Proceedings of TEAM 2015

7th International Scientific and Expert Conference
of the International TEAM Society

14–16th October 2015, Belgrade, Serbia

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15–16th October 2015,
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Publisher: Faculty of Mechanical Engineering, University of Belgrade

Editor in Chief: Prof. Aleksandar Sedmak

Editors: Zoran Radakovic, Simon Sedmak, Snezana Kirin

ISBN **978 – 86 -7083 – 877 – 2**

Circulation: 200 copies

Copied by Faculty of Technology and Metallurgy, Research and Development Centre of Printing Tehnology, Karnegijeva 4, Belgrade, Serbia

All papers are reviewed

The authors are only responsible for the accuracy and contents of all published material.

CIP - Каталогизација у публикацији
Народна библиотека Србије, Београд

62(082)(0.034.2)

INTERNATIONAL TEAM Society. International Scientific and Expert Conference (7 ; 2015 ; Beograd)
Proceedings of TEAM 2015 [Elektronski izvor] / 7th International
Scientific and Expert Conference of the International TEAM Society, 15/16th October 2015, Belgrade, Serbia ; [Editor in Chief Aleksandar Sedmak]. - Belgrade : Faculty of Mechanical Engineering, 2015 (Belgrade : Faculty of Technology and Metallurgy, Research and Development Centre of Printing Technology). - 1 elektronski optički disk (CD-ROM) ; 12 cm

Sistemski zahtevi: Nisu navedeni. - Nasl. sa naslovne strane dokumenta. - Tiraž 200. - Bibliografija uz svaki rad.

ISBN 978-86-7083-877-2

a) Техника - Зборници
COBISS.SR-ID 218229516

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CONTENT

7th International Scientific and Expert Conference TEAM 2015
Technique, Education, Agriculture & Management
Belgrade, October 15-16, 2015

SELECTION OF STEELS FOR VITAL STRUCTURES AND TURBINE COMPONENTS OF THE HYDRO POWER PLANT 'DJERDAP 1'

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Abstract

Vertical Kaplan turbines, manufactured in Russia and with nominal power of 200 MW, have been installed in 6 hydroelectric generating units at 'Djerdap 1'. During the refurbishment of hydroelectric generating sets A4, A5 and A6, non-destructive and destructive tests were carried out on parent material and weld metal in order to complete the state analysis and assessment of damage level and causes of damage occurrence at vital structures and components, which showed that the selection of suitable material has a crucial role regarding the safe operation of hydro-electric power plants. This paper contains comparative results of mechanical tests performed in order to obtain mechanical properties of materials used for the fabrication of the upper rings of guide vane apparatus installed in 1973 and made of steel St 3 (GOST 977-88) and those recently made through the use of steel S 235 (EN 10025-2), as well as for turbine covers, made of steels S 355 NL (EN 10025-2) and S 355 NL + Z25 + N (EN 10025-3).

Keywords: Refurbishment, turbine equipment, hydromechanical equipment, steel selection

1. Introduction

For the state analysis of turbines in power plant Djerdap, [1], and assessment of the level of damage and degradation, as well as determination of causes of damage occurrence during the refurbishment of hydroelectric generating sets A4, A5 and A6, various non-destructive and destructive tests were performed on parent material and welded joints. Degradation of parent material and welded joints of upper rings of guide vane apparatus is presented in paper [2], while degradation of parent material and welded joints of turbine covers is presented in paper [3].

2. Results of non-destructive tests

Upper rings of guide vane apparatus were created by welding four segments together (identified as 1-2, 2-3, 3-4 and 4-1), made of steel St 3 [4]. Welding of these segments was performed through the application of submerged arc welding.

A large number of surface crack-type linear indications was detected through the application of magnetic particle tests (MT) at all segments. Indications detected at segment 4-1 are shown in figure 2.

In figure 3 segment 4-1 of the upper ring of guide vane apparatus is shown, at which defects like the lack of root penetration and lamellar tearing in the root area of the welded joint were detected. Lamellar tearing was caused by pulling of the 40 mm thick sheet metal in the zone of fusion of parent and filler material.

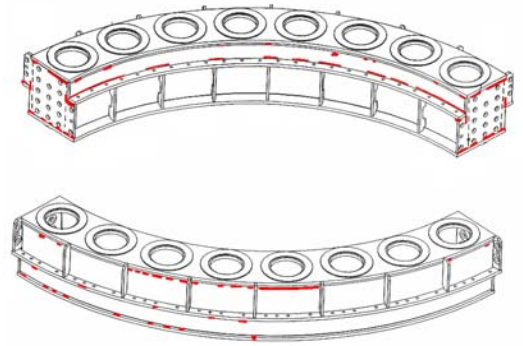

Figure 1. Display of magnetic particle test results, segment 4-1

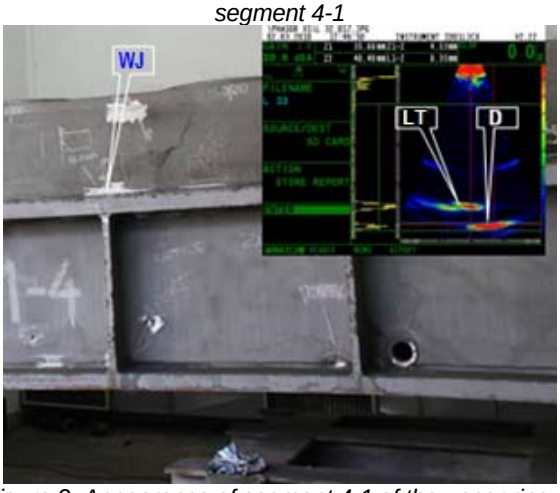

Figure 2. Appearance of segment 4-1 of the upper ring of guide vane apparatus

Turbine cover, shown in figure 4, has been fabri–cated by welding four segments together (identified as 1-2, 2-3, 3-4 and 4-1), made of steel St 3 [4]. In figure 5 one of the segments (segment 4-1) is shown, at which welded joints were inspected, or to be more specific weld metal, heat-affected zone and parent material, in order to detect surface indications (flaws) by magnetic particle testing and internal indications (flaws) by ultrasonic testing.

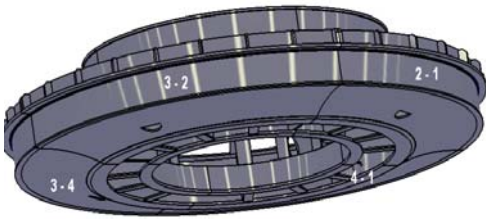

Figure 3. Turbine cover

In figure 3 locations at turbine cover segment 4-1 where surface indications (flaws) in welded joints were detected through the application of magnetic particle testing are shown.

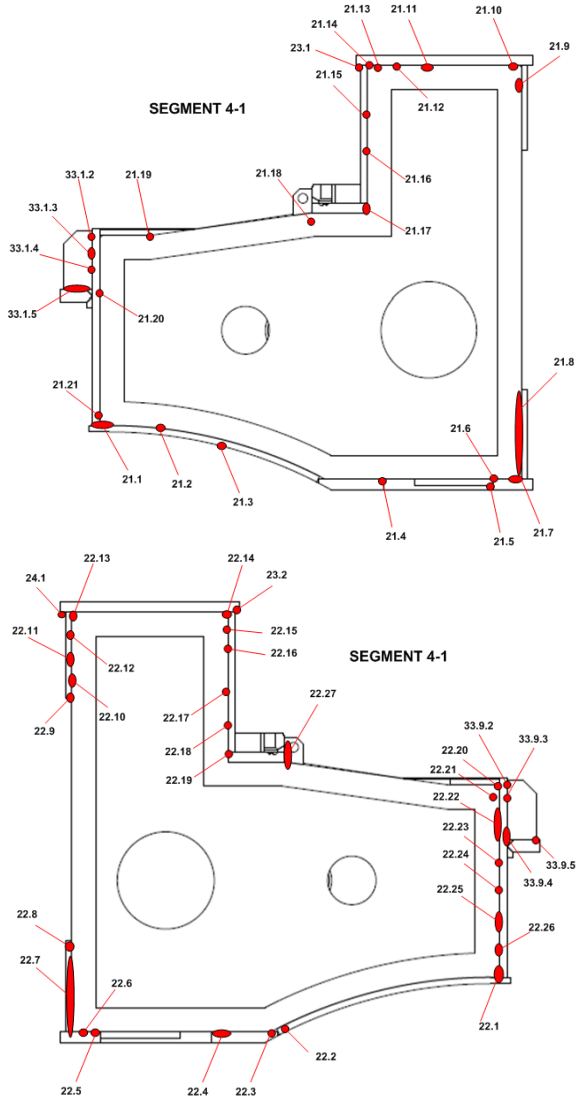

Figure 4. Appearance of results of magnetic particle testing performed at turbine cover segment 4-1

Figure 6 shows the locations where internal indications (flaws) in welded joints of turbine cover segment 4-1 were detected through the use of ultrasonic testing, while figure 7 shows echographs created during the inspection of welded joints and parent material. Lack of root penetration and lamellar tearing in parent material detected during the test are schematically presented in figure 8.

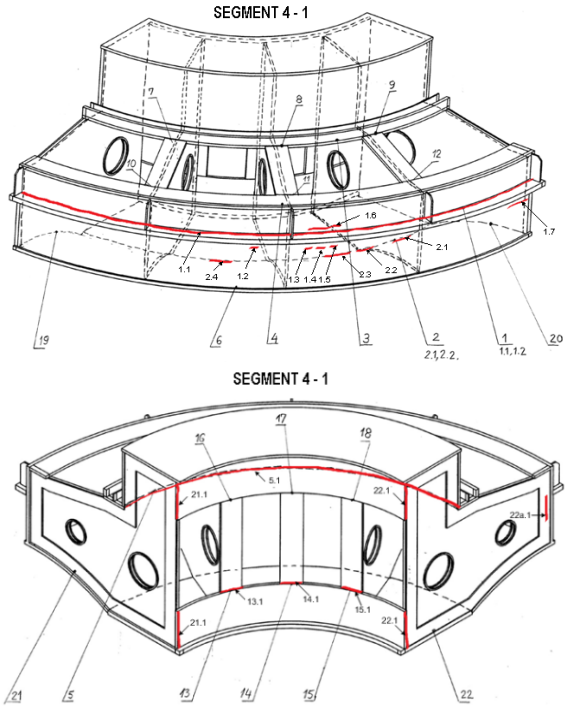

Figure 5. Appearance of results of ultrasonic testing performed at segment 4-1 of the turbine cover

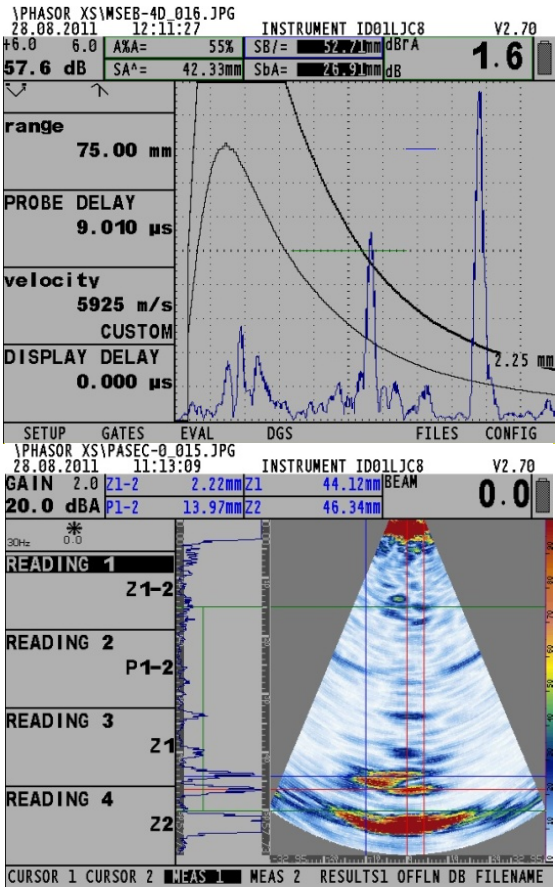

Figure 6. Lamellar tearing indications in the area of the welded joint and echographs - segment 4-1 turbine cover

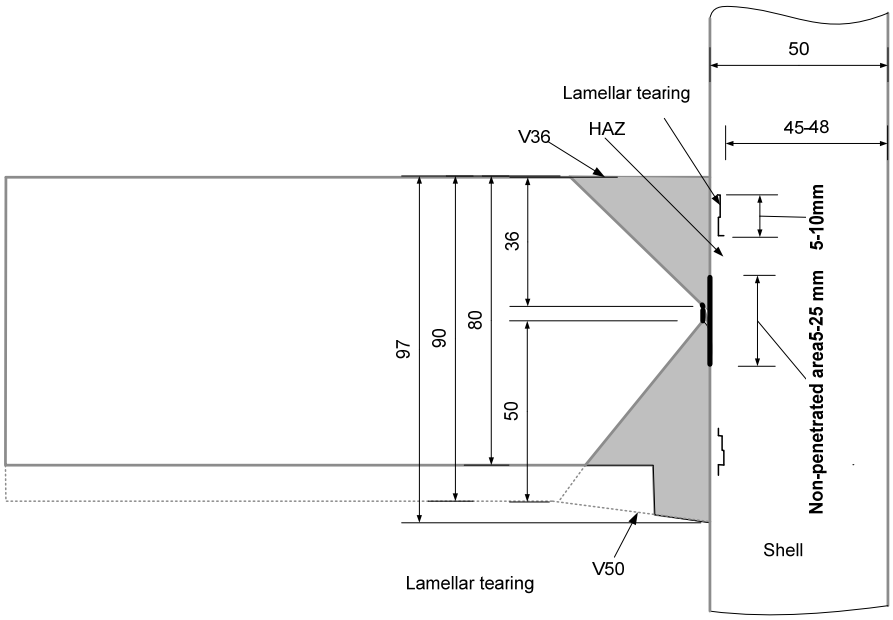

Figure 7. Appearance of lamellar tearing in the welded joint

3. Results of destructive tests

Results of destructive tests performed on samples taken from the upper ring of guide vane apparatus of hydroelectric generating set A6 are presented in this paper.

On the basis of results of chemical composition analyses carried out through the application of the gravimetric and volumetric (G-V) method, performed on samples taken from segments of the upper ring of guide vane apparatus, it can be concluded that chemical compositions, regardless of deviations of C and Mn in segment 3-4, correspond to requirements for steel St 3 [5], Table 1.

For the testing of mechanical properties in the longitudinal (marked as **l** in figure 9) and transverse direction (marked as **t** in figure 9) of the 40 mm thick metal sheet, circular cutting has been performed in order to obtain a sample with diameter of 380 mm from the internal wall (internal coating) of segment 4-1 of the upper ring of guide vane apparatus, as well as cutting of the 450 mm long sample from the welded joint of the 50 mm thick metal sheet (welded joint V50) for metallographic testing of parent material and of the welded joint, or, more precisely, of the material from heat-affected zone and of weld metal from the flange of the upper ring of guide vane apparatus, taken from segment 3-4.

Table 1 Results of chemical analyses of delivered samples, mass percentage

Segment	C	Si	Mn	S	P
2-3	0,17	0,19	0,46	0,026	0,014
3-4	0,12	0,28	0,74	0,023	0,015
1-4	0,20	0,26	0,60	0,034	0,015
In accordance with standard [5]	0,14 – 0,22	0,15 – 0,30	0,40 – 0,65	≥ 0,050	≥ 0,040

Figure 8. Photograph of the sample cut out from segment 4-1 of the upper ring of guide vane apparatus

For tensile testing of the metal sheet in longitudinal and transverse direction, from the surface and central layer of the samples were taken, thickness wise, and 2 standard specimens have been produced, 8 mm in diameter in the measurement section, according to standard [6], figure 10.

For determination of causes of the occurrence of lamellar cracks or lamellar tearing in zones of welded joints of the upper ring of guide vane apparatus, tests in order to determine the ductililty and contraction of the cross-section in “Z” direction were carried out. Three specimens have been fabricated, 6 mm in diameter, figure 11.

Tensile tests have been carried out on a universal machine for tensile, pressure and bending tests "Alfred Amsler", with the maximum range of 98,1 kN. Results of tensile tests showed that tensile properties of parent material meet the requirements of standards [6] and [7] for steel St 3, table 2.

Table 2. Mean values of tensile test results, ERPS EN 10002-1

Sampling position	$R_{p0,2}$ [N/mm^2]	R_m [N/mm^2]	$A_{5,65}$ [%]
Longitudinal direction - surface layer	301	466	28.50
Longitudinal direction - central layer (thickness wise)	293	465	29.25
Transverse direction - surface layer	296	463	31.35
Transverse direction - central layer (thickness wise)	295.5	466.5	30.40
Transverse direction, steel St 3, in accordance with [7]	min. 235	370-480	min. 25

Significantly lower values of contraction than minimum values prescribed by standard [8] were obtained by testing of tensile properties in "Z" direction, table 3. According to standard [8], as well as standards DIN 50180, SEL 096 and DAST 014, steel sheets used for structures with an enhanced ability to deform in direction transverse to the surface of the product need to have a value of contraction 25% at least. Fracture surfaces of tested specimens were bright with rough structure, without significant contraction of cross-section or visible elongation, figure 11.

From the sample taken from segment 4-1 of the upper ring of guide vane apparatus, standard specimens for impact energy, with dimensions 10x10x55 mm and 2 and 3 mm deep U-notch, were fabricated, figure 11.

Values higher than minimum values prescribed by [9] were obtained by impact tests, carried out in longitudinal and transverse direction on specimens with 2 and 3 mm deep U-notches, as requested by [7]. Impact energy results for specimens taken from the surface layer differ from those obtained for specimens taken from the central layer (thickness wise) up to 50%, tables 4 and 5. Appearance of fracture surfaces for one of test specimens is presented in figure 12.

Results of destructive tests performed on samples taken from the turbine cover of hydroelectric generating set A4 are presented in this paper.

On the basis of results of chemical composition analyses by spectrophotometric method, performed on samples taken from segments of the turbine cover, it can be concluded that chemical composition of segment 4-1 meets the requirements prescribed for steel St 3 [5], table 6.

Table 3. Results of contraction tests, in accordance with standard [8]

Sampling position	Ep	d_0 [mm]	d_1 [mm^2]	Z [%]	Zsr [%]
"Z" direction	1	6.0	5.8	6.56	8.69
	2	6.0	5.7	9.75	
	3	6.0	5.7	9.75	
Prescribed values		Z15		min. 10	min. 15
		Z25		min. 15	min. 25
		Z35		min. 25	min. 35

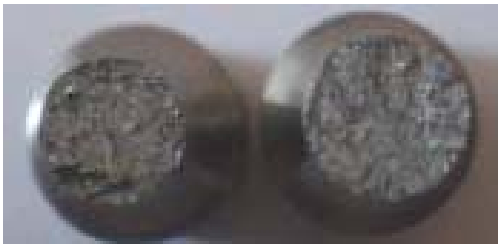

Figure 9. Appearance of fracture surfaces of the specimen for the testing of contraction in z-direction

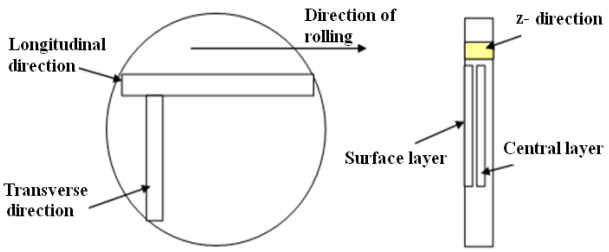

Figure 10. Sampling of specimens for tensile testing

Table 4. Mean values of impact test results for specimens with U2-type notch

Sampling position	T [^{0}C]	$KU_{2/300}$ [J]	$KU_{2/300}$ (KCU) [J/cm^2]
Longitudinal direction - surface layer	+20	59.8	74.8
Longitudinal direction - central layer (thickness wise)	+20	54.9	68.7
Transverse direction - surface layer	+20	80.8	100.9
Transverse direction - central layer (thickness wise)	+20	74.9	93.6
Transverse direction, steel St 3, prema standardu [7]	+20	min. 49	

Table 5. Mean values of impact test results for specimens with U_3-type notch

Sampling position	T [^{0}C]	$KU_{3/300}$ [J]	$KU_{3/300}$ (KCU) [J/cm^2]
Longitudinal direction - surface layer	+20	57.6	82.2
Longitudinal direction - central layer (thickness wise)	+20	74.6	106.5
Transverse direction - surface layer	+20	69.9	99.9
Transverse direction - central layer (thickness wise)	+20	105..6	151.8
Transverse direction, steel St 3, prema standardu [7]	+20	min. 49	

Figure 11. Appearance of fracture surfaces of the specimen for impact testing

Table 6. Results of chemical analysis performed on delivered sample, mass percantage

Segment	C	Si	Mn	S	P
1-4	0,19	0,27	0,58	0,035	0,012
standard [5]	0,14 – 0,22	0,15 – 0,30	0,40 – 0,65	max. 0,050	max. 0,040

Circular cutting of a sample with the diameter of 300 mm taken from turbine cover segment 4-1, figure 13, was performed in order to determine mechanical properties in longitudinal and transversal direction of 50 mm thick sheet metal.

Figure 12. A photograph of the sample taken from turbine cover segment 4-1

Two standard specimens have been fabricated, with 8 mm diameter in the measurement section, in accordance with standard [6], figure 11, and used for tensile testing of the metal sheet in longitudinal and transverse direction. They were taken from the surface and central layer, thickness wise.

For determination of causes of the occurrence of lamellar cracks or lamellar tearing in zones of welded joints of the turbine cover, tests in order to determine the ductililty and contraction of the cross-section in "Z" direction were performed. Three specimens have been fabricated, 6 mm in diameter, figure 11.

Tensile tests have been carried out on a universal machine for tensile, pressure and bending tests "Alfred Amsler", with the maximum range of 98,1 kN.

Results of tensile tests showed that tensile properties of parent material in longitudinal and transversal direction meet the requirements of standards [6] and [7] for steel St 3, table 7.

Significantly lower values of contraction than minimum values prescribed by standard [8] were obtained by tensile tests in "z" direction, table 8. According to standard [8], as well as standards DIN 50180, SEL 096 and DAST 014, steel sheets used for structures with an enhanced ability to deform in direction transverse to the surface of the product need to have a value of contraction 25% at least.

From the sample taken from segment 4-1 of the turbine cover, standard specimens for impact tests, with dimensions 10x10x55 mm and 2 mm deep U and V notch, were fabricated, figure 11.

Values lower than minimum values prescribed by standard [7], as well as those within the prescribed range defined in standard [9], were obtained by impact tests, carried out on specimens with 2 mm deep notches, tables 9 and 10.

Table 7. Mean values of tensile test results, in accordance with standard [6]

Sampling position	$R_{p0,2}$ [N/mm^2]	R_m [N/mm^2]	$A_{5,65}$ [%]	Z
Longitudinal direction - surface layer	247	418	36	60.0
Longitudinal direction - central layer (thickness wise)	222	400	40	60.5
Transverse direction - surface layer	251	414	37	61.0
Transverse direction - central layer (thickness wise)	221	402	49. 5	50.0
Transverse direction, steel St 3, in accordance with [7]	≥ 235	370-480	≥ 23	≥ 25

Table 8. Results of contraction tests in z direction, in accordance with standard [8]

Sampling position	Specimen	d_0 [mm]	d_1 [mm^2]	Z [%]	Zsr [%]
"Z" direction	1	10.0	9.7	5.91	7.75
	2	10.0	9.2	15.36	
	3	10.0	9.9	1.99	
Prescribed values		Z15		≥ 10	≥ 15
		Z25		≥ 15	≥ 25
		Z35		≥ 25	≥ 35

Table 9. Mean values of impact test results for specimens with U_2-type notch

Sampling position	T [^{0}C]	$KU_{2/300}$ [J]	$KU_{2/300}$ (KCU) [J/cm^2]
Longitudinal direction - surface layer	+20	80.7	101.0
Longitudinal direction - central layer (thickness wise)	+20	85.3	106.7
Transverse direction - surface layer	+20	62.1	77.7
Transverse direction - central layer (thickness wise)	+20	71.9	89.9
Transverse direction, steel St 3, GOST 14637-89	+20	min. 49	

Table 10. Mean values of impact test results for specimens with V_2-type notch

Sampling position	T [^{0}C]	$KV_{2/300}$ [J]	$KV_{2/300}$ (KCU) [J/cm^2]
Longitudinal direction - surface layer	+20	35.1	44.1
Longitudinal direction - central layer (thickness wise)	+20	32.4	44.5
Transverse direction - surface layer	+20	25.8	32.3
Transverse direction - central layer (thickness wise)	+20	40.2	50.3
Transverse direction, steel St 3, GOST 14637-89	+20	min. 49	

4. Mechanical properties of material for the fabrication of new upper ring of guide vane apparatus and turbine cover structures

Results of performed tests showed that there are 2 equally important causes for the degradation of parent material and weld metal on a vital mechanical structure:

• degradation due to flaws in steelmaking technology
• degradation caused by flaws during manufacture of the welded structure.

Both mentioned causes influenced the occurrence of lamellar tearing in parent material, as well as in weld metal.

On the basis of analyses performed in order to determine causes and level of degradation of parent material and welded joints at the upper ring of guide vane apparatus and turbine cover, structural steels with improved chemical composition and mechanical properties were selected for the manufacture of new structures. Chemical composition [10] and mecha–nical properties of steel S 235 [11], of which new upper ring of guide vane apparatus was made, as well as of steels S 355 NL [12] and S 355 NL + Z25 + N [12], of which new turbine cover was made, are presented in tables 11 - 13.

Table 11. Chemical compositions of steels S 235, S 355 NL and S 355 NL + Z25 + N, mass percentage

Steel grade	C	Si	Mn	P	S	Cr	Ni	Mo	V	N	Nb	Ti	Cu	Al	C_{ek}
S 235	max 0.22	max 0.266	max 1.334	max 0.015	max 0.007	–	–	–	–	–	–	–	–	–	max 0.45
S355 NL	max 0.18	max 0.5	0.9 - 1.65	max 0.025	max 0.02	max 0.3	max 0.5	max 0.1	max 0.12	max 0.015	max 0.05	max 0.05	max 0.55	max 0.02	max 0.45
S 355 NL + Z25 + N	max 0.20	max 0.55	0.85 - 1.75	max 0.03	max 0.25	max 0.35	max 0.55	max 0.13	max 0.14	–	max 0.06	max 0.06	–	–	max 0.45

Table 12. Mechanical properties of steels S 235, S 355 NL, S 355 NL + Z25 + N and St 3

Steel grade, sheet thickness	YS [N/mm^2]	TS [N/mm^2]	TS in **z** direction [N/mm^2]	$A_{5,65}$ [%]
S 235, 40 mm ≤ t ≤ 100 mm	min 215	min 360	27	min 22
S 355 NL, 40 mm ≤ t ≤ 100 mm	min 315	470 – 630	25	min 22
S 355 NL+Z25+N, 40 mm ≤ t ≤ 100 mm	min 315	470 – 630	25	min 22
St 3, transversal direction, in accordance with [7]	min 235	370 – 480	min 25	min 23

Table 13. Mean impact energy values, V_2 notch

Steel grade, sheet thickness	T [^{0}C]	KV [J]
S 235, 40 mm ≤ t ≤ 100 mm, longitudinal direction	+20	27
S 235, 40 mm ≤ t ≤ 100 mm, transversal direction	+20	27
S355 NL, 40 mm ≤ t ≤ 100 mm, longitudinal direction	+20	47
S355 NL, 40 mm ≤ t ≤ 100 mm, transversal direction	+20	27
S 355 NL + Z25 + N, 40 mm ≤ t ≤ 100 mm, longitudinal direction	+20	47
S 355 NL + Z25 + N, 40 mm ≤ t ≤ 100 mm, transversal direction	+20	27
St 3, transversal direction, in accordance with [7]	+20	min. 49

5. Conclusion

Magnetic particle testing and utrasonic testing were performed during and after the manufacture of new upper ring of guide vane apparatus and turbine cover through the application of steels S 235, S 355 NL and S 355 NL + Z25 + N, which are not prone to lamellar tearing in the area of welded joints when a suitable welding technology is carried out. Apart from a non-allowable 4 mm long area with insufficient penetration, detected by means of ultrasonic testing, test results were satisfactory. In order to reduce expenses and period of time required for the reparation of the area where insufficient penetration was detected (human resources, material expenses for the preparation and reparation, consumption of filler material), appropriate analytical and numerical calculations were carried out, and it was determined that such a structure will operate safely during the following forty years [13], which has been confirmed by the manufacturer „Силовые машины" from Saint Petersburg.

6. Acknowledgment

The authors acknowledge the support from the Serbian Ministry of Education, Science and Technological Development for Projects TR 35002 and TR 35006.

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