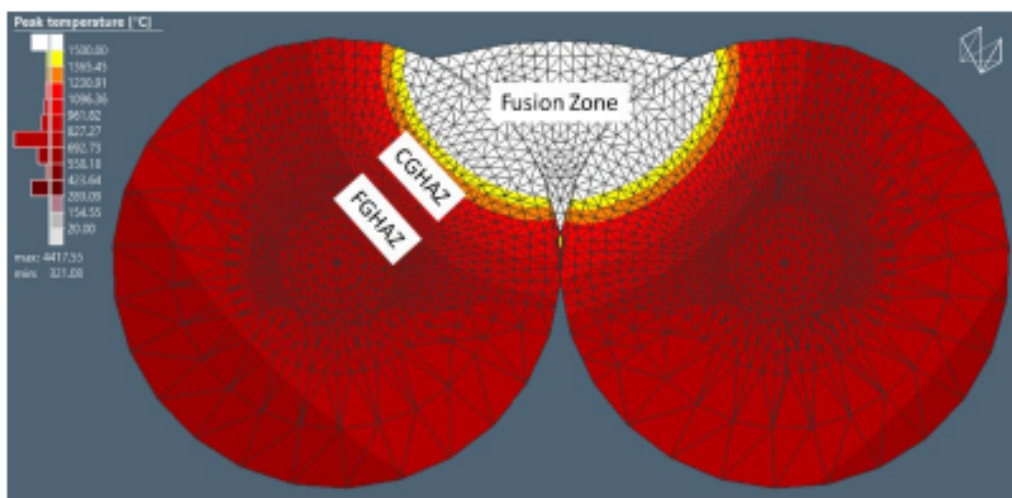




Capacity and Acceptance Criteria of Welded Splices on Cold-Bent Reinforcing Steel

FINAL REPORT



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13. ABSTRACT (Maximum 200 words) Cold-bent reinforcing steel hoops and spirals are critical components in Alaska's concrete-filled pipe pile bridge systems, especially in seismic regions. Current welding codes (AWS D1.4:2018) prohibit welding within two bar diameters of a bend, yet this practice has been used for decades without reported failures. This report presents the results of a study investigating the strength and ductility of welded splices on cold-bent ASTM A706 Grade 60 reinforcing steel. For this study, lap-splice welds were prepared on cold-bent hoops of two different bar sizes (#4 and #5) and at low and high heat input. Weld heat-affected zone microstructures were characterized using optical microscopy on etched weld cross-sections. Microhardness tests revealed an increase in hardness close to the fusion line and an adjacent softened region in the heat-affected zone. At high heat input and small bar size the softening extends throughout the entire bar diameter and removes the cold-work in the bar. Tensile tests showed a reduction in ductility for welds made on pre-strained bars. However, all tensile tests met the tensile-to-yield ratio requirement in AWS D1.4:2018. The result of this study do not indicate any immediate concern for welded hoops and spiral bars in the pipe pile system.				
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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
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LENGTH

in	inches	25.4	mm
ft	feet	0.3048	m
yd	yards	0.914	m
mi	Miles (statute)	1.61	km

AREA

in ²	square inches	645.2	millimeters squared	cm ²
ft ²	square feet	0.0929	meters squared	m ²
yd ²	square yards	0.836	meters squared	m ²
mi ²	square miles	2.59	kilometers squared	km ²
ac	acres	0.4046	hectares	ha

MASS (weight)

oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg

VOLUME

fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft ³	cubic feet	0.0283	meters cubed	m ³
yd ³	cubic yards	0.765	meters cubed	m ³

Note: Volumes greater than 1000 L shall be shown in m³

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C
----	------------------------	-------------	---------------------	----

ILLUMINATION

fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m ²	cd/cm ²

FORCE and PRESSURE or STRESS

lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
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LENGTH

mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi

AREA

mm ²	millimeters squared	0.0016	square inches	in ²
m ²	meters squared	10.764	square feet	ft ²
km ²	kilometers squared	0.39	square miles	mi ²
ha	hectares (10,000 m ²)	2.471	acres	ac

MASS (weight)

g	grams	0.0353		oz
kg	kilograms	2.205		lb
mg	megagrams (1000 kg)	1.103	short tons	T

VOLUME

mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m ³	meters cubed	35.315	cubic feet	ft ³
m ³	meters cubed	1.308	cubic yards	yd ³

TEMPERATURE (exact)

°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
----	---------------------	-----------	------------------------	----

ILLUMINATION

lx	lux	0.0929	foot-candles	fc
cd/cm ²	candela/m ²	0.2919	foot-lamberts	fl

FORCE and PRESSURE or STRESS

N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

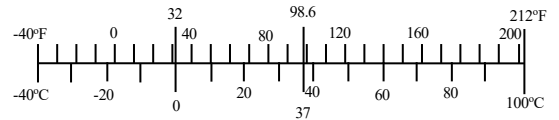


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CHAPTER 1 - INTRODUCTION AND RESEARCH APPROACH

Problem Statement and Research Objective

Cold-bent reinforcing steel (rebar) hoops and spirals are an integral part of the concrete-filled steel pipe pile bent system of bridge structures. The structural adequacy of the bridge bent system is essential for its performance, especially in seismic regions. Welding reinforcing steel splices is a long-standing practice in bridge construction. Welded splices on rebar hoops and spiral bars need to conform to the American Welding Society (AWS) D1.4: 2018 Structural Welding Code - Steel Reinforcing Bars [1]. The standard describes filler metal selection, preheat/interpass temperatures, and performance and procedure qualification requirements for welding of reinforcing steel bars. However, welded splices on hoops and spiral bars are not in compliance with AWS D1.4:2018. Section 6.2.4 does not allow welding within two bar diameters of the bend. The clause was introduced in 1998 to avoid potential cracking after welding at the portion of the bar that was potentially made brittle as a result of cold-bending.

Despite this code provision and decades of research on the pipe pile system, no known defects have arisen from welded splices on cold-bend reinforcing steel. However, the reliability of the welded splices to behave as anticipated is extremely important in plastic hinge regions of the pipe pile. Specific testing of cold-bent reinforcing steel welds has not been completed to ensure that current materials and methods do not adversely affect the strength and ductility of the welded splices. This study aimed to address this gap to confirm that welding on cold-bent hoops and spiral bars is not detrimental to weld mechanical properties.

The primary objective of this research was to investigate the effect of welding on cold-bent ASTM A706 Grade 60 reinforcing steel [2]. Specific research objectives were as follows:

- (1) to determine changes in microstructure and microhardness in the heat-affected zone of welded cold-bent reinforcing steel,
- (2) to compare the tensile strength and ductility for welds made on cold-bent reinforcing steel hoops versus welds on bars without additional cold-bent,
- (3) to determine the monotonic stress-strain behavior locally in the heat-affected zone of welded cold-bent reinforcing steel hoops, and
- (4) to identify specific requirements and/or acceptance criteria for welding on cold-bent reinforcing steel beyond those in AWS D1.4.

Scope of Study

The primary aim of this research project was to experimentally validate that welding on cold-bent hoops and spiral bars is not detrimental to weld mechanical properties. Specific considerations regarding the scope of this research were as follows:

All testing was performed on ASTM A706 Grade 60 reinforcing steel which is routinely specified in Alaska and other seismic states for reinforced concrete members expected to form plastic hinges. Testing was done on bar sizes #4 and #5, both of which are typically used for this application. A difference in cooling rate was expected that could affect weld heat-affected zone microstructure and hardness. Bars were cold-bent prior to welding to 19 and 36 in. diameter hoops, respectively, to accommodate standard diameter pipe piles.

This study focused on welded hoop splices as these are known from full-scale testing of the concrete-filled steel pipe pile bent system to experience higher strains as compared to spiral bars [3]. Single-pass welded lap-splices commonly used in hoop and spiral rebar fabrication were prepared by an experienced rebar fabricator at the low and high end of the allowable heat input as specified in the fabricator's AWS D1.4 Welding Procedure Specification (WPS). Shielded metal arc welding (SMAW) was used with AWS A5.5 E8018-C3 welding rod. Lap-splice welds were subjected to microstructure characterization on etched cross-sections using light optical microscopy, Vickers hardness measurements and guided bend testing. A limited number of additional welds were made in a direct butt joint configuration at the OSU laboratory to facilitate cross-weld tensile testing. Additional tensile testing was performed on simulated microstructures to obtain the stress-strain behavior locally in the heat-affected zone region.

Research Approach

(Task 1) *Literature review.* This task reviewed and summarized existing research on (1) welding on cold-bent (cold worked or work hardened) carbon and low alloy steel, (2) current procedure specifications, practices, and guidelines for reinforcing steel welding, in particular for reinforced concrete bridge structures, and (3) existing information and material test data for welded ASTM A706 Grade 60 reinforcing steel.

(Task 2) *Metallurgical characterization of welded cold-bent reinforcing steel hoops.* In this task, metallurgical characterization was performed on transverse cross-sections of welded hoop reinforcing steel. Welds were prepared by J.D. Steel Company Inc. (Palmer, AK) and sent to OSU for metallurgical characterization. J.D. Steel is an in-state rebar fabricator involved in the

majority of rebar welding for bridge structures in Alaska. Production welds (single-pass welded lap-splices) were made on ASTM A706 Grade 60 hoop reinforcing steel using J.D. Steel's AWS D1.4 Welding Procedure Specification (WPS). Lap-splice welds were prepared at both the WPS's low end of allowable heat input, and high end of allowable heat input. All welds were made on size #4 and #5 bars, cold-bent to 19 and 36 in. diameter hoops, respectively. Welds were made on straight bars using the same welding procedure. Characterization of all welds was performed using light optical microscopy (LOM) and Vickers microhardness measurements with a focus on the weld heat-affected zone. Baseline properties of non-welded cold-bent hoops were established for comparison. Microstructure and hardness results were compared to identify the effect of cold-work, heat input and bar diameter.

(Task 3) *Stress-strain behavior of welded cold-bent reinforcing steel hoops.* The impact of welding on the strength and ductility of the cold-bent hoops was addressed in three subtasks:

(Task 3.1) *Cross-weld tensile testing* was performed on butt welded ASTM A706 Grade 60 reinforcing #4 bars. Straight bars were pre-strained to 10% prior to welding to simulate the cold-bent of the hoop bars. Cross-weld tensile tests were performed at ambient temperature. Tensile strength was determined by dividing the obtained maximum load by the nominal cross-sectional area of the samples. AWS D1.4 [1] requires the tensile strength of the welded joint to be no less than 125% of the minimum specified yield strength of the type and grade of bars to be joined. To further understand the local stress-strain behavior across the weld, digital image correlation (DIC) was utilized during tensile testing.

(Task 3.2) *Guided bend testing.* As supplementary information to the tensile testing in Task 3.1, guided-bend testing was performed on lap-splice welds on cold-bent ASTM A706 Grade 60 hoops. Bend testing provided visual information on the ductility of the lap-splice welds made on cold-bent reinforcing steel hoops.

(Task 3.3) *Tensile testing on simulated heat-affected zone microstructures.* The effect of cold-work on the monotonic stress-strain behavior in the weld heat-affected zone was further characterized by using physical simulation of heat-affected zone microstructures in a Gleeble system and subsequent tensile testing. Samples were machined from ASTM A706 Grade 60 straight bar. A Gleeble system was used to simulate the weld thermal cycle and temperature gradient experienced in the weld heat-affected zone on samples with pre-strain and without pre-strain to evaluate the effect of cold-work. Pre-straining of the samples was performed in the Gleeble at room temperature prior to thermal simulation to reflect the degree of cold work experienced in the cold-bent reinforcing steel hoops. A heat transfer finite element model informed peak temperatures and cooling rates for the heat-affected zone simulations.

Microstructures and hardness of simulated samples were compared to data from actual heat-affected zone microstructures of welded lap-splices. Gleeble simulated heat-affected zone samples were then tensile tested to quantify the monotonic stress-strain response. Testing was performed at ambient temperature.

(Task 4) *Analysis and Recommendations.* The experimental results informed recommendations for the preparation of welded splices on cold-bent ASTM A706 Grade 60 reinforcing steel.

Methodology

Materials. ASTM A706 Grade 60 reinforcing steel has a restricted chemical composition and carbon equivalent to enhance its weldability [2]. In this study, ASTM A706 Grade 60 rebar in two bar diameters was investigated. Note that after the lap-splice welds had already been prepared for the project, it was discovered that the rebar used for these welds originated from two different mills. There are differences in composition, corresponding carbon equivalent and tensile properties as listed in **Table 1** and **Table 2**. The implications of these differences are discussed in the result section. All rebar met the requirements specified in ASTM A706/A706M-22a [2].

Table 1: Composition and corresponding calculated carbon equivalent (CE) for ASTM A706 Grade 60 rebar (all in weight-%). Requirements from ASTM A706/A706M-22a are given as a reference.

Steel Mill	Bar Size	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Sn	CE
ASTM A706/A706M-22a (maximum values)		0.33	1.56	0.043	0.053	0.55	N/A	N/A	N/A	N/A	N/A	N/A	0.55
Mill 1	#4 (Ø 0.5 in.)	0.28	1.21	0.012	0.023	0.22	0.26	0.07	0.13	0.02	0.032	0.021	0.50
	#5 (Ø 0.625 in.)	0.28	1.22	0.013	0.021	0.26	0.38	0.08	0.14	0.02	0.030	0.021	0.51
Mill 2	#4 (Ø 0.5 in.)	0.26	1.12	0.006	0.018	0.28	0.24	0.07	0.07	0.02	0.034	N/A	0.46
	#5 (Ø 0.625 in.)	0.26	1.17	0.008	0.020	0.26	0.27	0.07	0.07	0.02	0.037	N/A	0.47

Table 2: Tensile properties for ASTM A706 Grade 60 rebar. Requirements from ASTM A706/A706M-22a are given as a reference.

Steel Mill	Bar Size	Tensile Strength, psi [MPa]	Yield Strength, psi [MPa]	Elongation, %	Tensile/Yield Ratio
ASTM A706/A706M-22a		min. 80,000 [550]	60,000 – 78,000 [420 - 540]	14*	≥ 1.25
Mill 1	#4 (Ø 0.5 in.)	99,500 [685]	65,500 [450]	15	1.52
	#5 (Ø 0.625 in.)	102,000 [705]	67,500 [465]	17	1.51
Mill 2	#4 (Ø 0.5 in.)	91,000 [625]	61,400 [425]	16	1.48
	#5 (Ø 0.625 in.)	94,700 [655]	62,000 [430]	16	1.53

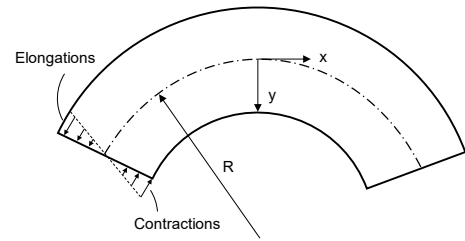
*Minimum % elongation is only applicable for #3 to #6 size bars.

The rebar was received by J.D. Steel as coiled material which was then put through two sets of straightening rollers, one vertical bank and one horizontal bank that straightened the rebar in both planes. Note that this coiling and subsequent straightening constitutes an initial cold forming that all rebar was subjected to, but that was not considered for the purpose of this study. The Mill 1 rebar was cut into segments after straightening and is designated as “straight bars” (no additional cold-bent) for the remainder of this report. The Mill 2 rebar was cold-bent against a former, rolling it into 19 and 36 in. diameter hoops for the #4 and #5 bar size, respectively. This rebar is designated as “cold-bent hoops” for the remainder of this report. The maximum theoretical tensile strain at the outer surface of the rebar during cold-bent was estimated to be 2.6 and 1.7% (**Table 3**). This calculation assumes zero elongation at the neutral axis, and that the neutral axis did not shift during bending. It is noted that due to spring back the actual maximum strain experienced was slightly higher, but still well below 5%.

Table 3: Estimated maximum theoretical tension strain experienced during the cold-bending.

	Bar size #4 (Ø 0.5 in.)	Bar size #5 (Ø 0.625 in.)
Bend Radius, R	9.5 in.	18 in.
Maximum y-value	-0.25 in.	-0.3125 in.
Maximum theoretical strain, ϵ^*	0.0263	0.0174

* $\epsilon = -\frac{y}{R}$ from [4]



Weld Geometry and Preparation. Single-pass welded lap-splices commonly used in hoop and spiral rebar fabrication were prepared by J.D. Steel Company Inc. (Palmer, AK), an experienced rebar fabricator that is involved in most of the rebar welding for bridge structures in Alaska. Shielded metal arc welds (SMAW) were made at both the low and high end of the allowable heat input as specified in the fabricator’s AWS D1.4 Welding Procedure Specification (WPS). AWS A5.5 E8018-C3 welding rod was used as specified. **Table 4** lists all lap-splices made and associated welding parameters. **Figure 1** depicts the direct lap joint geometry as specified in AWS D1.4: 2018 [1]. Single-flare-V-groove-welds were made on the tension side of the cold-bent hoops with a weld length of 12 inches. Welds were made on the straight bars using the same welding procedures. Photographs of the as-received welds are provided in **Appendix 0**.

Table 4: Lap-splice welds performed on ASTM A706 Grade 60 reinforcing steel and associated welding parameters.

Steel Mill	Bar Size	Bend Diameter	%Cold Work	Voltage	Current	Travel Speed	Heat Input	Quantity
Mill 1	#4 (Ø 0.5 in.)	N/A	N/A	21 V	90 A	9 IPM	13 kJ/in.	2
					160 A	5 IPM	40 kJ/in.	2
	#5 (Ø 0.625 in.)	N/A	N/A	21 V	90 A	9 IPM	13 kJ/in.	2
					160 A	5 IPM	40 kJ/in.	2
Mill 2	#4 (Ø 0.5 in.)	19 in.	2.6	21 V	90 A	9 IPM	13 kJ/in.	2
					160 A	5 IPM	40 kJ/in.	2
	#5 (Ø 0.625 in.)	36 in.	1.7	21 V	90 A	9 IPM	13 kJ/in.	2
					160 A	5 IPM	40 kJ/in.	2

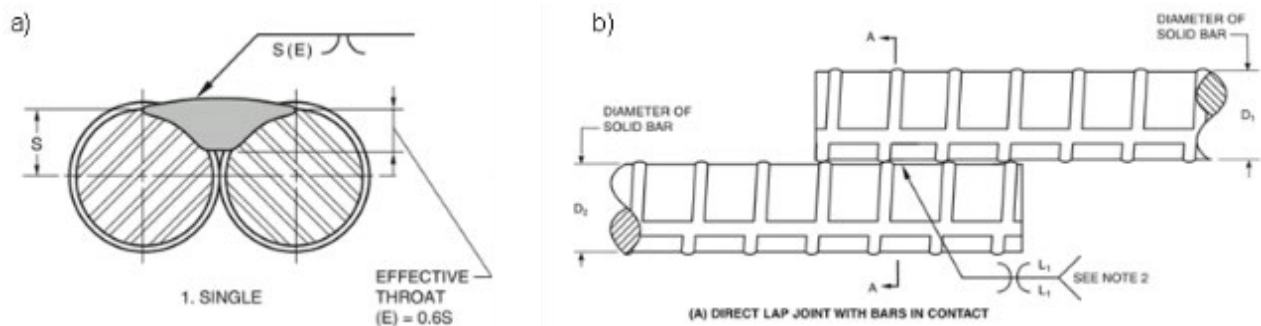


Figure 1: Joint geometry of welded lap-splices: (a) cross-section of the single flare-v-groove weld and (b) direct lap joint with bars in contact per AWS D1.4:2018 [1].

In addition to the lap-splice welds, direct butt welds were prepared at the OSU laboratory to facilitate cross-weld tensile testing. Butt welds were prepared on size #4 straight bars (Mill 1) only. Prior to welding, a subset of the bars was pre-strained at room temperature to approximately 10% in a tensile frame to introduce cold-work. The amount of pre-strain was intentionally higher as compared to the estimated maximum strain in the cold-bent hoops. Four welds each were prepared on bars with and without applied pre-strain. **Figure 2** depicts the direct butt joint geometry as specified in AWS D1.4: 2018 [1]. Butt joints were made as multi-pass single-V-groove welds using shielded metal arc welding (SMAW) at 90 A with AWS A5.5 E8018-C3 welding rod.

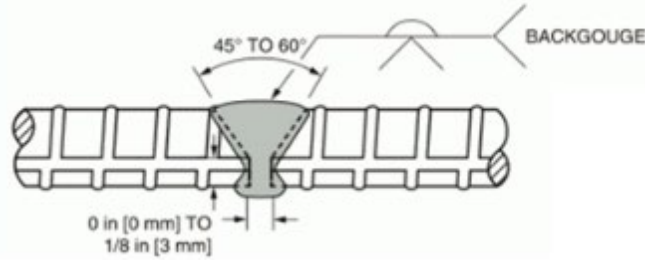


Figure 2: Joint geometry of single-V-groove direct butt weld per AWS D1.4:2018 [1].

Metallographic Preparation. Samples for metallographic preparation were taken from all received bars prior to welding for characterization of the base metal microstructure. For the cold-bent hoops, the sample orientation relative to the tensile/compressive axis was recorded. Transverse weld cross-sections were extracted from the welded lap-splices near the center of the welds for analysis of bead shape and heat-affected zone width and microstructure. Standard metallographic preparation techniques were used, including surface preparation with 400-600 grit paper followed by polishing with 9, 6, 3, and 1 μm diamond suspension. The samples were finished with a 0.05 μm colloidal silica polish. Etching was done with 2% Nital to reveal the microstructure in the base metal rebar and across the welds. Etched microstructures were observed under a light optical microscope (LOM). LOM images were used to estimate and compare prior austenite grain size (PAGS) in the base metal microstructures and the coarse grain heat-affected zone (CGHAZ) of the welds. In both microstructures, grain boundary ferrite was nearly continuously present at the prior austenite grain boundaries and was used to estimate PAGS according to the Heyn lineal intercept method from ASTM E112-21: Standard Test Methods for Determining Average Grain Size [5].

Hardness Testing. Microhardness was measured on polished cross-sections of the base metal bars and the welds using an automated Vickers hardness tester (LECO LM100AT) with a 200 g load (HV 0.2) and 150 μm spacing. Hardness traverses were placed along and perpendicular to the tensile-to-compressive axis when measuring on the cold-bent hoops. On the weld cross-sections, hardness traverses were taken from the fusion zone into the heat-affected zone and base metal rebar, as illustrated in **Figure 3**. Hardness maps were obtained across the heat-affected zone for selected weld samples.

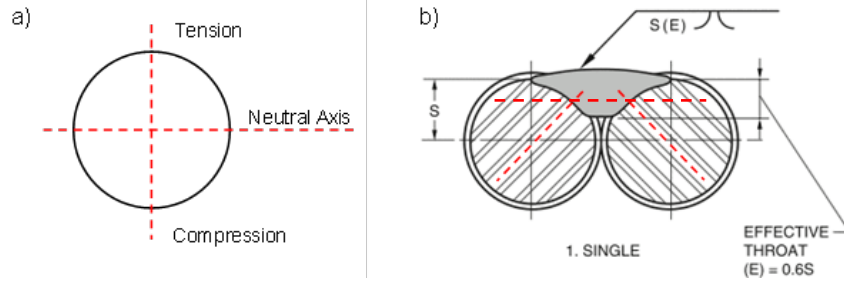


Figure 3: Schematic of microhardness traverses on cross-sections of (a) cold-bent base metal hoops with tension-to-compression axis orientation recorded, and (b) single flare-v-groove welded lap-splices with full traverse across the weld, and two diagonal traverses towards the center of both bars.

Cross-Weld Tensile Testing. Tensile tests were performed using subsize specimens according to ASTM E8 Standard Test Methods for Tension Testing of Metallic Materials [6]. However, the gauge length of the samples was increased from 25 to 40 mm to ensure the entire extent of the heat-affected zone, and a portion of the base metal was in the reduced sample section as shown in **Figure 4**. Testing was done on machined dog-bone samples to facilitate digital image correlation (DIC) which allows the observation of strain localization and evolution in different regions of the weld during the tensile test. The test samples were extracted by milling from the direct butt welds. The gauge section surfaces were manually ground using 120 through 800-grit SiC paper. One side of the gauge section was etched with 2% Nital to reveal the base metal, heat-affected zone (HAZ), and weld metal regions and accurately mark these regions for local digital extensometers. A DIC speckle pattern was then applied on the gauge section surface as shown in **Figure 5**. The testing setup used an MTS 810 test frame with a displacement rate of 1 mm/min through sample failure, resulting in a strain rate of 0.025 mm/min. A FLIR Chameleon[®] 3 camera and a ring light were used for recording the DIC pattern during tensile testing at a capture rate of 5 frames/s. The DIC images were processed using VIC 2D commercial software. Multiple digital extensometers were applied to measure the strain distribution across the entire gauge section as well as locally in the different weld regions.

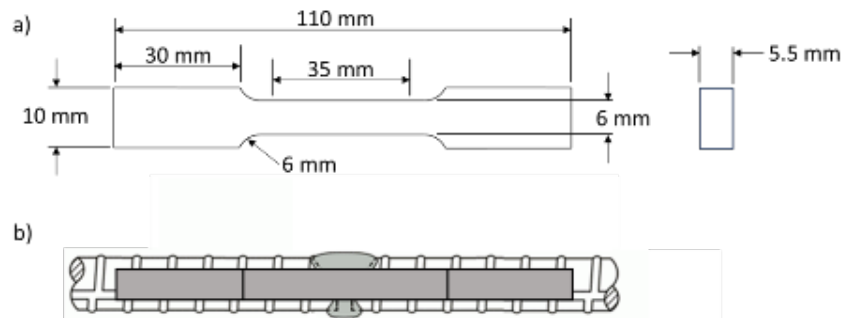


Figure 4: (a) Sample geometry for tensile testing of direct butt welds utilizing digital image correlation (DIC), and (b) extraction layout with reference to butt weld geometry.

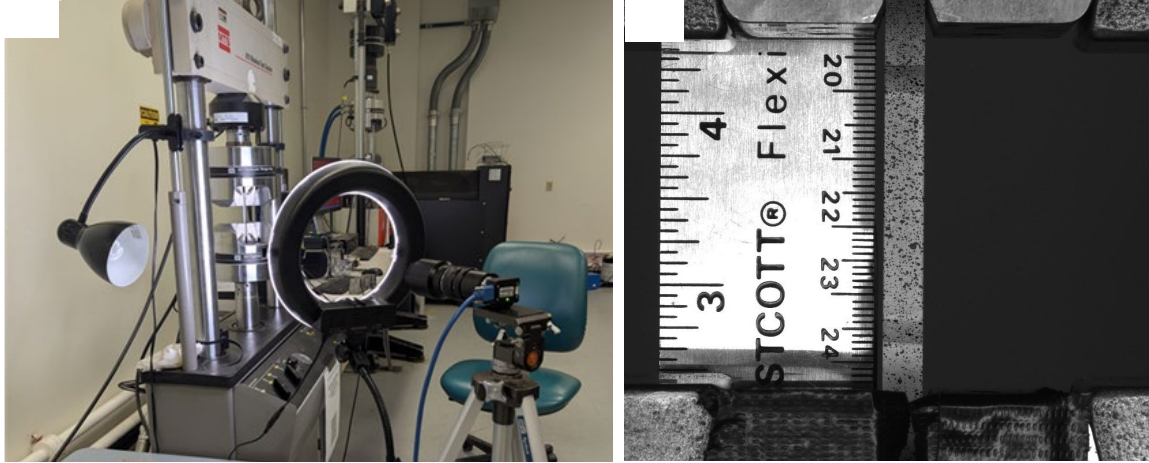


Figure 5: (a) Tensile test setup with camera and ring lighting for digital image correlation (DIC), and (b) sample with speckle pattern applied for DIC prior to tensile testing.

Bend Testing. Guided bend tests were performed on the welded lap-splices for visual analysis of weld ductility. Three longitudinal bends each were performed on all lap-splice weld conditions (Table 4). A top ejecting guided bend test fixture was used as shown in Figure 6. Samples were bent to 180 degrees. AWS B4.0:2016 Standard Methods for Mechanical Testing of Welds [7] was used as a reference to perform the bend tests, however, the tests deviated from the standard as described in the following. Bend tests were conducted with the weld face in tension in the as-welded condition using a 1.5 in. plunger diameter which was determined as follows:

$$A = T(50/e - 1/2)$$

where, A is the radius of the plunger ($\pm 1/16$ in.), e is the elongation of the outer surface (in %) and T is the specimen thickness (bar diameter) ($\pm 1/64$ in.) [7]. The 1.5 in. plunger diameter was used for all tests which resulted in a higher maximum elongation for the welds on the #5 size bars. This was due to the available test configurations. It was opted to perform a more conservative test rather than one reaching lower strain. Also note that due to the curved geometry of the welds on the cold-bent hoops, these welds experienced a lower maximum elongation during the bend test as compared to the welds on the straight bars. Lastly, the lap-splice welds were not machined into flat, rectangular samples for bend testing because the curvature of the cold-bent hoop welds did not allow for machining. After testing, the bend samples were analyzed under a stereomicrograph up to 100x magnification with emphasis placed on the heat-affected zone.



Figure 6: Test configuration for top-ejecting guided-bend test with lap-splice weld loaded.

Gleeble Simulation and Tensile Testing. A Gleeble-3800 system (**Figure 7**) was used for physical simulation of the microstructure in two different regions of the heat-affected zone, namely the coarse grain heat-affected zone (CGHAZ) and the fine grain heat-affected zone (FGHAZ). The Gleeble samples were then subjected to tensile testing to obtain the stress-strain behavior locally in the CGHAZ and FGHAZ regions. For Gleeble simulation cylindrical samples with a reduced gauge section were machined from the straight #4 bars. The sample geometry is shown in **Figure 8**. A simple 2D heat-transfer finite element model of the welded lap-splice geometry was set up in Simufact Welding software (Hexagon) to extract the thermal history for locations of interest in the HAZ. Peak temperatures and cooling times from the model were used to inform the Gleeble simulation of CGHAZ and FGHAZ microstructures. Simulations were done on 10% pre-strained samples and on samples without applied pre-strain. The samples without pre-strain were heated to the peak temperature and subsequently free cooled in the Gleeble while holding the force at 0 kN to allow for thermal expansion. The simulations on the pre-strained samples were performed in two steps. First the samples were pulled in tension to 10% pre-strain at room temperature using an extensometer in the Gleeble. Once the force was relieved the grips shifted requiring unloading and refixturing of the samples. Then the samples were heated to the peak temperature and free cooled in the Gleeble using the same procedure as for the samples without pre-strain. The microstructures obtained in the Gleeble were compared with CGHAZ and FGHAZ microstructures in the welded lap-splices in terms of prior austenite grain size (PAGS), phases present and microhardness. Then, three Gleeble samples each with simulated GCHAZ and FGHAZ microstructures were tensile tested at room temperature in an MTS 810 test frame with a displacement rate of 1 mm/min through sample failure, resulting in a strain rate of 0.025 mm/min.

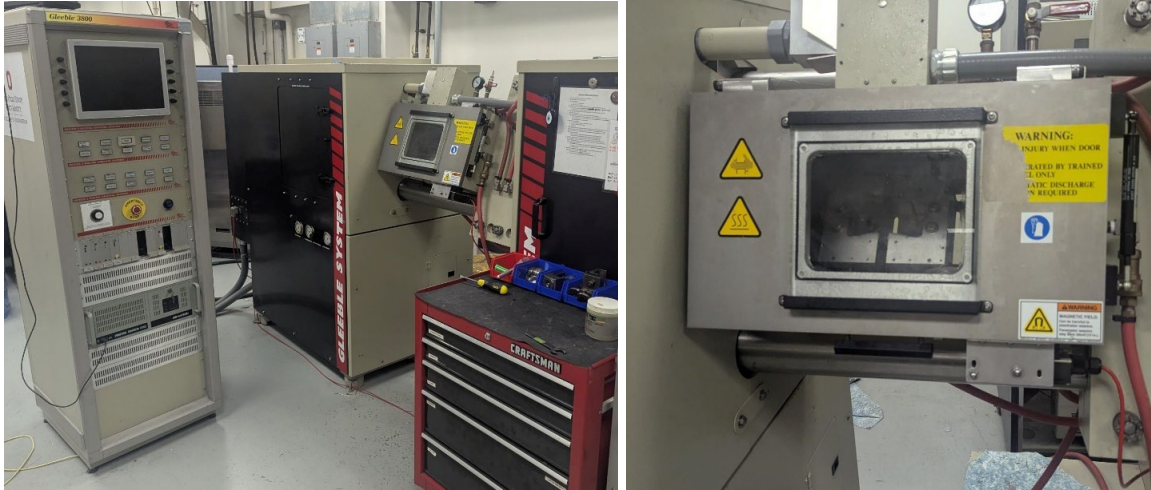


Figure 7: Gleeble 3800 system used for physical simulation of heat-affected zone microstructures.

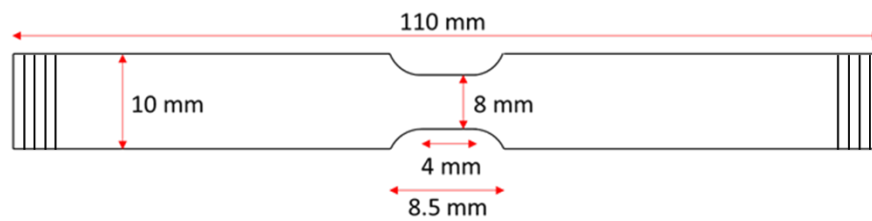


Figure 8: Geometry of cylindrical Gleeble samples for simulation of heat-affected zone microstructures and subsequent tensile testing. Threaded ends were used.

CHAPTER 2 – FINDINGS

Rebar Base Metal Microstructures and Hardness

All received ASTM A706 Grade 60 rebar had a ferritic-pearlitic base metal microstructure. Micrographs from light optical microscopy (LOM) on the #4 size cold-bent hoops and straight bars are shown in **Figure 9**. Ferrite is etched brightly and present as grain boundary ferrite (GF) outlining the prior austenite grain boundaries. Some polygonal ferrite can also be observed. The darker etched constituent is fine pearlite (P), which is a lamellar mixture of ferrite and cementite. From **Figure 9** it is apparent that the prior austenite grain size (PAGS) in the straight bars (Mill 1) is much coarser as compared to the cold-bent hoops (Mill 2) (**Table 5**). Micrographs of the #5 size rebar microstructures are given in **Appendix 1**. A similar difference in PAGS was observed between the straight bars and cold-bent hoops. This is likely due to differences in composition and thermo-mechanical processing during rebar manufacturing at the two steel mills. As noted earlier, this difference was not discovered until after the lap-splice welds for this project had been prepared. While this limits a direct comparison, it still allows for an assessment of the effect of heat input and bar size on microstructure and hardness changes in the heat-affected zone (HAZ) of the cold-bent hoops.

Results from Vickers microhardness measurements on the rebar base metals are summarized in **Table 5**. Minimum, maximum, and average hardness values are given from hardness traverses on bar cross-sections (see **Figure 3**). Results from measurements on the cold-bent hoops along and perpendicular to the tensile-to-compressive axis are shown in **Figure 10**. Hardness tends to increase toward the outer edges of the cold-bent bars when measured in the tensile-to-compressive axis. This is attributed to the cold work introduced during bending. Note that this trend was not as obvious in all cross-sections. This may be because the rebar was coiled before cold-bending of the hoops which might have introduced some variability in the actual cold work depending on the diameter of the coiled material. The average hardness was higher in the #4 size cold-bent hoops as compared to the #5 size hoops due to the higher percentage of cold work (**Table 5**). The hardness measured across the diameter of the straight bars was relatively uniform (**Figure 11**). On average, the #5 size straight bars showed a slightly higher hardness as compared to the straight #4 bars.

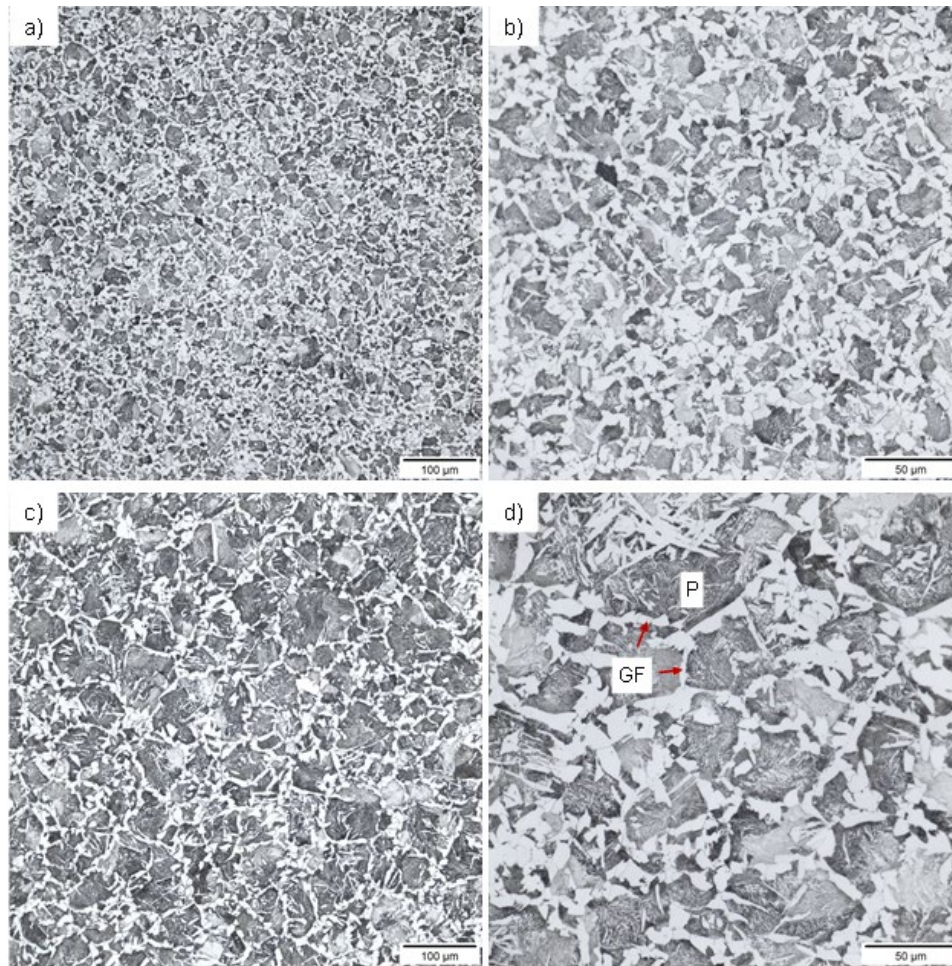


Figure 9: Etched (2% Nital) base metal microstructures at two magnifications of the ASTM A706 Grade 60 rebar (#4 bar size) from light optical microscopy of (a, b) the cold-bent hoops (Mill 2), and (c, d) the straight bars (Mill 1). Note that all micrographs were taken from the center of the rebar cross-section. GF – Grain boundary ferrite, P – Pearlite.

Table 5: Results from measurement of prior austenite grain size (PAGS) and microhardness on the ASTM A706 reinforcing steel straight bars (Mill 1) and cold-bent hoops (Mill 2).

Steel Mill	Bar Size	Bend Diameter	% Cold Work	Prior Austenite Grain Size, μm	Microhardness, HV 0.2		
					Max	Min	Avg.
Mill 1	#4 ($\varnothing$ 0.5 in.)	N/A	N/A	45 ± 7	225	197	215 ± 6
	#5 ($\varnothing$ 0.625 in.)	N/A	N/A	47 ± 6	249	204	223 ± 8
Mill 2	#4 ($\varnothing$ 0.5 in.)	19 in.	2.6	19 ± 3	263	176	232 ± 13
	#5 ($\varnothing$ 0.625 in.)	36 in.	1.7	19 ± 1	256	189	214 ± 10

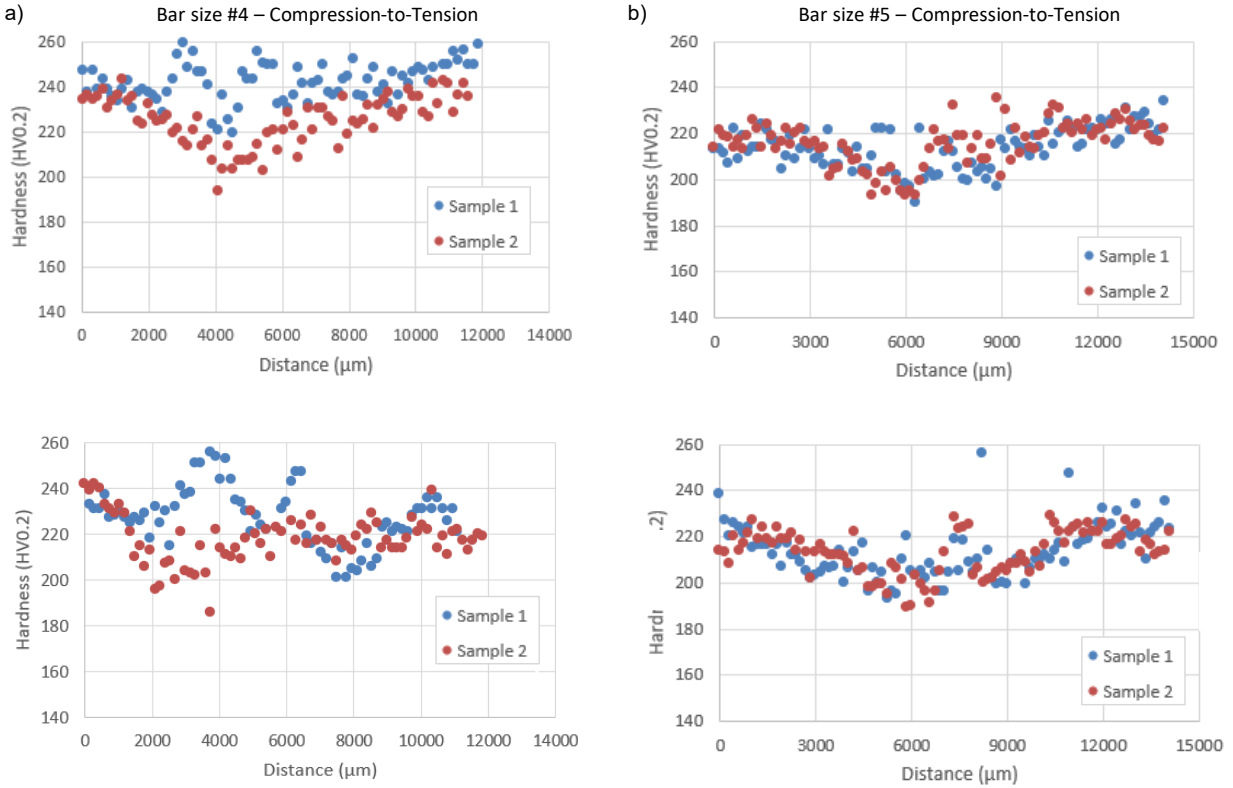


Figure 10: Microhardness traverses (HV 0.2) on the cold-bent hoops along the compression-to-tension axis and perpendicular to it (neutral axis). Hardness traverses from two bar cross-sections each are shown for the (a, c) #4 and (b, d) #5 size hoops.

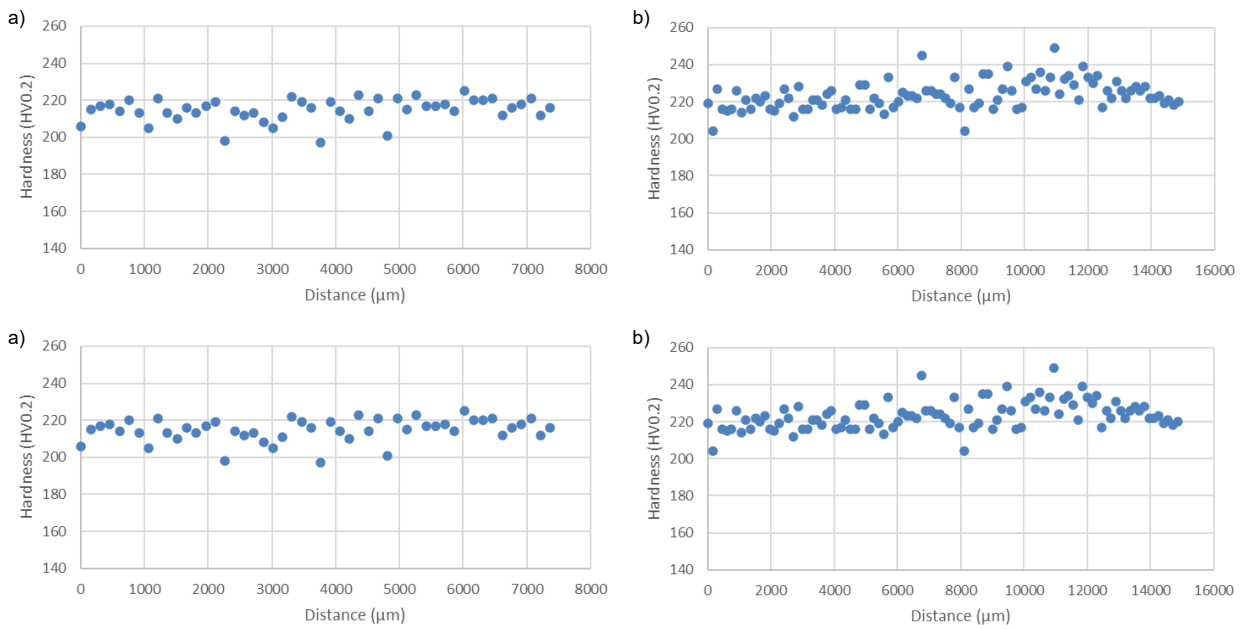


Figure 11: Microhardness traverses (HV 0.2) on the straight bars for (a) #4 and (b) #5 size bars.

Lap-Splice Weld Cross-Sections, Microstructures and Hardness

Macrographs of the lap-splice welds on the cold-bent hoops and straight bars made with low (13 kJ/in.) and high heat input (40 kJ/in.) are shown in **Figure 12** and **Figure 13**. AWS D1.4:2018 [1] specifies that the effective throat (E) for flare-V-groove welds shall be 0.6 of the bar radius (s). All welded lap-splices had an effective weld throat that equaled or exceeded this requirement. Measurement results are provided in **Appendix 2**. The effective throat increased at high heat input for the welded #4 size bars. This was less apparent on the #5 size bars. Multiple cross-sections extracted along the length of the welds revealed some variability in terms of weld bead size. This is likely a result of the manual welding process. Some cross-sections showed the heat concentrated towards one bar. This is important to keep in mind when comparing HAZ microstructure and hardness as a function of bar size and heat input in the following paragraphs.

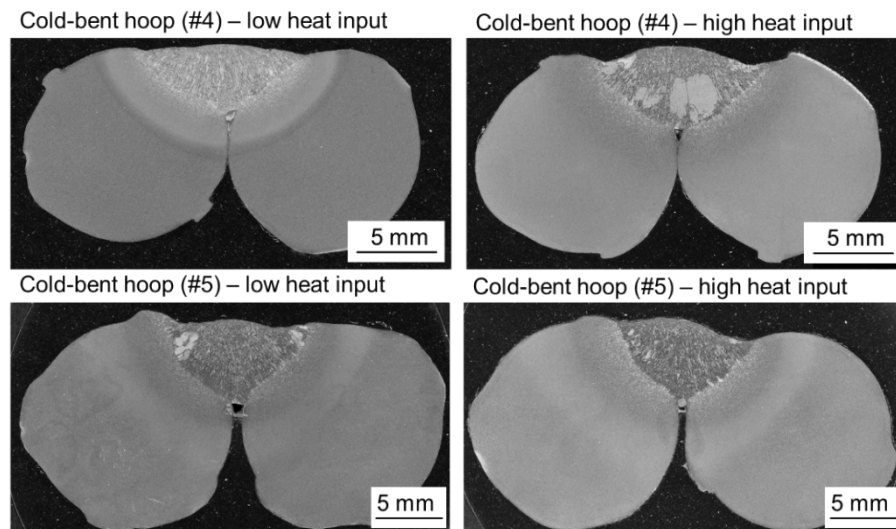


Figure 12: Macrographs of welded lap-splices on ASTM A706 Grade 60 cold-bent hoops made with low (13 kJ/in.) and high heat input (40 kJ/in.). Note the difference in scale.

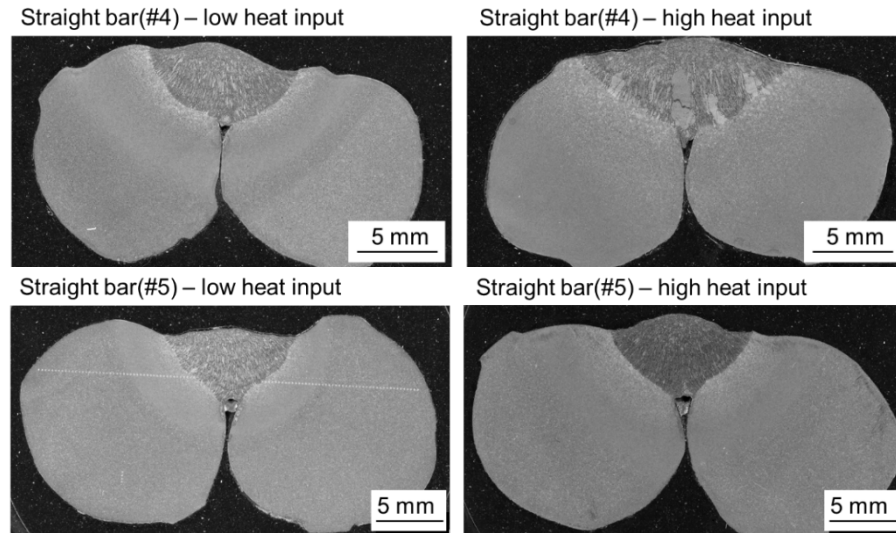


Figure 13: Macrographs of welded lap-splices on ASTM A706 Grade 60 straight bars made with low (13 kJ/in.) and high heat input (40 kJ/in.). Note the difference in scale.

The weld microstructure was characterized with a particular focus on the heat-affected zone (HAZ). Different microstructural regions form in a low carbon steel weld HAZ, namely, the coarse grain (CGHAZ), fine grain (FGHAZ) and inter-critical (ICHAZ) heat-affected zone. These regions form due to different peak temperatures, hold times at temperature and cooling rates that are experienced as a function of distance from the fusion line [8]. The width of the HAZ regions increased at high heat input. A higher heat input creates a shallower temperature gradient in the HAZ such that higher peak temperatures are reached as a function of distance from the fusion line. Also, cooling rate decreases at high heat input. **Figure 14** shows a comparison between the low and high heat input weld on the cold-bent #4 hoops. The Nital etch highlights the different regions of the HAZ as compared to the base metal (BM). While all three HAZ regions and much of the rebar base metal can be observed in the low heat input weld, the width of the CGHAZ and FGHAZ is much larger at high heat input. The FGHAZ extends through the entire bar cross-section. No base metal microstructure was retained. The effect of heat input was noticeable, but much less pronounced for the larger bar size. The HAZ did not extend through the entire bar cross-section, even at high input. Images of the straight bar welds are provided in **Appendix 2**. The same trends in terms of HAZ width were observed as a function of heat input and bar size.

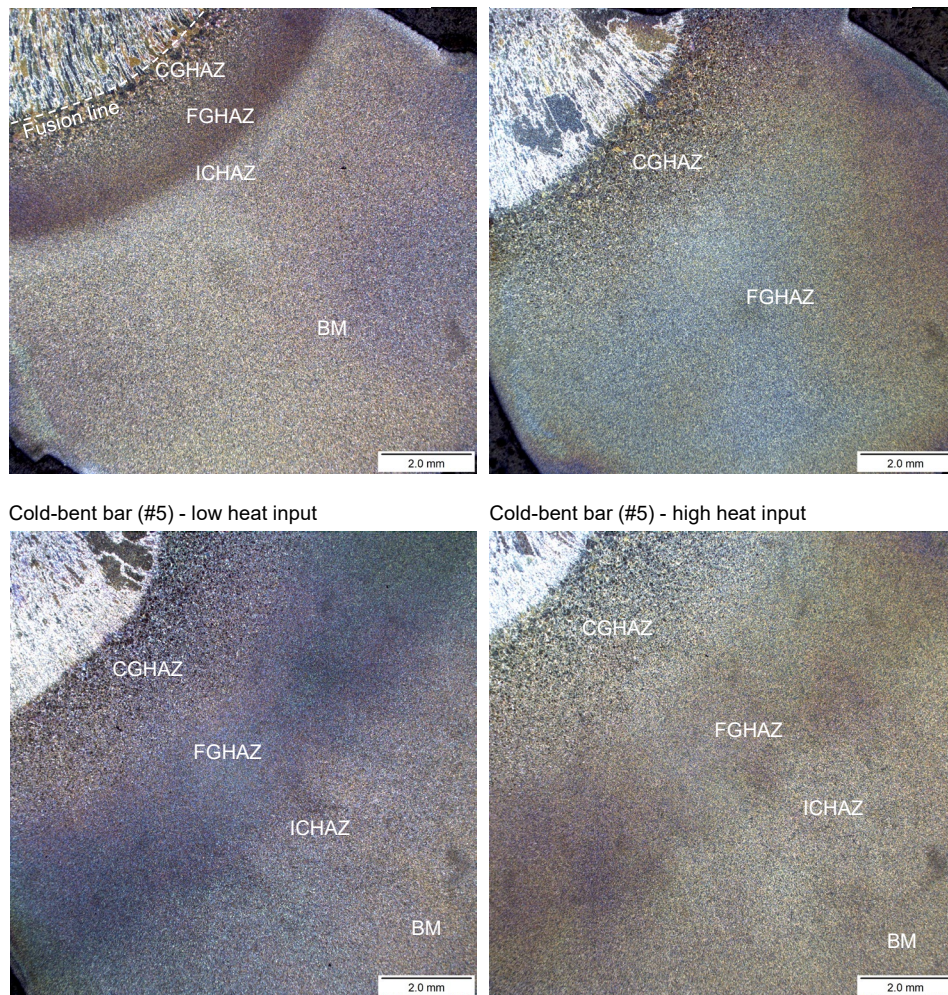


Figure 14: Overview of the weld heat-affected zone (HAZ) in the low heat input and high heat input weld on the cold-bent hoops. Coarse-grain heat-affected zone (CGHAZ), fine-grain heat-affected zone (FGHAZ), inter-critical heat-affected zone (ICHAZ), and base metal (BM). Note the increased width of the HAZ regions at high heat input.

Figure 15 shows micrographs from optical microscopy of the CGHAZ and FGHAZ regions for the high heat input weld on the cold-bent #4 hoops. The CGHAZ immediately adjacent to the fusion line shows grain boundary ferrite (GF) outlining the prior austenite grain boundaries. This region was completely austenitized from the weld thermal cycle i.e., the ferritic-pearlitic microstructure of the rebar base metal transformed into austenite due to the heat of welding. Upon cooling, the austenite transformed back. This transformation initiated along the austenite grain boundaries where a network of grain boundary ferrite (GF) formed first. The inside of the austenite grains then transformed into a mixture of acicular ferrite (AF) and pearlite (P). Farther away from the fusion line in the FGHAZ, the base metal microstructure also fully transformed into austenite during the weld thermal cycle. However, lower peak temperatures were experienced in this region so that the austenite grains had limited time to grow. Upon cooling,

the austenite transformed into fine ferrite and pearlite in the FGHAZ. Note that the FGHAZ has a much smaller grain structure as compared to the rebar base metal (see **Figure 9**).

The HAZ microstructures of the low heat input weld on the cold-bent #4 hoops are shown in **Figure 16**. The faster cooling associated with the lower heat input resulted in finer prior austenite grains throughout the CGHAZ and FGHAZ as compared to the high heat input weld (see **Figure 15**). In the CGHAZ only a small amount of grain boundary ferrite (GF) can be observed along the prior austenite grain boundaries. Most of the austenite grains transformed into acicular ferrite (AF). Widmanstaetten ferrite (AC) and dark etching pearlite (P) are also present. Some amount of bainite may also form due to the faster cooling, but higher magnification microscopy would be necessary to clearly identify this phase. The FGHAZ is a mixture of very fine ferrite and pearlite.

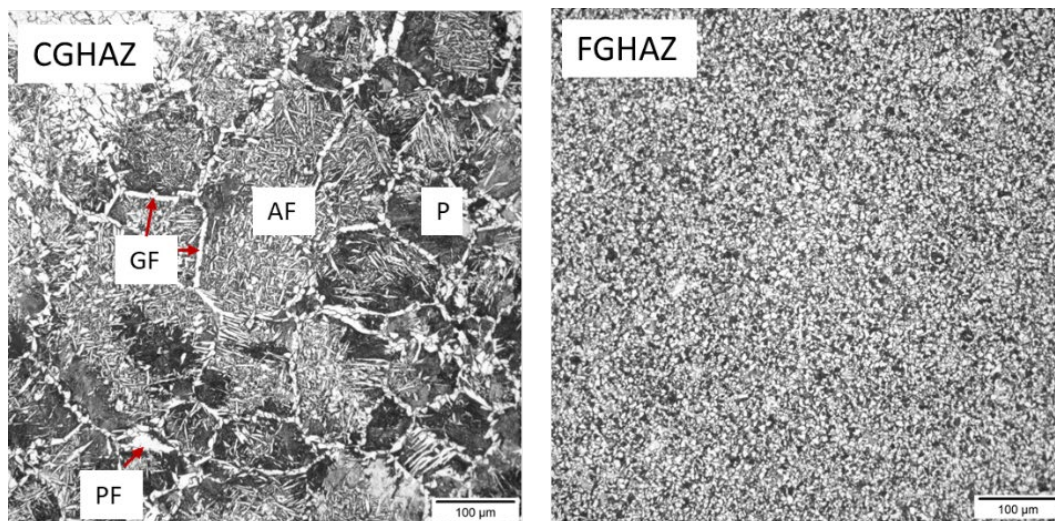


Figure 15: Etched (2% Nital) heat-affected zone (HAZ) microstructures from high heat input lap-splice weld on cold-bent #4 hoops of ASTM A706 Grade 60 rebar: Coarse grain heat-affected zone (CGHAZ) and fine grain heat-affected zone (FGHAZ).

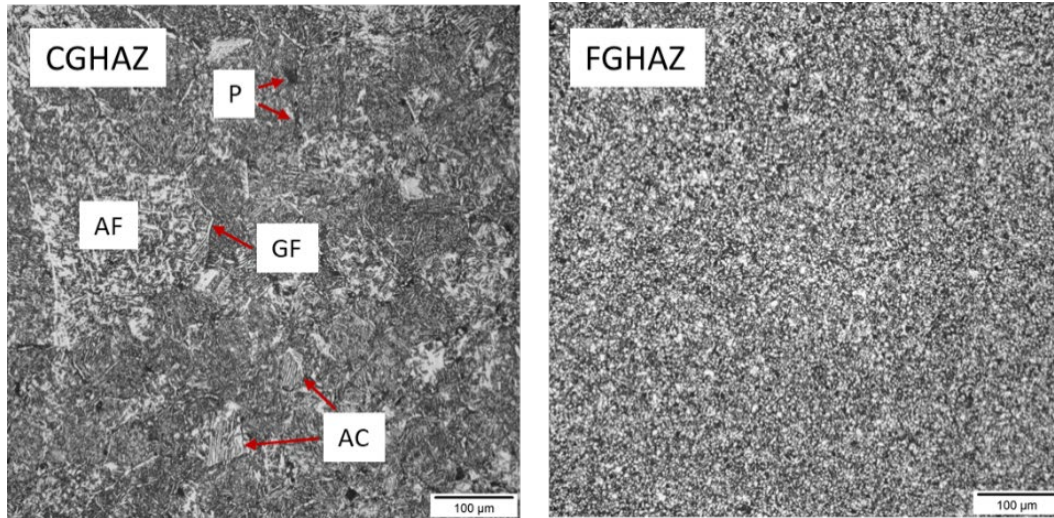
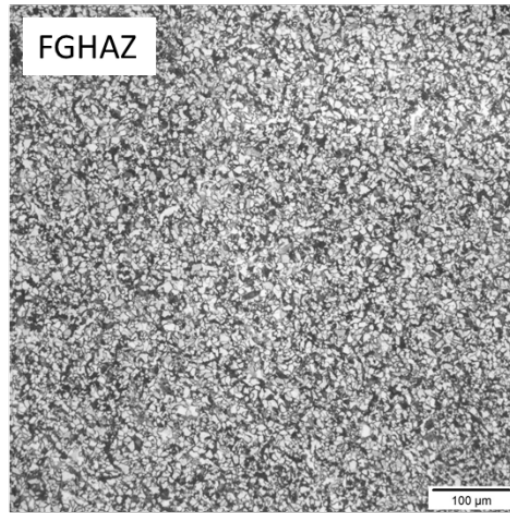
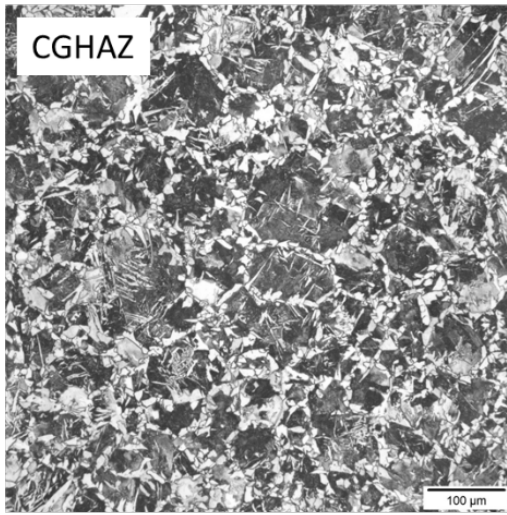


Figure 16: Etched (2% Nital) heat-affected zone (HAZ) microstructures from low heat input lap-splice weld on cold-bent #4 hoops of ASTM A706 Grade 60 rebar: Coarse grain heat-affected zone (CGHAZ) and fine grain heat-affected zone (FGHAZ).

The HAZ microstructures at low and high heat input in the cold-bent #5 hoops did show fewer differences in terms of grain size and phases present (**Figure 17**). Similar microstructures were observed in the CGHAZ and FGHAZ for the low and high heat input weld. This is likely because the HAZ width did not differ as much as a function of heat input despite the nominal difference in heat input (see **Figure 14**). The HAZ did not extend through the entire diameter of the bars. A smaller amount of acicular ferrite was observed in the CGHAZ as compared to the welds on the smaller #4 bar size. Instead, grain boundary ferrite, Widmanstaetten ferrite and pearlite were primarily observed in optical microscopy.

Cold-bent hoop(#5) – low heat input



Cold-bent hoop(#5) – high heat input

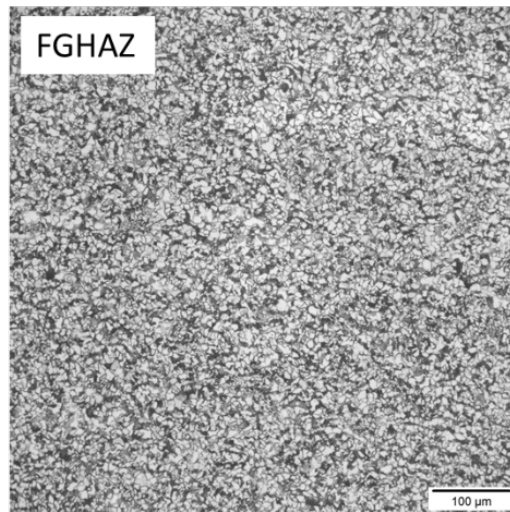
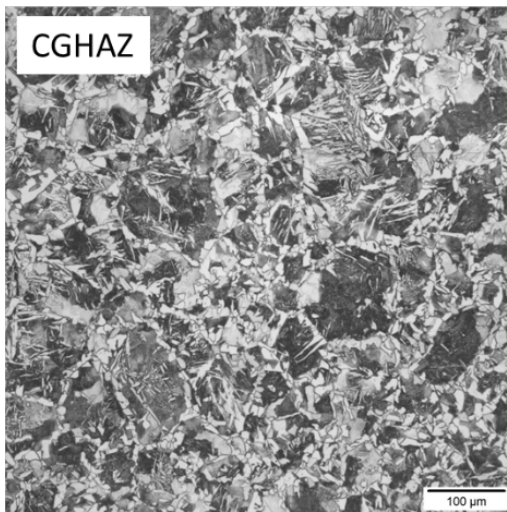


Figure 17: Etched (2% Nital) heat-affected zone (HAZ) microstructures from low heat input (top row) and high heat input (bottom row) lap-splice weld on cold-bent #5 hoops of ASTM A706 Grade 60 rebar: Coarse grain heat-affected zone (CGHAZ) and fine grain heat-affected zone (FGHAZ).

The CGHAZ and FGHAZ microstructures of the straight bar welds are shown in **Appendix 2**. The CGHAZ exhibited grain boundary ferrite, acicular ferrite, and some pearlite. The prior austenite grain size in the CGHAZ was slightly smaller at low heat input as compared to the high heat input weld. This was more apparent on the welded #5 size bars. The amount of acicular ferrite in the CGHAZ of the straight bar welds was larger as compared to the welds on the cold-bent hoops. This may be due to an increase content in acicular ferrite promoting elements (Mn and Cr) in the composition of the straight bars (see **Table 1**).

Weld Mechanical Properties

Welded Lap-Splice Hardness Testing

Hardness testing was performed on the lap-splice welds along several traverses across the fusion zone and heat-affected zone (see **Figure 3**). **Figure 18** shows the results for welds made on the cold-bent hoops. All welds follow a similar trend. The weld metal has the lowest hardness as compared to the HAZ and base metal. The hardness is highest in the CGHAZ closest to the fusion line and then decreases at further distance from the fusion line. The peak hardness in the CGHAZ is highest at low heat input and small bar size (#4). This weld shows a pronounced hardness dip in the HAZ, in particular in the hardness traverses that go towards the lower hardness center of the bars (see **Figure 10**). At high heat input, the low hardness HAZ extends through the entire bar diameter. The difference in HAZ hardness between the low and high heat input welds on the larger #5 bar size is less pronounced.

The hardness traverses for welds made on the straight bars (**Figure 19**) are similar to the welds on the cold-bent hoops. No significant differences can be discerned. The low heat input welds tend to show a higher peak hardness close to the fusion line and retain a slightly higher hardness in the HAZ as compared to the high heat input welds.

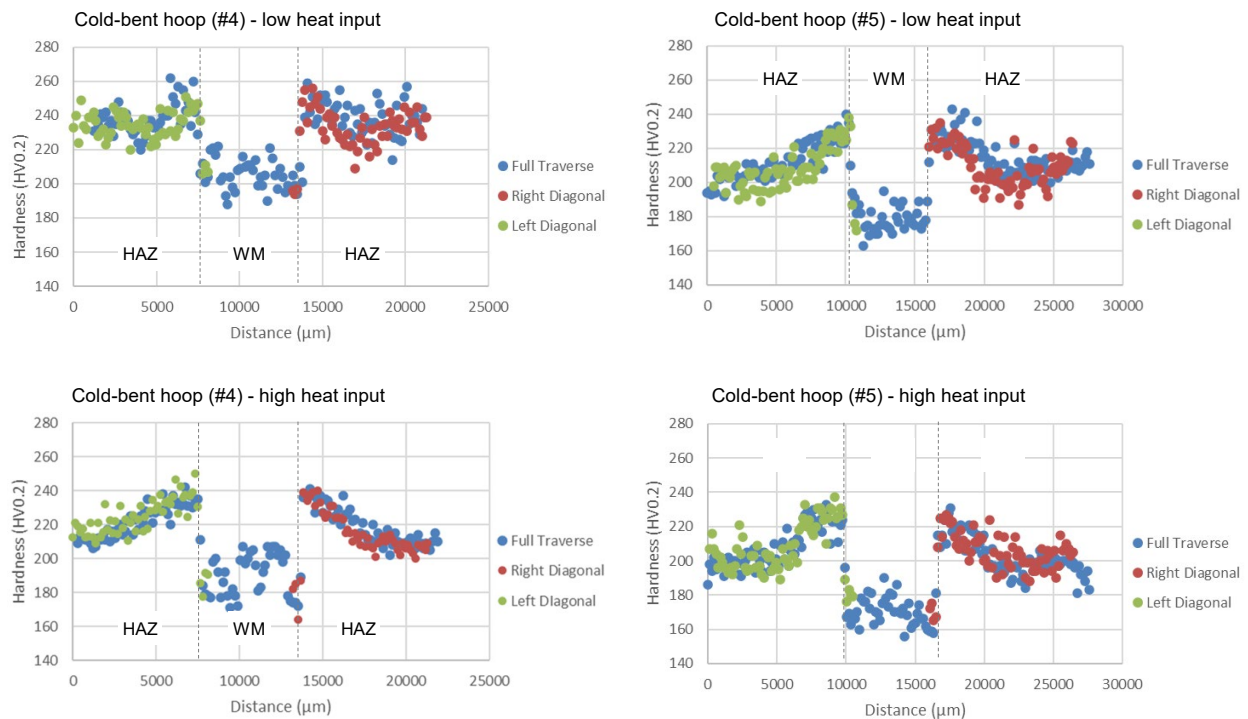


Figure 18: Hardness traverses (HV0.2) taken across the welded lap-splices on the cold-bent hoops. Full traverse includes the weld metal (WM) and heat-affected zones (HAZ) in both bars. Additional hardness traverses were taken through the HAZ towards the center of the bars (see **Figure 3b**).

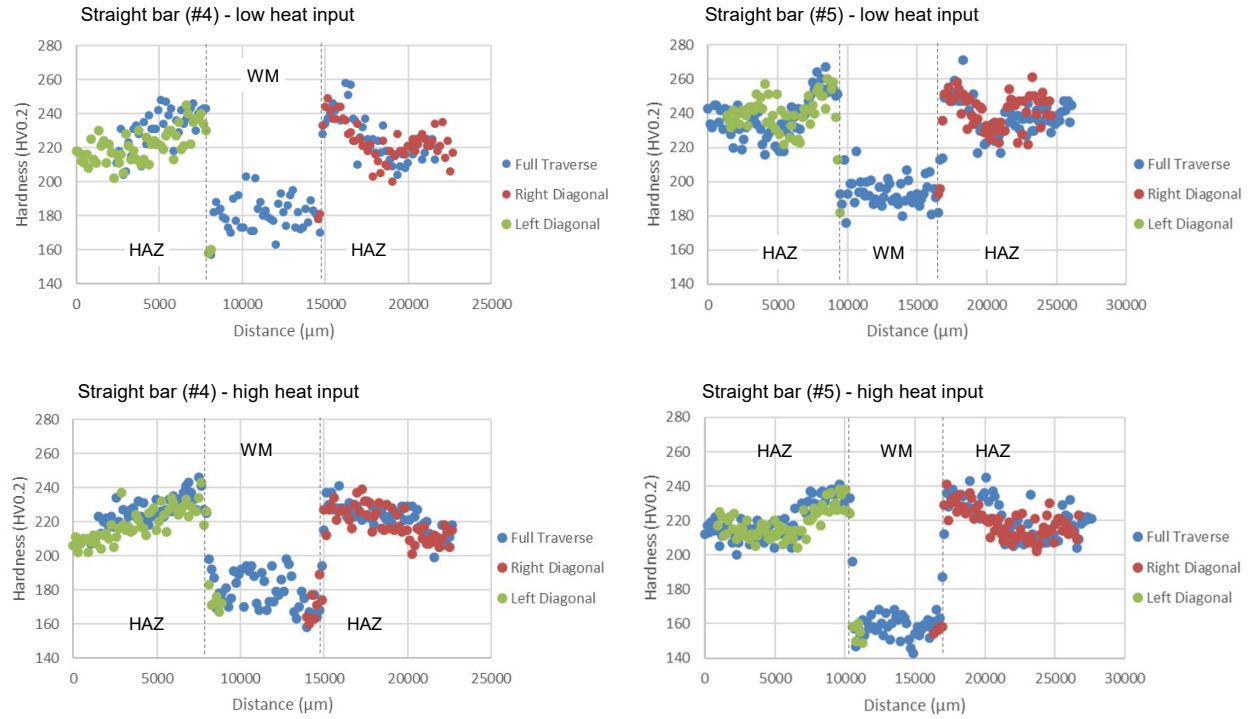


Figure 19: Hardness traverses (HV0.2) taken across the welded lap-splices on the straight bars. Full traverse includes the weld metal (WM) and heat-affected zones (HAZ) in both bars. Additional hardness traverses were taken through the HAZ towards the center of the bars (see **Figure 3b**).

Hardness maps were obtained across the HAZ of selected lap-splice welds to further examine hardness changes in the HAZ as a function of distance from the fusion line and correlate to HAZ microstructures. **Figure 20** shows the HAZ hardness across the welded cold-bent hoops and the straight bars for the #4 size bars at low and high heat input. Hardness maps for the welded #5 size bars are given in **Appendix 2**. Close to the fusion line, the CGHAZ shows the highest hardness. The acicular ferrite in this region promotes hardness. This is followed by a softened region at further distance from the fusion line which corresponds to the fine ferritic-pearlitic microstructure of the FGHAZ (**Figure 20b** and **Figure 21**). At low heat input, the hardness recovers towards the base metal. The cold-bent hoops show softening in the FGHAZ and then a gradual increase in hardness towards the base metal, because the peak temperatures are still high enough to remove some of its cold-work (**Figure 20a**). At high heat input, the cold-bent hoops lose their cold-work through the entire bar diameter. The softening in the straight bars also extends through the entire bar at high heat input.

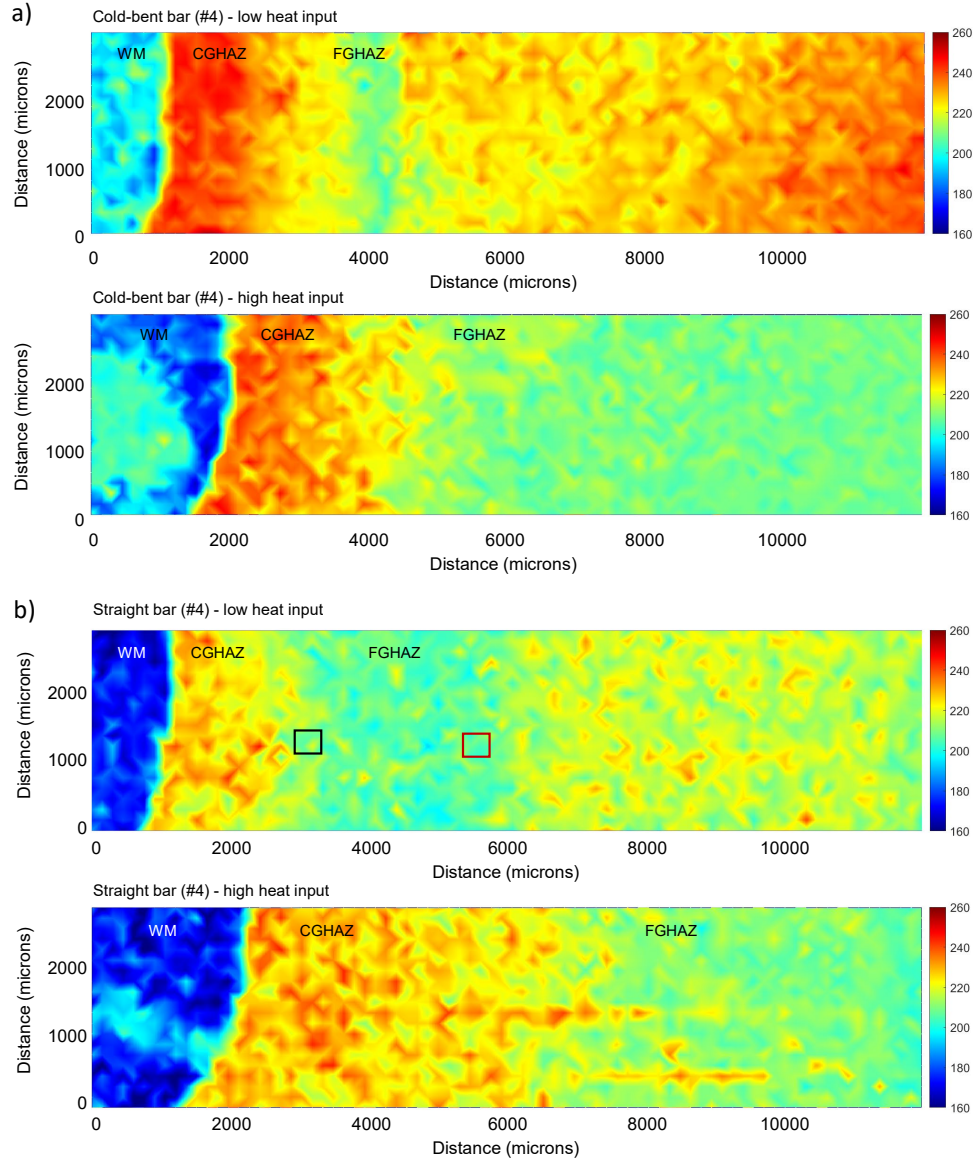


Figure 20: Hardness map (HV0.2) of lap-splice weld on (a) cold-bent #4 hoops at low and high heat input, and (b) on straight #4 bars at low and high heat input. Boxes indicate regions where micrographs shown in **Figure 20** were obtained from.

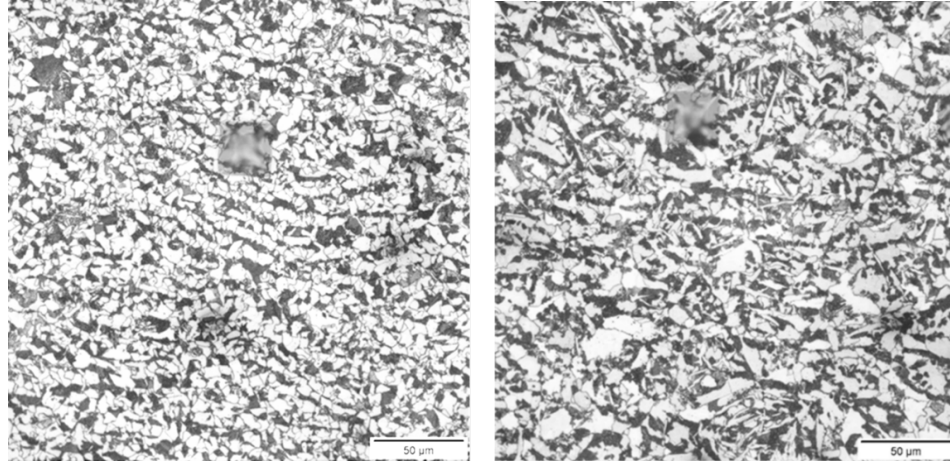


Figure 21: Micrographs taken from the softened region of lap-splice weld on straight #4 bars using low heat input. The microstructure is made up of fine ferrite and pearlite resembling the FGHAZ. The left and right images correspond to the black and red boxes shown in **Figure 19**, respectively. Note that hardness indents are visible in both micrographs.

Cross-Weld Tensile Testing

Cross-weld tensile tests were conducted on direct butt welds made on straight bars (#4 bar size) some of which were pre-strained prior to welding to approximately 10% in a tensile frame to simulate the effect of the cold-work in the hoops. Hardness traverses on bar cross-sections in **Figure 22** show that the applied pre-strain caused an increase in base metal hardness of about 40 HV. Hardness maps were obtained across the HAZ of the butt welds on bars with and without pre-strain (**Figure 23**). The high-hardness CGHAZ is not continuous along the fusion line in the direct butt welds, rather spots of high hardness are present. This is due to the multi-pass nature of these welds. Subsequent passes provided a tempering effect for some regions which reduced the CGHAZ hardness. The softened FGHAZ region was also observed.

Cross-weld tensile tests were performed on machined dog-bone samples to facilitate digital image correlation (DIC). Digital extensometers were placed on the weld metal, HAZ, and base material, as shown in **Figure 24**. Note that the resolution of the DIC setup did not allow placing extensometers across individual HAZ regions, i.e. the CGHAZ and FGHAZ.

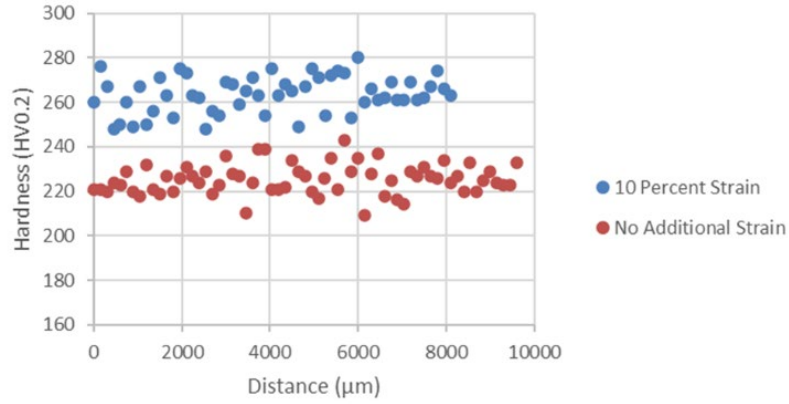


Figure 22: Hardness traverses (HV0.2) on cross-sections of straight (#4) bars with and without 10% applied pre-strain.

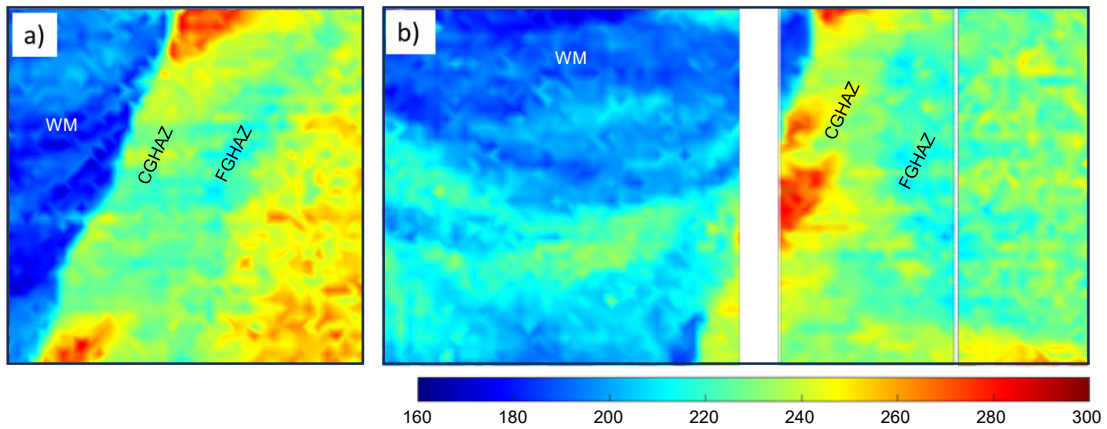


Figure 23: Hardness maps (HV0.2) across the HAZ of the direct butt welds on (a) 10% pre-strained bars and (b) on bars without pre-strain. Note that the hardness map in (b) is stitched from multiple maps.

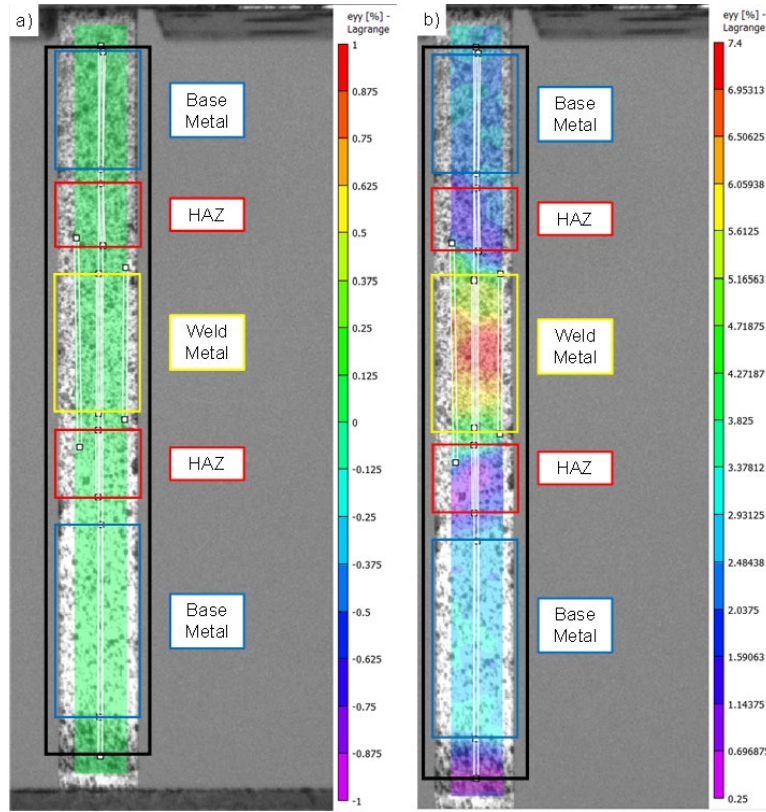


Figure 24: (a) Layout of digital extensometers used for DIC including global (black rectangle) and local extensometers for the base material, HAZ, and weld metal corresponding to the yellow, red, and blue rectangle, respectively. (b) Strain distribution from DIC during tensile testing showing strain localization in the weld metal.

Stress-strain curves obtained from DIC locally in the weld metal, HAZ and base metal are shown in **Figure 25**. Additional curves are provided in **Appendix 3**. Note that the final strain shown does not reflect the strain at fracture because the DIC software was not able to track the local strain once necking of the samples was severe towards the end of the tensile test. The welds on the pre-strained bars showed an increase in yield strength in the HAZ and the base metal of around 50 MPa as compared to the welds made on bars without applied pre-strain. In addition, a decrease in ductility was observed in the HAZ and the base metal for the pre-strained samples. The majority of strain was accumulated in the weld metal for both sets of samples. Failure occurred in the weld metal in all samples due to the lower strength of the filler metal used.

Figure 26 contains the global stress-strain data as recorded from the tensile frame to show the curve through failure. The ultimate tensile strength and elongation was lower in the pre-strained samples compared to the welds made on bars without pre-strain. AWS D1.4:2018 [1] requires the tensile strength to be no less than 125% of the minimum specified yield strength of the base material being joined. All samples met this requirement (**Table 6**).

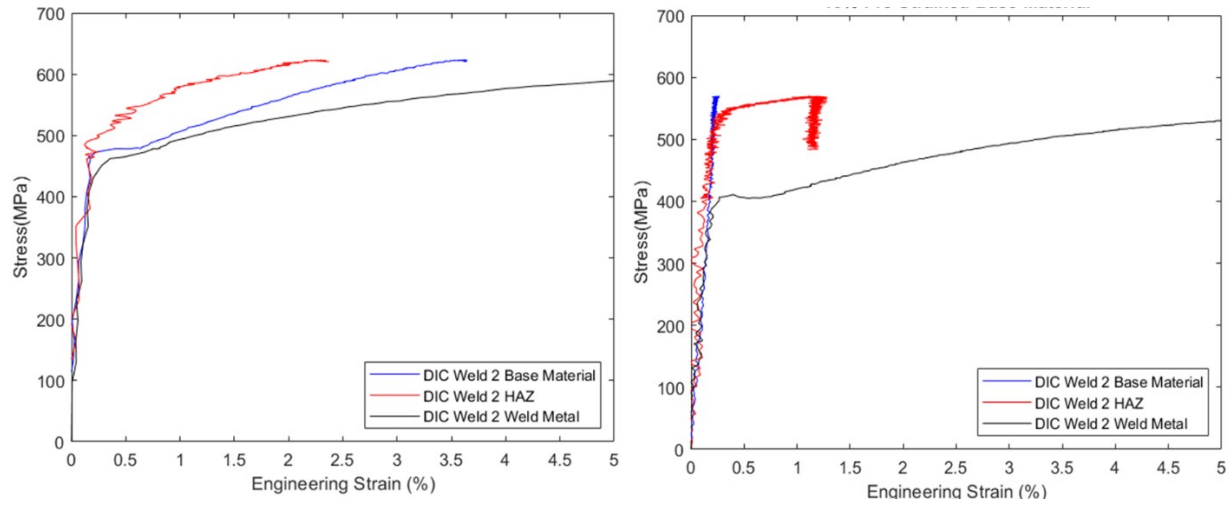


Figure 25: Stress-strain curves for the base material, HAZ, and weld metal from DIC on butt welds made (left) on bars without pre-strain, and (right) on bars that were pre-strained (10%) prior to welding.

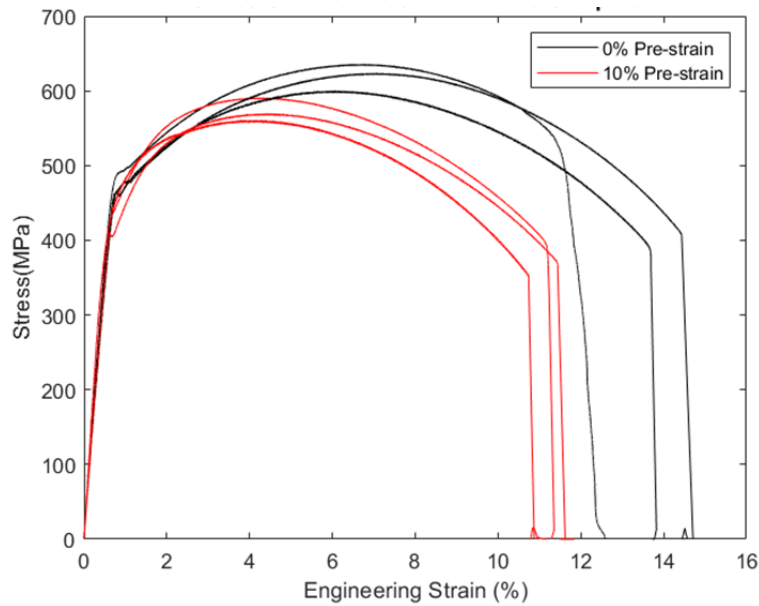


Figure 26: Stress-strain curves over the entire gauge section of the DIC samples from welds made on 10% pre-strained bars (red) and from welds made on bars without applied pre-strain (black).

Table 6: Tensile test results from direct butt welds on ASTM A706 Grade 60 straight bars (Mill 1) with 10% pre-strain applied prior to welding and on bars without pre-strain. Note that machined dog-bone samples were tested.

Pre-Strain	#Sample	Tensile Strength, psi [MPa]	Minimum Specified Yield Strength, psi [MPa]	Tensile/Yield Ratio	Failure Location
N/A	1	634	420	1.51	Weld Metal
	2	622	420	1.48	Weld Metal
	3	599	420	1.43	Weld Metal
10%	1	590	420	1.40	Weld Metal
	2	568	420	1.35	Weld Metal
	3	561	420	1.34	Weld Metal

Bend Testing

Guided bend tests were performed on all lap-splice welds as an additional indication of the ductility of the welds. Note that AWS D1.4 [1] does not require bend testing. Also note that due to the welded cold-bent bars having a bend radius prior to bend testing the amount of strain applied during the test was lower than that of the welded straight bars. Bend testing was performed in the as-welded condition. An example of a bent sample after testing is shown in **Figure 27**. Visual observation after testing revealed indications (cracking) in the HAZ adjacent to the fusion line. In general, HAZ cracks were larger in the welded straight bars likely due to the higher strains reached during the bend test. Similarly, HAZ cracks were opened slightly more in the welds on the larger #5 size bars due to the higher strain on the outer surface for these samples. In summary, the bend testing did not reveal any significant differences in terms of ductility of the welds made on cold-bent versus straight bars.

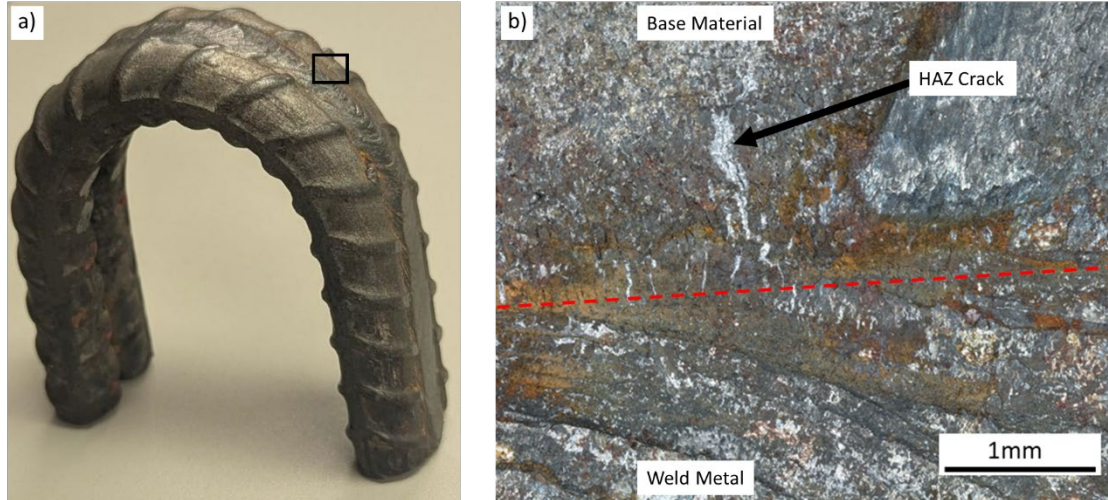


Figure 27: (a) Photograph of guided bent test sample of lap-splice weld (high heat input) on straight #4 bar, and (b) higher magnification stereo microscope image of an indication (cracking) in the HAZ of the sample. Red dashed line indicates the fusion line.

Gleeble Simulation and Tensile Testing

The thermal history experienced in the CGHAZ and FGHAZ during lap-splice welding was simulated in Simufact Welding. **Figure 28** shows the maximum temperature distribution in the weld cross-section and a plot of the thermal cycles in the CGHAZ and FGHAZ regions. These curves were used to program the Gleeble system to simulate the CGHAZ and FGHAZ microstructures. Microstructures and hardness obtained in the gauge section of the Gleeble samples were in good agreement with what was observed in the welded lap-splices (**Figure 29** and **30**). Results from hardness tests are listed in **Table 7**. No significant difference was observed as a function of pre-strain.

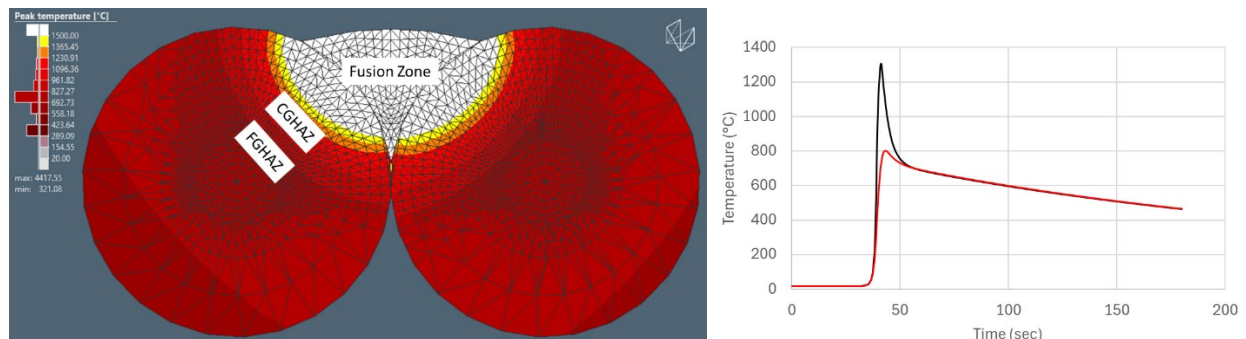


Figure 28: 2D heat transfer finite element model of lap-splice welds: Peak temperature distribution (left) and thermal history in the CGHAZ (black) and FGHAZ (red) with a peak temperature of 1300°C and 800°C, respectively.

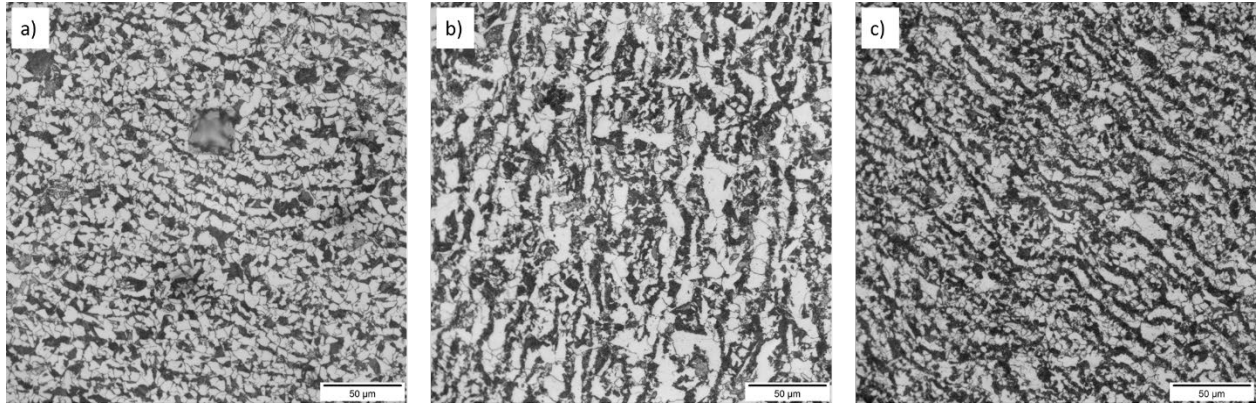


Figure 29: Comparison of FGHAZ microstructures: (a) lap-splice weld, (b) Gleeble simulation on bars without pre-strain, and (c) Gleeble simulation on bars with 10% pre-strain.

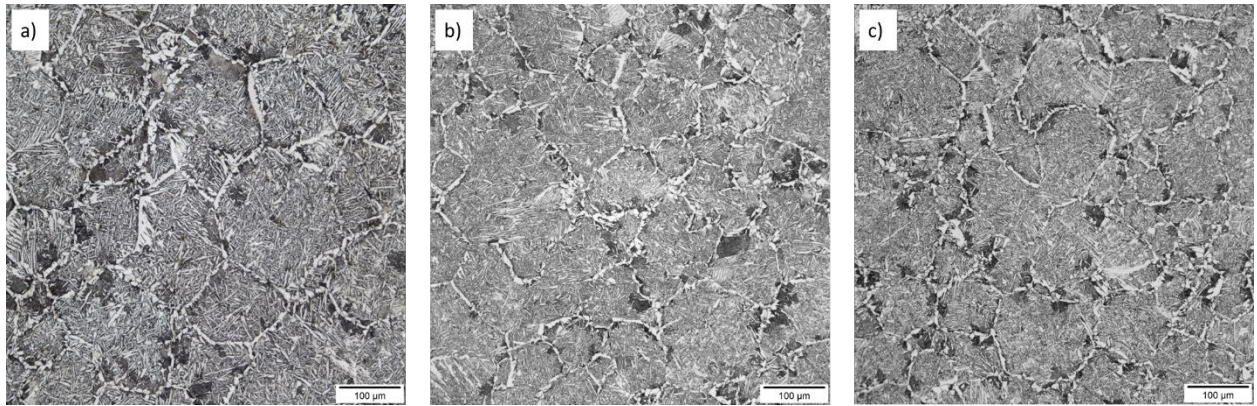


Figure 30: Comparison of CGHAZ microstructures: (a) lap-splice weld, (b) Gleeble simulation on bars without pre-strain, and (c) Gleeble simulation on bars with 10% pre-strain.

Table 7: Average hardness (HV0.2) and standard deviation in the FGHAZ and CGHAZ for the welded samples and the Gleeble simulated microstructures.

	Welded Sample	Unstrained Gleeble	Pre-strained Gleeble
FGHAZ	210 ± 11	216 ± 7	222 ± 5
CGHAZ	250 ± 9	265 ± 15	268 ± 13

Gleeble samples with simulated GCHAZ and FGHAZ microstructure were subjected to tensile testing. The stress-strain curves for the CGHAZ and FGHAZ samples are shown in **Figure 31**. Note that due to the small sample geometry, an extensometer could not be used to record strain data. Strain data was instead recorded from the jaw displacement in the tensile frame and converted to strain by the gauge length. This resulted in different slopes throughout the elastic region of the curves since the frame data also includes the regions outside of the gauge section during the elastic portion of the test. A summary of the tensile test results is given in **Table 8**. All

samples failed in the gauge section. The CGHAZ samples reached a higher yield strength and ultimate tensile strength (UTS), but lower total elongation as compared to the FGHAZ samples. There was little elongation after the UTS was reached in the CGHAZ samples indicating a much more brittle behavior as compared to the FGHAZ samples. These differences were observed for both the samples with 10% pre-strain (red) and the samples without pre-strain (black) (**Figure 31**). The pre-strain had an effect on the strain hardening behavior in the tensile tests. The onset of strain hardening occurred earlier for the pre-strained CGHAZ and FGHAZ samples. In addition, the pre-strained samples showed a lower total elongation as compared to the respective CGHAZ and FGHAZ samples without pre-strain.

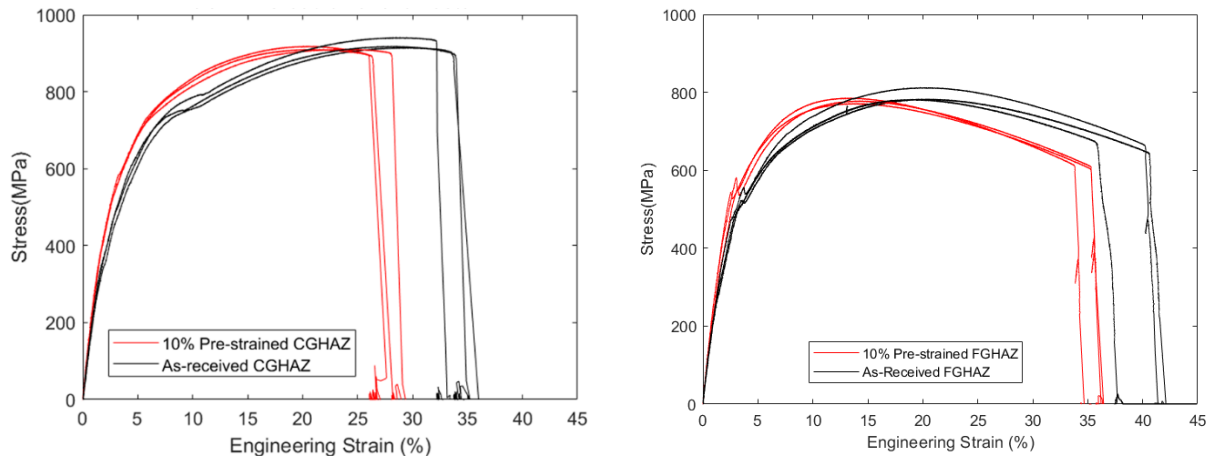


Figure 31: Stress-strain curves of the Gleeble tested HAZ microstructures. Black lines indicate the as-received material without pre-strain, and the red line shows the 10% pre-strained material.

Table 8: Results from tensile tests on Gleeble samples.

Microstructure	Pre-Strain	#Sample	Yield Strength, psi [MPa]	Ultimate Tensile Strength, psi [MPa]	Ultimate Tensile Strain [%]	Strain at Fracture [%]
FGHAZ	N/A	1	522	783	21	41
		2	488	782	20	36
		3	556	812	21	40
	10%	1	543	772	14	35
		2	581	786	13	34
		3	550	778	14	35
CGHAZ	N/A	1	724	915	29	34
		2	720	918	28	34
		3	742	941	29	32
	10%	1	730	918	20	26
		2	732	911	21	26
		3	724	911	24	28

CHAPTER 3 - INTERPRETATION, APPRAISAL, AND APPLICATIONS

General Recommendations

AWS D1.4:2018 [1] Section 6.2.4 does not allow welding within two bar diameters of bent reinforcing steel. Yet welded splices on cold-bent hoops and spiral bars have been used for decades without reported failures associated with this practice. This research project was performed to analyze whether welding on cold-bent reinforcing steel results in a degradation of the mechanical properties of the welds. The findings in the prior sections do not indicate any immediate concern regarding the strength and ductility of these welds. This should reassure designers of bridge systems. The safety of all those who travel using bridges that incorporate these welds does not seem to be in jeopardy. This also means that there is no need for a repair or replacement initiative to change existing structures.

The research team recommends that the AWS D1.4 committee look further into this to allow welding on cold-bent reinforcing steel when applicable. A larger scale study should be performed to determine the limitations in bar size, degree of bending and number of bends performed that welds can safely be performed on.

Limitations of Study

This study is only applicable for ASTM A706 Grade 60 reinforcing steel of #4 and #5 bar sizes that were cold-bent to approximately 2.6 and 1.7%, respectively. Other steel grades, bar sizes, higher degrees of bending, and multiple bending cycles prior to welding would need to go through additional testing to verify the results are consistent with what was found in this study.

CHAPTER 4 - CONCLUSIONS AND SUGGESTED RESEARCH

Conclusions

Through microstructural analysis, hardness measurements, and bend and tensile testing, the performance of welds on cold-bent hoops of ASTM A706 Grade 60 reinforcing steel was investigated. The findings show that the bending of the hoops results in an increased hardness toward the outer edges of the bar diameter, especially in the tensile-to-compression axis. During welding, the high temperatures result in changes to the microstructure and hardness of the bars. As expected for a low alloy steel, there is a region of increased hardness close to the weld fusion line in the coarse-grain heat affected zone (CGHAZ), and an adjacent softened region at a further distance in the fine-grain heat affected zone (FGHAZ). For the smaller bar size and high heat input tested in this study, the softening extends through the bar diameter and removes the initial cold-work from bending of the hoops. In the larger bars or at low heat input, softening occurred in a region of the weld heat-affected zone only i.e., not across the entire bar. Similar microstructure and hardness changes were observed for the bars that were not cold-bent prior to welding. The bend test on as-welded lap splices did not show any differences in ductility between the welded cold-bent hoops and straight bars. Cross-weld tensile tests on samples machined from direct butt welds showed a decrease in strength and ductility for the welds made on 10% pre-strained bars. However, all samples met the tensile-to-yield ratio requirements in AWS D1.4:2018 [1]. All samples failed in the lower strength weld metal. Digital image correlation showed an increase in yield strength and a decrease in ductility locally in the heat-affected zone and the base metal for the welds made on 10% pre-strained bars. Gleeble simulated samples with CGHAZ and FGHAZ microstructures exhibited an earlier onset of strain hardening and a lower total elongation in subsequent tensile tests when a 10% pre-strain had been applied.

In summary, the findings of this study demonstrated that microstructure and hardness changes from welding on cold-bent hoops are similar to what is seen in straight bars. Monotonic tensile tests showed a decrease in ductility for welded pre-strain bars, however all tensile samples met the tensile-to-yield ratio requirements in AWS D1.4:2018 [1]. The results do not indicate any immediate concern regarding the mechanical properties of welds made on cold-bent hoops of ASTM A706 Grade 60 reinforcing steel.

Suggested Research

This work should be expanded to include other steel grades, bar sizes, higher degrees of bending, and multiple bending cycles prior to welding to better understand the applications and limitations associated with welding on cold-bent ASTM A706 reinforcing steel. Tensile testing on lap-splice

welds is also suggested to verify the results from the cross-weld tensile tests. The lap-splice geometry introduces a location of high stress concentration in the weld heat-affected zone and a shear component during tensile tests. Bending and straightening of bars or pre-straining bars prior to welding would allow for comparison of lap-splice tensile behavior as a function of cold-work and an assessment of mechanical performance under a load parallel to the weld.

REFERENCES

- [1] *AWS D1.4: 2018 Structural Welding Code - Steel Reinforcing Bars*, 2018.
- [2] *ASTM A706/A706M-22 Standard Specification for Deformed and Plain-Low Alloy Steel Bars for Concrete Reinforcement*, 2022.
- [3] P. F. Silva, S. Sritharan, F. Scible, and M. J. Nigel Priestley, “Full-Scale Test of the Alaska Cast-in-Place Steel Shell Three Column Bridge Bent,” University of California, San Diego, California, FHWA-AK-RD-99-02, Feb. 1999.
- [4] H. Kuhn and D. Medlin, Eds., “Stress-Strain Behavior in Bending,” in *Mechanical Testing and Evaluation*, ASM International, 2000, pp. 109–114. doi: 10.31399/asm.hb.v08.a0003262.
- [5] *ASTM E112-21: Standard Test Methods for Determining Average Grain Size*, 2021.
- [6] *ASTM E8 Standard Test Methods for Tension Testing of Metallic Materials*.
- [7] *AWS B4.0:2016 Standard Methods for Mechanical Testing of Welds*, 2016.
- [8] G. E. Linnert, *Welding metallurgy: carbon and alloy steels*, 4th ed. Miami, Fla.: American Welding Society, 1995.

APPENDICES

Appendix 0 – Photographs of As-Received Lap-Splice Welds

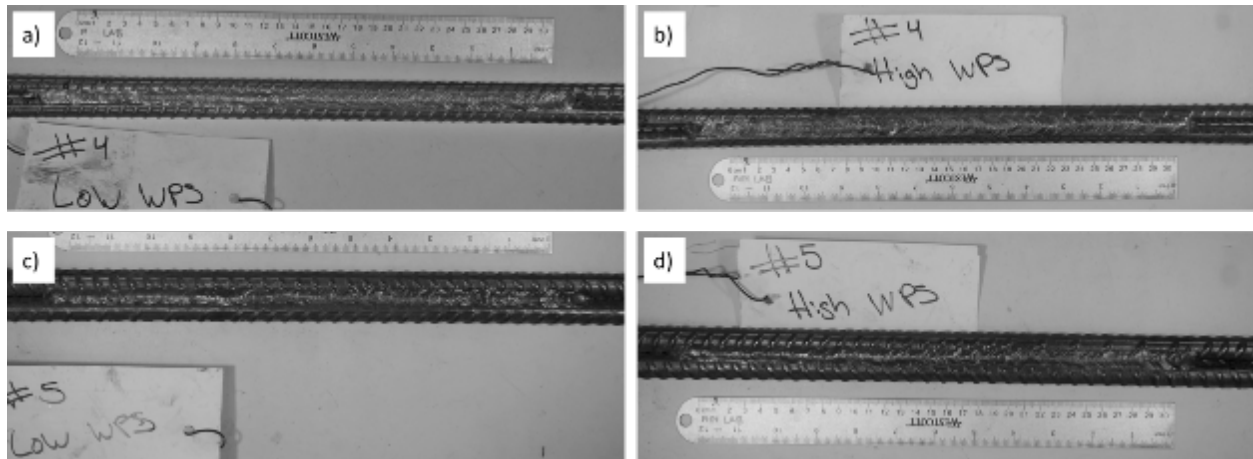


Figure 32: Photographs of lap-splice welds on straight bars (Mill 1) of ASTM A706 Grade 60 rebar.

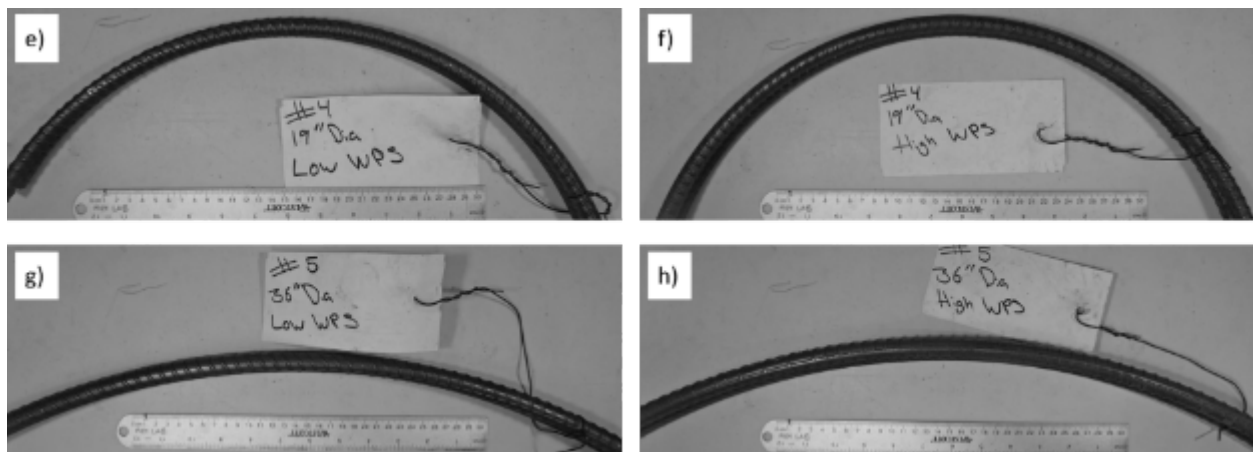


Figure 33: Photographs of lap-splice welds on cold-bent hoops (Mill 2) of ASTM A706 Grade 60 rebar. Welds were performed on the tension side of the hoops which is the side closer to the top of the page in the images.

Appendix 1 – Rebar Base Metal Microstructure and Hardness

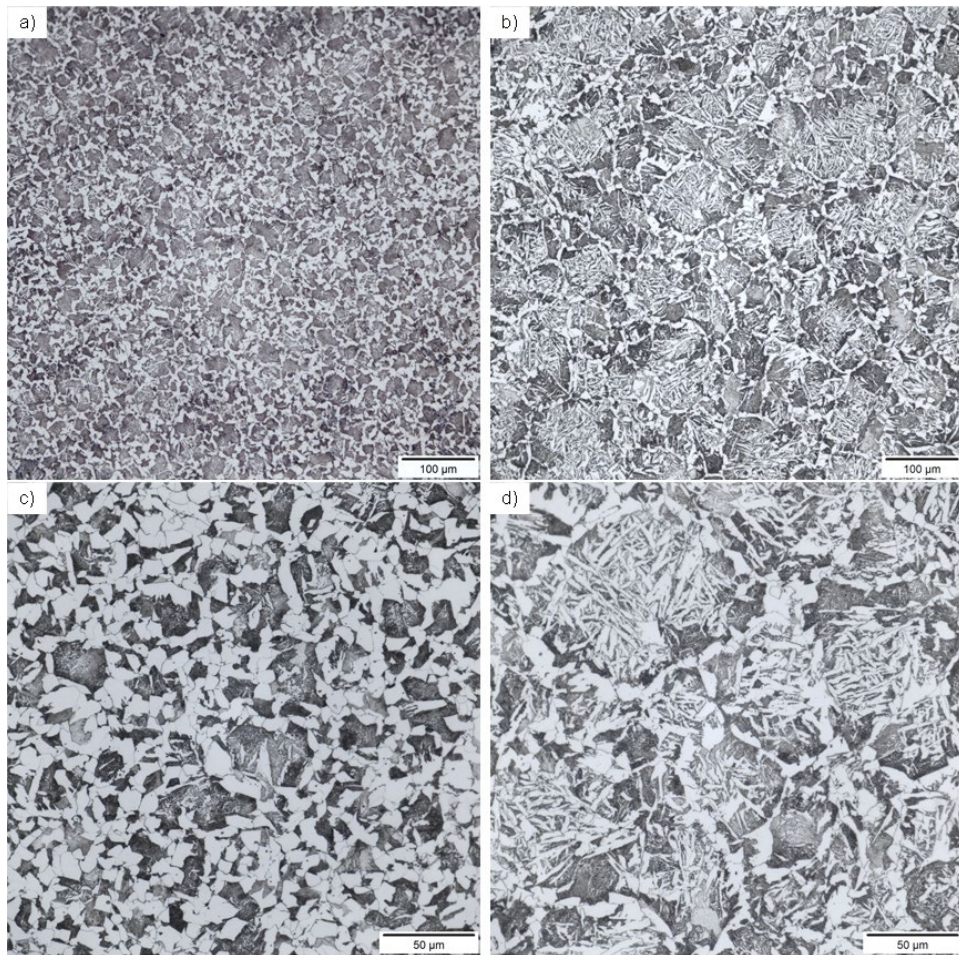


Figure 34: Etched (2% Nital) base metal microstructures of the #5 size ASTM A706 Grade 60 rebar from light optical microscopy for (a, c) the cold-bent hoops (Mill 2), and (b, d) the straight bars (Mill 1).

Appendix 2 – Lap-Splice Weld Microstructures and Hardness

Table 9: Effective throat measurements for all welded lap-splices. AWS D1.4:2018 [1] requires minimum throat is $0.6*s$, where s is the radius of the bar.

	Effective Throat (mm)
#4 Minimum ($0.6*s$)	3.6
#4 Low Heat, Cold-Bent	3.92
#4 High Heat, Cold-Bent	4.21
#4 Low Heat, Straight	3.75
#4 High Heat, Straight	4.9
#5 Minimum ($0.6*s$)	4.8
#5 Low Heat, Cold-Bent	6.31
#5 High Heat, Cold-Bent	5.19
#5 Low Heat, Straight	4.96
#5 High Heat, Straight	4.88

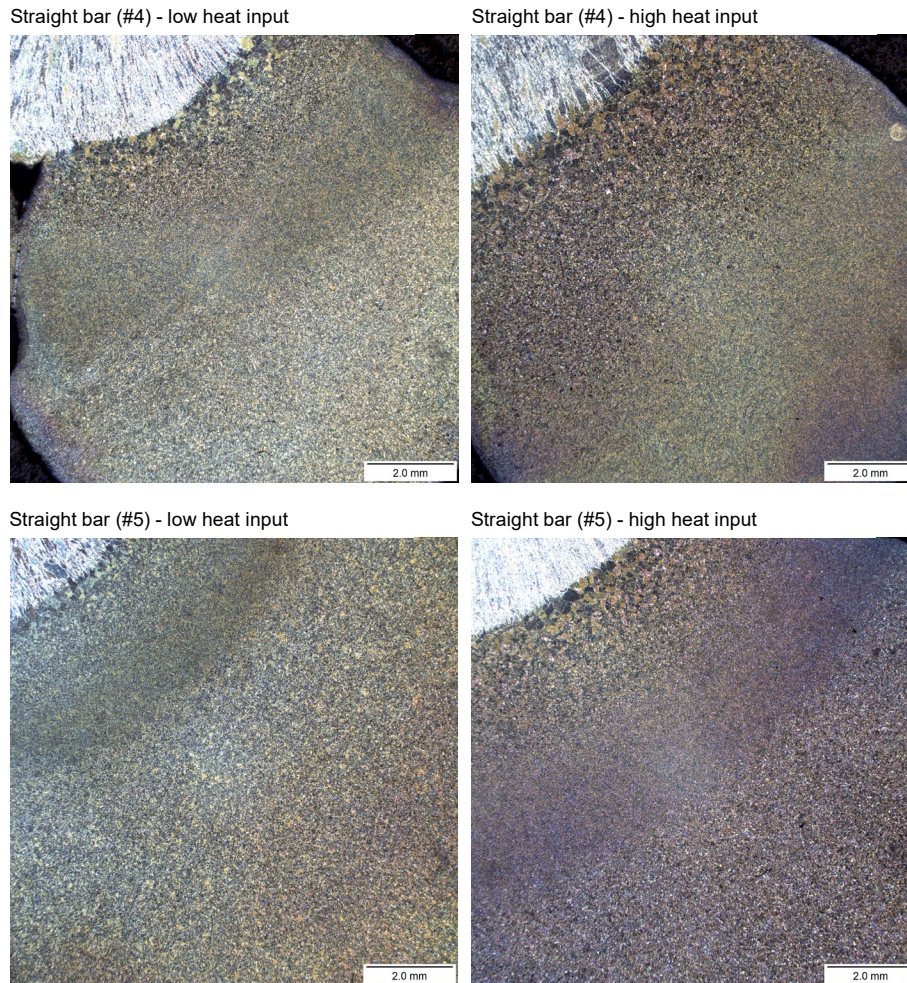
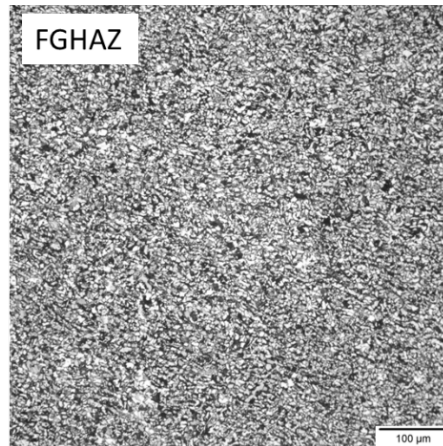
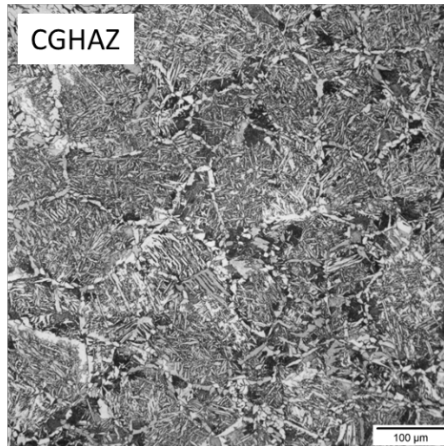


Figure 35: Overview of the weld heat-affected zone (HAZ) in the low heat input and high heat input welds on the straight bars of #4 (top) and #5 (bottom) bar size.

Straight bar (#4) – low heat input



Straight bar (#4) – high heat input

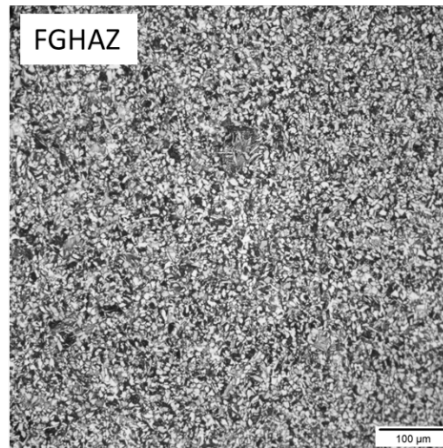
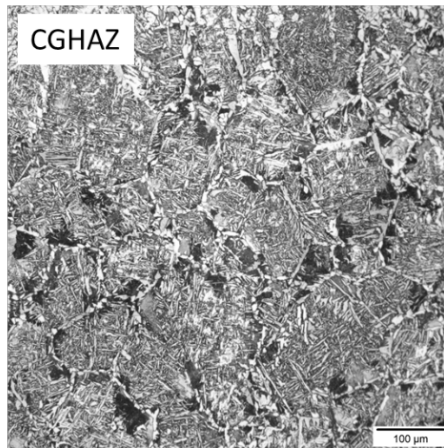
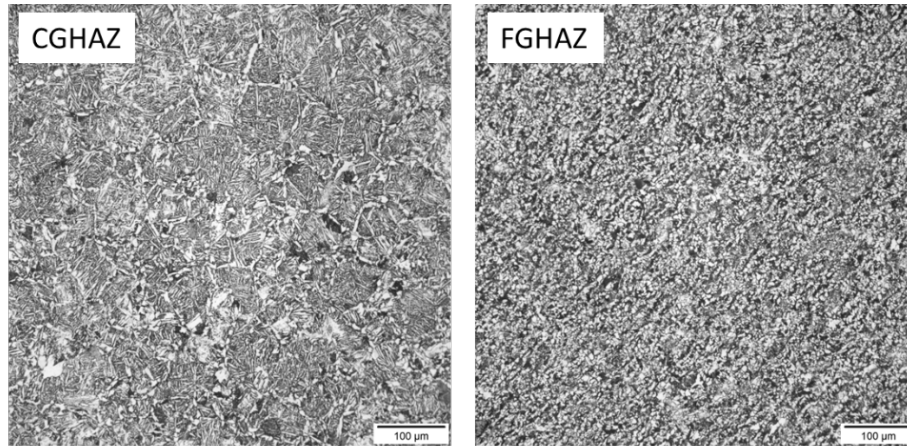


Figure 36: Etched (2% Nital) heat-affected zone (HAZ) microstructures from low heat input (top row) and high heat input (bottom row) lap-splice weld on straight #4 bars of ASTM A706 Grade 60 rebar: Coarse grain heat-affected zone (CGHAZ) and fine grain heat-affected zone (FGHAZ).

Straight bar (#5) – low heat input



Straight bar (#5) – high heat input

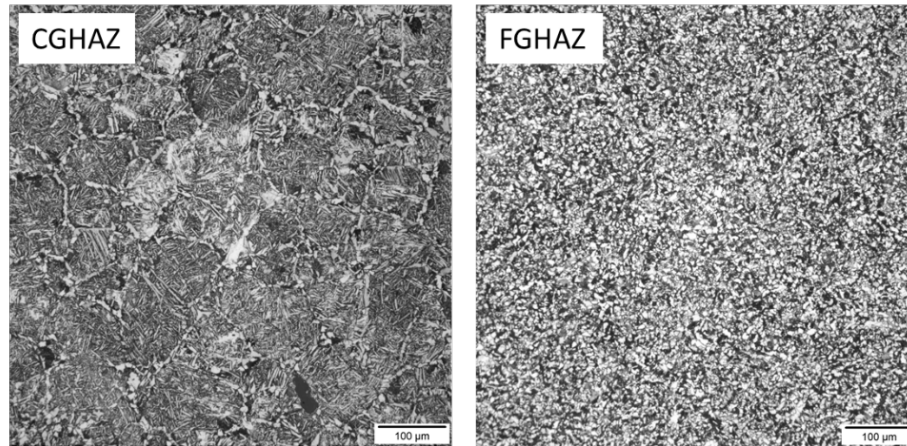


Figure 37: Etched (2% Nital) heat-affected zone (HAZ) microstructures from low heat input (top row) and high heat input (bottom row) lap-splice weld on straight #5 bars of ASTM A706 Grade 60 rebar: Coarse grain heat-affected zone (CGHAZ) and fine grain heat-affected zone (FGHAZ).

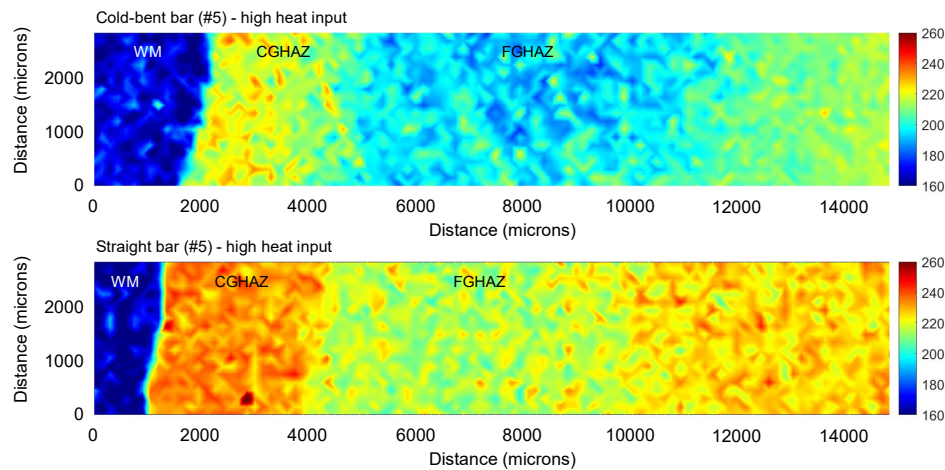


Figure 38: Hardness maps (HV0.2) of lap-splice weld on #5 bar size at high heat input: (top) cold-bent hoop and (bottom) straight bars.

Appendix 3 – Tensile Test Results of Direct Butt Welds

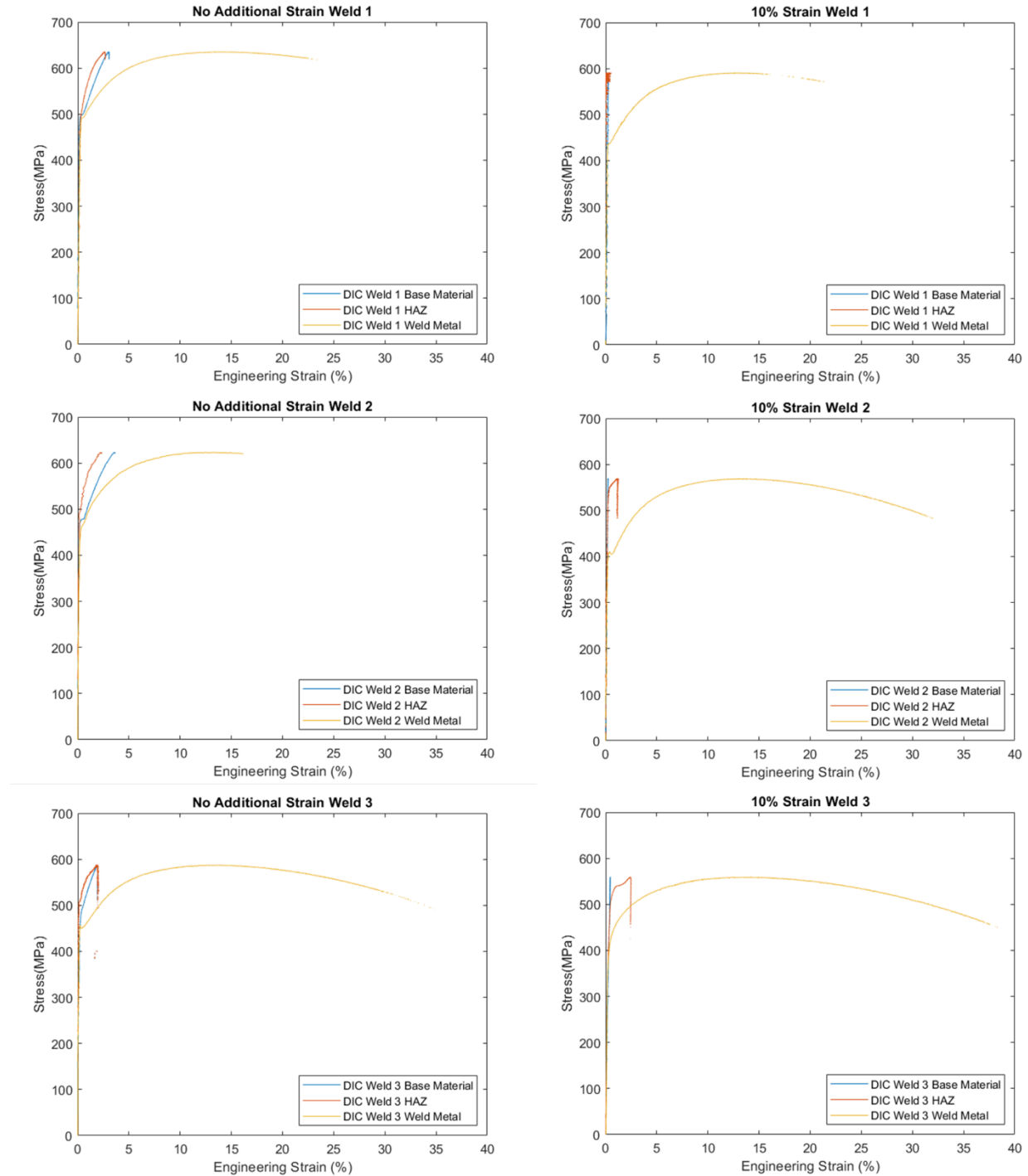


Figure 39: Stress-strain curves from local digital extensometers (DIC) from the weld metal, HAZ and base metal regions (see **Figure 24**).