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ADVANCES IN MANUFACTURING SCIENCE AND TECHNOLOGY
Vol. 41, No. 4, 2017
DOI: 10.2478/amst-2017-0022

MECHANICAL PROPERTIES AND METALLOGRAPHIC CHARACTERISTICS OF GIRTH WELDED JOINTS MADE BY THE ARC WELDING PROCESSES ON PIPE STEEL GRADE API 5L X70

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Summary

In the paper the results of welding of girth welded joints of steel pipe API 5L grade X70 (L485M) are presented. Manual metal arc (MMA) and metal active gas welding (MAG) were applied. Two welding filler metals for MMA were used to weld the girth welded joints and one for MAG process. The results of mechanical tests and distribution of residual stress of the girth welded joints are presented. Results indicated that MMA and MAG welding processes allowed to achieved the proper girth welded joints from the quality and mechanical properties point of view. Moreover, results of microscopic examination of welded joint, based on light microscopy are presented. In the root passes of MMA girth welded joint ferrite prevails with a grain size of several dozen micrometres. On the borders of ferrite grains, a second structural component, occurring as small islands of a few micrometres in diameter, can be distinguished, which may be either martensitic-austenitic (M/A) component, bainite or fine perlite. In the cap passes a bainitic structure was observed. In the case of MAG welded joints the weld microstructure consists of primary austenite grains, and on the primary boundaries the ferrite can be recognized. This ferrite forms a continuous phase and Widmanstätten ferrite, which lathes grow into the interior of the grains.

Keywords: API 5L X70 steel pipeline, girth welded joints, arc welding processes

Właściwości mechaniczne i mikrostruktura złączy doczołowych obwodowych rur ze stali API 5L X70 wykonanych metodami łukowymi

Streszczenie

W artykule przedstawiono wyniki badań spoin spawanych doczołowych obwodowych rur stalowych – gatunek API 5L X70 (L485M). Spoiny wykonano metodą spawania ręcznego elektrodą otuloną i spawania półautomatycznego MAG. Do spawania elektrodami otulonymi zastosowano dwa gatunki materiałów dodatkowych, natomiast do spawania metoda MAG jeden gatunek materiału. Przedstawiono analizę wynikow badań właściwości mechanicznych połączeń spawanych obwodowych oraz określono rozkład naprężeń resztkowych. Stwierdzono, że procesy spawania ręcznego elektrodami otulonymi i półautomatycznego MAG pozwoliły na wykonanie spoin spełniających wymagania zarówno jakościowe, jak i właściwości mechanicznych. Wykonano badania mikroskopowe połączeń spawanych za pomocą mikroskopu świetlnego. Wykazano, że w obszarze grani (ściegi graniowe) dominuje struktura ferrytyczna o rozmiarze ziarna do kilkadziesiąt mikrometrów. Obserwowano na granicach ziaren ferrytu dodatkowe wydzielenia drugiego składnika mikrostruktury (o średnicy ziarna kilkanaście mikrometrów): wyspy martenzytyczno-austenityczne (M/A), bainit lub drobny perlit. Stwierdzono, że w obszarze ściegów licowych dominuje struktura bainityczna. Ustalono również, że w przypadku złączy spawanych

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półautomatu MAG mikrostrukturę cechują pierwotne ziarna austenitu o większych rozmiarach (także obserwowano na pierwotnych granicach austenitu ciągłe wydzielanie ferrytu oraz ferryt Widmanstättena o płytkach wrastających w kierunku wnętrza ziarn.

Słowa kluczowe: rury ze stali API 5L X70, złącza doczołowe obwodowe, spawanie łukowe

1. Introduction

The strong demand for natural gas in European, North American and Asian countries is expected for the immediate future. In the case of Poland, over 2000 km gas pipelines for the next 10 years are planned to be produced by Gas Transmission Operator GAZ SYSTEM S.A. [1]. Moreover, in recent years spiral welded pipes (conventional grades, e.g. API 5L X70 or API 5L X80) have been used with success [2]. However the proper welding technology especially for girth welded joints has to be developed [3]. Basic welding processes actually used in production of steel pipelines are traditional automatic and semi-automatic GMAW (MIG/MAG), SSAW, MMAW and in limited scope - Tungsten Arc Welding – TIG (GTA) and SAW in a workshop for butt welded joints of double jointers. It should be noted, that the quality of welded joints is the most crucial parameter of a quality assurance system and in-service monitoring. Almost all registered disastrous catastrophic failures of pipelines started in the area of welded joints. Also non-arc welding processes have already been examined and evaluated over the past 30 years. One of the very efficient methods is resistance flash welding [4]. Large diameter pipelines have been installed onshore in Russia and Ukraine using this process but it has not generally been developed elsewhere. The second process category is laser welding [5] and hybrid laser arc welding (HLAW) [6].These are relatively efficient and also fairly robust and can be used on site. HLAW combines the benefits of both processes: laser welding and arc welding processes. The third one-shot process is Friction Stir Welding (FSW) [7] which is very repeatable for steel welded butt joints up to 12.7 mm wall thickness and is underway to expand its capability up to 20 mm. The fourth one-shot process is atmospheric electron beam welding (EBW). HLAW, EBW and FSW have been shown to improve productivity compared to typical arc welding processes. The increased productivity comes from either an increase in the maximum achievable welding speed or by increasing the single-pass weld thickness which reduces the total number of passes and weld metal volume required to complete a pipeline butt welded joint. These processes have some limitation: very high investment cost, limited flexibility of the application, hazards for operators, etc. Thus, the manual metal arc welding as well as MAG welding technologies are steel the most popular techniques for pipeline application.

Ghomashchi and co-workers [8] revealed that the microstructure of girth welded joint of API 5L X70 steel produced by the MMA welding with cellulosic electrodes composed of Widmanstätten and acicular ferrites, lamellar pearlite and aggregated ferrite–carbide. The upper and lower bainite morphologies were also detected.

Anderson Laursen et al. [9] presented the results of influence of weld thermal cycle on residual stress of API 5L X70 welded joint. The transverse and longitudinal residual stress, were measured in regions of the root pass (bottom) and finishing (top), through the technique of X-ray diffraction by a portable diffractometer. They revealed, that compressive residual stresses were found in the weld metal and tensile in the HAZ. Lower values of residual stress were found in root passes welded by GTAW process and in welded joint with less thickness. Hamdi and co-workers [10] also presented the profiles of residual stresses in welded API 5L X70 plates. The sin Ψ2 method, by measurement of the X-ray diffraction was applied. They revealed that the residual stress is concentrated in the fusion zone, which is a mechanically vulnerable site, due to the spread of micro-cracks that develop into the macro cracks.

The methods of prediction of the mechanical properties, as yield strength, tensile strength, impact energy, and hardness, and the fracture mechanical values of girth welded joints are presented by Felber [11]. The tested materials were the base material, the weld metal, and the heat-affected zone of welds, using MMA and MAG welding processes. It was revealed that the proper prediction of mechanical properties is burden of uncertainty. Therefore, the mechanical properties have to be determined based on real mechanical tests.

The aim of the study was to develop the technology of welding of girth welded joints of steel pipe API 5L grade X70 (L485M) with a diameter of 914.4×17.1 mm. In the presented work the effect of welding process on mechanical properties and microstructure of weld metal was examined. The results of mechanical tests as well as residual stress measurements were also presented.

2. Experimental procedure

Investigations were carried out on high strength microalloyed API 5L X70 pipeline grade steel (L485 acc. to PN-EN ISO 3183), with a diameter of 914.4 mm (36") and wall thickness of 17,1 mm (Fig. 1). The mechanical properties of the investigated steel are presented in Table 1.

Welding trails were performed using MMA and MAG welding processes, in accordance with the developed at the Instytut Spawalnictwa individual Welding Procedure Specifications (WPS). Two covered electrode and one welding wire were used to produce the girth welded joints. The characteristics of filler material are given in Tables 2 and 3. Welding procedure was qualified in accordance with PN-EN ISO 15614-1 standard. Non-destructive and mechanical testing of the test pieces were performed. Visual examination and other NDT testing (UT, RT) were performed 48 hours after the completion of the welding of each test piece. No significant imperfections were observed. Thus, the quality level B according to EN ISO 5817 was estimated. Test specimens for mechanical tests from the position shown in Fig. 2 were taken.

Fig. 1. Specimens pipes with a diameter of 914.4 mm (36"), wall thickness of 17.1 mm and 250 mm in length, API 5L X70 steel

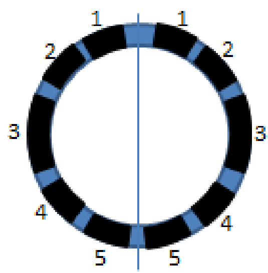

Fig. 2. Welding procedure qualification test – sampling of test specimens for girth butt welds, where: 1 – macro, micro and hardness test specimens (PA - downhand), 2 – tensile and bend tests, 3 – fracture toughness specimens, 4 – tensile and bend tests (PE - overhead), 5 – macro, and hardness test specimens (PE – overhead)

Table 1. The mechanical properties of steel API 5L X70 (L485)

Specimen				**Mechanical properties**						
No	**Dimension**			**$F_{0.5}$**	**F_m**	**$R_{0,5}$**	**R_m**	**L_u**	**A_5**	Remarks
	$a_0 \times b_0$ mm	L_0 mm	S_0 mm^2	kN	kN	MPa	MPa	mm	%	
4A	17.1×25.3	120	432.6	239.6	275.3	553.9	636.4	145.7	21.4	Transversal to the pipes axis
4B	17.1×25.2	120	430.9	243.2	273.3	564.5	634.3	144.7	20.6	
5A	17.1×25.0	120	427.5	258.3	279.6	604.1	654.0	147.4	22.8	

5B	17.15×24.9	120	427.0	259.6	279.1	607.8	653.5	146.9	22.4	Parallel to the pipes axis

Table 2. Selected filler metal for MMA and MAG welding

No	**Grade of filler metal/producer**	**Acc. to standards**	**diameter, mm**	**Description**
1	Pipeliner 6P+/ Lincoln Electric (Root passes)	PN-EN ISO 18275:2012	3.2	All-position cellulosic pipe electrode designed for all position pipe welding, including vertical down root pass welding Designed for root pass welding of pipe up to and including X80, fill and cap pass welding up to and including X60
2	FOX EV 85/ Böhler (Cap passes)	PN-EN ISO 18275:2012 E 69 6 Mn2NiCrMo B 4 2 H5	4.0	Basic coated electrode with high ductility and crack resistance, for high-strength fine-grained steels up X80. Very low hydrogen content.
3	LMN MoNiVa / Lincoln Electric (Root and cap passes)	PN-EN ISO 16834 - A G 69 4 M Mn3Ni1CrMo;	1.2	Solid wire for welding high strength steels with yield strength up to 690 MPa

Table 3. Mechanical properties of weld metal for filler material of MMA and MAG welding processes

Specimen				**Mechanical properties**							
No	**Dimension**			F_e	F_m	R_e	R_m	L_u	A_5	d_u	**Z**
	d_0 mm	L_0 mm	S_0 mm^2	**kN**	**kN**	**MPa**	**MPa**	**mm**	**%**	**mm**	**%**
Pipeliner 6P+											
6PA/R/1	9.93	50	77.4	35.9	42.8	463.5	553.0	58.6	17.2	8.20	31.8
6PA/R/2	9.95	50	77.7	36.3	42.3	466.5	544.5	60.3	20.6	8.17	32.6
FOX EV 85											
B8/R/1	9.91	50	77.1	66.33	71.10	859.9	921.8	59.2	18.4	6.11	62.0
B8/R/2	9.92	50	77.2	68.13	72.13	881.6	933.3	58.4	16.8	6.12	61.9
LMN MoNiVa											
3/R/1	9.88	50	76.63	58.79	64.23	766.9	837.8	56.6	13.2	8.07	33.3
3/R/2	9.92	50	77.25	59.14	63.36	765.3	819.8	54.7	9.4	8.45	27.4

According to PN-EN 15614-1, the following destructive tests for butt welded joints were carried out: metallographic examination acc. to PN-EN ISO 17639: 2013-12E, hardness test (Fig. 3) acc. to PN-EN ISO 9015-1: 2011, bending test acc. to PN-EN ISO 5173: 2010 / A1: 2012, transverse tensile test acc. to PN-EN ISO 4136: 2013-05, and finally impact tests acc. to PN-EN ISO 148-1: 2010.

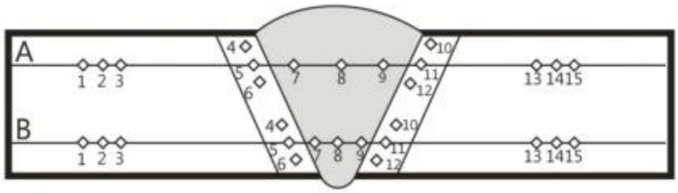

Fig. 3. Scheme of hardness measurements

The trepanation method was applied in order to determine the residual stress in welded joints. The measurement is based on the preparation of the measurement bases equally spaced and of predetermined length, wherein the metal balls mechanically pressed into the material are used as the measuring points. Then, using a mechanical extensometer measuring is carried out in the distance between the data points of bases. Extensometer equipped with contact rods is set on balls and displays the result readout on the dial indicator. The study utilizes the mechanical extensometer produced by the Fritz-Staeger company. This instrument allows to carry out measure with accuracy of measurements 10^{-4} mm on bases in length of 20 40, 60 and 100 mm. The measurement bases are steel balls with diameter of ϕ 1,588 mm (1/16"), which are pressed into the holes with a diameter of 1,3 mm drilled into the test piece. The detailed description of this method is presented in the previous paper [12].

3. Results and discussion

The purpose of the study was to determine the differences of microstructure and mechanical properties of the girth welded joints depending on the welding technology and the applied filler material. The microstructure of base material API 5L X70 steel in Fig. 4 is presented and is composed of acicular ferrite and granular bainite, with the presence of a small amount of martensite–austenite constituent (MA).

The MMA girth welded joints were made with two different filler materials. The root passes were made with covered electrode grade Pipeliner 6P+ and cap passes were made with covered electrode grade FOX EV 85. The results of macroscopic examination of girth welded joints are presented in Fig. 5a. The MAG girth welded joint was made with wire grade LMN MoNiVa (Fig. 5b).

In the MMA girth welded joint made with FOX EV85 filler material for cap passes and Pipeliner 6P + for root passes, from the microstructure point of view, the two different areas can be clearly distinguished (Fig. 6). The root passes, formed by several weld beads, about 5 mm thick, were separated from the cap passes of the welded joints by a clear boundary. In the root passes (bottom part)

ferrite prevails with a grain size of several dozen micrometres. On the borders of ferrite grains, a second structural component, occurring as small islands of a few micrometres in diameter, can be distinguished, which may be either martensitic-austenitic (M/A) component, bainite or fine perlite.

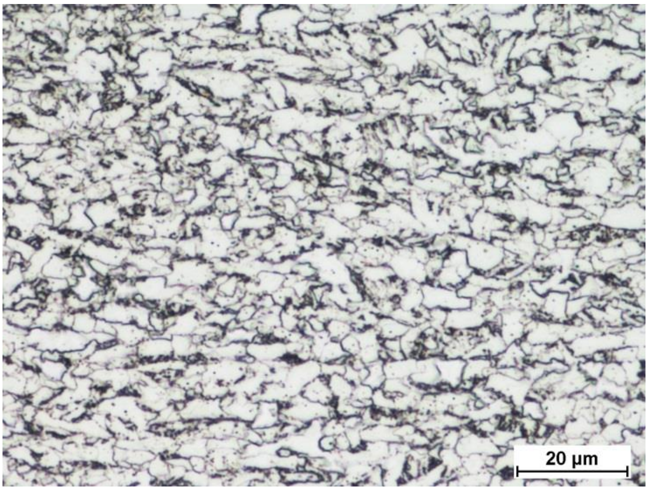

Fig. 4. Microstructure of steel API 5L X70 (L485)

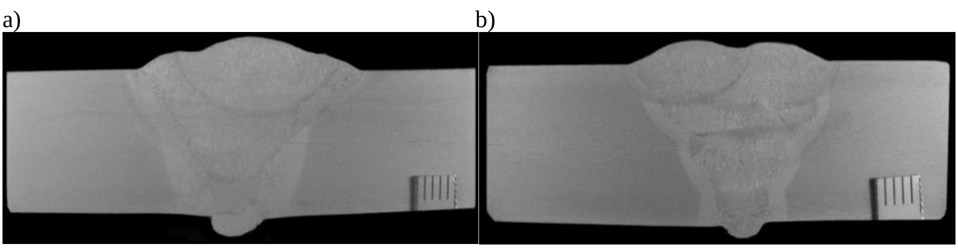

Fig. 5. Macroscopic examination of girth welded joints, a) FOX EV 85 + Pipeliner 6P+ for root passes, b) LMN MoNiVa for root and cap passes

Also, in the case of girth welded joints made with the MAG method, distinctive zones of different microstructure can be distinguished. The microstructure near the fusion line of the welded joint made with LMN MoNiV filler material in the light microscope for weld metal shown in Fig. 7. The microstructure of the weld metal is a fine bainite. The maxiumum hardness of the weld metal is 319 HV10, which corresponds to the observed microstructure.

a) b)

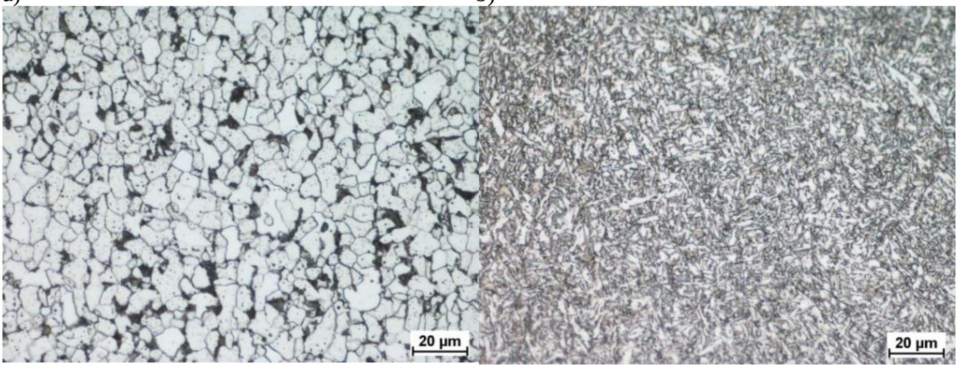

Fig. 6. Microstructure of MMA girht welded joint – weld metal: a) root passes made with covered electrode Pipeliner 6P+, b) cap passes made with covered electrode FOX EV85

a) b)

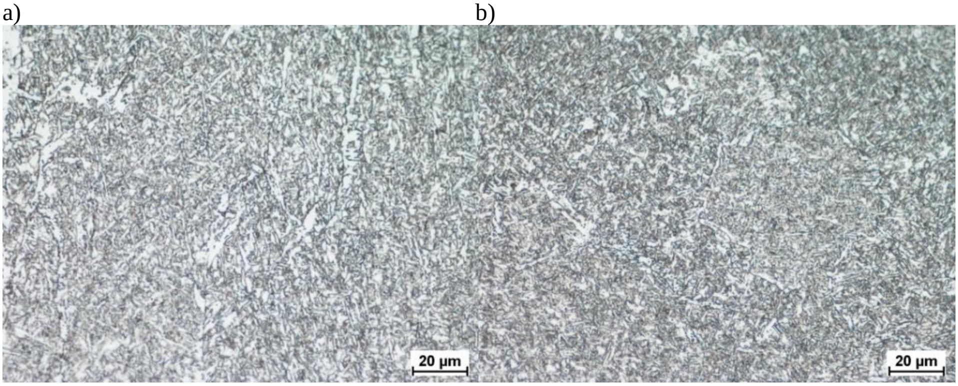

Fig. 7. Microstructure of weld metal in the MAG girth welded joint made with LMN MoNiVa, a) root passes, b) cap passes

Table 4. Results of hardness tests for MMA and MAG welded joints (Fig. 3)

No Lin	**Hardness in point HV10**														
	Filler material Pipeliner 6P+ FOX EV85														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Line A	222	219	221	206	220	238	299	278	295	226	218	211	225	226	222
Line B	220	220	218	192	198	218	179	182	184	237	206	197	228	227	229
Filler metal LMN MoNiVa															
Line A	213	213	206	204	220	261	276	319	300	225	203	206	204	200	192

Line B	218	226	229	216	215	220	245	249	253	217	219	214	214	189	192

Table 5. Results of mechanical properties of MMA and MAG girth welded joints

Specimen			**Mechanical properties**								
No	Dimension		F_m	R_m	Bend angle °	Impact energy [J]/ toughness [J/cm^2]					
	$a_0 \times b_0$ [mm]	S_0 [mm^2]	[kN]	[MPa]		+20°C			-10°C		
Filler material Pipeliner 6P+ FOX EV85											
85E/R/1	15.9×25.0	397.5	271.3	682.4							
85E/R/2	16.0×25.0	400.0	272.7	681.7							
85E/FBB	15.2×27.5	418.0			180						
85E/RBB/1	15.3×27.8	425.3			180						
85E/RBB/2	15.2×27.3	415,0			180						
65/VWT	8.0×10.0	80.0				120 150.0	112 140.0	120 150.0	86 107.5	102 127.5	86 107.5
65/VHT	8.0×10.0	80.0				100 125.0	156 195.0	160 200.0	210 262.5	104 130.0	82 102.5
65/VHT 2	8.0×10.0	80.0				216 270.0	224 280.0	216 270.0	214 267.5	88 110.0	122 152.5
65/VHT 5	8.0×10.0	80.0				222 277.5	218 272.5	222 277.5	200 250.0	206 257.5	198 247.5
Filler metal LMN MoNiVa											
1E/R/1	17.0×24.8	421.6	268.3	636.5							
1E/R/2	17.0×24.8	421.6	270.9	642.5							
1E/FBB	16.0×27.1	433.6			180						
1E/RBB	16.0×26.9	430.4			180						
1F/VWT	8.0×10.0	80.0				102 127.5	108 135.0	100 125.0	98 122.5	88 110.0	84 105.0
1F/VHT	8.0×10.0	80.0				120 150.0	136 170.0	222 277.5	94 117.5	96 120.0	88 110.0
1F/VHT 2	8.0×10.0	80.0				206 257.5	198 247.5	210 262.5	102 127.5	96 120.0	96 120.0
1F/VHT 5	8.0×10.0	80.0				216 270.0	180 225.0	210 262.5	196 245.0	192 240.0	200 250.0
Remarks: bend test: d=4g, d=60mm											

The mechanical properties of MMA and MAG girth welded joints are given in Tables 4 and 5.

The results of hardness measurements revealed that the maximum hardness in HAZ is 261HV10. This result is acceptable (max hardness, acc. to ISO 15614:1 have to be lower than 380HV10). Moreover, the result indicated that the lowest hardness is in weld metal of MMA girth welded joint in root passes (179HV10).

This cause, the fact that the root passes were made by Pipeliner 6P+. This covered electrode, guarantee the lower strength of weld metal as well as lower hardness.

The tests of mechanical properties of girth welded joints confirmed the requirements of the project [13]. During tensile tests, for all specimens, rupture out of the welded metal were observed. Also the bend tests revealed that the plasticity of welded joints is adequate. No significant imperfections for bend angle 180° were observed. Acc. to the standards requirements the single and average Charpy V-notch toughness at each position shall not be less than 60 J and 80 J at –10°C, for single sample and average value, respectively [13]. The conducted experiments revealed that the Charpy V-notch toughness, for all samples, is much higher than minimum requirements.

The distribution of residual stress in welded joints was also measured. Higher level of stress in the welded joint was observed for filler metal type LMN MoNiVa (474 MPa), and lower for covered electrode type FOX EV85. However, in the heat affected zone the higher level of stress was shown for the filler metal FOX EV85 (222 MPa), and the lower for LMN MoNiVa. The views of plate after cutting are shown in Fig. 8. The results of measurements are shown in Fig. 9.

a) b)

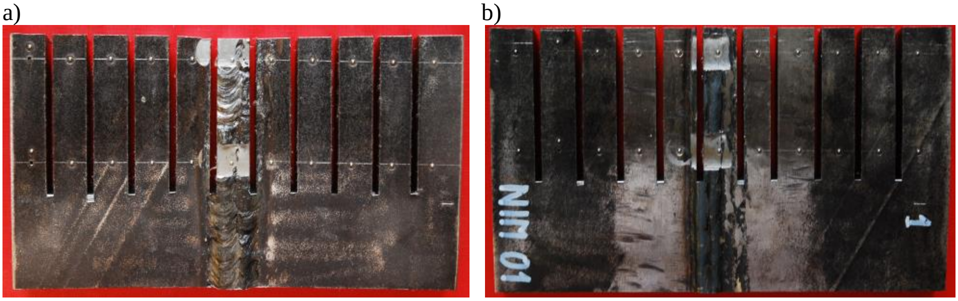

Fig. 8. Welded plate with basses after cutting, filler material a) Pipeliner 6P+ FOX EV85, b) LMN MoNiVa

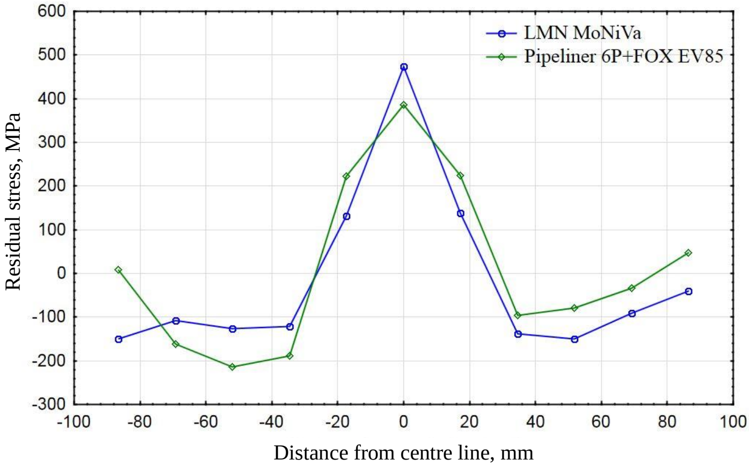

Fig. 9. Results of experimental measurement of residual stress of MMA and MAG welded joints

Summary

The purpose of the study was to determine the differences of microstructure of the girth welded joints and mechanical properties depending on the welding technology and the applied filler material. The results of this research are summarized as follows:

- the MMA as well as MAG welding processes guarantee the proper quality of girth welded joints,
- the maximum hardness in the girth welded joints did not go beyond the limits (380HV10),
- in the root passes of MMA girth welded joint ferrite prevails, meanwhile in the cap passes a bainitic structure was observed. In the case of MAG welded joints the weld microstructure consists of primary austenite grains, and on the primary boundaries the ferrite can be recognized,
- during tensile tests, for all specimens, rupture out of the welded metal was observed,
- higher level of residual stress in the welded joint was observed for filler metal type LMN MoNiVa than for covered electrode type FOX EV85.

Acknowledgements

The authors would like to thank Research Fund for Coal and Steel *(*RFCS*)*. The research was performed within the framework of the SBD-SPipe Project, Grant Agreement Number: RFSR-CT-2013-00025.

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Received in September 2017