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High-Performance Methods for Welding Steel P460NL2

Abstract: The article discusses comparative test results concerning two welding methods, i.e. SAW and MAG. The tests involved the making of welded joints in steel P460NL2, the verification of the chemical composition of supplied steel, the comparison of the quality of joints (in accordance with PN-EN ISO 5817) as well as the performance of macroscopic tests and the comparison of mechanical properties and hardness.

Keyword: pressure steel P460NL2, MAG welding, SAW welding, comparison

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Introduction

Nowadays it is possible to observe increasingly high requirements concerning structural steels, particularly as regards their yield point, weldability and brittle crack resistance. Another challenge is connected with the necessity of providing increased welding efficiency. Growing market-dictated demands force technologists and design engineers to use more effective welding methods, ensuring high process efficiency without compromising good properties of joints [1–2].

One of the solutions is the use of high-performance welding methods to join structures where submerged arc is applied to make long joints having simple geometry, whereas MAG welding technology is used to weld elements of complex shapes [3]. At the same time, efforts are made to provide the wider possibility of welding crucial structures using both of the above-named methods interchangeably [4]. Presently, the two methods are used in the fabrication of pressure vessels and equipment made of low-alloy steel P460NL2. Structural low-alloy steels are characterised by high metallurgical purity, particularly in terms of non-metallic inclusions. The precise adjustment of chemical composition as well as maintaining the special regime of steel production combined with technological process control enable the making of steels characterised by various processing and functional properties [5].

Structural low-alloy steel P460NL2 is used to make products exposed to high pressure and, additionally, low temperature (e.g. pressure vessels, tankers or large-diameter pipelines). Steel P460NL2 is characterised by relatively good weldability, yet to prevent hot cracking, it is subjected preheating up to a temperature of min. 100°C [3–6].

Objective of study

The study and related tests aimed to compare two welding methods when making butt joints in steel grade P460NL2. Elements were analysed in relation to their mechanical properties, the quality of joints made in accordance with the PN-EN ISO 5817 standard, as well as a

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heat input and a time needed to make one running metre of the weld. The welding methods subjected to analysis and involving the use the consumable electrode were the MAG method and the SAW method (submerged arc welding involving the use of the solid electrode wire). All of the joints were subjected to visual, metallographic macroscopic tests as well as strength tests, i.e. tensile tests, bend tests, impact strength tests and hardness measurements.

Test materials

Base materials used in the tests were 13.4 mm thick plates (140 mm × 600 mm) made of steel P460NL2. The initial stage of the tests involved the verification of the chemical composition of the base material. The chemical composition analysis results were compared with the requirements specified in the PN-EN 10269-1:2014 standard. The chemical composition analysis (verifying contents of C, Mn, Si, P, S, Cr, Cu and Ni and involving two fragments of the base material of the steel plates) was performed using a Q4 TASMAN spark emission spectrometer (BRUCKER).

The MAG welding was performed using the Ultra Mag G4Si1 electrode wire (EN ISO 14341-A-G 46 5 M 4Si1/G 46 3 C 4Si1) (Lincoln Electric), used in the MAG and TIG welding of structural, pressure, boiler and ship steels. The tensile strength of the weld deposit amounted to more than 590 MPa. The shielding gas was the standard mixture of M21 82% Ar+18% CO_2 (EN ISO 14175-M21-ArC-18). The shielding gas flow rate amounted to 15 dm3/min. The SAW process was performed using the OE SD3 1Ni 0.5 Mo electrode wire (OERLIKON) (EN ISO 14171-A-S3Si), used in the welding of structures exposed to elevated temperature (e.g. high-pressure boilers, pipes, steam turbine housings, steam chambers, pressure vessels and heat exchangers). The metallurgical shielding was provided by the OP 121TT flux (OERLIKON) (EN ISO 14174: SA FB 1 55 AC H5), i.e. fully basic agglomerated flux used in submerged arc welding. The above-named flux is widely used in the welding of steel structures and fine-grained low-alloy steels, where high weld integrity, toughness at low temperatures and crick resistance are required.

Technological welding tests

All of the welding tests were performed at Sieć Badawcza Łukasiewicz – Instytut Spawalnictwa. The MAG joints were made using the Lincoln Electric POWER WAVE 455M/STT welding power source having a maximum welding current of 500 A. The SAW joints were made using a submerged arc welding station composed of an A2 Multitrac welding tractor (ESAB) featuring a welding head connected with a drive unit and a flux feed system and a digital ESAB A2-A6 PEK control system (Fig. 1). The welding unit was powered by an ESAB LAF 1001 welding power source.

The joints were made of 13.4 mm thick plates (600 mm ×140 mm) subjected to mechanical treatment and cleaning. The longer edge

Table 1. Results of the chemical composition analysis concerning the test steel and the requirements of the standard in relation to contents of alloying elements

	Contents of alloying element (% by weight)								
Specimen material P460NL2	C	Mn	Si	P	S	Cr	Cu	Ni	Mo
PN-EN 10269-1:2014 requirements	max. 0.20	1.10-1.70	max. 0.60	max. 0.020	max. 0.005	max. 0.30	max. 0.70	max. 0.80	max. 0.10
Test results	0.19	1.48	0.41	0.012	0.0005	0.045	0.01	0.01	0.01

subjected to MAG welding was previously subjected to X-groove joint preparation (Fig. 2). The X-groove joint preparation was also used in relation to the submerged arc welding process, yet the width of the threshold amounted to 5 mm (Fig. 3).

The welding process technological parameters in relation to the two welding methods are presented in Tables 3–4.

Methodology and test results

The first stage of the tests involved the performance of visual tests aimed to assess the quality

Fig. 1. Welding tractor (A2 Multitrac ESAB)

Fig. 2. Plates used in MAG welding: a) schematic diagram presenting the processing of the plates along with dimensions, b) top view, c) plates after mechanical treatment with X-groove joint preparation

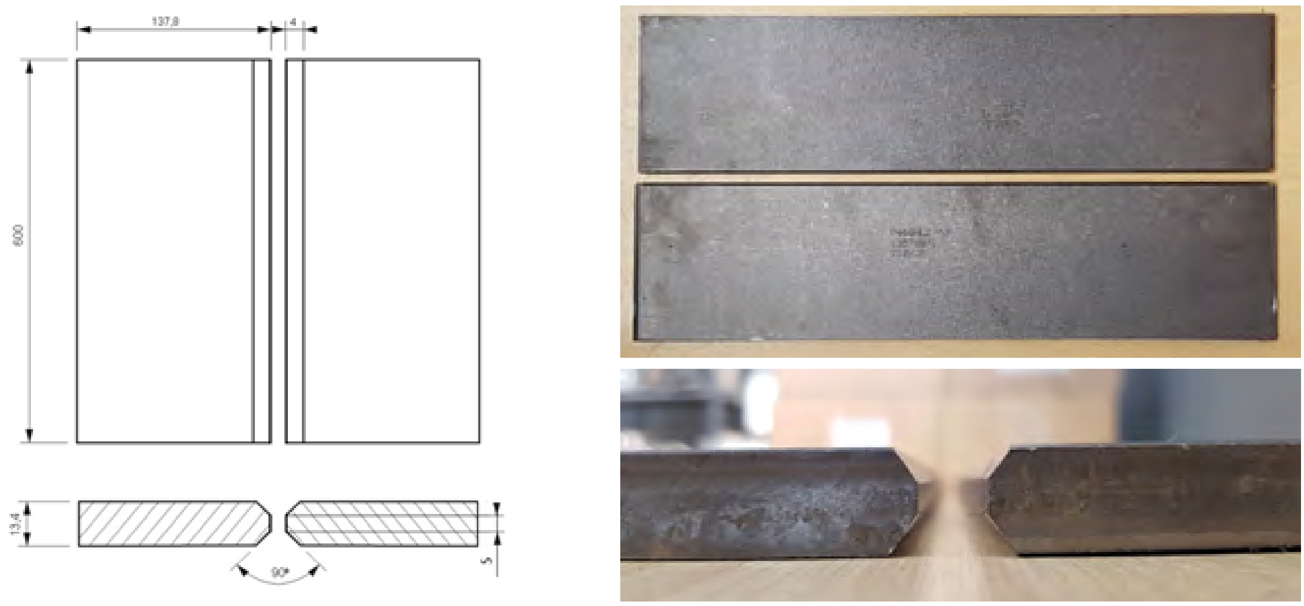


Fig. 3. Plates used in the SAW process: a) schematic diagram presenting the processing of the plates along with dimensions, b) top view, c) plates after mechanical treatment with X-groove joint preparation; threshold h=5 mm

Table 3. Process parameters used in MAG welding

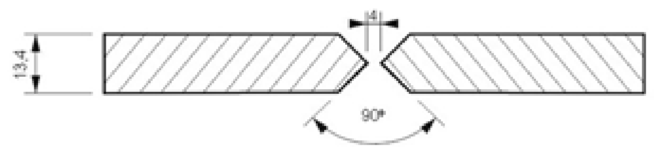
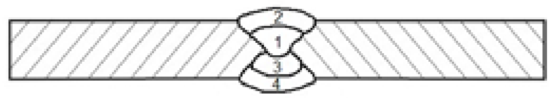
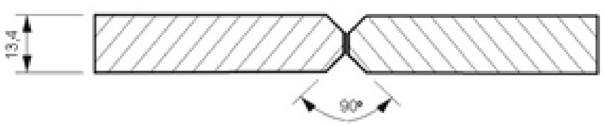
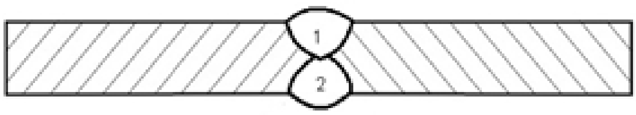
Welding preparation (sketch)										
Joint structure						Welding sequence				
										
Run	Welding process	Filler metal size, mm	Current [A]		Arc voltage [V]	Current type/ polarity	Filler metal wire feed rate [m/min]	Travel rate [cm/min]	Heat input [kJ/mm]	
			min.	max.					min.	max.
1	135	1.2	150	160	18.0	DC/+	4.0	22.0	0.59	0.63
2-4	135	1.2	210	220	18.0	DC/+	6.5	35.0	0.52	0.54

Table 4. Process parameters used in submerged arc welding

Welding preparation (sketch)										
Joint structure						Welding sequence				
										
Run	Welding process	Filler metal size, mm	Current [A]		Arc voltage [V]	Current type/ polarity	Filler metal wire feed rate [m/min]	Travel rate [cm/min]	Heat input [kJ/mm]	
			min.	max.					min.	max.
1	121	2.4	465	470	28.0	DC/+	60.0	1.30	1.32	
2-4	121	2.4	465	470	28.0	DC/+	60.0	1.30	1.32	

of the joints. The tests were performed in accordance with the PN-EN ISO 17637:2011 standard, whereas the quality level was identified in accordance with the PN-EN ISO 5817:2014 standard, where the required acceptance criterion was quality level B. The visual tests of the butt joints did not reveal the presence of surface imperfections. Both joints were qualified as representing quality level B in accordance with PN-EN ISO 5817:2014. The subsequent stage involved the preparation of metallographic specimens for macroscopic tests. The tests aimed to enable the observation (by the unaided eye or using low magnification, i.e. 20x–30x) of the specimen sampled from the welded joint and subjected to grinding, polishing and etching in Adler's reagent. The macrostructural images are presented in Figures 4 and 5.

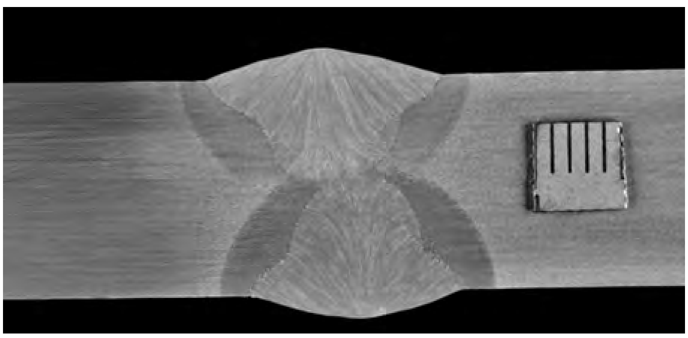


Fig. 4. Macrostructure of the SAW butt joint made of steel P460NL2

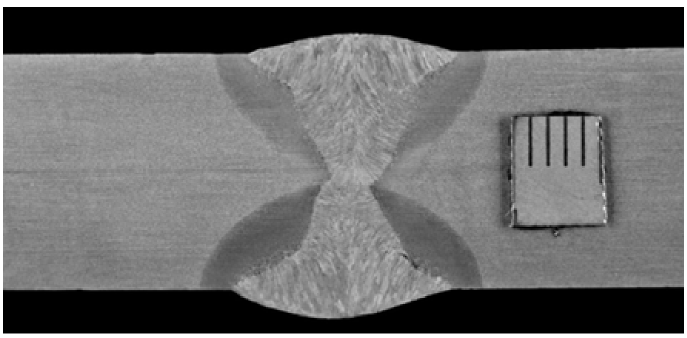


Fig. 5. Macrostructure of the MAG butt joint made of steel P460NL2

The structural tests were supplemented with the analysis of mechanical properties and hardness measurements. The static tensile test was performed in accordance with the PN-EN ISO 4136:2013 standard. The flat specimens having the rectangular cross-section were tested at ambient temperature. The static tensile test involved the use of an MTS 810 testing machine having force range ±1000 kN. The test was performed at a temperature of 23°C and an air humidity of 42%. The test enabled the identification of the tensile strength of the joints (see Table 5).

The subsequent stage included side bend tests of butt welds (SBB) performed in accordance with the PN-EN ISO 5173 standard. The bend tests involved specimens sampled from the test joint. The test objective was to verify the susceptibility of the joint to plastic strains. The SBB tests involved 4 specimens. The diameter of the bending mandrel amounted to 40 mm. After the specimens had been bent to a bend angle of 180 , they were inspected for the presence of imperfections (if any). The bend tests did not reveal the presence of scratches or cracks.

Impact strength tests of the butt welded joint were performed in accordance with the PN-EN ISO 9016 standard. The specimens with the Charpy V notch were subjected to an impact performed using an Amsler RKP 300 hammer and an initial energy of 300 J. The tests involved 4 series of 3 specimens having the notch made in the weld axis (designated as VWT) and in the HAZ (designated as VHT). The tests were performed at a temperature of -20°C. The test results are presented in Table 6.

Table 5. Dimensions of the specimens and the mechanical properties of the welded joints

Specimen designation	***a*** **[mm]**	***b*** **[mm]**	S_0 **[mm²]**	F_m **[kN]**	R_m **[MPa]**	**Remarks**
MAG460-1	13.6	24.8	337.3	233.9	693.6	rupture outside weld
MAG460-2	13.7	24.8	339.8	235.3	692.6	rupture outside weld
SAW460-1	13.5	25.0	337.5	234.1	693.5	rupture outside weld
SAW460-2	13.6	25.0	340.0	233.7	687.3	rupture outside weld
Description of symbols	*a* – specimen thickness [mm], *b* – width of the specimen working part [mm], S_0 – initial cross-section of the specimen [mm²], F_m – highest tensile force [kN], R_m – tensile strength [MPa]					

Table 6. Impact test results with specimen description and dimensions

Specimen designation	**Cross-section in the notch area [mm]**	S_0 **[mm²]**	**Impact energy [J]**	**Toughness [J/cm²]**	**Fracture**
MAG460/VWT/1	8x10	80	68	85.0	mixed
MAG460/VWT/2			52	65.0	mixed
MAG460/VWT/3			48	60.0	mixed
MAG460/VHT/1			164	205.0	plastic
MAG460/VHT/2			186	232.5	plastic
MAG460/VHT/3			124	155.0	plastic
SAW460/VWT/1			78	97.5	mixed
SAW460/VWT/2			54	67.5	mixed
SAW460/VWT/3			60	75.0	mixed
SAW460/VHT/1			196	245.0	plastic
SAW460/VHT/2			108	135.0	plastic
SAW460/VHT/3			78	97.5	mixed

Hardness measurements were performed using the Vickers hardness test, in accordance with the PN-EN ISO 6507-1 standard. Hardness measurements were performed in accordance with the PN-EN ISO 9015 and PN-EN ISO 6507 standards, using an indenter force of 98.1 N (HV10). The specimens represented the cross-section of the butt welded joint. The hardness measurements involved the areas of the base material, heat affected zone (HAZ) and weld. The tests involved the use of a KB-50BYZ-FA automatic hardness tester. Each specimen was provided with 15 measurement imprints in two lines. During the tests, the temperature amounted to 21 °C, whereas humidity amounted to 39%. The test results are presented in Figures 7–8. The schematic arrangement of measurement points in presented in Figure 6.

Analysis of test results and concluding remarks

The study discussed in the article involved the performance of numerous tests aimed to analyse and compare two selected welding methods in relation to structural pressure steel P460NL2. The first stage involved the analysis of the chemical composition of the base material. The tests revealed that contents of all key alloying elements were restricted within ranges assumed in the PN-EN 10269-1:2014 standard (specifying the maximum concentration of alloying elements in the steel). Welded joints were first subjected to visual tests, which, in both cases, did not reveal the presence of surface imperfections. As a result, the joints were qualified as representing quality level B in accordance with the PN-EN ISO 5817:2014 standard. The macroscopic metallographic tests did not reveal the presence of any imperfections in the cross-sections of the specimens. Both the SAW and MAG welded joints were characterised by full penetration and the vary narrow heat affected zone. The quality of the joints was assessed on the basis of macroscopic metallographic test results and the criteria specified in the PN-EN ISO 5817 standard.

The subsequent stage included the performance of strength-related tests. The static tensile test, performed in accordance with the requirements specified in the PN-EN ISO 4136 standard, revealed that the mechanical and plastic properties of both types of joints corresponded to those specified in the PN-89/H-84023/05 standard and declared in relation to steel P460NL2. The static bend tests of the butt welded joints (SBB) (performed in accordance with the PN-EN ISO

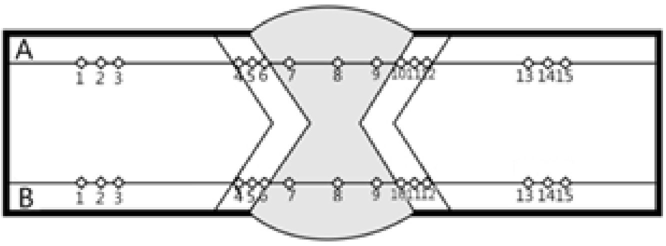
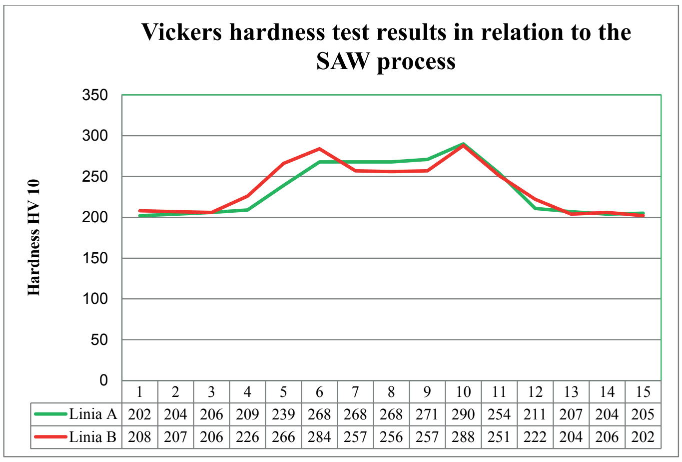
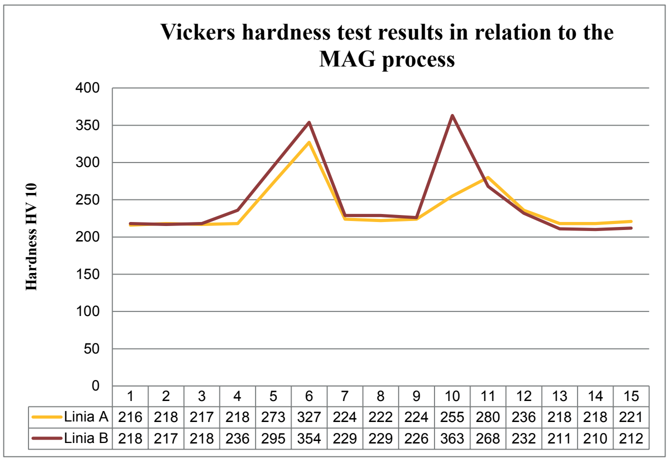


Fig. 6. Schematic arrangement of measurement points



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Linia A	202	204	206	209	239	268	268	268	271	290	254	211	207	204	205
Linia B	208	207	206	226	266	284	257	256	257	288	251	222	204	206	202

Fig. 7. Vickers hardness test results in relation to the SAW process



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Linia A	216	218	217	218	273	327	224	222	224	255	280	236	218	218	221
Linia B	218	217	218	236	295	354	229	229	226	363	268	232	211	210	212

Fig. 8. Vickers hardness test results in relation to the MAG process

5173:2010 standard) did not reveal any imperfections (i.e. cracks or partial tear) in the specimens bent to an angle of 180°. The aforesaid results were obtained in relation to both MAG-welded and SAW joints. The identification of brittle crack resistance required the performance of toughness analysis. The obtained test results are presented in related Tables. The analysis of the results revealed that both joints were characterised by similar brittle crack resistance within the temperature range subjected to analysis. Assuming the standard brittle crack resistance criterion (amounting to a minimum of 27 J in relation to nominal cross-section specimens), the obtained test results revealed that the test joints made of steel P460NL2 were resistant to brittle cracking at test temperatures. The specimens sampled from the joints were subjected to Vickers hardness tests performed under an indenter force of 98.1 N. The tests were performed in two measurement lines – in the cross-sections of the joints, in accordance with the requirements specified in the PN-EN ISO 9015-1 standard. The highest hardness (i.e. 363 HV10) was observed in the HAZ of the MAG welded joint. The hardness values in the analysed cross-sections of the welded joint remained low, which did not entail any remarks concerning the maximum acceptable joint hardness of 380 HV (in accordance with PN-EN ISO 15614-1:2017).

The welding process parameters of both welding methods were used to calculate the time necessary for making a running metre of the weld. Without counting the times of additional support activities, the making of one running metre of the weld using the MAG lasted 13 minutes and 24 seconds. In turn, the time needed to make one running metre of the weld using the SAW method amounted to 3 minutes and 20 seconds.

Concluding remarks

The above-presented test and analysis results justified the formulation of the following conclusions:

1. The joints made of steel P460NL2 using the MAG and SAW methods satisfied the requirements of the PN-EN 10269:2014-02 standard in terms of tensile strength and brittle crack resistance.
2. The mechanical and plastic properties of the MAG and SAW-welded joints were similar, yet a heat input was significantly higher as regards the SAW method (SAW – 1.32 kJ/mm vs MAG – 0.63 kJ/mm).
3. Submerged arc welding makes it possible to significantly increase the efficiency of the process (in comparison with MAG welding) and yet obtain similar joint properties. The time needed for making one running metre of the weld using the SAW method amounted to 3 minutes and 20 seconds whereas that obtained using the MAG method amounted to 13 minutes and 24 seconds.
4. Depending on needs and technological possibilities, it is possible to apply MAG or SAW welding to join crucial structures made of steel P460NL2.

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