INVESTIGATION OF THE MATERIAL PROPERTIES OF GRADIENT TUBES FOR BIOMASS POWER GENERATION INSTALLATIONS

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Abstract

Subject of this article are the results of gradient tubes analysis (material of the shell: 347H, material of the body: 11CrMo9-10) based on Amec Foster Wheele specifications requirement. The aim of the analysis was the determination of mechanical and technological properties of gradient tubes in order to install the gradient tubes in a commercial boiler. The NDT, outer shell thickness measurement, chemical analysis, tensile testing at 20°C and at elevated temperatures, flattening test**,** leak tightness test and metallographic examination of longitudinal and cross sections were used to prove the quality of gradient tubes. For this contribution, the gradient tubes (38mm outer diameter, 5mm wall thickness which austenitic shell is ~ 0,8mm thick) made by BENTELER were used.

The work was done within the project GRAMAT supported by EU Research Fund for Coal and steel (www.gramat.org). The projects main aim is to acquire knowledge necessary to develop new cost-effective manufacturing technology of boiler tubes made from semi products with through thickness gradient chemical composition, tailored to carry both creep loading (low alloyed body) and fireside corrosion (high alloyed shell). Gradient tubes for the project are manufacturing in production facilities in BENTELER – Germany and PODBREZOVA IRONWORKS – Slovak Republic from semi products manufactured by unique casting technique (ŽDAS – Czech Republic); and to be tested by Amec Foster Wheeler – Finland in selected biomass boiler.

Keywords: gradient tubes, alternative fuel-power, mechanical properties,

1. INTRODUCTION

Today, biomass and renewable feedstock more generally are foreseen as one of the most promising energy sources to mitigate green-house gas emissions. However, this is also determined by constant increase of power plant production efficiency which, of course, requires development of materials capable to withstand higher steam parameters in high corrosion environment.

All recent material solutions for boilers (co)burning “alternative feedstock” have been withdrawn from the applications successfully utilised in “classical” mainly coal powered power plants. Consequently, the applications of these material solutions in renewable feedstock boilers do not fully take advantage of their properties. For example, from viewpoint of applied pressure and temperature it is possible to use conventional creep resistant materials based on 0.5 – 2.25wt % Cr successfully utilised in modern coal-fired power plants. However, due to specific feedstock properties and related high temperature fire side corrosion issues, the application of low alloyed steels is very limited. High temperature corrosion has been reported at temperatures close to 500°C and higher while in environments at temperature ranges from 300°C to 450°C it is decreased. As a consequence, alternative fuel-fired boilers are working with tube wall temperatures that do not exceed 500°C. Therefore, alternative fuel-power generator installations in current state are not able to employ same temperatures and pressures as modern USC (ultrasupercritical) coal power plants. In comparison to coal power generator parameters (10 – 30MPa and 620°C), standard parameters of steam produced in boilers combusting mix of pulp chips and 6% of plastics reach 6MPa / 480°C.

On the other hand, renewable power generation industry represents a very specific field requiring unique (currently missing) tailored solutions. Driving force for increasing steam parameters is also very high. Higher steam parameters increase net efficiency and lead to higher electricity production per tonne of burned material and corresponding better usage of energy contained in the biomass. It was calculated that increase of steam pressure from 4 to 5MPa result in an additional annual income in amount of approx. 250kEuro in a 19MW power plant.

The gradient tubes represent the most promising solution to fulfil these requirements, provided that a new production technology based on existing production facilities is developed. The challenge is to bridge the gap between gradient tubes advantages and cost-affectivity necessary for their wide use. Expected impacts: increased renewable power energy installations steam parameters leading to decrease of pollutant emission; shift of renewable power generation plant efficiency towards efficiency of conventional fuels combustion processes; saving resources of strategic materials as nickel; increase of cost-affectivity of renewable power generation leading to wider use of alternative fuels for energy production.

The issues related to gradient tubes production are still matter of research. However, the successful rolling trials gradient tubes brought about enough testing materials.

2. EXPERIMENTAL PROGRAM

Twelve meters of seamless hot – rolled gradient tubes of ø38mm and wt of 5mm, made of material no. 1.7383 (body_11CrMo9-10)1.4912 (shell_347H/ X7CrNiNb18-10) were used for experimental analysis. The tubes were delivered in quenched and tempered condition in accordance with EN 10216-2 for no. 1.7383 (11CrMo9-10). The dimensional accuracy and straightness are in accordance with EN 10216-5:2013 and EN 10216-2:2002. Gradient tubes were rolled in existing facilities (BENTELER) from semi product manufactured by unique casting technique (ŽDAS, Inc.). **Table 1** and **Table 2** show the chemical composition of both materials (product analysis/ cast analysis). Permissible deviations of the product analysis from specified limits on cast analysis are in accordance with EN 10216-5 (8.2.2) and EN 10216-2 (8.2.2). The **Table 3** shows testing methods and relevant standards for analysis of gradient tubes.

Table 1 Chemical composition - 347H (wt. %) – shell of tube (~ 0,8mm)

	C	Si	Mn	P max.	S max.	Cr	Ni	Nb	N
Standard ASTM SA182 Grade A182F347H	0.04 - 0.10	≤ 1.00	≤ 2.00	0.040	0.015	17.00 - 19.00	9.00 - 12.00	8xC 1,20	≤ 0.1100
Cast analysis	0,06	0,47	1,47	0,022	0,007	17,95	11,20	0,57	0,0118
Product analysis	0,074	0,43	1,56	0,025	<0,002	17,4	11,5	0,58	-

Table 2 Chemical composition - 11CrMo9-10 (wt. %) – body of tube

	C	Si	Mn	P max.	S max.	Cr	Mo	Ni	Al
Standard ASTM SA182 Grade A182F347H	0,08 - 0,15	≤ 0,50	0,40 - 0,80	0,025	0,020	2,00 - 2,50	0,90 - 1,10	≤ 0,30	≤ 0,040
Cast analysis	0,10	0,21	0,59	0,007	0,001	2,25	0,96	0,20	0,006
Product analysis	0,106	0,22	0,63	0,010	<0,002	2,29	0,83	0,21	0,006

Table 3 Methodology of experiments of gradient tubes

Type of testing method	Standards
NDT for the detection of longitudinal and transverse imperfections	EN ISO 10893-10 to acceptance level U2, sub-category C
Manual NDT for detection of diffusion joint	EN ISO 17635, EN ISO 11666, EN ISO 17640,
Chemical analysis	Laboratory equipment: ARL 4460, LECO TC 600Laboratory equipment: ARL 4460
	C, S – LECO CS 244; STN EN 24935 Mo, Si – PE ICP 5500 System; MS08-LAB-2008, P - SPEKOL 11, STN EN 10184 Mn, Cr, Ni - PE ICP 5500 System; EN ISO 10700, STN EN 10188, STN EN 10136, STN EN 24943
Tensile test at room temperature*	STN EN ISO 6892-1:2010
Tensile test at elevated temperature (450°C)*	STN EN ISO 6892-1:2010; STN EN ISO 6892-2:2011
Flattening test*	EN ISO 8492:2014
Impact toughness	EN ISO 148-1
Leak tightness tests	EN 10216-2, EN 10216-5
Metallographic analysis	Microstructure analysis: STN EN ISO 17639:2014 (replaced: STN EN 1321) Grain size measurement: ASTM E-112

**The results obtained are mean value out of three tests*

3. RESULTS AND DISCUSSION

3.1 Non-destructive testing

Gradient tubes of test category 2 were subjected to an ultrasonic testing (UT) and Eddy Current Testing (EC) for the detection of longitudinal and transverse imperfections, in according with EN ISO 10893-10 to acceptance level U2, sub-category C. By NDT testing (ultrasonic and eddy current) of test specimens no.2 to no.3, the longitudinal and transverse cracks were detected. Longitudinal cracks only were observed along the length of the test specimen no.4 (tube no.4) [1]. Although several imperfections have been made, the vast majority of selected tubes were free of defects.

Manual NDT testing (ultrasonic pulse reflection method) was performed on tube no.4. The aim of this testing was to identify diffusion joint between the materials. For the purpose of the NDT testing the Panametrics Epoch IV Ultrasonic Flaw Detector with the single element and double element perpendicular probe transducers of diameter ø10mm and ø24mm at 2 and 4MHz was used. The diffusion joint was detected all along the tested tubes; however some local flaws were detected one section [1].

The leak tightness tests were carried out in accordance with EN 10216-2, EN 10216-5. The leak-tightness was confirmed on each tube [1].

3.2 Tensile test at room temperature and at 450°C

The tests were carried out at room temperature in accordance with STN EN ISO 6892-1:2010 and at the temperature of 450°C in accordance with STN EN ISO 6892-1:2010, STN EN ISO 6892-2:2011. The mechanical properties of the gradient tubes are in accordance with the standard requirements (**Table 4**/ **Fig. 1**). Extraction of the test specimen for impact test is not according to EN ISO 148-1 [1].

Table 4 Mechanical properties of gradient tubes

Steel name	**Steel number**	**Tensile properties at room temperature**				**Tensile properties at the temperature of 450°C**	**Minimum average absorbed energy at the 20°C**	
		$R_{p0,2}$ [MPa]	R_m [MPa]	A_{min}* [%]		$R_{p0,2}$ [MPa]	KV [J]	
		T<16		l	t		l	t
11CrMo9-10	**1.7383**	355	540-680	20	18	257	40	27
X7CrNiNb18-10	**1.4912**	205	510-710	40	30	-	100	60
Gradient sample		491	648	61	-	443	89	-

**l = longitudinal, t = transverse*

a) sample after tensile test at room temperature

b) sample after tensile test at elevated temperature (450°C)

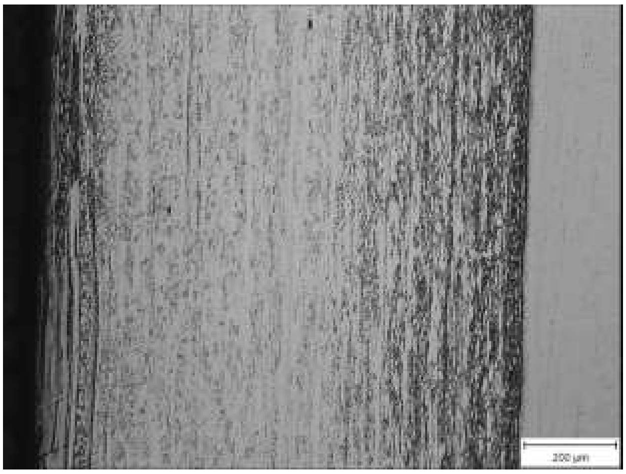
Fig. 1 Samples after tensile test

3.3 Technological properties of gradient tubes

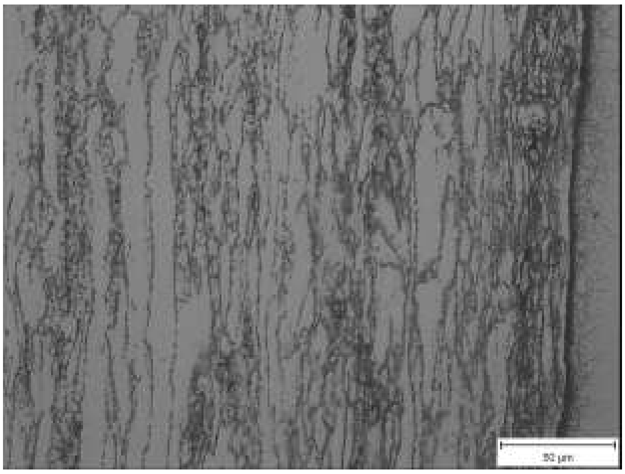
The flattening tests were carried out in accordance with STN EN ISO8492:2014. The cracks were observed on two samples [1].

3.4 Metallographic analysis

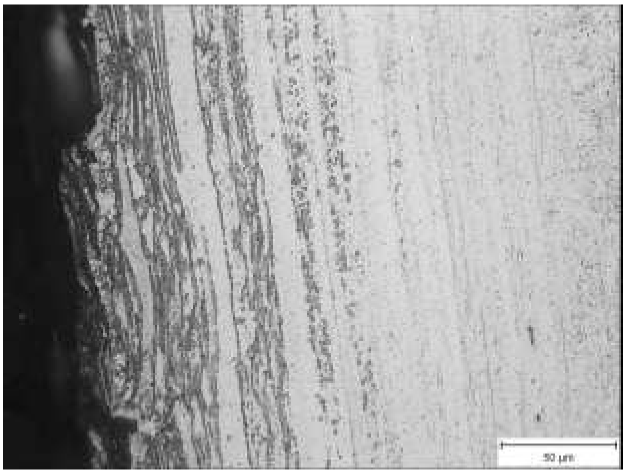
Microstructure analysis has been performed by optical microscope OLYMPUS 51GX. Longitudinal and cross sections have been prepared. Specimens were grinded, polished and etched. Plastically deformed austenitic microstructure of the outer shell (X7CrNiNb18-10) was observed by means of metallographic examination of longitudinal and cross section; grain size 8 of recrystallized grain according to ASTM E-112. Three distinct layers within the shell were observed. Layer close to the outer surface of the shell and close to the interface show continuous network of carbide phase on grain boundaries, see **Fig. 2b/c**. Microstructure of inner body of the tube (11CrMo9-10) consists of ferrite and bainite with the grain size 8 and finer according to ASTM E-112 (**Fig. 2e**). Along the austenite – ferrite interface the decarburization (average 297μm in depth) of 11CrMo9-10 steel was observed (**Fig. 2f**). By means of EDX analysis, the oxides, silicates and aluminates were identified along the austenite-ferrite interface [1].



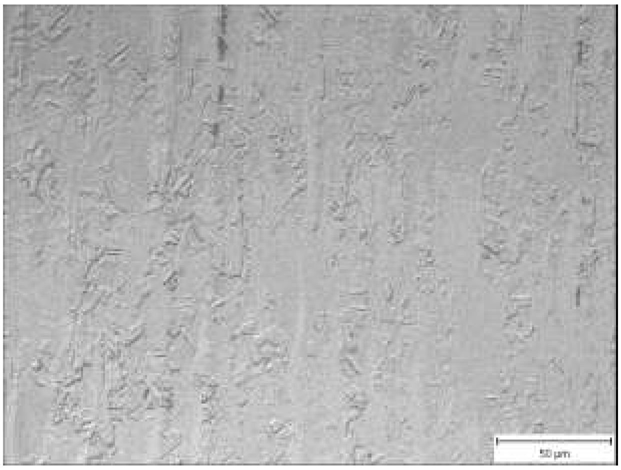
a) microstructure of X7CrNiNb18-10 steel - longitudinal section



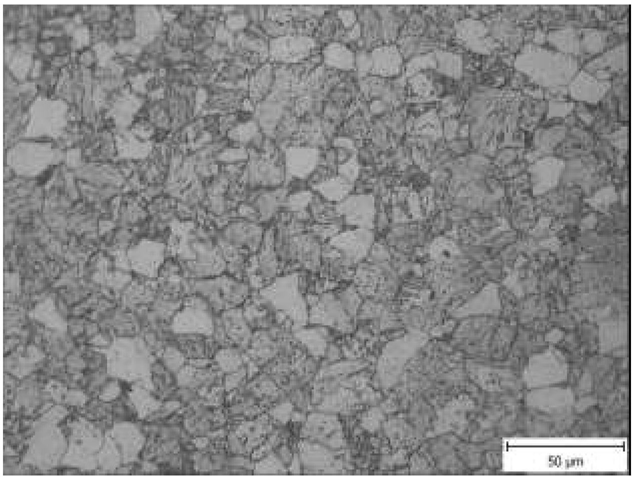
b) microstructure of X7CrNiNb18-10 steel - longitudinal section – close to austenite-ferrite interface



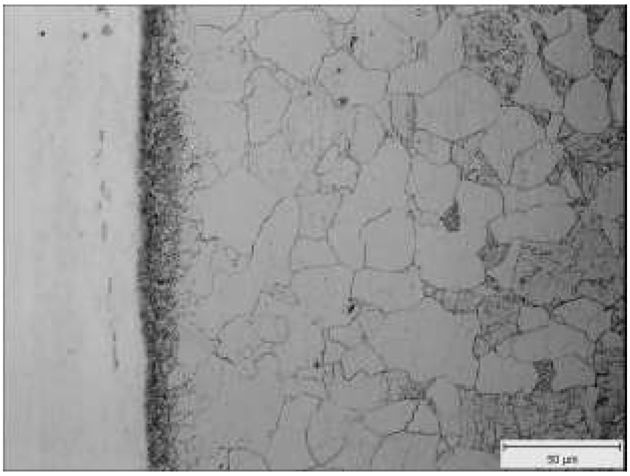
c) microstructure of X7CrNiNb18-10 steel - longitudinal section – close to outer surface of the shell



d) microstructure of X7CrNiNb18-10 steel - longitudinal section – mid-thickness of the shell



e) microstructure of 11CrNi9-10 steel longitudinal section – mid-thickness of the shell



f) microstructure of 11CrNi9-10 steel longitudinal section – mid-thickness of the shell

Fig. 2 Metallographic analysis of gradient tube

CONCLUSION

According to investigation of both materials we can conclude that:

- The produced gradient tube is suitable for the on-site long term experiments.
- The chemical composition, mechanical properties and technological properties of the materials of gradient tube produced at the BENTELER are in accordance with relevant standards EN 10216-5 and EN 10216-2, in the tested tubes.
- Tough, at many locations the tube contained surface defects and cracks at the shell-body interface. These parts of the tube cannot be used in boiler applications. Therefore, the manufacturing process needs more optimization for the next generation gradient tube to obtain better and more reliable tube quality.
- The relatively thick decarburization – sensitization layer at the shell-body interface has been produced during rolling or more likely the heat treatment. In this layer the material doesn't meet the required properties and has to be discarded in the thickness used for lifetime estimations; strength calculations (body) and high temperature corrosion resistance (shell). Therefore, to increase the lifetime of the tube the heat treatment of the material will be refined for the next generation material. Large residuals can act as fatigue crack initiation sites at the interface or lead to local delamination of the shell material.

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