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R. KRAWCZYK*#

AN ANALYSIS OF THE JOINTS' PROPERTIES OF THICK-GRAINED STEEL WELDED BY THE SAW AND ESW METHODS

The article presents an analysis of properties of welded joints of thick-grained steel of P460NH type used more and more often in the modern constructions. A process of examining a technology of welding has been carried out on the thick-walled butt joints of sheet metal by two methods of welding namely submerged arc welding (SAW – 121) and electroslag (ESW – 722). The article deals with a topic of optimizing a process of welding thick-walled welded joints of fine-grained steel due to their mechanical properties and efficiency.

Keywords: welding, properties of joints, fine-grained types of steel, non-destructive, and destructive testing, optimizing a process of welding

1. Introduction

At the time of a continuous economy growth there is an increasing need for steel constructions particularly in the following sectors: power engineering and metallurgy. Mentioned need refers mostly to manufacturing huge and heavy welded constructions such as steam turbine castings for conventional and nuclear power plants, or convection heaters for metallurgy. Above constructions are characterised by a great number of thick-walled welded joints. Manufacturers of such constructions often stand in front of a problem which method of welding is the most appropriate to make joints. In order to make a right decision specialists need to possess all the necessary information relating to the technology of welding, characteristics of materials, and also properties of welded joints.

The aim of an article is to take examinations of a technology of welding of thick-walled welded joints made from fine-grained steel standard annealed, and designed for pressure devices. Examination of a welding technology taken according to the PN-EN ISO 15614-1 standard includes a preparation of a technology of welding, and doing destructive and non-destructive tests of welded joints. Two methods of welding were used to make sample thick-walled joints namely submerged arc welding by the solid welding electrode (SAW 121) currently the most popular method to weld such kind of elements, and electroslag welding (ESW – 722) currently very rarely used in the world for construction welding. Results of examinations of welding technologies should provide numerous valuable information, which are vital to make proper decisions while choosing a technology of welding.

2. Characteristics of welding methods

Two methods of welding [1] were used to take an examination of the welding technology i.e.:

- 121 – submerged arc welding by the solid welding electrode (SAW),
- 722 – electroslag welding by the solid welding electrode (ESW).

Above methods fulfil the requirements which are put on thick-walled joints both by means of technology and efficiency.

Welding by the SAW method

Welding by the submerged arc (Eng. Submerged Arc Welding; SAW) method refers to melting the edges of the joint's elements and the material of the melting electrode by the heat of an electric arc under a layer of granular flux. A source of the heat is an electric arc, which is arcing in a gaseous atmosphere made of a melted flux between a melting electrode and a welded material [2]. The flux also stabilizes the arc in welding process, forming on the bead surface and influences of the deposited metal chemical composition. The process is characterized by a long residence time of the material in the liquid state from several to tens of seconds depending on the welding conditions particularly current, voltage and welding speed. During the melting and crystallization of the metal a range of physical and chemical influence on weld shape, chemical composition and mechanical properties takes place. This method is characterised by a high purity of metallurgy, and very good properties of the joints of all types of steel used for welding constructions, as well as other materials. The 121 method is also characterised by the

* CZĘSTOCHOWA UNIVERSITY OF TECHNOLOGY, 69 J. H. DĄBROWSKIEGO STR., 42-201 CZĘSTOCHOWA, POLAND

\# Corresponding author: ryszardkrawczyk@spaw.pcz.pl

high efficiency of welding, and is often dedicated to make joints of thick-walled elements. It allows to weld only in the flat and horizontal positions of welding in mechanized conditions [3]. The basic parameters of submerged arc welding include:

- welding current type [A],
- arc voltage [V],
- type and diameter of the electrode [mm],
- welding speed [m/min],
- type of flux, the thickness and width of the layer [mm],
- length of protruding section of the electrode [mm],
- angle of the electrode or the welded joint [°].

The main advantage of submerged arc welding is a very high quality of the obtained welds with also high performance welding.

Welding by the ESW method

Electroslag Welding (Eng. Electroslag welding: EMS) method refers to melting the edges of the joint's elements and the material of the melting electrode by the layer heat of liquid slag coming from the molten flux. The heat source is a layer of molten slag to be heated resistively by current flow through the liquid slag between the electrode immersed in the slag bath and the melted material [8,9]. Slag bath underlying the process activities is formed from molten flux, and is in a liquid state during the whole process. The layer of liquid slag melts immersed in the electrode and the edges of the joined materials in a limited space shores of welded components and forming separators. Electroslag welding process is carried out in a vertical or near-vertical position most often in a single pass [10]. Electroslag welding process is carried out in a vertical or near-vertical most often in a single pass. This method is used for welding of thick-walled elements typically ranging from 30 to 450 mm under the mechanized conditions and is characterized by high performance welding [2,11].

The basic electroslag welding parameters are:

- welding current type [A],
- supply voltage [V],
- quantity and diameter electrodes [1-3pcs], [mm],
- electrode feeding speed,
- speed and amplitude of oscillation of the electrode [m/h], [mm],
- flux type and slag layer thickness [mm],
- distance between the electrodes [mm],
- welding speed [m/h].

The main advantage of electroslag welding is a very high performance welding allows to make joint on almost any thickness without costly chamfering edge.

3. Materials used for examinations

Metal plates from the 1.3 group according to the PN ISO 15608 [4] of the P460NH type according to the PN EN 10028-3 [5] standard were used for examinations as the basic materials. Above materials belong to the welding type of steel, fine-grained, standard annealed to use in elevated temperatures, intended to use inter alia in pressure devices [12]. Normalized fine-grained types of steel are characterised by the thigh mechanical properties, and due to a high carbon equivalent (higher content of manganese, and a presence of other elements) are more susceptible to harden in the HAZ than low carbon types of steel. What is more, they are more exposed to form cold cracks. Thus, it is recommended to follow these rules [13-15]:

- to reduce an amount of a diffused hydrogen inserted into the weld by removing contaminations, rust, and moisture from an area of welding, as well as using a low-hydrogen welding processes,
- to use heating elements of greater thickness in order to avoid creating martensite in the HAZ,
- to use appropriate technological solutions in order to reduce shrinkage stresses [6].

If the following requirements are fulfilled than we can accept that special safety regulations are not required assuming that a low-hydrogen process of welding was used for steel of R_m = 490-690 MPa resistance (recommendations of the International Welding Institute)

$$C \leq 0{,}20\% \text{ i } Ce \leq 0{,}45\% \text{ and } g \leq 25 \text{ mm}$$

Or

$$C \leq 0{,}20\% \text{ i } Ce \leq 0{,}41\% \text{ and } 25 < g \leq 37 \text{ mm}$$

In the fine-grained types of steel there is a limited growth of austenite grains in the HAZ. It is caused by the precipitations of carbides, nitrides or carbonitrides of micro-alloyed elements. Fine-grained austenite while changing in the process of melting of welded joint makes structures of high impact value. A general characteristics of fine-grained type of steel used in the P460NH examinations is presented in the tables 1, 2 and 3.

Meeting the requirements of the PN-EN 10028-3 standard allows to presume a compatibility with appropriate requirements of the 97/23/WE pressure directive. Steel produced according to the above standard can be used to make pressure devices, which can be exploited in the European Union.

TABLE 1

Chemical composition (a ladle chemical analysis) [5]

Type of steel		% weight														
symbol	No.	C max	Si max	Mn	P max	S max	Al_{total} min	N max	Cr max	Cu max	Mo max	Nb max	Ni max	Ti max	V max	Nb+Ti+V max.
P460NH	1.8935	0,20	0,60	1,10 do 1,70	0,025	0,015	0,020	0,025	0,30	0,70	0,10	0,05	0,80	0,03	0,20	0,22

TABLE 2

Mechanical properties in an ambient temperature [5]

Type of steel		Regular state of delivery	Thickness of the material *t*, [mm]	Boundary of plasticity R_{eH} min., [MPa]	Tensile strength R_m, [MPa]	Elongation after breaking *A* min., [%]
Symbol	Number					
P460NH	1.8935	+N	≤ 16	460	570 to 720[b]	17
			16 < t ≤ 40	445		
			40 < t ≤ 60	430		
			60 < t ≤ 100	400	540 to 710	
			100 < t ≤ 250	[a]	[a]	[a]

[a] Values can be agreed while inquiring about an offer and ordering
[b] There is a permissible maximum value of 730 MPa for products of 16mm thick

TABLE 3

Minimal impact values [5]

Type of steel	Thickness of a product [mm]	Work of fracture KV [J] min									
		Transverse					Longitudinal[a]				
		–50	–40	–0	0	+20	–50	–40	–20	0	+20
P460NH	5 do 100	—	—	30	40	50	—	—	45	65	75

[a] Above values refer to products of 40 mm thick

4. Examinations of a technology of welding

Certain examinations of sample welded joints were taken in order to make an assessment of a technology of welding taking into account acceptance criteria included in the standard, which relates to an examination of a technology of welding namely the PN-EN ISO 15614-1 standard. Examinations were taken on the sample joints made according to the initial technology conditions for the SAW – 121 and ESW – 722 methods of welding.

Sample welded joints

The PN-EN ISO 15614-1 standard describes requirements relating to an assessment of an initial manual welding technology by means of examinations taken on the sample joints. Sample joints for examinations were prepared from the P460NH steel:

- steel of 40 mm thick metal plates with an X bevelled for a double-sided butt welding according to the requirements of the mentioned standard for SAW – 121 method,
- steel of 30 and 55mm thick metal plates with an I bevelled for a butt welding according to the requirements of the mentioned standard for ESW – 722 method.

For welding by SAW – 121 and ESW – 722 methods a joints measuring 300×700 mm was prepared. An initial manual welding technology for making sample joints was prepared where detailed welding conditions for particular processes were included. For the method 121 welded joint used of the groove angle of 60°, height of root face 2 mm and 3 mm spacing of root face. For welded joints by 722 method applied the distance between the edges of welded elements, respectively: 25÷28 mm to 30 mm thick joints and 30÷35 mm to 55 mm thick joints. To perform the test joint by SAW method adopted performance penetration bead and first filling by MAG – 135 method. The key data of an initial manual welding technology of sample welded joints is given in tables 4, 5 and 6.

TABLE 4

Details relating to the SAW method in the flat position – PA with a joint penetration made by the MAG method

Bead sequence	Welding process	Filler metal size [mm]	Current [A]	Voltage [V]	Travel speed [cm/min]	Polarity	Heat input [KJ/cm]
1	135	1,2	150-170	20-22	24-26	DC/+	4,9-5,6
2	135	1,2	180-200	23-25	21-23	DC/+	7,7-8,5
3	121	4,0	350-380	26-27	55-60	DC/+	8,9-9,2
4-n	121	4,0	450-500	29-31	30-32	DC/+	23,5-26,3
1’-n’	121	4,0	450-500	29-31	30-32	DC/+	23,5-26,3
Solid wire-classification:		135: G2Mo according to the EN ISO 14341-A (OK AristoRod 13.09) 121: G3Mo according to the EN ISO 14171-A (OK AristoRod 12.34)					
Shielding gas type: Ferromix C18 – M21 according to the PN-EN ISO 14174							
Flux type: S A AB 1 67 AC H05 according to the PN-EN ISO 14175 (OK Flux 10.71)							
Drying time: 3h				*Drying temperature:* 300-350°C			
Gas flow rate: [l/min]: 14 – 18				*Preheat temperature:* ≥ 100°C			
Heat treatment: not applicable				*Interpass temperature:* ≤ 250°C			

TABLE 5

Details relating to the ESW method in the vertical position PF 30 mm plate thickness

Bead sequence	Welding procesess	Filler metal size [mm]	Current [A]	Voltage [V]	Travel speed [cm/min]	Polarity	Heat input [KJ/cm]
1	722	3,0	480-530	37-39	1,9-2,3	DC/+	500 – 490
Solid wire-classification: S3Mo wg PN EN 756 (OK Autrod 12.34)							
Flux type: TU-St-B wg PN-67/M-69356							
Drying taime: 2-3h				*Drying temperature:* 300-350°C			
Heat treatment: N/A				*Interpass temperature:* ≤ 250°C			

TABLE 6

Details relating to the ESW method in the vertical position PF 55 mm plate thickness

Bead sequence	Welding procesess	Filler metal size [mm]	Current [A]	Voltage [V]	Travel speed [cm/min]	Polarity	Heat input [KJ/cm]
1	722	3,0	480-530	39-40	1,7-1,8	DC/+	602 – 636
Solid wire-classification: S3Mo wg PN EN 756 (OK Autrod 12.34)							
Flux type: TU-St-B wg PN-67/M-69356							
Drying taime: 2-3h				*Drying temperature:* 300-350°C			
Heat treatment: N/A				*Interpass temperature:* ≤ 250°C			

A view from the face side of the weld of fragments of welded joints made by the SAW method is shown in the picture 1, while a welded joint made by the ESW method in the picture 2 and 3.

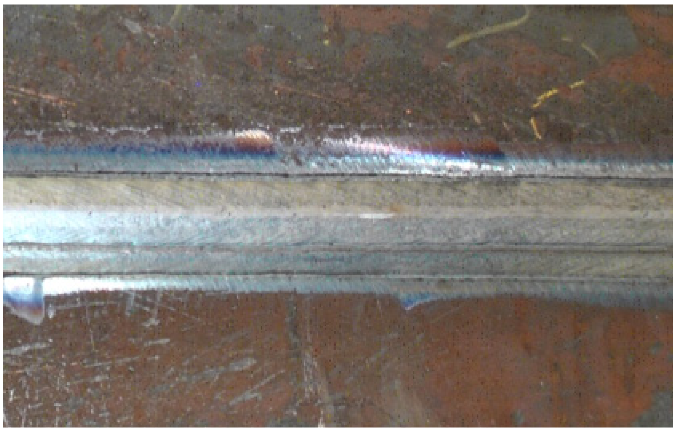


Fig. 1. A view of the face of weld made by 121 method in a PA position

Fig. 2. A view of the face of weld made by 722 method in PF /g30 mm position

Fig. 3. A view of the face of weld made by 722 method in PF /g55 mm position

Examinations of sample welded joints

Checking a technology of welding according to the PN-EN ISO 15614-1 standard requires carrying out examinations on the sample joints in compliance with the requirements included in table 7, and relating to a given example i.e. butt joints of metal sheets with a full joint penetration.

TABLE 7

Range of control and examination of sample joints according to the PN-EN ISO 15614-1 standard [7]

Sample joint	Type of examination	Scope of examination
Butt joint with a complete joint penetration	Visual testing Radiographic or ultrasonic testing Detecting surface cracks Transverse tensile test Transverse bend test Impact strength test Hardness test Macroscopic examinations	100 % 100 % 100 % 2 samples 4 samples 2 sets required 1 sample

At first, non-destructive testing were done in a full range for all sample joints i.e. visual testing (VT), magnetic particle testing (MT), ultrasonic testing (UT), and radiography testing (RT). Taking into account requirements of the PN-EN ISO 15614-1 standard a number of examination methods was extended into a radiography testing. Tests were done after 48 hours from finishing a welding process. Quality level B was taken as an acceptance criterion according to the PN-EN ISO 5817 standard. Suitable standard specifications were used to do non-destructive testing and an inspection of joints, as well as proper acceptance criteria presented in table 8 are used.

TABLE 8

Standard specifications used to do the NDT

Examination method	**Taken examinations**	**Acceptance criteria**
Visual testing	PN-EN ISO 17637	PN-EN ISO 5817 – B
Magnetic particle inspection	PN-EN ISO 17638	PN-EN ISO 23278 – 2x
Ultrasonic testing	PN-EN ISO 17640	PN-EN ISO 11666 – 2
Radiography testing	PN-EN ISO 17636	PN-EN ISO 10675 – 1

After obtaining positive results from NDT, samples were taken for destructive testing including tensile and transverse bend tests, impact strength test, macroscopic examination and hardness penetration pattern. Appropriate standard specifications were used to do destructive testing, and to make an assessment of joints, as well as relevant acceptance criteria were adopted, which is given in the table 9.

TABLE 9

Standard specifications used to do the DT

Examination method	**Taken examinations**	**Acceptance criteria**
Tensile test	PN-EN ISO 4136	Min. R_m = 570 MPa
Transverse bend test	PN-EN ISO 5173	Bending angle 180°
Impact strength test	PN-EN ISO 9016	Min. $KV_{(0°C)}$ = 65 J
Macroscopic examination	PN-EN ISO 17639	PN-EN ISO 5817 – B
Hardness test	PN-EN ISO 9015-1	Max. 380 (HV10)

Results of examinations of sample welded joints

Taken examinations of sample welded joints according to an accepted range of examinations and acceptance criteria presented above allowed to obtain positive results of both non-destructive and destructive testing. Details of non-destructive testing are presented in table 10.

Details of the destructive testing are presented in the following tables 11 to 14.

TABLE 10

Results of the NDT of sample welded joints

Type of joint	**Results of the NDT according to acceptance criteria**				**Comments**
	VT	**MT**	**UT**	**RT**	
121PA/P460NH	B	2X	2	1	Lack of indications
722PF/P460NH/30	B	2X	2	1	Lack of indications
722PF/P460NH/55	B	2X	2	1	Lack of indications

TABLE 11

Results of tensile and transverse bend tests of sample welded joints

Type of joint	**Results of tensile tests**			**Results of transverse bend tests**		
	$R_{m\ ave}$, **[MPa]**	**Grade**	**fracture**	α **[°]**	**Grade**	**Cracks**
121PA/P460NH	643	+	flawless	180	+	lack
722PF/P460NH/g30	620	+	flawless	180	+	Lack
722PF/P460NH/g55	630	+	flawless	180	+	Lack

TABLE 12

Results of the mean values hardness test of sample welded joints – in brackets indicates the maximum value in a series of measurements

Type of joint	**Line no**	**Mean test results HV10**					**Grade**	**Comments**
		BM	**HAZ**	**W**	**HAZ**	**BM**		
121PA/P460NH	I	187 (193)	235 (248)	242 (245)	245 (259)	194 (199)	+	–
	II	204 (216)	257 (276)	260 (266)	246 (264)	206 (209)	+	–
	III	181 (191)	245 (262)	233 (235)	247 (264)	179 (180)	+	–
722PF/P460NH/30	I	169 (175)	188 (209)	210 (212)	185 (221)	172 (173)	+	–
	II	176 (189)	210 (245)	218 (227)	212 (230)	183 (186)	+	–
	III	168 (170)	192 (218)	210 (213)	190 (216)	171 (171)	+	–
722PF/P460NH/55	I	164 (168)	190 (228)	196 (216)	187 (219)	166 (167)	+	–
	II	155 (160)	213 (260)	218 (224)	190 (230)	155 (157)	+	–
	III	169 (173)	199 (243)	217 (219)	193 (228)	168 (170)	+	–

TABLE 13

Results of impact strength of sample welded joints – work of fracture KV (0^{o}C); in brackets are minimum values obtained in the series

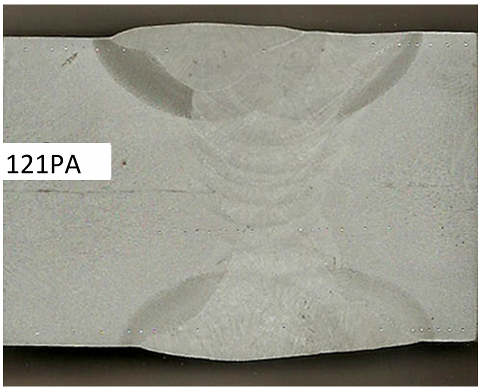
Type of joint	An area of an examination	Average results of examinations KV [J]		Grade	Comments
		W	HAZ		
121PA/P460NHg40	t 2	95 (80)	99 (82)	+	fracture without imperfections
	t/2	103 (98)	118 (84)	+	fracture without imperfections
	t-2	77 (62)	119 (116)	+	fracture without imperfections
722PF/P460NHg30	t 2	**43 (34)**	**25 (8)**	+	fracture without imperfections
	t/2	**33 (30)**	**22 (10)**	+	fracture without imperfections
	t-2	**41 (30)**	**35 (10)**	+	fracture without imperfections
722PF/P460NHg55	t 2	**25 (22)**	139 (136)	+	fracture without imperfections
	t/2	**22 (14)**	121 (98)	+	fracture without imperfections
	t-2	**35 (24)**	145 (140)	+	fracture without imperfections

TABLE 14

Results of macroscopic examinations of sample welded joints

Type of joint, a cross-section view and description

121PA/P460NHg40

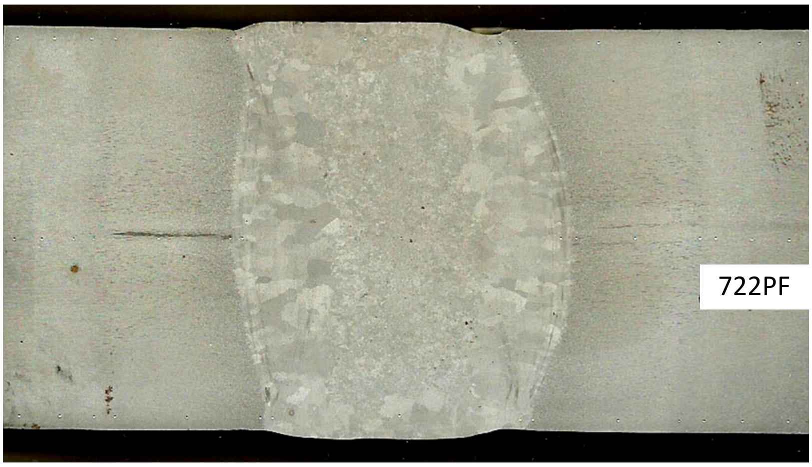


Complete joint penetration. A proper fusion into a base material. A regular sequence of beads. A width of HAZ is 2-4,5 mm. Weld's geometry and the whole joint is regular. Lack of important welding defects (slight inclusions). In the central area of the base material there is a dark strip of a different structure. Zoom ×1.

722PF/P460NHg30

Correct fusion in the base material. The homogeneous regular cross-section. HAZ width of 17-20 mm. The geometry of the weld line correct and equal faces. None of material imperfections (small inclusions point). In the central zone of the base material visible dark band with a different structure. Zoom ×1.

722PF/P460NHg55



Correct fusion in the base material. The homogeneous regular cross-section. HAZ width of 25-29 mm. The geometry of the weld line correct and equal faces. None of material imperfections (small inclusions point). In the central zone of the base material visible dark band with a different structure. Zoom ×1.

Tensile strength and transverse bend tests of sample welded joints made by the 121 and 722 methods gave positive results with similar effects. Requirements related to the technology of welding were also fulfilled.

The highest level of hardness was found in HAZ and in joint welded by the 121 method in the PA position. Joint and then heat affected zone was characterised by the highest hardness in all examples. In the 121 method the same level of hardness was found both in the weld and in HAZ. Base material was characterised by the lower hardness in all examples. In all examples a level of hardness proved a regularity of the technology of welding.

The highest work of fracture was obtained in the welded joint made by the 121 method in the flat position PC (the lowest amount of heat input). A joint welded by the 722 method in the vertical upwards progression PF (the highest amount of heat input) was characterised by the lowest work of fracture. Joints welded by 722 method in the vertical position PF characterized by variable impact strength. In a welded joint by 722 method plates with a thickness of 30mm was low breaking work both in the weld and in the heat affected zone while in the joint plates with a thickness of 55mm low breaking work achieved in the weld and very high heat affected zone. The requirements for impact testing examined welding technology were fulfilled only for a welded joint 121 method. Both joints welded by 722 method did not meet the expected requirements.

Results of macroscopic examinations showed a proper structure of all sample joints, moreover, there were any important welding defects and only a slight point inclusions. In the particular samples of welded joints there were significant differences in widths of HAZ. The largest width (25 ÷ 29mm) were found in the joint with a thickness of 55mm welded by 722 and slightly less (17 ÷ 20 mm) in the joint with a thickness of 30mm. The lowest width (2 ÷ 4.5) was obtained welded joint by 121 method. Apart from the used method, and the welding position welded joints fulfilled the requirements of the quality level B according to the PN-EN ISO 5817 standard.

5. An assessment of welding efficiency

Sample welded joints were also assessed due to their efficiency of welding. This factor is essential not only from an economical point of view, but also thermal properties obtained in particular processes. Table 15 provides comparative results connected with efficiency of used methods of welding in examining a technology of welding fine-grained steel.

Welding by the electroslag (short time of welding with one penetration bead) became the most efficient. Much less efficient method of welding was the submerged arc. An efficiency of a welding process by the electroslag in comparison to the submerged arc appeared to be 15% bigger. In this evaluation does not include breaks needed to rotate items and cleaning of welds in the process of submerged arc welding. In an electroslag welding process such kind of needs does not occur. The opposite relationship is the energy consumption in different process which involves direct heat input. The greatest amount of heat introduced into the junction area having a thickness of 55 mm welded by electroslag 722 method and the smallest in the submerged arc welding of 121 method. The ratio of the heat input in both processes is approximately 25 times.

TABLE 15

An efficiency of used methods of welding

Type of sample joint	121 – PA	722/g30 – PF	722/g55 – PF
A number of beads of the weld	13	1	1
Time of welding 1RM of the weld, [mm]	60	44	55
An average amount of heat input, [KJ/cm]	25	495	620

6. Summary

Performed a comprehensive examination welding technology of thick-grained steel in the genre P460NH realized by methods 121 and 722 in accordance with DIN EN ISO 15614-1 has shown positive results in the study:

1. a non-destructive both surface (VT, MT) and volume (UT and RT) in all the welds both with the 121 and 722 methods,
2. strength in tension and bending tests on all welded joints,
3. hardness distribution in all the welds,
4. the impact only on the welded joint by 121 method.

Negative results obtained in impact strength tests for both the welded joints by electroslag method (722). In the joint with a thickness of 30mm negative results obtained in all tests in both the weld and HAZ while the joint with a thickness of 55 mm only on weld samples. Because of the negative results obtained in welding electroslag welding technology fine-grained steel by this method can't be permitted even though achieved very positive results of other tests. Particularly advantageous results in welded joints by electroslag method related to their very good plasticity reported in the bending test, and hardness distribution studies.

Therefore, it can be concluded that the most advantageous welding method for thick-walled fine steel joints is a submerged arc welding process (121). This method combines both high performance but lower than obtainable in the process of electroslag the fulfillment of all the requirements for mechanical properties required for fine grain steels. However, application of this method should take into account the limitations imposed among others welding position and significant dimensions of the welding head.

Taking everything into account, it can be claimed that while choosing a proper technology of welding both quality requirements of finished joints, possibilities of implementing the process and economical issues should be considered.

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