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The Combined Welding of Advanced Steel P460NL2 mod. Used in Railway Tanks

Abstract: The article presents results of technological tests concerned with the welding of steel P460NL2 mod. using combined methods, i.e. the laser + submerged arc method and the hybrid (laser + MAG) method, in relation to various geometries of joint preparation. Criteria adopted in the tests were based on requirements (strength, toughness and hardness) concerning joints and specified in document VdTUV 531 as well as in the PN-EN ISO 15614-1, PN-EN ISO 15614-11 and PN-EN ISO 15614-14 standards. The above-named tests were supplemented with macroscopic metallographic tests. The tests revealed that appropriately adjusted technological parameters of the hybrid welding process and of the combined welding process enabled the obtainment of properly formed welded joints. The hybrid welded joints failed to satisfy the requirements of the above-named standards as their hardness was higher than the maximum permissible hardness, i.e. 380 HV10. The combined welding process enabled the making of proper joints characterised by a maximum hardness of 360 HV10, a strength of 665 MPa and an impact energy of 27 J, thereby satisfying the requirements of related technical regulations. The obtained data constitute technological guidelines for the development of a technology which, after qualification, could be used in industrial practice.

Keywords: combined welding. steel P460NL2, hybrid welding, railway tanks

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Introduction

Welding technologies are the most popular processes used to join metals and their alloys [1]. The necessity of increasing the efficiency of these processes with maintaining or even improving the quality of joints entails the search for new technological solutions [2, 3]. Presently, the most popular joining methods applied in the automotive industry include the MAG and MIG welding processes [2-4]. The primary advantages of the above-named technologies include high efficiency and full process automatability, whereas their disadvantages are weld porosity as well as the lack of inter-run and side-wall fusion [2-5].

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Increasing industrial demands make design engineers and technologists search for new innovative joining methods [1]. Increasingly popular in industrial practice are technologies based on laser beam welding (LBW) [6]. Laser welding is characterised by deep penetration, high welding rates, low linear energy and the narrow heat affected zone (HAZ). Regrettably, deep penetration and the narrow HAZ translate into the unfavourable shape of the weld, characterised by the significant height-width ratio, responsible for the formation of gas pores at the bottom of penetration and hot cracks in the weld axis [4].

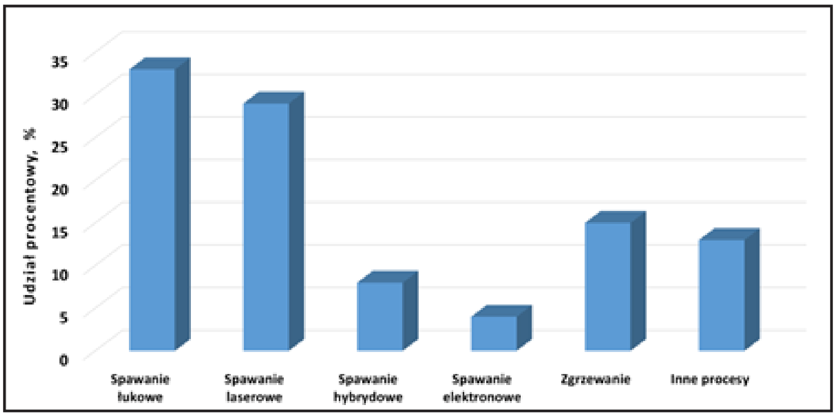


Fig. 1. Various methods used in welding engineering [1,4]

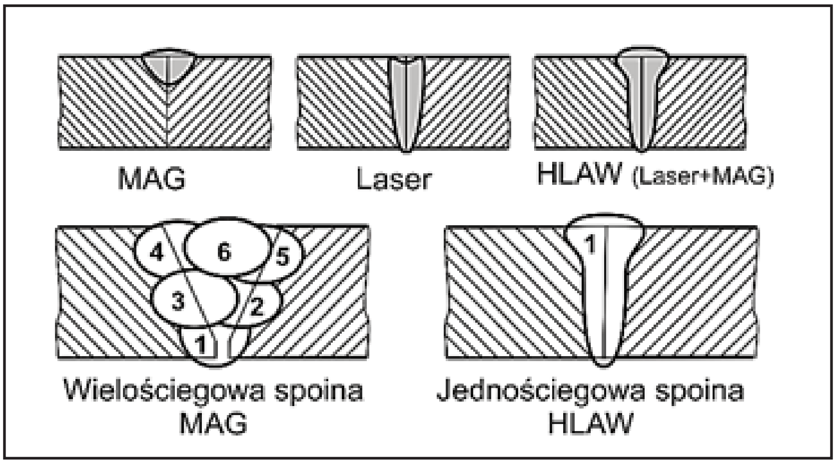


Fig. 2. Different shapes and geometry of welds made using the MAG, laser beam and hybrid laser + MAG welding processes [1]

Research centres and manufacturers dealing with joining technologies incessantly work on new or improved metal welding technologies aimed to increase the efficiency and improve the quality of welding processes (Fig. 1). One of solutions enabling the accomplishment of the above-named goals is the combination of the laser beam welding and the gas-shielded arc welding technologies. The hybrid, laser + electric arc (e.g. in the MAG method), welding process is referred to as Hybrid Laser Arc Welding (HLAW) [4].

The HLAW process is an "intermediate" method between laser welding and arc welding. The steplessly adjustable power of laser and that of electric arc make the method more flexible as adjusting welding linear energy and optimising the shape of the weld [2]. The differences between the shape and the geometry of welds

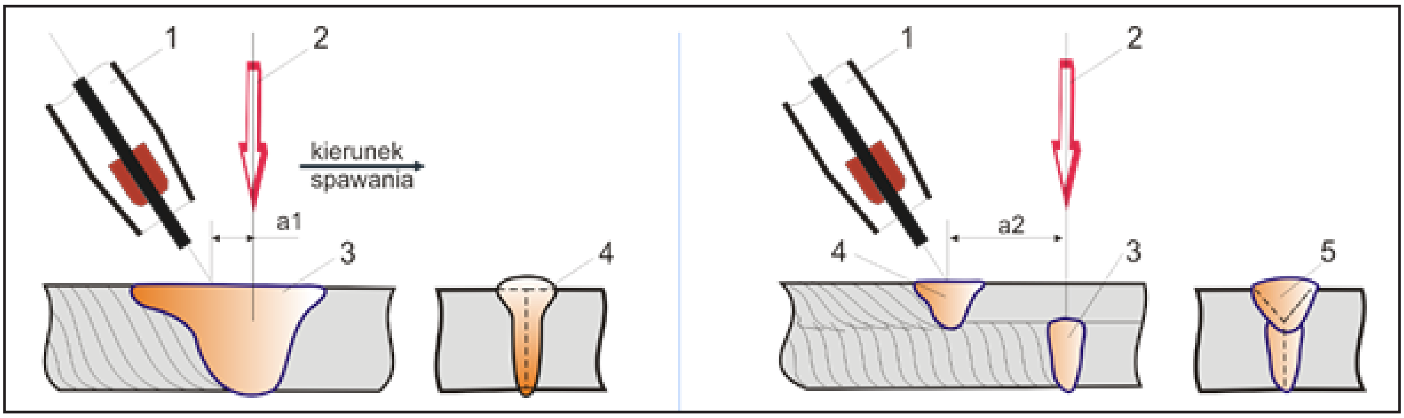


Fig. 3. Schematic diagrams presenting the simultaneous welding with laser and electric arc: a) schematic diagram of the hybrid laser + electric arc welding process (1- arc welding torch, 2 – laser beam, 3 – liquid metal pool common for both methods, 4 – weld in cross-section; b) schematic diagram of the combined laser + electric arc welding process (1 - arc welding torch 2 – laser beam, 3 – molten metal pool formed as a result of the laser beam effect, 4 - molten metal pool formed as a result of arc effect, 5 - weld in cross-section); a1, a2 – distance between the electrode wire tip and the laser beam axis [9]

made using the MAG method, laser welding and hybrid laser + MAG welding method are presented in Figure 2.

The HLAW method involves the use of the laser radiation beam and electric arc within one hybrid process (Fig. 3a). The method involving the simultaneous welding with laser and electric arc, where the two heat sources do not affect each other in one molten metal pool (Fig. 3b) is not a hybrid method but, in accordance with the PN-EN ISO 15614-14 standard, constitutes a combined process [7,8].

Combined processes can be used to weld structural elements of lorries, machines or railway rolling stock. An important characteristic of combined systems is the overlapping of two or more welding thermal cycles and the formation of the heat affected zone as a result of the interaction of the aforesaid cycles. In turn, in the HLAW process, the width and the shape of the HAZ only results from the effect of the hybrid process thermal cycle. The above-named feature can be used in the laser + submerged arc or hybrid + submerged arc welding system. Laser or hybrid welding provide the deep penetration of the material even in relation to a welding threshold of up to 10 mm and a narrow weld with the heat affected zone having a width of approximately 1 mm. In turn, submerged arc welding makes it possible to fill the weld groove and provide the simultaneous heat treatment of the laser weld (resulting from the use of high welding linear energy) [9, 10].

The development of advanced welding technologies translates into the dynamic development of various industrial sectors and entails increased demand for structural steels characterised by high mechanical and technological properties. Both design engineers and various carriers are interested in steels characterised by high properties at low temperature. The interest is connected with the development of steel structures characterised by increasingly high shape complexity combined with reduced weight and increasingly high performance requirements [11,12].

The article presents the most recent test results concerning technologies applied in the welding of advanced steel P460NL2 mod. used in the production of railway tanks. The steel belongs to a group of fine-grained steels intended for operation at low temperature. Steel P460NL2 mod. is discussed in detail in document VdTUV 531 [13]. The chemical composition and mechanical properties of the steel are presented in Table 1.

Presently, Chemet SA is one of very few plants in Europe successfully welding steel P460NL2 and providing required joint properties at a temperature of -40°C. The steel is used to make railway tanks for the transport of gas. The shell thickness is restricted within the range of 12.5 mm to 15 mm. The capacity of the tank is restricted within the range of 113 m^3 to 117 m^3 . In Chemet SA, the arc welding process applied in the production of tanks is performed at a rate of approximately 0.6 m/min.,

Table 1. Chemical composition and properties of steel P460NL2 mod. in accordance with VsTUV 531

Steel grade	Standard	Chemical composition, [%]										
		C	Si	Mn	P max.	S max.	Cr max.	Cu max.	Ni max.	Mo max.	V	N max.
P460NL2	VdTUV 531	0.20	0.10-0.60	1.00-1.70	0.030	0.020	0.0	0.20	0.40	0.10	0.10-0.20	0.025
		R_e [MPa] min.			R_m [MPa]			A_5 [%] min.			Impact energy [J] min.	
		460			630-725			17			-20°C	27
											-40°C	27

using linear energy restricted within the range of 10 kJ/cm to 12 kJ/cm.

Chemet SA, within the project entitled *Pilot technological line for the manufacturing of new tank containers using an innovative combined welding method financed by the National centre for Research and Development within Submeasure 1.1.1. Industrial tests and research works performed by companies within Smart Growth Operational Programme 2014-2020* (POIR.01.01.01-00-0720/19) developed a cutting-edge laser + submerged arc welding technology making it possible to join the sheathing of tank containers made of steel P460NL2 mod. Apart from enabling the process automation, the aforesaid technology makes it possible to increase efficiency by nearly thrice and reduce the consumption of filler metals by 50%.

The article presents results of technological tests concerning the welding of steel P460NL2 mod. using a system combining the laser + submerged arc method and the hybrid (laser+ MAG) method in various geometries of joint preparation. The criteria adopted in the tests were based on requirements concerning joint-related mechanical properties (strength, toughness and hardness) specified in document VdTUV 531 as well as in the PN-EN ISO 15614-1, PN-EN ISO 15614-11 and PN-EN ISO 15614-14 standards. The above-named tests were supplemented with metallographic tests. The test results made it possible to formulate technological guidelines enabling the implementation of the technology in industrial practice.

Test materials

The base material used in the tests had the form of 13.5 thick mm plates (150 mm x 350 mm) made of steel P460NL2. The chemical composition of the base material was subjected to verification analysis. The tests involved the use of a Q4 TASMAN 170 spark emission spectrometer (Bruker). The chemical composition of the test steel is presented in Table 2. The welding of steel P460NL2 by means of the hybrid (laser + MAG) method involved the use of a Union K 5 Ni (EN ISO 14341-A – G 50 5 M21 3Ni) filler metal wire having a diameter of 1.2 mm (Voestalpine Bohler Welding).

The shielding gas used in the MAG method was mixture M21 82% Ar + 18 CO_2 (PN-EN ISO 14175 – M21 – ArC-18), recommended by manufacturers for the welding of structural steels. The shielding gas was fed at a flow rate of 16 l/min. The submerged arc welding of steel P460NL2 mod. involved the use of an OE-SD3 1 Ni 1/2Mo (EN ISO 26304-A – S3NiMo) filler metal wire having a dimeter of 2.4 mm and OP 121 TT (ISO 14174 – SA FB 1 55 AC H5) welding flux (Oerlikon).

Technological welding tests

The technological welding tests were performed in the Laser Technologies Laboratory and in the Arc Welding Laboratory at Sieć Badawcza Łukasiewicz - Instytut Spawalnictwa. The hybrid (laser + MAG) welding tests were performed using a robotic laser station (Fig. 4a) equipped with:

- 6-axial KUKA KR30HA industrial robot having a positioning accuracy of min. 0.15 mm,
- TruDisk 12002 disk laser (Trumpf) provided with a system of optical fibres having diameters of 200 μm, 300 μm, 400 μm and 600 μm, enabling the connection of the resonator with the welding head,
- hybrid welding head (KUKA) enabling the transmission of a beam having a power of 12 kW,
- tilting turntable enabling the positioning of element being welded.

Table. 2. Chemical analysis-based composition of the plates

Steel grade	Standard Analysis	Chemical composition, [%]									
		C	Si	Mn	P	S	Cr	Cu	Ni	Mo	V
P460NL2	LBS/14/19/ZT	0.19	0.41	1.48	0.012	0.0005	0.045	0.01	0.01	0.01	0.1

The MIG/MAG arc welding power source used in the test was a PHOENIX 452 RC PULS KUKA machine (EWM Hightec Welding GmbH) having a maximum welding current of 450A and equipped with a list of operating programmes in the synergic mode. The welding power source control system was integrated with the robot controller via the programme.

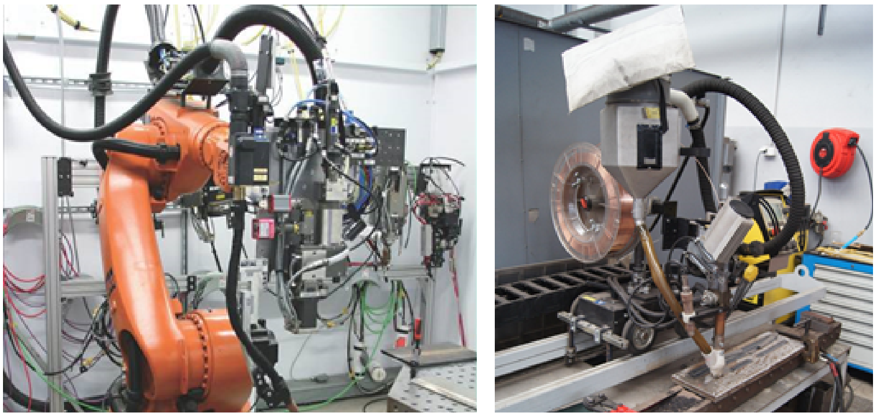


Fig. 4. Robotic welding stations used in the tests at Łukasiewicz - Instytut Spawalnictwa: TruLaser Robot 5120 laser welding station provided with a TruDisk 12002 disk laser: a – main view, b – D70 hybrid welding head mounted on the industrial robot wrist, b) laboratory submerged arc welding station.

Hybrid welding requires the recording of parameters of both heat sources (laser and MAG electric arc) affecting the stability of the process and the quality of joints. The hybrid welding station at Łukasiewicz - Instytut Spawalnictwa was provided with a PCD505 parameter control and documentation system (KUKA).

The submerged arc welding tests were performed using a welding station equipped with:
– A2 Multitrac submerged arc welding tractor (ESAB) provided with a PEK controller and a flux collecting system,
– welding power source – an LAF 1001 welding rectifier (ESAB),
– welding tractor guide bar; welding table with an auxiliary device enabling the fixing and positioning of specimens during the entire welding process,
– K.J.T. 8851 digital thermometer (AZ-Biall Sp. z o.o.)

The main view of the laboratory submerged arc welding station is presented in Figure 4.

The tests concerning the welding of plates made of steel P460NL2 mod. were performed in 3 variants related to the manner of plate edge preparation and the applied welding method (Table 3). Variant 1 involved Y-butt joint preparation, a weld grove bevel angle of 600, a threshold height of 8 mm (Fig. 5a) and the making of a butt weld in two runs using a hybrid method. The first run melted the threshold and formed the weld root, whereas the second run filled the weld groove, forming excess weld metal.

Variant 2 involved square butt weld preparation (Fig. 5b) and the making of a butt weld with full penetration in one run using the hybrid method. Variant 3 involved Y-butt joint preparation, a weld grove bevel angle of 600, a threshold height of 6 mm (Fig. 5c) and the making of a butt weld using two i.e. laser welding and arc welding processes. The first run, made using the laser beam, melted the threshold and formed the weld root, whereas the second run, made using submerged arc, filled the weld grove, forming excess weld metal and thermally processing the weld made using the laser beam.

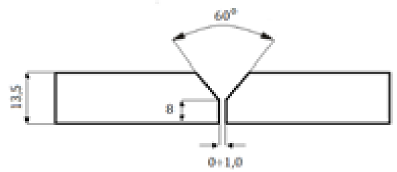
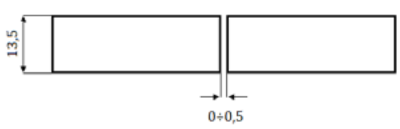
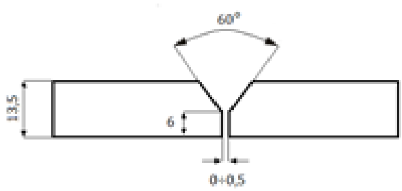
Variant 1 HLAW Laser + MAG	
Variant 2 HLAW Laser + MAG	
Variant 3 Laser + submerged arc	

Fig. 5. Pre-weld matching and preparation of the test plates in the 3 variants

The technological welding parameters used when welding 13.5 mm thick plates made of steel P460NL2 are presented in Table 3.

Testing methodology and test results

The visual tests of the weld face and weld root were performed in accordance with the requirements specified in the PN-EN ISO 17637 standard. The specimens used in the metallographic tests had been sampled from surfaces perpendicular to the welding directions. The metallographic specimens were subjected to etching in 5% Nital 5for 10 seconds. The macrostructure of the joints is presented in Figure 6.

The structural tests were supplemented with tests of mechanical properties and hardness measurements. A static tensile test was performed using a Zwick Z1200 testing machine, whereas impact strength tests were performed at a temperature of 20°C and -40°C using an RKP-450 Charpy pendulum machine and specimens with the V-notch. Hardness measurements were performed under a load of 98N (HV10), using a hardness tester (Struers) and applying the Vickers hardness testing method (in accordance with the requirements of the PN-EN ISO 9015 standard). The results of mechanical properties tests and those of hardness measurements are presented in Table 4.

Table 3. Parameters used in the hybrid welding of 13.5 mm thick joints in steel P460NL2.

<table>
<tr><th></th><th>Joint no.</th><th>P [kW]</th><th>V_s [m/min]</th><th>V_d [m/min]</th><th>I [A]</th><th>V [V]</th><th>Cor. V [V]</th><th>g [mm]</th><th>a [mm]</th><th>f [mm]</th><th>Q [kJ/mm]</th></tr>
<tr><td rowspan="4">Variant 1</td><td>A_12</td><td>3,5</td><td>1</td><td>8,5</td><td>250</td><td>20</td><td>3</td><td>0,4</td><td>2</td><td>-5</td><td>0,51</td></tr>
<tr><td>A_13_1</td><td>5</td><td>1</td><td>8,5</td><td>250</td><td>20</td><td>3</td><td>0,8</td><td>2</td><td>-5</td><td>0,60</td></tr>
<tr><td>A_13_2</td><td>3,5</td><td>1</td><td>13</td><td>280</td><td>23</td><td>3</td><td>-</td><td>2</td><td>-3</td><td>0,59</td></tr>
<tr><td colspan="11">Joint no. A_12 and A_13_1 – arc leading welding (A-L) – penetration run;
Joint no. A_13_2 – laser leading welding (L-A) – filling run,</td></tr>
<tr><td rowspan="5">Variant 2</td><td>A_15</td><td>6,5</td><td>1,2</td><td>10</td><td>275</td><td>20</td><td>3</td><td>0,2</td><td>2</td><td>2</td><td>0,60</td></tr>
<tr><td>A_5</td><td>7</td><td>0,8</td><td>12</td><td>275</td><td>22</td><td>3</td><td>0,5</td><td>2</td><td>2</td><td>0,97</td></tr>
<tr><td>A_9</td><td>7</td><td>1</td><td>10</td><td>275</td><td>20</td><td>3</td><td>0,4</td><td>2</td><td>2</td><td>0,75</td></tr>
<tr><td>A_14</td><td>7</td><td>1,2</td><td>10</td><td>275</td><td>20</td><td>3</td><td>0,4</td><td>2</td><td>2</td><td>0,62</td></tr>
<tr><td colspan="11">Joint no. A_5, A_9, A_14 and A_15 – arc leading welding (A-L)</td></tr>
<tr><td rowspan="3">Variant 3</td><td>A_31 laser</td><td>5</td><td>1,5</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>0</td><td>-7</td><td>0,30</td></tr>
<tr><td>A_31_2 submerged arc</td><td>-</td><td>0,4</td><td>3</td><td>450</td><td>28</td><td>-</td><td>-</td><td>-</td><td>-</td><td>1,52</td></tr>
<tr><td colspan="11">Joint no. A_31 – laser welding – penetration run; joint no. A_31_2 – submerged arc welding, filling run</td></tr>
<tr><td colspan="12">

- *P* – laser beam power [kW]
- V_s – welding rate [m/min]
- V_d – filler metal wire feeding rate [m/min]
- *I* – welding current [A]
- *U* – arc voltage [V]
- *Cor. V* – arc voltage correction (arc power source setting) [V]
- *g* – gap at the interface of the plates [mm]
- *a* – distance between the laser beam focus and the electrode wire tip [mm]
- *f* – position of the focus in relation to the surface of the plates [mm]
- *Q* – heat input [kJ/mm
- T_P – preheating temperature [°C].

</td></tr>
</table>

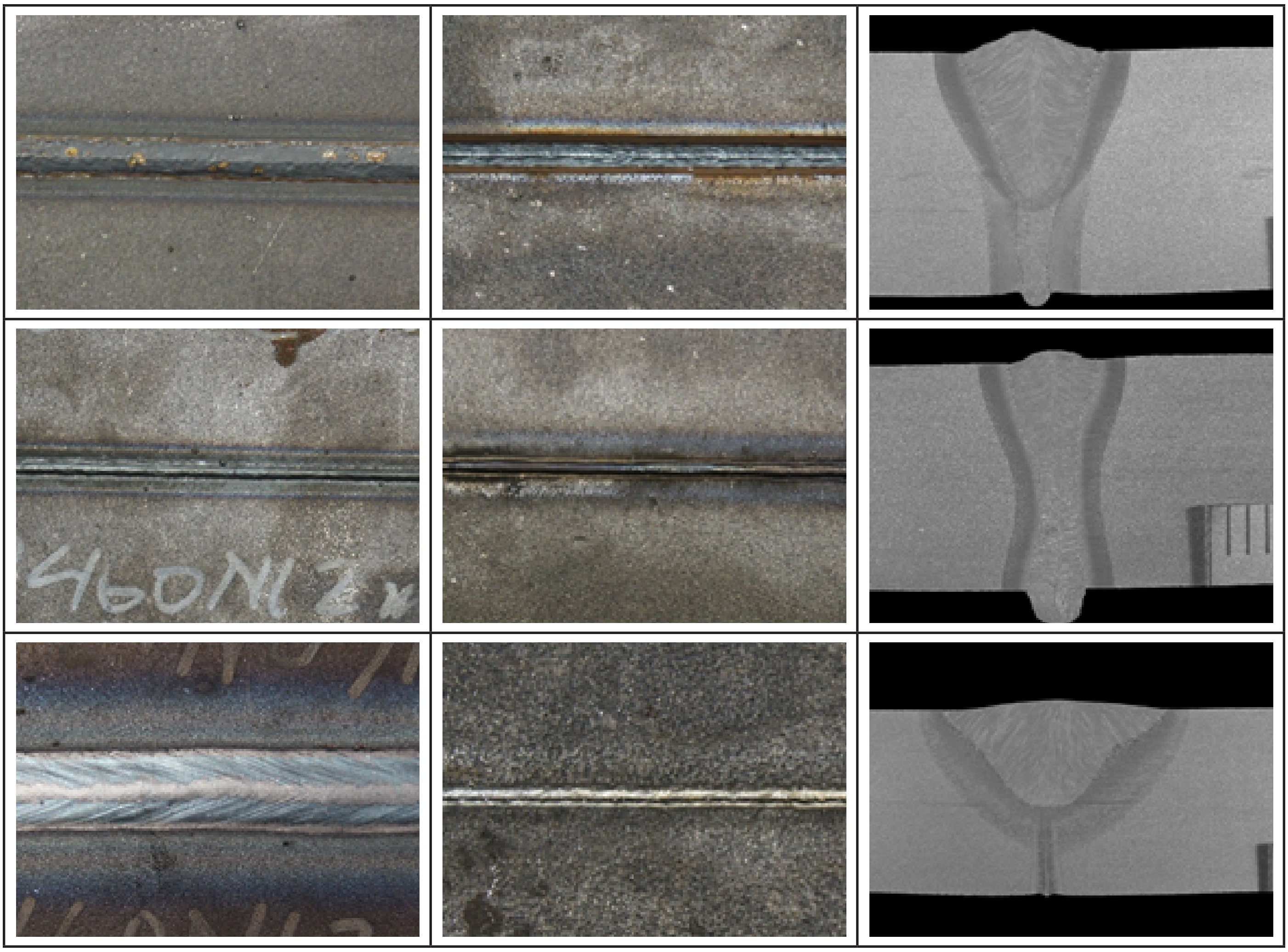


Fig. 6. Structure of exemplary joints made during the technological tests: a) weld face after welding (variant 1, HLAW), b) weld root after welding (variant 1, HLAW), c) joint macrostructure (variant 1, HLAW), d) weld face (variant 2, HLAW, unbevelled joint), e) weld root, (variant 2, HLAW, unbevelled joint), f) joint macrostructure (variant 2, HLAW, unbevelled joint), g) weld face after submerged arc welding (variant 3, laser + arc, h) weld root after submerged arc welding (variant 3, laser + arc) joint macrostructure, (variant 3, laser + arc)

Analysis of test results and conclusions

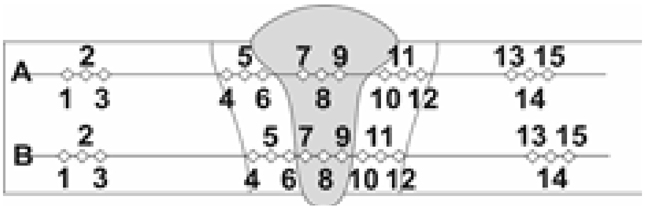
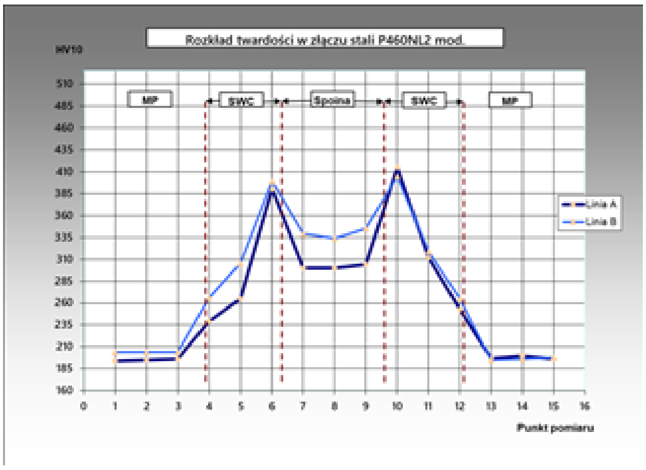
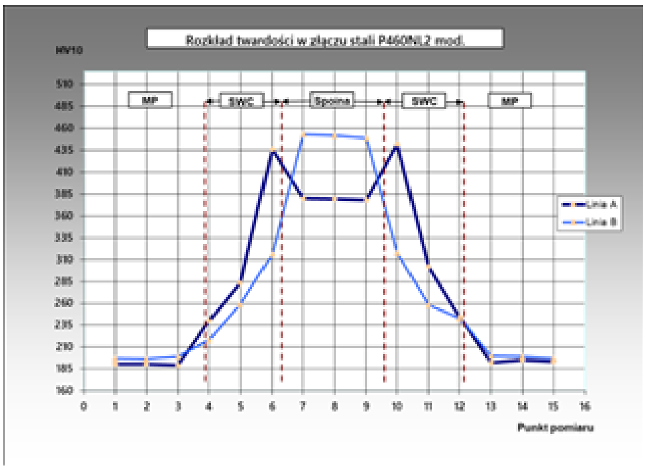
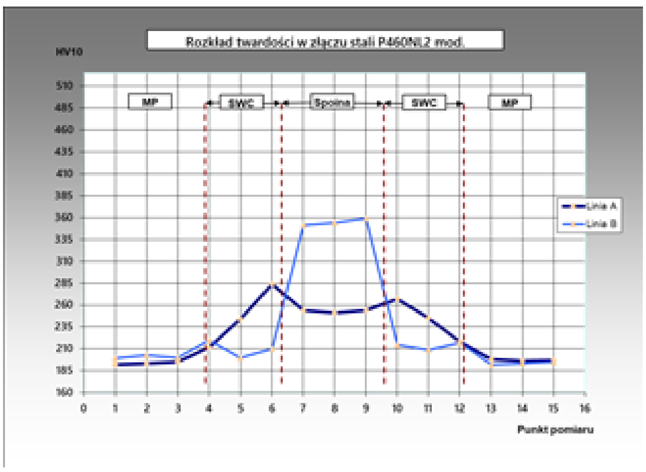
The research work involved the performance of the technological tests concerning the hybrid welding (HLAW) and the combined welding (laser + submerged arc) of advanced 13.5 thick steel P460NL2 mod. used in the production of pressure vessels and intended for operation at low temperature. The welding tests were performed using robotic stations at Łukasiewicz - Instytut Spawalnictwa, equipped with a TruDisk 12002 disk laser and a KUKA KR30HA robot (Fig. 4).

The analysis of the technical documentation of tank cars for the transport of gas resulted in designing three welding variants, i.e. a Y-bevelled joint made using the hybrid welding method, a butt joint with square preparation made using the hybrid welding method and a Y-bevelled joint made using the combined welding method, involving the melting of the welding threshold (8 mm) by means of the laser beam and filling by means of submerged arc (Fig. 5).

The primary objective of the tests was to make joints satisfying the requirements specified in VdTUV 531, including the obtainment of impact energy exceeding 27 J in relation to the hardness of the joint below 380 HV. The second criterion was the satisfaction of the requirements related to quality level B in accordance with PN-EN ISO 19319 in relation to the laser welded joint, PN EN ISO 5817 in relation to the arc welded joint and PN-EN ISO 12932 in relation to hybrid welded joints.

The visual tests revealed that joint no. A_12 was characterised by incomplete penetration. As a result, in the subsequent tests the power of the laser beam was increased to 5 kW, whereas the gap at the interface of the plates was increased to 0.8 mm; the remaining parameters stayed the same (variant 1, Table 3).

Table 4. Mechanical properties of the test joints

	Tensile strength R_m [MPa]	**Impact energy [J] -40°C**	**Toughness [J/cm²] -40°C**	**Hardness distribution in the joint** 
Variant 1	663	Weld 46, 40, 36 HAZ 31, 33, 35	Weld 58, 50, 45 HAZ 39, 41, 44	
Variant 2	661	Weld 48, 29, 33 HAZ 31, 33, 30	Weld 60, 36, 41 HAZ 39, 41, 38	
Variant 3	665	Weld 34, 49, 65 HAZ 34, 45, 46	Weld 43, 61, 81 HAZ 43, 56, 58	

The assessment of the quality of joint no. A_13 revealed that it satisfied the requirements of quality level B in accordance with PN-EN ISO 12932 and was characterised by the uniform, smooth and spatter-free weld face and the properly shaped weld face and weld root (Fig. 6a, b). The foregoing was confirmed by welding parameters recorded by the PCD 505 system, showing that the course of the hybrid welding process was stable. The macrostructural tests of the joints did not reveal the presence of welding imperfections (Fig. 6c). The tensile strength of the joint (rupture outside the weld) amounted to 663 MPa; the impact energy both in the weld and in the joint exceeded a criterion of 27 J at a temperature of -400C (Table 4).

The hardness measurements of joint no. A_13 revealed that the highest hardness, amounting to 415 HV10, was measured at the weld-HAZ interface, whereas the lowest hardness was measured in the base material – on average 200 HV10. The difference between the hardness of the base material and that of the HAZ amounted to 48% (215 HV10). The hardness in the weld was restricted within the range of 300 HV10 to 345 HV10 (point 7÷9 of measurement line A, B) (Table 4).

The PN-EN ISO 15614-14:2013 standard concerning hybrid welding procedure classification provides information related to the maximum permissible hardness in joints. In accordance with the above-named standard, the maximum permissible hardness in joints made in the related type of steel should amount to 380 HV10. In view of the foregoing, joint no. A_13 was recognised as failing to meet the requirements of the aforesaid standard.

The subsequent stage of the research work included the hybrid welding of test plates (having a thickness of 13.5 mm + 13.5 mm) made of steel P460NL2 and subjected to square butt weld preparation (variant 2, Table 3). The visual tests revealed that, because of gas pores and hot cracks present in the weld axis, joints nos. A_5 and A_15 failed to satisfy the requirements of quality level B in accordance with the PN-EN ISO 12932 standard. The weld root of joint no. A_9 contained imperfection no. 502, i.e. excess weld metal defined in accordance with the PN-EN ISO 6520-1:2009 standard as "reinforcement of the butt weld on the face is too large" (Fig. 6e, f). The weld root satisfied the requirements of quality level C, whereas the weld face satisfied the requirements of quality level B in accordance with PN-EN ISO 12932 (Fig. 6d, e). The strength of the joint amounted to 661 MPa; the specimen ruptured in the base material. The impact energy in the HAZ at a temperature of -40°C amounted on average to 32 J; the impact energy in the weld amounted to 37 J (Table 4). The highest hardness was measured in the cross-section of joint no. A_14, i.e. at the weld-HAZ interface, and amounted to 453 HV10 (point no. 7 of measurement line B, Table 4). The mean hardness value of the base material amounted to 190 HV10. The difference between the hardness of the base material and that of the weld amounted to 263 HV10. In accordance with the requirements specified in the PN-EN ISO 15614-14:2013 standard concerning hybrid welding procedure qualification, the permissible hardness of the joint made in the above-named type of steel should amount to 380 HV10. In view of the foregoing, joint no. A_14 did not satisfy the requirements of the above-named standard (Table 4).

During the laser beam welding of the welding threshold having a height of 8 mm, the plates were matched without any gap. The welding of the root run the laser radiation beam was performed using the same welding head as that used in the hybrid welding. The groove was filled using submerged arc (variant 3, Table 3).

The visual tests performed in accordance with the PN-EN ISO 17637 standard revealed that joint no. A_31, made using the laser beam, was characterised by the uniform and properly shaped root (Fig. 6g). The filling run (made using submerged arc) was smooth, with the properly shaped spatter-free face (Fig. 6h). The weld root satisfied the requirements of quality level B in accordance with the PN-EN ISO 19319 – 1 standard, whereas the weld face satisfied the requirements of quality level B in accordance with the PN-EN ISO 5817 standard. The macrostructural tests did not reveal any internal welding imperfections in the joint (Fig. 6c). The tensile tests revealed that the rupture took place in the base material in relation to a stress of 665 MPa. The impact energy in the weld amounted to 49 J, whereas that in the HAZ amounted to 42 J (Table 4).

The highest hardness amounting to 359 HV10 was measured in the central part of the weld, whereas the lowest hardness amounting on average to 195 HV10 was measured in the base material (Table 4). The difference between the hardness of the base material and that of the weld amounted to 164 HV10.

In accordance with the requirements of the PN-EN ISO 15614-1 standard related to arc welding procedure qualification and the PN-EN ISO 15614-11 standard related to laser beam welding procedure qualification, the permissible hardness of the joint made in the above-named type of steel should amount 380 HV10, therefore joint no. A_31 satisfied the requirements of the above-named standards.

The analysis of the test results justified the formulation of the following conclusions:

– Appropriately adjusted technological parameters of the hybrid welding process and of the combined welding process enabled the obtainment of properly formed butt joints in 13.5 mm thick plates made of steel P460NL2 mod.. The joints represented quality level B in accordance with the requirements of the PN-EN ISO 15614-14 (variant 1 and 2) as well as PN-EN ISO 13919-1 and PN-EN ISO 5817 standards (variant 3).
– The maximum hardness of the hybrid welded joint made in two runs (variant 1) amounted to 415 HV10. In accordance with the requirements of a related standard, hardness in the welded joint should not exceed 380 HV10. The above-named joint did not satisfy the requirements of related regulations.
– Hybrid welding performed in accordance with variant 2 (hybrid welding performed in one run) led to an increase in joint hardness to 453 HV10. The above-named joint did not satisfy the requirements of related standards.
– The combined welding process (variant 3, i.e. laser + submerged arc) enabled the making of proper joints characterised by a maximum hardness of 360 HV10, a strength of 665 MPa and an impact energy of 27 J, thereby satisfying the requirements of related technical regulations. The obtained data constitute technological guidelines for the development of a technology which, after qualification, could be used in industrial practice.

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