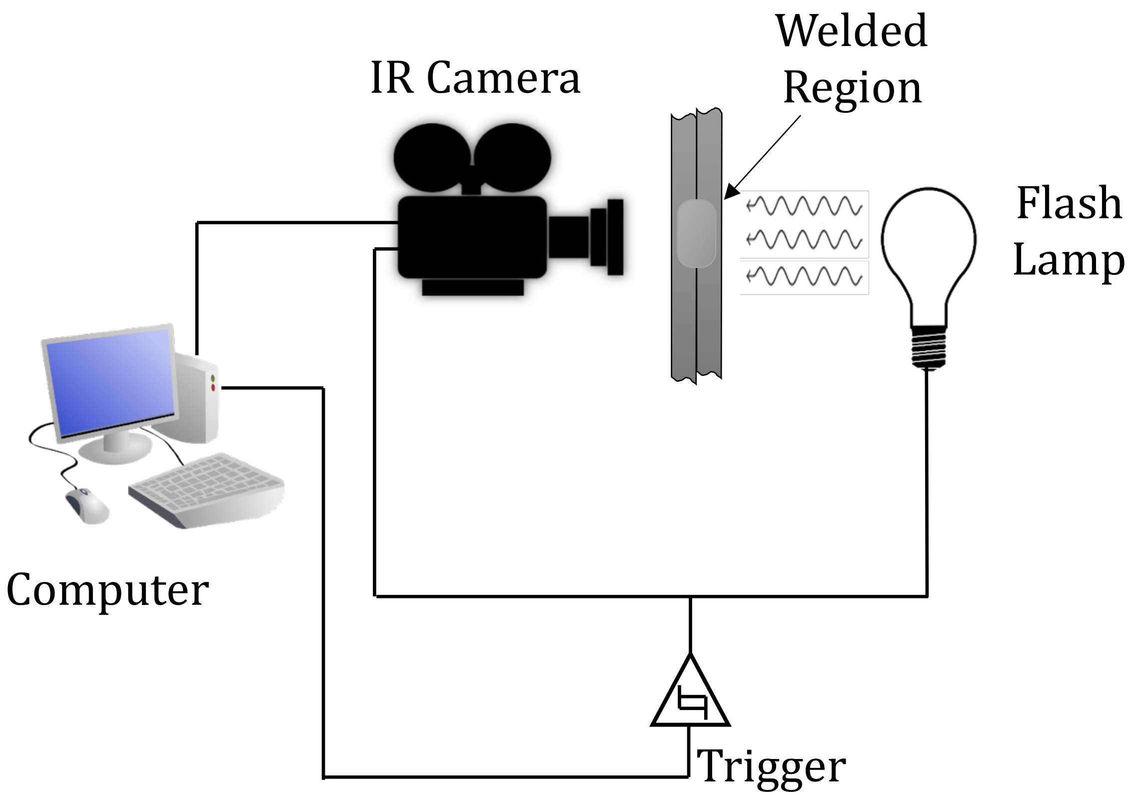


Figure 2. Schematic of experimental set-up. Pulsed light acted as the heat source and an infrared (IR) camera was positioned on the opposite side of the sample for data collection.

Pulsed thermography was employed, using a flash lamp (Elinchrom 1200RX) to provide a single pulsation of heat at 1200 Ws with a duration of 1/1450 seconds. The samples were mounted to a garolite fixture on the end of the lamp to ensure consistency in placement relative to the camera and light source. Care was taken to isolate the strobe light from the camera, to avoid overexposure and contamination of the data. The camera was triggered to record slightly before the pulsed light was triggered. A FLIR SC8300 thermal camera was used with a frame rate of 187 frames/sec.

Post Weld Imaging (Induction)

Additionally, post-weld through-transmission thermography imaging was conducted using induction for excitation as shown in Figure 3. An induction heater (Ambrell EasyHeat 0112) of 1200 watts was used to provide pulse heating. During heating, the sample was positioned on a ring stand so that the sample was at a distance less than 1 mm from the induction heater. The camera was set to record for 3.5 seconds, beginning at the time of the heater excitation. The entire sample set was evaluated using the induction heating method.

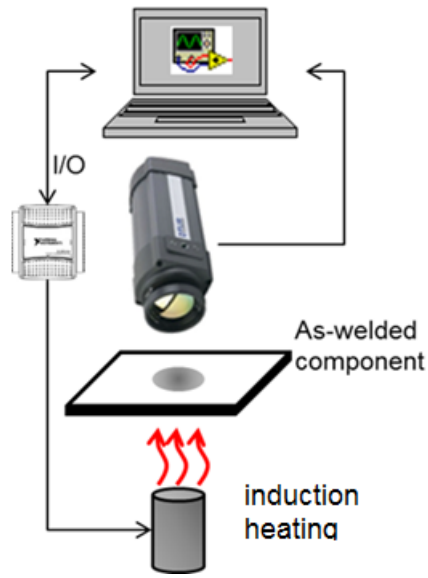


Figure 3. Schematic of experimental set-up. Pulsed induction heating acted as the heat source and an infrared (IR) camera was positioned on the opposite side of the sample for data collection.

Results and Discussion

All data has been collected and processed.

Metallographic Results

The structure of Al-steel resistance spot welds is very distinct compared to similar metal spot welds, refer to Figure 4. In aluminum-aluminum and steel-steel spot welds, for instance, the weld structure consists of a single weld nugget comprised of a mixture of material from both metal sheets. In contrast, aluminum-steel spot weld joints feature a planar interface between the aluminum and steel with a weld nugget contained only within the aluminum alloy sheet. The aluminum weld nugget is separated from the steel substrate by a layer of intermetallic compounds at the faying interface. These intermetallic compounds are primarily Fe_2Al_5 adjacent to the steel substrate and $FeAl_3$ adjacent to the aluminum alloy weld nugget. In some instances, a very small steel nugget can form in the center of the steel sheet surrounded by a large heat affected zone (HAZ).

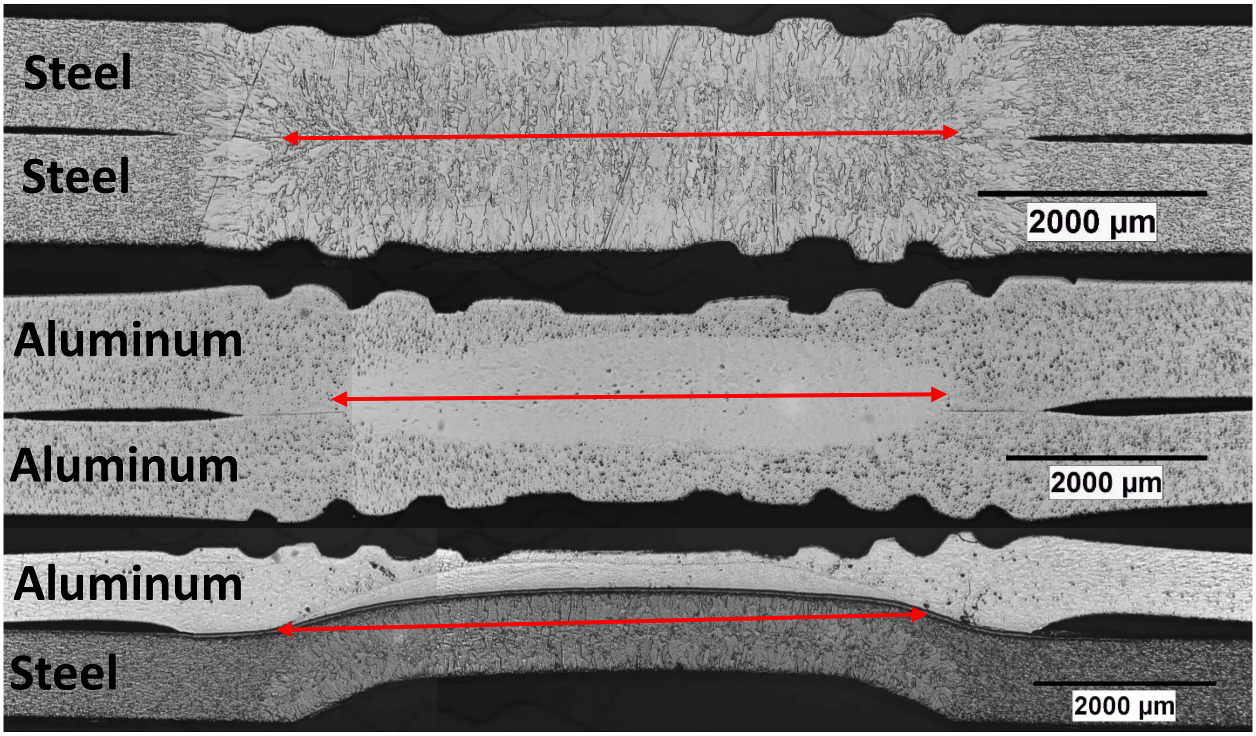
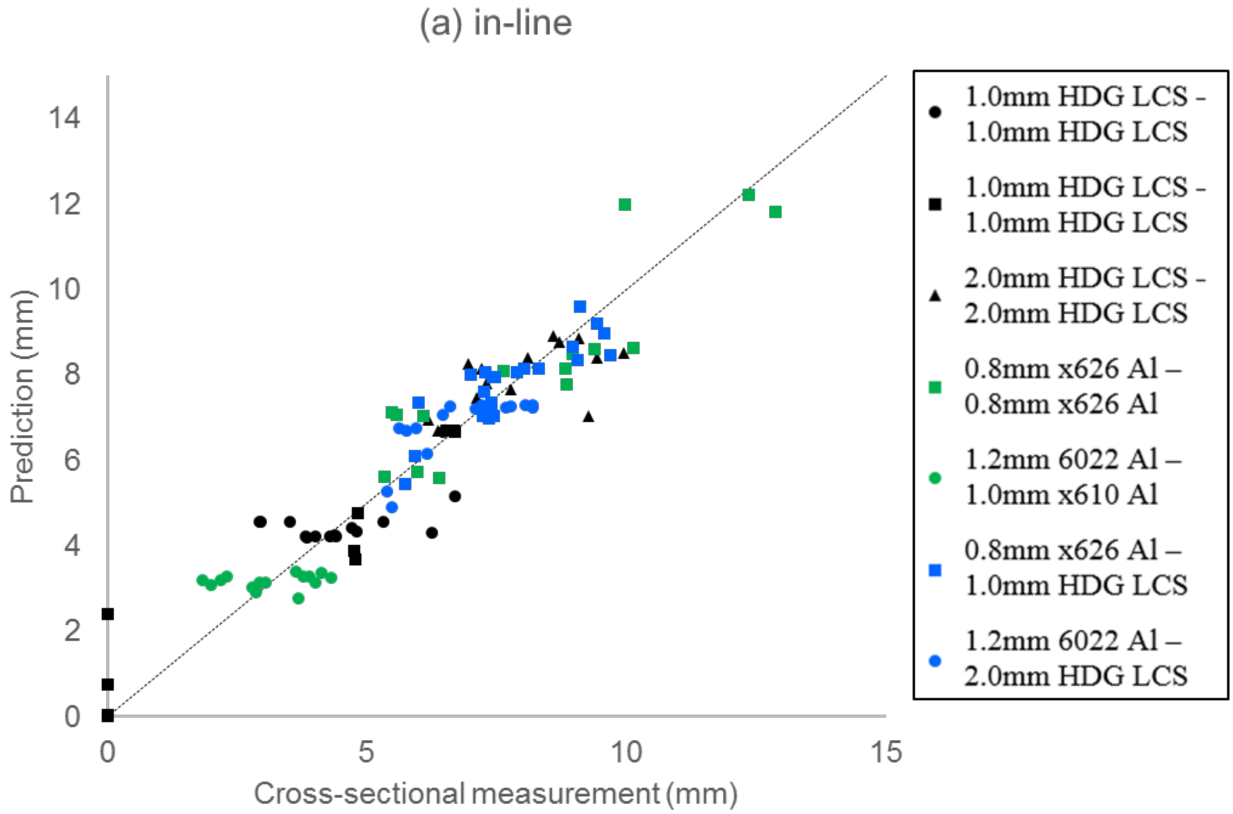


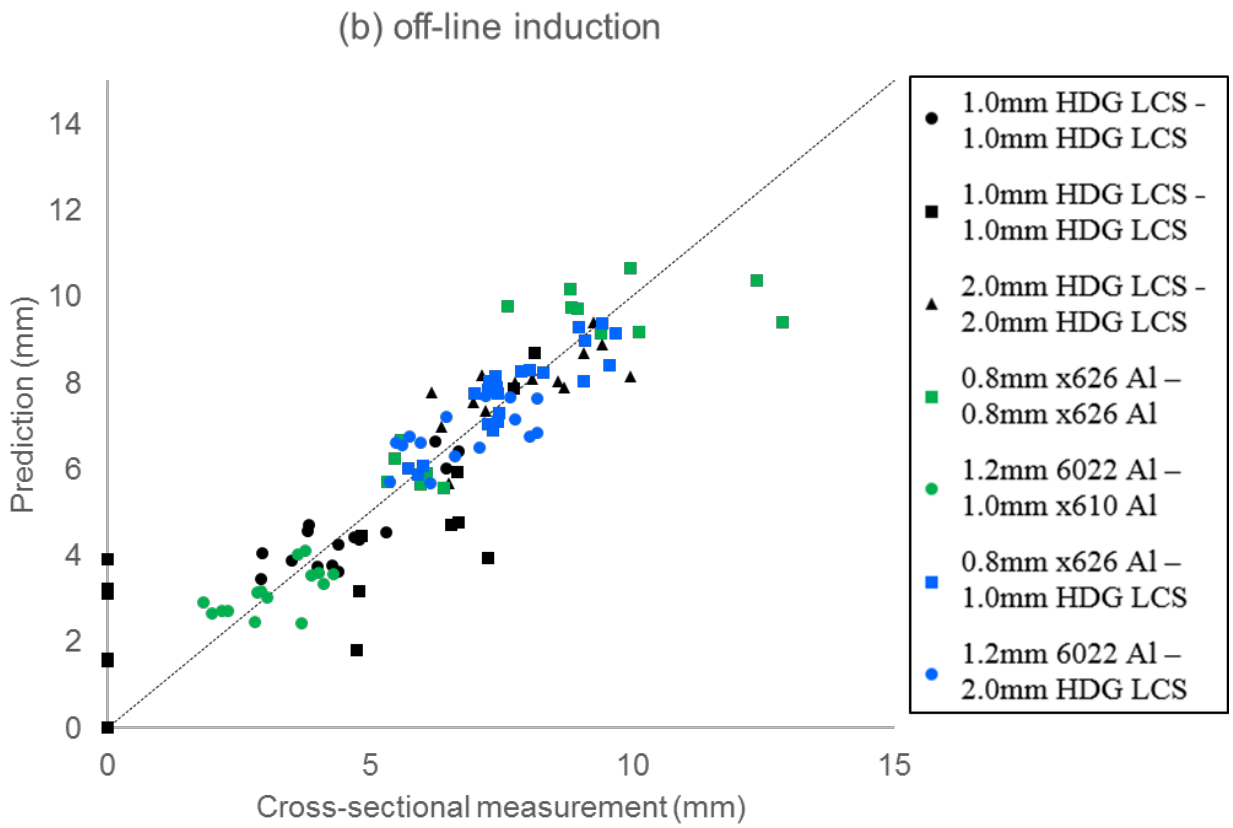
Figure 4. Examples of steel, aluminum, and aluminum-steel weld cross-sections with nugget diameters highlighted by red arrows

Three nugget diameters for each stack-up and weld size have been measured. This data is used as a comparison to the nugget diameters predicted by each of the nondestructive evaluation methods.

IR NDE Results

Figures 5a-5c contain the predicted weld nugget diameters for the entire sample set analyzed by (a) in-line IR NDE, (b) off-line pulsed induction heating and (c) off-line pulsed flash lamp heating methods respectively. The comparison to the cross-sectionally measured diameters is also plotted. The individual measurements are denoted by the black dots, and the expected 1:1 relation is denoted by the dashed line. A proportional trend is observed between the predicted versus real diameters. Overall, in-line and off-line induction heating methods yielded better prediction, while the off-line flash lamp heating method has a relatively scattered prediction. This is due to the low signal to noise ratio resulted from the very small temperature changes (typically on the order of 0.1°C) induced by the flash lamp method.


(a) in-line
Prediction (mm)
Cross-sectional measurement (mm)
0
2
4
6
8
10
12
14
0
5
10
15
1.0mm HDG LCS - 1.0mm HDG LCS
1.0mm HDG LCS - 1.0mm HDG LCS
2.0mm HDG LCS - 2.0mm HDG LCS
0.8mm x626 Al – 0.8mm x626 Al
1.2mm 6022 Al – 1.0mm x610 Al
0.8mm x626 Al – 1.0mm HDG LCS
1.2mm 6022 Al – 2.0mm HDG LCS


(b) off-line induction
Prediction (mm)
Cross-sectional measurement (mm)
0
2
4
6
8
10
12
14
0
5
10
15
1.0mm HDG LCS - 1.0mm HDG LCS
1.0mm HDG LCS - 1.0mm HDG LCS
2.0mm HDG LCS - 2.0mm HDG LCS
0.8mm x626 Al – 0.8mm x626 Al
1.2mm 6022 Al – 1.0mm x610 Al
0.8mm x626 Al – 1.0mm HDG LCS
1.2mm 6022 Al – 2.0mm HDG LCS

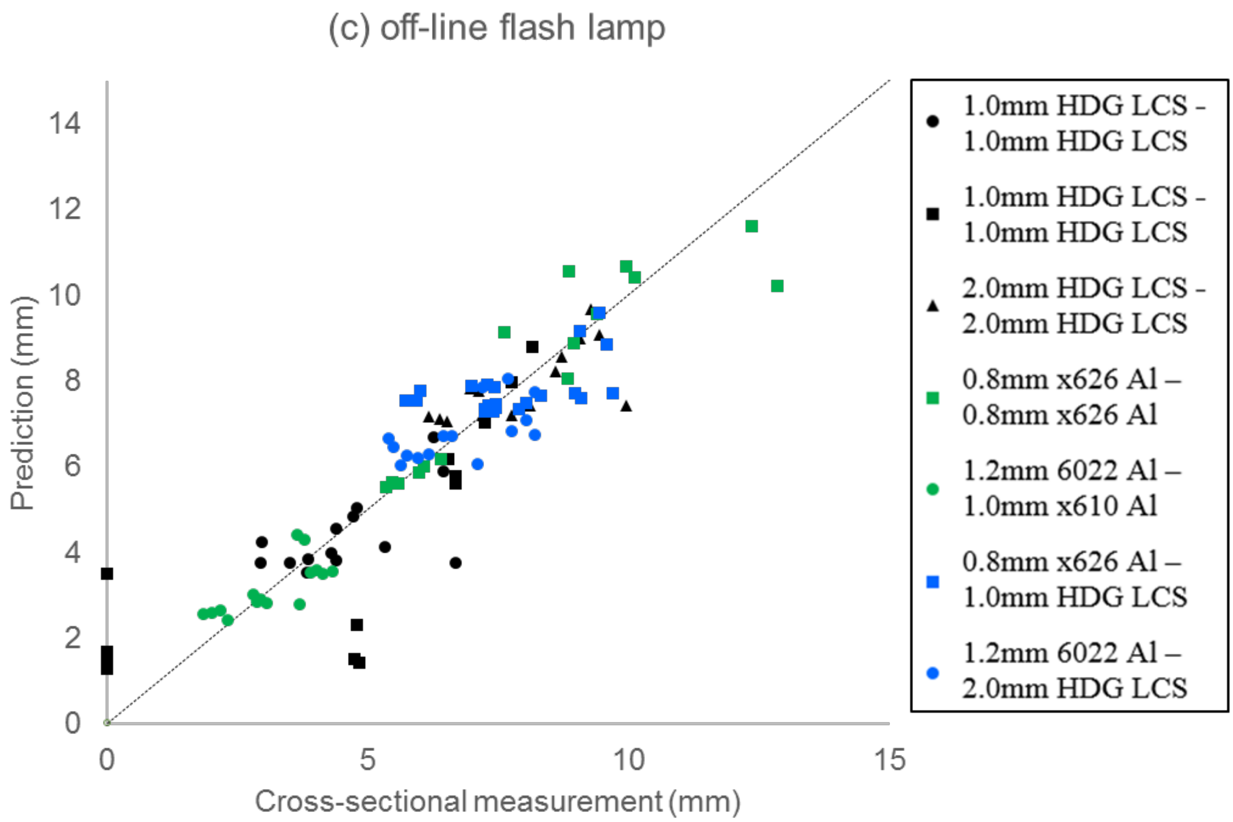


Figure 5. Predicted diameters versus real measured diameters for the entire sample set, where measurements are denoted by the black dots and the expected trend is represented by the dashed gray line. (a) in-line IR NDE, (b) off-line pulsed induction method and (c) off-line pulsed flash lamp

6. SUBJECT INVENTIONS (AS DEFINED IN THE CRADA)

N/A.

7. COMMERCIALIZATION POSSIBILITIES

Further evaluation and discussion are on-going. Potential technology licensing may be expected.

8. PLANS FOR FUTURE COLLABORATION

ORNL will continue to work with GM and other auto OEMs to further test and refine this IR NDE technology. Spot welds made with new lightweight materials will be tested. New algorithms/approaches including artificial intelligence and machine learning will be utilized to facilitate data analysis.

9. CONCLUSIONS

Steel-steel, Al-Al an Al-steel spots welds produced at different welding conditions were measured using in-line and off-line (pulsed induction and pulsed flashlamp heating) methods. Data obtained from in-line measurements and off-line pulsed induction heating methods exhibited a relatively good proportional relationship, while the off-line flashlamp heating method yielded a scattered prediction due to the low signal-to-noise ratio resulted from the very small temperature changes induced by the flash lamp method.