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INTEGRITY ASSESSMENT OF AUTOCLAVES AFTER RECONSTRUCTION

PROCENA INTEGRITETA AUTOKLAVA NAKON REKONSTRUKCIJE

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Keywords
- autoclave
- pressure vessel
- reconstruction
- NDT
- structural integrity

Abstract

The paper describes the reconstruction procedure of 3 autoclaves, i.e. equipment used for drying raw coal. Due to material degradation in working conditions and damage, the lower part of the autoclave, of steel Altherm 55 (commercially known) is completely replaced by 18 Mn Mo4-5+NT (commercially known), in order to extend service life of this pressure equipment and increase plant reliability. The reconstruction procedure of autoclaves is presented, i.e., the welding technology for the lower (new) part of the autoclaves. Structural integrity assessment is performed by NDT methods and hydrotests on reconstructed equipment before recommissioning, as well as for the strict criterion of the quality requirement of welded joints exposed to dangerous working fluids.

Ključne reči
- autoklav
- posuda pod pritiskom
- rekonstrukcija
- IBR
- integritet konstrukcije

Izvod

U radu je opisana rekonstrukcija 3 autoklava, tj. opreme za sušenje sirovog uglja. Usled degradacije materijala uzrokovane radnim uslovima i oštećenjem na donjem delu autoklava od materijala Altherm 55 (komercijalni naziv), isti je zamenjen materijalom 18 MnMo4-5+NT (komercijalni naziv) sa ciljem produžetka radnog veka opreme pod pritiskom i povećanjem pouzdanosti postrojenja. Prikazan je postupak rekonstrukcije autoklava, odnosno, tehnologija zavarivanja donjeg (novog) dela. NDT ispitivanja i hidrotestovi su urađeni u cilju procene integriteta rekonstruisane opreme pre ponovnog puštanja u rad i generalno, strožijih zahteva u pogledu kvaliteta zavarenih spojeva i opasnosti izazvanih radnim fluidom.

INTRODUCTION

Process equipment in service conditions can be exposed to damage, primarily corrosion, and most often encountered in combination with thermal loads /1-3/, significantly affecting the decrease in service. In addition to in-service conditions, the decrease of service life can be affected by poor construction design and potential excessive repair welding activities on the equipment /4/, causing excessive heat input. Damage mechanisms that lead to the repair or reconstruction of the autoclave are extremely complex. Flaws in design (in autoclave structure) and extreme working conditions, that some parts are exposed to, as erosion, abrasion, temperature fatigue, and corrosion, can also significantly influence the remaining service life.

In order to restore the functionality of working equipment, and before placing back into service, it is necessary to assess the integrity of the reconstructed part. Various methods for integrity assessment of processing equipment can be distinguished (both, reconstructed and new), that usually depend on the type of equipment, working conditions to which the equipment is exposed to, and most of all, on safety risks. Besides the fracture mechanics approach and application of Failure Analysis Diagrams (FAD), or risk analysis /5-9/, NDT methods can be used for integrity assessment and repair /10-13/, mainly for welded joints, as the most critical places on structures. The finite element method is also effective in the case of determining the stress state of parts exposed to other (additional) loads in addition to working loads, /14/. Also, this method can be used as a verification tool of a redesign solution. The goal of the mentioned reconstruction is to eliminate the cause of shell bursting by crack penetration in the zone of segment supports, /15/. In addition to these methods, multidisciplinary methods of integrity assessment can be found as well, whose application is oriented on predicting material behaviour due to working conditions, as is shown in the case of reactor steel in some studies /16, 17/.

In-service working condition often cause cracks to occur on autoclaves, mainly along the shell wall on bottom part of autoclave structure, resulting in fluid leakage through the vessel wall in the zone of fixed supports (middle shell zone), lower shell zone, and autoclave bottom lid. In this particular case, damages are noticed on the lower part of 3 autoclaves during their (periodical) maintenance, which has led to their reconstruction, i.e. need for complete replacement of the autoclaves' lower part (middle and lower shell zones, and bottom lid). Microstructural examination of the upper part of autoclaves (less problematic) provide insight into existing condition of autoclave base material - steel Altherm 55. The welding technology for joining the upper (old) and lower (new) part of autoclaves of 18 MnMo4-5+NT had to be verified by testing procedures before commissioning. Integrity assessment of redesigned autoclaves is performed using NDT methods and well-prepared hydrotests.

FACILITY DESCRIPTION

Raw coal drying (mainly lignite) is performed in pressure vessels, called autoclaves. An autoclave represents a stable, cylindrical, vertical pressure vessel, and is an integral part of a coal drying facility of working pressure $p = 25$ bar, and working temperature $t = 224$ °C. The working fluid is saturated water vapour, while the volume of the autoclave is 58.54 m^3. Drying is performed according to the ‘Fleissner’ process /18, 19/, by introducing co-saturated water vapour into autoclaves with a maximal overpressure of 25 bar. The extracted moisture from the coal and the co-saturated steam condensate are collected in a special pressure vessel, directly connected to the autoclave.

In this facility, the autoclave is vertical, with slightly conical tilt (angle $\alpha = 1.06°$), while the lids are hemispherical. According to Regulations (*'Pravilnik o tehničkim zahtevima za projektovanje, izradu i ocenu usaglašenosti opreme pod pritiskom, Sl. Glasnik 87/11'*- in Serbian), these autoclaves belong to category IV, i.e., pressure vessel with high level of danger (Fig. 1).

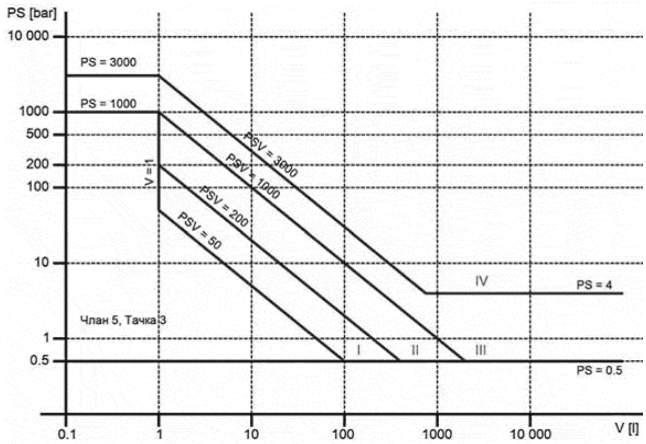

Figure 1. Annex II of Regulations (*in Serbian* ‘Pravilnik o tehničkim zahtevima za projektovanje, izradu i ocenu usaglašenosti opreme pod pritiskom, Sl. Glasnik 87/11’), pressure vessel categorization.

DAMAGES ON AUTOCLAVES

Experience has shown that certain impact forces are generated during loading of the autoclave with coal and discharging of dried coal. Vibrations caused by these ‘shock’ forces are transmitted through autoclave supports to steel structures carrying the autoclave. Such vibrations cause damages mainly on the autoclave shell, as well as on welded joints, initiating cracks and other damage on welded joints. Some damages observed on autoclaves caused by these impact forces are shown in Fig. 2. Figure 2a shows damage on the lower lid of one of the three autoclaves. Wall damage is caused by abrasion. Figure 2b shows a through-thickness crack on bottom lid of one of the three autoclaves. One of the main problems of the autoclave in this facility is erosion of shell wall material (Fig. 2c). In this case the erosion is on the upper shell of one of the three autoclaves.

Due to the constant above-mentioned crack occurrences, erosion, and other damage mechanisms in the lower part of autoclave, more frequent periodical inspections are needed for vessels and the repair of the observed damages in service.

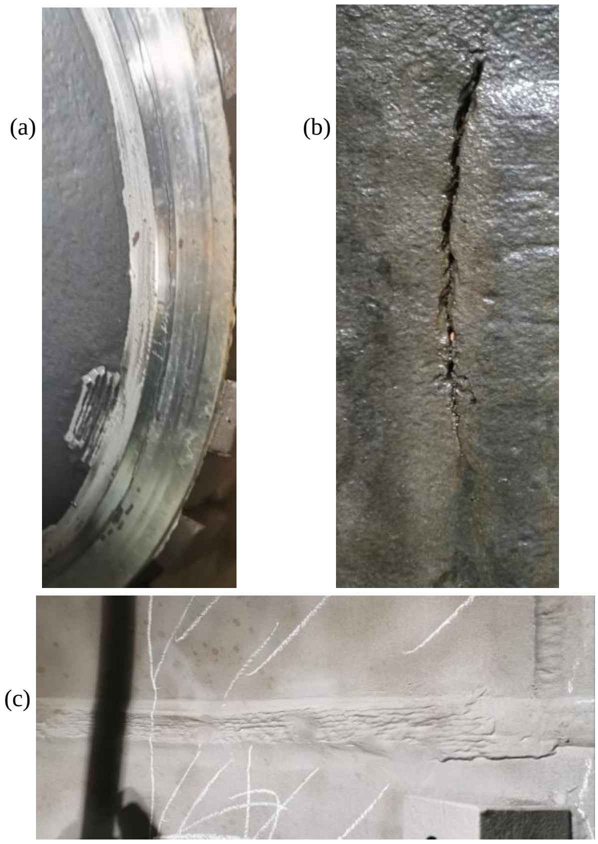

Fig. 2. Some observed damages to autoclaves; a) damage on the lover lid of an autoclave, with abrasion damage and cracking; b) through-thickness crack; c) erosion of shell wall material

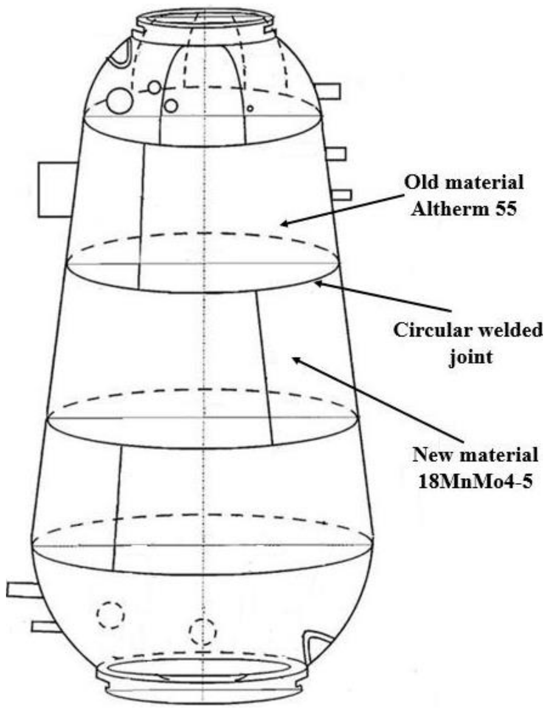

Figure 3. Autoclave reconstruction plan; upper (less damaged) part of Altherm 55, and new lower part of 18MnMo4-5 +NT.

All of the above affects the need for replacement of lower shell segment, and partly the middle shell segment (in the support zone) as well, due to degradation of Altherm 55 base material, caused by operational and excessive welding activities. Accordingly, the replacement of these fatigue-damaged and worn out segments on three autoclaves must be carried out. Figure 3 shows the reconstruction plan for the lower part of autoclave, i.e. replacement with a new bottom part made of 18MnMo4-5+NT material.

RECONSTRUCTION OF AUTOCLAVES

Base material Altherm 55

The base material of autoclaves is a steel commercially known as Altherm 55. It has experienced problems caused by operating conditions, as well as by heat input caused by welding and repair affecting the change of microstructure. Determining the material quality before welding activities represents an important step during reconstruction, /20/, and one applied method is the replica method. For this purpose, microstructural tests of the upper part (less damaged) of the autoclaves are performed. In that way, an insight is gained into the condition of the base material after 40 years in operation.

The microstructure of Altherm 55 steel is coarse-grained, with a mixture of ferrite, perlite, and bainite (Fig. 4). Microstructural examination on the upper part of one of the three autoclaves after 40 years operation is shown in Fig. 4. These examinations indicate that the base material is ferrite-perlite and without any serious damage.

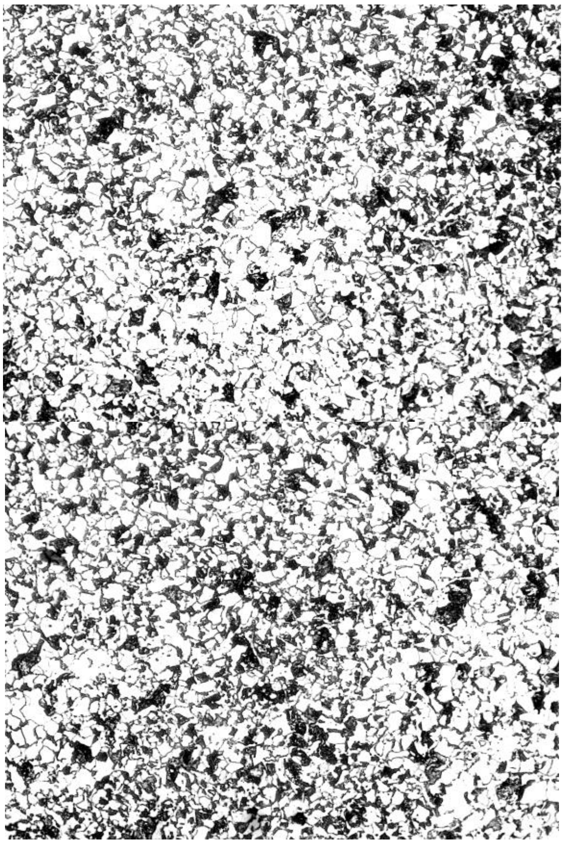

Figure 4. Microstructure of Altherm 55 on upper shell segment, magnified 200×.

Figure 5 shows the microstructure of Altherm steel 55 taken by replica method from the lid of one of the autoclaves (200× magnification). It can be seen that the micro

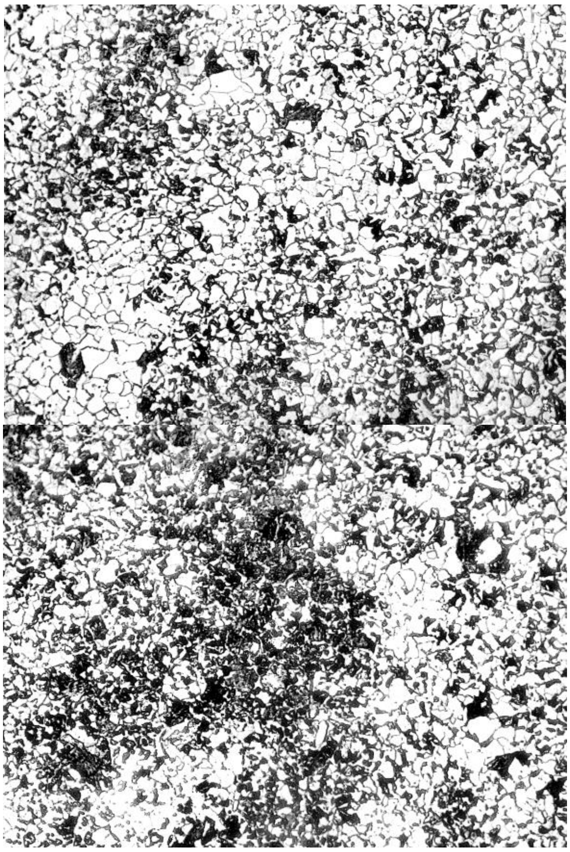

Figure 5. Steel Altherm 55 microstructure on an autoclave lid, with uneven distribution of perlite, magnified 200×.

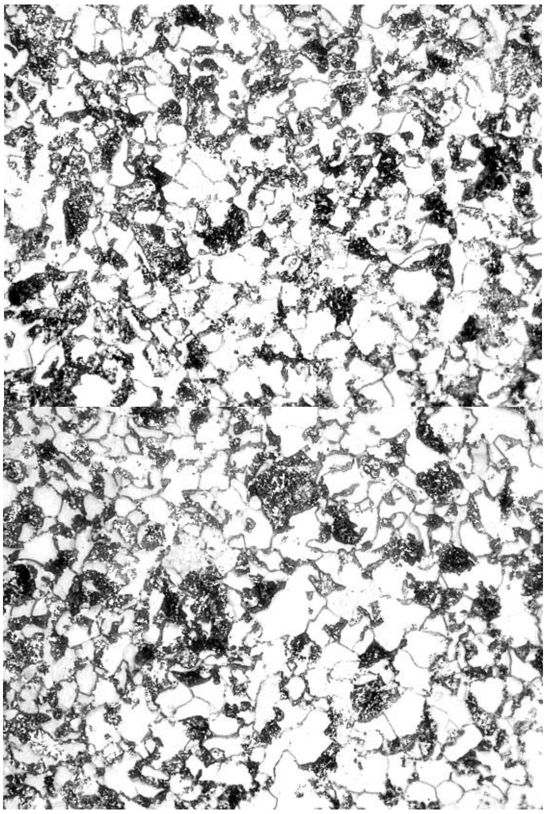

Figure 6. Microstructure of steel Altherm 55 on lid of one of the autoclaves: magnification 500×.

structure of the lid base material is also ferrite-pearlite with an uneven distribution of pearlite. Microstructure of Altherm 55 with magnifications of 500× are shown in Fig. 6. The chemical composition of Altherm 55 is given in Table 1. Tensile properties are given in Table 2, including the operating temperature of the autoclave, i.e. 250 °C.

Table 1. Chemical composition of steel Altherm 55 (wt.%).

Element	C	Mn	Si	S	P	Nb	V	Cr
%	0.23	1.59	0.44	0.015	0.023	0.001	0.01	0.18

Table2. Mechanical properties of steel Altherm 55.

Temperature [°C]	Yield stress [MPa]	Ultimate tensile strength [MPa]	Elongation [%]	Cross section reduction [%]
room	377	597	30	67
250	333	554	-	60

Weldability assessment based on carbon equivalent C_{ek} = 0.53 is calculated according to Eq.(1):

$$C_{ek} = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Ni + \%Cu}{15} . \quad (1)$$

Steel 18 MnMo4-5 + NT

The chemical composition of this material is given in Table 3, while mechanical properties are shown in Table 4 (according to standard recommendations SRPS EN 10028-2). Yield stress at operating temperature 250 °C is $R_{p0.2}$ = 301 MPa, guaranteed by the manufacturer. The weldability of this steel, based on carbon equivalent is poor, which means it is necessary to apply certain measures as well when defining welding technology.

Table 3. Chemical composition of steel 18 MnMo4-5+NT (wt.%).

Element	C	Mn	Si	S	P	Mo	N	Cr
%	≤0.2	1. 9-1.5	≤0.4	≤0.005	≤0.015	0.45-0.6	≤0.012	0.3

Table 4. Mechanical properties of steel 18 MnMo4-5+NT.

Temperature [°C]	Yield stress [MPa]	Ultimate tensile strength [MPa]	Elongation [%]
room	345	510	20

The yield stress of this material at operating temperature 250 °C is $R_{p0.2}$ = 301 MPa, guaranteed by the manufacturer. The weldability, as based on carbon equivalent is poor, being necessary to apply certain measures as well when defining the welding technology.

Based on the calculation of the conical shape shell without connections on the lower autoclave segment (according to recommendations from SRPS EN 13445-3), the adopted shell wall thickness of the middle autoclave segment is 30 mm. This value increased by 20 % due to erosion.

Welding technology

Pressure vessels used for raw coal drying have very strict requirements regarding the quality of welded joints, mainly due to potential danger caused by the working fluid. Therefore, special attention should be paid in defining the welding technology. Grooves of longitudinal welded joints are shown in Fig. 7, i.e., joints of the middle and lower autoclave shells (new assembly) made of 18 MnMo4-5+NT steel, as well as the plan for filling the grooves. Figure 8 shows the grooves for the circular welded joint, i.e. the joint of the new assembly (middle and lower shell segments and bottom lid of 18 MnMo4-5 + NT), and upper autoclave part (steel Altherm 55), as well as the order of filling passes.

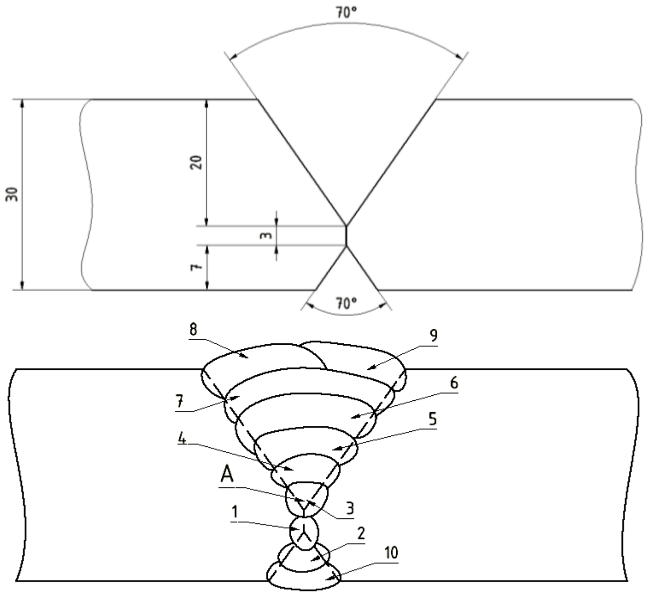

Figure 7. Longitudinal welded joint groove and groove filling plan (material 18 MnMo4-5+NT).

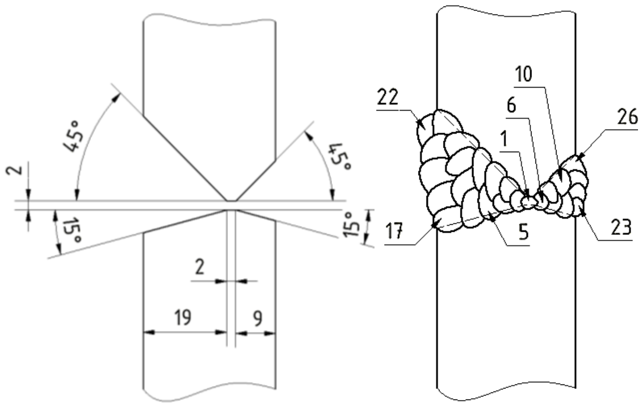

Figure 8. Circular welded joint groove and filling plan (Altherm 55 and 18 MnMo4-5+NT steel).

The required welded joint quality of both steels can be obtained by performing appropriate preheating before the welding. For longitudinal and circular joints, preheating temperature was 230 °C for both materials, whereby the longitudinal joints, due to their stress state (~ two times higher than in circular welds), were subjected to stress annealing at 600 °C. Heat treatment was performed in order to reduce residual stresses caused by cold rolling in the manufacturing process of the autoclave shell, and also as heat input during welding.

The root pass of the longitudinal weld was performed by manual arc welding procedure (111) with EVB Mo electrode by Jesenice /21/, while the filling passes are performed by submerged arc welding method (121) using welding wire UNION S 2 Mo in combination with UV 309 P powder by Böhler, /22/. Drying of the wire and powder is carried out at 400 °C/1 h and 350 °C/2 h, respectively. Drying of the FOX DMO Kb is done at 300-350 °C/2 h.

Circular welded joints are performed using basic low-alloyed electrode FOX DMO Kb manufactured by Böhler, /22/. The chemical composition of all mentioned electrodes is given in Table 5, while the welding parameters for both types of welds and electrode sizes are given in Table 6.

Table 5. Chemical composition of electrode EVB Mo, wire Union S 2 Mo, and electrode FOX DMO Kb (wt.%).

	C	Mn	Si	Mo
EVB Mo	0.10	0.80	0.50	0.50
Union S 2 Mo	0.10	1.0	0.12	0.50
FOX DMO Kb	0.08	0.80	0.35	0.45

Table 6. Welding parameters for longitudinal and circular welds.

Layer	Welding procedure	Filler material	Filler diameter (mm)	Current (A)	Voltage (V)	Polarity	Welding speed (cm/min)	Heat input (kJ/mm)
Longitudinal welds								
A	111	EVB Mo	Ø 3.25	110-120	21-23	DC+	10 - 14	0.25
1-4	121	UNION S 2 Mo	Ø 3	340-350	27-29	DC+	60	0.87
5	121	UNION S 2 Mo	Ø 3	370-380	29-31	DC+	60	1.01
(n+1)-m	121	UNION S 2 Mo	Ø 3	380-390	30-32	DC+	60	1.07
Circular welds								
1	111	FOX DMO Kb	Ø 2.5	90-100	22-24	DC+	7 - 14	1.03-1.43
2-3	111	FOX DMO Kb	Ø 2.5	100-110	22-24	DC+	10 - 18	1.15-1.45
4-26	111	FOX DMO Kb	Ø 3.25	130-140	22-24	DC+	10 - 18	1.35-1.65

Table 7. Methods and scope of NDT on reconstructed autoclaves.

NDT	Scope	
	Top lid and upper shell segment - old part	Bottom lid, lower and mid shell segment – new part
VT	100 % - all welded joints	
PT	20% - construction for temporary carrying the upper autoclave part	100% - welded joints on the load lifting lugs
MT	100% - groove edges on longitudinal and circular joints 100% - all butt weld joints 50% - all fillet weld joints	
UTT	18 m.t. - top lid 24 m.t. - upper shell segment each 4 m.t. - all connections	/
UT	100% - upper shell segment 30% - top lid	10% - longitudinal welded joints 10% - circular welded joints 100% - intersections of longitudinal and circular joints
RE	1 RE - top lid 1 RE - upper shell segment	/
HT	12 m.t. - top lid and upper shell segment	4 m.t. – all joints

POST-WELD TESTING

NDT tests were carried out after welding activities and cold water pressure tests (i.e. hydrotest). The following NDT tests are applied on all 3 reconstructed autoclaves: visual testing (VT); penetrant testing (PT); magnetic particle testing (MT); ultrasonic thickness testing (UTT); ultrasonic testing of welded joints (UT); hardness measurements. The scope and results of these applied NDT methods is discussed as follows.

NDT testing

Due to high level of danger, a thorough plan and scope of applied NDT testing is made in order to check that all welded joints meet the designed quality class 'B' according to SRPS EN ISO 5817, /23/. The methods used to assess the integrity of the reconstructed autoclaves are shown in Table 7. All welded joints meet the quality requirements.

Hydrotest

Water pressure testing of all 3 reconstructed autoclaves is performed according to recommendations of SRPS EN 13445-5 at test pressure p = 33 bar, with clean water without particles that may cause corrosion, in the temperature range 10-50 °C. The test time was 90 min, while the test pressure on all 3 autoclaves was 30 bar. The water pressure testing diagram is shown in Fig. 8. Water pressure testing is in compliance with the national regulations from 'Pravilnik o pregledu opreme pod pritiskom tokom veka upotrebe', Sl. glasnik RS 114/21 (in Serbian), /21/.

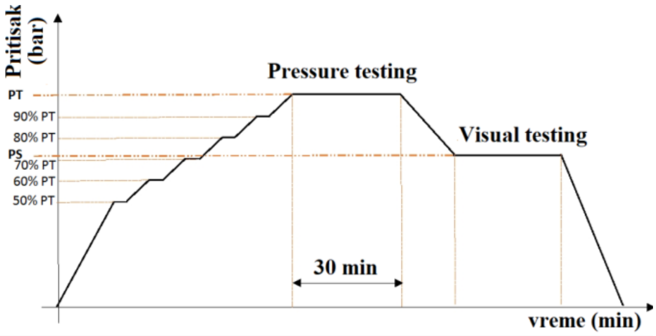

Figure 8. Hydrotest diagram plan of reconstructed autoclaves

Results of the hydrotest show no signs of destruction on reconstructed autoclaves, nor permanent deformation, leakage, and tearing on the welded joints and other parts of the autoclaves, as well as the pressure drop on the control manometer during the test.

CONCLUSIONS

Technical justification for autoclave reconstruction lies in the fact, and also concerning previous tests and repairs, that the bottom lid material and the lower shell segment of Altherm 55 should be replaced due to excessive welding activities in numerous repairs. Repairs are initiated by crack occurrence and material erosion. This is confirmed by microstructural examination that indicated changes in microstructures, even in the less exposed parts of the autoclave. The most dangerous observed defects are through-thickness cracks. In this regard, further degradation of the material can be expected, along with the occurrence of more penetrating cracks that could lead to serious accidents.

Along with reliability, in-service safety, as well as obvious technical justification for reconstruction, the economical aspect for justifying the reconstruction is more than obvious, taking into account the costs of new- and reconstructed equipment that was returned back in service in a short time.

In addition, the reconstruction extends the service life of these 3 autoclaves. NDT tests and hydrotests confirmed the efficiency of the applied welding technologies, which on the other hand had confirmed the structural integrity of the reconstructed autoclaves before recommissioning.

ACKNOWLEDGEMENTS

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