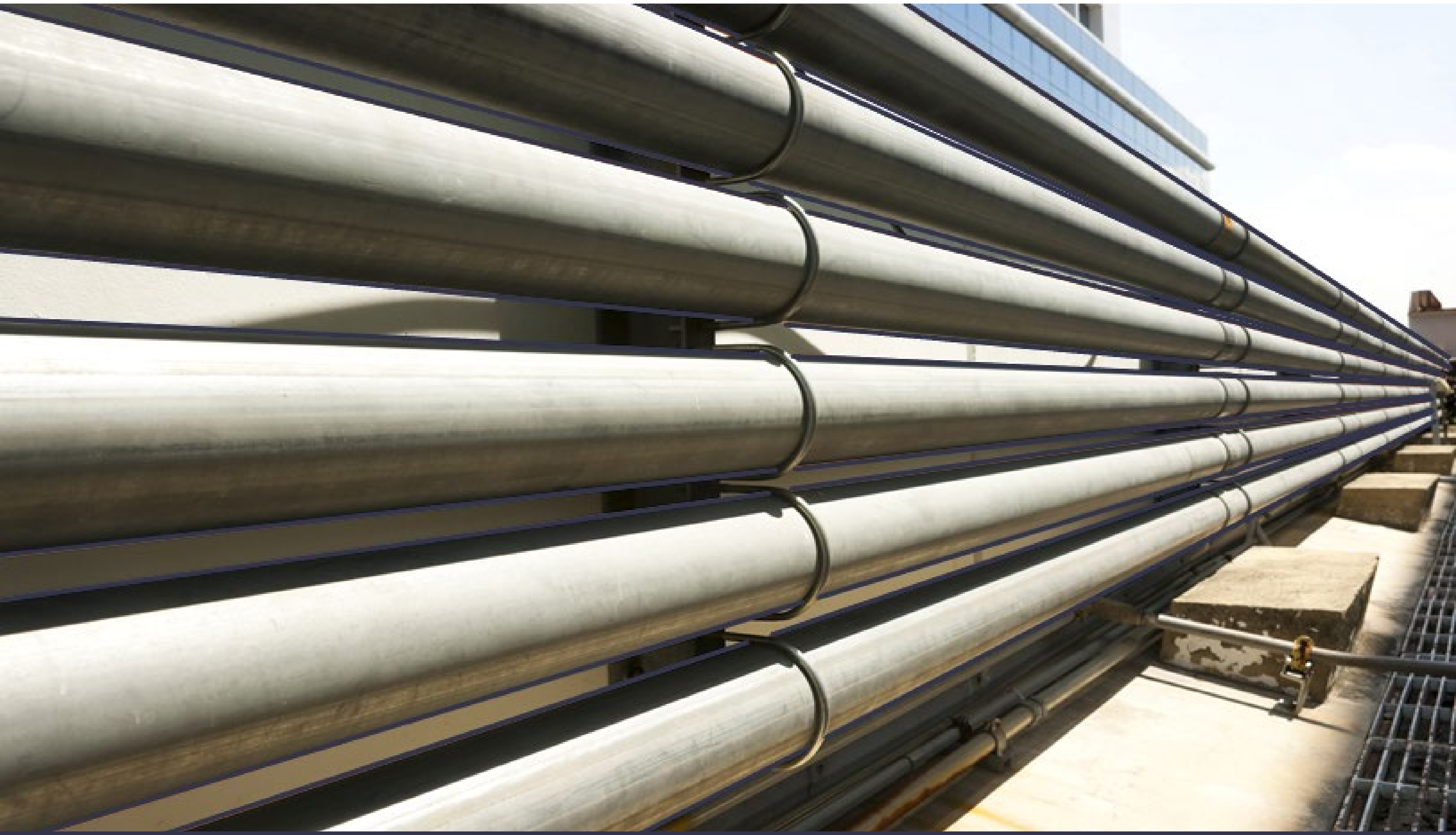
U.S. Department of Transportation (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA)
Final Report No. 26-30994-6000754R-Task 7

Validation to Confirm Threats Result from Hydrogen Service

Michiel P. Brongers, PE
August 24, 2026



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to

U.S. Department of Transportation (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA)

on

August 24, 2026

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Executive Summary

This Task 7 report was prepared by Kiefner and Associates, Inc. (Kiefner) as part of the research project titled "Investigate Damage Mechanisms for Hydrogen (H_2) and Hydrogen/Natural Gas Blends to Determine Inspection Intervals for In-Line Inspection (ILI) Tools" for the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA), under Contract 693JK32310011POTA.

This report supports PHMSA by validating whether observed pipeline integrity threats in hydrogen service are directly attributable to hydrogen or influenced by other mechanisms. The study confirms that hydrogen can significantly reduce fracture toughness and accelerate fatigue crack growth, thereby shortening the remaining life (RL) of defects and requiring more conservative integrity management, including reduced inspection intervals.

Hydrogen-related threats—including embrittlement, hydrogen-assisted cracking, and hydrogen-induced cracking—were evaluated alongside interacting mechanisms, including fatigue and stress-corrosion cracking (SCC). No single ILI technology can detect all hydrogen-related threats; a combination of inspection methods and improved data standardization is recommended.

The study also evaluates hardness as an indicator of susceptibility to hydrogen damage. Results show that while automated hardness mapping provides broader coverage, it may miss peak hardness in narrow weld regions, where manual measurements are more reliable. Overall, effective integrity management in hydrogen service requires integrated inspection strategies, refined threat definitions, and careful assessment of weld properties.

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List of Acronyms and Abbreviations

AI	Artificial Intelligence
AMPP	Association for Materials Protection and Performance
API	American Petroleum Institute
ART	Acoustic Resonance Technology (ILI technology)
ASME	American Society of Mechanical Engineers
CE	Carbon Equivalent
CFR	Code of Federal Regulations
CGR	Crack Growth Rate
CNT	Circumferentially Notched Tension (specimen)
CP	Cathodic Protection
CSA	Canadian Standards Association
DC	Direct Current (ERW)
DEF	Deformation (ILI technology)
DNV	Det Norske Veritas
DSAW	Double Submerged Arc Weld
DVGW	German Technical and Scientific Association for Gas and Water
DOT	U.S. Department of Transportation
ECA	Engineering Critical Assessment
EMAT	Electromagnetic Acoustic Transmission (ILI technology)
ERW	Electric Resistance Welded
FFS	Fitness-For-Service
FW	Flash Weld
GEO	High-Resolution Geometric (ILI technology)
gf	Force Measured in Grams
GW	Girth Weld
HAC	Hydrogen-Assisted Cracking
HAZ	Heat-Affected Zone
HB	Brinell Hardness
HE	Hydrogen Embrittlement
HEC	Hydrogen-Enhanced Cracking
HF	High Frequency (ERW)
HIC	Hydrogen-Induced Cracking
HSC	Hydrogen Stress Cracking
HTHA	High-Temperature Hydrogen Attack
HV	Vickers Hardness
ID	Inside Diameter (Surface)
IDOD	Internal/External Sensors
IGEM	Institution of Gas Engineers and Managers
ILI	In-Line Inspection
IM	Integrity Management
IMU	Inertial Measurement Unit
IPC	International Pipeline Conference
kgf	Force Measured in Kilograms
Kiefner	Kiefner and Associates, Inc.
LF	Low Frequency (ERW)
LFM	Low Field Axial Magnetic Flux Leakage (ILI technology)
MDS	Multiple Data Set
MFL	(High Field) Magnetic Flux Leakage (ILI technology)
NDE	Non-Destructive Examination

NG	Natural Gas
OD	Outside Diameter (Surface)
PHMSA	Pipeline and Hazardous Materials Safety Administration
POD	Probability of Detection
POI	Probability of Identification
POS	Probability of Sizing
PWHT	Post-Weld Heat Treated
RES	Residual Magnetic Flux Leakage (ILI technology)
RL	Remaining Life
SCC	Stress Corrosion Cracking
SDO	Standards Developing Organization
SME	Subject Matter Expert
SMFL	Spiral Magnetic Flux Leakage (ILI technology)
SOHIC	Stress-Oriented HIC
SSAW	Single Submerged Arc Weld
SSC	Sulfide Stress Cracking
SSWC	Selective Seam Weld Corrosion
TAP	Technical Advisory Panel
UT-CD	Ultrasonic Technology Crack Detection (ILI technology)
WPS	Welding Procedure Specification
WT	Wall Thickness

1 INTRODUCTION

This Task 7 report was prepared by Kiefner and Associates, Inc. (Kiefner) as part of the research project titled "Investigate Damage Mechanisms for Hydrogen (H_2) and Hydrogen/Natural Gas Blends to Determine Inspection Intervals for In-Line Inspection (ILI) Tools" for the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA), under Contract 693JK32310011POTA.

The literature on hydrogen embrittlement (HE) is extensive. One of the earliest HE-references[1] is from 1874, when Prof. Sir William Thompson reported:

> *"… a remarkable change in some of the physical properties of iron caused by its temporary immersion in hydrochloric and sulphuric acids. This change is at once made evident to any one by the extraordinary decrease in toughness and breaking-strain of the iron so treated, and is all the more remarkable as it is not permanent, but only temporary in character, for with lapse of time the metal slowly regains its original toughness and strength.", and;*

> *"… The amount of carbon in the steel appears, moreover, to be connected…; for in mild Bessemer steels, containing about 0.20 to 0.25 per cent of carbon, the change is a very little more marked than in iron.", and "With an increased percentage of carbon the action, however, is more marked and of longer duration.", and "… piece of steel containing, say, 0.60 per cent of carbon … render it so brittle that no amount of exposure to the air or heat will ever completely restore it."*

Since the 1950s, many articles and reports on HE have been published. "Classic" HE references describing materials compatibility, mechanisms, mechanics, design, and prevention, include a 1954 Technical Report by Fromberg et al.[2], the 1988 ASTM Special Technical Publication (STP) 962[3], two 2012 volumes by Gangloff and Somerday[4,5], a 2012 technical reference by San Marchi and Somerday[6], a 2023 book by Nagumo[7], and a 2024 book by Matsunaga et al.[8].

When performing an integrity assessment of a pipeline carrying hydrogen gas, one might wonder whether pressurized gaseous hydrogen is the actual cause of the integrity threat, a contributing factor, or a benign condition present but unrelated to that threat. Most researchers agree that reduced fracture toughness and increased fatigue crack growth rates are the dominant direct hydrogen-related threats for transmission and distribution pipelines. Hydrogen blending with natural gas (NG) does not eliminate HE, and a material properties assumption for 100% hydrogen exposure is prudent for integrity management.

Hydrogen effects are often suspected in pipeline failures, but they are challenging to prove because the microstructural features can be invisible ("embrittlement" is not a feature but a material property) or obscured by damage related to the leak or rupture incident (e.g., deformation, fire damage). In other cases, hydrogen might be a contributing factor to a failure, but not the primary cause. Examples of such situations include acceleration of the crack growth rate (CGR) of fatigue cracking, corrosion-fatigue cracking, and stress corrosion cracking (SCC).

Based on the combined findings from the prior Tasks 1 through 6 work[9,10,11,12,13,14] of this project, the present report provides further discussion and:

1. Describes different hydrogen-related failure mechanisms and effects, and how they may be incorporated with the recognized integrity threats per ASME B31.8S[15] "Managing System Integrity of Gas Pipelines";
2. Provides data on reduced fracture toughness and increased fatigue crack growth rates with hydrogen;
3. Discusses non-hydrogen threats that may be affected by hydrogen (e.g., SCC);
4. Explains that low partial pressure of hydrogen can cause HE (e.g., 1% hydrogen blended in NG, or 100% hydrogen at a low operating pressure);
5. Explains how different methods to determine maximum hardness in carbon steel welds can be used to screen for HE susceptibility before pipeline repurposing; and
6. Presents how hardness mapping compares with individual hardness indent measurements, as described in industry standards such as API STD 1104[16,17], ANSI/NACE MR0175/ISO 15156[18], ASME B31.12[19], and ASME B31.8S[15].

2 OBJECTIVE

The objective of this task was to assess whether the threats discussed in prior tasks are truly due to hydrogen effects or whether other failure mechanisms may be dominant. The intention of this document is that it can be used for further discussion by industry groups, standards development organizations (SDOs), and in technical forums organized by DOT/PHMSA.

3 SCOPE

The scope of work consisted of reviewing and evaluating the research findings compiled in the prior tasks of this project, which gathered information from the global industry's experience with the transportation of hydrogen and hydrogen-blended gas by pipeline. The results were discussed with the Project Team, which included metallurgical, corrosion, and integrity engineers, and with the Technical Advisory Panel (TAP), which consisted of subject-matter experts (SMEs), representatives from pipeline operating companies, universities, ILI companies, independent consultants, and government. The intent was to capture the various opinions on pressurized gaseous hydrogen as an actual cause of a mechanical integrity threat, a contributing factor, or a benign condition present but unrelated to that threat.

By improving the understanding of which threats are hydrogen-caused, hydrogen-related, or hydrogen-agnostic, more informed decisions can be made for pipeline integrity management, including setting reinspection intervals.

4 DISCUSSION

4.1 Literature Review

4.1.1 Overview

For the literature review (Task 1 of this project), 1,100+ papers, articles, and reports were collected; refer to APPENDIX A – LITERATURE LIST. This represents a comprehensive body of work addressing hydrogen transport in pipeline systems, with emphasis on materials performance, asset integrity, regulatory frameworks, and infrastructure repurposing. Spanning foundational studies from the mid-20th century through the most recent research (2023–2026), the documents collectively establish a technical basis for the safe design, operation, and conversion of NG pipelines to hydrogen or hydrogen-blended service.

A dominant theme across the literature review was hydrogen interactions with pipeline materials, particularly HE, fatigue, and fracture behavior in carbon and low-alloy steels commonly used in transmission and distribution pipelines (e.g., Specification API 5L [20] grades X52 to X100). Experimental investigations, fracture mechanics analyses, and computational modeling examined hydrogen diffusion, trapping, crack initiation, and crack growth under cyclic and static loading. Several studies focused on weld metal, heat-affected zones (HAZs), vintage steels, and seam welds, identifying microstructural features and environmental conditions that influence susceptibility to hydrogen-assisted degradation.

The literature review also addressed pipeline integrity management and assessment methodologies. These documents describe fitness-for-service (FFS) approaches, defect acceptance criteria, and burst- or fatigue-life prediction methods adapted for hydrogen environments. Advances in ILI, ultrasonic testing, electromagnetic acoustic transducers, and crack-detection reliability were discussed alongside probabilistic risk assessment and integrity threat characterization. Case studies and compendia from industry research consortia summarized historical failures, lessons learned from inspections, and best practices for managing cracking, corrosion, and hard-spot threats.

In addition to the technical research, the literature review included references to codes, standards, and regulatory guidance. Key documents from SDOs, such as the American Society of Mechanical Engineers (ASME), American Petroleum Institute (API), Canadian Standards Association (CSA), Det Norske Veritas (DNV), Institution of Gas Engineers and Managers (IGEM), German Technical and Scientific Association for Gas and Water (DVGW), and the Association for Materials Protection and Performance (AMPP), define requirements for pipeline design, construction, testing, and operation in hydrogen service. It was found that the various Codes and Standards cross-reference each other, with most leading back to ASME B31.12[19] and BS7910[21].

Collectively, the referenced works provide an integrated technical foundation for assessing hydrogen pipeline readiness and inform future research, standards development, and regulatory decision-making.

4.1.2 Hydrogen Terminology

The term "hydrogen" can refer to three distinct chemical and physical forms:

- Hydrogen atom, H: A single particle with one proton and one electron. When adsorbed onto a metal, the electron joins the delocalized electron sea of the metal lattice.
- Hydrogen ion, H^+: A positively charged proton formed when a hydrogen atom loses its valence electron.
- Hydrogen molecule, H_2: A stable diatomic compound of two hydrogen atoms sharing their electrons. It remains a gas at ambient temperatures, even under extreme pressure.

When discussing hydrogen ingress and HE with respect to pipeline integrity, we refer to hydrogen atoms and their possible detrimental effects on the mechanical properties of the steel.

4.1.3 Sources of Hydrogen Ingress

The source of hydrogen atoms is typically not relevant to HE mechanisms; instead, the steel microstructure and chemistry determine how hydrogen atoms distribute throughout the material and may alter its mechanical behavior. In pipelines carrying gaseous hydrogen, the obvious source is hydrogen gas contacting the inside diameter (ID) surface of the pipe. Gaseous hydrogen is the subject of the present research. Examples of other possible sources include (1) hydrogen generated by cathodic over-protection, (2) unintentional hydrogen ingress during welding, and (3) hydrogen generated from (wet) corrosion reactions.

4.1.3.1 Pressurized Gas as a Source of Hydrogen

In carbon steel pipelines carrying high-pressure hydrogen-containing gas, many factors can affect hydrogen molecule dissociation, the resulting generation of hydrogen atoms, their adsorption on the metal surface, and their absorption/diffusion into the steel's microstructure. The essential mechanism for hydrogen dissociative adsorption is complex and influenced by factors such as hydrogen partial pressure, temperature, fluid composition, and pipe surface condition.

The rate of uptake is affected by the dissociation rate of hydrogen molecules into hydrogen atoms at the metal surface, the adsorption of hydrogen atoms to the metal surface, and the diffusion rates of those hydrogen atoms into and through the steel. Hydrogen uptake occurs at ambient temperatures, increases more rapidly with increasing pressure, and is influenced by surface conditions. For pipelines that are exposed 24/7, the rate of uptake is less important than the duration of exposure. Saturation will be reached over weeks, months, or years.

The local concentration of hydrogen atoms within the steel depends on factors such as the driving force from the partial pressure of hydrogen gas at the surface, the time-dependency of diffusion at a given temperature, the time of exposure, the availability of hydrogen traps (e.g., vacancies, grain boundaries, and inclusions) in the crystal microstructure, and the local stress/strain conditions. Hydrogen atoms preferentially concentrate in high-strain areas (e.g., the plastically deformed steel at a dent, or the fusion metal and HAZ of non-post-weld heat-treated [non-PWHT] long-seam or girth welds).

4.1.3.2 Cathodic Over-Protection as a Source of Hydrogen

Cathodic overprotection can occur when a cathodic protection (CP) rectifier is set to deliver excessive current, driving the electrochemical potential at the steel's outer diameter (OD) surface too negative. The resulting chemical reaction is usually the electrochemical reduction of hydrogen ions to generate hydrogen atoms at the steel surface at coating holidays or underneath a disbonded external corrosion coating. Some of the hydrogen atoms recombine into hydrogen gas molecules, and some permeate into the steel.

The mere presence of diffused hydrogen atoms in steel is not a threat to integrity. In theory, it is a reversible process when the source is removed (CP turned off) and the hydrogen atoms are allowed time to naturally dissipate from the steel. However, in practice, CP will continue to be applied, and unless the excessive current is eliminated, there is no time to "air out".

4.1.3.3 Welding as a Source of Hydrogen

Hydrogen ingress due to poor welding practices can occur during new construction, repair welding, or in-service welding. During new construction or repair welding (not in-service), hydrogen ingress can occur if welding is performed in adverse (wet) weather conditions. Hydrogen ingress can also occur during in-service welding if low-hydrogen rods are not fully baked out after exposure to air or if in-service weld procedures are not strictly followed.

The high temperature of the welding process can cause water to form steam and chemically split, forming hydrogen that, in turn, can dissolve in the molten fusion metal of the weld. Upon cooling, weld shrinkage causes residual stresses and strains in the weld fusion metal and HAZ. Those residual stresses, combined with hydrogen in the microstructure, can result in cracks that form immediately after welding or be delayed for hours or days after the weld has cooled. This mechanism is referred to by a variety of names, including "delayed hydrogen cracking", "cold cracking", "hydrogen stress cracking (HSC)", or, more generically, "hydrogen-induced cracking (HIC)".

4.1.3.4 Corrosion as a Source of Hydrogen

Corrosion reactions, whether at the ID of a pipe (internal corrosion due to wet gas) or at the OD (external corrosion of a buried pipe), can generate hydrogen gas at the surface. The gas can be trapped under the coating or within the surrounding ground, leading to long-term exposure of the steel. As explained earlier, hydrogen gas can dissociate into hydrogen atoms, which can then diffuse into the pipe wall thickness (WT).

For corrosion to occur, moisture (water) is required, along with hydrogen-containing constituents that can act as hydrogen donors, such as hydrogen sulfide (H_2S), hydrogen chloride (HCl), or hydrogen cyanide (HCN), at the ID surface of the pipe. In transmission or distribution pipelines with pure hydrogen or hydrogen/NG blends, the moisture content will be low, and thus the driving force for hydrogen ingress from corrosion reactions is expected to be negligible. In the case of hydrogen sulfide, corrosion under external or residual stress is referred to as "sulfide stress cracking (SSC)".

4.1.4 Effects of Hydrogen on Mechanical Integrity

The detrimental effects of adsorbed hydrogen on the mechanical properties of ferritic steels have been demonstrated in numerous studies and are generally referred to as HE. However, there are many different types of ambient-temperature hydrogen effects, and the generic term "HE" can be confusing. In much of the classic literature, HE does not only refer to the loss of steel's ductility. Instead, it covers hydrogen blistering, hydrogen-assisted cracking, and brittleness.

Hydrogen effects can occur in the base metal, weld fusion metal, or HAZ. Some are named after their mechanism, and others after the source of hydrogen. Some are reversible; others are not. Some depend on stress, while others do not. Therefore, it is recommended to use consistent terminology for hydrogen effects, as described below, and summarized in Table 1.

• Hydrogen Ingress	Reversible; No cracks
• Hydrogen Embrittlement (HE)	Reversible; Embrittles steel; No cracks
• Hydrogen-assisted cracking (HAC)	Irreversible; Hydrogen gas micro-fissures the steel
• Hydrogen-Induced Cracking (HIC)	Irreversible; No external stress; Cracks grow
• Hydrogen Stress Cracking (HSC)	Irreversible; With external or residual stress; Cracks grow
• Stress-Oriented HIC (SOHIC)	Irreversible; HSC parallel to external stress
• Sulfide Stress Cracking (SSC)	Irreversible; Source of Hydrogen is wet hydrogen sulfide corrosion
• Hydrogen-Enhanced Cracking (HEC)	Hydrogen can enhance the CGR of fatigue, corrosion-fatigue, or SCC

In addition to the mechanisms mentioned above, hydrogen-related damage can occur at elevated temperatures, such as high-temperature hydrogen attack (HTHA). HTHA is typically associated with hydrogen industrial chemical processing and manufacturing, and does not occur in pipelines. Therefore, it is outside the scope of the present research.

Table 1. Summary of Hydrogen Terminology

Terminology	External Environment	External Stress Required?	Cracks	Visible in Microstructure?	Reversible
Hydrogen ingress	H_2-containing gas	Not Needed	NO	NO - Ingress is invisible	YES
Hydrogen embrittlement (HE)	H_2-containing gas	Not Needed	NO	NO - Embrittlement is invisible	YES
Hydrogen-assisted cracking (HAC)	H_2-containing gas	YES, Either External or Internal Stress	YES	YES - Buried cracks inside metal, or surface cracks	NO
Hydrogen-induced cracking (HIC)	H_2-containing gas	NO, but HIC may accelerate if YES	YES	YES - Buried cracks inside metal	NO
Hydrogen blistering	H_2-containing gas	NO	YES	YES – As blisters	NO
Hydrogen stress cracking (HSC), also known as "Cold Cracking"	H_2-containing gas	YES, or Residual Stress	YES	YES - Buried cracks inside the metal can be associated with the weld	NO
Stress-oriented HIC (SOHIC)	H_2-containing gas	YES	YES	YES - Buried cracks inside metal, parallel to stress	NO
Sulfide stress cracking (SSC)	H_2S and water	YES	YES	YES - Surface Cracks	NO
Hydrogen-enhanced cracking (HEC)	H_2-containing gas	YES, Cyclic (Fatigue or Corrosion-Fatigue) or Static (SCC)	YES	YES - Surface Cracks	NO

4.2 Hydrogen-Related Threats Detectable by ILI

4.2.1 Available ILI Tools for Hydrogen Threats

Several ILI technologies capable of detecting cracks are suitable for gas (hydrogen/NG) pipelines. This includes the latest in circumferential magnetic flux leakage (MFL) and helical MFL tools, as well as considerations for ultrasonics. A summary of ILI technologies is provided here:

- **Traditional Ultrasonics ILI**
  Ultrasonics have taken the lead in crack detection, but they can be limited in detecting certain crack morphologies due to the physics involved. In a liquid system, the industry has seen enormous improvement and maturation of ultrasonic technology crack detection (UTCD) tools in detecting and sizing crack-like defects. However, this technology is typically impractical for gas lines due to the need for a liquid couplant, and it is also often unavailable or unreliable in smaller-diameter pipelines.
- **Circumferential MFL ILI**
  Although circumferential tools have traditionally been used to screen for axial pipeline cracks, only recently have new developments emerged using multiple technologies on a single platform to significantly advance understanding of the capabilities of MFL combination technologies to detect and size crack-like anomalies at both axial and off-axis angles. Additionally, certain technologies are beginning to reliably detect circumferential and off-axis cracks.
- **Helical MFL ILI**
  Helical MFL tools apply a magnetic field at an angle and provide an advantage over traditional axially-oriented MFL tools. Helical MFL can efficiently detect crack-like defects in the pipe wall and long seams, including selective seam weld corrosion (SSWC), hook cracks, lack of fusion, and surface-breaking laminations.
- **Electromagnetic Acoustic Transmission (EMAT) ILI**
  EMAT tools use ultrasonic waves directly, eliminating the need for a liquid-coupled transducer and making EMAT technology particularly applicable to the gas pipeline industry. Now in their maturation stage, many EMAT tools continue to show promise for crack detection in gas pipelines. However, resolution issues limit EMAT's ability to identify and size crack-like indications. Thus, the probability of detection (POD) is good, while the probability of identification (POI) and probability of sizing (POS) are challenging.
- **Novel Ultrasonics ILI**
  Acoustic Resonance Technology (ART) is an innovative ultrasonic technology for ILI in pipelines. Unlike traditional methods that require a liquid couplant, ART uses high-pressure gas to transmit sound waves and acquire detailed measurements of the pipe wall, including crack detection. ART is an emerging technology that has not yet advanced widely.

4.2.2 Characterization of Hydrogen Threats by ILI

The characterization of threats arising from hydrogen service (Task 6 of this project) focused on defining ILI-detected threats as anomalies. The characterization was based on previous and ongoing research, publicly available literature, and the results from Task 2 (Risk Analysis) and Task 3 (Code Review).

The primary difficulties with assessing hydrogen-related threats using ILI include:

- There exists no single ILI technology to detect and size all threats that are highly affected by hydrogen.
    - An obvious difficulty for the industry when evaluating pipelines for threats associated with hydrogen blending or full hydrogen pipelines is that the anomalies of interest cannot be identified by a combo of axial magnetic flux leakage (MFL) and deformation (DEF) tools, as is typically deployed for integrity management (IM) using ILI tools.
    - Kiefner recommends careful consideration of a combination of axial, non-axial, low-field MFL tools, and DEF tools to be implemented as necessary to detect anomalies and address the impact of hydrogen on the pipeline system.
    - For new or newly converted hydrogen or hydrogen-blended pipelines, there is also a potential for the implementation of a baseline UTCD ILI tool to be run prior to the introduction of hydrogen gas in the pipeline. This may be necessary to establish a baseline for identifying defects in the pipeline and evaluating remaining life (RL) intervals, as well as anomalies that require monitoring during future inspections.
- There is inconsistent use of verbiage from reported ILI anomalies to "translate" them to defined threats per ASME B31.8S.
    - Operators and ILI vendors alike have preferred verbiage for ILI reports that does not necessarily align with the threats defined in ASME B31.8S.
- There is a poor or unknown understanding of the POD and the POI for the anomalies of most concern in hydrogen pipelines.
    - This is further exacerbated by the previous issue of an individual ILI technology's inability to capture a full breadth of understanding of an anomaly.

Therefore, Kiefner recommends the following regarding threat analysis for ILI tools:

- Determine the physical property/properties that the ILI tool aims to detect and size, and relate them to the threats defined in ASME B31.8S.
- Incorporate a standard method of reporting defects by ILI that maps the threats defined in ASME B31.8S.
- Ensure ILI tool validation is performed with an appropriate field method for the threat requiring evaluation.
- Communicate validation results with the ILI vendor to grow the basis of knowledge, so that the industry can continue to improve over time.

4.3 Interacting Threats from Hydrogen Service

Hydrogen threats do not always occur in isolation, as shown in Figure 1. In this example, the time-to-failure due to fatigue cracking is affected by reduced ductility, reduced fracture toughness, and increased fatigue CGR.

- First, the time-to-initiation of a crack is expected to be shorter, because in an embrittled material (reduced fracture toughness), a smaller defect or notch can initiate a crack.
- Second, the time-to-grow from crack initiation to a critical flaw size will be shorter, because in the presence of hydrogen, a fatigue crack grows faster (increased CGR).
- Third, the critical flaw size is expected to be smaller, because an embrittled material has less strain capacity (reduced ductility), and less crack resistance (lower fracture toughness, and possibly reduced ultimate tensile strength).

Taken together, these interaction effects result in shorter predicted remaining lives of defects, and thus, a shorter reinspection interval will be required to monitor their evolution and ensure safety.

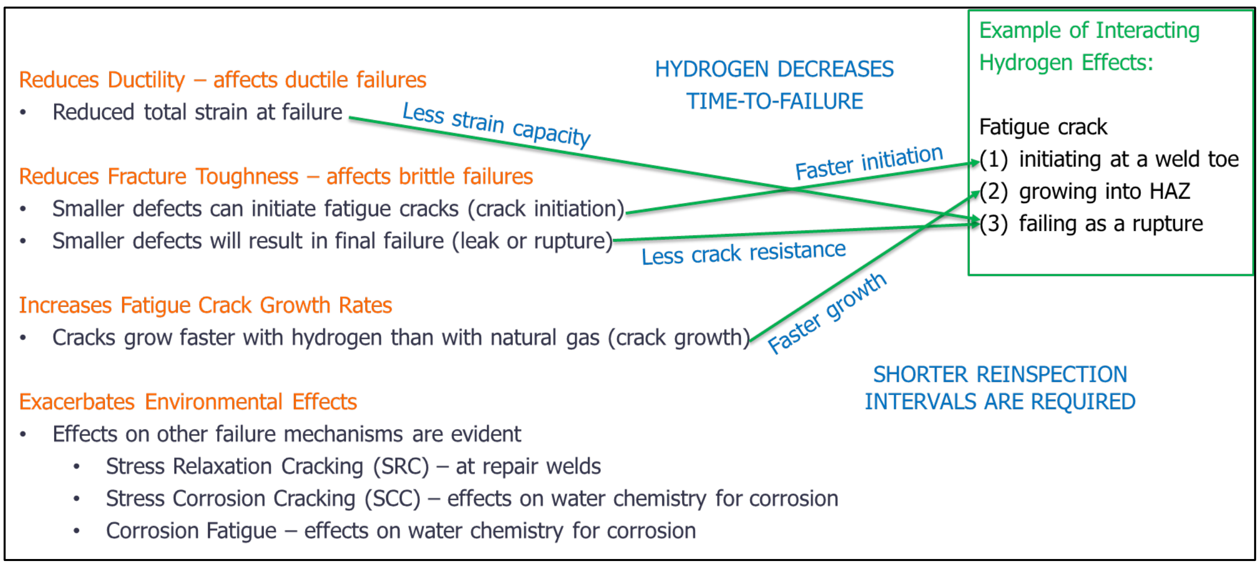


Figure 1. Example of Interacting Hydrogen Effects

4.4 Remaining Life (RL) Modeling for Pipelines in Hydrogen Service

In studies evaluating material properties, the primary values reported are yield strength (no or little change in hydrogen compared with air), tensile strength (no or little change compared with air), and loss of ductility (notable reduction compared with air). Fracture toughness data are scarce, and few reports address weld-related properties. Sandia's 2012 Technical Reference[6] for hydrogen compatibility of materials provides properties for a variety of materials.

Today, there is no satisfactory model available for predicting properties of hydrogen-exposed materials as a function of time. However, it is generally understood that once steel is embrittled and remains exposed to a hydrogen environment, its properties do not deteriorate further over time. The "bulk" material properties are only a part of the input for remaining life calculations. Microstructural features, flaw sizes, local stress/strain conditions, and crack growth rates are also important. Flaws may initiate and grow in hydrogen environments, and the advancing size of, for example, a crack will change the local stress/strain distribution around it. Fatigue CGR data have been measured for a wide variety of pipeline steels and are available in Sandia's publicly accessible hydrogen materials technical database.[22] The HELPR software[23] is a useful tool for performing probabilistic fatigue fracture calculations in hydrogen using that database.

Several methodologies for fatigue CGR assessments are included in hydrogen-related Codes and Standards. However, data on accelerated fatigue CGRs are relatively limited, as they address only a few loading R-ratios (minimum stress divided by maximum stress). Typically, R=1.0 and R=0.5, while gas pipelines typically operate with less severe pressure fluctuations (R=0.9). Thus, fatigue-life calculations should be based on models that capture crack growth behavior across the full fatigue (pressure-cycle) spectrum, including the threshold, stable, and rapid growth regions. ASME B31.12 Code Case 220 is the only method that formalizes fatigue design curves for gaseous hydrogen that account for the loading R-ratio, the stress intensity factor range, ΔK, and the hydrogen gas pressure g(P) as a function of overall pressure, P.

Although most hydrogen-related Codes and Standards describe integrity management practices in general terms, the specific relationship between CGRs and inspection intervals is often not explicitly addressed. In the literature search for this study, no documents were found describing methodologies for assessing hydrogen effects on specific defect types beyond a general "crack-like" feature. Probabilistic fatigue assessment for pipelines in hydrogen service is another area for further study, to explicitly account for uncertainty in flaw size, POD, POI, ILI/non-destructive examination (NDE) sizing error, fracture toughness, fatigue crack growth rate (FCGR) scatter, residual stress, and pressure history.

Examples of RL calculations are provided in the Task 4 Final Report[12] of this study, including crack-like features in the pipe body and welds, such as longitudinal, circumferential, and off-axis flaws, and mechanical damage (dents). Since hydrogen accelerates fatigue crack growth and reduces fracture resistance, flaw populations that might be slow-growing or benign in NG service can become more concerning in hydrogen service. Consequently, RL was assessed across a range of flaw sizes, fracture toughness values, pipe geometries, and pressure cycle severities, including flaw sizes near or below the practical detection limits of ILI and NDE tools.

4.5 Updating the Threat Definitions in ASME B31.8S

To account for hydrogen-related material degradation, in the current study, a review was performed of the threat definitions in ASME B31.8S[15] "Managing Systems of Integrity of Gas Pipelines" (Supplement to ASME B31.8). The currently recognized integrity threats listed in ASME B31.8S were compiled in the 1990s and have not been updated since; for details, refer to the Task 3 Final Report[11].

Kiefner recommends adding the following missing integrity threats applicable to **any gas transmission pipeline** to Paragraph 2.2 of future versions of ASME B31.8S:

- "Time-Dependent – Fatigue Cracking";
- "(b) Resident (1) Manufacturing-Related Defects (a) Defective Pipe Seam – Low Toughness Seam";
- "(b) Resident (1) Manufacturing-Related Defects (a) Defective Pipe Seam – Defect In or Near an Electric Resistance Welded (ERW) Seam"; and
- "(b) Resident (2) Welding/Fabrication-Related – At In-Service/Repair Welds – Hydrogen Stress Cracking".

Kiefner recommends adding the following missing integrity threats applicable to **gas transmission pipelines in hydrogen and hydrogen-blended service** to the future ASME B31.8S hydrogen chapter:

- "Time-Dependent – Hydrogen-Induced Cracking (HIC)";
- "Time-Dependent – Fittings and Sharp Transitions";
- "(b) Resident (2) Welding/fabrication-related – Near girth welds, and near in-service/repair welds – Arc burn/strike on pipe body";
- "(b) Resident (2) Welding/fabrication related – At welded sleeves and fittings – Type B sleeves and Puddle welds";
- "(b) Resident (2) Equipment – Other Material/Equipment Failure – Disbonded Coating Caused by Hydrogen"; and
- "(c) Random or Time Independent (3) Weather-Related and Outside Force – At locations that may experience an electrical arc or fire – Fire damage".

4.6 Hydrogen Blending

Hydrogen gas concentrations between 1 and 20% are most proposed for blending with NG, and such concentrations have been used in pilot projects worldwide. The pipeline industry is also interested in higher concentrations. Hydrogen blending is a complex challenge involving social, economic, and technical considerations. Various research organizations, industry organizations, commercial entities, and communities have contributed to the knowledge developed to date. However, each project has its particular focus and objectives. Combined research is not readily available.

The current study investigated how different hydrogen/NG blends affect pipeline integrity management intervals. The following conclusions were formulated based on the results:

1. Laboratory testing shows that exposure to hydrogen-blended NG has a detrimental effect on the material properties of pipeline steels. The extent to which these effects affect pipeline integrity has not been fully studied, particularly for high-stress pipelines.
2. No lower bound has been established in laboratory testing where hydrogen blending has been found not to have a detrimental effect on material properties.

3. Global practical experience with blended hydrogen/NG of different concentrations shows that using hydrogen blended gas is feasible and that the detrimental effects of hydrogen on steel may not greatly impact pipeline integrity. This experience is based on low-stress and distribution pipelines. More experience with hydrogen blending on high-stress pipelines is needed. However, the fatigue life of defects in pipelines carrying hydrogen/NG may be shorter than for NG alone, warranting a shorter reinspection interval for those pipelines.
4. Based on a review of databases and other sources with information on hydrogen-related incidents and accidents, hydrogen production and distribution pilot projects, blending facilities, and pipelines to transport hydrogen-containing gas blends, there were no counter-indications toward the successful use of hydrogen/NG blending. However, most project descriptions provided little technical information.
5. In the absence of shared integrity management, component performance, and material property data from operators who have run pilot or small-scale projects with blended hydrogen/NG systems, it is not possible to reliably estimate the RL of such systems with postulated or known flaws.

4.7 Hardness as an Indicator of Hydrogen Embrittlement Susceptibility (New in Task 7)

Hardness and carbon content of ferritic carbon steels have long been recognized as possible indicators of HE susceptibility, but hardness by itself is not detrimental to RL. Higher hardness and strength have been correlated with lower fracture toughness, and steels with higher hardness are known to crack more easily in standardized tests such as NACE TM0284 for HIC resistance and NACE TM0177[24] for SSC and SCC in hydrogen sulfide environments. While HE susceptibility is expected to increase with a steel's hardness, exceptions do exist. When steel is strengthened by alloying, hardness increases, but the alloy elements can also improve resistance to HE. The vast majority of gas transmission pipelines are constructed from unalloyed carbon steel.

In pipelines, microstructural hard spots can be associated with processing (pipe manufacturing) and welding. Recommended Practice API RP 1160[25] defines a hard spot as an "area in the pipe with a hardness level considerably higher than that of the surrounding metal, usually due to localized quenching or alloy segregation." The current research identified the need to further investigate hard spots in hydrogen and hydrogen-blended service pipelines, to quantify the relationships among local hardness, microstructure, through-wall extent, fracture resistance, and hydrogen-assisted crack initiation/growth.

4.7.1 Detecting Hard Spots by ILI

Faissat et al.[26] explored how an operator can determine whether hard spots exist in a pipeline. When a benign product, such as NG, is transported by pipeline, hard spots are often considered as non-injurious stable threats. However, with hydrogen in the pipeline, locally hardened material can pose an increased risk of cracking and thus be injurious during operations. Cracks can initiate from hard spots and grow over time, eventually leading to pipe failure.

Faissat et al. used a multiple data set (MDS) ILI tool to screen for hard spots in a 54-mile (87 km) 10-inch diameter pipeline. The ILI platform included seven technologies:

- Spiral magnetic flux leakage (SMFL);
- Low field axial magnetic flux leakage (LFM);
- Residual magnetic flux leakage (RES);
- High field axial magnetic flux leakage (MFL);
- High resolution geometry (GEO);
- Internal/external sensors (IDOD); and
- Inertial measurement unit (IMU).

The combined use of all these tools enabled the non-destructive assessment of hard spots beyond length, width, and a single hardness value. The MFL, LFM, and GEO data from a detected hard spot were compared with the hardness-mapping results from field validation digs (in-ditch NDE), as shown in Figure 2. The field hardness measurements were taken from the pipe surface (presumably the OD), so the hardness through the WT was not known from these measurements. An example of the pipe surface hardness mapping is given in Figure 3. The hardness measurements were carried out using a 5 kgf (50 N) General Electric Brand MIDC10DL portable hardness tester fitted with an Ultrasonic Contact Impedance (UCI) testing probe (MIC 205 probe). The device's precision was 5% of the measured hardness value.

Faissat et al. showed that the combined ILI technologies could detect hard spots and that the Brinell Hardness (HB) measurement accuracy was ±50 HB. This is approximately equivalent to a Vickers Hardness (HV) of ±52 HV. This is a large range of hardness, and therefore, it cannot practically be compared with a hardness criterion. However, the ILI provided a good representation of the shape and size of the hard spots, which may be sufficient for identifying and prioritizing the anomalies within the scope of an integrity management program.

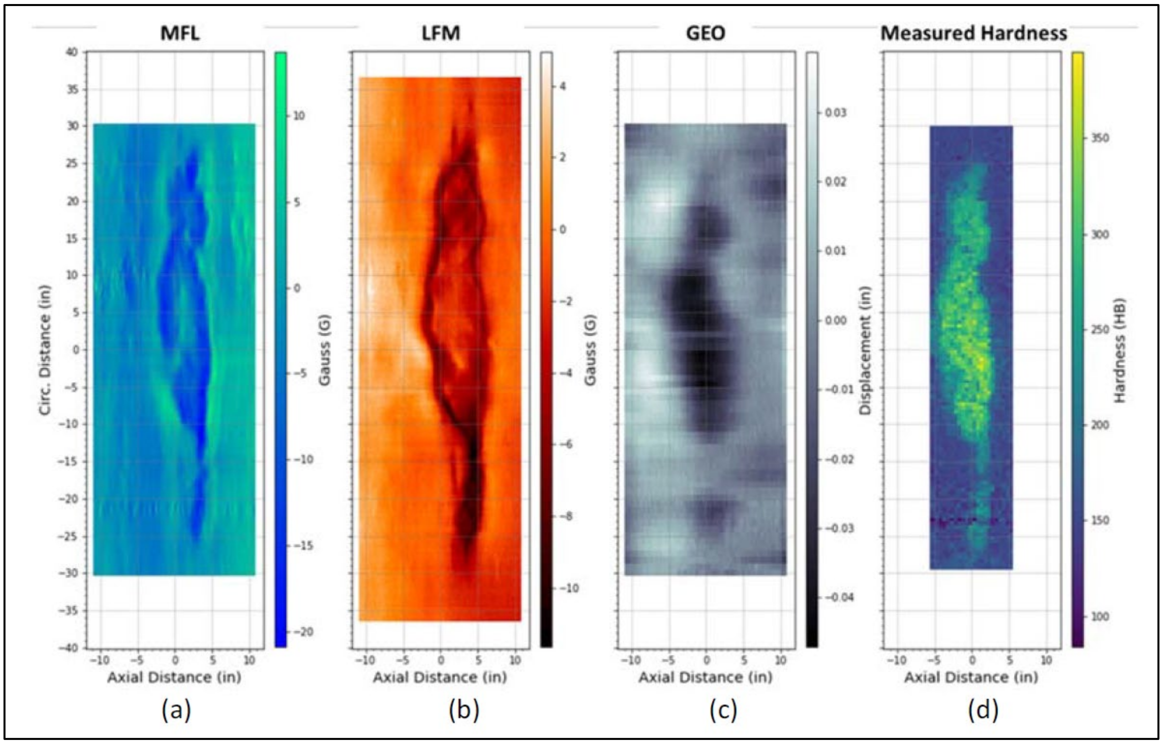


Figure 2. MDS Data Sets for a Hard Spot, Showing (a) MFL data, (b) LFM data, (c) GEO data, and (d) Field-Measured Brinell Hardness Map[26]

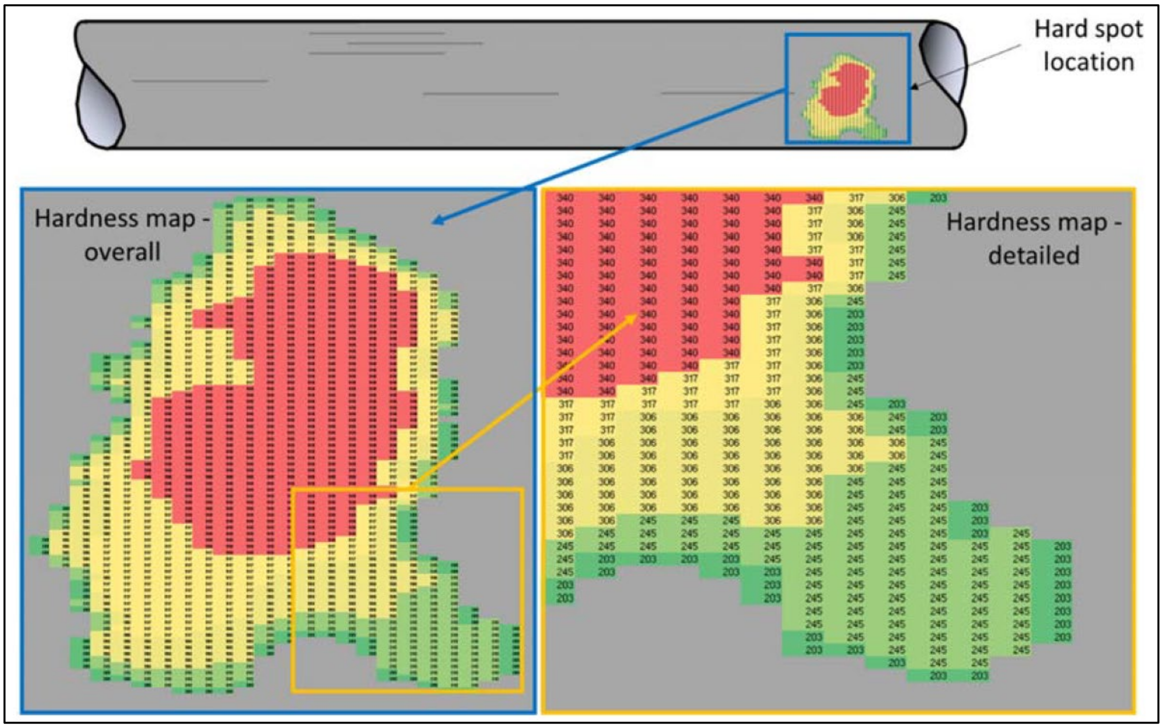


Figure 3. Example of Mapping Pipe Surface Hardness (Gray Indicates Base Metal Hardness)[26]

Faissat et al. reported that an initial analysis combining the data sets (DEF, MFL, SMFL, and RES) from each module of the MDS tool did not yield any signals resembling hard spots. Not until a secondary analysis (re-analysis) of the data was performed, 23 "possible hard spots" were identified from the RES/LFM records. Faissat et al. explained that the analysis was made more challenging to identify hard spots in this pipeline, which is mainly seamless, compared with a seam-welded pipe, due to variations in permeability and changes in WT introduced during seamless manufacturing. Due to semi-periodic, seamless variations, the RES and MFL signals are affected by background noise, limiting the lower threshold for hard-spot detection.

From the 23 possible hard spots, eight were selected for excavation and in-situ hardness testing. Ultimately, the field-verified hardness values indicated that none of the features qualified as hard spots. All locations showed slight changes in hardness levels in the identified regions compared to the reference area. This clarified the RES signals and supported the analysis that these were not classic hard spots but rather a slight hardness increase resulting from seamless pipe production.

Faissat et al. argued that the true negative confirmation gives confidence that this pipeline does not contain hard spots of significant hardness, because if it did, the MDS tool would have detected them. In addition, the tool identified no rogue spools and no significant crack-like features in the pipeline.

4.7.2 Relation Between Hardness and Fatigue Crack Initiation

Recent research by Yurek et al.[27] on the relationship between hardness and fatigue crack initiation was conducted on the base metal of a 1949-vintage API 5L Grade X42 pipeline steel. Simulated hard spots were created by austenization and direct water quenching. Fatigue testing was performed on instrumented, circumferentially notched tension (CNT) specimens.

The testing showed that at high stresses (above the base material's yield strength), hydrogen significantly reduced the fatigue life of the simulated hard-spot material. This manifested as a reduction in both the cycles to initiate a crack (N_i) and the total fatigue life (N_f). However, a simulated hard spot did not promote earlier crack initiation, faster crack propagation, or earlier failure for net-section stresses less than the yield strength of the base metal. This was true in air and in high-pressure hydrogen.

Therefore, for the maximum applied stresses relevant to pipeline operation, Yurek et al. concluded that the increased strength of the simulated hard spot increases the number of stress cycles to crack initiation and failure in both air and hydrogen.

5 ASSESSING WELD INTEGRITY BY HARDNESS MAPPING

This chapter was compiled based on research performed in this project. These results will also be published[28] in the Proceedings of the International Pipeline Conference (IPC) in Calgary, Alberta, Canada, in September 2026. The data presented at the IPC were supplemented with additional measurements obtained after the submittal deadline for that paper.

5.1 Nomenclature

d_V	Diagonal length of a Vickers indentation
F	Force
HV 0.5	Vickers Hardness – with 500 gf load
HV 1	Vickers Hardness – with 1 kgf load
HV 5	Vickers Hardness – with 5 kgf load
HV 10	Vickers Hardness – with 10 kgf load

5.2 Introduction

The growing interest in hydrogen/NG blending in transmission pipelines has highlighted the importance of hardness as a measure of potential susceptibility to HE and HIC[29]. This is especially true for welds, given the different microstructures in the weld metal and HAZ. According to DOT-PHMSA Advisory Bulletin PHMSA-2024-0176[30]:

> *"Hard spots, if not identified and mitigated, pose a threat to the integrity of the pipeline from interacting threats such as coating degradation, soil chemistry, and/or increased hydrogen exposure, which can result in hydrogen-induced cracking. Pipeline owners and operators should consider expanding their hard spot threat evaluation to all pipe manufactured prior to 1970, regardless of manufacturer; collecting and analyzing data associated with hard spot magnetic flux leakage in-line inspection tools; and following industry best practices when conducting in-line inspection data analysis."*

Schematics of weld cross-sections showing where and how many hardness indents to perform are included in current standards for pipeline welding (API STD 1104, 22nd Edition, 2021[17] "Welding of Pipelines and Related Facilities", material recommendations for cracking-resistant steels ANSI/NACE MR0175-2021/ISO15156-2:2020[18] "Petroleum and Natural Gas Industries - Materials for Use in H_2S-Containing Environments in Oil and Gas Production; Part 2 Cracking-Resistant Carbon and Low-Alloy Steels, and the Use of Cast Irons", hereby referred to as NACE MR0175, and design Code ASME B31.12[19] "Hydrogen Piping and Pipelines". Typically, Codes and Standards require sets of two or three indents in the weld metal and HAZ, at the weld root/near the inside surface, at mid-wall/mid-thickness, and at the weld cap/near the outside surface. The measured values are then compared with the maximum allowable hardness criteria.

5.2.1 History of Hardness Mapping

In the 1970s-1980s, electromechanical automation of hardness mapping was developed by integrating motorized X-Y stages, programmable load application, and optical measurement systems. These systems could perform grid-based indentation patterns, automatically measure indentation diagonals via optical microscopy, and export data to computers for plotting. These technological developments allowed a transition from individual indents to line scans and 2-D hardness maps, while reducing human error and improving repeatability.

In the 1990s-2000s, digital cameras replaced manual optical measurements. Image-processing software algorithms were developed to automatically detect indent edges and compute hardness values. Grid size and indent spacing were programmable, and color-contour maps of hardness were generated. Automated hardness mapping became a standard lab tool, with applications in welding qualification, failure analysis, and case hardening studies.

In the 2000s-2015, instrumented nanoindentation, high-density mapping, and correlative techniques were developed. This further allowed investigations of property-structure correlations at the micro- and nanoscale.

Since 2015, smart and artificial intelligence (AI)-assisted mapping using fully automated systems has been developing. The automation now integrates autofocus, surface detection, indent application, indent measurements, AI, and data analytics via machine learning and processing of large datasets.

5.2.2 Application of Hardness Mapping in this Project

Over the past decades, automated hardness-mapping technology has been developed to enable the measurement of many more data points on metallographically prepared transverse cross-section specimens, compared with manually applied individual indents.

For research on weld hardness, it is entirely feasible to obtain hundreds, if not thousands, of readings across a single weld area, which is very different from the limited number of indents obtained by manual operation, as specified in the most widely used standards. In addition, the standards specify measurements using HV with a 10 kgf (HV 10) load, which produces large indents and thus requires an unnecessarily large indent spacing. Instead, a smaller indentation load can be used, creating smaller indents and allowing for smaller spacing.

In this research, the hardness maps of several different weld types were evaluated and compared with small sets of manually obtained hardness values to determine whether the API, NACE, and ASME standards for hardness locations are sufficient for locating hard spots. The data were statistically analyzed to demonstrate the potential benefits of hardness mapping over individual hardness indents for assessing weld integrity in hydrogen pipelines.

As a result of the higher density of hardness measurements from mapping, one could expect that weld characterization would improve, and that the user would get greater confidence that the location with the maximum hardness will be detected. However, while that is generally true for bulk properties of weld zones, our research showed that determining the maximum hardness within narrow weld structures, such as the bondline in an ERW, or a HAZ location as close as possible to the weld metal, is more reliable with a manual process than with hardness mapping, even with hardness indent spacings as low as 0.250 mm.

5.3 Background on Vickers Hardness Testing

The HV test employs a square-based diamond pyramid indenter, which is pressed into the test material under a defined load. ASTM E92-23[31] "Standard Test Methods for Vickers Hardness and

Knoop Hardness of Metallic Materials" specifies that the lengths of the two resulting diagonals shall be measured and converted to an HV value using Equation 1:

$$HV = \frac{1.8544F}{{d_V}^2} \tag{1}$$

In this equation, HV is the Vickers hardness, F is the force applied by the indenter in kilograms (kgf), and d_V is the average diagonal length of the Vickers diamond indentation in millimeters.

Both API 1104 and NACE MR0175 specify requirements for hardness testing methods, including the type of testing and the placement of hardness indents used for welding qualification. API 1104, 21st Edition[16] and 22nd Edition[17] specify the use of Vickers HV 10 (10 kgf load) or lower test loads. API 1104 Section 10, "Repair and Removal of Weld Defects," provides multiple schematics for hardness testing based on the type of weld repair.

NACE MR0175 permits Vickers HV 5 (5 kgf load) or HV 10 test loads, as well as the Rockwell 15 N scale.

ASME B31.12 requires that the hardness survey be performed in accordance with ASTM E92[31] using a 10 kg load. ASME B31.12 allows other hardness-testing methods for welding procedure qualification when permitted by the engineering design.

At present, API 1104, 21st Edition[16], 2013 "Welding of Pipelines and Related Facilities" is used by pipeline operators because it is the edition incorporated by reference in the U.S. Code of Federal Regulations (CFR) Title 49 Part 192[32], "Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards."

5.3.1 ASTM E92 Standard for Vickers Measurements

ASTM E92, the standard used in this study, provides requirements for hardness-testing machines and procedures for performing HV tests.

ASTM E92 defines HV number as the calculated result from an HV test, which is proportional to the test force applied to the square-based pyramidal diamond Vickers indenter divided by the surface area of the permanent indentation made by the indenter after removal of the test force. HV values are not designated by a number alone because it is necessary to indicate which force has been employed in the test. HV testing can be performed with test forces ranging from 9.807×10^{-3} N to 1176.80 N (1 grams-force (gf) to 120 kgf). ASTM E92 states that for homogeneous materials and test forces ≥ 100 gf, microindentation HV numbers are in reasonable agreement with macroindentation HV numbers. This study used indentation forces of 500 gf and 10 kgf, referred to as HV 0.5 and HV 10, respectively.

HV tests have been found to be very useful for materials evaluation, manufacturing process quality control, and research and development. In this study, HV testing was used to investigate the effectiveness of different testing parameters (applied load, indent spacing) to determine the maximum hardness in weld specimens, using individual indentations (manual process) versus mapping (automated process) for different weld types.

Finding the maximum hardness in welds is important for repurposing and new construction of pipelines for service with gaseous hydrogen, because welds contain different microstructures, and HE poses a greater integrity threat in high-hardness materials and in high-hardness zones of otherwise lower-hardness materials. More studies are needed to evaluate whether a single HV 0.5 indent within the risk range (hardness exceeding a criterion) out of several hundred measurements, for example, would be sufficient to indicate that an entire weld or a localized zone within a weld is susceptible to HE/HIC.

Vickers hardness testing is a microindentation method (using a small diamond indenter), whereas Brinell hardness testing is a macroindentation method (using a larger ball indenter). Microindentation hardness tests extend testing to materials that are too thin or too small for macroindentation tests. However, because HV reveals hardness variations within a material, a single test value may not be representative of the material's bulk hardness.

Linepipe steels used for transmission pipelines are of limited thickness (in this study, 4.78 mm (0.188 in.) to 12.7 mm (0.500 in.)), and the weld HAZs and weld metal or bondline can be narrow. Therefore, microindentation hardness measurements are appropriate, provided that enough test values are recorded.

In accordance with ASTM E92[31], it is necessary to ensure that the spacing between indentations is large enough so that adjacent tests do not interfere with each other. The minimum required indentation spacing is 2.5 times the diagonal length of the indent, measured from center to center. In addition, the distance from the specimen edge shall not be closer than 2.5 times the diagonal length of the indent, measured from the indent center to the specimen edge.

There is no general method for accurately converting HV values to other hardness values. ASTM E92 states that such conversions are, at best, approximations and should be avoided except for special cases where a reliable basis for the approximate conversion has been obtained. When reporting converted hardness values, the original measurement number and test scale shall also be reported.

5.3.2 ASTM E384 Standard Test Method Microindentation Hardness

API 1104[16,17] (discussed below) references ASTM E384 [33] “Standard Test Method for Microindentation Hardness of Materials” for indentation spacing requirements. ASTM E384 covers microindentation tests made under test forces in the range 9.8×10^{-3} to 9.8 N (1 to 1000 gf), which is the lower range of what ASTM E92 covers. ASTM E384 does include the HV 0.5 (500 gf) tests that were conducted in this study.

Microindentation hardness testing is generally performed to quantify variations in hardness that occur over small distances. Pipeline steel material factors that can affect hardness test results include specimen homogeneity, crystal orientation, and texture effects such as elongated grains from pipe manufacturing. An example of a narrow structure in a pipeline weld is the bondline in an ERW. API 1104 requires that hardnesses in a HAZ be measured at locations as close as possible to the weld metal. Thus, both the placement and the size are important for microindentations.

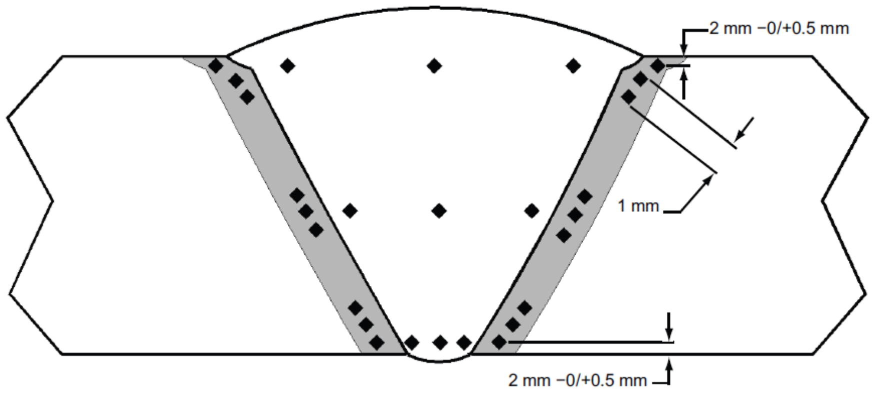
To determine localized hardness differences, a sensitive system is required to measure size differences in very small physical indentations. Testers that create indents at low test forces must be carefully constructed to accurately apply the test forces exactly at the desired location and must have a high-quality optical system to precisely measure the diagonals of the small indents. Test forces in the upper range of the force range may be used to evaluate bulk hardness. In general, the Vickers indenter (square pyramid) is better suited for determining bulk (average) properties than the Knoop hardness indenter (elongated, rhombic-based pyramid), as HV is not altered by the choice of the test force, from 25 gf to 1000 gf, because the indent geometry is constant as a function of indent depth.

The minimum recommended spacing between separate indents and the minimum distance between an indent and the specimen surface are the same in ASTM E92 and ASTM E384. When selecting an indent spacing, the user should consider the material area with the lowest expected hardness in the specimen's cross-section, as that area will produce the largest indents and thus the smallest acceptable spacing.

5.3.3 API STD 1104 for Pipeline Weld Repairs

API 1104 (21st Edition[16], 2013) contains requirements for hardness testing of completed welds for Welding Procedure Specification (WPS) development and repair welding. The specific sections of API 1104 include: Section 10 (Repair and Removal of Weld Defects), Section 12 (Mechanized Welding with Filler Metal Additions), Section 13 (Automatic Welding Without Filler Metal Additions), Annex A ((normative) Alternative Acceptance Standards for Girth Welds) - if specified in the engineering critical assessment (ECA) process, and Annex B ((normative) In-Service Welding). Annex B specifically includes hardness testing requirements to address hard zones in completed welds to reduce the risk of hydrogen cracking during service.

Specific requirements for microhardness testing are referenced to ASTM E384[33], with indent spacing and placement dependent on the API 1104 Section being used. Hardness standards evolve over time, as illustrated in Figure 4A (API 1104, 21st Edition[16], 2013) and Figure 4B (API 1104, 22nd Edition[17], 2021), which present schematics for individual hardness indents for a full-scale weld repair per API 1104.

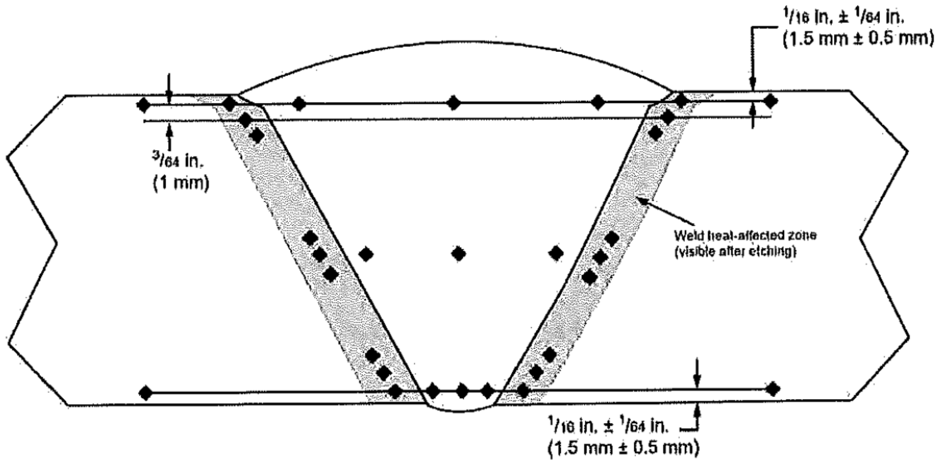


NOTE Heat-affected zone (HAZ) hardness impressions must be entirely within the HAZ and located as close as possible to the fusion boundary (between the weld metal and HAZ).

Figure 21—Hardness Locations for Full Thickness Repair Procedure Qualification

(A)

Figure 4. Schematic for Individual Hardness Indents for Full-Thickness Repair per API 1104, (A) 21st Edition[16] (2013)



NOTE Heat-affected zone (HAZ) hardness impressions must be entirely within the HAZ and located as close as possible to the fusion boundary (between the weld metal and HAZ). The wall thickness of the specimen may prevent all the indents as shown from being made, particularly along the mid-point of the specimen.

Figure 22—Hardness Locations for Full-thickness Repair Procedure Qualification

(B)

Figure 4. Schematic for Individual Hardness Indents for Full-Thickness Repair per API 1104, (B) 22nd Edition[17] (2021)

5.3.4 ANSI/NACE MR0175/ISO 15156 for Cracking-Resistant Materials in H_2S-Containing Environments

Material Recommendation ANSI/NACE MR0175/ISO 15156[18], which is referenced in API 1104, requires specific locations for HV testing of a weld cross-section specimen. This reference is used to map hardness in completed welds, with the purposes of WPS development, weld repairs, and ensuring that materials are resistant to SSC in sour service. NACE MR0175 states for carbon and low alloy steels:

> *"The equipment user shall consider HIC/SWC [stepwise cracking] as defined in ANSI/NACE MR0175/ISO 15156-1 when evaluating flat-rolled carbon steel products for sour service environments containing even trace amounts of hydrogen sulfide (H_2S) and shall consider HIC/SWC testing of these products. Annex B provides guidance on test methods and acceptance criteria to evaluate resistance to HIC/SWC."*

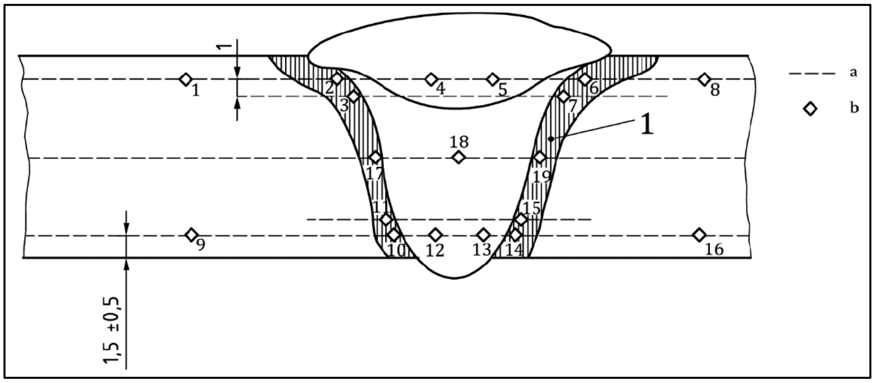
For carbon steel, carbon manganese steel, and low alloy steel welds, NACE MR0175 Annex A specifies the acceptable maximum hardness values for HV 10 or HV 5 as follows:

- Weld root: 250 HV
- Base metal and HAZ for weld overlays: 250 HV
- Weld cap: 275 HV(*)

(*) The maximum shall be 250 HV, unless all three of the following conditions are met:

- The equipment user agrees to the alternative weld cap hardness limit;
- The parent material(s) are over 9 mm thick; and
- The weld cap is not exposed directly to the sour environment.

Figure 5 shows a schematic for individual hardness indents for a butt-weld survey per NACE MR0175.



Key

1 weld heat-affected zone (visible after etching)

a Lines of survey.

b Hardness impressions: Impressions 2, 3, 6, 7, 10, 11, 14, 15, 17 and 19 should be entirely within the heat-affected zone and located as close as possible to the fusion boundary between the weld metal and the heat-affected zone.

The top line of survey should be positioned so that impressions 2 and 6 coincide with the heat-affected zone of the final run or change of profile of the fusion line associated with the final run.

Figure 2 — Butt-weld survey method for Vickers hardness measurement

Figure 5. Schematic for Individual Hardness Indents for Butt-Weld Survey Method for Vickers Hardness Measurement per ANSI/NACE MR0175-2021/ISO 15156-2:2020[18]

5.3.5 ASME B31.12-2023 for Hydrogen Piping and Pipelines

ASME B31.12[19] requires that hardness testing shall be conducted for welding procedure qualification tests for materials. Base metal and welding procedure qualification tests shall be made from the same base metal, chemically similar, and in the same heat treatment condition as specified for the piping. The thickness of base metal coupons shall not be less than the thickness of the piping.

The required placement and loads of the HV indentations are described as follows:

> *"(1) The hardness survey shall be performed on a transverse weld cross section that has been polished and etched to identify the weld metal, fusion line, and HAZ.*
>
> *(2) The hardness test shall be carried out in accordance with ASTM E92 using a 10-kg load. Other hardness testing methods for welding procedure qualification may be used when permitted by the engineering design.*
>
> *(3) Two Vickers hardness traverses of the weld joint should be made on a weld sample in the minimum PWHT condition. These hardness traverses should be performed at 1.5 mm (1⁄16 in.) from the internal and external surfaces as shown in Figure GR-3.10-1 [Figure 6 in this paper]. The HAZ readings should include locations as close as possible [approximately 0.2 mm (0.008 in.)] to the weld fusion line. Each traverse includes 10 hardness readings for a total of 20 hardness readings per weld sample."*

Figure GR-3.10-1
Location of Vickers Hardness Indentations

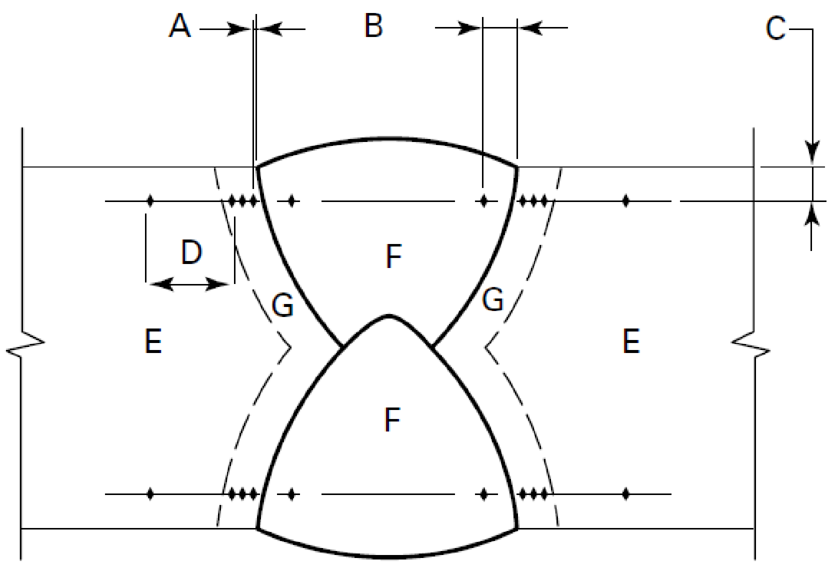


Figure 6. Schematic Showing Locations of Individual Hardness Indents per ASME B31.12-2023[19]

The acceptance criteria state that the hardness measurements shall not exceed the limits specified in ASME B31.12 after the required PWHT. Other hardness testing limits may be used if specified in the engineering design.

For carbon steel, ASME B31.12 specifies the acceptable maximum hardness values as HV 10 as follows:

- Carbon steel (Base Metal Group, P-No. 1) 235 HV 10
  (*) The P-Number for ASME BPVC, Section IX, QW/QB-422.
  (**) When other hardness testing methods are used, the acceptance criteria shall be equivalent to these Vickers HV 10 values.

The hardness value of 235 HV in ASME B31.12 is lower than the 250 HV specified in NACE MR0175, which admittedly addresses a potentially more aggressive hydrogen exposure through corrosion in hydrogen sulfide-containing environments than would be experienced in hydrogen or hydrogen/NG blended service. NACE MR0175 is a widely accepted standard globally, based on many years of experience. Thus, it appears that the required hardness per ASME B31 is overly conservative.

5.3.6 Incorporation of ASME B31.12 Hardness Requirements into ASME B31.8 Hydrogen Exception Chapter

At the time of writing this paper, the ASME B31.8 Technical Committee, Operation and Maintenance Subgroup, Hydrogen Task Group, is drafting an exception chapter for pipelines in gaseous hydrogen or hydrogen-blended service. The objective is to move the content from B31.12 into B31.8 and avoid possible duplications or contradictions between these Codes.

Within the new ASME B31.8 exception chapter for hydrogen, hardness requirements are being defined for the "high-stress" option (S = SMYS, may be > 52.2 ksi) and for a "low-stress" option (S = SMYS, and S ≤ 52.2 ksi, and design factor F ≤ 0.5 (≤50% SMYS)), as follows:

- High-stress option: 275 HV 10
- Low-stress option: 250 HV 10

As mentioned earlier, the existing maximum hardness requirement of 235 HV per ASME B31.12 may be overly conservative. These newly proposed hardness values are proposed by pipeline operators, with the expectation that they can be achieved in pipelines slanted for repurposing to hydrogen or hydrogen/NG blended service. These hardness values are higher than those specified in NACE MR0175, which addresses a potentially more aggressive hydrogen exposure through corrosion in hydrogen sulfide-containing environments than would be experienced in hydrogen or hydrogen/NG blended service.

Other issues regarding the proposed hardness values for the ASME B31.8 exception chapter include that HV 10 indents may not meet the required spacing per ASTM E92, and that HV 10 indents are likely too large for narrow weld geometries.

5.4 Approach to Hardness Testing in this Project

5.4.1 Hardness Testing Equipment

In this study, hardness measurements were performed using HV 10 and HV 0.5 test loads. According to ASTM E92, the minimum required spacing between indentations is 2.5 times the diagonal length of the indent, measured from center to center. To establish appropriate spacing for automated testing, an initial test indent was made in the base material of each specimen, and its diagonal lengths were measured. For the first round of testing, the automated mapping was set to an HV 10 load with a 0.800 mm indentation spacing. In subsequent rounds, the load was decreased to HV 0.5, and with the smaller indent size, hardness tests were conducted at spacings of 0.500 mm and 0.250 mm.

Individual hardness measurements were performed using a LECO LM247AT testing machine. With this method, each indentation is placed by viewing the specimen and manually aligning the indenter to the desired position. The size of the indentations is measured using a light microscope equipped with a filar-type eyepiece, by moving the filar lines to the corners of the diamond indent and reading the results. For this study, an eyepiece and lens with a combined magnification of 500 times were used.

Hardness mapping was performed using a Wilson VH3100 testing machine equipped with Buehler's DiaMet Enterprise software. With these tools, a grid of indentations can be specified with a predetermined starting location and indentation spacing. The machine starts making indentations from the top-left corner of a specimen and advances row by row until the grid is complete. The machine automatically focuses and measures the diagonals of each indentation, which is converted to a hardness reading. For the hardness mapping in this study, magnifications of 10 to 20 times were used for HV 10 measurements, and magnifications of 20 to 40 times were used for HV 0.5 measurements, in accordance with ASTM E384.

5.4.2 Specimen Requirements

Automated hardness mapping requires the polished specimen (in this case, a weld cross-section) to possess flat, smooth, and coplanar surfaces to ensure accurate measurements. As a result, cold epoxy mounting is often unsuitable, as it may not provide the necessary surface uniformity. Similarly, hand-polishing techniques can introduce unevenness or out-of-plane conditions, compromising the instrument's ability to deliver consistent readings. To maintain the required surface quality, all specimens in this study were prepared using a hot-mounting press, followed by automated polishing.

In accordance with ASTM E92, the specimen surface should not be etched before making an indentation. Etched surfaces can obscure the indentation edge, making an accurate measurement of its size difficult. In the present study, the specimens were ground and polished to a 3 µm diamond finish before hardness measurements. The specimens were etched after the hardness indents and measurements were completed, so that the indent placement in the base metal, HAZ, weld metal, or bond line could be visually determined.

Figure 7 shows a schematic for individual hardness indents on ERW long-seam weld cross-sections in this study.

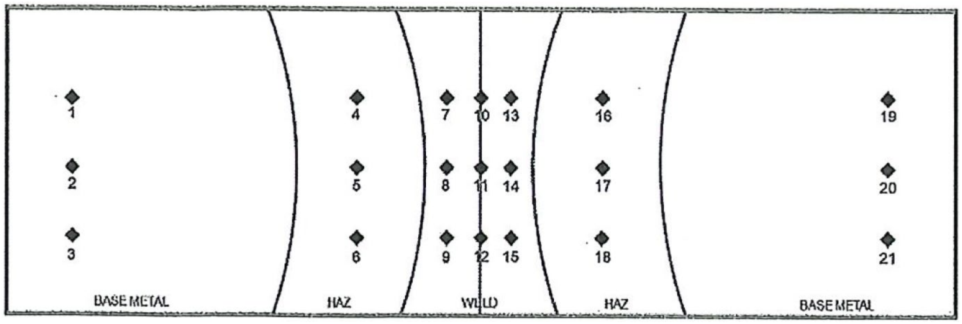


Figure 7. Schematic Showing Where Individual Hardness Indents Were Taken on ERW Long-Seam Weld Cross-Sections

5.5 Specimen Selection

The weld specimens for this work were selected from prior Kiefner pipeline integrity projects. The intent was to test a variety of weld types, steel grades, vintages, manufacturers, carbon equivalent (CE) values, WTs, and diameters. Table 2 shows background information for each specimen. For a few of the specimens, some information was unknown.

The welds listed in Table 2 are organized by girth welds (GWs), a fillet weld, and longitudinal (seam) welds. All GW specimens were single submerged arc welds (SSAWs). Within the category of seam welds, different weld types were included: a double submerged arc weld (DSAW), a flash weld (FW), a direct current (DC) ERW, a low frequency (LF) ERW, a high frequency (HF) ERW that had undergone PWHT, and another ERW with PWHT.

Table 2. Summary of Weld Specimens for Hardness Testing

#	Weld	Type	Vintage, Manufacturer, Grade, Diameter, Wall Thickness
1	GW	SSAW	Installed 1983, manufacturer unknown, API 5LX Grade X52, 10.75 in. OD, 0.188 in. WT
5	GW	SSAW	Installed 1959, Bethlehem Steel/ Youngstown, API 5LX Grade X42, 16 in. OD, 0.250 in. WT
6	GW	SSAW	Installed 1959, Youngstown Sheet & Tube, API 5LX Grade X52, 20 in. OD, 0.344 in. WT
10	GW	SSAW	Girth weld of 4.5 in. OD pipe, 0.203 in. WT
11	Fillet	Fillet Weld	In-service fillet weld connecting a Type B sleeve to a pipe.
4	Seam	DSAW	Installed 1985, Berg Steel Pipe Corp., API 5L Grade X52, 24 in. OD, 0.500 in. WT
2	Seam	FW	Installed 1962, A.O. Smith, API 5LX Grade X60, 26 in. OD, 0.250 in. WT
7	Seam	DC-ERW	Installed 1959, Youngstown Sheet & Tube, API 5LX Grade X52, 20 in. OD, 0.344 in. WT
8	Seam	LF-ERW	Installed 1958, Tex-Tube, Inc., API 5L Grade B, 6.625 in. OD, 0.188 in. WT
3	Seam	HF-ERW (with PWHT)	Installed 1994, Newport Steel, API 5L Grade X52, 8.625 in. OD, 0.188 in. WT
9	Seam	ERW (with PWHT)	Installed 1961, manufacturer unknown, API 5LX Grade X42, 8.625 in. OD, 0.188 in. WT

5.6 Results

The figures and tables with the results of this study are provided later in this report. The purpose of introducing them here is to use some of the results as inputs into the discussion of applied loads and selected indentation spacing.

As mentioned earlier, at present, ASME B31.12 requires a maximum of 235 HV for carbon steels in hydrogen service. NACE MR0175 requires a maximum of 250 HV for weld roots, base metals, and HAZ for weld overlays, and a maximum of 250 HV for weld caps for service in hydrogen-sulfide-containing environments. The ASME B31.8 exception chapter for hydrogen considers a maximum of 250 HV for the low-stress option and 275 HV for the high-stress option. It is for that reason that the focus of the results presented here was to find the maximum hardness for each specimen.

Figures 8 through 21 show photomicrographs and hardness maps for all the specimens. Tables 3 through 24 list the hardness results for individual indents and hardness maps, sorted by mean, minimum, maximum, and range, as well as by base metal, weld metal or bondline, and HAZ. Table 25 summarizes the maximum hardness of the specimens using the individual indentation test method and mapping at different loads and spacings.

5.7 Discussion About Hardness Results

In this section, the hardness test results from the different test methods for GW, fillet weld, and longitudinal seam weld specimens are described. The objective of this research on welds in pipelines for hydrogen service was to determine practical conditions for reliably measuring the maximum hardness in weld specimens and characterizing hardness across different weld zones. A discussion of the competing requirements for the parameters used in hardness testing is provided. In addition to the technical considerations for load, spacing, and the number of indentations, commentary is provided on test efficiency and test effectiveness for determining the maximum hardness across different weld types.

Test efficiency can be evaluated by the time required for specimen preparation and test performance. Efficiency is influenced by the required spacing between indentations and, accordingly, by the total number of indentations per specimen. In our tests, hardness maps were constructed with 200 to 6,900 indents, determined by the spacing used (800 µm, 500 µm, and 250 µm) and the pipe WT (up to 12.7 mm (0.500 in.)). The tests were conducted so that the mapping grid, in a single run, would cover the base metal on both sides of the weld, both HAZs, and the weld metal. The user should consider the machine's capacity to handle that much data, as well as the time required for the test itself and the analysis.

Indentations too close to the ID and OD surfaces of the pipe WT should be avoided. If too few hardness tests are taken within a weld area (HAZ or weld metal), then API 1104 and/or NACE MR0175 requirements for the number and placement of indentations would not be met. If a very low load, and accordingly a small spacing, were used, the number of indentations would become impractically large. Also, a load could be so small that the resulting indentations would approach the size of the grains in the microstructure, which should also be avoided.

The authors observed that, to compare different indentation spacings and loads in the present study, specimen preparation was labor-intensive and required multiple cycles of polishing, etching, repolishing, and re-etching between tests. Automated hardness mapping systems generally require coplanar, as-polished specimen surfaces to ensure measurement accuracy. In this study, these requirements were met using a hot-mounting press and an automated polishing system.

In routine automated hardness mapping applications outside the scope of this study, the desired spacing and load will be known, and specimen preparation will therefore be limited to producing a single as-polished surface to enable reliable detection of indentation diagonals. Microscopy to determine which indentations were in the weld metal, HAZ, and base metal was performed manually, regardless of the hardness measurement method. Taking individual hardness indents is time-consuming, as each specimen requires manual realignment for each indent. On the other hand, taking automated hardness measurements requires familiarity with the software and practice to set up the area of interest. The time required to process data after the machine completes hardness measurements can negate the time saved by avoiding manual adjustments to individual indents.

The overall coverage of hardness testing is obviously better with the larger number of datapoints from hardness mapping than with the smaller number from individual indents. However, the indents are placed according to a grid, and an automated hardness machine does not place them in the HAZ as close to the weld metal as possible (as required by API 1104), nor does it place them exactly in the center of a narrow bondline. As a result, the maximum hardness was missed during mapping for 6 of the 11 specimens tested in this study. For these six specimens, the greatest difference between the maximum hardness measured by individual indents and hardness mapping was 17.9 HV (Specimen 5). In contrast, for the five specimens in which hardness mapping recorded a higher maximum hardness, the largest discrepancies were 172.8 HV for SSAW Specimen 10 and 74.3 HV for Fillet Weld Specimen 11.

Note that all 11 specimens were tested with individual indents at HV 0.5, all 11 were tested HV 10 with 0.800 mm spacing, seven were tested at HV 0.5 and 0.500 mm spacing, and five were tested at HV 0.5 and 0.250 mm spacing.

Figure 8 shows the relation between hardness and indentation size for HV 0.5, HV 1, HV 5, and HV 10 loads, and the required minimum spacing for hardness indentations per ASTM E92.

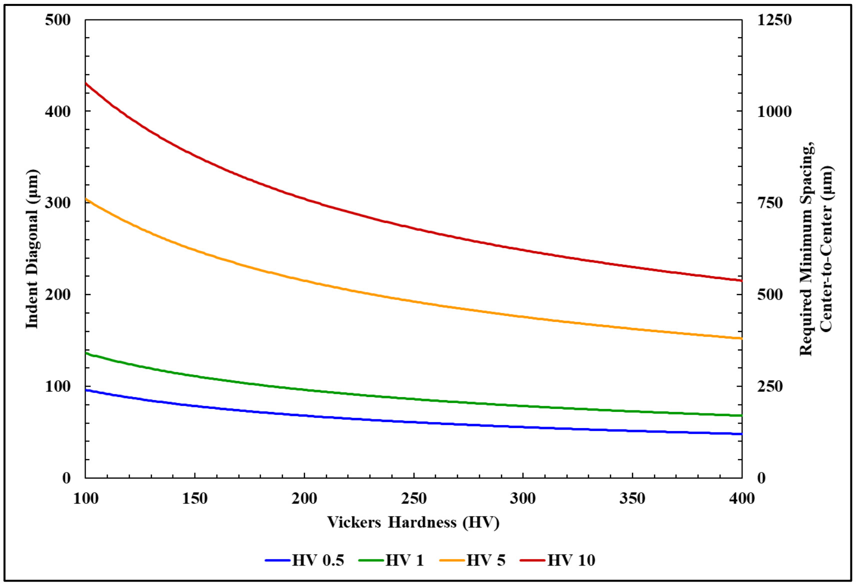


Figure 8. Vickers Hardness Versus Indent Size and Required Minimum Spacing

Figure 9 illustrates how to determine the minimum required spacing for the specimens in this study, as described next.

- Among the 11 specimens, the lowest base metal hardness at 10 kgf was 117.4 HV 10 on Specimen 10. This hardness produced an indentation diagonal of 0.3974 mm, which, per ASTM E92, requires a spacing of 2.5 x 0.3974 = 0.993 mm (993 µm).
- Among the 11 specimens, the lowest base metal hardness at 500 gf was 121.8 HV 0.5 on Specimen 10. This hardness produced an indentation diagonal of 0.0872 mm, which, per ASTM E92, requires a spacing of 2.5 x 0.0872 = 0.218 mm (218 µm).

The maps made using 500 µm and 250 µm spacings with HV 0.5 measurements satisfied the 218 µm minimum requirement. However, the map with 800 µm spacing and HV 10 measurements did not satisfy the 993 µm minimum requirement.

At the start of our research, HV 10 test indents were made in the base metal of all specimens to obtain an approximation of the typical hardness expected. It was estimated that 150 HV 10 would be typical, and because the objective was to determine the maximum rather than the minimum hardness, it was decided at that time to start testing with 800 µm spacing and 10 kgf loads. Later, testing was expanded with 500 µm and 250 µm spacings and 0.5 kgf (500 gf) loads.

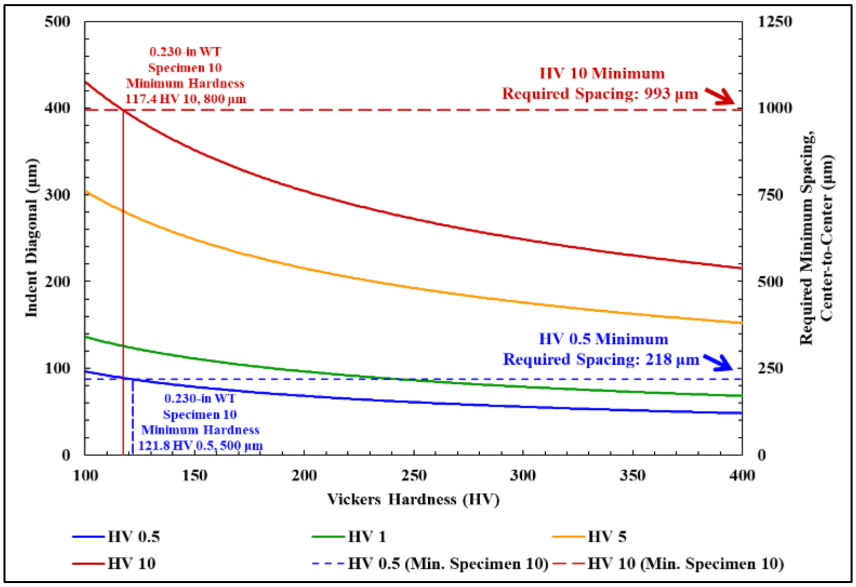


Figure 9. Vickers Hardness Versus Indent Size and Required Minimum Spacing with Examples for HV 10 and HV 0.5

Figure 10 illustrates how the indentation sizes for one of the specimens (Specimen 10) were distributed along the HV 10 and HV 0.5 lines. The spacing of 800 µm was insufficient for the HV 10 loads (green line crosses red line), but the spacing of 500 µm was sufficient for the HV 0.5 loads (purple line does not cross the dark blue line).

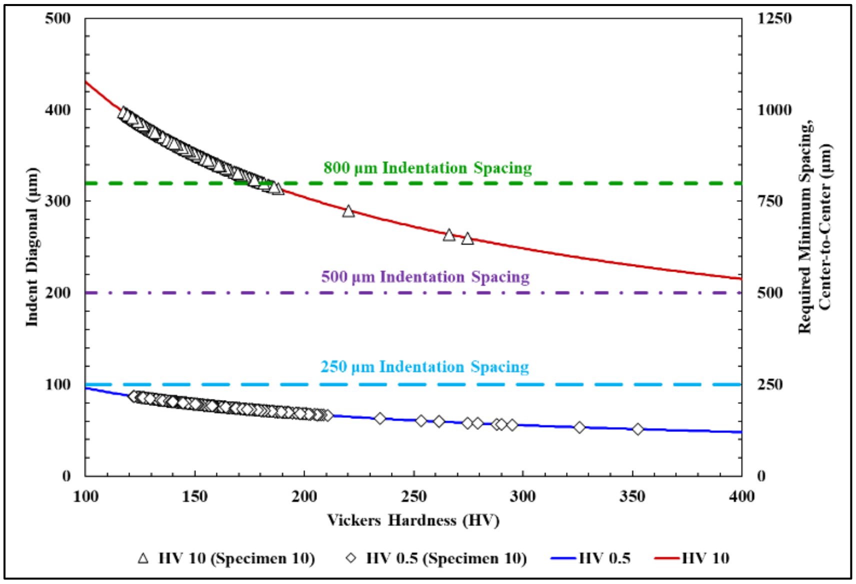


Figure 10. Vickers Hardness Versus Indent Size and Required Minimum Spacing with Data for Specimen 10 at 10 kgf Load and 500 gf Load

Figure 11 shows the test results for the number of indents achievable at different spacings. The results showed that tests with a 500 µm spacing were appropriate for pipe WT of 6.35 mm (0.250 in.) or greater, because the number of indentations across the WT satisfied the API requirement of 9 indents. However, the 500 µm spacing was insufficient for the specimen with 4.78 mm (0.188 in.) WT. HV 0.5 measurements with a spacing of 250 µm are appropriate for pipe WT smaller than 6.35 mm (0.250 in.). To illustrate this further, the 250 µm line was also drawn in Figure 10, showing it was sufficient for the HV 0.5 loads (the light blue line does not cross the dark blue line).

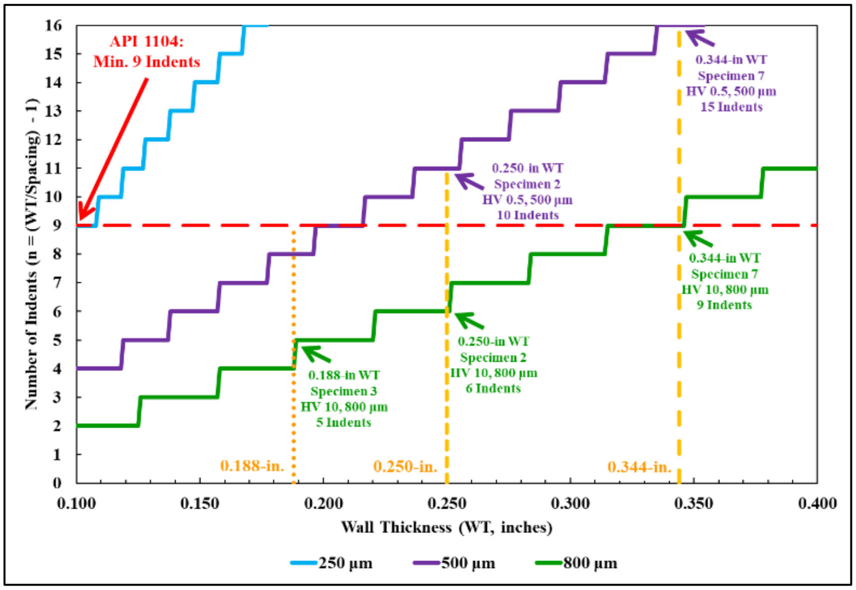


Figure 11. Number of Indents Across the Wall Thickness for Three Different Spacings and With Examples for Three Different Wall Thicknesses

5.7.1 Girth Welds and Fillet Welds

In this study, four GWs were hardness-tested using individual indents and mapping. As shown in Table 25, the maximum hardness was measured using the individual indentation test method in three specimens, and in one specimen using mapping.

- For girth welds, the largest difference (172.8 HV) between individual indents and automated indents was found in GW (SSAW) Specimen 10, with $HV_{(max, individual)}$ = 198.9 HV and $HV_{(max, mapping)}$ = 371.7 HV.
- One fillet weld (Specimen 11) was measured in this study. The difference between the individual indents and automated indents was 74.3 HV, with $HV_{(max, individual)}$ = 245.6 HV and $HV_{(max, mapping)}$ = 319.9 HV.

5.7.2 Seam Welds

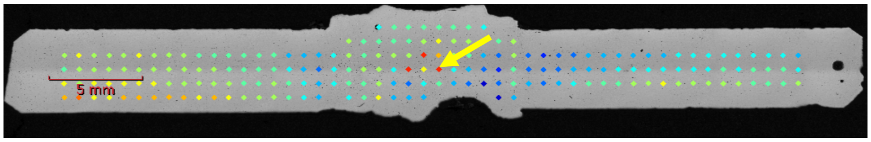
Some older LF-ERW bondlines exhibit skewed or partially obliterated morphologies due to inadequate mill quality control, whereas most modern HF-ERW bondlines are characterized by very narrow widths. Therefore, placing an HV 10 indent directly in the bondline can be difficult, if not impossible. To ensure that hardness indents are placed exactly where needed, the authors recommend using HV 0.5 indents and that the technician be experienced with the hardness technique and methodology.

For ERW seams, the maximum hardness for seam welds may be more reliably found by individual indents, because of the more precise placement of the indenter, as compared with mapping. This consideration is particularly important given that the ERW bond lines in the specimens examined in this study were measured to be as narrow as 16 µm. This width is smaller than a typical diamond indentation diagonal, for example, approximately 60.9 µm at a 250 HV hardness with a 500 kgf load, and is especially small relative to a typical indentation spacing of 500 µm. In the case of mapping, an indent can be as far as half the spacing away from the center of the ERW bondline. In the case of an ERW seam weld with a narrow bondline, it may be better to manually locate the hardest area, since an automated survey may not always guarantee that an indent is placed exactly at the center of the bondline.

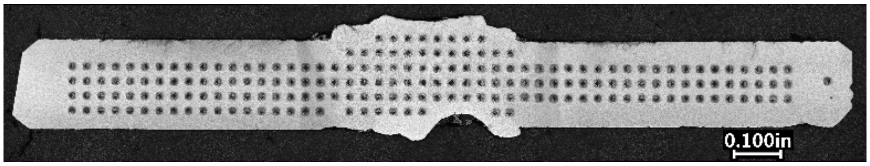
In this study, six seam welds were hardness-tested using individual indents and mapping. Table 25 summarizes the maximum hardness of all specimens for the different methods used. The maximum hardness in three specimens was determined using the individual indentation test method, and the maximum hardness in three specimens was determined by mapping.

For seam welds, the largest difference (18.7 HV units) between individual and automated indents was observed in Seam Weld (FW) Specimen 2, with 222.7 HV (max, individual) and 241.4 $HV_{(max, mapping)}$.

PWHT of ERW long-seams, when properly performed at the mill using induction heating, essentially anneals the HAZ. This makes the entire area softer and more ductile, reducing the risk of excessively hard areas after welding.



(A)



(B)

Figure 12. Specimen 01 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm and (B) As-Etched HV 10 at 0.800 mm

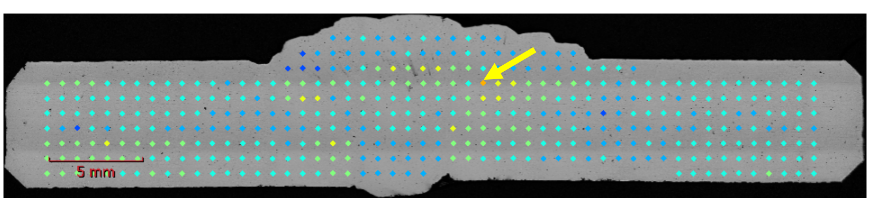
Table 3. Hardness Statistics for Specimen 01

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm
	HV 0.5	HV 10
Mean	166.1	167.2
Min	138.8	143.0
Max	**195.3**	**193.0**
Range	56.5	49.9

Table 4. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 01

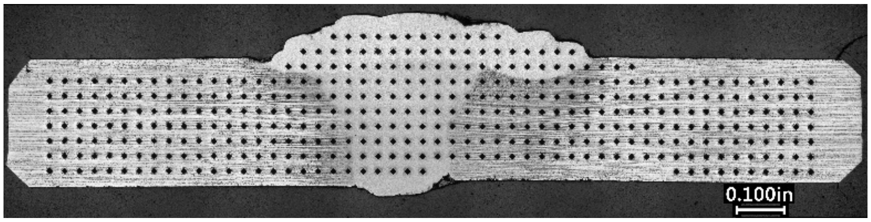
Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm
	HV 0.5	HV 10
Base Metal	177.6	169.5
Weld Metal	172.7	166.0
HAZ	160.3	155.1

(*) 4 indents in the base metal, 9 indents in the weld metal, and 18 indents in the HAZ, according to Figure 4B.

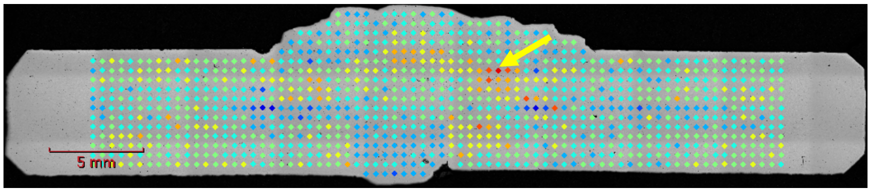


(A)

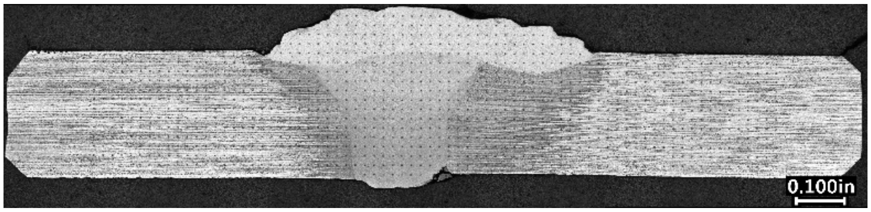
Figure 13. Specimen 05 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm (Continued on next page)



(B)



(C)



(D)

Figure 13. (Continued) Specimen 05 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (B) As-Etched HV 10 at 0.800 mm, (C) As-Polished HV 0.5 at 0.500 mm, and (D) As-Etched HV 0.5 at 0.500 mm

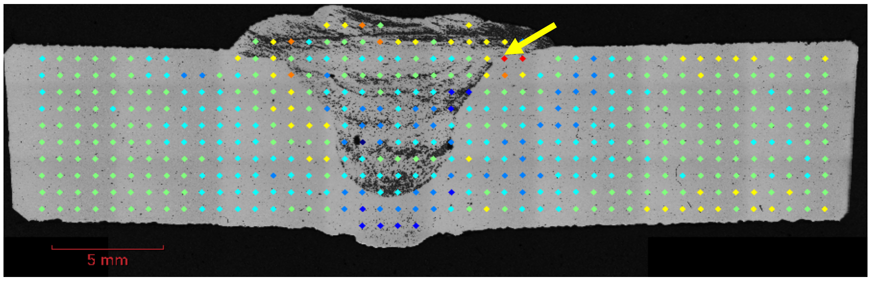
Table 5. Hardness Statistics for Specimen 05

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm
	HV 0.5	HV 10	HV 0.5
Mean	171.9	154.4	160.2
Min	139.0	138.7	126.8
Max	**219.4**	**182.5**	**201.5**
Range	80.4	43.8	74.7

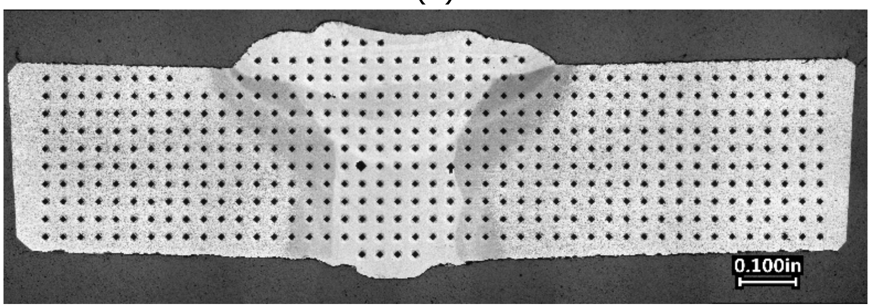
Table 6. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 05

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm
	HV 0.5	HV 10	HV 0.5
Base Metal	164.9	153.9	159.9
Weld Metal	153.4	150.8	157.3
HAZ	182.8	160.4	165.8

(*) 4 indents in the base metal, 9 indents in the weld metal, and 18 indents in the HAZ, according to Figure 4B.



(A)



(B)

Figure 14. Specimen 06 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm and (B) As-Etched HV 10 at 0.800 mm

Table 7. Hardness Statistics for Specimen 06

Indent Load and Spacing	**Individual Indents***	**Mapping 0.800 mm**
	HV 0.5	**HV 10**
Mean	188.2	180.5
Min	152.2	151.6
Max	**219.0**	**212.1**
Range	66.8	60.5

Table 8. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 06

Indent Load and Spacing	**Individual Indents***	**Mapping 0.800 mm**
	HV 0.5	**HV 10**
Base Metal	187.5	180.9
Weld Metal	174.7	176.5
HAZ	195.1	185.4

(*) 4 indents in the base metal, 9 indents in the weld metal, and 18 indents in the HAZ, according to Figure 4B.

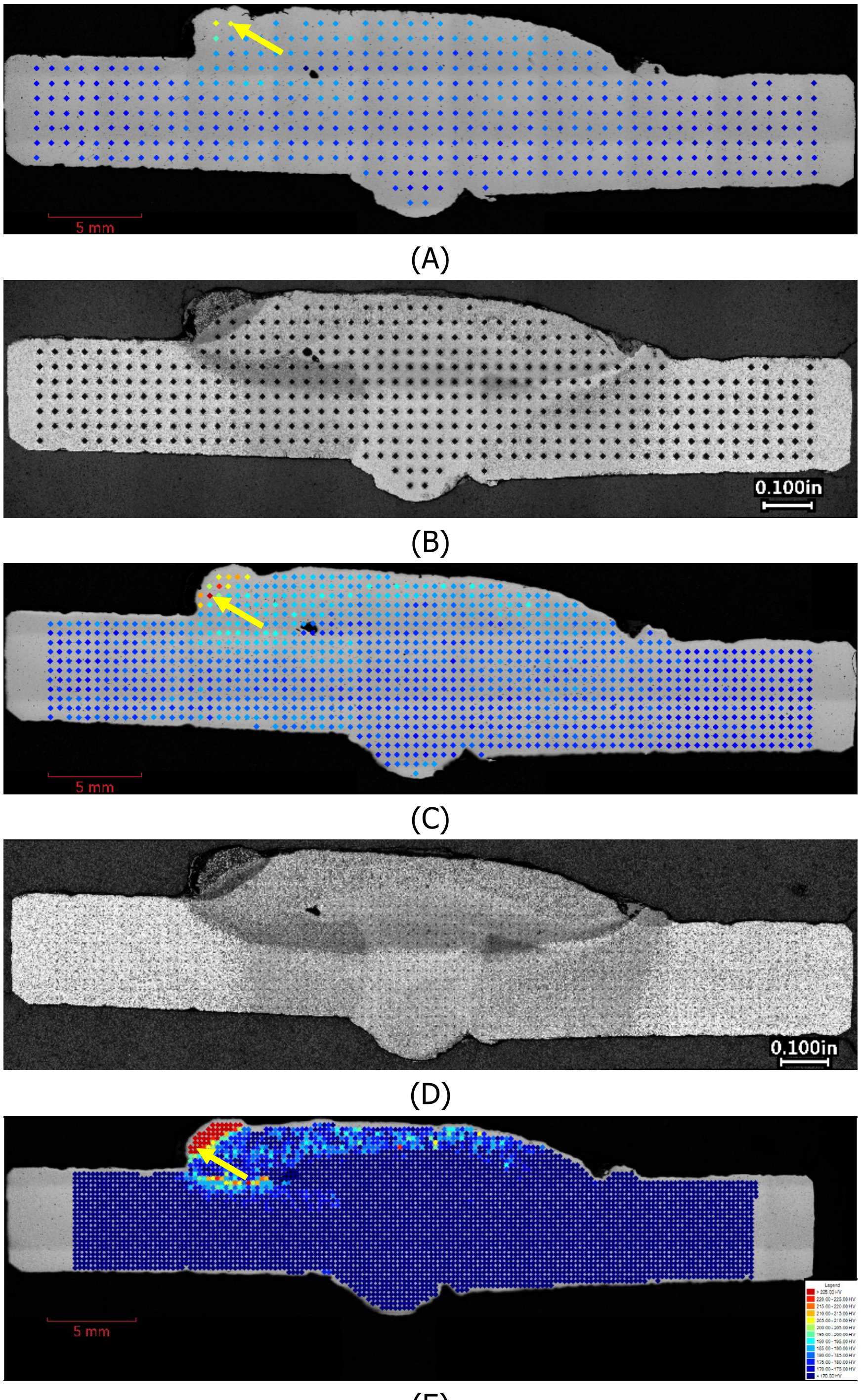
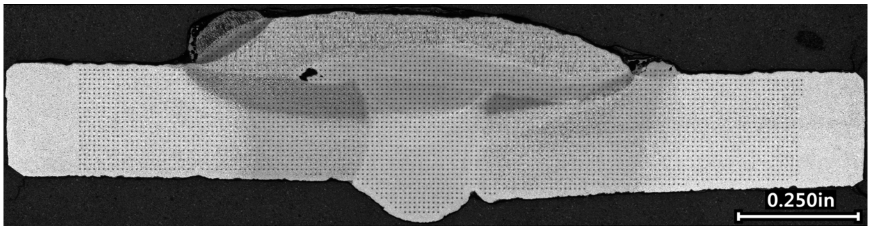


Figure 15. Specimen 10 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm, (B) As-Etched HV 10 at 0.800 mm, and (C) As-Polished HV 0.5 at 0.500 mm (D) As-Etched HV 0.5 at 0.500 mm, and (E) As-Polished HV 0.5 at 0.250 mm (Continued on next page)



(F)

Figure 15. (Continued) Specimen 10 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (F) As-Etched HV 0.5 at 0.250 mm

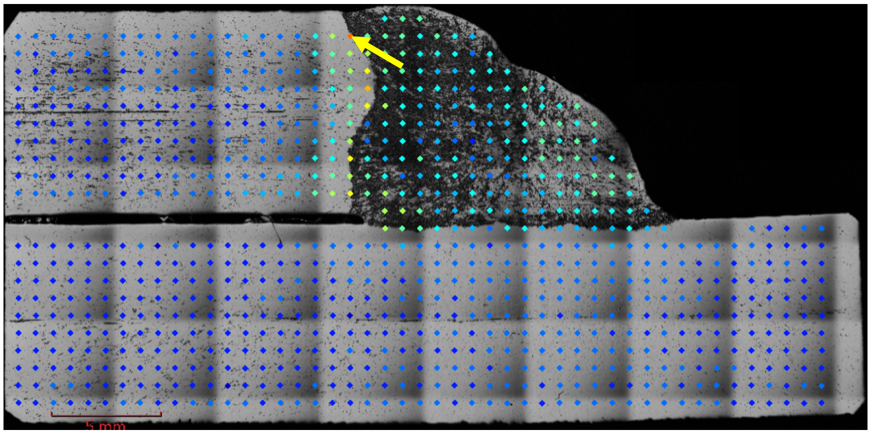
Table 9. Hardness Statistics for Specimen 10

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Mean	157.3	149.9	158.6	151.2
Min	125.5	117.4	121.8	112.8
Max	**198.9**	**274.5**	**352.3**	**371.7**
Range	73.4	157.1	230.5	258.9

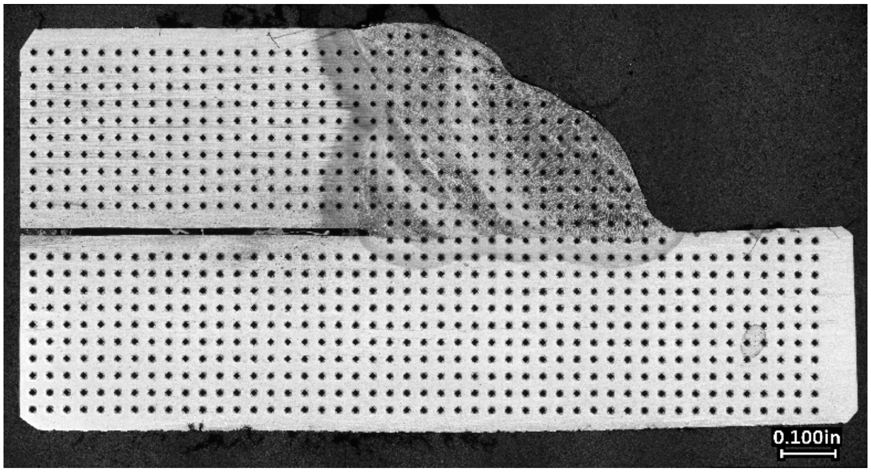
Table 10. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 10

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Base Metal	132.6	134.0	145.7	137.0
Weld Metal	149.3	160.6	169.0	161.0
HAZ	166.7	155.4	160.9	153.7

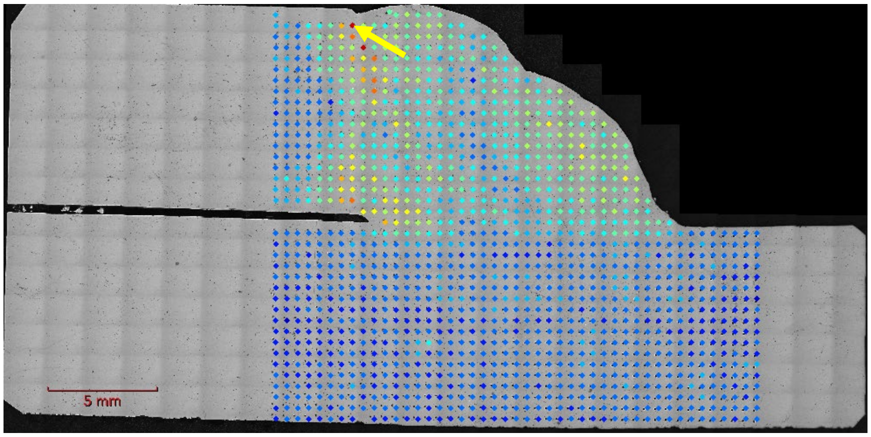
(*) 4 indents in the base metal, 9 indents in the weld metal, and 18 indents in the HAZ, according to Figure 4B.



(A)

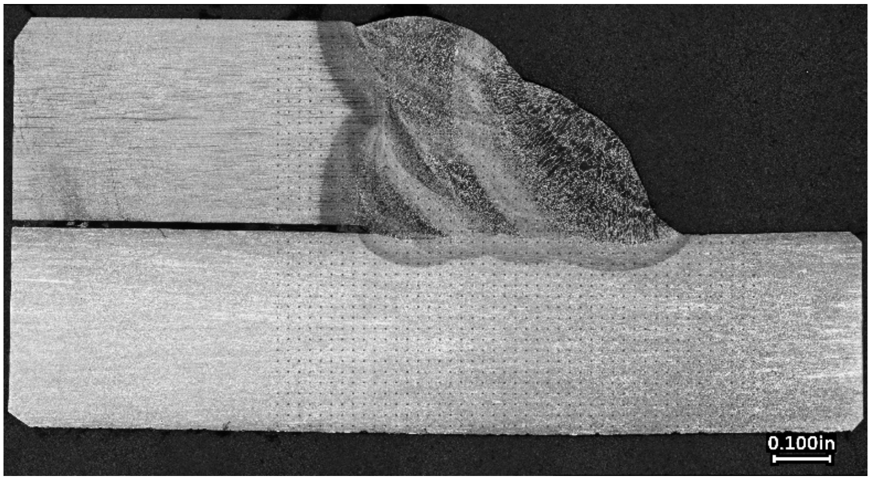


(B)

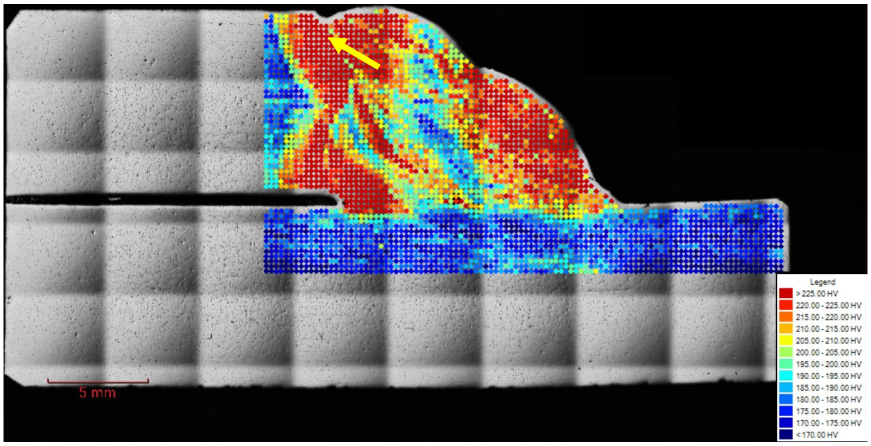


(C)

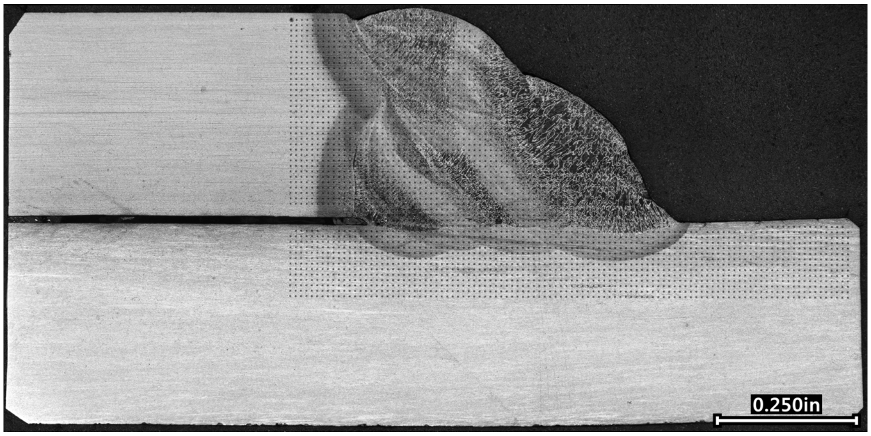
Figure 16. Specimen 11 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm, (B) As-Etched HV 10 at 0.800 mm, and (C) As-Polished HV 0.5 at 0.500 mm (Continued on next page)



(D)



(E)



(F)

Figure 16. (Continued) Specimen 11 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (D) As-Etched HV 0.5 at 0.500 mm, (E) As-Polished HV 0.5 at 0.250 mm, and (F) As-Etched HV 0.5 at 0.250 mm

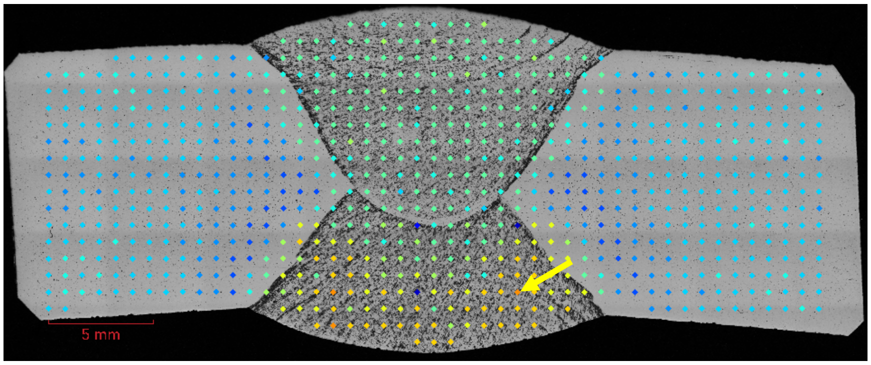
Table 11. Hardness Statistics for Specimen 11

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Mean	210.4	177.7	190.6	218.7
Min	154.4	147.6	152.2	169.6
Max	**245.6**	**284.5**	**310.3**	**319.9**
Range	91.2	136.9	158.2	150.3

Table 12. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 11

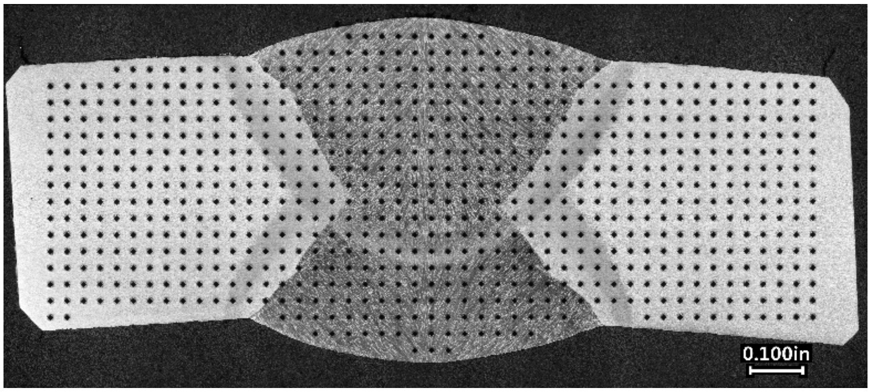
Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Base Metal	170.0	169.4	175.8	191.9
Weld Metal	219.6	204.3	215.2	217.5
HAZ	214.9	206.0	212.1	248.0

(*) 4 indents in the base metal, 9 indents in the weld metal, and 18 indents in the HAZ, similar to Figure 4B.

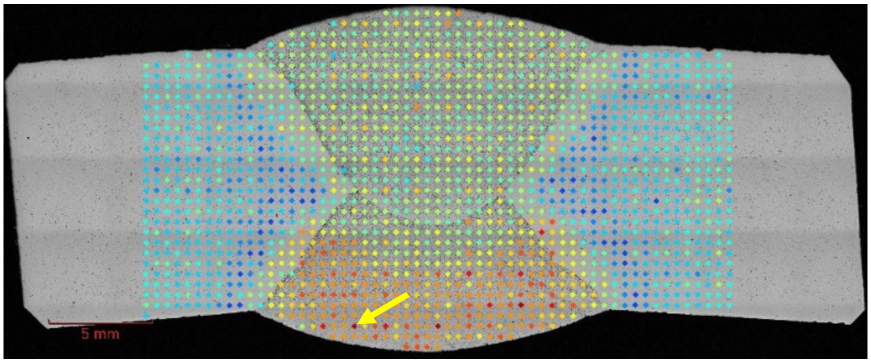


(A)

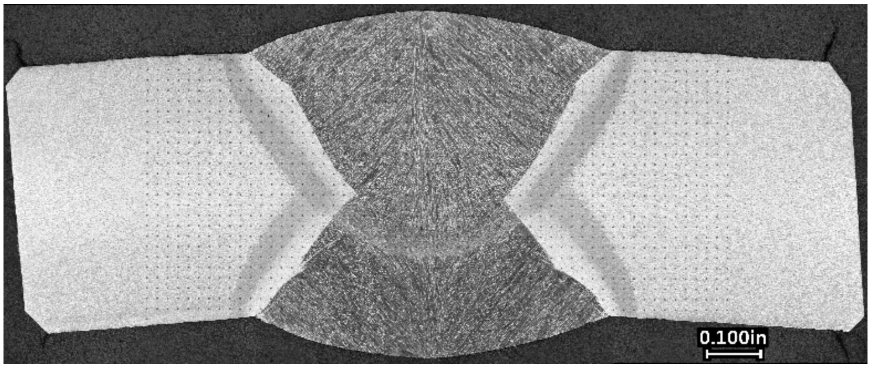
Figure 17. Specimen 04 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm (Continued on next page)



(B)

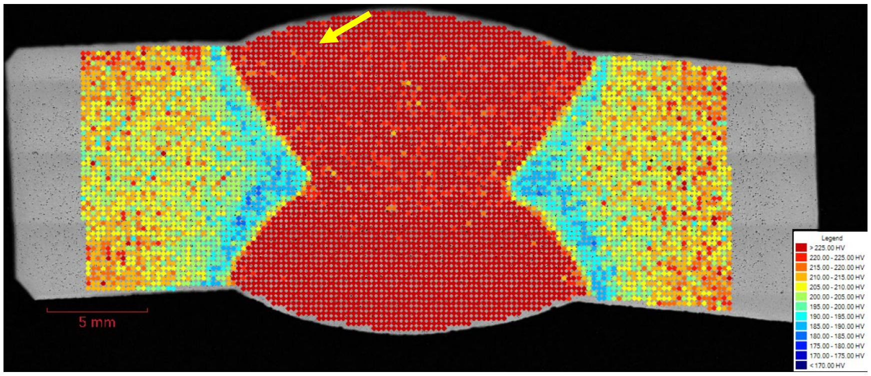


(C)

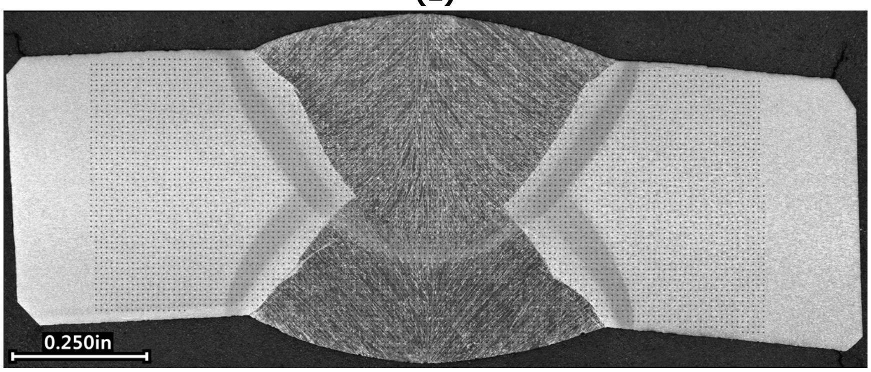


(D)

Figure 17. (Continued) Specimen 04 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (B) As-Etched HV 10 at 0.800 mm, (C) As-Polished HV 0.5 at 0.500 mm, and (D) As-Etched HV 0.5 at 0.500 mm (Continued on next page)



(E)



(F)

Figure 17. (Continued) Specimen 04 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (E) As-Polished HV 0.5 at 0.250 mm, and (F) As-Etched HV 0.5 at 0.250 mm

Table 13. Hardness Statistics for Specimen 04

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Mean	228.9	213.9	226.5	222.7
Min	197.0	168.4	180.2	181.0
Max	**284.1**	**263.8**	**291.6**	**283.8**
Range	87.1	95.5	111.4	102.8

Table 14. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 04

Indent Load and Spacing	Individual Indents**	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Base Metal	219.4	203.0	208.4	207.5
Weld Metal	248.0	230.2	242.8	240.8
HAZ	209.9	208.9	218.6	215.1

(*) 6 indents in the base metal (2 traverses on either side of weld through thickness), 9 indents in the weld metal (three traverses through weld thickness), and 6 indents in the HAZ (two traverses on either side of weld through thickness).

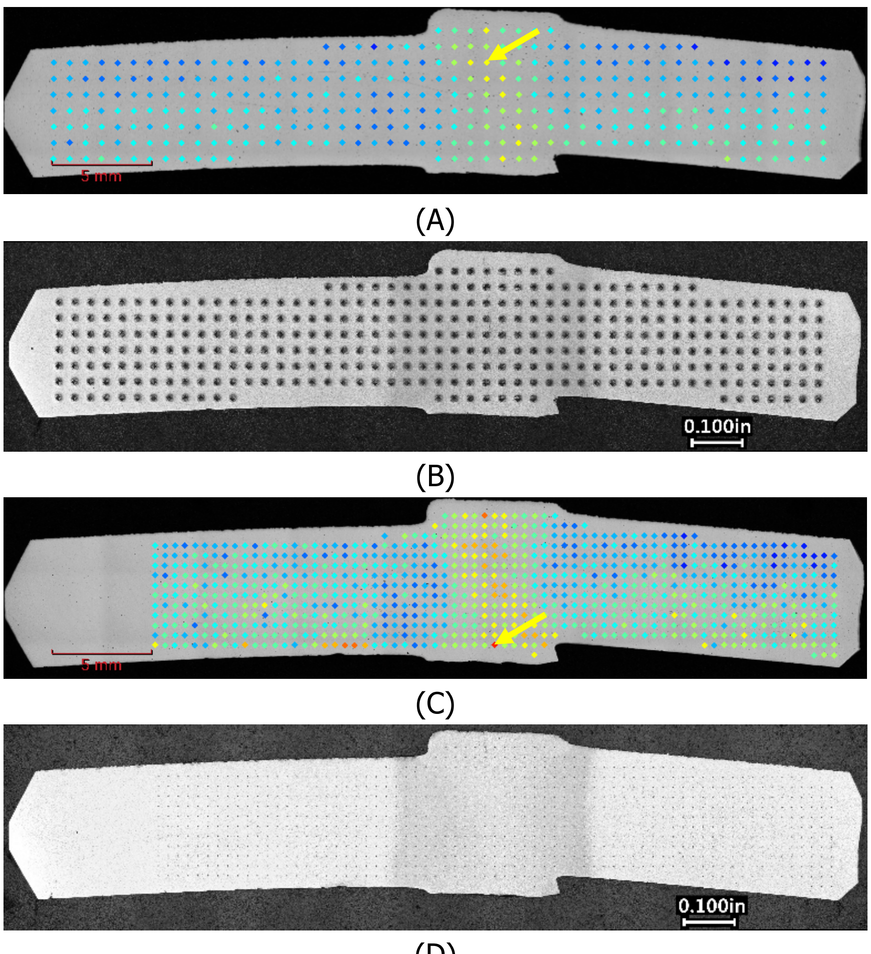
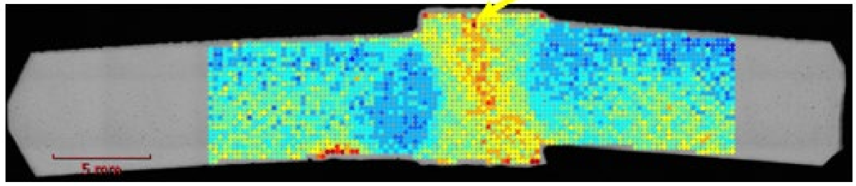


Figure 18. Specimen 02 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm, (B) As-Etched HV 10 at 0.800 mm, (C) As-Polished HV 0.5 at 0.500 mm, and (D) As-Etched HV 0.5 at 0.500 mm (Continued on next page)



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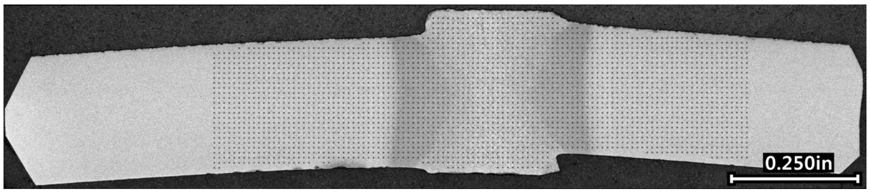


(F)

Figure 18. (Continued) Specimen 02 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (E) As-Polished HV 0.5 at 0.250 mm and (F) As-Etched HV 0.5 at 0.250 mm

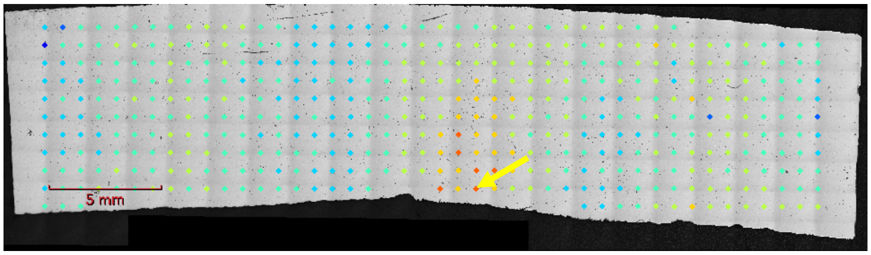
Table 15. Hardness Statistics for Specimen 02

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Mean	202.9	190.3	194.1	196.1
Min	183.5	178.1	176.3	176.3
Max	**222.7**	**208.7**	**220.0**	**241.4**
Range	39.2	30.7	43.7	65.1

Table 16. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 02

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Base Metal	194.8	189.1	193.2	194.2
Bondline	215.8	**	**	**
HAZ	203.7	193.5	196.0	199.0

(*) 6 indents in the base metal, 3 indents in the bondline, and 12 indents in the HAZ, according to Figure 4.
(**) Narrow weld bondline prevents accurate location mapping of indents. Also, the width of HV 10 indents may exceed the width of the bondline.



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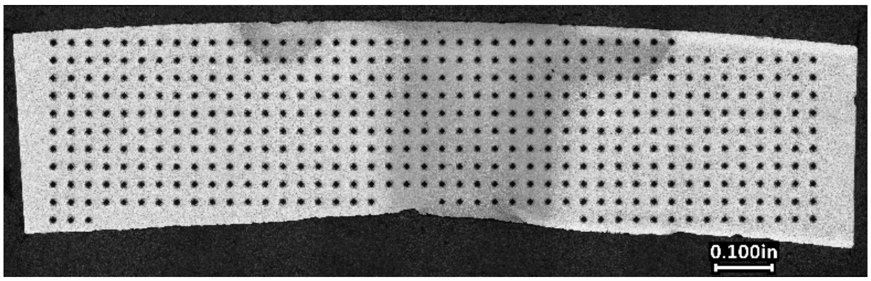

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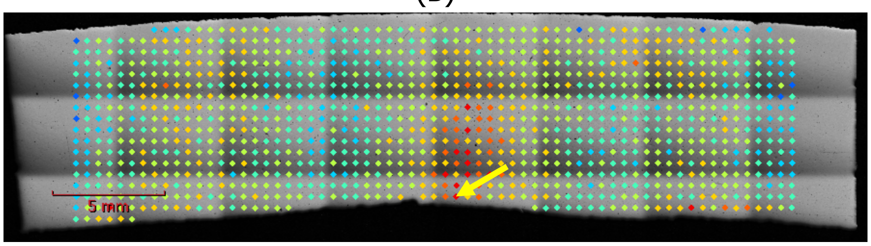
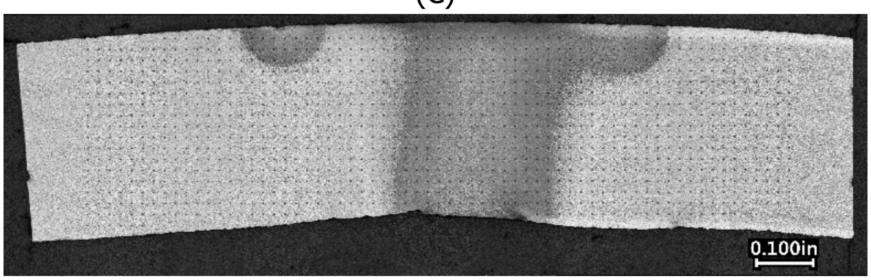


(C)



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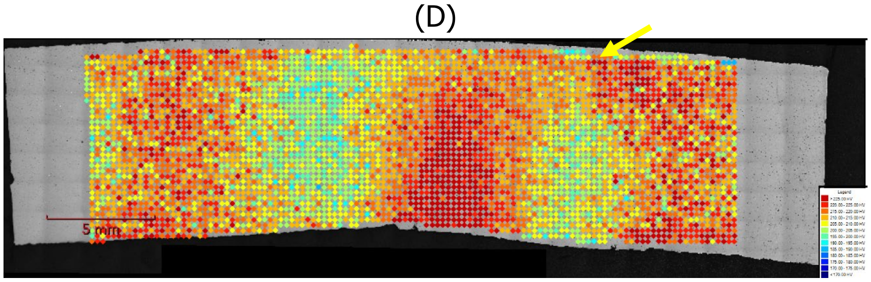
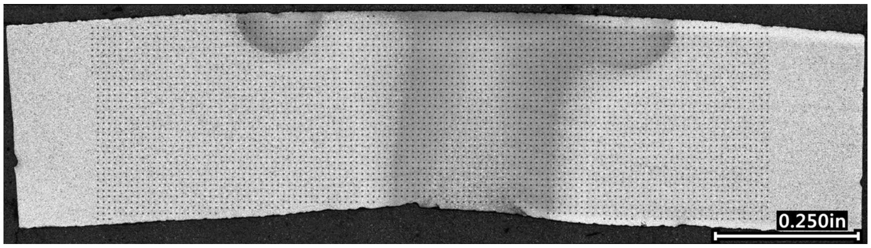


(E)

Figure 19. Specimen 07 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm, (B) As-Etched HV 10 at 0.800 mm, (C) As-Polished HV 0.5 at 0.500 mm, (D) As-Etched HV 0.5 at 0.500 mm, and (E) As-Polished HV 0.5 at 0.250 mm (Continued on next page)



(F)

Figure 19. (Continued) Specimen 07 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (F) As-Etched HV 0.5 at 0.250 mm

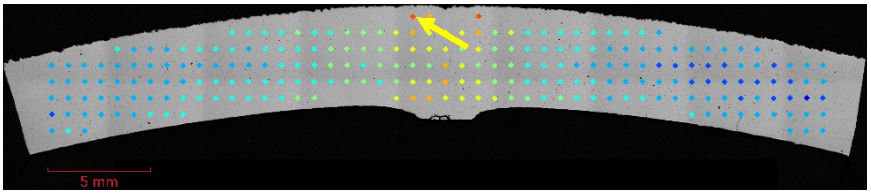
Table 17. Hardness Statistics for Specimen 07

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Mean	221.8	207.3	212.6	214.2
Min	200.9	177.8	185.0	186.8
Max	**260.5**	**235.6**	**248.2**	**259.1**
Range	59.6	57.7	63.2	72.3

Table 18. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 07

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm	Mapping 0.250 mm
	HV 0.5	HV 10	HV 0.5	HV 0.5
Base Metal	213.0	204.5	209.8	212.1
Bondline	237.5	**	**	**
HAZ	222.3	214.3	220.5	219.6

(*) 6 indents in the base metal, 3 indents in the bondline, and 12 indents in the HAZ, according to Figure 4.
(**) Narrow weld bondline prevents accurate location mapping of indents. Also, the width of HV 10 indents may exceed the width of the bondline.



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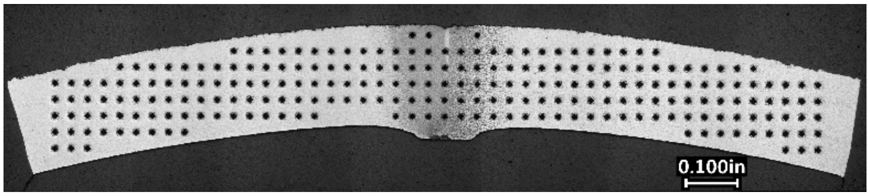
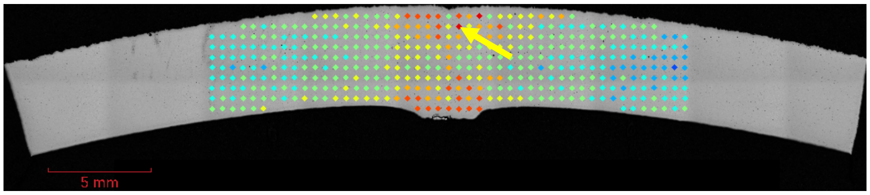
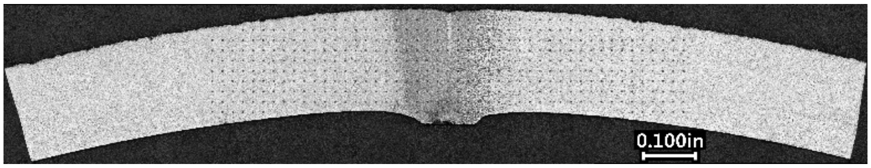


(B)



(C)



(D)

Figure 20. Specimen 08 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm, (B) As-Etched HV 10 at 0.800 mm, (C) As-Polished HV 0.5 at 0.500 mm, and (D) As-Etched HV 0.5 at 0.500 mm

Table 19. Hardness Statistics for Specimen 08

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm
	HV 0.5	HV 10	HV 0.5
Mean	178	163.9	175.7
Min	145	139.4	149.8
Max	**206**	**201.1**	**210.7**
Range	61	61.7	60.8

Table 20. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 08

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm	Mapping 0.500 mm
	HV 0.5	HV 10	HV 0.5
Base Metal	156.0	159.9	171.4
Bondline	184.7	**	**
HAZ	187.4	185.1	191.0

(*) 6 indents in the base metal, 3 indents in the bondline, and 12 indents in the HAZ, according to Figure 4.
(**) Narrow weld bondline prevents accurate location mapping of indents. Also, the width of HV 10 indents may exceed the bondline width.

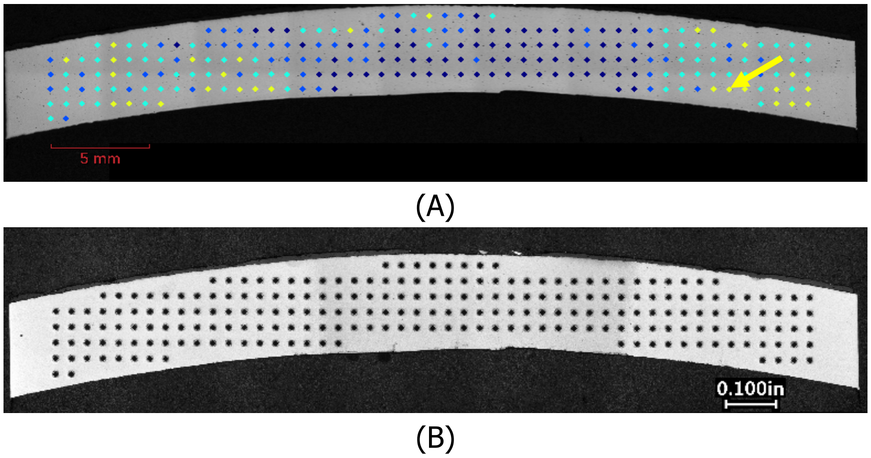


Figure 21. Specimen 03 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm and (B) As-Etched HV 10 at 0.800 mm

Table 21. Hardness Statistics for Specimen 03

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm
	HV 0.5	HV 10
Mean	187.1	183.0
Min	171.4	169.6
Max	**199.3**	**195.0**
Range	27.9	25.4

Table 22. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 03

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm
	HV 0.5	HV 10
Base Metal	189.7	186.3
Bondline	185.6	**
HAZ	186.1	178.1

(*) 6 indents in the base metal, 3 indents in the bondline, and 12 indents in the HAZ, according to Figure 4.
(**) Narrow weld bondline prevents accurate location mapping of indents. Also, the width of HV 10 indents may exceed the bondline width.

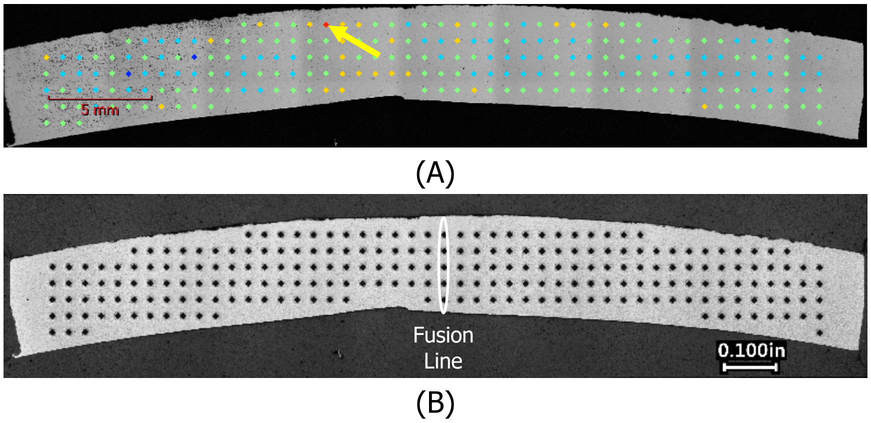


Figure 22. Specimen 09 Vickers Hardness Mapping with Arrow Pointing to Maximum Hardness Indent (A) As-Polished HV 10 at 0.800 mm and (B) As-Etched HV 10 at 0.800 mm

Table 23. Hardness Statistics for Specimen 09

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm
	HV 0.5	HV 10
Mean	173.6	166.4
Min	151.8	158.1
Max	**187.7**	**176.3**
Range	35.9	18.2

Table 24. Average Hardness per Region as Measured by Individual Indents Versus Mapping for Specimen 09

Indent Load and Spacing	Individual Indents*	Mapping 0.800 mm
	HV 0.5	HV 10
Base Metal	173.4	166.4
Bondline	174.6	**
HAZ	***	***

(*) 6 indents in the base metal, 3 indents in the bondline, and 12 indents in the HAZ, according to Figure 4.
(**) Narrow weld bondline prevents accurate location mapping of indents. Also, the width of HV 10 indents may exceed the bondline width.
(***) The longitudinal seam weld was from a pipe that underwent full-body normalizing at the mill, so the HAZ was not discernible.

Table 25. Maximum Hardness Measured Using Manual Indents Versus Mapped Indents at Two Different Spacings

#	Weld	Type	Individual Indents	Mapping		
				0.800 mm	0.500 mm	0.250 mm
			HV 0.5	HV 10	HV 0.5	HV 0.5
1	GW	SSAW	**195.3**	193.0	NM	NM
5	GW	SSAW	**219.4**	182.5	201.5	NM
6	GW	SSAW	**219.0**	212.1	NM	NM
10	GW	SSAW	198.9	274.5	352.3	**371.7**
11	Fillet	Fillet Weld	245.6	284.5	310.3	**319.9**
4	Seam	DSAW	284.1	263.8	**291.6**	283.8
2	Seam	FW	222.7	208.7	220.0	**241.4**
7	Seam	DC-ERW	**260.5**	235.6	248.2	259.1
8	Seam	LF-ERW	206	201.1	**210.7**	NM
3	Seam	HF-ERW (with PWHT)	**199.3**	195.0	NM	NM
9	Seam	ERW (with PWHT)	**187.7**	176.3	NM	NM

NM = not measured

5.8 Conclusions

Based on the results of this study, the following conclusions were formulated:

1. Hardness mapping using an indent spacing of 500 µm in combination with HV 0.5 indents (500 gf load) is an appropriate choice for cross-section specimens with a pipe WT of 4.8 mm (0.250 in.) and a weld that is not characterized by narrow weld structures.
2. For specimens with a WT of less than 4.8 mm, a spacing of 250 µm with HV 0.5 indents is recommended.
3. For specimens with welds characterized by narrow weld structures, such as the bondline in an ERW, or a HAZ location as close as possible to the weld metal, manual hardness measurement with individual indents is recommended. The ERW bond line may be as narrow as 16 µm, and the HAZ immediately adjacent to the weld metal is frequently the region of maximum hardness, which may not be captured due to the spacing of the hardness-mapping grid.
4. An apparent advantage of hardness mapping is that as more data points are collected, the automated hardness readings may be more reproducible. However, even with the larger number of data points, hardness mapping of narrow weld structures does not necessarily place the indenter at the hardest location.
5. A small indentation spacing, and accordingly a large number of indents, is required to satisfy both API 1104 and MR0175 requirements for the number and placement of hardness indents.
6. Determining the hardness of narrow weld structures, such as the bondline in an ERW or a HAZ location as close as possible to the weld metal, is more reliable with a manual process than with hardness mapping.
7. Hardness mapping did not consistently capture the maximum hardness value, despite the substantially larger number of measurements compared with individual indents. For most specimens, the mapped hardness values were within 20 HV of the individually measured maximum hardness values. However, the maximum hardness identified by mapping in 2 of the 11 specimens exceeded the individually measured maximum hardness by 74.3 HV (Specimen 11) and 172.8 HV (Specimen 10).
8. Hardness mapping covers a much larger surface area than individual hardness indents, and thus, can also identify localized regions of elevated hardness that may be missed by individual indents, as demonstrated by Specimens 10 and 11.
9. To reliably identify the hardest region of a weld, the mapping spacing should be minimized.
    a. In four of the seven specimens mapped at 800 µm and 500 µm spacing, different maximum-hardness locations were identified.
    b. In four of the five specimens mapped at 500 µm and 250 µm spacing, different maximum-hardness locations were identified.

6 APPENDIX A – LITERATURE LIST

The list in this Appendix was compiled from the Task 1 literature review on this project.

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