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Welding of Joints in New Generation Martensitic Steel THOR®115

Abstract: The present development of materials used in the power engineering industry for elements of boilers characterised by supercritical parameters creates new challenges for the welding engineering sector. The implementation of new combinations of alloying agents aimed to obtain the most favourable mechanical properties, including creep resistance and oxidation resistance, does affect the weldability of steels. Martensitic steels containing 9% of Cr are characterised by high creep resistance and low oxidation resistance at temperature exceeding 600°C. In turn, steels containing 12% of Cr, i.e. VM12-SHC or X20CrMoV12-1, are characterised by significantly higher oxidation resistance but lower strength at higher temperature. In 2018, Tenaris (an Italian concern) developed new steel containing 12% of Cr and designated as THOR®115 (Tenaris High Oxidation Resistance). This article presents experience gained when making welded joints of pipes using various filler metals (W CrMo91, S Ni 6082 and EPRI P87). The research work included the performance of a series of non-destructive tests (VT, PT and RT) as well as destructive tests (tensile tests, bend tests, hardness measurements and macro and microscopic metallographic tests) aimed to confirm the high quality of the joints.

Keywords: THOR®115, Martensitic steels, filler metals, quality of welded joints

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Introduction

In the years to come the power engineering industry will face a challenging search for new solutions aimed at increasing the efficiency of technologically advanced power units. This goal will dominate the work of various specialists in many research centres all over the world. Some of the areas which may help accomplish the aim include the design and use of structural materials capable of failure-free operation at increasingly high temperature and under increasingly high pressure. Materials which for over 30 years have been regularly developed and improved to satisfy needs of modern power engineering are steels having the microstructure of alloy martensite having a chromium content restricted within the range of 9% to 12%. The required properties were obtained in the steels by modifying their chemical composition, providing them with appropriate amounts of alloying components such as vanadium, tungsten, nickel, copper and cobalt

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as well as the use of microagents including nitrogen, boron and niobium combined with the reduced content of carbon. The developmental directions concerning the above-named steels are two-fold [1-6]:

- modification of steels having a chromium content of approximately 9% and an addition of molybdenum. The use of additions (vanadium and tungsten) and microagents (nitrogen, niobium and boron) led to the obtainment of new steels X10CrMoVNb9-1 (P/T91), X10CrWMoVNb9-2 (P/T92), X11CrMoWVNb9-1-1 (E911) and THOR 115;
- modification of steel having a 12% chromium content and additions of molybdenum and vanadium. The use of additions (tungsten, nickel, copper and cobalt) and microagents (nitrogen, boron and niobium) enabled the obtainment of new steels 12Cr-2.6W-2.5CoVNbB (NF12), 12Cr-0.5Mo-2WVNb (TB12M), 12Cr-1Mo-1WVNb (HCM12), 12Cr-0.5Mo-2WCuVNb (HCM12A) and X12CrCoWVNb12-2-2 (VM12).

Steel grades most commonly used in power engineering include X10CrMoVNb9-1 (T/P91), X10CrWMoVNbNB9-2 (T/P92) and X12CrCoWMoVNb12-2-2 (VM12) as well as older X20CrMoV12-1. European research project COST 536 resulted in the development of martensitic steel grade X13CrMoCoVNbNB9-2-1 (PB2), originally intended as the next stage in the development of the above-named group of steels [7]. However, production-related difficulties and rising costs precluded the implementation of the steel grade. Presently, leading manufacturers continue their search for new solutions aimed to improve operating parameters of technologically advanced power units. Once popular steel X20CrMoV12-1 has been withdrawn from most power units. Its anticipated "successor" was steel VM12-SHC (designed by Tenaris), intended for operation at a temperature of up to 650°C. The primary factor improving the mechanical properties of the steel was the partial replacement of molybdenum with tungsten. Expected results included an approximately 30% increase in creep resistance and higher hardenability. It was also forecast that the boron microagent would stabilise $M_{23}C_6$ carbides. Steel VM12-SHC was launched yet initial tests (performed within European project COST 536) revealed that although the steel was characterised by very high heat resistance, its creep resistance was lower than that of steel P92 [22,23,31]. The low creep resistance of steel VM12-SHC was responsible for its withdrawal from use. To fill the market gap left by the aforesaid steel, in 2015 the Tenaris company started work on new martensitic steel THOR®115 (Tenaris High Oxidation Resistance Steel). In 2018, the research work was finished and the company is presently launching the steel in the power engineering market. Steel THOR®115, being the modification of steel ASME BPVC 2013 grade 91, belongs to ferritic steels characterised by higher creep resistance. Table 1 presents the comparison of chemical compositions of popular martensitic steels used in the power generation sector.

Table 1. Comparison of chemical compositions of popular steels used in the power generation industry [1]

Grade	Chemical composition, %								
	C	Si	Mn	Cr	Mo	Nb	V	W	Others
P91	0.08÷ 012	0.20÷ 0.50	0.30÷ 0.60	8.00÷ 9.50	0.85÷ 1.05	0.06÷ 0.10	0.18÷ 0.25	-	N=0.03÷0.07
P92	0.07÷ 0.13	<0.50	0.30÷ 0.60	8.50÷ 9.50	0.30÷ 0.60	0.04÷ 0.09	0.15÷ 0.25	1.50÷ 2.00	N=0.03÷0.07 B=0.0005÷0.005
E911	0.09÷ 0.13	0.10÷ 0.50	0.30÷ 0.60	8.50÷ 9.50	0.90÷ 1.10	0.06÷ 0.10	0.18÷ 0.25	0.90÷ 1.10	N=0.05÷0.09 B=0.0005÷0.005
THOR®115	0.09	0.15	0.47	10.78	0.51	0.034	0.24	-	Ni=0.15

An increase in the content of chromium improved oxidation resistance, whereas a decrease in the content of molybdenum and that of niobium prevented the formation of secondary phases (e.g. Laves phase or phase Z) after long-lasting operation at high temperature. Tests revealed that, in comparison with steel grade 91, the formation of phase Z in steel THOR®115 was significantly delayed (Fig. 1).

THOR®115 is also characterised by favourable heat conductivity (Fig. 2a), limited thermal expansion (Fig. 2b) and, consequently, higher thermal fatigue resistance.

Initial tests also revealed the high creep resistance of steel THOR® 115. In 2015, the first pipes made of the aboveo-named steel were installed in commercially operated boilers of a heat recovery steam generator (HRSG) in Italy [1, 8, and 9]. Because of the fact that steel THOR®115 is still a relatively new material, the Authors used their own experience when adjusting welding and heat treatment parameters [2-4, 7]. All joints were made in the ZELKOT Company from Koszęcin, Poland.

Test scope and materials

The test materials were butt joints in pipes made of steel THOR®115 by Tenaris Dalmine S.P.A.. The external diameter of the pipes amounted to 50.8 mm, whereas the thickness of their walls amounted to 10.1 mm (Fig. 3). The tests aimed

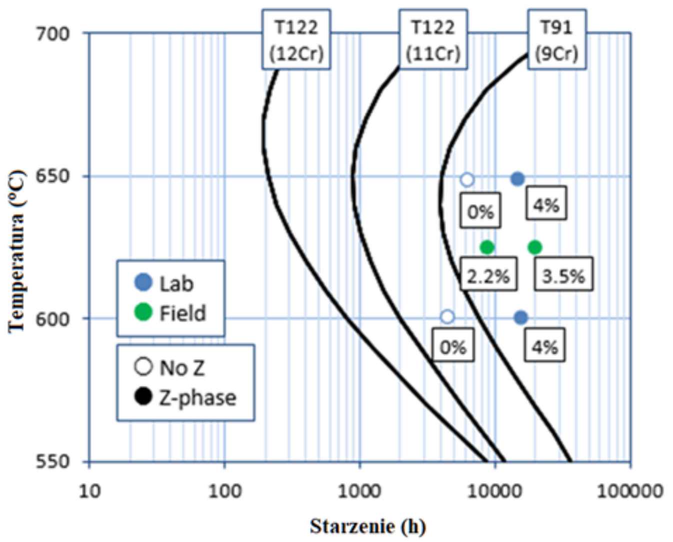


Fig. 1. Compared development of phase Z in selected steels and in relation to selected operating temperatures [8]

to develop a technology enabling the making of butt joints in pipes made of steel THOR®115 using the traditional TIG welding method (141) and various filler metals.

The first stage of the tests, aimed to identify the primary properties of steel THOR®115, involved the analysis of chemical composition, microscopic metallographic tests, strength tests including tensile tests (at room temperature and elevated temperature), impact strength tests and bend tests involving the base material of the pipes. The subsequent stage involved the making of butt joints using the TIG method and various filler metals. The joints were afterwards subjected to non-destructive tests (VT and PT) as well as strength tests including

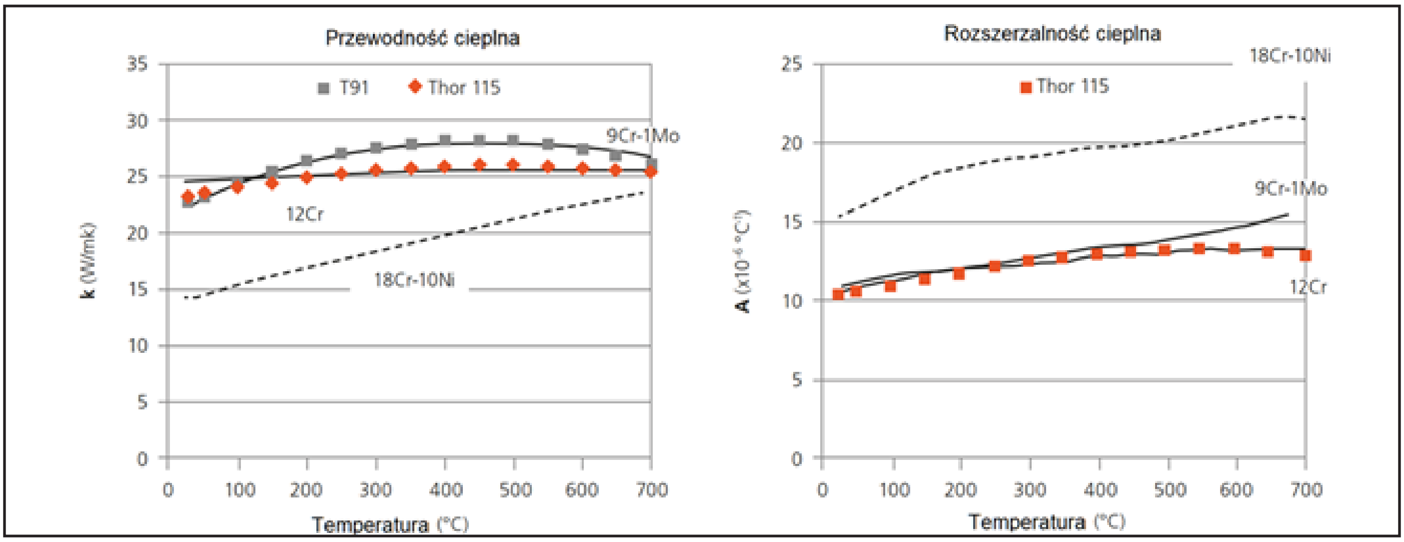


Fig. 2. Heat properties of steel THOR®115 [8]

Fig. 3. Pipe fragments used in the tests

tensile tests (at room and elevated temperature), impact strength tests and macro and microscopic metallographic tests.

Tests

Identification of the primary properties of steel THOR®115

The analysis of chemical composition was performed using a Q4 TASMAN spark emission spectrometer. The results of the analysis are presented in Table 2. The microscopic metallographic tests were performed in accordance with the requirements specified in the PN-EN ISO 17639 standard [31]. The specimens were subjected to grinding and, subsequently, polishing. The tests were performed using an Eclipse MA 200 inverted metallographic microscope (Nikon). The microstructure of the specimens was revealed using Nital (etchant). The microstructural photographs are presented in Figure 4.

The tensile tests involving the base material of the pipes were performed in accordance with the requirements specified in PN-EN 6892-1 [11] PN-EN ISO 6892-2 [12], using an MTS Criterion C45 static testing machine (+/-100kN) equipped with an ND-40 induction heating system. The tests were performed both at room temperature (RT) and at a temperature of 600°C, 625°C and 650°C. The test results are presented in Table 3. In Figure 5, in the diagram presenting mean values $R_{0.2}$ and R_m, following related requirements specified in document VdTÜV WB 580, the minimum required values of R_m are marked with the black line [13].

The impact test was performed in accordance with the requirements specified in the PN-EN ISO 148-1 [14] standard. The tests were performed at room temperature. The test results are presented in Table 4. **The cold bend test** involving the base material of the pipes was performed in accordance with the requirements

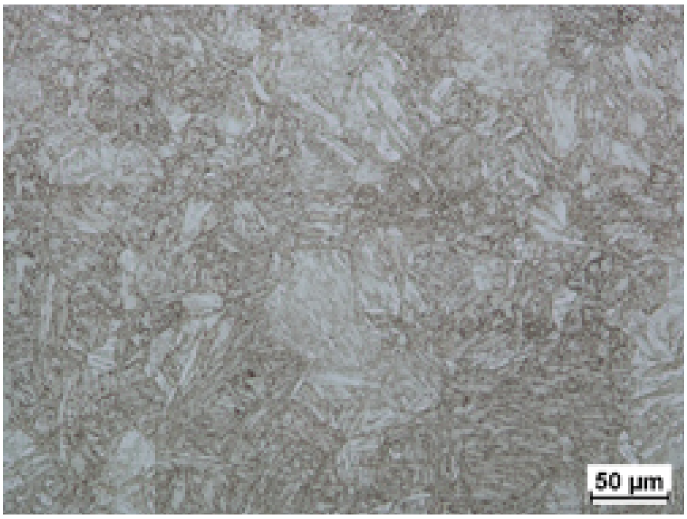


Fig. 4. Microstructure of test steel THOR®115; etchant: electrolyte; structure: tempered martensite

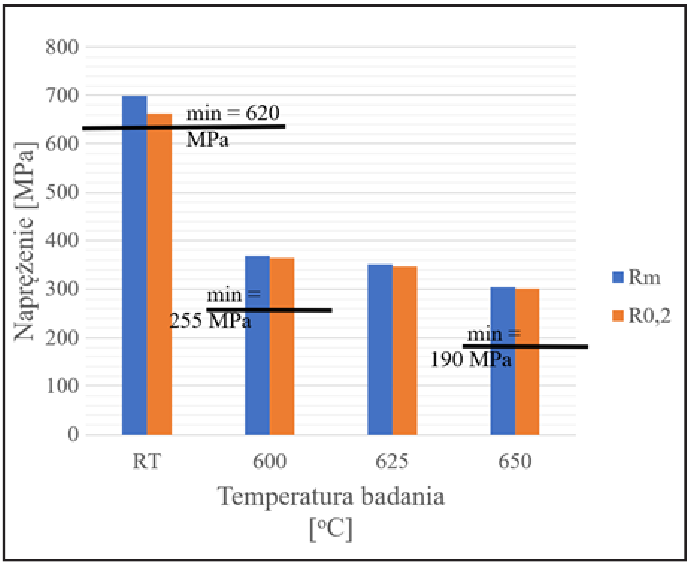


Fig. 5. Static tensile test results related to steel THOR®115

Table 2. Analysis of the chemical composition of test steel THOR®115

Element	C	Si	Mn	Cu	Ni	Cr	Mo	N	V	Ti	Nb	P	S
Content %	0.09	0.15	0.47	2.75	0.15	10.78	0.51	0.042	0.24	0.002	0.034	0.016	0.002

Table 3. Tensile test results related to the base material of the pipes made of steel THOR®115

Specimen designation	Specimen dimensions		Mechanical properties of the material			
	d_0 [mm]	S_0 [mm2]	$F_{0.2}$ [kN]	$R_{0.2}$¬ [MPa]	F_m [MPa]	R_m [MPa]
Base material – room temperature (RT)						
MR/R/RT/1	5.95	27.80	18.0	647.4	19.3	693.5
MR/R/RT/2	5.90	27.34	18.5	676.7	19.2	703.4
MR/R/RT/3	5.91	27.43	18.1	660.9	19.1	697.8
Mean value			**18.2**	**661.7**	**19.2**	**698.2**
Base material – 600°C						
MR/R/600/1	5.96	27.90	10.1	362.0	10.2	366.3
MR/R/600/2	5.98	28.09	10.3	366.7	10.4	370.8
MR/R/600/3	5.96	27.90	10.2	365.6	10.3	371.1
Mean value			**10.2**	**364.8**	**10.3**	**369.4**
Base material – 625°C						
MR/R/625/1	5.95	27.80	10.4	374.0	10.5	378.4
MR/R/625/2	5.96	27.90	9.5	340.5	9.6	345.2
MR/R/625/3	5.98	28.09	9.1	324.0	9.3	329.6
Mean value			**9.7**	**346.2**	**9.8**	**351.1**
Base material – 650°C						
MR/R/650/1	5.92	27.52	8.5	308.8	8.6	312
MR/R/650/2	5.98	28.09	8.2	292.0	8.3	293.8
MR/R/650/3	5.98	28.09	8.5	302.7	8.6	306.3
Mean value			8.4	301.2	8.5	304.0

specified in the PN-EN 12952-5 [15]. The bend test was performed at room temperature. In relation to the pipes having external diameters < 76.1 mm and the R/D ratio > 1.8 (where R - bend radius, D - external diameter of the pipe) and subjected to cold bending it was not necessary to perform post-weld heat treatment, whereas in relation to the pipes having the R/D ratio < 1.8 it was necessary to perform post-weld heat treatment. After bending, the pipes were subjected to visual tests (VT) and magnetic particle tests (MT). The tests did not reveal the presence of any imperfections. After the non-destructive tests, the bent pipes were divided into fragments every 30° and sampled for metallographic specimens. The macrostructural photographs of the cut-out fragments were used in measurements of the maximum and minimum diameters of the pipes (d_{max} and d_{min}). The diameter measurements were followed by the identification of departure from circularity u (of the pipes) using the following formula:

$$u = 2 \cdot \frac{d_{max} - d_{min}}{d_{max} + d_{min}} \cdot 100\%$$

The test results are presented in Tables 5 and 6. The tests confirmed conformity with the requirements specified in the PN-EN 12952-5 [15] standard.

Table 4. Impact test results

Specimen designation	Specimen dimensions			
	a_0 x b_0 [mm]	S_0 [mm²]	Impact energy [J]	
MR/1	7.5 x 8	60.0	144	41[1)] 31[2)]
MR/2			138	
MR/3			140	
Mean value:			**141**	

[1)] Minimum requirements consistent with VdTÜV WB 580 [13] – in relation to the standard specimen (10.0 mm x 8.0 mm)
[2)] In relation to the specimen having the reduced cross-section (7.5 mm x 8.0 mm)

Table 5. Cold bend test results related to the pipes made of steel THOR®115; dimensions: ø38 mm x 4.6 mm; bend radius R=100mm (R/D=1.18); without post-weld heat treatment

Bend angle [°]	d_{max} [mm]	d_{min} [mm]	u [%]	Thickness reduction [mm]	Thickness reduction [%]
0	38.42	38.18	0.63	4.60	0.00
30	37.68	36.70	2.64	4.59	0.22
60	38.08	36.51	4.21	4.59	0.22
90	38.21	36.60	4.30	4.56	0.87
120	38.28	36.70	4.21	4.59	0.22
150	38.29	36.66	4.35	4.54	1.30
180	33.19	38.16	0.08	4.60	0.00

Table 6. Cold bend test results related to the pipes made of steel THOR®115; dimensions: ø38 mm x 4.6 mm; bend angle R=45mm (R/D=2.63); with post-weld heat treatment

Bend angle [°]	d_{max} [mm]	d_{min} [mm]	u [%]	Thickness reduction [mm]	Thickness reduction [%]
0	38.18	37.80	1.00	4.60	0.00
30	37.86	34.47	9.37	4.30	6.52
60	38.12	34.50	9.97	4.37	5.00
90	38.14	34.54	9.91	4.38	4.78
120	38.25	35.06	8.70	4.40	4.35
150	38.14	35.34	7.62	4.22	8.26
180	38.28	38.11	0.45	4.60	0.00

Table 7. List of the filler metals used in the tests; in accordance with PN-EN ISO 21952:2008 [27]

Steel grade	Chemical components, %										
	C	Mn	Si	Cr	Ni	Mo	Nb	Ti	V	Al	Fe
W CrMo91	0.09	0.51	0.25	9.0	0.63	0.94	0.052	-	0.22	-	rest
S Ni 6082	0.035	2.99	0.08	20.0	rest	-	2.42	0.35	-	-	1.27
EPRI P87	0.11	1.55	0.16	8.52	rest	2.02	1.09	-	-	-	38.8

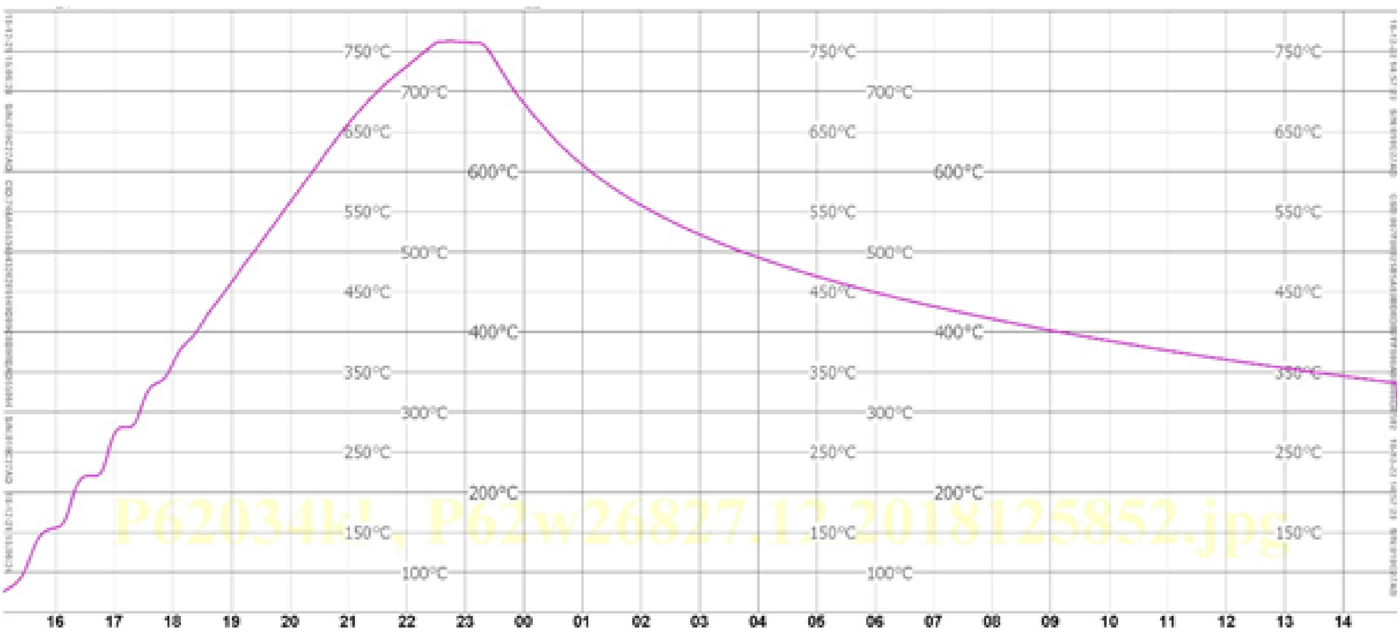


Fig. 6. Thermal cycle of the stress relief annealing of the welded joints made of steel THOR®115

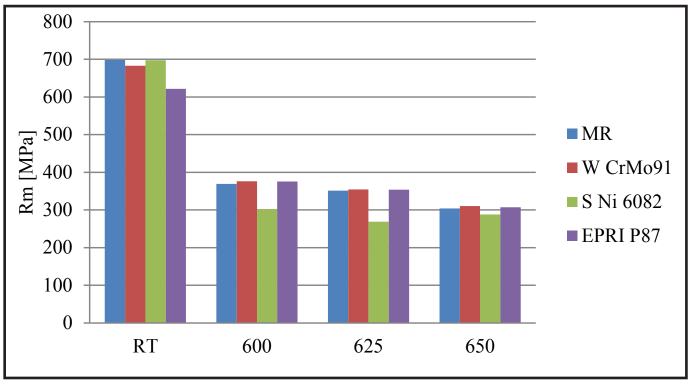
Making of TIG butt welded joints

The next stage of the tests involved the making of test joints. Similar test joints were made using a pipe having an external diameter of 50.8 mm and a wall thickness of 10.1 mm. The pipe was made of steel THOR®115, the chemical composition of which is presented in Table 2. The joints were made using the TIG method (141) in the PH position (5G upwards in accordance with ASME). Because of the present lack of a special filler metal dedicated to the welding of steel THOR®115, the Tenaris company recommends using the filler metal applied in the welding of steel grade 91, i.e. W CrMo91. To determine the effect of various filler metals on the quality of joints, the welding tests also involved the use of two other filler metals, i.e. S Ni 6082 and EPRI 87 (Table 8). After welding, the joints were subjected to stress relief annealing performed at a temperature 760°C for 60 minutes (Fig. 6).

Table 8. Tensile test results in relation to the bend tests of the pipes made of steel THOR®115

Specimen designation[1)]	Tensile strength R_m, MPa			
	RT	600	625	650
1/R/1	682.3	376.2	355.8	309.8
1/R/2	678.9	374.8	350.1	305.4
1/R/3	686.6	378.1	358.2	315.2
Mean value	**682.6**	**376.4**	**354.7**	**310.1**
2/R/1	693.5	300.5	291.6	270.8
2/R/2	703.4	298.7	285.3	265.7
2/R/3	696.7	306.5	286.3	270.4
Mean value	**697.9**	**301.9**	**287.7**	**269.0**
3/R/1	621.8	376.2	355.8	309.8
3/R/2	601.2	370.8	356.8	311.5
3/R/3	641.2	380.4	349.5	299.3
Mean value	**621.4**	**375.8**	**354.0**	**306.9**

[1)] Designations: Base material: 1 – W CrMo91, 2 – S Ni 6082, 3 – EPRI P97, RT – room temperature: 600°C, 625°C and 650°C – tensile test temperature, R – tension



Tests

The making of the welded joints was followed by the performance of non-destructive tests, i.e. VT, PT and RT. The tests were performed taking into consideration quality level B in accordance with the PN-EN ISO 5817 standard [17]. After the performance of the NDTs, the joints were sampled for specimens to be subjected to destructive tests.

The scope of destructive tests included the following:

- tensile test,
- bend test,
- impact strength tests,

Table 9. Impact strength test results

Specimen designation[1)]	Tensile strength KV, J	
	HAZ	Weld
1/KV/1	167	163
1/KV/2	168	140
1/KV/3	173	148
Mean value	**169**	**150**
2/KV/1	172	108
2/KV/2	160	112
2/KV/3	170	110
Mean value	**167**	**110**
3/KV/1	66	140
3/KV/2	76	136
3/KV/3	60	152
Mean value	**67**	**143**

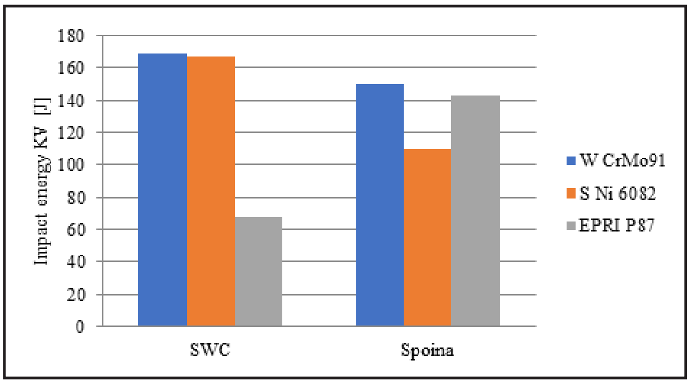
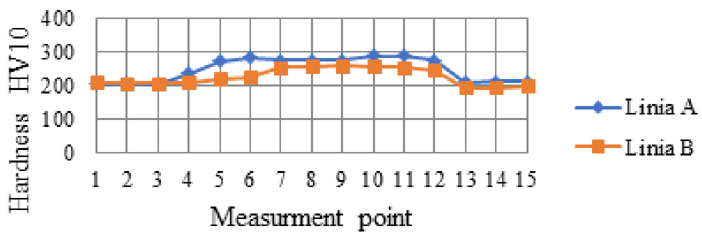
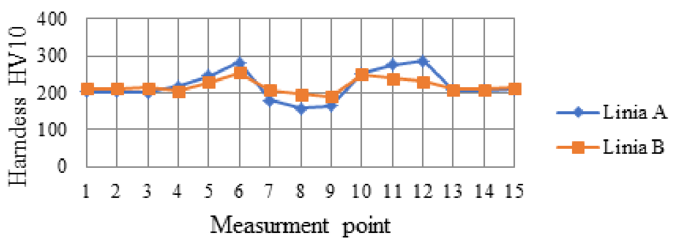


Table 10. Hardness test results /Line A; Line B/

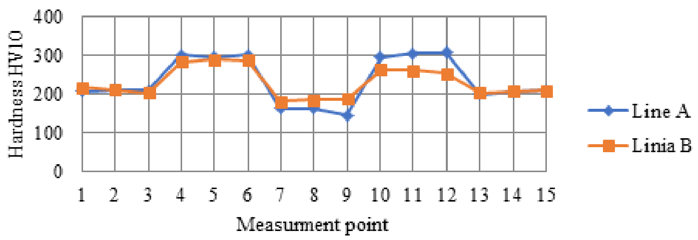
W CrMo91															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Line A	204	206	204	236	273	282	274	274	274	288	288	275	208	212	212
Line B	210	207	207	210	220	225	253	257	258	256	253	247	193	194	199



S Ni 6082															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Line A	203	203	200	217	245	282	179	158	165	251	275	286	206	207	209
Line B	212	212	213	205	229	255	206	196	189	250	240	231	208	210	213



EPRI P87															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Line A	207	211	210	302	295	301	163	162	144	295	305	308	200	206	209
Line B	217	212	203	284	289	287	181	186	187	263	261	254	203	208	209



– macro and microscopic metallographic tests,
– hardness measurements.

The tensile test of the welded joint was performed in order to determine its tensile strength (R_m). The test was performed in accordance with the requirements specified in the PN-EN 6892-1 [11], PN-EN ISO 6892-2 [12] and PN-EN ISO 4136 standards [18] using an MTS Criterion C45 static testing machine (+/- 100kN) equipped with an ND-40 induction heating system. The tests were performed both at room temperature and at an elevated temperature of 600°C, 625°C and 650°C. The test results are presented in Table 8.

The impact strength test was performed at an ambient temperature of +20°C using specimens with the Charpy V notch incised in the weld, fusion line and in the heat affected zone, in accordance with the requirements specified in the PN-EN ISO 148-1 [14] and PN-EN ISO 9016 standards [19]. The tests were performed to identify impact energy values in relation to the weld and HAZ. A criterion contained in PN-EN 12952-6 [20] states that the minimum impact energy in relation to specimens having a normal cross-section (10 mm x10 mm) in the HAZ should amount to 24 J at room temperature, whereas the PN-EN 10216-2 [21] specifies that the minimum impact energy in relation to the BM should amount to 27 J. The impact energy test results related to the weld and the HAZ were higher than those specified in the above-named standard. The tests involved specimens having the reduced cross-section (7.5 mm x 8 mm). Because of this, the values presented in the Figures were, in accordance with related requirements, proportionally higher. The obtained test results are presented in Table 9.

The face bend tests and **the root bend test** of the welded joint were performed in accordance with the PN-EN 15614-1 [22], PN EN ISO 7438 [23] and PN-EN ISO 5173 standards [24]. According to PN-EN 15614-1 [22], the test criterion is the obtainment of a bend angle of 1800 without the formation of scratches and cracks on the surface of a specimen subjected to the test. The results obtained in the tests satisfied the requirements specified in the related standard.

The hardness measurements were performed in accordance with the PN-EN 15614-1 [43] and PN-EN 12952-6 [20] as well as PN EN ISO 6507-1 [25] and PN-EN ISO 9015-1 standards [26]. The above-named standards state that the maximum hardness of martensitic steels subjected to post-weld heat treatment should amount to 350 HV10. The measurement results are presented in Table 10.

The macroscopic metallographic tests were performed in accordance with the PN-EN ISO 17639 [10] standard. The adopted assessment criterion was quality level B in accordance with the PN-EN ISO 5817 standard [17]. The test joints satisfied the above-named criterion. The photographs of the macrostructures of the butt joints are presented in Table 11.

The microscopic metallographic tests were performed in accordance with the PN-EN 17639 standard [10]. The test results did not reveal the presence of any welding imperfections in the micro and macroscale and confirmed the presence of the proper microstructure in all of the zones of the butt welded joints. The photographs and descriptions of the structures present in the characteristic zones of the welded joint are presented in Table 12.

Concluding remarks

The above-presented tests justified the formulation of the following conclusions:

1. The TIG welded joints made in steel THOR®115 in the PH position were characterised by high quality in relation to all of the filler metals, which was confirmed by related destructive tests.
2. To confirm the usability of the test steel the Authors intend to perform advanced microscopic tests and creep tests. The above-named tests will enable the more accurate analysis of joints and confirm their usability on an industrial scale.

Table 11. Results of macroscopic metallographic tests

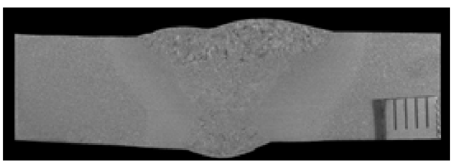
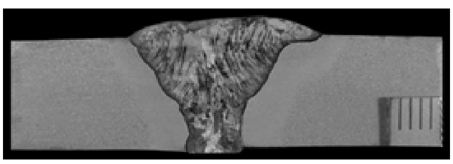
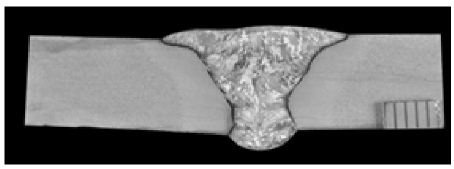
W CrMo91	S Ni 6082	EPRI P87
		
Etchant: Adler Quality level B in accordance with PN-EN ISO 5817 [17]	Etchant: Adler Quality level B in accordance with PN-EN ISO 5817 [17]	Etchant: Adler Quality level B in accordance with PN-EN ISO 5817 [17]

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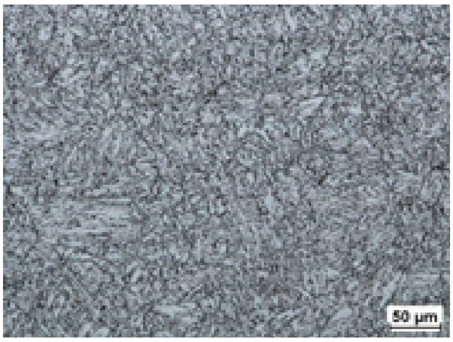
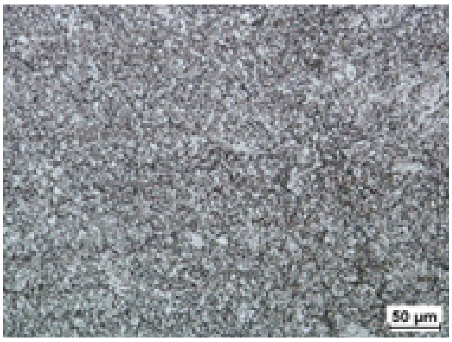
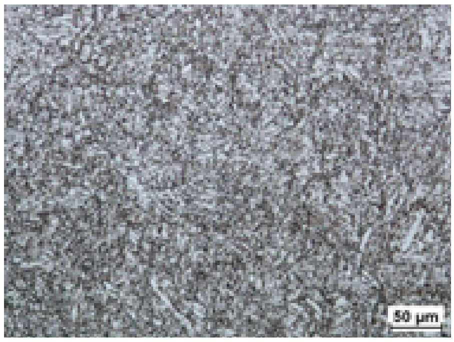
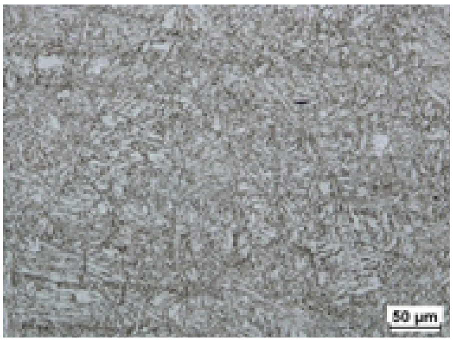
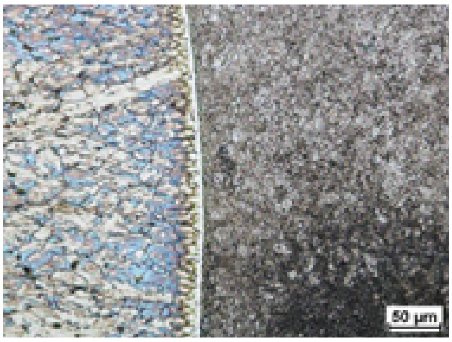
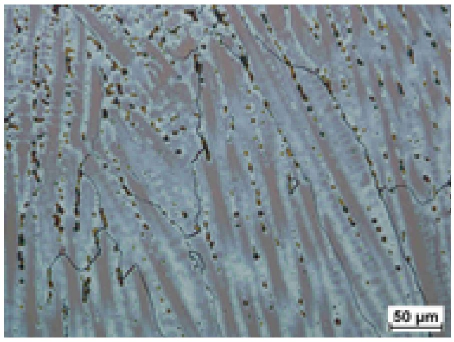
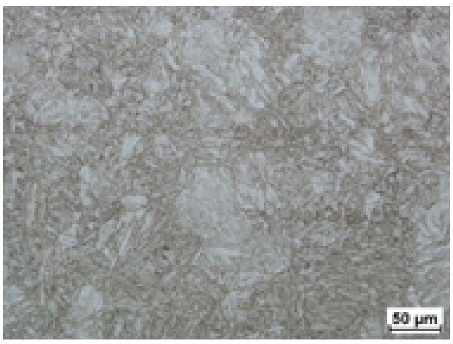
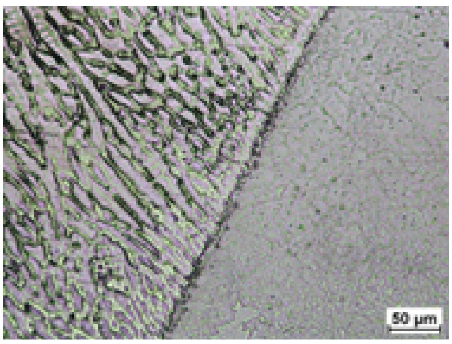
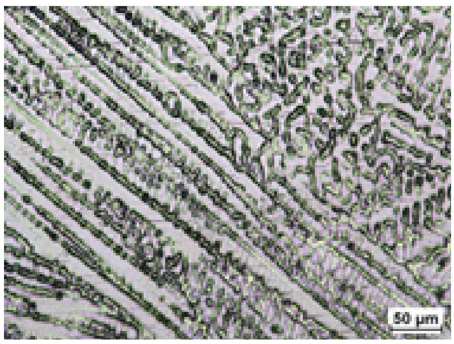
Table 12. Results of microscopic metallographic tests

W CrMo91		
		
BM Electrolytic etching Mag. 200x Tempered martensite	HAZ Electrolytic etching Mag. 200x Tempered martensite	Weld Electrolytic etching Mag. 200x Tempered martensite
S Ni 6082		
		
BM Electrolytic etching Mag. 200x Tempered martensite	HAZ Electrolytic etching Mag. 200x Austenite – temp. martensite	Weld Electrolytic etching Mag. 200x Austenite
EPRI P87		
		
BM Electrolytic etching Mag. 200x Tempered martensite	HAZ Electrolytic etching Mag. 200x Austenite – temp. martensite	Weld Electrolytic etching Mag. 200x Austenite

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