Welding Procedure Qualification Record (WPQR) for Welds Fabricated At Proximity

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Research Article

Keywords: Proximity welds, welding procedure qualification record, NORSOK M-101

Posted Date: November 11th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1015690/v1

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on March 16th, 2022. See the published version at https://doi.org/10.1007/s00170-022-09022-5.

Abstract

Maintaining minimum allowable distance between proximity welds has always been considered a subject of debate between design engineers, welding engineers/inspectors and fabricators/engineering contractors. The scattered nature of guidelines available in welding codes and standards for maintain minimum allowable distance pose 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 a proximity on an S355 steel tubular section having 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 toe as 5, 10 & 15mm 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 mechanical test met minimum specified values as defined in the NORSOK code, research findings revealed 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 successive thermal cycles. These observations can form basis for 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.

1 Introduction

Welding is the most widely accepted method for joining of two structural members with or without the use of filler wire, when it comes to fabrication of steel components, ranging from offshore jacket, floating structures, piping's and pipelines to bridges, aircrafts etc. [1, 2]. In the past many accidents and delays have been related to weld failures, however this issue persists, despite of improvement in welding techniques and inspection procedures[3]. For instance, Alexander L. Kielland offshore accommodation rig failure in constrained geometry of its brace hydrophone support was reported due to insufficient fillet weld size and high residual stress leading to overload of welds and catastrophic fatigue cracking [4]. Recent delay of Equinor's Johan Castberg floating platform, storge and offloading (FPSO's) Hull for Barents Sea has been accredited to faulty welds [5]. Wind turbines fixed and floating types popularity cannot be ignored, as accidents due to cracks in welds are gaining attention in contrast to usually reported cracks in bolt of turbines [6]. Such incidents in large structures cannot be overlooked as consequences due to failure leading to loss of life, climate, and property are very high and irrevocable.

Fabrication of large structure like offshore jacket structures, onshore and offshore wind monopiles and tubular truss bridge structures often brings forward the challenge of welds coming in proximity of each other as shown in figure 1. This challenge of maintaining minimum distance between welds is often debated among designers, inspectors, and contractors who often rely on international codes and standards for recommendations [7]. A detailed assessment of these codes and practices for maintaining minimum distance criteria between welds has been performed previously by the authors in [8] where clear lack of consensus has been found regarding maintaining final distance that is based on factor of 4 or 5 times thickness or 1 or 1.5 times the diameter. In replacement procedures of compact layout of piping racks, unavoidable situation of placement of new weld to an existing weld of branched connections, nozzles etc. are often encountered or in offshore jacket critical joints e.g., overlapping braces. International codes and standards in case of repair or replacement procedure offer no or lack of guidance on defining minimum distance between welds and defining welding procedures for proximity welds are left to engineer and contractors' engineering judgement.

DNVGL-ST-0126 code on support structures for wind turbines [10] recommends a maintaining distance between consecutive girth welds to be not less than 300 mm for outer diameter 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 the area between proximity welds which has experienced multiple cycle of heating and cooling with undefined welding procedures qualifications record (WPQR) and unprescribed residual stresses profiles used in defect assessment prescribed in fitness for service (FFS) codes[11, 12]. The importance of potential factors that degrade welding quality in terms of defects, requires assessment of the most vulnerable welding procedure specifications (WPSs) and imperfection factors that contribute to the majority of defective welds [13]. Pressure vessel research council (PVRC) Phase 2 [14, 15] highlights the over conservativeness in residual stress profiles at a distance away from weld as per FFS codes such as BS7910, API 579 RP-1/ASME FFS-1 etc. Industrial focus is also shifting towards producing intelligent welding procedure qualification system where initial welding procedure parameters are taken as the input values as done by authors in past [16, 17]. With this background the aim of current study was set to define WPQR for two different girth welds, placed at proximity with a minimum distance between their weld toe as 5mm, 10mm & 15 mm respectively. All necessary fabrication procedure and mechanical testing was performed in accordance with NORSOK M-101[18], code for structural steel fabrication by adopting prequalified welding procedure specification (WPS), in collaboration with reputed industrial partners. The remainder of the paper is structured as follows: In Section 2, experimental details are mentioned. Thereafter in Section 3, results are presented and discussed. Subsequently, in Section 4, conclusion is drawn.

2 Experimental Set-up

A schematic diagram of experimental set up shown in figure 2, pictorially display fabrication steps from 'a' till 'f'. Structural steel grade, seamless pipes was selected for this experiment, having dimensions of outside diameter as 219.1 mm and thickness of 8.18 mm. As shown in figure 1.a & d. vee joint geometry was machine cut for welds 'A & B' in accordance with prequalified WPS from M/s Rosenberg Worley. As shown in figure 1.b, initially weld 'A' was fabricated as single weld on a pipe section having an overall length of 700 mm. Weld 'B' was welded after weld 'A' was completed by maintaining a proximity distances between their weld toes as 5mm, 10 mm ad 15 mm respectively as shown in figure 1e and summarized in Table 1.

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 10 15	Tungsten inert gas (TIG)	141	Vee Joint	Argon	PA/1G/Flat
B		Metal Active Gas(MAG)-metal cored +flux cored	138+136	Vee Joint	20% carbon dioxide (CO_2) in pure argon (Ar)	PA/1G/Flat

Welding parameter as per-qualified WPS for weld 'A & B' and digital weld log data maintained during the experiments in this study are mentioned in Table 2 & 3. Mechanical and material composition of tubular pipe and filler wire are also mentioned in Table 4-5. In this current 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) method for root pass, as it employs short circuiting technique for better root penetration and FCAW (136) method for remaining passes for faster production. Weld A all passes were completely fabricated with TIG (141) welding process. This demonstrates the practical situation of critical welded joints which were fabricated under shop conditions by using controlled procedure like TIG and during on site repair or replacement situation, welded with a faster and more mobile procedure like MAG + FCAW.

Table 2
Welding parameters for Weld A, TIG welding process (141)

Pass	Filler (mm)	Welding process	Current (A)	Voltage (V)	Polarity	Travel speed (mm/min)	Gas flow (l/min)	Heat input (kJ/mm)
1	2.4	141	100-135	10-20	DC-	39-40	15-20	1.5-2.49
2	2.4	141	140-180	10-14	DC-	75-80	15-20	1.05-2.02
Fill	2.4	141	160-230	11-15	DC-	85-120	15-20	0.88-2.44
Cap	2.4	141	160-230	11-15	DC-	85-120	15-20	0.88-2.44

Table 3
Welding parameters for Weld B, MAG +FCAW welding process (138+136)

Pass	Filler (mm)	Welding process	Current (A)	Voltage (V)	Polarity	Travel speed (mm/min)	Gas flow (l/min)	Heat input (kJ/mm)
1	1.2	138	90-125	14-16	DC+	65-85	16-20	0.89-1.85
2	1.2	136	160-220	22-29	DC+	180-400	16-20	0.53-2.13
Fill	1.2	136	180-250	22-29	DC+	180-400	16-20	0.59-2.42
Cap	1.2	136	180-250	22-29	DC+	180-400	16-20	0.59-2.42

Table 4
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 5
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

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

NORSOK M-101[18] code used for qualification of WPQR was adopted in this project catering to Norwegian continental shelf (NCS) offshore welded tubular structures used in exploration and processing industry. NORSOK M-101 code for WPQR is strictly valid within the limitations specified in ISO 15614-1[19], widely accepted code for welding qualification around the world. Welding was performed under controlled conditions after optimizing the welding parameters as mentioned in Table 2 & 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 & ISO 15614-1 as mentioned in Table 6.

Table 6
Examination of the test weld for WPQR as per NORSOK M-101

Joint Configuration	**Joint thickness (mm)**	**Mechanical tetsing**			
		Tensile test	**Bend test**	**Charpy V notch**	**Hardness & macro**
Butt welds (Tubular)	t ≤50 mm	2	4	4 sets	1

Visual and radiographic examination was also performed and the general procedure and acceptance criteria mentioned in EN codes code for each method is summarized in Table 7 as per ISO 15614-1[19]. Charpy specification as per EN ISO 9016-2012 was performed however in case of WPQR for proximity weld, Charpy location shown in figure 3 were selected. The notch for Charpy specimens was made as shown in figure 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 case of weld proximity distance of 5mm, six samples and four sets of Charpy locations were extracted as fusion line (FL+5mm) was not possible due to 5mm proximity distance. In proximity case of 10 & 15mm case, total eight samples and four sets were extracted due to sufficient proximity distance.

Table 7
Examination and testing of the test pieces

Activity description	Specification/Procedure	Accpetance 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 17639:2013	EN ISO 5817:2014 B/C
Transverse tensile test	ISO 4136:2012, ISO 6892-1:2016 Method A1	NS-EN 15614-1: 2017, NS-EN 10225:2009
Charpy V Impact test	NS-EN ISO 148-1:2016, ISO 9016:2012	NS-EN 15614-1: 2017, NS-EN 10225:2009
Vickers Hardness test	NS-EN ISO 9015:2011	NS-EN 15614-1: 2017

3 Results And Discussion

3.1 Visual and Radiographic examination

As briefed in Table 7, all mechanical and Non-destructive testing (NDT) was performed in accordance with relevant EN standards. Visual and NDT testing of radiography was performed to 100% extent on each sample of proximity distance. Due to spray mode in MAG+FCAW welding process weld B had wider and irregular cap weld bead in contrast to smooth weld cap bead of weld A, which has welded with TIG process as shown in figure 4. As per acceptance criteria of ISO 10675-2016, both joints were accepted in accordance with NDT radiography testing as shown below in figure 5.

3.2 Macro testing

Macro examination was performed in accordance with NS-EN 17639-2013 and was accepted as per criteria of NS-EN ISO 5817:2014 with imperfection inside quality level B as shown in figure 6.a-c. In proximity case of 5 mm between its weld toes, overlapping of heat affected zone cannot be observed as shown in figure 6.a however no visual changes in alien metal (metal subjected to successive cycle of heating & cooling) were observed between proximity welds.

3.3 Hardness testing

Vickers hardness testing on each case of weld proximty distance of 5, 10 & 15 mm was peformed as per NS-EN ISO 9015-1:2011 as per positions marked shown in figure 7. The indentation marks shown in figure 7 can be seen clearly seen in macro graphs of each weld promxity case in figure 6a-c. As proximity distance was area of concern, hence hardness meassurement points between adjacent weld toes at ‘weld cap level’ for 5 mm proximity is shown in figure 8.a. It can be observed that high hardness values is noticed at proximty distance (PD-A&B) between two weld metal (WM-A&B) and their respective adajacent HAZ-A&B in constrast to parent metal PM as shown in figure 8a. This proximty distance or area called as ‘alien metal’ has experienced microstructural changes due to high restraint and succesive thermal cycles of multipass welds as noticed in [20] for proximty welded joints K -brace joint of offshore jacket structures.

A maximum value of 210HV was observed close to HAZ value of 225HV on either side for proximty distance 5mm welds as shown in figure 8a. Cold cracking chances increases if hardness values are between 350-400HV. This region may be prone to cracking as it has accumlated high stresses and chances of martensitic formation have been sustained due to succesive thermal cycle of heating and cooling[20]. Similar hardness points profiles for weld proximity distance of 10 & 15 mm have been shown in figure 8b & c. As proximity distance is increasing, drop in hardness values can be seen and comparable to PM in case 10& 15mm case. In case of 10 mm proximity distance, highest value of 186 HV was observed at alien metal and 167 HV in case of 15 mm distance which is almost equivalent to parent metal.

3.4 Charpy testing

Charpy testing was performed in accordance with KV8, NS-EN ISO 148-1:2016; ISO 9016:2012. As discussed previously in figure 3, due to limited space for FL+5mm samples only six specimens were available for 5 mm proximity distance whereas FL +5 mm was possible for 10- & 15-mm proximity distance as shown in figure 9. Sample size was kept as 5x10x55 mm as thickness of pipe was 8.2 mm hence a conversion factor of 2/3 was applied, when calculating energy values as per code EN 1614-2017.

It can be observed from figure 10 that the least energy values of 55J at proximity region i.e., weld A-FL+2 mm for 5mm proximity distance was observed in contrast to 10 & 15mm case. To draw fair comparison, FL+2 mm Charpy values are highlighted in figure 10 and values of 62 J & 66 J was observed i.e., between weld A-B for 10 & 15mm case. Due to high hardness and high restraint in 5mm proximity case, drop in energy values can be observed. This drop can be attributed to high hardness values observed in section 3.3. However, microstructure graphs shown in section 3.6 later, also substantiates, that high hardness values at proximity regions for changed morphology of grain size in proximity region.

3.5 Tensile & Bend tests

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

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
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

Figure 11 illustrates the tensile plots for all weld proximity cases tested under monotonic loading. Tensile results sufficiently meet the required strength of 460-620 MPa, however all values were found to be less than pipe measure value of 553 MPa referred from material test certificate mentioned in Table 5. Elongation values in all cases were found to be less than 22% indicating the high restrain and residual stresses caused by welds placed at proximity.

Bend tests were also performed as per EN ISO-5173:2010 at designated location of root and face as mentioned in NORSOK M-101 & EN 15614-2017. For thickness less than 12 mm, two samples each for face and root bend are tested. During testing for all weld proximity samples of 5, 10 & 15 mm did not reveal any one single flaw greater than 3 mm in any direction. Flaws appearing at corners of test specimen are ignored as mentioned in EN 15614-2017.

3.6 Microstructure characterization

Due to high values in hardness and drop in Charpy values for 5mm weld proximity case a need to further investigation of microstructure characterization was initiated. Optical microstructures across the weld interface starting from parent metal to HAZ of weld A to proximity region to HAZ of weld B was performed on macro specimen samples of weld proximity 5mm specimen as shown in figure 12a-d. The microstructures at HAZ showed acceptable weld interface without any defects however different orientation of grains was observed in region identified as proximity region/alien metal i.e., between two welds as shown in figure 12c.

Microhardness results at designated location of HAZ and proximity area between welds (PA) corresponds to values of 225 HV close to 210 HV respectively as shown in figure 8a. Based on this information, microstructure in HAZ regions can be mainly composed of composed of ferrite (50 to 80%), bainite (0 to 30%), pearlite (0 to 20%), martensite (0 to 20%) corresponding to Vickers hardness values for steel S355[20] referred from Table 9 [21]

Table 9
Microstructures and the corresponding Vickers hardness ranges of a low-alloyed steel[21]

Microstuctures	Average Vickers Hardness (approximately
Ferrite	84
Austenite	263
Perlite (granular)	211
Perlite (lamellar)	316
Cementite	632 - 684
Martensite	421 - 948

The optical images seem to confirm regions of perlite (P) and ferrite (F) in parent metal as shown in figure 12 a. Acicular ferrite (AF-large light areas) with grain boundary ferrites (GBF) can be observed in weld metal A& B. HAZ depending upon temperature range is divided intocoarse-grained HAZ (CGHAZ), fine-grained HAZ (FGHAZ), and the inter-critical HAZ (ICHAZ) [8]. In HAZ, structure is formed upon temperature attained between Ac1 and Ac3 i.e., upper & lower critical temperatures as shown in figure 12 b & d. As proximity area/ alien metal corresponds to fine grained structure in contrast to CGHAZ & FGHAZ hence it can be identified as a region close to ICHAZ that's is subjected to successive cycle of heating and cooling between Ac1 and Ac3 temperatures i.e., 725-915°C with finer grain as confirmed form thermocouple data.

Martensite presence is difficult to identify and quantify its fraction however sufficient evidence of martensite -austenite (M-A) islands have been identified in inter-critically reheated coarse-grained heat affected zone (ICCGHAZ) undergoing partial austenisation and forming austenitic-martensitic (M-A) phases which are brittle and known as local brittle zones (LBZ) [22]. However, their presence needs further investigation by performing scanning electron microscopy (SEM) analysis.

4 Conclusion

Welding procedure qualification record (WPQR) was performed on grade S355 tubular pipes girth welds having a proximity distance between its weld toes of 5, 10 & 15mm. Welds are fabricated with two different welding process in accordance with pre-qualified welding procedure specification (WPS). WPQR was performed in accordance with NORSOK M-101which follows EN 15614-2017 standard, and all relevant mechanical tests were performed. Based on detailed mechanical evaluation, increase in Vickers hardness values, and drop in Charpy values for 5mm weld proximity case was observed. It is also pertinent to mention here that drop in elongation values in all cases can be attributed to the high restraint and residual stress caused by welds placed at proximity. It was also inferred from microstructure characterization that there was formation of fine grains at proximity region between welds for 5mm distance which has experienced multiple cycle of heating and cooling.

This region identified as 'proximity region or alien metal', requires careful assessment in defect assessment and inspection procedures in relation to compact welded joints found in offshore jacket structures and high constraint situation developed during pipe replacement procedures in compact layouts. Detailed assessment and record keeping of previous welding procedure input welding parameters and mechanical tests can help in future qualification of new welding procedures for welds placed at proximity and provide technical justifications and guidelines to engineers, inspectors, and contractors for maintaining minimum distance between welds. Authors plans to measure residual stress profiles and fatigue life between proximity welds for detailed assessment in their future work. Data collected from welding procedure for such critical qualifications can also form basis for intelligent qualification of welding procedures and risk assessment by use of machine learning.

Declarations

Acknowledgment

This work has been carried out as part of a PhD research project, performed at the University of Stavanger, Norway. We would like to acknowledge the support of M/s Rosenberg Worley, Stavanger, Q-lab Forsand, and University of Stavanger, Norway lab engineer, Jan-Tore Jakobsen for their support in fabrication and testing of samples. The research is fully funded by the Norwegian Ministry of Education.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Norrish J (2006) 1 - An introduction to welding processes, in Advanced Welding Processes, J. Norrish, Editor, Woodhead Publishing. p. 1-15
2. Ratnayake RMC, Brevik VA (2014) Experimental Investigation of Underwater Stud Friction Stir Welding Parameters. Mater Manuf Process 29(10):1219–1225. DOI: 10.1080/10426914.2014.930891
3. Ratnayake RM (2013) An algorithm to prioritize welding quality deterioration factors: A case study from a piping component fabrication process. International Journal of Quality & Reliability Management 30. DOI: 10.1108/02656711311325584
4. Lotsberg I (2016) Fatigue Design of Marine Structures. Cambridge University Press, Cambridge
5. Link M (2021) Equinor: Several Factors Behind Faulty Welds on Johan Castberg FPSO Hull. Available from: https://www.marinelink.com/news/equinor-several-factors-behind-faulty-486965#.YH4FKi90m_8.linkedin[cited 2021 29/09/2021]
6. Talkshop Ts (2014) 100m Turbine collapse: Not bolts this time – weld failure in the main tower. Available from: https://tallbloke.wordpress.com/2014/12/17/100m-turbine-collapse-not-bolts-this-time-weld-failure-in-the-main-tower/[cited 2021 29/10/2021]
7. Larsson M, Larsson M, Ratnayake RM (2021) Investigation of Fatigue Strength Behaviour in Dual Weld S420 Steel Joints Fabricated at a Close Proximity. 10.1007/978-981-15-9121-1_27
8. Bhardwaj S, Ratnayake RMC (2020) Challenges due to Welds Fabricated at a Close Proximity on Offshore Structures, Pipelines, and Piping: State of the Art. in ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering. DOI: 10.1115/omae2020-18586
9. NORSOK (2021) Design of steel structures N-004. Norway, Standards Norway
10. DNVGL (2018) DNVGL-ST-0126. DNVGL
11. Larsson M, Larsson M, Ratnayake RM (2021) Experimental Investigation of Weld Joints Manufactured at Close Proximity in S420 Structural Steel. 10.1007/978-981-15-9121-1_25
12. Larsson M et al (2021) Experimental Residual Stress Investigation of Weld Joints Fabricated at a Close Proximity in S420 Structural Steel. 10.1007/978-981-15-9121-1_26
13. Ratnayake RM (2014) A methodology for assessing most vulnerable welding procedure specifications and imperfection factors. International Journal of Data Analysis Techniques and Strategies 6:362–383. DOI: 10.1504/IJDATS.2014.066606
14. Bhardwaj S, Chandima Ratnayake RM (2020) Residual stress estimation in defect assessment procedures at weld toe and away locations on girth welds: Review of key parameters. 102848. https://doi.org/10.1016/j.tafmec.2020.102848

15. Dong P et al (2014) On residual stress prescriptions for fitness for service assessment of pipe girth welds. International Journal of Pressure Vessels and Piping 123–124:19–29. DOI: https://doi.org/10.1016/j.ijpvp.2014.07.006
16. Zhan X et al (2016) The feasibility of intelligent welding procedure qualification system for Q345R SMAW. The International Journal of Advanced Manufacturing Technology 83(5):765–777. DOI: 10.1007/s00170-015-7295-8
17. Mathew J et al (2018) "Prediction of welding residual stresses using machine learning: Comparison between neural networks and neuro-fuzzy systems". Applied Soft Computing 70:131–146. DOI: https://doi.org/10.1016/j.asoc.2018.05.017
18. NORSOK (2011) M-101 Structural steel fabrication: Norway
19. 15614-1 E (2017) Specification and qualification of welding procedures for metallic materials — Welding procedure test
20. Acevedo C (2011) Influence of Residual Stresses on Fatigue Response of Welded Tubular K-Joints. EPFL
21. ISF WaJI (2004) Chapter 4-Classification of Steels. Welding of Mild Steels
22. Lomozik M (2000) Effect of the welding thermal cycles on the structural changes in the heat affected zone and on its properties in joints welded in low-alloy steels. Weld Int 14(11):845–850. DOI: 10.1080/09507110009549281

Figures

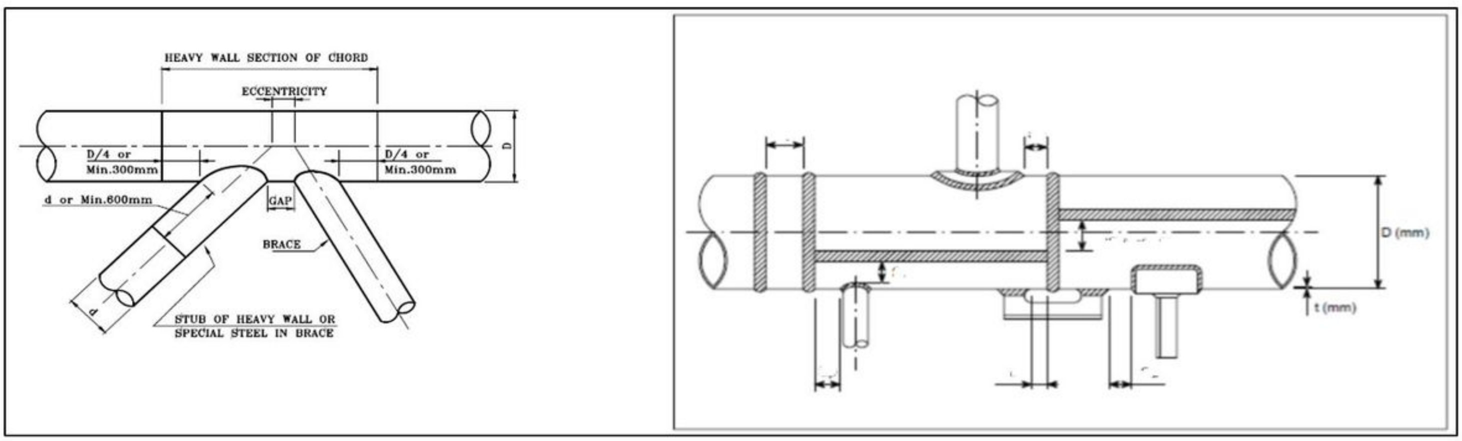


Figure 1

a) Detail of offshore joints [9] b) Minimum distance between welds in pressure vessels

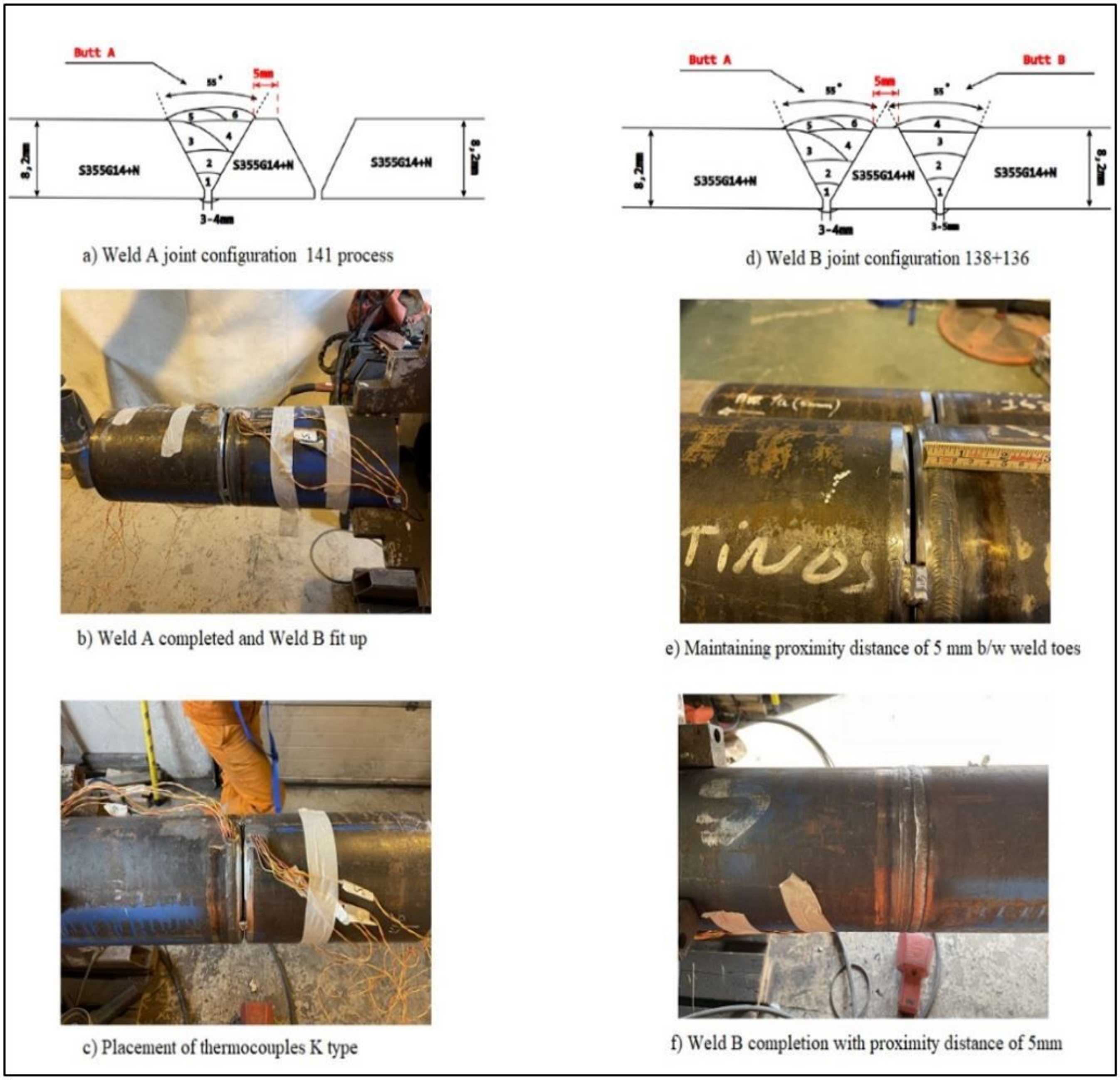


Figure 2

Schematic diagram of experimental set up from a) to f)

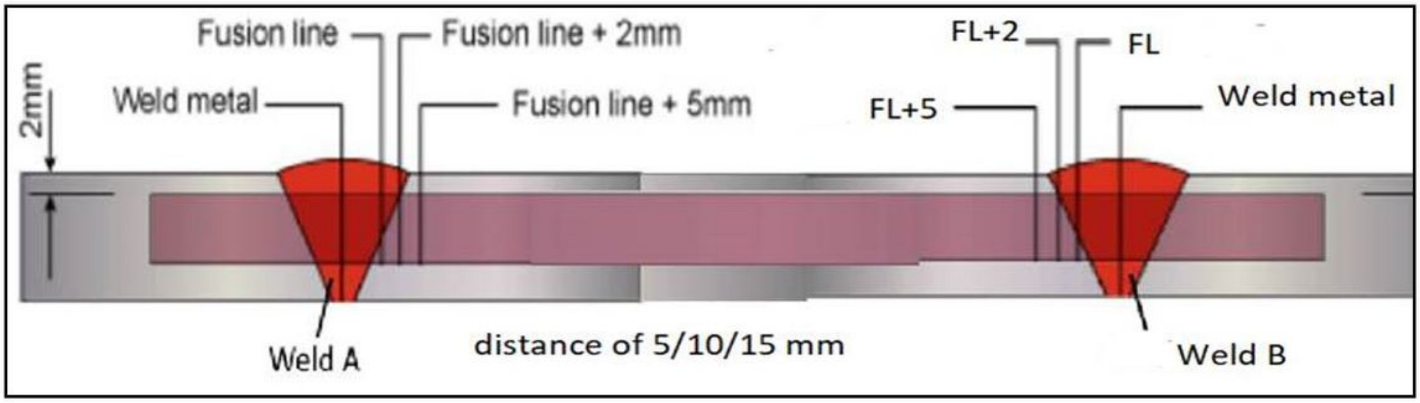


Figure 3

Schematic of location for Charpy tests

Figure 4

Visual image of Weld A & B

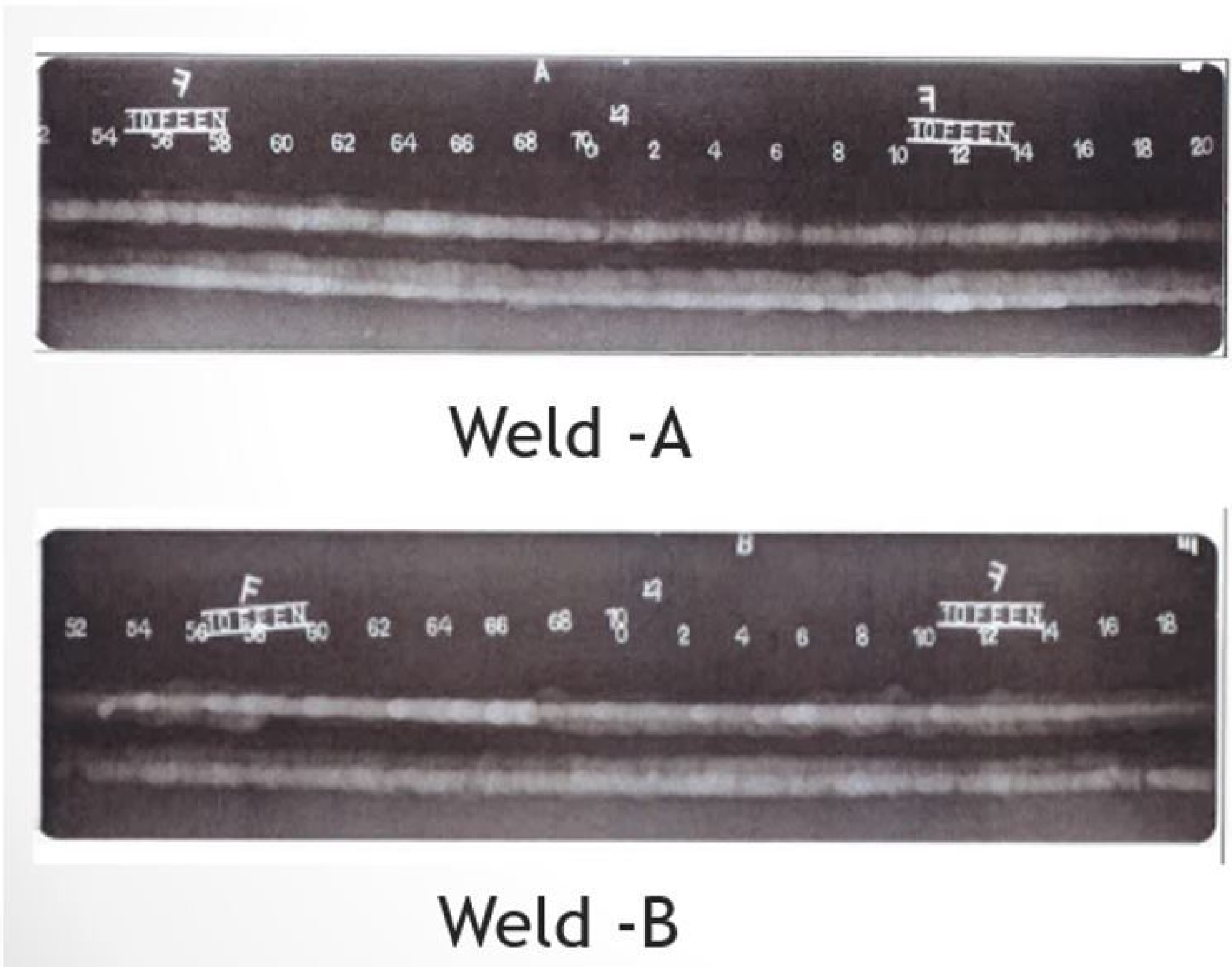


Figure 5

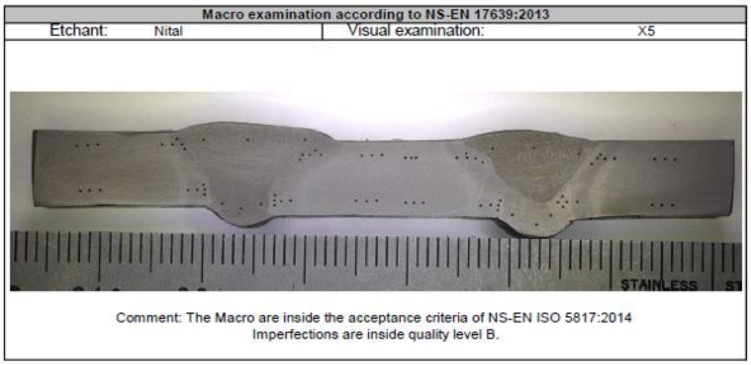
Radiographic images for Weld A and B

Macro examination according to NS-EN 17639:2013

Etchant: Nital | Visual examination: X5

Comment: The Macro are inside the acceptance criteria of NS-EN ISO 5817:2014
Imperfections are inside quality level B.

Fig 6a.



Macro examination according to NS-EN 17639:2013

Etchant: Nital | Visual examination: X5

Comment: The Macro are inside the acceptance criteria of NS-EN ISO 5817:2014
Imperfections are inside quality level B.

Fig 6b

Macro examination according to NS-EN 17639:2013

Etchant: Nital | Visual examination: X5

Comment: The Macro are inside the acceptance criteria of NS-EN ISO 5817:2014
Imperfections are inside quality level B.

Fig 6c.

Figure 6

a. Macro examination and hardness points location for 5 mm weld proximity b. Macro examination and hardness points location for 10 mm weld proximity c. Macro examination and hardness points location for 15 mm weld proximity

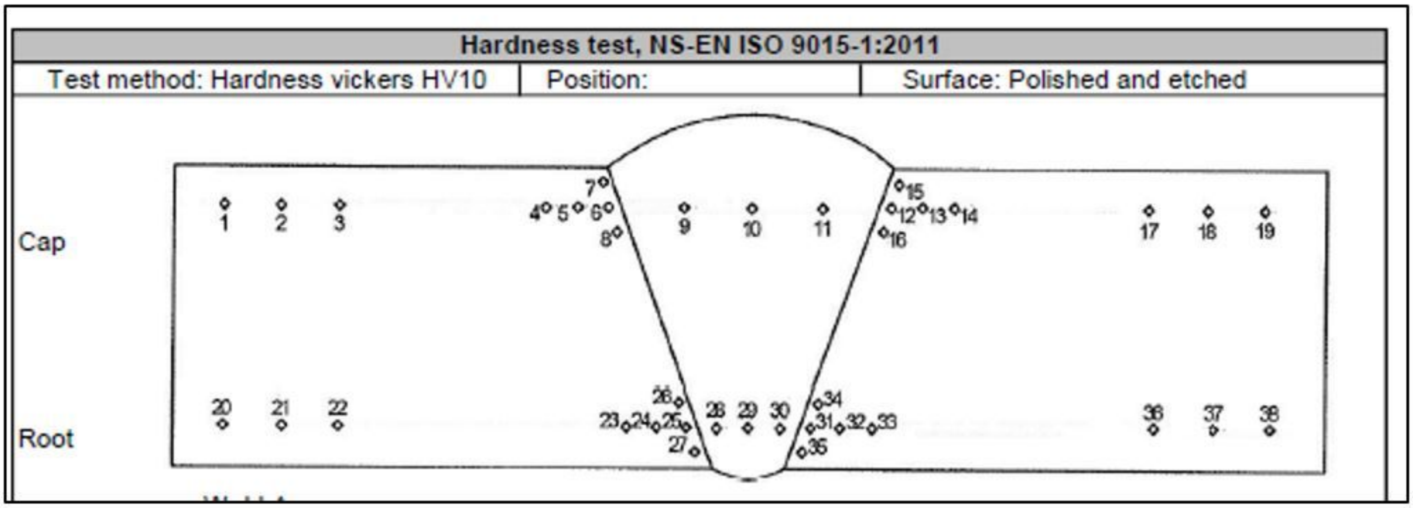


Figure 7

Hardness measurement points horzintally at cap and root level

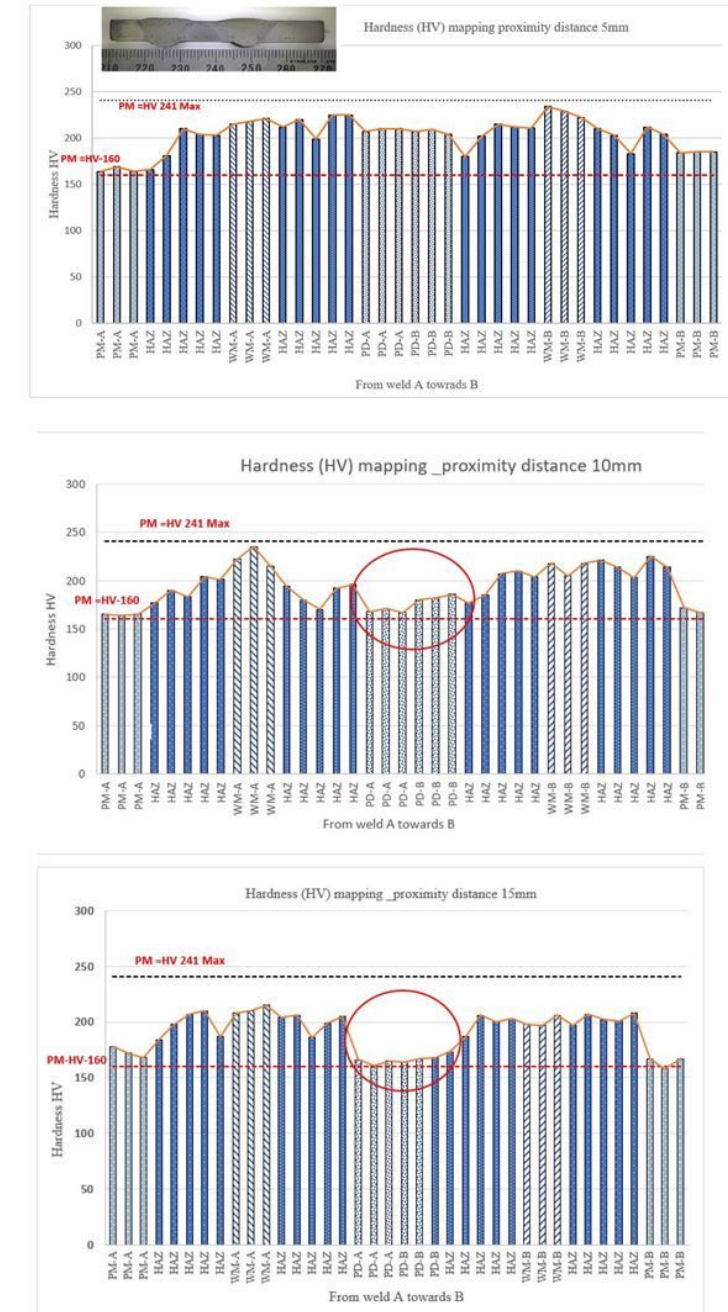


Figure 8

a. Vickers hardness profile from left side PM of weld A to right side PM of weld B at cap level for proximity distance of 5mm b. Vickers hardness profile from left side PM of weld A to right side PM of weld B at cap level for proximity distance of 10mm c. Vickers hardness profile from left side PM of weld A to right side PM of weld B at cap level for proximity distance of 15mm

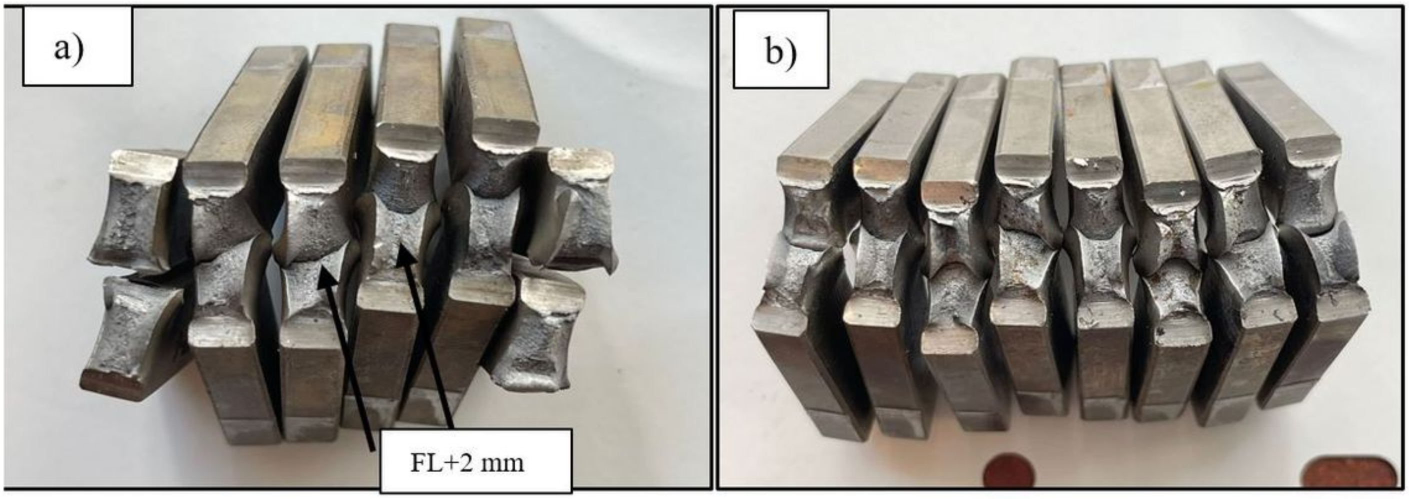


Figure 9

Charpy tested samples at -20◦ C for a) 5mm and b)10&15mm case

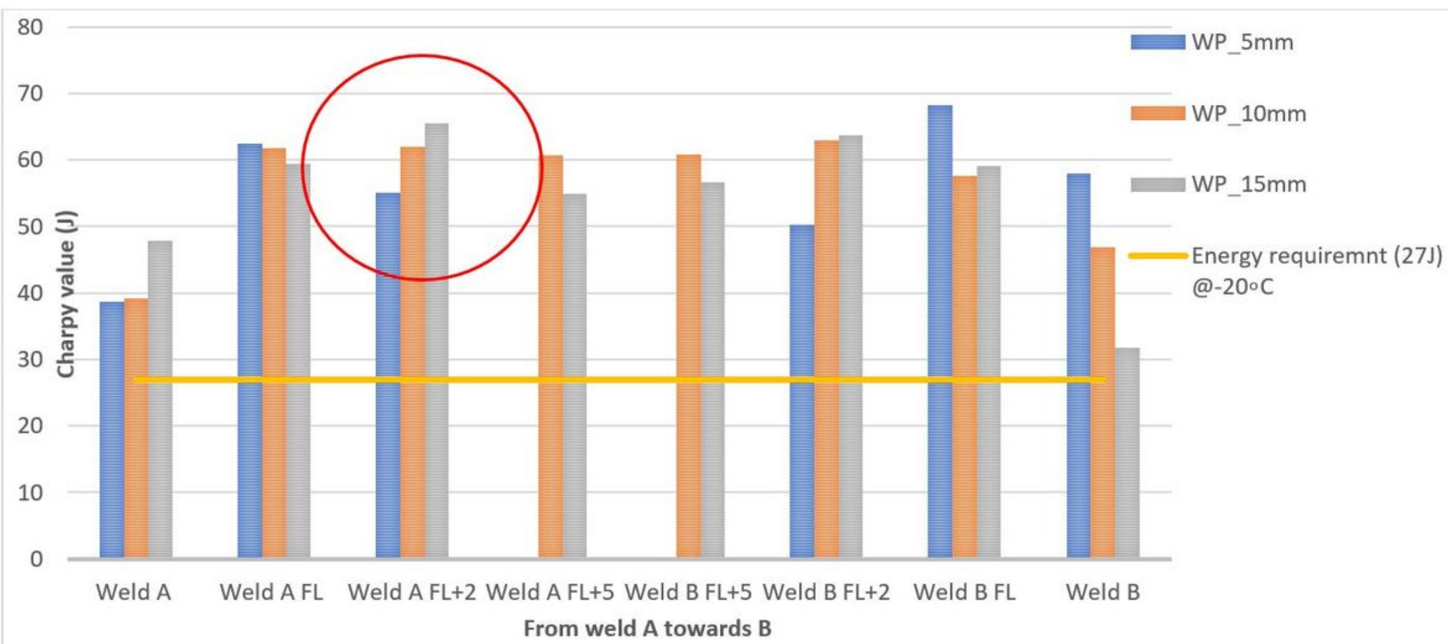


Figure 10

Charpy testing values for all proximity distances of 5, 10 & 15 mm

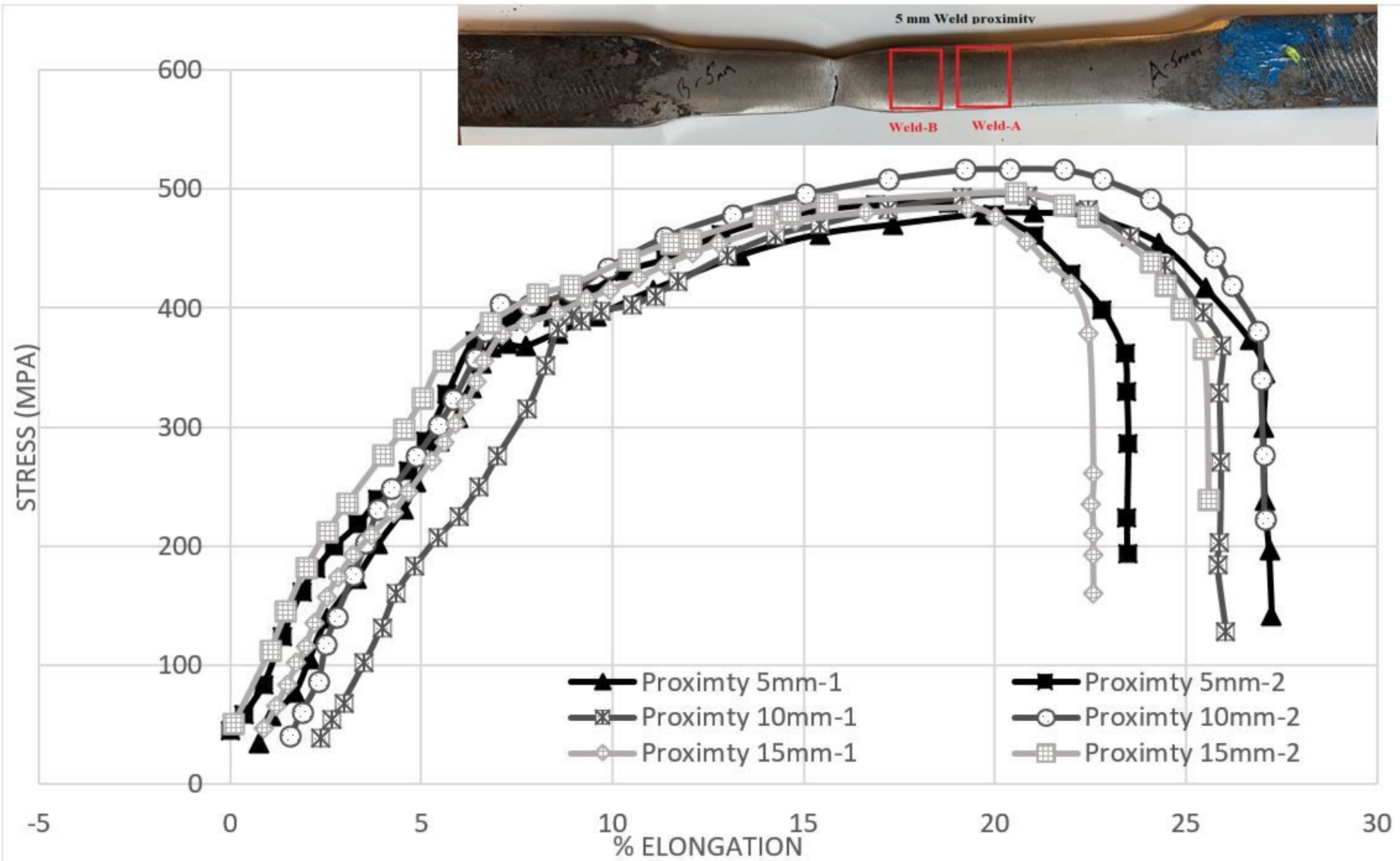


Figure 11

Tensile test plots for transverse weld joints for all proximity cases

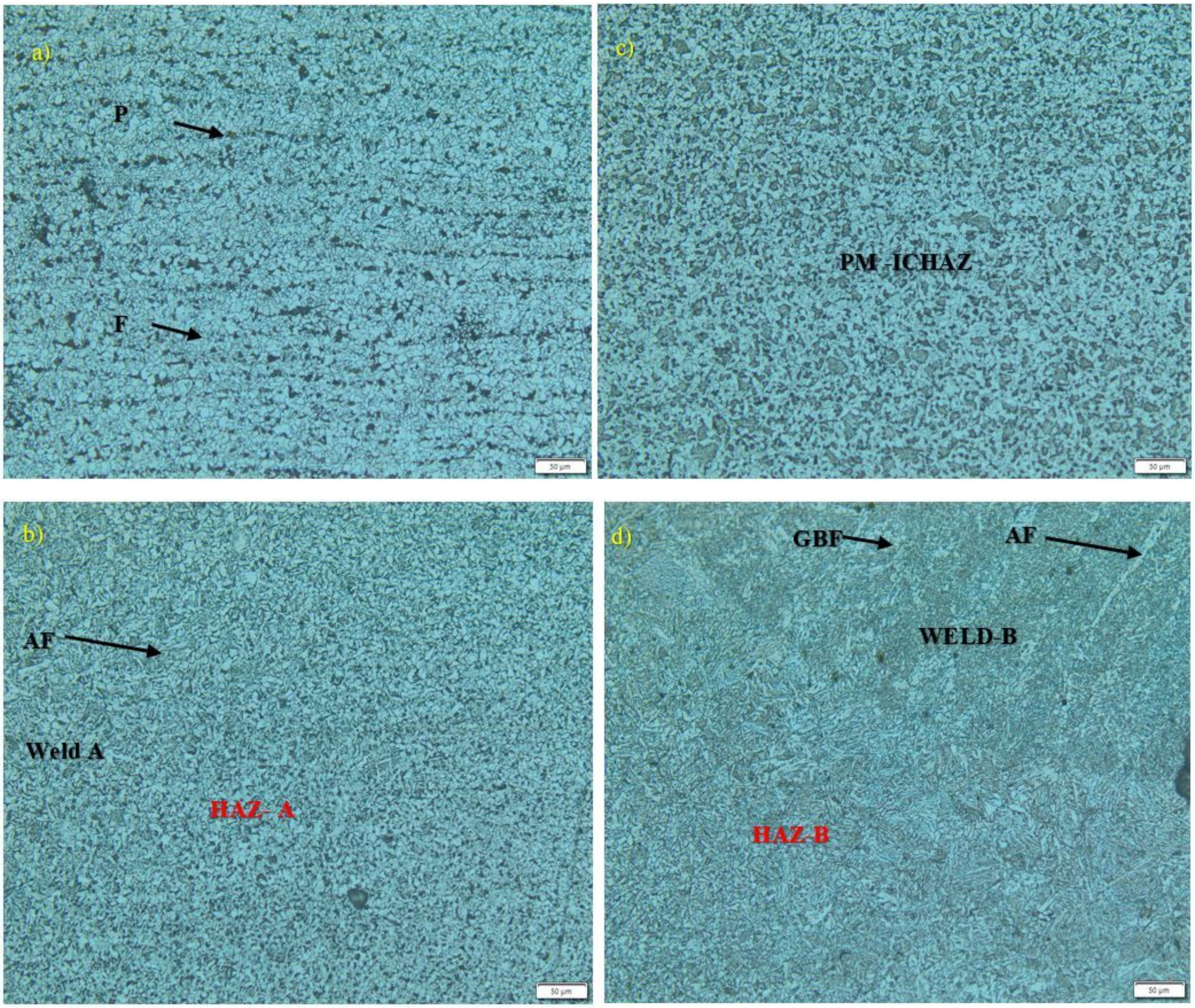


Figure 12

Optical microstructures for weld proximity 5mm case a) Parent metal (PM) b) HAZ of weld A c) Proximity area /alien metal between welds (PA) d) HAZ of weld B