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Analysis of the process of qualifying the welding technology of S355JR structural steel using the submerged arc welding method

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ABSTRACT

Purpose: This paper presents the issue of welding technology qualification using the example of structural steel S355JR with a plate thickness of 25 mm and 100 mm, bevelling ½V. The main objective of this work was to attempt to perform a full qualification of the submerged arc welding process in accordance with the requirements of PN EN ISO 15614. Particular attention was paid to the issue of the qualification of welding technology. The samples were subjected to non-destructive testing, i.e. visual and penetrant testing, as well as ultrasonic testing and heat treatment. This was followed by destructive testing, including macroscopic testing and hardness testing. According to the proposed procedure for the recognition of submerged arc welding technology, once the necessary tests had been carried out and the protocols with positive results had been obtained. The documentation had been completed, the analysis needed to obtain certificates of conformity for factory production control and welding quality was carried out.

Design/methodology/approach: Submerged arc welding is often used for highly responsible butt joints, particularly when joining thick components. This has been achieved through the proper design of the preparation of the parts to be welded and the development of a welding technology that practically eliminates the pre-phase that occurs in traditional technology, thereby eliminating the risk of it affecting the quality of the welded joint.

Findings: During the implementation of submerged arc welding, a number of technological problems were encountered. The first test joints contained many defects, i.e. sticking and slag inclusions inside the welds. In addition, obtaining welds with the correct profile and removing the slag from the weld groove was difficult. These obstacles were eliminated experimentally by carrying out successive tests using different parameters and welding groove geometries.

Practical implications: The correct implementation of any welding process depends on its input parameters. These parameters include welding current, welding speed, welding current, wire diameter, welding voltage and many others. Submerged arc welding (SAW) is widely used in the industry for manufacturing as it is more reliable, provides deep penetration in the work, ensures a smooth finish on objects, and results in high productivity.

Originality/value: The technology was developed for a company that manufactures control discs for steam turbines.

Keywords: Welding technology qualification, Welding quality, S355JR steel, Submerged arc welding

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MANUFACTURING AND PROCESSING

1. Introduction

All companies producing and repairing steel structures should be certified and qualified in the correct application of welding technology. The main document describing the procedure for recognising steel welding technology and the scope of qualification is the European standard EN ISO 15614-1 [1-3].

EN ISO 15614-1 deals with the specification and qualification of the welding process for steel components and the testing of submerged arc welded joints. The standard specifies a qualification process for the production of welded joints, which determines the production capacity of a plant to produce a joint in production. Such a joint is sent to a laboratory (meeting the requirements of EN ISO/IEC 17025) for testing. The result of the tests verifies whether the technology can be accepted or whether changes need to be made to the instructions and the test joint re-made [4,5]. Testing was carried out to qualify the company as being able to operate a submerged arc welding machine and to certify the machine operator. Figure 1 shows a FANUC- Robot M900iA submerged arc welding (SAW-submerged arc welding) station, where a submerged arc welding test was carried out on components (plates) made of S355JR steel with thicknesses of 25 mm and 100 mm [6,7].

Fig. 1. FANUC-Robot M900iA submerged arc welding station

Welding procedure qualification is checking the correctness of a welding procedure given in the preliminary welding procedure manual (pWPS) by performing specified tests on a welded joint made in accordance with the pWPS.

A pWPS is a welding procedure instruction that the manufacturer assumes to be correct but for which a welding procedure qualification procedure has not yet been carried out. This procedure is carried out to verify that the manufacturer is qualified to perform welding based on the technology instruction and to confirm that welded joints made per these assumptions/instructions meet the specified requirements [8,9].

The qualification of the welding technology should correspond to the manufacturer's production conditions in terms of welding equipment, the possibility to carry out welding work in the production premises, the preparation of the edges for welding, the cleaning of the material before welding, the heat treatment before and after welding. During the welding technology qualification procedure, the manufacturer shall demonstrate and document that the tested welding technology is suitable for use under the manufacturer's production conditions. The qualification of welding technology for use is only valid if the manufacturer maintains the same technical and organisational conditions as during the procedure for qualifying this welding technology [10,11].

Qualification stages of welding technology according to EN ISO 15614-1:

- detailed analysis of welding production (determination of the relevant welding variables:) welding process, grade of base material, dimensions of components, type of joints - thickness, diameter, welding position);
- selection of the test joint; development of the preliminary welding technology manual - pWPS;
- execution of the test joint; non-destructive and destructive testing of the welding technology;
- issuing of a Welding Procedure Qualification Record (WPQR) by a notified body;
- development of the Welding Procedure Specification (WPS) [11,12].

An algorithmic elaboration of the welding technology qualification steps is shown in Figure 2.

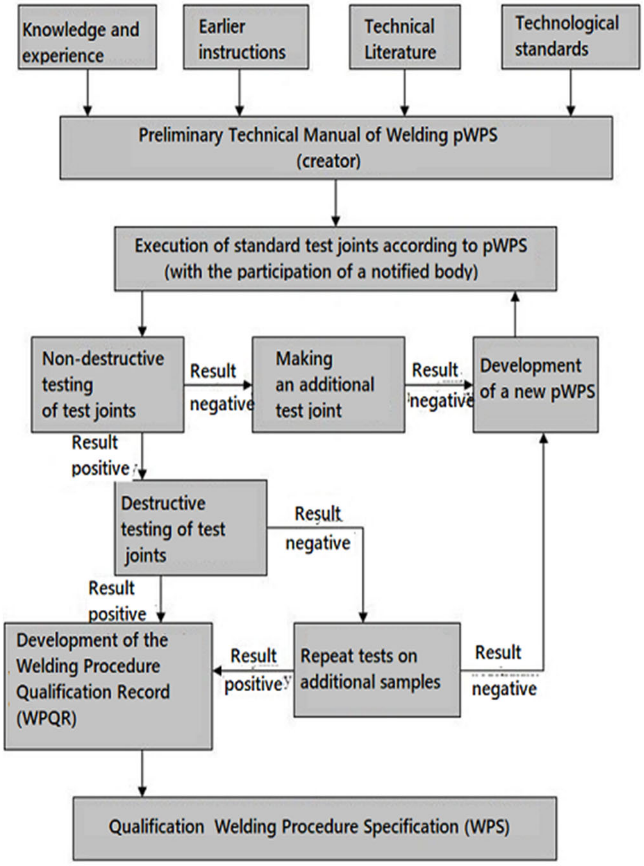


Fig. 2. Welding technology qualification algorithm [12]

2. Preparation of samples for testing

The welding technology for the joints of S355JR steel assumed the choice of the method by which the joints were made [12,13]. In this case, the submerged arc welding (121 - SAW) method was adopted, which also dictates the welding position (PA flat position, 0-15° bevel). The type of joint, the height of the specimen and the base material were then determined based on the design of the workpiece, where in this case, it is a ½V butt joint with full fusion. The heights of the specimens are 25 mm and 100 mm; Figure 3 shows the prepared parts for welding.

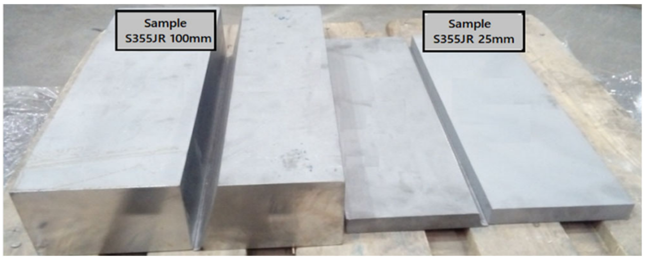


Fig. 3. Preparation of elements for submerged arc welding test

There is a momentary instability in the process at the beginning and end of the weld, causing the weld in these areas to lack the required properties. In order to maintain the homogeneity of the weld over the entire length of the joint, run-out plates are used at the beginning and end of the weld, which is cut off after welding, as shown in Figure 4 for a 25 mm weld, while Figure 5 shows the welding process for a 100 mm weld [14,15].

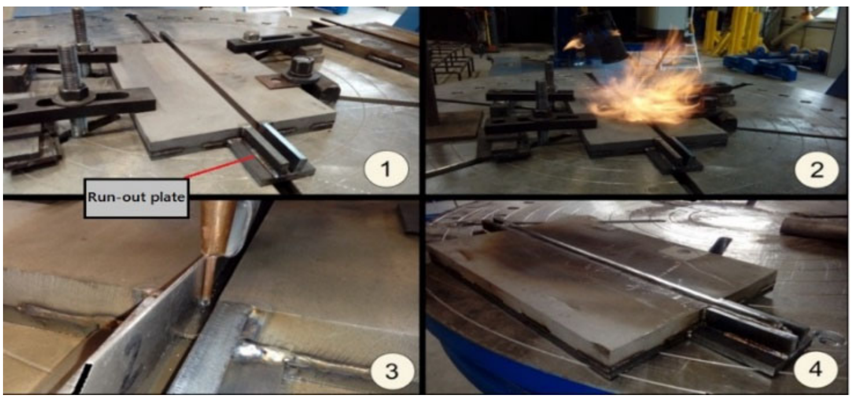


Fig. 4. Welding process of the 25 mm S355JR sample: 1. Elements (plates) prepared for welding (with run-out plates), 2. Heating up the sample, burning off water and oil residues, 3. Positioning the welding wire in the throat of the groove before welding the root, 4. Fully welded sample

Fig. 5. Welding process of a 100 mm S355JR sample: The welding process of the sample (1 and 2), the shape of the bead (3), departing slag (4), face of weld (5 and 6)

Table 1.
Welding parameters of the samples S355JR 25 mm and 100 mm

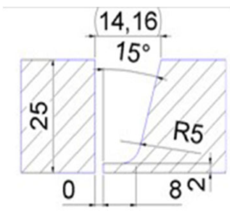
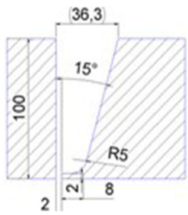
Sample S3555JR / thickness	25 mm	100 mm
Welding process	121 (SAW)	121 (SAW)
Joint type	BW	BW
Welding position	PA	PA
Base material	S355JR	S355JR
Dimension of testing plates, mm	2x25x150x450	2x100x150x450
Illustrative drawing of the welding joints		
Filler material (wire)	Ø4, BA-S3Si	Ø4, BA-S3Si
Flux	BF10, SA FB 155 AC	BF10, SA FB 155 AC
Preheat temperature	100-150°C, max 300°C	100-150°C, max 300°C
Welding current I, A	550	550-650
Arc voltage U, V	30-32	28-32
Welding speed, cm/min	45-70	36-50
Number of runs	11	43

Table 1 summarises the welding parameters for the 25 mm and 100 mm joints.

Prior to welding, the components were heated at 150°C in a POK-2 resistance chamber oven and then transported to the welding station, where the temperature of the components was maintained using thermal blankets and reheated with a gas torch. During welding, the temperature of each stitch was measured using a Cyclops 160L pyrometer; the temperature between stitches was approximately 300°C.

3. Research results

The joined plates were subjected to defectoscopic, non-destructive and destructive testing, including macroscopic testing, at the weld site. Visual, penetrant and ultrasonic tests were carried out, and this sample was then heat treated. No defects were found [16].

Visual examination was carried out using a calliper and a welding gauge to measure the geometric dimensions of the weld. Using a magnifying glass, the weld was visually inspected for cracks, underfilling, unfilled weld grooves, pores, overhangs and leaks. The visual inspection did not reveal any discrepancies. Weld quality acceptance level B was found.

The tests were carried out in accordance with the standard. The sample was then subjected to penetrant testing, according to Helling [16]. Penetration testing was carried out on the entire weld surface at a background illuminance of 980lx using a kit from Helling [16]. The completed welded joint also achieved weld class B on the basis of penetration testing.

Ultrasonic testing was carried out using a SONATEST 350M, using an angled head for weld integrity testing, as weld inspection requires the sound waves to be directed at an angle and a straight head to detect and size delaminations, Table 2 shows the ultrasonic test results for a 25 mm thick S355JR specimen. In contrast, Table 3 shows the test results for a 100mm thick S355JR specimen [17,18]. According to the standard, the test specimen passed with a weld quality level B. Quality level B corresponds to the highest requirements for welds.

After non-destructive testing, the run-out plates were cut off, and the specimen was then annealed to remove post-weld stresses without changing the steel structure. The heat treatment was carried out in a DLR-61 electric chamber furnace. The heating rate for the S355JR 25mm sample was 120°C/h, followed by a holding time of 2 hours after reaching 620°C, after which the sample was cooled at 60°C/h. On the other hand, for the S355JR 100mm sample, the heating rate of the sample was 40°C, then after reaching 680°C, the holding time was 4.5 hours, after which the sample was cooled at 55°C/h. Table 4 summarises the heat treatment parameters.

Table 2.
Results of ultrasonic testing of the sample S355JR 25 mm

Instrument: SONATEST 350M Couplant: Oil Method: DAC curve / DAK-curve			Extent of testing acc. to: 100% accessible surface 100% of welding+ HAZ		Instructions [17,18]	
Probe			Calibration		Test setting	
Type	MHz	Ref. block No.	Ref. sensitivity, db	Ref. distance, mm	Testing sensitivity, db	øFBH, mm
SMA4-45ZR	4	No.1	33	R100	56	1,5
SMA4-70ZR	4	No.2	29	R25	49	1,5
Test result: No recordable indications						

Table 3.
Results of ultrasonic testing of the sample S355JR 100 mm

Instrument: SONATEST 350M Couplant: Oil Method: DAC curve / DAK-curve			Extent of testing acc. to: 100% accessible surface 100% of welding+ HAZ		Instructions, [17,18]	
Probe			Calibration		Test setting	
Type	MHz	Ref. block No.	Ref. sensitivity, db	Ref. distance, mm	Testing sensitivity, db	øSDH, mm
SMA4-45ZR	4	No.2	37	25	55	1,5
SMA4-70ZR	4	No.2	29	25	57	1,5
SMA4-60ZR	4	No.2	29	25	16	1,5
Test result: No recordable indications						

Table 4.
Parameters of stress relieving annealing of tested samples

	Stress relieving		
Sample	25 mm	100 mm	Unit
Heating rate	120	40	°C/h
Holding temperature	620	680	°C
Holding time	2	4.5	h
Cooling rate	60	55	°C/h

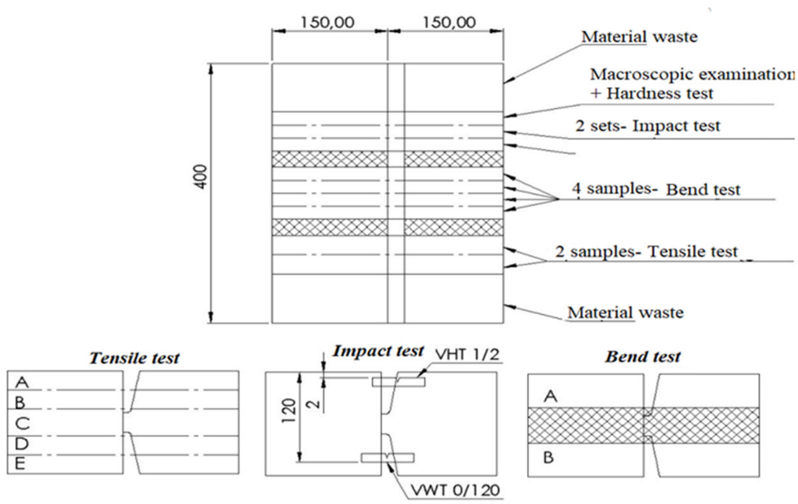


Fig. 6. Separation of samples for strength tests

After the heat treatment, the sample was subjected to destructive testing. The destructive tests carried out included:

- transverse tensile test,
- transverse bending test,
- impact test,
- hardness test,
- macroscopic test.

We, therefore, proceeded to separate the samples for destructive testing accordingly (Fig. 6).

Samples for the tensile test were taken from the entire weld cross-section, of which samples from zone C, i.e. without fusion, are not taken into account in the final results. Samples for the joint impact test were taken in such a way that it was possible to cut a wedge in the weld zone and the heat-affected zone. Samples for the bending test were taken from the entire cross-section, excluding the non-fusible zone. Table 5 shows the results of the tensile tests. The highest force obtained during the test was F_m=351 kN, for which the value of the highest tensile stress is R_m=567 N/mm^2 for specimen S355JR 25 mm. Figure 7 shows the S355JR 25 mm specimens after the tensile test.

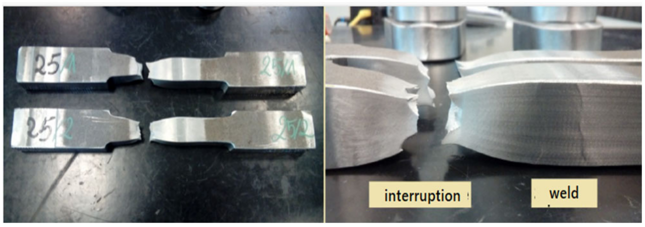


Fig. 7. Samples S355JR t=25 mm after the tensile test. The crack occurred outside the weld

Table 5.
The results of the tensile test of the welded joint (tensile strength)

Data	Tensile test acc. to			[19]	
	Apparatus:			ZD100	
	Tensile speed:			25 MPa/s	
Results	Piece dimension, mm		F_m	R_m	Place of rupture
	axb		kN	N/mm²	
	25.2	24.5	351.0	567	Basic material
	25.4	24.5	351.0	564	Basic material
Requirements:			---	≥551	---

Table 6.
The results of tensile test of welded joint (tensile strength)

Data	Tensile test acc. to			[19]	
	Apparatus:			ZD100	
	Tensile speed:			25 MPa/s	
Results	Piece dimension, mm		F_m	R_m	Place of rupture
	axb		kN	N/mm²	
	24.9	46.9	633	542	Basic material
	25.0	47.9	648	541	Basic material
	24.7	46.6	623	542	Basic material
	25.0	47.5	639	538	Basic material
Requirements:			---	≥551	---

Table 6 shows the tensile test results for the S355JR 100mm specimen. The highest force obtained during the test was F_m=648 kN for which the ultimate tensile stress value is R_m=542 N/mm^2.

Table 7 shows the results of the impact tests for the 25 mm S355JR sample. The average value for the three specimens taken from the weld (VWT0/2) is 222 [J]. The average value for the three specimens taken from the SWC (VHT1/2) is 187 J. The minimum fracture work for S355JR steel at approximately 20°C is 27 J. Figure 8 shows the prepared specimens for the impact test and the specimens after the impact test.

Table 7.
Results of impact tests sample S355JR 25 mm

Data	Tensile test acc. to				[20]	
	Apparatus:				ZD100	
Results	Test pos.	Type KV_2 /J				Temp.
		1	2	3	Aver	
	VWT0/2	225	222	219	222	23°C
	VHT1/2	187	168	205	187	23°C
Requirements:					≥27	---

Table 8 shows the results of the impact tests for the 100 mm S355JR sample. The average value for the six specimens taken from the weld (VWT0/2 and VWT0/90) is 222 J. The mean value for the three specimens taken from the SWC (VHT1/2 and VHT1/90) is 238 J. The minimum fracture work for S355JR 100 mm steel at approximately 20°C is 27 J.

Fig. 8. Samples S355JR t=25 before and after the impact test. The specimens show V notches in the weld axis (VWT) and in the heat affected zone (VHT)

Table 8.
Results of impact tests sample S355JR 100 mm

Data	Tensile test acc. to				[20]	
	Apparatus:				ZD100	
Results	Test pos.	Type KV_2 /J				Temp.
		1	2	3	Aver	
	VWT0/2	218	220	237	225	23°C
	VHT1/2	218	217	224	219	23°C
	VWT0/120	218	217	224	219	23°C
	VHT1/120	263	256	251	256	23°C
Requirements:					≥27	---

Table 9 shows the test results for specimen S355JR 25 mm RG (transverse bending), while Table 10 shows the test results for specimen S355JR 100 mm , with positive results for all specimens.

The result of the MA (macroscopic) tests and the specimen scan of S355JR 25 mm is shown in Figure 9.

Table 9.
The results of the test bend test sample S355JR 25 mm

Data	Bend test acc. to			[21]	
	Ambient temperature:			23±25°C	
Results	Piece dimension, mm	Bending conditions, mm	Rollers span, mm	Type and symbol of bend	Results
	10x25	d=40 α=180°	65	SBB	Satisfactory
	10x25	d=40 α=180°	65	SBB	Satisfactory
	10x25	d=40 α=180°	65	SBB	Satisfactory
	10x25	d=40 α=180°	65	SBB	Satisfactory

Table 10.
The results of the test bend test sample S355JR 100 mm

Data	Bend test acc. to			[21]	
	Ambient temperature:			23±25°C	
Results	Piece dimension, mm	Bending conditions, mm	Rollers span, mm	Type and symbol of bend	Results
	10x100	d=40 α=180°	62	SBB	Satisfactory
	10x100	d=40 α=180°	62	SBB	Satisfactory
	10x100	d=40 α=180°	62	SBB	Satisfactory
	10x100	d=40 α=180°	62	SBB	Satisfactory

DATA	Test standards and instructions		[22]		
	Test equipment		STEMI 2000C		
	Testing specification magn.		x2:100		
	Testing specification etch.		Mal1Fe		
	Test classification defects		[24]		
	No. DEFECTS	Name of defects	Symbol	Size [mm]	Notes
RESULTS	-	No defects were found	-	-	-

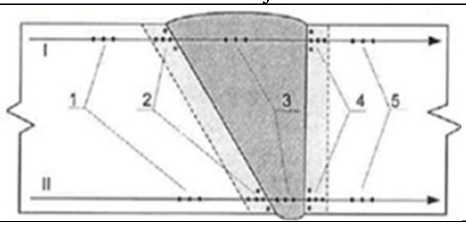
Fig. 9. Macroscopic examination of the S355JR 25 mm sample and the test results

The result of the MA (macroscopic) tests and the specimen scan of S355JR 100 mm is shown in Figure 10.

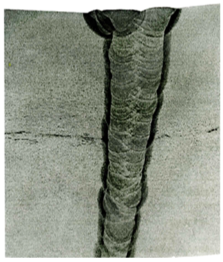
The results of the hardness measurements in Table 11 for the S355JR 25 mm sample do not exceed values above 320 HV. The difference between the highest hardness of the weld and the lowest hardness of the parent material must not exceed 100 HV and is 66 HV.

Table 11.
HV test results (hardness) sample S355JR 25 mm

Data	Test standards and instructions:			[23,24,25]	
	Test equipment:			Dura Scan 70	
	Load			98.1 N	
	Locating of hardness measurements at the area of the welded joint				



Results		Location	Area	Hardness HV10 Line I	Hardness HV10 Line II
	Weld	Basic material	1	162 169 171	158 163 163
		Heat affected zone	2	209 288 266,266,266	214 246 294,298,300
		Weld	3	214 216 211	215 225 217
		Heat affected zone	4	301,307,278 214 194	306,297,289 240 218
		Basic material	5	173 170 170	159 161 166



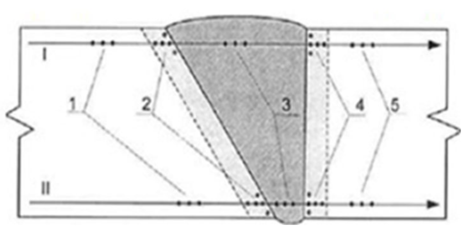
DATA	Test standards and instructions		[22]		
	Test equipment		STEMI 2000C		
	Testing specification magn.		x2:100		
	Testing specification etch.		Mal1Fe		
	Test classification defects		[24]		
	No. DEFECTS	Name of defects	Symbol	Size [mm]	Notes
RESULTS	-	No defects were found	-	-	-

Fig. 10. Macroscopic examination of the S355JR 100 mm sample and the test results

The hardness measurement results are shown in Table 12 for the 100 mm S355JR sample and do not exceed values above 320 HV. The difference between the highest hardness of the weld and the lowest hardness of the parent material must not exceed 100 HV and is 67 HV.

Table 12.
HV test results (hardness) sample S355JR 100 mm

Data	Test standards and instructions:			[23,24,25]	
	Test equipment:			Dura Scan 70	
	Load			98.1 N	
	Locating of hardness measurements at the area of the welded joint				



Results		Location	Area	Hardness HV10 Line I	Hardness HV10 Line II
	Weld	Basic material	1	146 148 149	146 149 146
		Heat affected zone	2	211 269 267,288,269	214 246 294,298,300
		Weld	3	221 211 207	201 212 210
		Heat affected zone	4	279,293,308 243 193	256,249,253 206 196
		Basic material	5	165 158 158	166 170 161

4. Conclusions

Once the tests have been carried out and positive protocols have been obtained. The rest of the documentation (welding and heat treatment report) has been completed; the inspection body can issue a WPQR welding qualification certificate. This certifies that the factory has acquired the knowledge and ability to weld the welded joints described therein. The document describes the scope of the authorisations received by the production facility and qualifies the method and parameters used during the process. In addition, it describes the results of the tests carried out on the qualification joint. WPQR certificates were produced for each sample. The qualification of a sample of S355JR steel with a plate thickness of t=25 mm entitles the plant to make joints in Group 1.2 steels with a plate thickness of t=12.5-50 mm using the additional materials used to weld the test joint and the same range of parameters.

Similarly, a sample of S355JR steel with a plate thickness of t=100 mm gives the facility the authority to perform joints with plate thicknesses of 1/2t to 2t based on the test joint. In this case, the scope covers t=50-100 mm thick joints in Group 1.2 steels. In the paper, the researcher, "An analysis of the joints' properties of fine-grained steel welded by the MAG and SAW methods", obtained similar results indicating that the mentioned method combines high efficiency and fulfilling all the requirements connected with mechanical properties. There is, however, a certain limitation related to the possibility of welding only in the flat position (PA), therefore it prevents welding constructions of complex shapes, which require different welding positions. The high impact strength of the work of fracture characterises joints welded by the 121 method.

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