SCAN TEAM REPORT

NCHRP Project 20-68, Scan 23-03

Advances in Evaluation of Weld Quality

Supported by the

National Cooperative Highway Research Program

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This report was prepared by the scan team for Domestic Scan 23-03: A*dvances in Evaluation of Weld Quality*, whose members are listed below. Scan planning and logistics are managed by Arora and Associates, P.C.; Harry Capers is the Principal Investigator. NCHRP Project 20-68 is guided by a technical project panel and managed by Sid Mohan, NCHRP Associate Program Manager.

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Scan 23-03 Advances in Evaluation of Weld Quality

REQUESTED BY THE

American Association of State Highway and Transportation Officials

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June 2025

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Table of Contents

List of Figures

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Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ASME	American Society of Mechanical Engineers
AWS	American Welding Society
DOT	Department of Transportation
FCAW	Flux-cored arc welding
FCAW-G	Gas-shielded FCAW
FCAW-S	Self-shielded FCAW
FHWA	Federal Highway Administration
GMAW	Gas metal arc welding
GMAW-S	Short circuiting GMAW
GTAW	Gas tungsten arc welding
IoT	Internet of Things
NCHRP	National Cooperative Highway Research Program
PennDOT	Pennsylvania Department of Transportation
SAW	Submerged arc welding
SMAW	Shielded metal arc welding
SME	Subject Matter Expert

Executive Summary

Introduction

This report summarizes the team findings and recommendations for Domestic Scan 23-03, *Advances in Evaluation of Weld Quality*. In the bridge industry, most quality management of welds is done through establishing ranges of acceptable parameters, spot-checking of said parameters by inspectors, and after-the-fact nondestructive testing and inspection. It was hoped that technologies used by other industries could provide a more automated, proactive approach to weld quality.

Scan Purpose and Scope

The objective of this scan was to examine the state of in-process weld inspection, and the resulting quality assurance used in fabrication outside the bridge industry.

General Findings and Observations

- Data analysis could be used for root cause analysis and for focusing training and inspection resources.
- Using visual systems to scan the joint prior to welding could be an effective defect prevention tool.
- Machine learning is a promising tool for identifying defective welds.
- The scan team did not find evidence that feedback loops are widely used for real-time adjustments to prevent defects, other than adaptive fill.
- None of the systems presented can replace all visual inspection by humans.
- No systems presented can currently reliably detect subsurface defects; one is potentially under development. The systems presented are also unlikely to predict cracks that form after welding has been completed.
- The most popular welding process used for bridge fabrication, submerged arc welding, is incompatible with systems that assess the arc and weld puddle and may have limited compatibility with systems that scan the weld surface. Gas metal arc welding, arguably the least popular process permitted by the American Association of State Highway and Transportation Officials (AASHTO)/American Welding Society (AWS) D1.5 Bridge Welding Code, is the most compatible with the various automated weld assessment methods.
- The needs of the bridge industry and available or developing technologies are not in good alignment. However, the needs of the bridge industry regarding weld quality technologies have not been rigorously assessed.

Team Recommendations

The team did not find technologies that would be practical for widespread implementation in the bridge industry at present. They did feel that some of the systems could be implemented with some further development, and have several recommendations detailed below, for future research.

CHAPTER 1

Introduction

1.1. Domestic Scan Background

The current state of the practice of the control of weld quality for highway bridges and structures relies essentially on the following:

- Qualification of weld procedures through destructive testing of sample welds that are representative of defined ranges of production parameters such as voltage, current, and travel speed (the speed at which the welding head travels along the joint), and enforcement of those ranges through in-process spot-checks.
- tInspection of the completed weld after the fact. Inspection can take the form of visual inspection of the surface of the completed weld, nondestructive testing of the surface of the completed weld (methods include magnetic particle and liquid penetrant testing; these surface methods are often considered to be enhancements of visual inspection), and volumetric nondestructive testing that gives information about the weld interior (methods include radiographic and ultrasonic testing).

The inspection procedures are manual inspections requiring considerable time and effort that disrupt the flow of fabrication and greatly add to the fabrication time. Using more advanced approaches to weld evaluation during the fabrication of steel bridges could potentially increase weld quality, eliminate the time and cost required for post-weld inspection, and provide a digital record of the weld geometry.

It was believed at the outset of the scan that in the shipbuilding and heavy equipment industries, the quality of welds is maintained by process control and inspection during the welding operation, with welding parameter data acquired continuously by the welding equipment used, and parameters adjusted as the weld is made, providing greater control and associated uniformity. Information gathered during the welding process would be recorded to provide a record of the weld quality. Post-weld inspection would then be adapted based on this information. It was thought that these industries use automated inspection techniques to perform the quality verification of welds.

1.2. Objectives, Purpose and Scope of Scan

The objective of this scan was to examine the state of in-process weld inspection, and the resulting quality assurance used in fabrication outside the bridge industry.

Specifically, the team was expected to examine and document:

- The processes and controls used to produce quality welds in industries other than highway.
- The equipment involved in weld inspection and quality assurance, the specifications used for equipment requirements, and quality control procedures and calibration of the equipment to the appropriate quality standards.

- The state of the in-process inspection includes items such as monitoring welding variables, measurement of weld size using laser scanning, and the resulting reliability of the weld quality using in-process inspection.
- The current state of practice within the AASHTO bridge community for comparative purposes.

1.3. Scan Team Information

The scan team consists of:

- Xiaohua "Hannah" Cheng, New Jersey DOT (Scan Team Chair)
    - Mark Daniels, Utah DOT
    - Leslie Daugherty, Alaska DOT&PF
    - Bryan Hartnagel, Missouri DOT
    - Reginald Lee, Georgia DOT
    - Michael Leonard, Massachusetts DOT
    - Justin Ocel, FHWA Resource Center
    - Cornelius Wright, Georgia DOT
    - Heather Gilmer, Pennoni, Subject Matter Expert (SME)

Biographical and contact information can be found in the Appendices.

1.4. Agencies, Organizations, Sites, Personnel, etc. Visited

Site visits were made to the following locations:

- Caterpillar Inc., Peoria, IL
    - Heavy equipment manufacturer (see Figure 1)
    - Technical presenters: Jean Bridge, Muriel Jansen

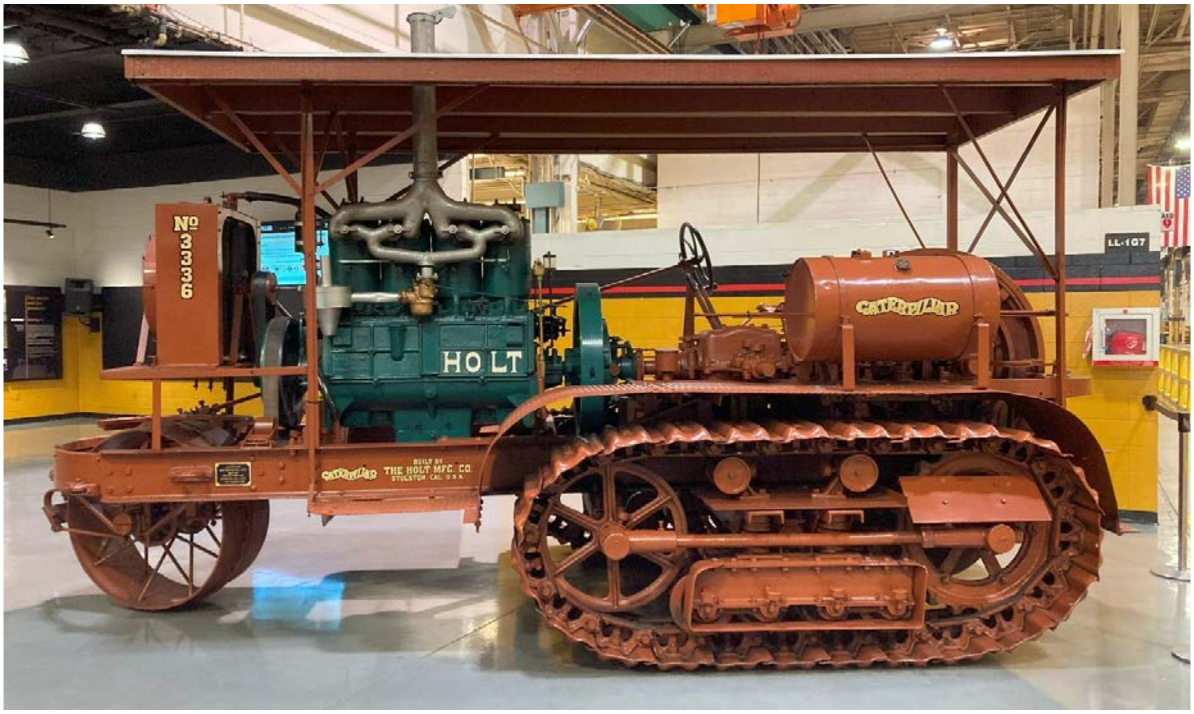


Figure 1. Antique early model on display at Caterpillar Inc., Peoria, IL (Source: Heather Gilmer)

- High Steel Structures, Inc., Lancaster, PA (see **Figure 2**)
  - Steel bridge fabricator
  - Tour host: Ronnie Medlock

Figure 2. High Steel Structures, LLC, Lancaster, PA (Source: High Steel Structures, LLC)

An in-person presentation was given by Josh Charnosky of the Pennsylvania Department of Transportation (PennDOT) at the High Steel Structures location.

Remote presentations were given by the following:

- ESAB® Corporation
    - Developer and producer of welding equipment and consumables
    - Presenter: Nate Roberts
- Intel® Corporation
    - Developer and producer of computer components and systems
    - Presenter: Tara Thimmanaik
- KEYENCE™ Corporation of America
    - Developer and producer of sensing and measuring equipment
    - Presenter: Chris Lewis
- The Lincoln Electric Company
    - Developer and manufacturer of welding equipment and consumables
    - Presenters: Brian Mees and Curt Decker
- Prof. Patricio Mendez
    - Professor and Director of the Canadian Centre for Welding and Joining at the University of Alberta in Edmonton, Alberta, Canada
- SERVO-ROBOT, Inc.
- Developer and producer of laser vision systems
- Presenter: Jeff Noruk

See Appendix A for the itinerary.

1.5. Scan Approach and Planning

The list of organizations to visit or speak with was developed by the team SME and narrowed down by the scan team. The SME researched and spoke with organizations based on suggestions in the original scan prospectus and recommendations from professional contacts, including scan team members. In-person locations were selected to avoid redundancy in the types of technology viewed.

High Steel Structures, Inc. was selected as a benchmarking location for current bridge practice because they are known to several of the scan team members as a large bridge producer representative of the current state. See **Figure 3**.

Figure 3. Scan team members touring High Steel Structures (Source: High Steel Structures, LLC)

In-person tours at other locations proved to be more difficult to schedule than had been expected. After initial interest from various organizations, some did not ultimately agree to in-person tours.

There were also limitations on the types of discussions and presentations that could be made because of the proprietary technology in use in many of these cases, especially considering that findings were to be presented in a publicly accessible report. This may be a concern for other scans focusing on leading-edge technologies.

Arora PC, the National Cooperative Highway Research Program's (NCHRP) management consultant for this scan, scheduled the visits and presentations. There were further difficulties in scheduling presentations because turnover can be high in technology fields, and some of the contacts provided by the SME had left their organizations before the scheduling took place.

Scan Findings and Observations

This section is organized by topic area/technology.

2.1. Observations

Most of the systems presented can be classified into one of these categories:

- Electric signal data collection and analysis
- Visual systems

The discussion of any specific products herein should not be taken as an inclusive listing of what is available on the market, or even from these welding equipment or sensor producers, nor as an endorsement of any of those products or of their producers. Each presentation had a different focus, and assumptions should not be made about the companies' overall capabilities based on this report.

2.1.1. Data collection systems

The most readily available source of welding data is from the welding power source. The major welding equipment suppliers have been making power supplies for decades that collect electrical signal data, and some also make generic devices that can be connected to any welding power supplies to provide this data collection. For those already using this equipment, the data is readily available, if underutilized. The primary variables that can be collected are voltage, current, and wire feed speed (which tends to correlate with current); other data can be collected through additional sensors or other observations. Currently, the primary use of this data is for productivity analysis.

ESAB presented the following data collection systems:

- WeldQAS
    - Standalone system (various sizes available depending on capability needed; see **Figure 4**) to be used with a producer's existing equipment
    - Records parameters, including welding current, welding voltage, arc time (time during which the welding arc is sustained), wire feed speed (the rate at which a welding electrode is consumed, i.e., melted to form the weld, often expressed in inches per minute), and force (a parameter used in resistance welding)
    - Various other sensors can be connected to measure parameters such as shielding gas flow rate, preheat and interpass temperatures, t8/5 cooling time (see section 2.4), distance, and travel speed
    - Data can be exported to a flash drive or to another location such as ESAB's InduSuite™ cloud-based welding management software
    - According to publicly available product literature, designed for gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and submerged arc welding (SAW)

Figure 4. ESAB WeldQAS (Source: ESAB Corporation)

- WeldCloud® Universal Connector
  - Small device (see Figure 5) that can be attached to any manufacturer's power source
  - Connects to the WeldCloud web-based interface (an InduSuite product) for aggregating and analyzing data
  - Parameters recorded include arc time, current, voltage, power use, wire feed speed, and deposition rate (quantity of electrode consumed and, thus, weld produced along the joint, often expressed in pounds per inch)
  - According to product literature, designed for GTAW and GMAW

Figure 5. ESAB WeldCloud Universal Connector (Source: ESAB Corporation)

- Power supplies with built-in data collection capability (e.g., Warrior EDGE® series; see **Figure 6**)
  - Built-in WeldCloud connectivity
  - Parameters recorded include arc time, current, voltage, power use, wire feed speed, and gas flow rate
  - According to product literature, designed for shielded metal arc welding (SMAW), GTAW, and GMAW

Figure 6. ESAB Warrior EDGE CX (Source: ESAB Corporation)

The process restrictions on the specific ESAB equipment listed above should be noted in the context that submerged arc welding (SAW) is currently the most popular welding process for steel bridge fabrication. See section 2.4 for discussion of several welding processes and their application to bridge fabrication.

Lincoln Electric® discussed their “flagship” Power Wave® series for power supplies:

- Sophisticated computerized process control with various modes optimized for particular needs (spatter reduction, deposition, etc.)
- Equipped with data collection capability by default

- Interfaces with Lincoln Electric's CheckPoint cloud-based software for data monitoring and analysis
- Parameters recorded include voltage, current, wire feed speed, arc time, and gas flow rate (using an additional sensor)
- According to the product literature, the Power Wave® S700 model (see **Figure 7**) is suitable for SMAW, GTAW, GMAW, flux-cored arc welding (FCAW), and SAW

Figure 7. Lincoln Power Wave S700 (Source: The Lincoln Electric Company)

The CheckPoint system reports on the data collected through the power source, including voltage, current, wire feed speed, gas flow rate (using a wire feeder with an additional sensor), arc time, deposition rate (if travel speed is assumed or recorded), welds per part, cycle time, and idle time between welds. A system is under development that identifies whether the data is "normal" or "abnormal" for a given weld based on data patterns and machine learning.

Both Lincoln Electric and ESAB offer a variety of data management and sharing options, including dashboards and aggregation of data from multiple machines (potentially from different manufacturers) and personnel. Various alerts and responses are possible. Lincoln Electric also discussed the more general concepts of the Internet of Things (IoT) and Industry 4.0. (A deeper exploration of these topics is beyond the scope of this report, but it must be acknowledged that data connectivity, onboard computers, etc., are becoming more and more important in technological developments worldwide.)

Without additional sensors, the welding power source electrical data alone cannot detect parameters that depend on distance traveled (length, travel speed, heat input, size of defect), preheat and thermal effects, torch position and contact-tip–to–work distance, etc. (Heat input is proportional to voltage and current, and inversely proportional to travel speed. It is a variable used extensively for welding procedure qualification in fatigue-sensitive applications such as bridges.)

2.1.1.1. Correlation of digital data to defects

Several parties are working on correlating electrical signals to defects. As one example, Prof. Patricio Mendez has been working on a project funded by the American Institute of Steel Construction as part of their "Need for Speed" initiative that "assesses the feasibility of welding electrical signal to discriminate the locations most likely to be problematic in welding during structural construction" (Wood & Mendez, 2023). The project is using Lincoln Electric's WeldScore™ (according to publicly available Lincoln Electric promotional material, WeldScore is a feature included in the Power Wave power supplies that allows one to compare welds to an optimal target) as a tool to discern "good" from "bad" welds. The research has been conducted using FCAW, primarily because the lab had that equipment on hand.

What is currently understood is that disturbances to the welding arc (e.g., contaminants, moisture, excess air flow/disruption in shielding gas) that result in weld defects also influence the electrical signal data. Modern consumables and arc-stabilizing technology used in many of today's power supplies make the welding process robust in the face of perturbations. Prof. Mendez's team had some difficulty artificially disrupting the arc, although an electrical signal associated with disturbances was typically evident. What is less clear is how to correlate the aberrations in data to specific types of defects.

The product literature for the ESAB WeldQAS system states that it uses "patented algorithms and welding parameters to detect pores, burn-through, wire defects … and other welding irregularities". However, according to Mr. Martin Meyer of ESAB, it is only applicable to short-circuit GMAW, a process largely prohibited in bridge welding (see section 2.4).

Prof. Mendez's research has made some preliminary correlation of the electrical data with "good" and "bad" welds using machine learning, but characterization of a specific defect type remains merely a promising possibility. None of the electrical data systems presented can currently determine defect dimensions and compare them to standard tolerances, and thus far none can detect slag inclusions. It is also unlikely that these systems will be able to predict cracks that form after the weld is complete, since such cracks have more to do with the thermal history of the weld than with the electrical parameters. However, with thermal sensors, at least part of the thermal cycle associated with cracking for a given combination of consumables and base material can be identified, which could mean that likely locations for cracking might be identified.

2.1.2. Visual systems

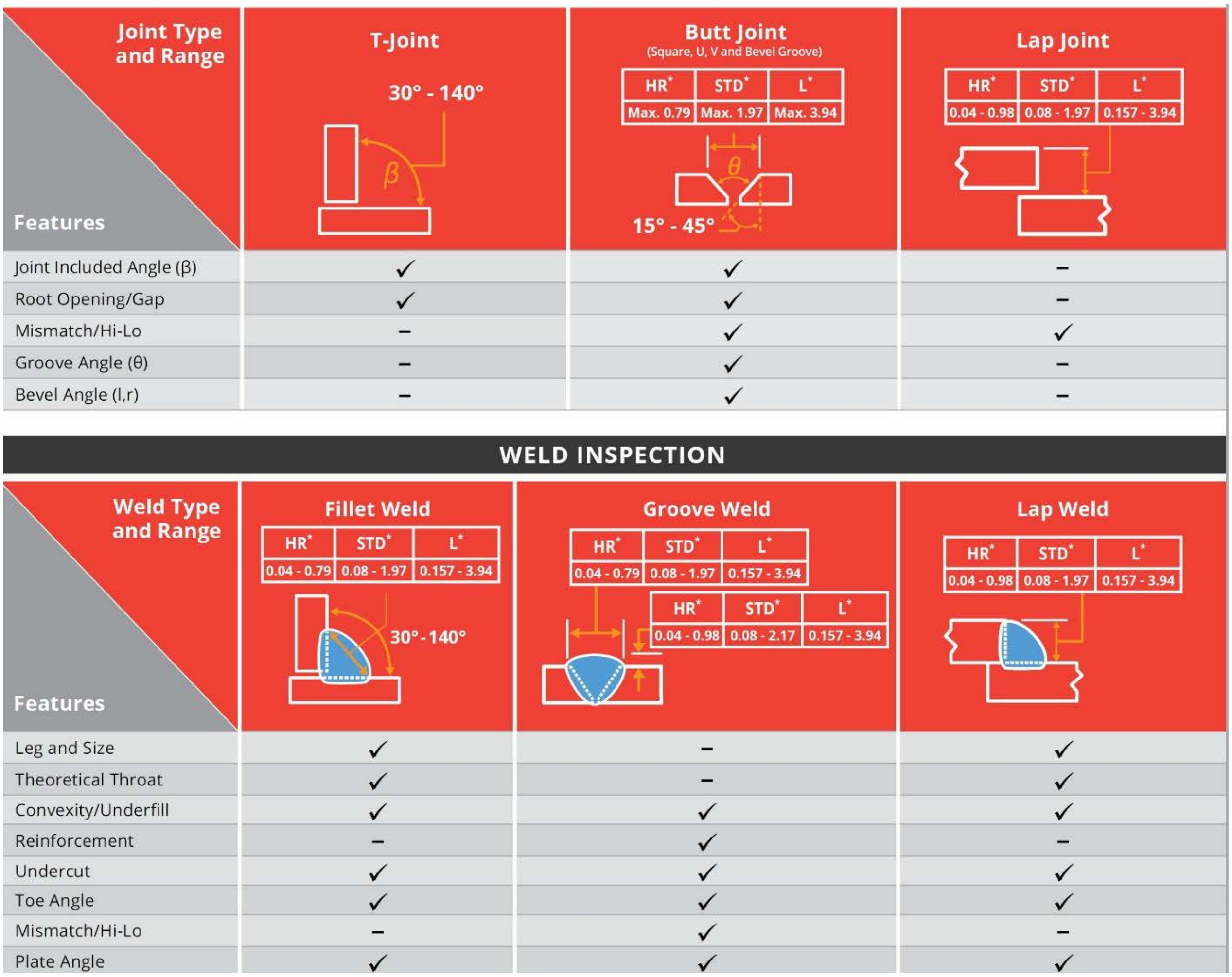
Visual systems come in laser and optical varieties. Several commercial laser scanning systems are available, all of which can detect and dimension many surface characteristics, such as weld defects (e.g., undercut, surface porosity, undersized welds). They are often intended to be part of a robotic system. The robotic focus of these systems generally stems from the need for laser scanners to position the welding head.

Some scanning systems are ready-made for weld assessment, while others would require considerable work to customize the system to detect weld defects, assess weld and joint profiles, etc.

2.1.2.1. Laser scanners

The systems most adapted specifically to the welding industry are those produced by SERVO-ROBOT, Inc. Wiki-SCAN 2.0™ (see **Figure 8**) is a hand-held scanner that is fairly simple to operate and is programmed to detect specific dimensions and defect types. It displays a simple weld profile composed of a handful of data points and identifies and dimensions the profile characteristics shown in **Figure 9**. It can also be used to scan weld joints before welding to verify correct joint preparation and dimensions. Acceptance criteria are programmed into the scanner, and the onboard system documents defects as they are detected through numerical data and by taking a photo using an onboard optical camera. The system has an encoder wheel for identifying defect locations along the joint.

Figure 8. Wiki-SCAN 2.0 hand-held laser scanner (Source: Justin Ocel)



Features \ Joint Type and Range	T-Joint	Butt Joint	Lap Joint
Joint Included Angle (β)	✓	✓	–
Root Opening/Gap	✓	✓	–
Mismatch/Hi-Lo	–	✓	✓
Groove Angle (θ)	–	✓	–
Bevel Angle (l,r)	–	✓	–

WELD INSPECTION

Features \ Weld Type and Range	Fillet Weld	Groove Weld	Lap Weld
Leg and Size	✓	–	✓
Theoretical Throat	✓	–	✓
Convexity/Underfill	✓	✓	✓
Reinforcement	–	✓	–
Undercut	✓	✓	✓
Toe Angle	✓	✓	✓
Mismatch/Hi-Lo	–	✓	–
Plate Angle	✓	✓	✓

Figure 9. Wiki-SCAN 2.0 profile features detected (Source: SERVO-ROBOT, Inc.)

The Pennsylvania Department of Transportation (PennDOT) has purchased a Wiki-SCAN 2.0 unit through their Productivity Innovation Fund and has undertaken a validation program to find the limits of its use. Josh Charnosky of PennDOT demonstrated the use of the device to the scan team, and scan team members had the opportunity to try it for themselves (see **Figure 10**).

Figure 10. PennDOT's Josh Chernowsky and scan team members experimenting with the Wiki SCAN 2.0 (Source: Heather Gilmer)

The Wiki-SCAN 2.0 system uses a red laser and is not suitable for outdoor use in bright sunshine but works well indoors in shop environments.

At this time, the Wiki-SCAN 2.0 device does not measure porosity, but perhaps could be augmented for this capability. Based on discussion with Jeff Noruk of SERVO-ROBOT, it appears that this could add considerable complexity to the on-board system. There are onboard dimensioning tools that an operator could use to size porosity, but since porosity is not detected as a defect (unless it affects throat measurement), the operator would need to return to this area after the encoded scan has been completed to take a photo of the pore and use the dimensioning tools. It is not obvious that this would be more effective than using a conventional metal scale, or even the "calibrated eye" of an experienced inspector. Furthermore, if inspectors must visually scan welds for porosity, they could also be performing a full conventional visual inspection rather than making two passes, one visual for porosity and one with the automated scanner. However, the Wiki-SCAN 2.0 system does have the advantage of creating an electronic record, which conventional methods do not. This system is currently in use at several manufacturers including Crown Equipment Corp. (Bylsma & Noruk, 2020 and 2025) and Caterpillar, Inc.; presumably these companies have found that, for their purposes, the advantages of the Wiki-SCAN 2.0 system outweigh its shortcomings.

SERVO-ROBOT's ARC-SCAN™ system is intended to be mounted on robotic, automated, or mechanized welding equipment and scans the weld immediately behind the arc. It, too, can be used to scan the joint before welding, although SERVO-ROBOT has several other systems specifically intended for this purpose. With the stability of machine-mounting and the use of position sensors, this system provides a more detailed image than Wiki-SCAN 2.0 and can reliably detect and measure porosity down to 1 mm (0.04 in.) in diameter. Many companies' in-line laser scanners provide very detailed point-cloud images (see **Figure 11** for an example), and the systems also provide tools for a human operator to dimension features that were not automatically diagnosed and sized.

Figure 11. Point-cloud image of a weld scanned and rendered using KEYENCE equipment (Source: KEYENCE Corporation of America)

SERVO-ROBOT has several systems that are designed to scan the weld joint before welding, both to position the welding head and to apply adaptive filling techniques to compensate for variation in groove cross-sectional area using their ADAP™ module to adjust the welding parameters in response to the joint geometry. There are other joint scanning and adaptive welding systems on the market as well that adjust welding parameters dynamically based on real-time data or pre-scanned geometry. In bridge welding, groove welds are usually multi-pass, so there is not much need to adapt a single pass to compensate for groove geometry; typically, additional passes are added until the groove is filled. However, adaptations are available for multi-pass welds as well. For example, SERVO-ROBOT'S ADAP can help offset the additional passes at the correct left–right position in the joint and at the correct height in the joint to ensure the best fill level and minimize excessive reinforcement height.

All weld scanning systems rely on direct line of sight to the weld, which makes them unsuitable for detection of subsurface defects. The requirement for line of sight also means that in-line scanning immediately after the weld would not be possible for slag-creating welding processes—essentially, all but GMAW, although the slag created by SAW is easily removed and measures could be put in place to address it so that a second scanning pass might not be required. The scanning systems can be and are used for scanning the weld joint prior to welding.

2.1.2.2. Optical systems

Intel has developed an AI-based solution incorporating off-the-shelf optical and computing systems that uses machine learning models to examine the weld puddle itself in real time. A high-definition ruggedized optical camera that ingests data at 30 frames per second is mounted on the same framework as the welding head and maintains a steady position with respect to the arc, even as the welding head moves with respect to the workpiece. The AI model uses the camera data to examine the puddle and other visual characteristics that correlate with porosity. The application requested from Intel's customer was a system that would detect porosity in fillet welds made using robotic equipment and GMAW and would stop the robotic welder as soon as the anomalous conditions that lead to porosity, such as flares or sparks, are detected. The machine learning system was trained on many sample videos that were coded as no weld, good weld, and porous weld. 16 consecutive frames (representing a half-second interval) were selected as the optimal duration of anomalous conditions for detecting porosity while avoiding false alarms (Thimmanaik et al., 2021).

Correlation of images with other weld types such as butt welds and with other defects, including subsurface defects, is under development at Intel. This work includes both optical cameras and microphones for both video and audio input (Stemmer et al., 2024). The optical system requires direct line of sight to the welding arc, which is incompatible with the use of the SAW process, in which the arc is, by definition, submerged, but can be compatible with other slag-forming processes since the arc itself is still visible. Unfortunately, as previously noted and as further discussed in section 2.4, SAW is currently the most popular process for steel bridge fabrication.

2.1.3. Other data inputs

Several of the presenters identified other sensors that could be used to contribute to the data environment:

- Thermal scanners
- Microphones
- Input from machine settings for travel speed
- Inertial sensors
- Gas flow meters

As noted above, gas flow meters are currently in use for some data collection systems, and encoders for distance (and thus travel speed and defect length) are currently in use for some scanning systems. The use of the other devices for defect detection or prediction is in development but there are presently no robust commercial systems.

2.2. Findings

The uses, or potential uses, of these systems regarding weld quality can be categorized as follows:

- Reduction or prevention of defects
- Compliance monitoring
- Detection of defects

2.2.1. Prevention of defects

The first category, prevention, would be the most beneficial, but appears not to be implemented on a real-time basis, at least not to a greater extent than arc-stabilizing technology already in use even in the bridge industry. A more likely implementation could be a fabricator analyzing the data to help target root causes of defects as part of continuous improvement. The scan team is not aware of anyone doing this, although the electrical signal data has theoretically been available for decades. Also, the use of these "smart" power supplies may not be as widespread in the structural/bridge industry as the vendors believe it is, so there may not be as much "leaving free data on the table" as claimed.

Several of the presenters noted the use of machine learning in defect identification. This can be highly effective in categorizing welds as defective or not, but the system essentially becomes a "black box" comprising a network of many variables, and the results may not be very useful for root cause analysis leading to defect prevention. Furthermore, identification of "good" and "bad" welds might not be possible to correlate with the strict numeric acceptance criteria currently in use. Acceptance of machine learning may require a move away from quantitative assessment.

One way in which the laser scanning systems presented in this report could be used to prevent defects might be to scan the joint prior to welding, rather than the weld itself. Improper fitup and joint dimensions (angle, root opening, etc.) can be a source of defects, and a pre-weld scan could help avoid issues resulting from poor fitup. Many robotic systems already do a preliminary scan prior to welding to ascertain the path the robot will take. The pre-scan can be used to stop the robot from making an unacceptable weld if the fitup is not within what is required, or the robot could adapt to the situation by deploying an alternative procedure more suitable for the fitup at hand. According to Prof. Mendez, Duane Miller, who recently retired from Lincoln Electric, makes a comparison between welds and hamburgers. We order a hamburger and expect it to be good, not because our individual hamburger has been inspected and tested, but because systems are in place in the kitchen that ensure a good hamburger. Ideally, welding process control can improve to the point that we are no longer dependent on after-the-fact inspection.

2.2.2. Compliance monitoring

The scan team agreed that it would be very easy to use data monitoring to determine compliance with approved welding procedures after the fact, for the particular parameters monitored. The currently marketed systems that monitor welding power source electrical signals are limited to just voltage, current, and wire feed speed; other variables such as travel speed, preheat, gas flow rate, and contact-tip–to–work distance would require additional sensors to ascertain. There are multiple software solutions for identifying portions of the dataset that indicate noncompliance. Caution is advised, however, for the use of such data to determine compliance as current welding codes do not offer tolerance bounds for this explicit purpose.

In the AASHTO/AWS D1.5 Bridge Welding Code, for instance, qualified ranges of welding parameters written into a given welding procedure specification (WPS) are not the full range of what could produce a weld meeting Code quality requirements; they are just those ranges that can be considered reliable because they fall within a certain prescribed variation from the exemplar specimen used for the qualification test. Welding variables fluctuate during welding, and with current structural industry inspection practice, monitoring parameters by either the fabricator's or the owner's inspectors is done on a relatively infrequent basis. There are probably many time periods when a welder is operating out of the bounds of the procedure undetected, with no ill effect.

Even under the current system, many owners would not go so far as to require a weld to be cut out and redone if the welder is found to be operating outside of qualified parameters. Typical responses range from issuing an informal warning to requiring the fabricator to perform a new test to qualify the parameters used. Using continuously recorded data would likely lead to far more discovery of "out of parameter" welding, but stopping to address each of those cases would cause much disruption and possibly unneeded repairs, without much gain in bridge quality.

However, akin to the potential "continuous improvement" application described above for data analysis, locating "out of parameter" areas could be used, for example, to target partial inspection, For example, where the welding code requires 10% or 25% inspection, one could use the data to predict areas that might be more likely to have problems, rather than the current practice of using a random or evenly distributed selection. Using certain thresholds to determine likely problem areas could also be an alternative to prescribed percentages for partial inspection.

The data could also be used to assess whether a given welder tends to stay within parameters, and perhaps requires less monitoring, or tends not to stay within parameters, which could indicate a need for further training and increased monitoring and supervision. Consistently compliant data could give owners confidence in the fabricator's quality management system and allow them to potentially reduce duplicative verification inspection and focus their resources elsewhere. Likewise, the data could be used to better focus the fabricator's inspection resources. Some scan team members also thought such compliance monitoring would have its greatest use for field welding, where the same level of control as indoor shop welding may not be feasible.

2.2.3. Defect detection

Defect detection was a result several scan team members were hoping for, because it has the potential to replace human inspection with something more reliable and efficient. However, as already noted, at this time the types of defects that can be identified and evaluated are limited.

2.2.3.1. Laser scanners

Of the laser scanners presented to the scan team, the Wiki-SCAN 2.0 device appears to be the most developed for the welding industry's particular needs, but it needs a human operator, and it is not obvious that this device will be more effective than an experienced inspector with a "calibrated eye", although it does produce a digital record. The inability of the current system to detect and evaluate porosity automatically means there will still be a need to conduct normal visual inspection.

The in-line machine-mounted laser scanners are potentially more reliable and thus more promising, but most are not as far along in their development for structural welding applications and are not suitable for manual or semiautomatic welding. Of the systems reviewed, ARC-SCAN appears to be the most tailored to welding applications. It could be implemented for mechanized, automatic, and robotic systems. However, provisions would need to be made to dislodge the slag from submerged arc welds ahead of the scanner. Furthermore, the slag from FCAW is probably too tightly adhered for any kind of in-line scanner. A second pass could be made after slag removal, but this is probably less efficient than a human inspector examining the weld in the process of slag removal. Again, though, the human inspector does not automatically produce a digital record.

As these systems only scan the surface of the weld, they can potentially substitute for surface examination methods such as visual inspection, magnetic particle testing (which can have slight subsurface capability), and liquid penetrant testing, but cannot substitute for volumetric methods such as ultrasonic and radiographic testing. Additionally, magnetic particle testing and liquid penetrant testing enhance visual inspection, particularly for very small or tightly closed discontinuities; a scanning system would have to be superior to the human eye in recognizing such discontinuities to replace these examination methods.

2.2.3.2. Optical systems

The only optical system-based solution presented to the scan was Intel's system that examined the arc and weld puddle. While this system is potentially quite promising, even for subsurface defects, it cannot be used with SAW, because the arc, as indicated by the process name, is submerged beneath a layer of flux. Unfortunately, SAW is the most popular process in bridge welding because of its high deposition rates and relatively less operator sensitivity than other processes. It is commonly used in mechanized applications. An audio-based solution could be a possible alternative.

The process most favored for robotic welding and additive manufacturing is GMAW, which is a slagless process. However, GMAW is deprecated by many bridge owners. This is primarily because of past issues with misuse of short-circuiting GMAW (GMAW-S). Although the AASHTO/AWS D1.5 Bridge Welding Code has provisions in place prohibiting GMAW-S, and the requirement for procedures to be qualified by testing prevents accidental GMAW-S, many owners are still hesitant to use GMAW. Also, some owners allow neither GMAW nor FCAW because the typical toughness values for these processes trend lower than the typical values for SAW and SMAW—although all processes are required to meet minimum Code toughness requirements, and all processes can potentially have minimum or very high toughness.

The increasing popularity of robotic welding and additive manufacturing could eventually lead to a greater acceptance of GMAW by bridge owners. Furthermore, developments in multi-wire GMAW have greatly increased deposition rates. However, the benefit of the optical arc-examining system currently is not worth the disruption of trying to switch processes.

2.3. General Observations and Conclusions

In general, most of the tools presented would be purchased and used by the fabricator rather than the owner.

All the systems offered digital output, and many offered the potential of remote monitoring.

Although there are systems in current use, from various manufacturers, that can use various inputs to set off alarms or stop production, it does not appear that any of the systems are currently used to create a feedback loop to adjust a process so that problems can be corrected and new defects avoided in real-time (other than the above-mentioned arc-stabilizing technology and adaptive fill technology based on a scan of the joint). Such a feedback system was one of the technologies hoped for in the scan prospectus.

Although during initial research the SME encountered some systems that are intended for small manufacturing cells and would not be suited to large bridge members, all the tools presented to the scan team should be suitable for large workpieces such as girders.

2.3.1. Proliferation of inputs

Scan team members noted that various research efforts are examining various inputs, but no one is looking at everything in combination, and that may be what is needed to get all the information required to diagnose all the defects we now detect with conventional inspection methods. However, mounting the equipment at or near the welding head (other than sensors incorporated into power supplies or wire feeders) is the most effective means of gathering the data, but all the possible sensors implemented at once would make for quite an ungainly piece of equipment. One team member pointed out that perhaps once all possible inputs are implemented on a research basis, it may be determined that certain inputs could be removed and the system streamlined.

In theory, everything that leads to a defect is detectable; it is a matter of what aspects of the welding process (potentially including cooling periods) need to be detected and included in the data environment. However, some inputs are more practical to detect than others. The industry may never get to the point where no human inspectors are needed, but it could get to the point where less inspection is needed, and where owners are comfortable with less verification of the fabricator's quality management.

2.3.2. Practical barriers to implementation

Should the industry get to the point of allowing these systems to substitute for conventional inspection, it might be necessary to consider changes to inspection provisions in the AASHTO/AWS D1.5 Bridge Welding Code, but such discussion is currently premature.

Additionally, provisions would need to be put in place for managing and transferring very large data sets. Some practices for this have already been established with the advent of digital and computed radiography, but the data files from the visual systems could be significantly larger. A balance will need to be struck between file size and scan resolution or information retention. Many of the vendors presenting had systems for cloud data storage and transfer. Furthermore, provisions would need to be put into place to ensure that the data presented has not been adulterated.

2.3.3. Understanding industry needs

Prof. Mendez noted that the equipment manufacturers are not developing systems tailored for the bridge industry because they are not hearing requests, while at the same time it may be that the bridge industry is not making requests because they do not know what is possible. Some of the systems presented during the scan arose from a customer requesting a solution to a specific problem. However, the bridge industry has not, as a whole, identified particular problems needing a solution. The utility and return on investment of these systems for both fabricator and owner cannot be properly assessed without a better understanding of the root causes that most need to be addressed.

Additionally, while better defect detection seems at first glance to be a desirable result, better defect detection without corresponding improvements in productivity will likely not be seen by fabricators to be in their interest. Bridge fabrication is a low-margin industry that frequently uses a low-bid contracting process, and many fabricators have internally determined the optimum balance of time spent striving for perfection versus performing rework on defects that are found through inspection. Perhaps our nation's bridges would better be served not so much through more advanced technology but rather through better incentivizing of quality over production.

For owners to accept the substitution of these systems for human inspection at either fabricator or owner level, they need to come to their own understanding of what would give them the comfort level they need and then balance additional up-front costs against potential reduction in life cycle cost.

2.4. Other Relevant Data Needed to Support the Analysis and Technical Discussions

2.4.1. Welding processes

2.4.1.1. Submerged arc welding

The most used process for steel bridge fabrication is submerged arc welding (SAW). This is a high-deposition process that is usually mechanized, meaning that the welding head is mounted on a self-propelled device, and the welder's role is typically to set the parameters, start and stop the welding process, and monitor the machine during welding. The welder is typically not directly interfacing with the machine during welding. The welding electrode is a continuously-fed wire from a large spool. The welding arc is shielded from the atmosphere by a layer of sand-like flux that covers the end of the welding consumable and the arc itself (see **Figure 12**). No arc is visible during the process. Flux is continuously deposited during the welding process through a tube that is mounted along with the welding head to the tractor-type device. This process is widely preferred because of its high deposition rates, ease of mechanization, ease of slag removal from the completed weld, relatively high toughness, and increased eye safety because the arc is submerged.

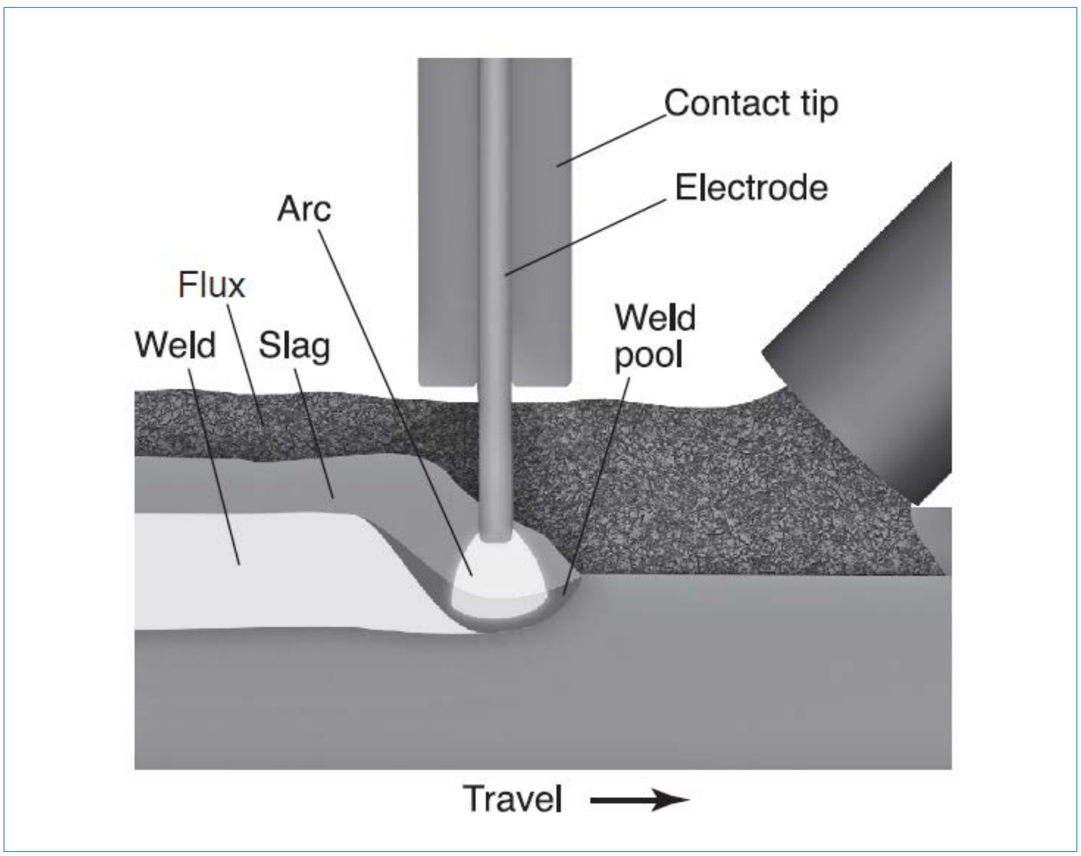


Figure 12. Submerged arc welding process (Source: The Lincoln Electric Company)

2.4.1.2 Shielded metal arc welding

Shielded metal arc welding (SMAW), informally known as "stick" welding, is a manual process using relatively short electrodes (informally called "rods") that are covered in a flux that, when current passes through the electrode, forms a shielding gas. See **Figure 13**. This process is considered less efficient than wire-fed processes because of the need to stop and change electrodes, and some shops no longer use it. SMAW produces a tightly-adhering slag layer on the completed weld that is typically removed using hand or power tools.

Figure 13. SMAW electrodes (Source: The Lincoln Electric Company)

2.4.1.3. Flux-cored arc welding

Flux-cored arc welding (FCAW) can be thought of as an "inside-out" SMAW electrode—a tubular hollow wire is filled with a granular flux that forms a shielding gas. Subtypes of FCAW are FCAW-S, self-shielded FCAW, in which the shielding gas formed by the flux is sufficient to shield the arc, and FCAW-G, gas-shielded FCAW, in which a supplemental shielding gas is used. See Figure 14. FCAW can be mechanized in a manner similar SAW, or can be semi-automatic, meaning that the wire feed speed is automated but the welding head location, and thus the travel speed, is manually controlled by the welder. FCAW is often used for short welds for which a mechanized setup is not practical. Like SMAW, FCAW produces a tightly adhering slag layer. For historical reasons, some bridge owners restrict the use of FCAW for bridge welding, but the AASHTO/AWS D1.5 Bridge Welding Code places no such restrictions on its use, and it is permitted for the same applications as SAW.

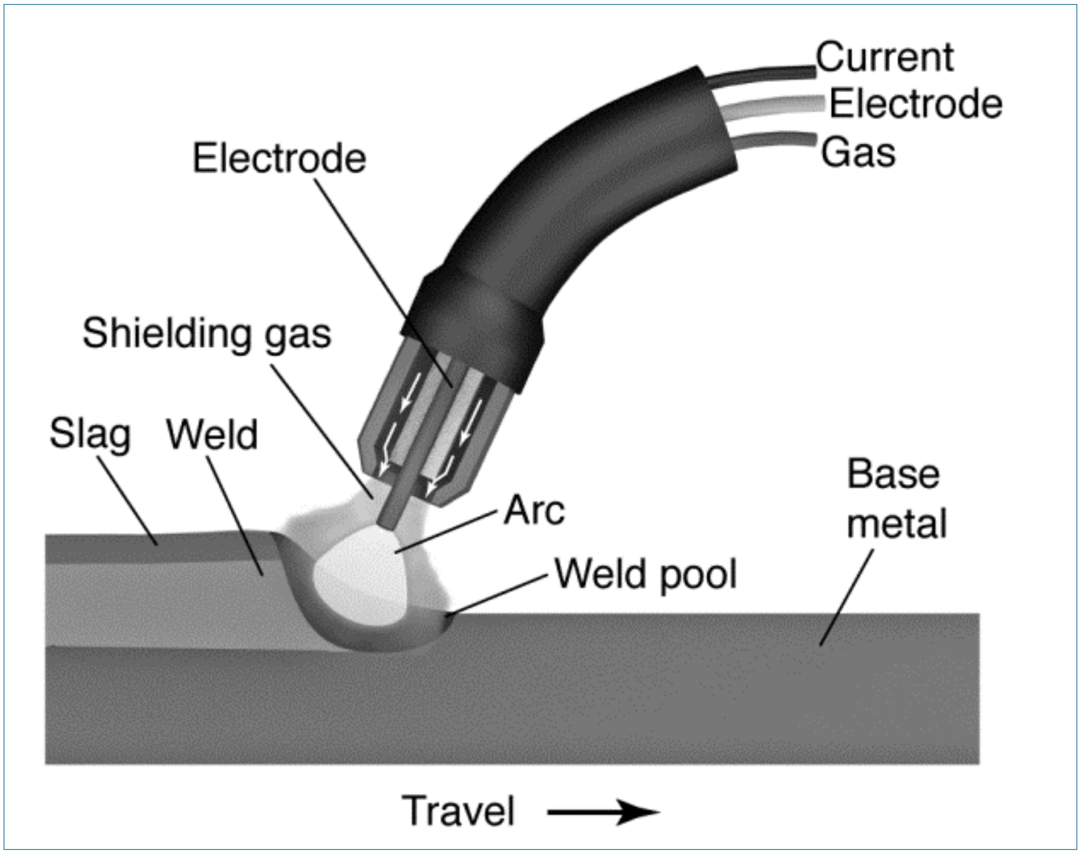


Figure 14. Submerged arc welding process (Source: The Lincoln Electric Company)

2.4.1.4. Gas metal arc welding

Gas metal arc welding (GMAW) is another wire-fed process that can be mechanized or semi-automatic. It also is popular for robotic applications, including additive manufacturing ("3D printing") because it does not produce slag that needs to be removed manually. It requires a shielding gas.

GMAW with metal-cored electrodes is like FCAW in that the electrode is a hollow wire filled with granular material, but in this case the granular material is metal powder for alloying purposes. Until a few decades ago, the American Welding Society welding codes considered GMAW with metal-cored electrodes to be a type of FCAW, and in the current American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, FCAW and GMAW are considered variations of the same process. Like FCAW, some bridge owners restrict the use of GMAW, but the AASHTO/AWS D1.5 Bridge Welding Code places no restrictions on GMAW with metal-cored electrodes, and it is permitted for the same applications as FCAW and SAW.

GMAW can also use solid wire electrodes with no granular metal core. The use of GMAW with solid electrodes for bridges is restricted because of a subtype of GMAW that uses solid electrodes, short-circuit GMAW (GMAW-S). GMAW-S is a low heat-input process that is particularly useful for welding thin materials or pipeline weld roots without burning through the base metal. For thicker material, however, this process can result in poor fusion between the weld and base metal, and historically there have been some in-shop failures of girders where this process was misapplied for web-to-flange welds. Consequently, the AASHTO/AWS D1.5 Bridge Welding Code curtails the use of GMAW with solid electrodes. GMAW-S is currently not permitted at all without Engineer approval, and only GMAW with metal-cored electrodes is permitted for fracture-critical applications so as not to allow even the possibility of GMAW-S.

2.4.1.5. Gas tungsten arc welding

The gas tungsten arc welding (GTAW) process uses a non-consumable tungsten electrode and shielding gas. It can be used with or without manually-fed filler metal; without filler metal, the weld is formed solely from melted base metal. GTAW is typically used for very thin material. It is outside the scope of the AASHTO/AWS D1.5 Bridge Welding Code but is sometimes used for attaching thin stainless-steel sheets used as sliding bearing surfaces.

2.4.2. Thermal controls

The cooling rate of a weld affects its microstructure and thus its mechanical properties, including toughness, ductility, hardness, and strength. It also affects the diffusion of hydrogen from within the weld and the likelihood of cracking, as well as residual stresses and distortion. Welding procedure specifications regulate parameters that affect the cooling rate, including travel speed, amperage, voltage, heat input (a function of the previous three parameters), preheat, interpass temperature, and post heat.

One of the parameters that can be recorded by some of the equipment discussed in this report is the t8/5 cooling time, which is the time it takes the weld to cool from 800°C to 500°C. This parameter is the reciprocal of the cooling rate between those temperatures. It is typically not directly managed during welding and is not mentioned in the AWS welding codes but can be used in procedure development.

Recommendations and Implementation Plan

3.1. Recommendations

Although there had been a perception at the outset of this scan that advanced systems were in regular use in other industries, none of the systems presented during the scan seem ready for broad implementation in the steel bridge industry on a widespread basis at this time.

3.1.1. Potential Future Research

- Better determination from bridge-industry stakeholders of what the real problems are that need to be solved
- Continuation of Prof. Mendez's research (either by his team or others) to determine:
  - What data variables need to be recorded by what sensors to identify all defect types needed
  - Better relationship of data signatures to defects
  - How few sensors would suffice in production
- Adding more data types (e.g., both electrical and optical, or optical and sound) into machine learning model
- Correlating laser scanner performance with experienced human "calibrated eye"
- Use of feedback:
  - Use of feedback loops for better quality, or other purposes
  - Instantaneous versus later analysis
  - More real-time adjustment based on feedback versus data analysis for continuous improvement
  - Use of data thresholds to trigger inspection rather than prescribed fixed percentages
- Applying machine learning to prior machine learning "yes/no" results to determine root causes
- Detection of subsurface defects
- Increasing use of GMAW
- Contracting mechanisms (not only at contractor level but at fabricator level) to encourage quality over rework

As no technology was found currently ready to implement, the only "implementation" appropriate at this time is (a) presentation of scan results at various venues and (b) encouragement of the identified potential research topics through typical research funding channels.

Appendix A: Scan Itinerary

- Week 1: Lancaster, PA
  - Monday, August 26, 2024
    - ESAB remote presentation
    - High Steel presentation and tour
  - Tuesday, August 27, 2024
    - Pennsylvania DOT in-person presentation and demonstration
  - Wednesday, August 28, 2024
    - Lincoln Electric remote presentation
    - KEYENCE remote presentation
    - Prof. Patricio Mendez remote presentation
    - Intel remote presentation
- Week 2: Peoria, IL
  - Monday, August 26, 2024
    - Caterpillar tour and presentation
    - SERVO-ROBOT remote presentation

Appendix B: Amplifying Questions

Questions for users of the technology (for each technology):

- What is the technology?
- What products do you produce using this technology? How much of that per year?
- How much of your welding for those products uses this technology?
- How did you decide what aspects of your production to use this technology in?
- How big is the product?
  - If fairly small (made in manufacturing cell), do you think this technology might be adaptable to very large items such as bridge girders?
- Is it primarily for:
  - Production?
  - Producing higher-quality welds?
  - Inspection after welds are produced?
- What made you consider this technology?
- What was the deciding factor for using it?
- Were there any impediments to adoption?
  - If so, what were they?
  - From which parties?
  - Was data storage or transmission an issue?
- How are welding parameters physically controlled, if not by this technology?
- Describe your QC/QA process regarding welding.
  - What is the frequency of inspection?
  - Do you use nondestructive testing? How much?
- Are your manufacturing, inspection, and quality requirements primarily based on internal criteria (up to the producer, voluntary), or external (dictated by others)?
  - If external, is it customer standard or industry/national/international standard?
  - What are those standards?
- What kind of automated feedback is possible with this system?
- [For visual scanning systems] Is this used real-time as the weld is being made, or after the weld is completed? Pre-weld inspection of joint & fitup?
  - If real-time, do you use it with submerged arc welding? Flux-cored arc welding?
  - Can adjustments be made without starting & stopping the weld?
  - Is it used for both fillet and groove welds?

- What kind of training or certification is needed to use it? How different is it from "conventional" welder training/certification/qualification?
- How is the equipment verified or calibrated?
- Have the customers requested or used the data?
- Has the use of this technology resulted in any changes to your quality system?
  - If so, what were they?
- Has the use of this technology resulted in any other changes to your production methods?
  - If so, what were they?
- Has the use of this technology reduced your reject/rework rate?
  - Did it increase it because of improved detection?
  - Did it decrease because of improved performance?
  - If so, in what way? Which defects?
- Has the use of this technology resulted in changes to customer requirements for your inspection practices or any other customer requirements?
  - If so, what are those changes?
  - Were you the party who requested the changes?
  - What concerns did the customer have prior to approving these changes?
- Are you able to tell us the cost of the equipment you've purchased to implement this technology?
  - Total and per setup?
  - Cost relative to "conventional" equipment?

Questions for equipment producers:

- is the technology?
- Is it primarily for
  - Production?
  - Producing higher-quality welds?
  - Inspection after welds are produced?
- What are its advantages from a quality standpoint?
- What kind of industries are using it?

- Do you see this technology as adaptable to large (long) bridge girders in a shop environment? Longitudinal or spiral seams in pipes?
- What kind of training or certification is needed to use it?
- How is the equipment verified or calibrated?
- What kind of automatic feedback is available with this system?
- [For visual scanning systems] Is this used real-time as the weld is being made, or after the weld is completed? Pre-welding joint inspection?
    - If real-time, what welding process will/won't it work with? (E.g., will it only work with slagless processes?)
    - Can adjustments be made without starting & stopping the weld?
- How much does it cost?
- Are you familiar with AASHTO/AWS D1.5 or AWS D1.1?
    - If so, do you know about anything in D1.5 or D1.1 that would be an impediment to adoption of this technology?
- Have you discussed this technology with bridge owners or fabricators?
    - If so, did you get any feedback and from whom?
        - Positive or negative?
        - What was the positive?
        - What was the negative?

Questions for “mainstream” bridge fabricators that aren't using the technology (for each technology):

- What DOT products do you produce?
- To what welding codes?
- Have you heard of this technology?
- Have you tried it?
    - Why/why not?
    - If you did, why did you stop?
- If you haven't tried it, have you considered using it?
    - Why/why not?
    - If you have, what do you think the advantages would be?
- Production?
- Quality?

- What are the impediments?
  - Internal (fabricator themselves), external (e.g., customers), both?
  - Cost? Regulatory?
  - Durability/maintenance?
  - Data transmission/storage?
  - Other?
- What changes in steel bridge requirements or practices would make it feasible for you?
- What changes in steel bridge requirements or practices would make it advantageous for you?
- Is there other technology you have heard about that we haven't asked you about?
- Are there any other questions we should be asking?

Questions for DOTs (for each technology):

- What is your jurisdiction?
- Approximately what tonnage of steel bridges per year is produced for your state?
- Do you require quality beyond AASHTO/AWS D1.5?
- What is your DOT's current in-house (or contracted) inspection/verification practice?
- Have you heard of this technology?
- Do you know anyone who uses it?
- Does it interest you?
  - If so, what about it interests you?
- What don't you like about it?
- Can you envision implementation?
  - If so, in what way?
  - If not, why not?
- Is there something that might be changed about it that would make it more appealing to you?
- Does this technology conflict with your current specifications?
- Do you think this could be used to permit some changes to your requirements for fabrication?
- Do you think this could be used to change your own inspection/verification practices?
- Are there any other questions we should be asking?

Appendix C: Team Member Biographies

Xiaohua "Hannah" Cheng, Ph.D., P.E., is Supervising Engineer with Structural Engineering Services of New Jersey Department of Transportation (NJDOT). Her primary duties include development and update of design/construction/maintenance policies, manuals, standards, and guidance for State highway bridges, safety features and traffic structures by implementation of AASHTO, FHWA and State requirements, new technologies and lessons learned. Her duties also include the development of special design and construction criteria for major bridge projects, such as extreme events and resolutions of issues encountered during construction and fabrication. Her work also includes supervision and management of the Bridge Resource Program (BRP), Local Aid bridge rehabilitation selection program, and staff augmentation program. She develops problem statements, reviews proposals and oversees State research projects in various topics, such as Bridge Scour, Seismic Design, Steel Orthotropic Deck, Weigh in Motion (WIM), multi-hazard bridge design, transportation infrastructure, etc. Dr. Cheng serves AASHTO COBS (Committee on Bridges and Structures) as a member representing New Jersey. Within the COBS, she is serving on Technical Committees of Steel and Metals, Loads and Analysis, Traffic Structures, and Research. She was/is a member of several committees, task forces, and panels of TRB (Transportation Research Board), NCHRP (National Cooperative Highway Research Program), and ASCE (American Society of Civil Engineers). Before joining in NJDOT, she was a researcher in bridges and structures with ATLSS Research Center, Lehigh University, and Public Works Research Institute (PWRI), Japan, and worked with consultants as a structural engineer. She is a registered Professional Engineer in Pennsylvania.

Mark Daniels holds a Master's Degree in Civil Engineering and is a licensed Structural Engineer. He has over 20 years of building and bridge design experience, including steel fabrication and erection, seismic design, and bridge design. His current role is Structures Design Manager at the Utah Department of Transportation.

Leslie Daugherty is the Chief Bridge Engineer with the Alaska Department of Transportation & Public Facilities (DOT&PF) in Juneau, Alaska. She graduated with a Bachelor of Science in Civil Engineering and Master of Science in Welding Engineering from Ohio State University. She is the chair of the AASHTO Committee on Bridges and Structures (COBS) Technical Committee for Bridge Components and a member of the COBS Technical Committee for Steel & Metals. She is currently the Chair of the TRB AKC70 Standing Committee on Fabrication and Inspection of Metal Structures. Ms. Daugherty is a licensed Professional Engineer in the States of Alaska, Pennsylvania, and Ohio, and a licensed Structural Engineer in the State of Alaska.

Bryan A. Hartnagel is the State Bridge Engineer of Missouri Department of Transportation. Dr. Hartnagel joined the staff of the Missouri Department of Transportation (MoDOT) in June 2002. Currently, he holds the position of State Bridge Engineer since August 2021. In this role he oversees the Program Delivery and Bridge Management sections in the Bridge Division. MoDOT maintains approximately 10,400 state owned structures and oversees the inventory of approximately 14,100 Local Public Agency structures. Bryan Hartnagel holds a bachelor of science (1989), a master of science (1993) and a doctor of philosophy (1997) in civil engineering from the University of Missouri – Columbia. Prior to joining MoDOT, Dr. Hartnagel held the positions of Research Assistant Professor at the University of Missouri – Columbia and Assistant Professor at Colorado State University. While at these positions Dr. Hartnagel taught courses in Statics, Strength of Materials, Structural Analysis and Steel Design. His doctoral research was on inelastic design of steel girder bridges. Dr. Hartnagel is a registered Professional Engineer in the states of Missouri and Colorado.

Reginald Lee serves as the Chief of the Inspection Service Branch within the Office of Materials and Testing at the Georgia Department of Transportation (GDOT). With over four decades of experience in the transportation industry, he brings deep expertise in highway materials and structural steel inspection. Mr. Lee earned his undergraduate degree in Civil Engineering Technology from Savannah State College. He holds ASNT Level II certifications in Visual Testing (VT), Ultrasonic Testing (UT), Magnetic Particle Testing (MT), and Penetrant Testing (PT). Throughout his career, he has managed key projects, including overseeing GDOT's structural steel fabrication and testing service consultant contracts. In addition to his technical leadership, Mr. Lee acts as a liaison between GDOT's Office of Materials and Testing (OMAT) and the State Bridge Office, ensuring alignment and collaboration across departments.

Michael Leonard is the Metals Control Engineer at the Massachusetts Department of Transportation (MassDOT). He has been with MassDOT for over 15 years, primarily serving in the Quality Assurance division. For the past three years, he has led the Metals Control program, overseeing the fabrication and quality compliance of all metal products used in MassDOT projects. In this role, Michael earned the distinction of becoming a voting member of the AWS D1.5 Bridge Welding Committee, contributing to national standards in bridge welding practices. He holds a Bachelor of Science in Civil Engineering from Rutgers University, where he specialized in Structural Engineering, graduating in 2010.

Justin Ocel has been a Senior Structural Engineer with the Federal Highway Administration's Resource Center since 2021, providing steel bridge expertise to internal and external stakeholders. He received Bachelor of Science and Doctorate degrees from the University of Minnesota, and a Master of Science from the Georgia Institute of Technology. Justin began his career with FHWA in 2009 as the Structural Steel Research Program Manager at the Turner-Fairbank Highway Research Center. His research program included a diverse range of topics regarding fatigue, welding technologies, assessment of cable stays to threats, steel truss gusset plated connections, slip and creep of coatings, and he participated in the NTSB collapse investigations of the I-90 Seaport Connector Tunnel ceiling, I-35W, FIU Pedestrian, and Forbes Avenue Bridges. He's authored 7 refereed journal articles, 28 FHWA reports, and delivered numerous conference presentations. He currently serves as the FHWA ex-officio to the AASHTO Committee on Bridges and Structures "Traffic Structures" committee, and formerly to the "Steel" and "Welding and Fabrication" committees. Justin is a registered Professional Engineer in the state of Virginia.

Cornelius D. Wright serves as the Inspection Services Assistant Branch Chief at the Georgia Department of Transportation (GDOT), bringing over 26 years of dedicated service to the department. In his role, he is a leader in overseeing the daily operations of quality assurance and nondestructive testing (NDT) to ensure the structural integrity and safety of Georgia's transportation infrastructure. With ASNT Level II certifications in Visual, Ultrasonic, Magnetic Particle, and Penetrant Testing, Mr. Wright possesses deep technical expertise. He also acts as a Project Manager for GDOT's structural steel fabrication and testing service consultant contract, ensuring compliance with state and federal requirements. Throughout his career, Mr. Wright has played a pivotal role in mentoring junior inspectors and collaborating with contractors, engineers, and agency partners. His decades of service reflect a steadfast dedication to public service and upholding the highest standards of quality and resilience in Georgia's transportation network

Justin Ocel has been a Senior Structural Engineer with the Federal Highway Administration's Resource Center since 2021 providing steel bridge expertise to internal and external stakeholders. He received a Bachelor of Science and Doctorate degrees from the University of Minnesota, and a Master's of Science from the Georgia Institute of Technology. Justin began his career with FHWA in 2009 as the Structural Steel Research Program Manager at the Turner-Fairbank Highway Research Center. His research program included a diverse range of topics regarding fatigue, welding technologies, assessment of cable stays to threats, steel truss gusset plated connections, slip and creep of coatings, and participating in the NTSB collapse investigations of the I-90 Seaport Connector Tunnel ceiling, I-35W, FIU Pedestrian, and Forbes Avenue Bridges. He's authored 7 refereed journal articles, 28 FHWA reports, and delivered numerous conference presentations. He currently serves as the FHWA ex-officio to the AASHTO Committee on Bridges and Structures "Traffic Structures" committee, and formerly to the "Steel" and "Welding and Fabrication" committees. Justin is a registered Professional Engineer in the state of Virginia.

Heather Gilmer is a nationally recognized steel fabrication expert with 25 years of experience in structural steel bridge fabrication and coating, providing technical consultation and quality management related to steel bridge projects. She is a highly regarded contributor to many bridge-related codes and standards and was a 2024 recipient of the AISC Lifetime Achievement Award. With her experience as both a Texas DOT engineer and a steel fabrication shop quality manager, Ms. Gilmer offers a multifaceted perspective on fabrication issues. She now is a Senior Engineer with Pennoni.

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Appendix F: References

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