



Welding procedure qualification record (WPQR) for welds fabricated at proximity

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Abstract

Maintaining the minimum allowable distance between proximity welds has always been considered a subject of debate among design engineers, welding engineers/inspectors and fabricators/engineering contractors. The scattered nature of guidelines available in welding codes and standards for maintaining the minimum allowable distance poses a significant challenge in the welding procedure and inspection criteria development process. This is especially critical for complex welded joints on submerged sections of offshore structures, in compact layouts/branched connections of topside piping components, and on topside structural joints (depending on the complexity). This manuscript presents the findings of an experimental study that was performed by fabricating two girth welds at proximity on an S355 steel tubular section with diameter of 219.1 mm and thickness of 8.18 mm. Proximity girth welds were fabricated on S355 tubular sections at three different distances between their weld toes, 5, 10, and 15 mm, respectively, using two different welding procedures. Welding procedure qualification record (WPQR) was performed, and all prescribed mechanical tests were recorded as per Norsok M-101, a structural steel fabrication code. Although all results from the mechanical test met the minimum specified values as defined in the Norsok code, the research findings revealed a noticeable difference in Charpy and hardness values for proximity region between adjacent welds. Considerable changes in final microstructure morphology were observed between proximity welds due to varying thermal cycles. These observations can form the basis for the future welding procedure qualification of critical welded joints, especially for proximity welds on critical welded joints of offshore structures and welds fabricated during replacement/repair procedures in compact piping layouts.

Keywords Proximity welds · Welding procedure qualification record · Norsok M-101

1 Introduction

Welding is the most widely accepted method for the joining of two structural members with or without the use of filler wire when it comes to the fabrication of steel and various advanced engineering alloys, ranging from offshore jackets, floating structures, piping and pipelines to bridges, and aircrafts [1–6]. In the past, many accidents and delays have been related to weld failures; however, this issue persists, despite the improvement in welding techniques and inspection procedures [7]. For instance, the Alexander L. Kielland offshore accommodation rig failure in the restrained geometry of its

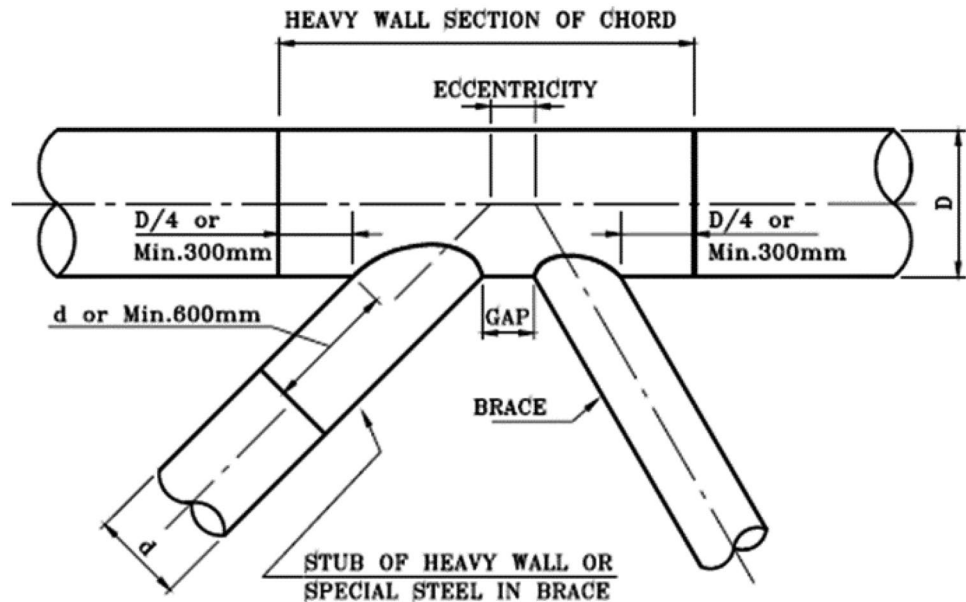
brace hydrophone support was reported to be due to insufficient fillet weld size and high residual stress, leading to an overload of welds and catastrophic fatigue cracking [8]. The recent delay of Equinor's Johan Castberg floating production, storage and offloading (FPSO) hull for Barents Sea has been credited to faulty welds [9]. The popularity of both fixed and floating types of wind turbines cannot be ignored, as accidents due to cracks in welds are gaining attention, in contrast to the usually reported cracks in the bolts of turbines [10]. Such incidents in large structures cannot be overlooked, as the consequences due to failure leading to loss of life, climate, and property, are very high and irrevocable.

The fabrication of large structures like offshore jacket structures, onshore and offshore wind monopiles and tubular truss bridge structures often brings forward the challenge of welds coming within proximity of each other, as shown in Fig. 1. This challenge of maintaining a minimum distance between welds is often debated among designers, inspectors,

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Fig. 1 Detail of offshore joints [13]



and contractors who often rely on international codes and standards for recommendations [11]. A detailed assessment of these codes and practices for maintaining minimum distance criteria between welds has been performed previously by the authors in [12] where a clear lack of consensus has been found regarding maintaining a final distance that is often based on a factor of 4 or 5 times the thickness or 1 or 1.5 times the diameter. In procedures for replacing compact layouts of piping racks, unavoidable situations of placing a new weld close to an existing weld of branched connections, nozzles, etc., are often encountered, as is the case in offshore jacket critical joints, e.g., non-overlapping braces. In the case of repair or replacement procedures, international codes and standards offer no guidance on defining, either the minimum distance between welds or welding procedures for proximity welds, and such decisions are often left to stakeholders' engineering judgment.

DNVGL-ST-0126 code on support structures for wind turbines [14] recommends maintaining a distance between consecutive girth welds of not less than 300 mm for an outer diameter of less than 300 mm and states that “*The minimum weld distances mentioned above have been derived based on practical experience. Shorter distances may be suitable but need to be proven both with respect to impact on stress concentration factor (SCFs) as well as residual stresses*”. This indicates a need to further investigate areas between proximity welds with an unqualified welding procedure qualification record (WPQR) which have experienced multiple cycles of heating and cooling and unprescribed residual stress profiles used during defect assessment procedures, as per fitness for service (FFS) codes [15, 16]. The importance of potential factors that degrade welding quality in terms of defects requires an assessment of the most vulnerable

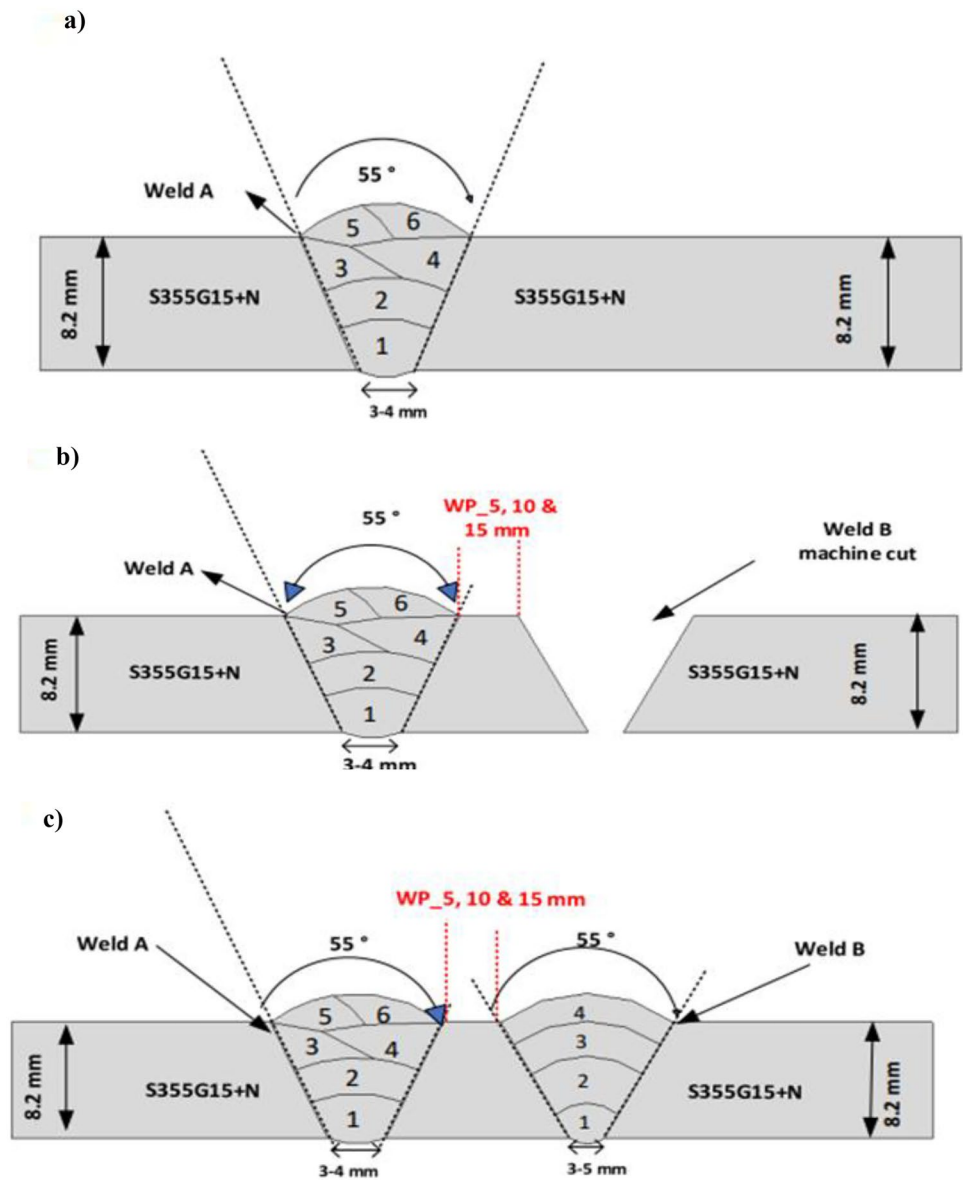
welding procedure specifications (WPSs) and imperfection factors that contribute to the majority of defective welds [17]. Pressure Vessel Research Council (PVRC) Phase 2 [18, 19] highlights the conservativeness in residual stress profiles at a distance away from welds, as per FFS codes such as BS7910, API 579 RP-1/ASME FFS-1, etc.

With this background, the aim of the current study is to qualify WPQRs for two different girth welds, placed at proximity with a minimum distance between their weld toes of 5 mm, 10 mm, and 15 mm, respectively. All necessary mechanical testing was performed in accordance with NOR-SOK M-101 [20], the code for structural steel fabrication, to understand changes in hardness and Charpy values at the proximity region. Lastly, detailed microstructure characterization was performed to understand the grain morphology at the proximity region due to the varying thermal cycles of two different welds. The remainder of the paper is structured as follows: Sect. 2 presents the experimental details. Thereafter, in Sect. 3, the results are presented and discussed. Subsequently, in Sect. 4, a conclusion is drawn.

2 Experimental set-up

A schematic diagram of the experimental set-up is shown in Fig. 2, pictorially displaying the fabrication steps from ‘a’ to ‘c’. Structural steel grade S355G14+N seamless pipes were selected for this experiment, with an outside diameter of 219.1 mm and a thickness of 8.18 mm. As shown in Fig. 2a–c, vee joint geometry was machine cut for welds A and B in accordance with prequalified WPS adopted from reputable industrial partners. As shown in Fig. 2b, initially, weld A was fabricated as a single weld on a pipe section

Fig. 2 Schematic diagram of experimental set up from (a) to (c)



and, subsequently, the vee groove for weld B was machine cut. Lastly, weld B was welded after weld A was completed, maintaining proximity distances between their weld toes of 5, mm, 10 mm, and 15 mm, respectively, as shown in Fig. 2c and summarized in Table 1.

In this study, welding parameters were maintained as per pre-qualified WPS for welds A and B, and digital weld log data was maintained during the experiments, as mentioned in Table 2. The mechanical and material composition of the tubular pipe and filler wire is also presented in

Table 1 Summary of fabrication procedure for each weld proximity case

Weld type	Proximity distance (mm)	Welding process	EN classification	Weld groove	Shielding gas	Welding position
A	5	Tungsten inert gas (TIG)	141	Vee Joint	Argon	PA/1G/Flat
B	10	Metal Active Gas(MAG)-metal cored + Flux cored Arc welding (FCAW)	138 + 136	Vee Joint	20% carbon dioxide (CO ₂) in pure argon (Ar)	PA/1G/Flat

Table 2 Welding parameters for Weld A, TIG welding process (141) and welding parameters for Weld B, MAG+FCAW welding process (138+136)

Pass	Weld	Filler (mm)	Welding process	Current (A)	Voltage (V)	Polarity	Travel speed (mm/min)	Gas flow (l/min)	Heat input (kJ/mm)
1	A	2.4	141	100–135	10–20	DC –	39–40	15–20	1.5–2.49
2	A	2.4	141	140–180	10–14	DC –	75–80	15–20	1.05–2.02
Fill	A	2.4	141	160–230	11–15	DC –	85–120	15–20	0.88–2.44
Cap	A	2.4	141	160–230	11–15	DC –	85–120	15–20	0.88–2.44
1	B	1.2	138	90–125	14–16	DC +	65–85	16–20	0.89–1.85
2	B	1.2	136	160–220	22–29	DC +	180–400	16–20	0.53–2.13
Fill	B	1.2	136	180–250	22–29	DC +	180–400	16–20	0.59–2.42
Cap	B	1.2	136	180–250	22–29	DC +	180–400	16–20	0.59–2.42

Tables 3 and 4, respectively. In this study, to simulate the practical situation of weld proximity encountered during repair and replacement procedures, weld B was welded with a different welding procedure, i.e., MAG-metal core (138) semi-automatic method for root pass, as it employs a short-circuiting technique for better root penetration and FCAW (136) semi-automatic method for the remaining passes for faster production. In weld A, all passes were completely fabricated with TIG (141), a semi-automatic welding process. This demonstrates the practical situation of critical welded joints fabricated under shop conditions, by using a controlled procedure like TIG, and during on-site repair or replacement situations, welded with a faster and more mobile procedure like MAG + FCAW.

NORSOK M-101 [20] code was used for qualification of WPQR and adopted in this project catering for the Norwegian continental shelf (NCS) and offshore-welded tubular structures used in oil exploration and the processing industry. NORSOK M-101 code for WPQR is strictly valid within the limitations specified in ISO 15614–1 [21], the widely accepted code for welding qualification around the world. Welding was performed under controlled conditions after optimizing the welding parameters as mentioned in Tables 2 and 3 in line with pre-qualified WPS. Three samples from each proximity distance were finally fabricated and were subjected to mechanical tests as per NORSOK M-101 and ISO 15614–1 as detailed in Table 5.

All necessary and recommended destructive and non-destructive testing (NDT) was performed, and the general

procedure and acceptance criteria for each method are summarized in Table 6, as per ISO EN15614-1 [21]. Charpy specification as per EN ISO 9016–2012 was performed; however, in the case of WPQR for proximity welds, Charpy locations shown in Fig. 3 were selected. The notch for Charpy specimens was made at locations shown in Fig. 3.

- Notch in center of weld
- Notch in fusion line (FL)
- Notch in heat affected zone (HAZ), 2 mm from fusion line
- Notch in HAZ, 5 mm from fusion line

Hence, in the case of a weld proximity distance of 5 mm, six samples and four sets of Charpy locations were extracted, as the fusion line (FL + 5 mm) was not possible due to the 5 mm proximity distance. In the proximity case of 10 and 15 mm case, a total of eight samples and four sets were extracted due to there being sufficient proximity distance.

3 Results and discussion

3.1 Visual and radiographic examination

As shown in Table 6, all mechanical destructive and NDT was performed in accordance with relevant EN standards. Visual and NDT testing of radiography was performed to 100% extent on each proximity distance sample. Due to

Table 3 Physical and material properties of tubular pipe grade S355 G14 + N

Yield point (min 355) Mpa			Tensile point (460–620) Mpa			Elongation min 22%			Impact test (5–25 J) @-40 °C			Hardness HRB max 99		
444			553			28			102			84		
C	Mn	Si	P	S	Cu	Ni	Cr	N	Mo	V	Ti	Nb	B	
0.14	1.19	0.337	0.016	0.003	0.07	0.02	0.06	0.0091	0.005	0.059	0.001	0.003	0.0005	

Table 4 Physical and material properties of **a)** Filler wire ESAB Tigrod 13.26 used in 141 welding process **b)** Filler wire SF-3AM used in 138 welding process **c)** Filler wire SF-47A used in 136 welding process

	Yield point (460 min) Mpa			Tensile point (530–680) Mpa			Elongation (20 min) %			Impact test (J) (47 J min) @ -40 °C		
	C	Mn	Si	P	S	Cu	Ni	Cr	MO	V	Nb	
a)	480			580			30			60		
	0.11	1.41	0.89	0.018	0.015	0.52	0.85	0.04	0.001			
b)	518			585			27			163		
	0.05	1.13	0.27	0.01	0.004	0.28	1.03	0.02	0.01	0.01	0.01	
c)	509			597			28			118		
	0.06	1.24	0.59	0.008	0.008	0.26	0.93	0.02	0.01	0.01	0.01	

spray mode in MAG + FCAW welding process Weld B, a wider and irregular cap weld bead was observed in contrast to a smooth weld cap bead of weld A [22], which was welded with TIG process as shown in Fig. 4. As per the acceptance criteria of ISO 10675–2016, both joints were accepted after performing radiography testing on proximity.

3.2 Hardness testing

Vickers hardness testing on each case of weld-proximity distances of 5, 10, and 15 mm was performed according to NS-EN ISO 9015–1:2011. As per indentation marks shown in Fig. 5, there was a recommended distance of 1 mm between indentations and, in HAZ ≤ 0.5 mm, between the center point of the indentation and the fusion line. The indentation marks shown in Fig. 5 can be seen clearly in macro graphs of each weld proximity case in Fig. 9a–c. As the proximity distance was the area of concern, hardness measurement points between adjacent weld toes at ‘weld cap and root level’ for 5, 10, and 15 mm proximity distances are shown in Fig. 6a, b, respectively. High hardness values were observed at the proximity distance (PD-A&B) between two weld metals (WM-A&B) and their respective adjacent HAZ-A&B, in contrast to the parent metal (PM). This proximity distance, or area known as ‘alien metal’, has experienced microstructural changes due to high restraint and successive thermal cycles of multipass welds, as noticed in [23] for proximity-welded joints K-brace joints of offshore jacket structures.

A maximum value of 210 HV was observed close to a HAZ value of 225 HV on either side for 5 mm proximity distance welds at cap level, as shown in Fig. 6a. Cold cracking chances increase if hardness values are between 350 and 400 HV. This region may be prone to cracking, as it has accumulated high stresses and chances of martensitic formation have been sustained due to successive thermal cycles of heating and cooling [23]. Similar hardness points’ profiles for weld proximity distances of 10 and 15 mm are shown in Fig. 6a, b for fair comparison. As the proximity distance is increasing, a drop in hardness values can be seen and is comparable to PM in the 10 and 15-mm cases. In case of 10-mm proximity distance, the highest value of 186 HV was observed at the proximity region and of 167 HV in the case of 15-mm distance, which is almost equivalent to parent metal value at weld cap level. It is also worth mentioning that hardness values at weld cap level in the 5-mm case are maximum in the HAZ area, in comparison to 10 and 15-mm cases.

3.3 Charpy testing

Charpy testing was performed in accordance with KV8, NS-EN ISO 148–1:2016 and ISO 9016:2012 at –20 °C. As discussed previously and shown in Fig. 3, due to the limited space for FL + 5 mm samples, only six specimens were available for 5-mm proximity distance whereas FL + 5 mm was possible for 10- and 15-mm proximity distances. Sample size was kept at 5 × 10 × 55 mm size, as the pipe thickness was 8.2 mm; hence, a conversion factor of 2/3 was

Table 5 Examination of the test weld for WPQR as per NORSOK M-101

Joint configuration	Joint thickness (mm)	Mechanical testing			
		Tensile test	Bend test	Charpy V notch	Hardness and macro
Butt welds (Tubular)	t ≤ 50 mm	2	4	4 sets	1

Table 6 Examination and testing of the test pieces

Activity description	Specification/procedure	Acceptance criteria
Visual testing	ISO 17637:2016	EN ISO 5817:2014 B/C
Radiographic testing	ISO 17636–2:2013	ISO 10675–1:2016
Macro examination	NS-EN 17,639:2013	EN ISO 5817:2014 B/C
Transverse tensile test	ISO 4136:2012, ISO 6892–1:2016 Method A1	NS-EN 15,614–1: 2017, NS-EN 10,225:2009
Charpy V Impact test	NS-EN ISO 148–1:2016, ISO 9016:2012	NS-EN 15,614–1: 2017, NS-EN 10,225:2009
Vickers Hardness test	NS-EN ISO 9015:2011	NS-EN 15,614–1: 2017

applied, when calculating energy values as per code EN 15,614–2017.

Figures 7 and 8, respectively, illustrate scanning electron microscope (SEM) micrographs of fracture surface at FL + 2 mm and the Charpy energy values chart. A region compromised of a mainly dimple-like ductile fracture zone is observed, as shown in SEM micrographs in Fig. 7a, for 5-mm WP distances. However, some cleavage river-like patterns, along with dimples, are observed in Fig. 7a, indicating some regions of brittle fracture, in contrast to Fig. 7b, where dominant dimples like a ductile fracture surface are observed for the 15-mm weld proximity case. Features like the area of the ductile fracture zone of HAZ and the shear lip of HAZ can also help in determining the dominant fracture mode in HAZ [24].

As shown in Fig. 8, low energy values are noted for 5 mm weld proximity (WP). It can be observed from Fig. 8 that the least energy values of 55 J at the proximity region, i.e., weld A-FL + 2 mm, were observed for the 5-mm proximity distance, in contrast to the 10 and 15-mm cases. To draw fair comparison, FL + 2 mm Charpy values are highlighted in Fig. 8, with values of 62 J and 66 J being observed, i.e., between welds A–B for the 10 and 15-mm cases. Due to high hardness and high restraint in the 5-mm proximity case, a drop in energy values can be observed. This drop can be attributed to the high hardness values observed, as explained in Sect. 3.2, and the mixed pattern of cleavage river and

dimples, leading to brittle and ductile fracture surfaces, respectively. However, microstructure graphs shown later in Sect. 3.4 also substantiates the high hardness values at proximity regions for changed morphology of grain size in the proximity region.

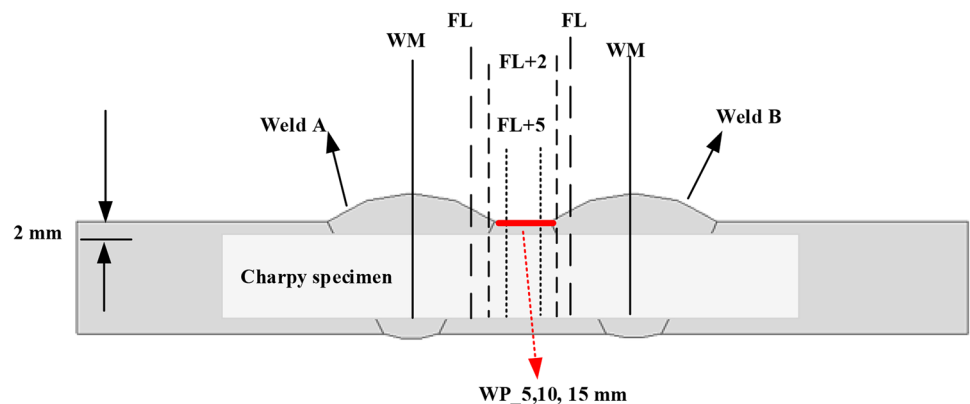
3.4 Macro testing

Macro examination was performed in accordance with NS-EN 17,639–2013 and was accepted as per the criteria of NS-EN ISO 5817:2014, with imperfection inside quality level B, as shown in Fig. 9a–c. In the proximity case of 5-mm between its weld toes, overlapping of the heat-affected zone cannot be observed, as shown in Fig. 9a; however, no visual changes in the proximity region (metal subjected to successive cycles of heating and cooling) were observed between proximity welds.

3.4.1 Microstructure characterization

Due to the high values in hardness and the drop in Charpy values for the 5-mm weld proximity case, there was a need to further perform microstructure characterization. Optical microstructures across the weld interface, starting from the parent metal to HAZ of weld A, then to proximity region to HAZ of weld B, were analyzed on macro specimen samples of 5-mm weld proximity, as shown in Fig. 10a–d. The

Fig. 3 Schematic of location for Charpy test locations



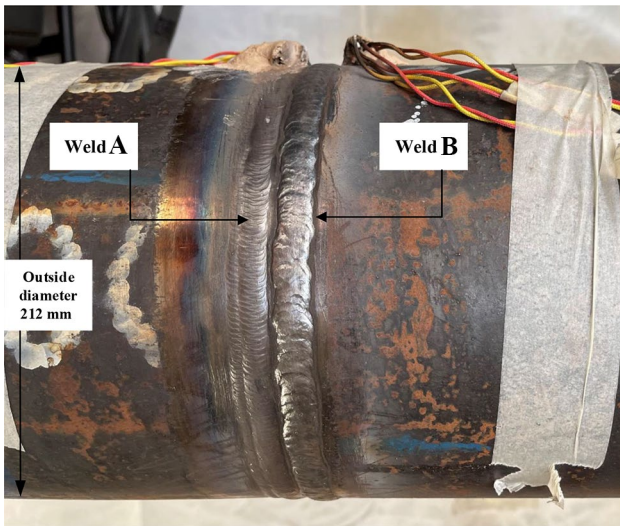


Fig. 4 Visual image of welds A and B

microstructures at HAZ showed acceptable weld interface without any defects; however, different orientation of grains was observed in the region identified as the proximity region/alien metal i.e., between two welds, as shown in Fig. 10d.

Microhardness results at the designated location of HAZ and the proximity area between welds (PA) correspond to values of 225 HV and 210 HV, respectively, as shown in Fig. 6a, for the 5-mm proximity case. Based on this information, the microstructure in HAZ regions can be mainly composed of ferrite (50 to 80%), bainite (0 to 30%), pearlite (0 to 20%), and martensite (0 to 20%) corresponding to Vickers hardness values for steel S355 [23]; refer to Table 7 [25].

The optical images seem to confirm regions of perlite (P) and ferrite (F) in the parent metal, as shown in Fig. 10 a. Acicular ferrite (AF-large light areas) with grain boundary ferrites (GBF) can be observed in weld metal A and B. Depending on the final temperature range attained, HAZ is divided into coarse-grained HAZ (CGHAZ), fine-grained

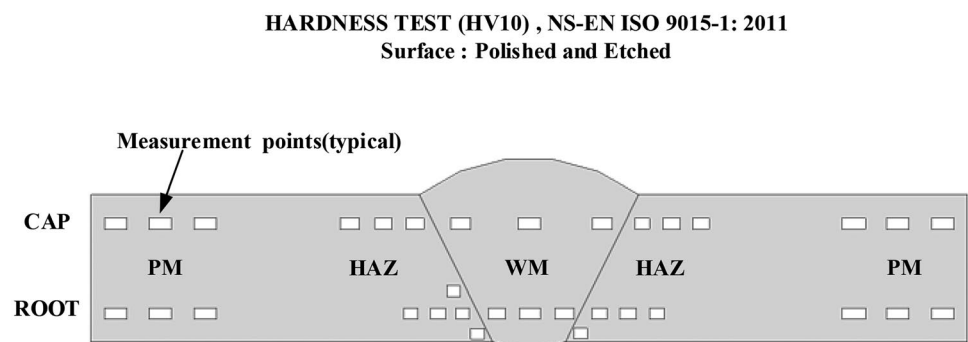
HAZ (FGHAZ), and the inter-critical HAZ (ICHAZ) [12]. In HAZ, the structure is formed upon temperature attained between Ac1 and Ac3, i.e., upper, and lower critical temperatures as shown in Fig. 10 b and d. As the proximity area/alien metal corresponds to a fine-grained structure in contrast to CGHAZ and FGHAZ, it can be identified as a region close to ICHAZ that is subjected to successive cycles of heating and cooling between Ac1 and Ac3 temperatures, i.e., 725–915 °C, with finer grain, as confirmed from thermocouple data.

It is difficult to identify the presence and quantify the fraction of martensite; however, sufficient evidence of martensite-austenite (M-A) islands has been identified in the inter-critically reheated coarse-grained heat affected zone (ICCGHAZ) undergoing partial austenization and forming austenitic-martensitic (M-A) phases, which are brittle and known as local brittle zones (LBZ) [26]. However, their presence needs further investigation by performing scanning electron microscopy (SEM) analysis which will be presented in future research.

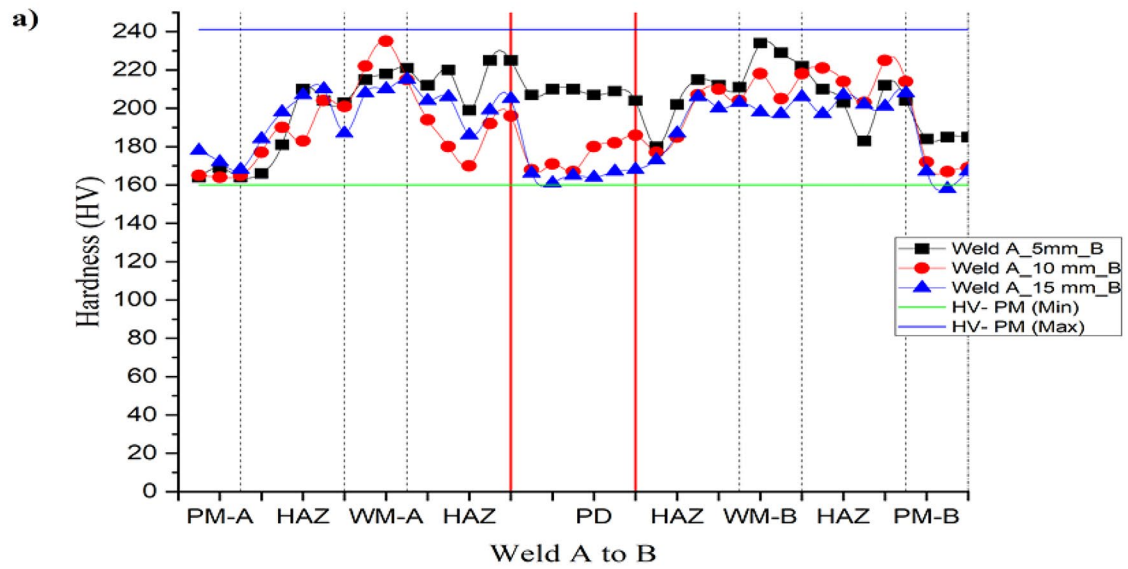
3.5 Tensile and bend tests

Tensile tests were performed for all three weld proximity cases (5-, 10-, and 15-mm), in accordance with ISO 6892–1:2016. Table 8 summarizes the values of all tensile test data along with its fracture location. It was interesting to note that values of tensile strength for the 5-mm weld proximity case were found to be somewhat lower than in the 10- and 15-mm cases. Fracture location could not provide any conclusion, as it changed from outside of weld A or B, i.e., sufficiently far from HAZ and the proximity region. It would have been interesting if failure had occurred between welds for the 5-mm case. However, in the case of 15-mm proximity, fracture occurred between welds in one case. It can be inferred that the 15-mm distance is sufficiently far, and the fracture location can be considered close to the parent metal.

Fig. 5 Hardness measurement point locations at cap and root level



Hardness (HV) mapping _proximity distance of 5, 10 & 15mm at weld cap level



Hardness (HV) mapping _proximity distance of 5, 10 & 15mm at weld root level

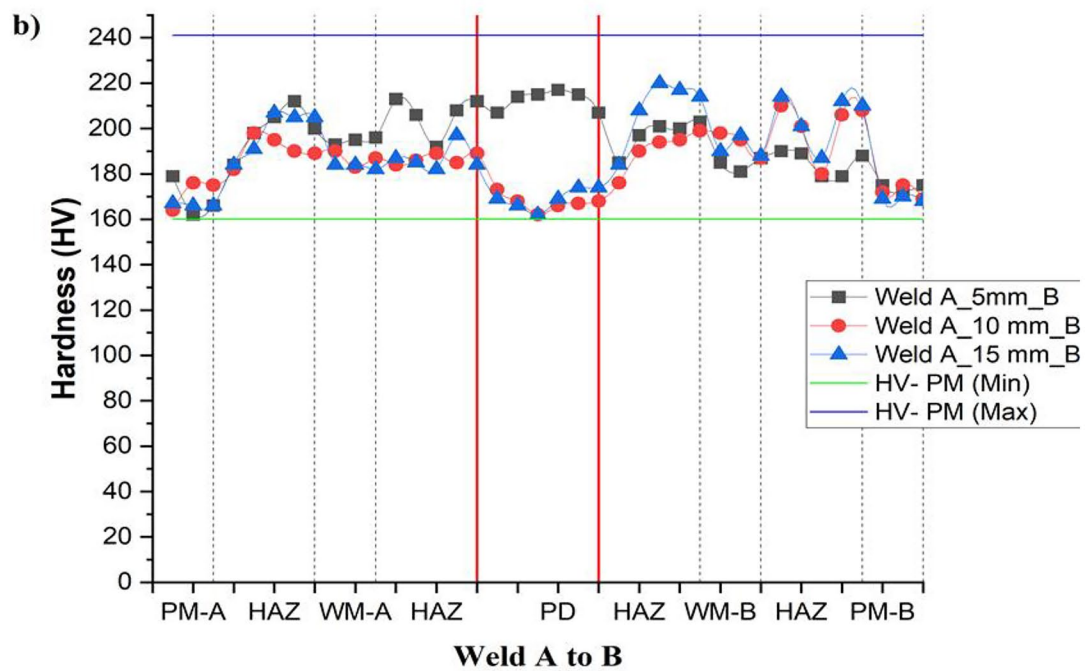
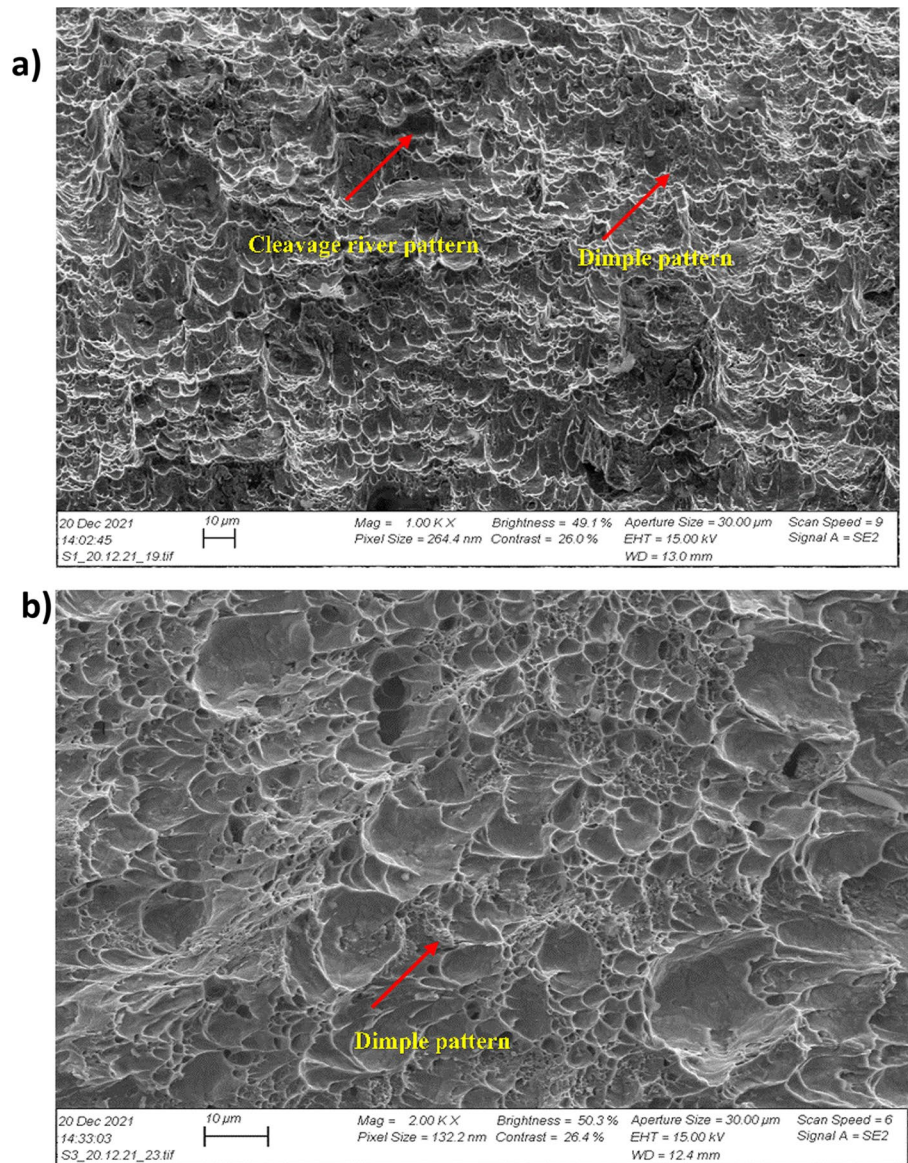


Fig. 6 Vickers hardness profile from left side PM of weld A to right side PM of weld B at a) cap b) root level for proximity distance of 5, 10, and 15 mm, respectively

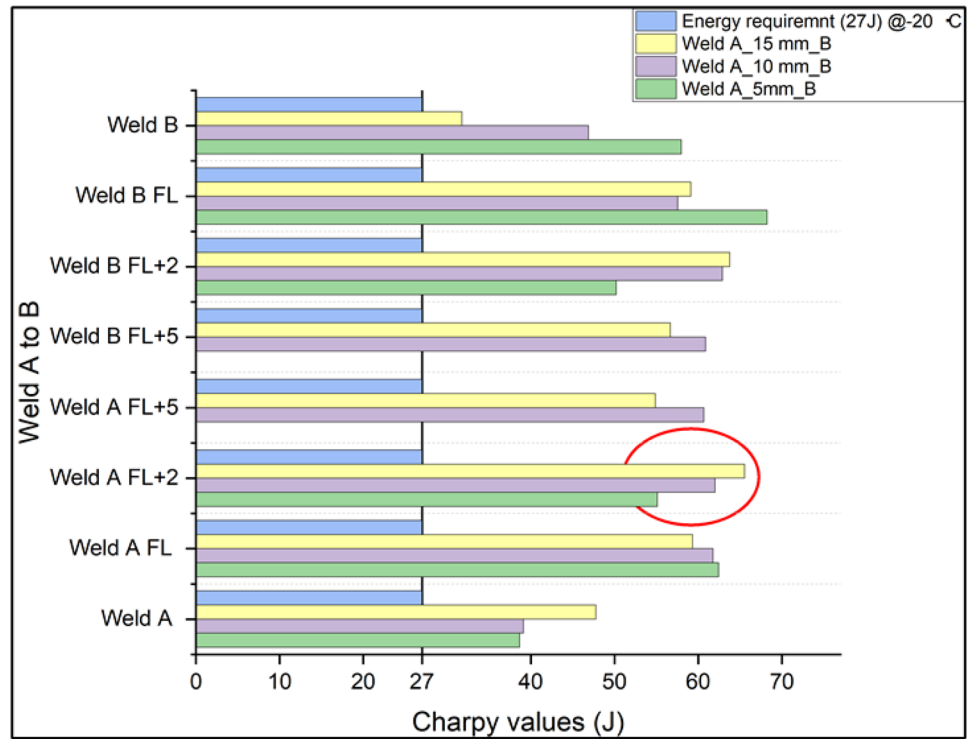
Fig. 7 SEM micrographs of FL + 2 mm fracture surface for proximity distances of **a)** 5, and **b)** 15 mm



Tensile results sufficiently meet the required strength of 460–620 MPa; however, all values were found to be less than the pipe measured value of 553 MPa, as referred to in the material test certificate mentioned in Table 3. Elongation

values in all cases were found to be less than 22%, indicating the high restraint and residual stresses caused by welds placed at proximity.

Fig. 8 Charpy testing values for all proximity distances of 5, 10, and 15 mm



Bend tests were also performed as per EN ISO-5173:2010 at the designated location of root and face, as mentioned in NORSOK M-101 and EN 15,614–2017. For thickness of less than 12-mm, two samples each for face and root bend were tested. For all weld proximity samples

of 5, 10, and 15-mm, testing did not reveal any one single flaw greater than 3-mm in any direction. Flaws appearing at corners of test specimen were ignored, as mentioned in EN 15,614–2017.

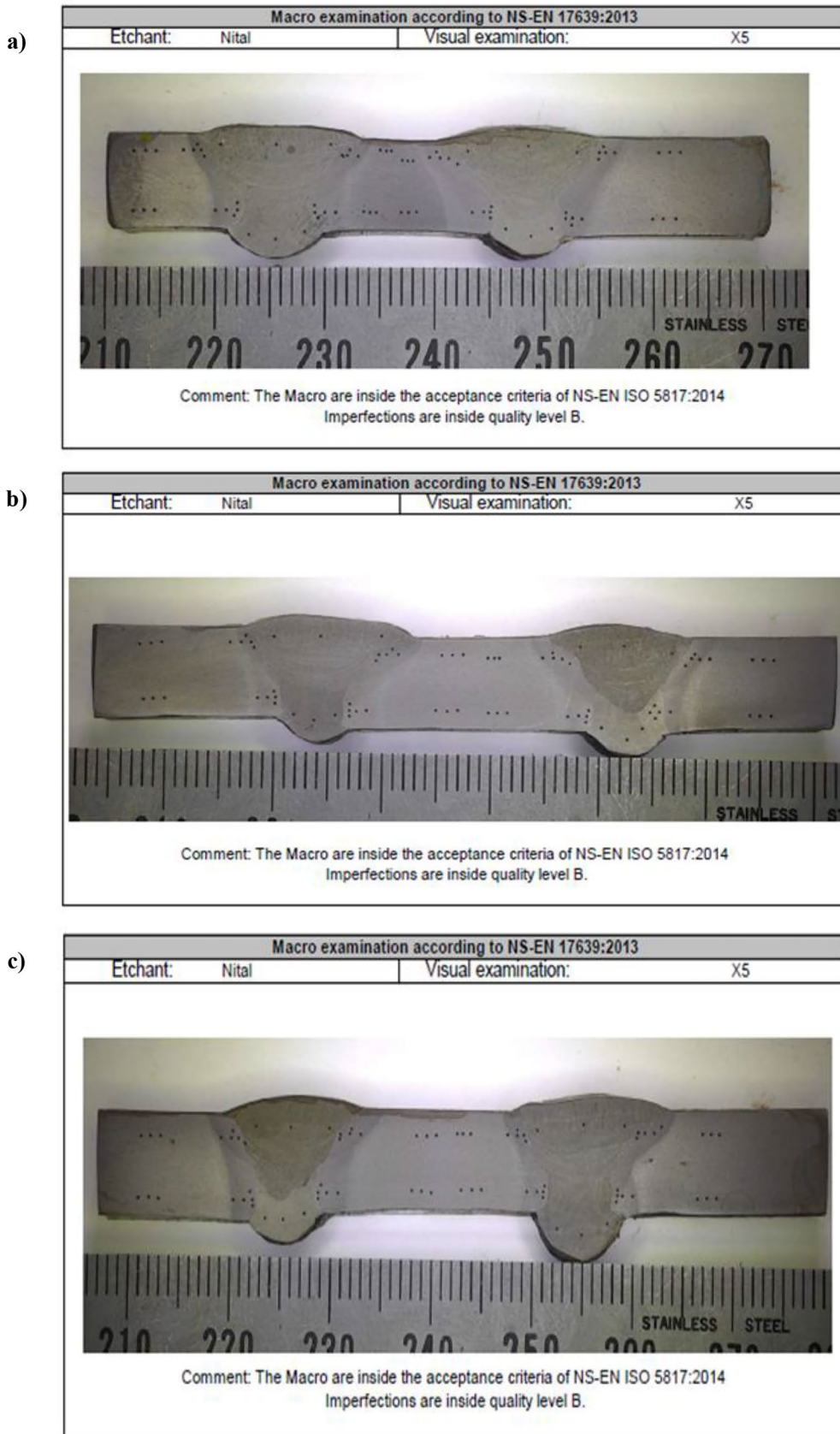


Fig. 9 a–c Macro examination and hardness points location for **a** 5-mm, **b** 10-mm, and **c** 15-mm weld proximity joints

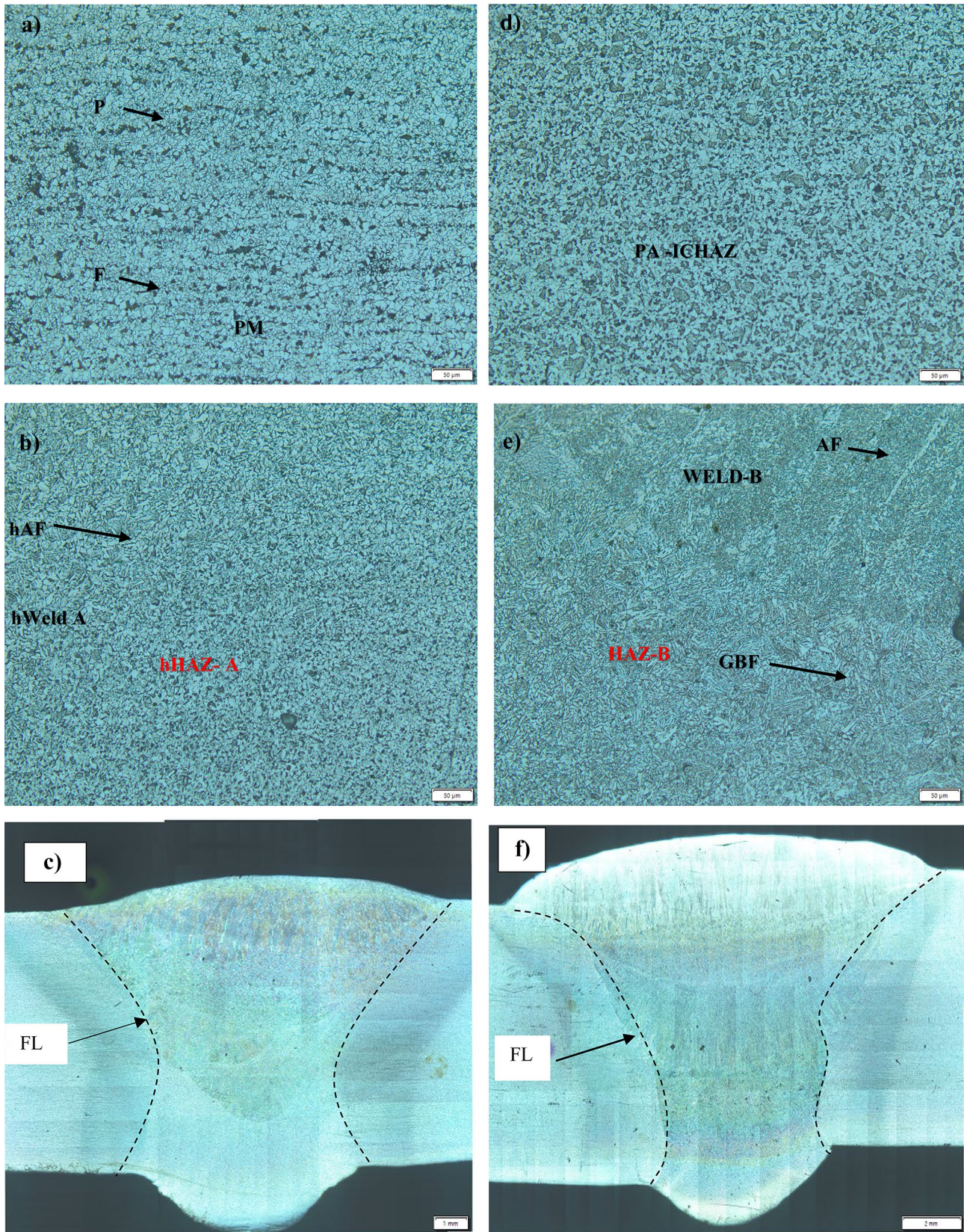


Fig. 10 Optical microstructures for 5-mm weld proximity case **a)** Parent metal (PM), **b)** HAZ of weld A, **c)** Weld A with fusion line (FL), **d)** Proximity area /alien metal between welds (PA), **e)** HAZ of weld B, **f)** Weld B with fusion line (FL)

Table 7 Microstructures and the corresponding Vickers hardness ranges of a low-alloyed steel [25]

Microstructures	Average Vickers hardness (approximately)
Ferrite	84
Austenite	263
Perlite (granular)	211
Perlite (lamellar)	316
Cementite	632–684
Martensite	421–948

Table 8 Examination and tensile testing data for all weld proximity cases

Weld proximity (mm)	No of samples	Test indent	Thickness (mm)	Width (mm)	Area (mm ²)	Tensile (Mpa)	Elongation %	Fracture location
5	2	Cross weld 1	8.61	24.93	214.6473	480	14.71	Basemetal B side
		Cross weld 2	8.16	24.91	203.2656	489	12.93	Basemetal A side
10	2	Cross weld 1	8.41	24.91	209.4931	493	16.31	Basemetal A side
		Cross weld 2	8.12	25.04	203.3248	516	17.36	Basemetal A side
15	2	Cross weld 1	8.2	25.09	205.738	487	12.10	Basemetal between welds
		Cross weld 2	8.58	24.92	213.8136	498	15.59	Basemetal A side

4 Conclusion

Welding procedure qualification record (WPQR) was performed on grade S355 tubular pipes' girth welds with a proximity distance between their weld toes of 5, 10, and 15 mm. Welds were fabricated with two different welding processes, in accordance with the pre-qualified welding procedure specification (WPS). WPQR was performed in accordance with NORSOK M-101, which follows EN 15,614–2017 standard, and all relevant mechanical tests were performed. Based on detailed mechanical evaluation, an increase in Vickers hardness values and a drop in Charpy values for the 5-mm weld proximity case were observed. It is also pertinent to mention here that the drop in elongation values observed in tensile test data in all cases can be attributed to the high restraint and residual stresses caused by welds placed at proximity. It was also inferred from the microstructure characterization that there was the formation of an inter-critically reheated coarse-grained heat affected zone (ICCGHAZ), as verified from thermocouple data, which is prone to cracking due to the presence of austenitic-martensitic (M-A) phases which are brittle and known as local brittle zones (LBZ).

After performing welding qualification on proximity welds, mechanical results justify the need to avoid such

situations, especially when the proximity distance is less than half the thickness of the joining member between adjacent weld toes i.e., 5 mm in this current study. One times the thickness and two times the thickness of the joining member, i.e., 10 mm and 15 mm also used in this current study, did not show any harmful effect, as verified by mechanical test results. The codes and standards also do not provide any recommendation for maintaining minimum proximity distances for repair and replacement welds [12]. The region identified as 'proximity region or alien metal' between adjacent welds requires careful defect assessment and inspection procedures in relation to the compact welded joints found in offshore jacket structures and high restraint situations developed during pipe replacement procedures in compact layouts. Detailed assessment and record keeping of previous welding process parameters and mechanical tests can help in the future qualification of new welding procedures for repair welds placed at proximity. In the future, the authors plan to measure residual stress profiles and fatigue life between proximity welds, for their detailed assessment and to provide practical recommendations to industrial partners for maintaining the minimum distance between proximity welds.

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Availability of data and material All data generated and analyzed during this research are included in this published article.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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