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Use of Plasma Method Variants When Welding Sheets Made of Steel X6CrNi18-10

Abstract: The article presents the course and results of tests aimed to identify the effect of the PAW (plasma welding) method variant (with cold wire and without the filler metal) or PPAW method (flux-cored) on the shape of the weld, the tensile strength and the aesthetics of butt joints made of 2.0, 4.0 and 6.0 mm thick sheets in steel X6CrNi18-10. The research involved bend tests, macro and microscopic metallographic tests as well as the tensile tests of joints. The tests revealed that the use of various variants of the plasma welding method enabled the obtainment of welded joints representing the same quality, yet varying significantly in terms of aesthetics and mechanical properties.

Keywords: plasma welding, joints quality assessment, properties of joints

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Introduction

Welding technologies utilising concentrated electric arc established themselves in the manufacturing industry in the early 1960s. One of the most popular arc-based technologies is plasma cutting constituting one of the primary thermal cutting methods. Presently, because of its unquestionable advantages, plasma is becoming increasingly frequently used when joining components in many industries.

Low-temperature plasma is formed as a result of the forced increase in the density of molecules ionised in the column of electric arc obtained by its narrowing (reduction of diameter) and leading to an increase in temperature. The increase in arc temperature and electric field intensity is accompanied by an increase in the kinetic energy of particles and the increase in arc ionisation degree. Plasma arc-based technologies have become popular in various industries because of numerous plasma arc advantages including the ease of arc initiation, arc stability, high power density and significant flexibility in the adjustment of parameters.

The article discusses the present state of the problem along with the course and results of technological tests involving the plasma arc welding of 2.0, 4.0 and 6.0 mm thick sheets made of acid-resistant steel X6CrNi18-10, performed without a filler metal as well as with the addition of powder or a cold wire. The tests aimed to identify the effect of the primary welding process variables on the quality, geometry and properties of welded joints.

Present State Analysis

A number of plasma arc advantages make plasma arc welding (PAW) a very interesting alternative to TIG and MAG/MIG welding, and, in some

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cases, also to electron beam and laser beam welding [1, 2]. The use of the PAW method requires the precise preparation of edges of elements to be joined. The above-named condition can be satisfied by the making of butt welds without a filler metal (the most frequently used method). However, in many cases, the unprecise matching of butt joint edges requires the use of a filler metal in the form of a wire.

In terms of the weld forming mechanism, there are two variants of the PAW (plasma arc welding) method, i.e. the melt-in and the keyhole method. The first variant is nearly identical to the TIG method, the liquid metal pool moves along with the motion of plasma arc along the length of edges being welded. The small stream of plasma gas ensures the lack of disruptions affecting the weld pool, the volume of which can be refilled using a filler metal in the form of a cold wire. This variant is used when making butt, angle, L-shaped, overlap, lap and edge joints. The second variant (*key-hole*) uses the electrodynamic energy of the plasma beam and is characterised by the formation of a capillary ("*key-hole*"). The phenomenon is possible as a result of appropriate synchronisation of current up-slope time and the stream of plasma gas. For a specific area of parameters, the depth of a capillary can correspond to the entire thickness of a material. Such a variant enables the obtainment of a small liquid metal pool. As a result, it is possible to eliminate root-forming strips. Key-hole welding enables the making of butt joints with square preparation having a thickness above 2.5 mm.

The plasma arc technology was developed to weld corrosion-resistant steels. However, it should be emphasized that the use of plasma arc makes it possible to join almost all weldable metals and their alloys; the only limitation being the thickness of elements being welded. Related reference publications state that a welding current of 400 A enables the joining of up to 15 mm thick sheets (using the keyhole technique).

The plasma arc based method was used when surfacing with powder as early as in the early 1960s [3÷6]. However, the making of welded joints using the PPAW (Powder Plasma Arc Welding) method is a relatively new solution. The PPAW is performed in a manner similar to surfacing, yet its purpose is the obtainment of a permanent metallic joint. Plasma arc narrowed by a copper liquid-cooled nozzle combined with an electrode pullback lead to the obtainment of a plasma beam having a nearly uniform cylindrical shape. Because of the fact that the plasma beam is narrow, it is necessary to use a ring-shaped shielding gas stream having a greater diameter. Powder having a granularity restricted within the range of 40 to 150 μm is transported from a container via gas (argon) to a welding torch, and next, in the form of a gas and powder mixture is supplied, via plasma arc, to the weld pool [7]. Powder plasma arc welding is usually used in hybrid laser-involving processes [8, 9]. The PPAW itself can be regarded as a method enabling the obtainment of joints made of thin-walled elements with greater efficiency than that of TIG and with fewer technological problems than in cases of the MIG/MAG methods, particularly in terms of applications involving robot welding stations. As mentioned before in relation to plasma arc welding (without a filler metal), joints can be made using two, i.e. key-hole and melt-in techniques. In turn, the making of joints using the PAW method with a cold wire or the PPAW method is performed only using the melt-in technique. The PPAW method enables the joining of all grades of weldable steels, copper alloys and nickel alloys. Weld made using the above-named method are characterised by proper penetration, smooth, pure and spatter-free weld face as well as by a small HAZ. As currently produced structural materials are characterised by increasingly higher mechanical properties enabling the making of welded products characterised by increasingly lower weight and smaller cross-sections, the PPAW technology is becoming increasingly popular [10÷12].

Test Rig and Materials

The tests involving the PAW and PPAW methods involved the use of sheets made of steel X6CrNi 18-10 according to PN-EN 10088-2:2014-12 [13], i.e. chromium-nickel steel having the austenitic structure. The technological welding tests concerning the PPAW method involved the use of EuTroloy 16670.04 powder (Messer Eutectic Castolin) having granularity restricted within the range of +45 to 90 µm and the chemical composition corresponding to that of the PN-EN ISO 14343-A G 18 8 Mn electrode wire used in the tests concerning the PAW method with a cold wire.

The technological welding tests were performed using a station equipped with a modern Eutronic GAP 3001 device (Castolin). The device was composed of a plasma arc power supply unit (up to 350 A) along with a gas console control system and a cooling unit, a GAP E52 torch for plasma arc mechanised welding and surfacing as well as an EP2 V1.0 powder feeder and a WF cold wire feeder, integrated with the power supply unit. The device was provided with a software programme enabling the controlling of the plasma source via a PC. The welding torch along with the powder feeder and the cold wire feeder were mounted on an automated MultiSurfacer D2 Weld station (Welding Alloys) provided with a microprocessor-based control system enabling the adjustment of the direction and rate of welding as well as the repeatable positioning of the torch (Fig. 1).

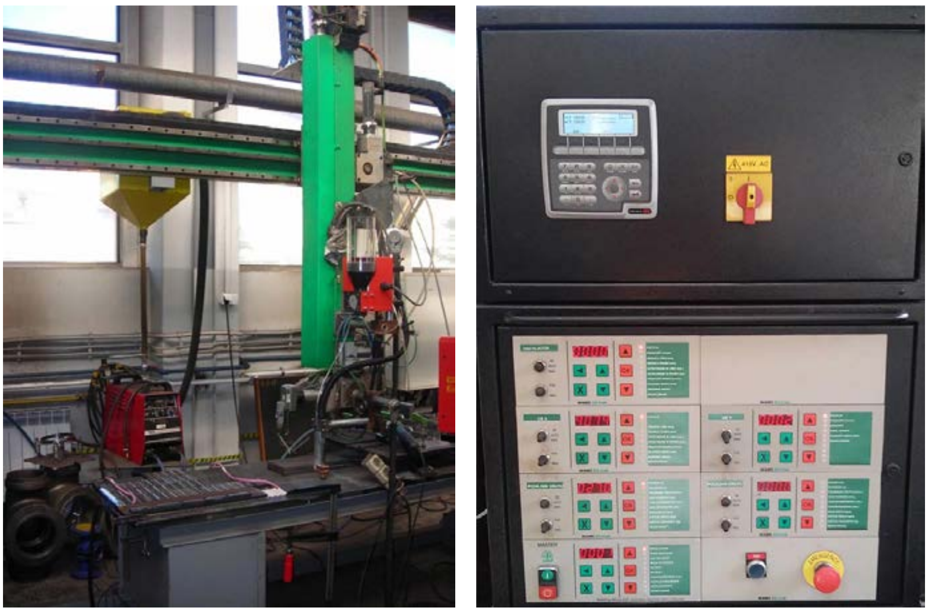


Fig. 1. Automated MultiSurfacer D2 Weld portal along with the control system, powder feeder and plasma torch

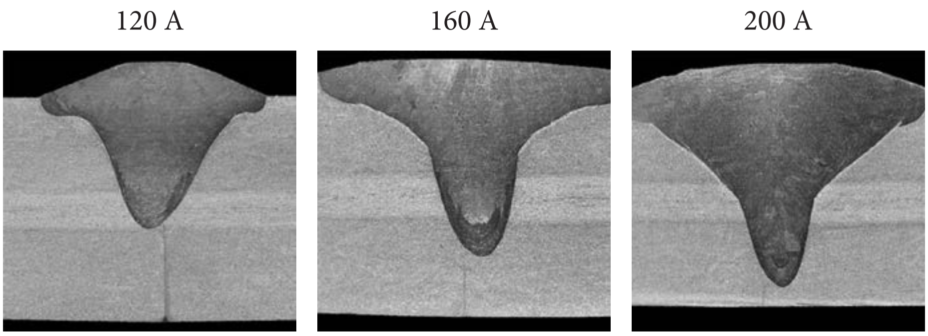


Fig. 2. Macrostructure of the test plasma arc welded butt joints made of the 10 mm thick sheets in steel X6CrNi 18-10 without using the filler metal

Plasma Arc Welding Process Tests

The methodology of plasma arc welding tests involved the performance of plasma arc welding tests (PAW and PPAW) using various process conditions and parameters. To identify the possibilities of the GAP 3001 device in terms of plasma arc welding without filler metal, the initial tests involved the making of joints using 10.0 mm sheets in steel X6CrNi 18-10. Figure 2 presents the effect of an increase in welding current on penetration depth.

The increase in welding current above 200 A led to the excessive evaporation of the material, causing the intense motion of the liquid metal in the weld pool and resulting in the formation of porosity and a non-uniform weld face as well as leading to the excessive evaporation of the weld area and the zone adjacent to it.

The subsequent PAW and PPAW welding tests were performed using the 2.0, 4.0 and 6.0 mm thick sheets made of steel X6CrNi 18-10. The initial technological tests involved specimens having dimensions of 150 mm × 100 mm. Before the making of joints, the sheets were cleaned and subjected to square butt weld preparation. The shielding gas (Go) used in the text was the mixture of argon with the 5% addition of hydrogen. The gas used as plasma gas (Gp) was argon. To ensure the repeatability of welding process conditions, the GAP 3001 device was fixed on a mechanised support. The first welding tests involved the plasma arc welding of 2.0, 4.0 and 6.0 mm thick sheets without a filler metal, using welding current restricted within the range of 90 to 220 A and a welding rate restricted within the range of 20 to 120 cm/min. The subsequent plasma arc welding tests involved the use of a cold wire fed a rate restricted within the range of 0.5 to 1.0 m/min. The final tests involved the use of the PPAW method and a filler metal in the form of powder fed at a rate restricted within the range of 1.55 to 5.00 g/min. The preliminary optimisation of welding technological parameters was followed by the making of 2.0, 4.0 and 6.0 mm thick butt joints using the elements having dimensions of 400 mm × 150 mm.

During the tests the following values of parameters remained constant:

- distance between the plasma nozzle and the material: 5 mm,
- rate of gas flow in the gas strip (100% argon): 15 l/min,

and:

- flow rate of plasma gas/powder-transporting gas: 1.5-2.0 l/min,
- shielding gas flow rate: 5-10 l/min.

The above-named parameters were adjusted on the basis of the preliminary welding tests, within which also the range of changes in individual technological parameters was adjusted. The use of any parameters from outside the range resulted in the obtainment of joints containing various imperfections including porosity, spatters on sheet surfaces (primarily after the PPAW method was used), the lack of penetration, burn-throughs and angular strains. Exemplary imperfections are presented in Figure 3.

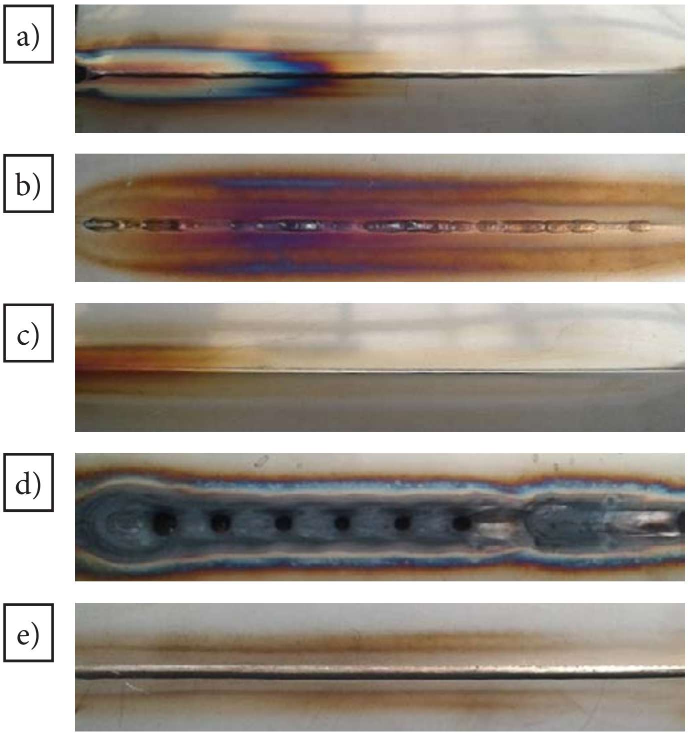


Fig. 3. Plasma arc welded joints made using the PAW and PPAW methods visible on the root side: a, b) dye penetration on the root side; c) lack of penetration; d) burn-throughs; e) joint without welding imperfections

The welded joints were subjected to visual and penetrant tests. Afterwards, joints without surface imperfections were subjected to macro and microscopic metallographic tests as well as to tensile and bend tests.

Test Results

All of the butt joints made of 2.0, 4.0 and 6.0 mm thick sheets using the PAW and PPAW method were first subjected to visual tests. Afterwards, one joint of each "sheet thickness-plasma arc welding method" combination representing quality level B according to PN EN ISO 5817: 2014-05 [14] was subjected to penetrant tests as well as macro and microscopic metallographic tests.

The metallographic tests involved the use of Adler's etchant. Afterwards, digital photographs were made. The macrostructures of selected welds made during the technological tests are presented in Table 1-6. Tables 1÷3 present the test results related to the individual welding methods, whereas Tables 4÷6 present the comparison of results concerning the joints of the sheets having the same thickness and made using various plasma arc welding methods. Afterwards, all the test specimens were subjected to microscopic metallographic tests. The structures of the specimens made using various plasma arc-based methods did not differ from one another or contain micro-imperfections. Table 7 presents exemplary results.

Table 1. Macrostructures of the butt joints made of steel X6CrNi 18-10 using the PAW method without a filler metal, mag. 3.0x

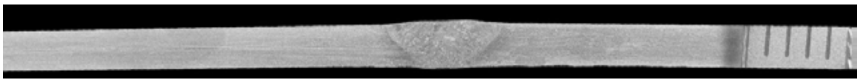
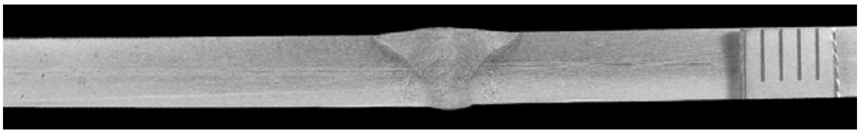
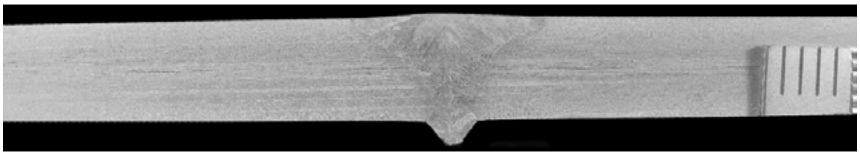
Thickness [mm]	Butt joint macrostructure
2.0	
4.0	
6.0	

Table 2. Macrostructures of the butt joints made of steel X6CrNi 18-10 using the PAW method with a cold wire (LMN 307), mag. 3.0x

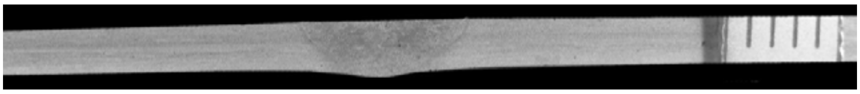
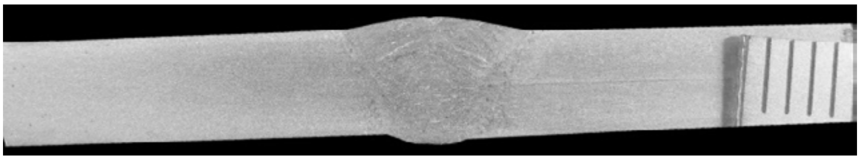
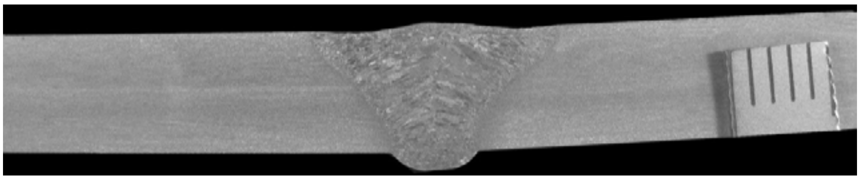
Thickness [mm]	Butt joint macrostructure
2.0	
4.0	
6.0	

Table 3. Macrostructures of the butt joints made of steel X6CrNi 18-10 using the PPAW method, mag. 3.0x

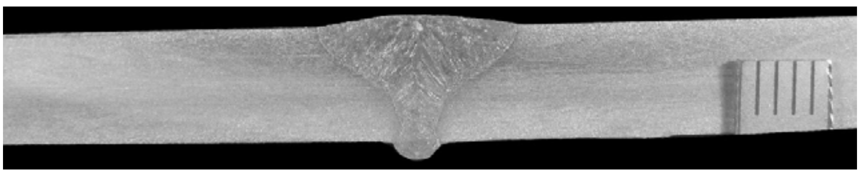
Thickness [mm]	Butt joint macrostructure
2.0	
4.0	
6.0	

Table 4. Comparison of the macrostructures of the butt joints made of 2.0 mm sheets in steel X6CrNi 18-10 using various plasma arc-based welding techniques, mag. 3.0x

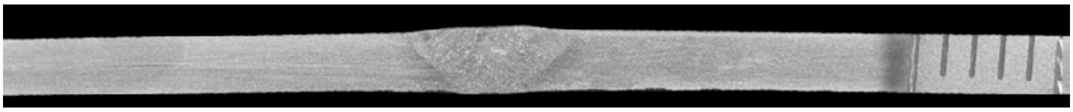
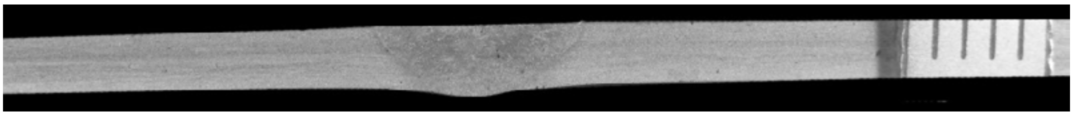
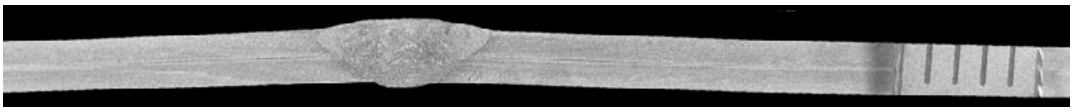
Welding method	Butt joint macrostructure
PAW	
PAW with cold wire	
PPAW	

Table 5. Comparison of the macrostructures of the butt joints made of 4.0 mm sheets in steel X6CrNi 18-10 using various plasma arc-based welding techniques, mag. 3.0x

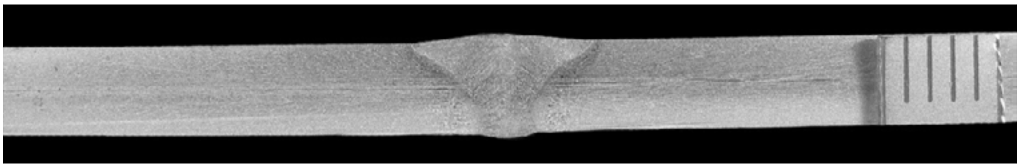
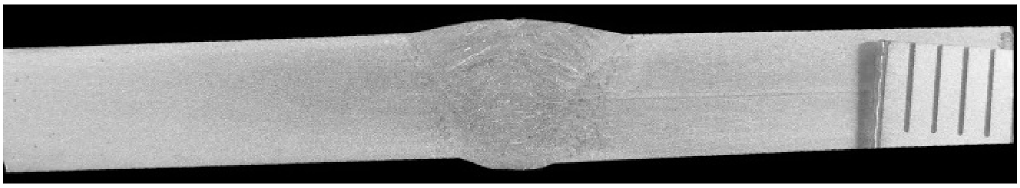
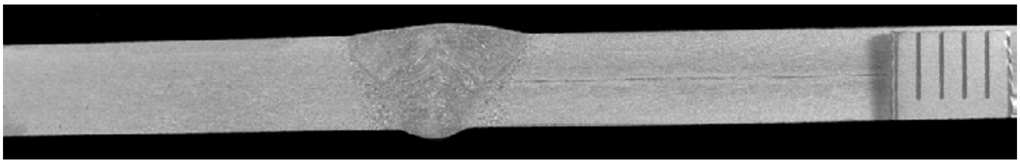
Welding method	Butt joint macrostructure
PAW	
PAW with cold wire	
PPAW	

Table 6. Comparison of the macrostructures of the butt joints made of 6.0 mm sheets in steel X6CrNi 18-10 using various plasma arc-based welding techniques, mag. 3.0x

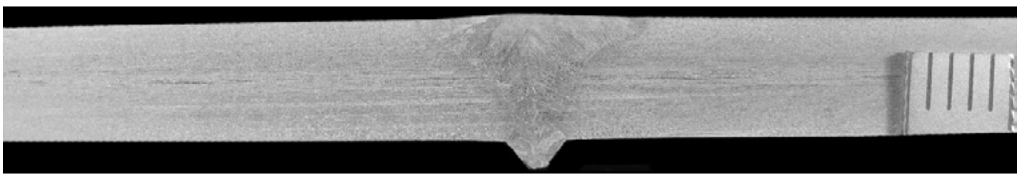
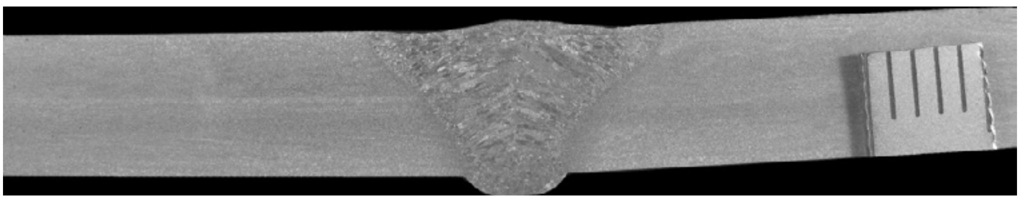
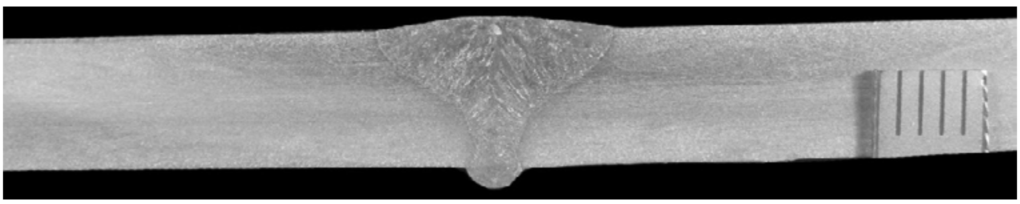
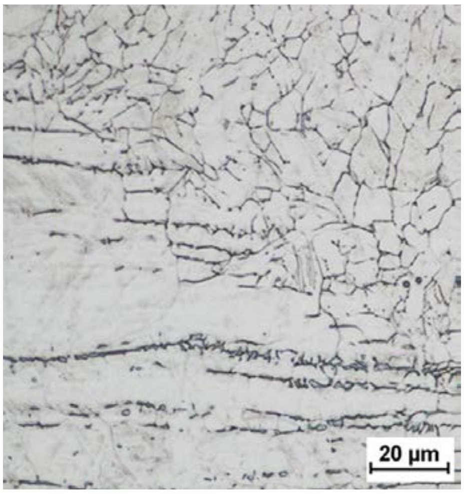
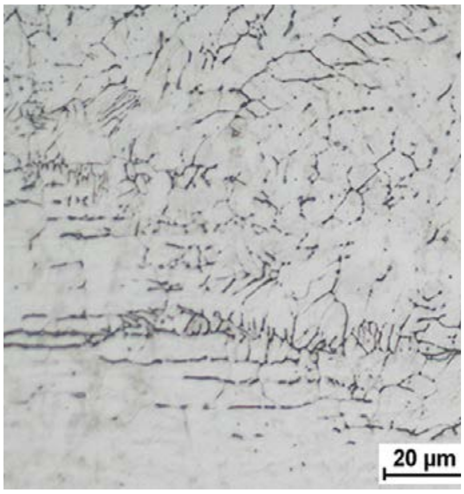
Welding method	Butt joint macrostructure
PAW	
PAW with cold wire	
PPAW	

Table 7. Microstructures of the butt joints made of 2.0 mm thick sheets in steel X6CrNi 18-10 in the fusion line (joints made using the PAW method with a cold wire and the PPAW method)

PAW with cold wire	PPAW
	

* left – base material; right – weld; mag. 500x

The subsequent stage of research included tensile tests and bend tests of the joints made using the plasma method without a filler metal (PAW) and with a cold wire (PPAW). The tensile tests were performed in accordance with PN-EN ISO 4136:2013-05 [15], whereas the bend tests were performed in accordance with PN-EN ISO 5173:2010/A1:2012 [16]. The tensile test results are presented in Table 8 (value R_m(w) constitutes the mean value based on five tests). The bend test results are presented in Table 9.

Table 8. Tensile test results concerning the welded joints made of steel X6CrNi 18-10 using the PAW and PPAW methods

Welding method	Type and grade of filler metal	Joint thickness [mm]	R_m(w)$^{1)}$ [MPa]	R_m(pm)$^{2)}$ [MPa]
PAW	without filler metal	2.0	**678.9**	540
		4.0	**638.5**	
		6.0	**617.6**	
	solid wire LMN 307 (X15CrNiMn 18 8) (ϕ 1.0 mm)	2.0	**670.4**	
		4.0	**659.1**	
		6.0	**620.8**	
PPAW	powder Eu-Troloy 16670.04 (X15CrNiMn 18 8)	2.0	**666.6**	
		4.0	**634.2**	
		6.0	**608.3**	

Note:
1) Rm(w) – tested tensile strength of the welded joint,
2) Rm(pm) – minimum tensile strength of the base material according to 10088-2:2014-12

Analysis of Test Results

The technological tests concerning the PAW (without a filler metal and with a cold wire) and the PPAW (with the addition of powder) methods using the Eutronic GAP 3001 device (Castolin) revealed that it was possible to obtain butt welds of 2.0, 4.0 and 6.0 mm thick sheets made of steel X6CrNi 18-10 representing quality level B according to the requirements of PN EN ISO 5817:2014-05 and characterised by high strength-related properties using all of the three plasma arc welding methods. During the technological welding tests concerning butt joint, the optimisation of parameters required the making of numerous joints, many of which contained welding imperfections (Fig. 3). The simplest method enabling the performance of a proper welding process, yet also the most susceptible to the formation of imperfections was the PAW method involving the use of a filler metal (wire LMN 307). However, it should be noted that the tests involving the above-named method were performed using the highest value of linear energy

Table 9. Bend test results concerning the welded joints made of steel X6CrNi 18-10 using the PAW and PPAW methods

Welding method	Type and grade of filler metal	Joint thickness [mm]	Diameter of bending mandrel [mm]	Obtained bend angle [°]	Required bend angle [°]
PAW	without filler metal	2.0	8	**180**	180
		4.0	16		
		6.0	20		
	solid wire LMN 307 (X15CrNiMn 18 8) (ϕ 1.0 mm)	2.0	8		
		4.0	16		
		6.0	20		
PPAW	powder EuTroloy 16670.04 (X15CrNiMn 18 8)	2.0	8		
		4.0	16		
		6.0	20		

and drew on the experience of previously conducted tests involving the PAW method without a filler metal. In cases of all of the welding methods and sheet thicknesses, the adjustment of proper linear energy was of vital importance as it prevented the formation of imperfections including dye penetration, burn-throughs or the lack of penetration. At the same time, in cases of 4.0 mm and 6.0 mm thick sheets it was necessary to decrease a welding rate because of undercuts appearing in the joints. The joints made using the PPAW method were characterised by the most aesthetic root and the convex face, which was confirmed by metallographic tests (Table 1÷6). The greatest problems concerning the optimisation of the parameters of the PAW method without a filler metal and of the PPAW appeared in relation to the 6.0 mm thick sheets. The visual and penetrant tests confirmed that a thickness of 6.0 mm constituted the "boundary" thickness enabling the obtainment of imperfection-free joints. The PAW method combined with the use of a cold wire enable the obtainment of welded joints of sheets thicker than 6.0 mm, yet characterised by inferior aesthetics and at risk of angular strain formation. The joints selected for the further tests did not reveal the presence of porosity or other surface imperfections.

The metallographic tests confirmed the results of the previous tests (lack of imperfections). In addition, the macroscopic tests revealed that the specimens representing all of the sheet thicknesses and made using the PAW method and the LNM 307 cold wire contained welds having greater cross-sectional areas and the widest HAZ in comparison with those made without a filler metal or using powder (Table 4÷6). This phenomenon could be ascribed to the higher value of linear energy and the greater amount of the filler metal supplied to the weld pool. The welds having the smallest cross-sectional areas were those made in the joints welded without the filler metal. The joints welded using the PPAW method revealed the narrowing of the welds on the root side along with the increase in the thickness of the material being welded.

The transverse tensile test (Table 8) revealed the decrease in the joint strength along with an increase in the thickness of sheets being joined. The strength of the individual thicknesses of joints was comparable in all of the welding methods tested, yet the highest values of R_m in relation to the joints made of the 2.0 mm thick sheets were obtained using the PAW method without a filler metal. In turn, as regards thicker sheets, the highest values were obtained in the joints made using the PAW method and the LMN 307 wire. The lowest tensile strength values were identified in relation to the joints made using the PPAW method. All of the joints ruptured in the welds. The differences of the results could be ascribed to various degrees of the stirring of the filler metal and the base material as well as to a heat input (linear energy) to the material depending on the welding method. As regards, the bend tests, all of the joints obtained a degree of 1800 without scratches and cracks on the specimen surfaces, which was tantamount to the positive result (Table 9).

Summary

The analysis of the test results justifies the statement that the technologies developed for the welding of 2.0, 4.0 and 6.0 mm thick sheets made of steel X6CrNi 18-10 using the PAW and PPAW methods were developed properly and enable the obtainment of welded joints representing quality level B according to PN EN ISO 5817:2014-12. The range of technological parameters representing proper welded joints is very narrow as regards the tested laser welding varieties and requires to be optimised in relation to all thicknesses and dimensions of sheets being joined. The use of the PPAW method resulted in the obtainment of joints characterised by the highest aesthetics, particularly in cases of 2.0 and 4.0 mm thick sheets. In turn, where the superior criterion is the strength of joints the use of the PAW method without a filler metal or with a cold wire (depending on the thickness of elements to be joined) is recommended.

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