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A study of welding technology for butt joints of L415 ME steel pipes designed for hydrogen transmission using high-performance automated welding engineering

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ABSTRACT

This paper aims to throw light on research into a narrow-gap welding technology which applies 135 method for L415 ME steel pipes for hydrogen transmission. Limits, non-destructive, and mechanical test results were discussed. The selected parameters enabled groove-free joints from 20.3 mm pipes reaching ISO 5817 level B. Radiographic and ultrasonic tests revealed no discrepancies. Welding provided 566 MPa tensile strength, exceeding base material, without hardness variation or martensitic structures. Base material hardness was ~200 HV, with welds reaching ~240 HV. Impact toughness averaged 300 J, meeting the requirements. Qualification for hydrogen pipelines demands compliance with EN ISO 12732 and EN ISO 15614-1. Automated dual-wire systems ensure EN ISO 15614-1 the compliance. L415ME steel's favorable composition allows for robust structural solutions that guarantee joint integrity and strength. The novelty of this paper is a new automated narrow-gap welding technology for hydrogen pipelines, combining joint design modifications, multi-head systems, and oscillatory movements to improve performance and reduce cracks.

Keywords: L415ME, welding joints, pipelines, hydrogen transmission.

INTRODUCTION

Transmission of hydrogen is essential for the clean energy transition, helping reduce greenhouse gas emissions. Green hydrogen, produced from renewable sources, is key due to its versatility and zero emissions. Unlike fossil fuels, hydrogen supports industry, transport, and power generation without air pollution. Growing demand for hydrogen highlights the need for strong infrastructure to ensure its efficient transmission [1].

EU hydrogen corridor projects emphasize the need for coordination to build a hydrogen-based energy system. Growing investments are driven by policies, environmental goals, and technology. Hydrogen is expected to be central to the EU's energy transition, with initiatives like the Nordic-Baltic Hydrogen Corridor. (Source gaz-system.co.uk November 2023: The project has been granted Project of Common Interest (PCI) status by the European Commission). The plan aims to enhance energy security in Central Europe, reduce reliance on imported fossil fuels, and support decarbonization [2]. Pipeline operators are developing standards for welding hydrogen pipelines, including additional hardness criteria for hydrogen applications [3, 4],

Procedures for welding of hydrogen pipelines have to always be qualified in line with the requirements of EN 12732 [5], EN 15614-1 [6] and EN ISO 15609-1 [7]. They are verified by testing, in accordance with EN ISO 15614-1 (level 2: 7.3 & 7.4) Welding procedures must meet qualification testing requirements, with the same welding equipment used for both qualification and production. For pipes with an external diameter >

168.3 mm, one test weld is required per EN ISO 15614-1 (level 2). For hydrogen applications, the maximum hardness is limited to 250 HV10.

Efforts focus on efficient pipelines using specialized materials and welding suitable for hydrogen. High-strength steel pipes like L415 ME resist high pressure and corrosion. The steel pipes designed for hydrogen transmission, particularly those fabricated from high-strength materials like L415 ME steel [8], are one of the vital components in the infrastructure. The welding technology employed in joining these pipes plays a pivotal role in ensuring the integrity and reliability of the transmission network [2].

In recent years, significant strides have been made in advancing welding technologies tailored for hydrogen transmission pipelines [9]. A thorough examination of the current literature reveals a multifaceted landscape characterized by innovative approaches and nuanced challenges [10]. Studies mentioned above offer valuable insights into the evolving state of the field. Hydrogen transport presents significant challenges due to its ability to penetrate steel structures, promoting hydrogen embrittlement, a phenomenon where hydrogen atoms weaken the metal and increase its susceptibility to cracking. This process occurs in three stages: physical adsorption, chemical adsorption, and absorption, often driven by high temperatures. To mitigate hydrogen embrittlement, measures such as material selection, process control, and protective coatings are employed, including non-electrolytic metallic coatings for high-strength components. Understanding and managing these mechanisms are crucial for ensuring the safety and durability of hydrogen transport infrastructure [9].

Welding plays a crucial role in pipeline construction. Nevertheless, a complex heat history combined with the widespread presence of hydrogen in the processing environment heightens the hydrogen expansion and cracking susceptibility of pipeline welds [11]. The most susceptible to cracking region in a welded pipe is the heat-affected zone (HAZ) near the joint, where a significant quantity of hydrogen remains after its solution at high temperatures, leading to a substantial reduction in ductility [12]. Moreover, the complex microstructure within this HAZ, which generally contains martensite, retained austenite, bainite, misfit dislocations, and their interfaces, provides multiple detrimental trapping sites, such as interfaces and dislocations, allowing hydrogen to affect local strength through various mechanisms mentioned earlier [13]. These trapping sites are in addition to the unfavorable inclusions such as MnS or other environmental contaminants left in the welded structure, making it more vulnerable to hydrogen expansion [14]. The coarsened grains in the HAZ also contribute to the increased HE susceptibility of welded steel pipes [15]. To mitigate this problem during welding, employing inert shielding gas to minimize hydrogen uptake is critical [16]. Additionally, selecting filler metals that result in low residual stress in the welded region is important to make the inevitable hydrogen pickup less harmful [17].

The influence of welding parameters on the microstructure and mechanical properties of L415 ME steel joints reveals all intricacies involved in achieving optimal weld quality [18]. This paper and other reviews shed light on the methodologies employed to enhance welding efficiency and performance. Feasibility and effectiveness of the cold-wire gas metal arc welding (CW-GMAW) process for narrow gap welding, demonstrating its ability to produce stable welds without groove sidewall erosion and efficiently fill grooves in fewer passes was studied in [19]. Another similar study investigated tandem gas metal arc welding for narrow gap welding in a vertical down position, finding that reducing the distance between wires and using a high welding speed improved weld quality by minimizing asymmetry and enhancing penetration depth [20]. Hongsheng explored the impact of oscillation width in vertical oscillation arc pulsed gas metal arc welding (P-GMAW) for narrow-gap welding, finding that increasing oscillation width improves sidewall fusion but excessive widths can lead to defects like porosity and undercutting [21]. Moreover, Ginzel provides a useful data for explanations of pipeline AUT details in terms of ultrasonic testing [22]. Testing of these pipelines more widely described and defined by following standards: EN ISO 3183 [23], BS EN 12732 [5] while qualification of welded joints is defined in: EN ISO 15614-1 [6], EN ISO 17637 [24], EN ISO 5817 [25].

It should be noted, however, that for applications involving hydrogen, the maximum hardness is limited to 250 HV10. This article addresses the development of a novel technology for automated narrow-gap welding. This approach is undoubtedly innovative, as the commonly used standard welding procedures include the requirement that the weld joint hardness in the heat-affected zone

(HAZ) should not exceed 350 HV. This limit is imposed to prevent the occurrence of cold cracks, which are unacceptable at any quality level according to the PN EN 5817 standard. This subject is particularly critical due to the hydrogen embrittlement effect, which can occur in pipelines used for hydrogen transmission. Therefore, the hardness of the welded joint, especially in the heat-affected zone (HAZ), must be carefully controlled [26]. The crucial role of the HAZ, as well as the requirements concerning its hardness and other properties, were extensively discussed in another study, where a similar steel grade for hydrogen pipelines was welded and evaluated [27].

As is well known, these cracks depend on three general factors: diffused hydrogen (a condition that cannot be fully mitigated due to the presence of hydrogen in the pipeline), martensitic or martensitic-bainitic microstructures (which are largely influenced by chemical composition and cooling rates), and residual stresses in the joint after welding. These stresses may be insufficiently controlled to achieve the desired operational properties. Therefore, it becomes necessary to apply modifications to the microstructures present after the welding process, which can be indirectly assessed through hardness measurements (hence the limit of 250 HV10). Additionally, modifications to the joint geometry and crystallographic orientation, which influence the magnitude of residual stresses in the welded joint, are critical. Such adjustments ultimately enable the achievement of the desired performance characteristics. A significant innovation aimed at achieving these objectives includes the application of geometric solutions for joint design, the use of multi-head welding systems with appropriate welding parameters, and the incorporation of oscillatory movements to further enhance the process.

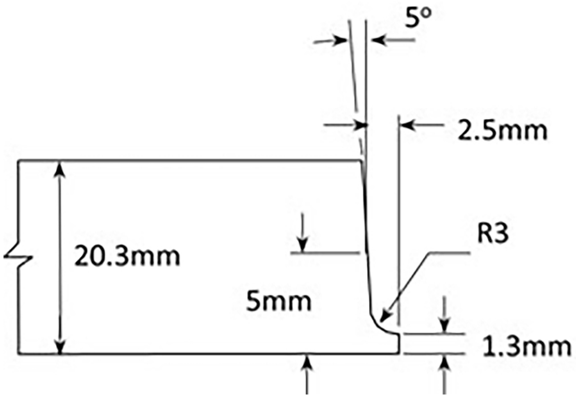

Figure 1. Preparation of the base material

MATERIALS AND METHODS

Narrow-gap welding technology

The new welding technique benefits mainly in the form of automation, increased weld speed and reduction of additional material consumption [6]. The welding process is implemented automatically, using four external heads, which ensure high repeatability of joints. In addition, this method is characterized by a high speed of work.

For instance, one weld on a DN 1000 pipe is made three times faster than in traditional methods. Modern technology also uses a special bevel, which significantly reduces the consumption of additional material compared to traditional techniques. This, has a positive effect on the quality of the joint. A CRC-Evans mandrel bevel was used to bevel the edges of the pipes. The beveling time was 2 minutes. Figure 1 illustrates guidelines for beveling the edges of the base material.

Conditions of the welding process

Welding was performed on an automated station for welding long-range pipelines. The station consists of two CRC-Evans two-head systems, operating in a tandem configuration, moving in synchronization on a specific tube orbit. The two-head systems are powered by four Fronius TPS3200 current sources and VR7000 electrode wire feeders. Figure 2a illustrates the arrangement. It is equipped with comprehensive digital monitoring and precise regulation of the welding parameters, including voltage, current, welding speed, oscillation and stop times. Figure 2b illustrates the automated welding station during the joint's test. In addition, a full registration of welding parameters, in real time, was introduced together with documentation. The high quality of the welds was obtained by unconnected and separately programmable movement of the double head and full tracking of both vertical and horizontal. Welded with G4Si1 wires with a diameter of 1 mm in the M21 gas shield (82% Ar and 18% CO_2) with a flow rate of 25 l/min [9]. The chemical composition of materials (wire and base material) is presented in the Table 2. In order to eliminate hydrogen in the welding process, the material was heated to a temperature approaching 100ºC . Top down welding position (PJ) was employed. The matter of the study are welded joints of L415ME steel pipes according to ISO 3183 (PSL2). The welded joints

Figure 2. (a) Two-head system P625, (b) automated welding station with four heads operating during the process of manufacturing a sample joint

were made using 135 method (welding process that uses a consumable filler wire continuously fed from a spool through a torch held by a manipulator arm) in the PJ welding position in the conditions:

- Gas – M21 (82% Ar i 18% CO2) acc. PN-EN ISO 14175.
- Wire - K600 Ø 1,0 mm, acc. ISO 14341-G 46 2 C1 4Si1/G.
- Power source – TPS 3200 from Fronius.
- Weld type, acc. ISO 9692-1:1.3.
- Parameters of the welding process: 160-240A, 15–24 V.

The analysis aims to provide foundation for the advancement of wedding technology for pipe production joints designed for the transmission of hydrogen, employing automate welding technologies.

The base material

Pipes, are the base material, made in line with PN-EN ISO 3183 standard [23]. For the purpose of the research, all joints were made on a pipe O1016 mm with a thickness of 20.3 mm produced of L415ME steel (with chemical composition and mechanical properties illustrated in the Table. 1 and 2). It is steel for pipelines, after thermomechanical treatment, formed from a two-stage steel rolling. The first stage is normalising, which takes place at a temperature lower by approx. 100÷150 °C than conventional rolling temperature. After thermomechanical treatment, the steel indicates reduced susceptibility to hardening in HAZ, in comparison to steels in the normalized state with similar strength properties.

Identification of welding parameters

Selected welding parameters were verified on the basis of lesson learned and on test plates. To obtain the melt layer Fronius CMT a welding technology, which is distinguished by a low level of heat input and an extremely stable welding arc, was applied. For the fill and face layers, standard pulse technology synergistic lines have been modified for narrow gap applications . The welding current ranged from 170 to 240A. Welding arc voltage ranged from 15–23.5V. The welding speed was from 40 to 55 cm/min. Linear energy ranged from 0.3 to 0.45 kJ/mm. Test joints were manufactured on the basis of developed technological instructions for welding (WPS). Welding parameters are shown in Table 3.

Qualification procedure for welding technology

Aiming to qualify the welding technology of L415ME steel pipes, intended for the construction of a pipeline for the transmission of hydrogen, after joining the welded joints underwent non-destructive testing (NDT): visual (VT), and, magnetic-powder (MT), radiographic (RT), ultra-high frequency (UT) TOFD/PA technique. Subsequently, a set of destructive tests was

Table 1. Chemical composition of steel L415ME

Steel classification	Maximum level [%]									Max. CEV
	C	Si	Mn	P	S	V	Nb	Ti	Other	
L415ME	0,12	0.45	1,6	0,025	0,015	0,09	0,06	0,07	V+Nb+Ti <0,15%	0,42
G4Si1 wire	0,08	0,95	1,70	<0.020	<0.020	<0.030	–	<0.15	V+Nb+Ti <0,50%	–

Table 2. Mechanical properties of steel L415ME

Steel symbol	Plasticity limit $R_{t0,5}$ [N/mm^2]	Strength Rm [N/mm^2]	Elongation A_{min} [%]
L415ME	415÷560	520	18

Table 3. Weling parameters

Pass	Welding method	Wire diameter [mm]	Charge [A]	Voltage [V]	Wire feed [m/min]	Welding speed [m/min]	Linear energy [kJ/mm]
1	135	1,0	160–240	15–23	7–8	0.4	0.4
2*	135	1,0	170–240	21–23	6–7	0.5	0.45
3	135	1,0	170–270	20–24	10	0.5	0.45
4*	135	1,0	170–270	21–24	10	0.5	0.45
5	135	1,0	170–270	21–24	10	0.5	0.45
6*	135	1,0	170–200	21–24	10	0.5	0.45
7	135	1,0	100	22–24	9,5	0,5	0.3
8*	135	1,0	100	22–24	9,5	0,5	0.3

***Note:** it is paired with odd stitch.

carried out, in accordance with the qualification procedures. The tests consisted of : tensile strength, bending angle determination, impact test, hardness measurements and macroscopic examinations. The tests were performed in accordance with recommendations stated in the following standards:

- EN ISO 12732 – Gas supply systems. Welding of steel pipe systems. Functional requirements.
- EN ISO 15614-1 – Specification and qualification of metal welding technology – Welding technology test – Part 1: Arc and gas welding of steel and arc welding of nickel and nickel alloys and additional welding [6].

Samples for mechanical testing of the pipes were taken from the areas indicated in Figure 3 and Table 4.

Study of the structure and properties of welds

According to the standards, laboratory tests started 24 hours after welding was terminated. Following a visual examination in accordance with EN 17637 [24], it was found that a joint made of a 1000 mm diameter pipe meets the quality requirements and the obtained acceptance level was defined as high as (B) according to EN ISO 5817 [25].

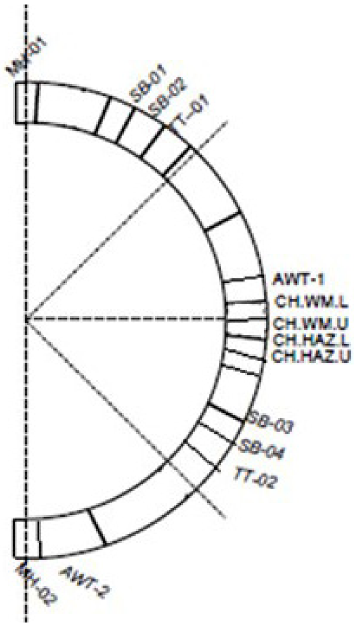

Figure 3. Diagram of sampling areas for mechanical testing of steel tubes L415ME

Table 4. Mechanical tests required to qualify the welding technology manual

Symbols	Type of tests	Samples quantity
TT 1;TT2	Tests of transverse samples stretching	2
SB1;SB2;SB3;SB4	Static bend test	4
MH1;MH2	Macroscope test	2
CH.WM.L	Impact toughness test- notch in the weld metal area	1
CH.WM.U	Impact toughness test- notch in the weld metal area	1
CH.HAZ.L	Impact toughness test-notch in the HAZ	1
CH.HAZ.U	Impact toughness test-notch in the HAZ	1
AWT1;AWT2	Static tensile test	2

Radiographic tests were carried out in accordance with EN ISO 17636-1. Ultrasound analyses were performed with the Pipewizard Olympus apparatus which has the function of automatic recording of test results. Ultrasound examinations carried out with the TOFD/PA technique, performed in accordance with EN ISO 13588.

Magnetic-powder tests performed in accordance with EN 17638 did not show surface incompatibilities on the tested samples. Acceptance level according to ISO 23278. Radiographic tests did not show non-compliance on the tested samples. These tests require the use of a Class B radiographic test technique according to ISO 17631-1 using a class C3 radiographic film in accordance with ISO 584-1 standards.

Ultrasound analyses and ultrasound examinations carried out with the TOFD/PA technique did not show any incompatibility on the tested samples. The tensile test of cross-sectional samples was carried out on the Zwick Roel type Z250 strength machine. The analysis was performed on transverse samples, in which the head and ridge headings were processed to the thickness of the base material. The Zwick Roel Z250 testing machine was employed to perform a bend test. Four transverse flat samples, taken from the indicated areas of the joints on the pipe, were used for this purpose. The intended bend angle was 180° for all samples tested.

The impact toughness test of the samples was conducted on the Zwick/Roell – HIT750P strength machine. It was made on the Charpy hammer with the initial energy of a hammer of 100 J. Due to the steel thickness of 20.3 mm, 10 mm thick samples with „V" shaped notch were applied. The sampling area for impact toughness tests and the position of the notch in the welded test joints were located in the weld metal area at the height of the root run and face stitches, and in the heat-affected zone at the height of the border and face stitches. Figure 6 illustrates the preparation of samples for the impact toughness tests. Observations of the macrostructure of welded joints were made using the Zeiss Axio microscope, with magnifications in the range of 5 times on metallographic fragments digested mainly with 5% nital reagent.

The hardness of the samples was tested by Vickers', using the Emco Dura Vision G5 hardness tester, at a load of 1 kg (9.8 N). Hardness measurements on samples from the welded joint were made in accordance with ISO 6507-1. Position of the measuring points according to ISO 9015 is shown in Figure 4.

RESULTS

Extensive studies of the structure and properties were conducted to evaluate the adopted welding strategy and confirm that the results met the specified requirements, i.e., with a proper microstructure and hardness not exceeding 250 HV10. For this purpose, destructive and non-destructive testing were carried out.

Non-destructive tests

Figure 5 shows a view of the weld from the face and the ridge. Visual evaluation confirmed high aesthetics of the face as well as the weld edges in the two joints. Both welds meet the B quality level according to ISO 5817.

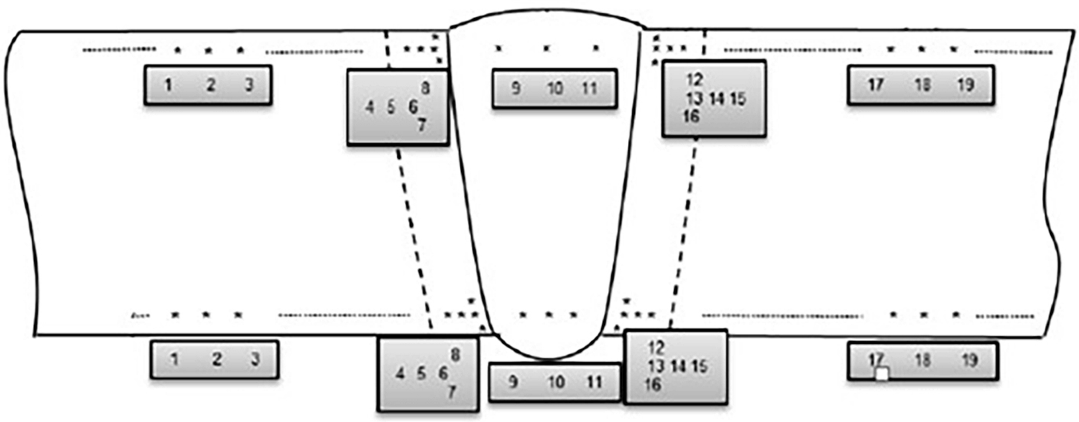

Figure 4. Location of the measuring points

Destructive tests

Tensile tests

The results of the tensile strength tests of the joints are shown in Table 5. The tensile strength test was performed with the assent of the requirements of the standard. All trials tested positive (Table 5 and 6). In each of the samples, the place of fracture was not the weld, but the base material. This leads to conclusion that the strength of the weld was greater than the strength of the base material.

Bend test

The results of the tensile strength tests of the joints are shown in Table 7, and the tensile view of the samples is shown in the Figure 6. The test for side bend was carried out in line with the requirements stated in the standard. This test confirmed the very good plastic properties of the joints. As a result of the tests performed for each sample, a bend angle of 180° was obtained without cracks in the scratches (Table 7). No incompatibilities were found on the samples.

Impact toughness test

Table 8 shows the results of impact toughness test measurements. The impact toughness test was performed following the guidelines presented in the standard. The breakthrough of the samples was matte with the characteristics of plastic

Figure 5. View of the weld from the face and the ridge

Table 5. Tensile test of cross-sectional samples -results

Method acc. ISO 4136		Room temperature		
Sample number	Size [mm]	Rm [MPa]	Split	Result
54801/4	24.98x19.01	566	MR	positive
54801/14	24.94x18.70	575	MR	positive
According to ISO 3183		≥520		

Table 6. Results of tensile tests in a weld

Method acc. ISO 5178			Room temperature		
Probe number	Diameter [mm]	$Rp_{0.2}$ [MPa]	Rm [MPa]	Extension [%]	Reduction of the space [%]
54801/5	Ø 4.01	558	663	27.1	66.5
54801/15	Ø 4.01	569	691	25.1	62.1
According to		≥475	–	–	–

material. No visible welding incompatibilities were detected on the breakthrough surface. The impact toughness was more than 126J. All trials tested positive (Table 8).

Microstructure analysis

The results of the macroscopic examination of the weld joint in a vertical downward position are presented in the Table 9. Figure 8 shows the macrostructure of the joint taken at 12 o'clock on the pipe.

The macroscopic examination was performed in accordance with the conditions specified in the standard. No incompatibilities were found on the samples and the regular shape of each sample surface indicates a correctly made joint (Table 9). On each of the samples a melting line between the additional material and the base material is noticeable. This fusion has a regular and correct shape. The weld has a clear, even melt and plain regular stitches (Fig. 8). The relatively small and uniform area of the heat affected zone (HAZ) was

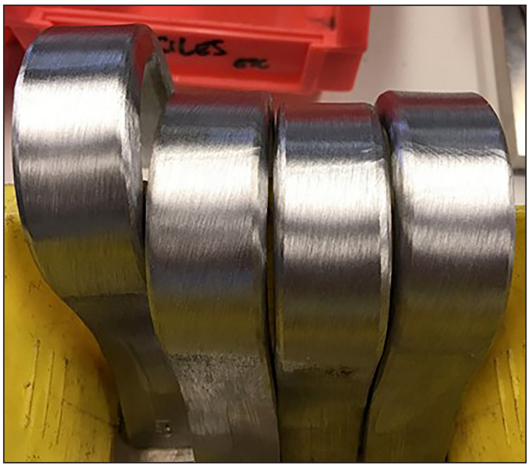

Figure 6. Weld's samples welded after the bend test

Figure 7. Sample preparation for impact toughness tests

Table 7. Results of side bend tests

Method acc. ISO 5173			Room temperature			
Sample number	Type	Dimention [mm]	Distance between the rolls [mm]	Bending angle [º]	Result	Comments
54801/2	Side	19×10	65	180	positive	–
54801/3	Side	19×10	65	180	positive	–
54801/10	Side	19×10	65	180	positive	–
54801/11	Sie	19×10	65	180	positive	–

Table 8. Results of impact toughness tests performed on Charpy's hammer

Method acc. ISO 9016							
Sample number	Notch	Size [mm]	Temperature [°C]	Fracture toughness [J]			
54801/6-1,2,3	Centre of the weld, melting zone (3h)	10×10	-20	1	2	3	average
				325	301	258	294
54801/7-1,2,3	Centre of the weld, face (3h)	10×10	-20	1	2	3	average
				139	128	126	131
54801/8-1,2,3	HAZ, melting zone (3h)	10×10	-20	1	2	3	average
				326	334	345	335
54801/9-1,2,3	HAZ, face (3h)	10×10	-20	1	2	3	average
				443	354	397	398
In compliance with API5L table G1				≥30			≥40

Table 9. Results of macroscopic tests

Method in compliance with ISO 17639 /ISO 5817 /ISO 6570-1 Magnification: 5×			
Sample number		Observation	Result
54801/1(12h)	Nital	no incompatibilities were detected	positive
54801/13(6h)	Nital	no incompatibilities were detected	positive
54801/16(3h)	Nital	no incompatibilities were detected	positive

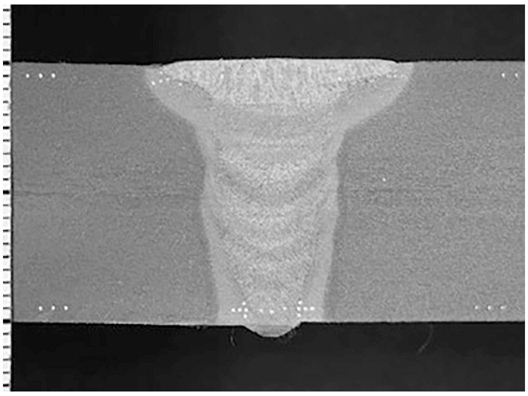

Figure 8. Cross-section nr. 54801/1(12h) Magnification: 5×

created by low-energy linear welding processes. The weld is free from internal incompatibilities.

Hardness measurement

The measurements results of the hardness of the welded joint, in the vertical down position taken at 12 o'clock on the pipe, are presented in Table 10. Hardness distribution in the joint is shown in Figure 9. Results of the measurements of the hardness of the welded joint, in the vertical down position, taken at 6 o'clock on the pipe are shown in Table 11. Hardness distribution in the joint is presented in Figure 10.

Table 10. The measurements results of the hardness of the welded joint at 12 o'clock

Sample number: 54801/ 1(12h)																			
Position	Base material			HAZ					Weld			HAZ					Base material		
Measurement spot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Face	195	196	196	183	211	232	231	229	225	225	220	229	233	218	194	237	199	201	201
Melting zone	196	195	198	197	214	227	224	231	228	226	229	226	225	213	201	226	201	201	200

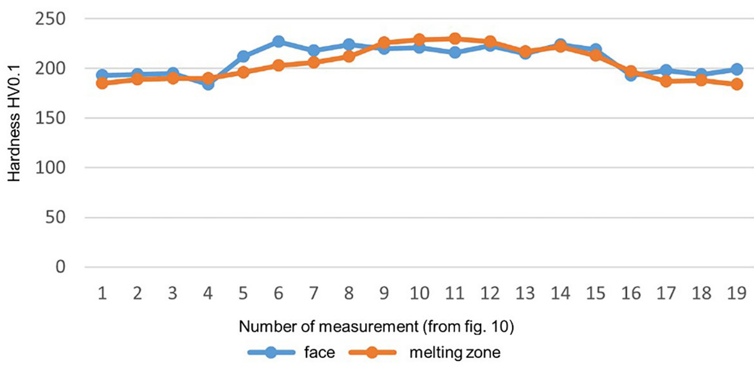

Figure 9. Hardness distribution in the joint at 12 o'clock

Table 11. Evaluation of the hardness test in the joint at 6 o'clock

Sample number: 54801/17(6h)																			
Position	Base material			HAZ					Weld			HAZ					Base material		
Measurement spot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Face	193	194	195	184	212	227	218	224	220	221	216	223	215	224	219	193	198	194	199
Melting zone	185	189	190	190	196	203	206	212	226	229	230	227	217	222	213	197	187	188	184

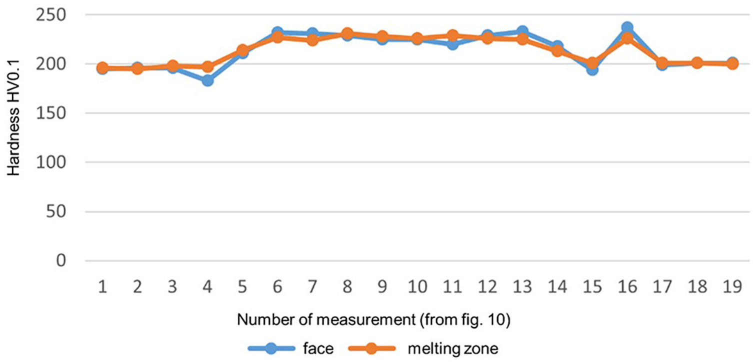

Figure 10. The position of hardness measurement in the weld at 6 o'clock

Table 12. Evaluation of measurements of the hardness of the welded joint at 3 o'clock

Sample number: 54801/18(3h)																			
Position	Base material			HAZ					Weld			HAZ					Base material		
Measurement spot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Face	198	199	197	192	217	239	235	243	240	243	243	247	235	243	230	197	217	211	216
Melting zone	198	200	198	188	198	213	211	218	233	228	236	222	218	221	201	186	195	192	198

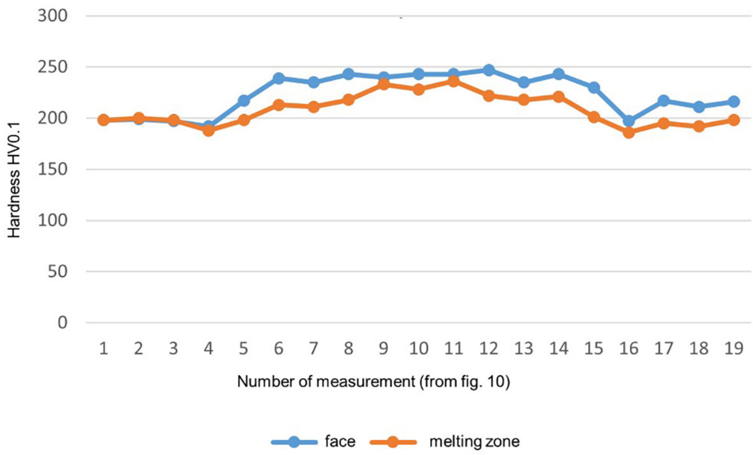

Figure 11. The point of measurements of the hardness of the welded joint at 3 o'clock

Evaluation of measurements of the hardness of the welded joint in the vertical down position, taken at 3 o'clock on the pipe, are summarized in Table 12. Hardness distribution in the joint is illustrated in Figure 11.

CONCLUSIONS

The conducted research and presented results have led to the following conclusions:

- The selected welding parameters enabled the creation of butt joints from 20.3 mm thick L415ME steel pipes without a gap in the welding groove. Visual inspections confirmed compliance with B-level dimensional requirements per ISO 5817. Both radiographic and TOFD/PA ultrasound tests indicated no defects in the tested samples.
- The welding method achieved a joint tensile strength of 566 MPa, surpassing the minimum strength of the base material (520 MPa). This demonstrates the effectiveness of the welding process in maintaining structural integrity.
- Within the applied linear welding energy range (0.35–0.45 kJ/mm), no excessive cooling rates or quenching structures were observed. Hardness values were controlled, with the base

material at ~200 HV, the weld at ~240 HV, and the heat-affected zone ranging between 190 HV and 240 HV. These results meet the requirements for hydrogen applications.
- The average impact toughness strength measured was 300J, with the lowest value at 126J, located 2 mm under the weld face. This still exceeds the required minimum value of 40J, ensuring suitability for demanding conditions.
- The applied welding technology, which utilized automated two-burner systems with specially designed synergic lines, met the standards outlined in EN ISO 15614-1 and EN ISO 12732. Additional hydrogen application requirements were also fulfilled.
- The study introduced a novel narrow-gap welding method that enhances the control of hardness in the heat-affected zone (max. 250 HV10), crucial for hydrogen environments. The innovative combination of geometric modifications, multi-head welding systems, and oscillatory movements effectively reduced residual stresses and improved joint performance.
- The L415ME steel's favorable chemical composition and the developed welding technology ensure reliable structural solutions for welded pipes. The limitation of linear arc energy prevents overheating and preserves the joint's strength properties, making it ideal for hydrogen pipeline applications.

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REFERENCES

1. EHB Implementation Roadmap: Public support as catalyst for hydrogen infrastructure. 2024.
2. Cornille J, Kneebone J, Conti I, Delbeke J. Five reflections on clean hydrogen's contribution to European industrial decarbonization from 2024 to 2030. Florence School of Regulation 2024.
3. Bruce W.A. In-Service Welding onto Hydrogen and Methane/Hydrogen Mixture Pipelines. Columbus, OHIO: 2023.
4. Bruce W.A, Etheridge B.C. Further development of heat-affected zone hardness limits for in-service welding. Materials and Joining, American Society of Mechanical Engineers 2012; 3, 71–81. https://doi.org/10.1115/IPC2012-90095.
5. BS EN 12732:2021 - TC Gas infrastructure. Welding steel pipework. Functional requirements 2021.
6. ISO 15614-1:2017 Specification and qualification of welding procedures for metallic materials — Welding procedure testPart 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys 2017.
7. ISO 15609-1:2019 Specification and qualification of welding procedures for metallic materials — Welding procedure specification Part 1: Arc welding 2019.
8. Gelder K Van, Thomas M.J.J.S, Kroese C.J. Hydrogen-induced cracking: determination of maximum allowed H 2 S partial pressures. Corrosion 1986; 42, 36–43. https://doi.org/10.5006/1.3584877.
9. Abe J.O, Popoola A.P.I, Ajenifuja E, Popoola O.M. Hydrogen energy, economy and storage: Review and recommendation. Int J Hydrogen Energy 2019; 44: 15072–15086. https://doi.org/10.1016/j.ijhydene.2019.04.068.
10. Park J-H, Moon H-S. Advanced automatic welding system for offshore pipeline system with seam tracking function. Applied Sciences 2020; 10: 324. https://doi.org/10.3390/app10010324.
11. Ronevich J.A, D'Elia C.R, Hill M.R. Fatigue crack growth rates of X100 steel welds in high pressure hydrogen gas considering residual stress effects. Eng Fract Mech 2018; 194: 42–51. https://doi.org/10.1016/j.engfracmech.2018.02.030.
12. Alvaro A, Olden V, Macadre A, Akselsen O.M. Hydrogen embrittlement susceptibility of a weld simulated X70 heat affected zone under H2 pressure. Materials Science and Engineering: A 2014; 597: 29–36. https://doi.org/10.1016/j.msea.2013.12.042.
13. Capelle J, Dmytrakh I, Azari Z, Pluvinage G. Evaluation of electrochemical hydrogen absorption in welded pipe with steel API X52. Int J Hydrogen Energy 2013; 38: 14356–14363. https://doi.org/10.1016/j.ijhydene.2013.08.118.
14. Zandinava B, Bakhtiari R, Vukelic G. Failure analysis of a gas transport pipe made of API 5L X60 steel. Eng Fail Anal 2022; 131: 105881. https://doi.org/10.1016/j.engfailanal.2021.105881.
15. Yue X. Investigation on heat-affected zone hydrogen-induced cracking of high-strength naval steels using the Granjon implant test. Welding in the World 2015; 59: 77–89. https://doi.org/10.1007/s40194-014-0181-4.
16. Kah P, Martikainen J. Influence of shielding gases in the welding of metals. The International Journal of Advanced Manufacturing Technology 2013; 64: 1411–1421. https://doi.org/10.1007/s00170-012-4111-6.
17. Sharma S.K, Maheshwari S. A review on welding of

high strength oil and gas pipeline steels. J Nat Gas Sci Eng 2017; 38: 203–217. https://doi.org/10.1016/j.jngse.2016.12.039.

18. Cai X, Fan C, Lin S, Yang C, Ji X, Hu L. Effects of shielding gas composition on arc characteristics and droplet transfer in tandem narrow gap GMA welding. Science and Technology of Welding and Joining 2017; 22: 446–453. https://doi.org/10.1080/13621718.2016.1253535.
19. Costa Assunção P.D, Ribeiro R.A.F. Dos Santos E.B, Gerlich A.P, de Magalhães Braga E. Feasibility of narrow gap welding using the cold-wire gas metal arc welding (CW-GMAW) process. Welding in the World 2017; 61: 659–666. https://doi.org/10.1007/s40194-017-0466-5.
20. Cai XY, Lin SB, Fan CL, Yang CL, Zhang W, Wang Y.W. Molten pool behaviour and weld forming mechanism of tandem narrow gap vertical GMAW. Science and Technology of Welding and Joining 2016; 21: 124–130. https://doi.org/10.1179/1362171815Y.0000000073.
21. Liu H, Xue R, Zhou J, Bao Y, Xu Y. Effects of oscillation width on arc characteristics and droplet transfer in vertical oscillation arc narrow-gap P-GMAW of X80 steel. Metals(Basel) 2023; 13: 1057. https://doi.org/10.3390/met13061057.
22. Ginzel E.A. Automated ultrasonic testing for pipeline girth welds. Olympus; 2006.
23. ISO 3183:2019. Petroleum and natural gas industries — Steel pipe for pipeline transportation systems 2019.
24. ISO 17637:2016. Non-destructive testing of welds — Visual testing of fusion-welded joints n.d.
25. ISO 5817:2023. Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections 2023;Edition 4.
26. Bouledroua O, Zelmati D, Hafsi Z, Djukic M.B. Hydrogen embrittlement effects on remaining life and fatigue crack growth rate in API 5L X52 steel pipelines under cyclic pressure loading. Eng Fail Anal 2024; 166: 108917. https://doi.org/10.1016/j.engfailanal.2024.108917.
27. Gao Z, Gong B, Xu Q, Wang D, Deng C, Yu Y. High cycle fatigue behaviors of API X65 pipeline steel welded joints in air and H2S solution environment. Int J Hydrogen Energy 2021; 46: 10423–10437. https://doi.org/10.1016/j.ijhydene.2020.12.140.