INVESTIGATIONS ON OXIDATION AND CORROSION CHARACTERISTICS OF THE ADVANCED BOILER MATERIALS AT STEAM TEMPERATURES UP TO 720 °C

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ABSTRACT

The reduction of the CO_2 emissions and the saving of the fuel resources push forward the development of advanced power plants with higher efficiencies worldwide. A significant increase of the efficiencies can be realised by an increase of the steam parameters.

The increase of the steam parameters requires the application of new advanced materials. For superheater and reheater tube materials, besides high creep rupture strength, high resistance to gas-side corrosion and steam-side oxidation are needed.

At high steam temperatures, the gas-side corrosion and steam-side oxidation behaviour has not been clarified sufficiently. The lack of knowledge in this area can only be improved by the performance of operating tests in existing plants under real conditions and for a long operating time.

In this paper, a research project is presented to determine the high-temperature corrosion and oxidation characteristics of different advanced boiler materials at steam temperatures up to 720 °C. This project is fully funded by the VGB E_{MAX}–Power Plant Initiative. A test superheater composed of different advanced boiler materials has been installed into the boiler of unit 3 of the Esbjerg Power Plant. For the test superheater, eight austenitic steels and two Nickel-based alloys have been chosen. In the test rig, the material specimens pass a steam temperature range from approximately 500 °C to 720 °C. The erection and commissioning of the test rig have taken place in the summer of 2004.

The test rig will be operated for four years and will be dismantled in the summer of 2008. After dismantling of the test loop, the materials will be investigated concerning the change of the microstructure, the corrosion rate on the flue gas side and the oxidation behaviour on the steam side. Both base materials and similar/dissimilar welds will be integrated in the investigation programme.

KEYWORDS

Supercritical boilers, advanced materials, flue gas corrosion, steam oxidation, material testing programme

INTRODUCTION

The reduction of the CO_2 emissions and the saving of the fuel resources push forward the development of advanced power plants with higher efficiencies worldwide. A significant increase of the efficiencies can be realized by an increase of the steam parameters.

Fig. 1 shows the development of the power plant efficiencies. The state-of-the-art power plants in Europe, Japan and China have realised steam parameters of up to 280 bar (SH) / 605 °C (SH) and

613 °C (RH). Current R & D projects (AD 700, COMTES700, Marcko 700) aim to reach steam conditions of 375 bar (SH) / 700 °C (SH) and 720 °C (RH). After realisation of such high steam parameters, a power plant efficiency of above 50 % can be reached.

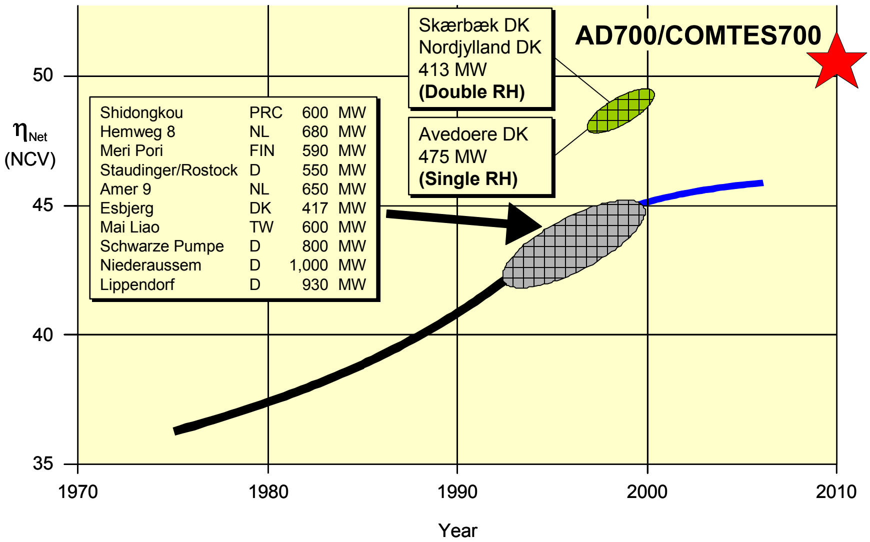

Fig. 1: Development of the power plant efficiency

The increase of the steam parameters requires the application of new advanced materials. For superheater and reheater tube materials, higher steam temperatures result in higher risks of the high temperature corrosion on the flue gas side and the oxide growth on the steam side. Advanced tube materials need higher creep rupture strength and higher resistance to corrosion and oxidation [1].

Although there are many studies on the mechanism of the high temperature corrosion on the flue gas side, a coherent understanding of the process is not available up to now. Similarly, the steam-side oxidation behaviour of the advanced materials has not been investigated extensively so as an exact prediction of the oxide growth rate to be possible. A detailed knowledge and a comprehensive understanding of the problems and their interrelation are essential for a safe conception of a power plant with the highest steam conditions.

Under this background, combined operating tests where the testing pieces are installed in an existing boiler are necessary and important, especially for the new developed materials, which have not been extensively tested. Such tests should be done at high steam temperature levels for a long operating time. In this project, a testing superheater composed of different advanced boiler materials has been installed into the boiler of unit 3 of the Esbjerg Power Plant and will be operated for steam temperatures at the outlet up to 720 °C. The main focus is concentrated on the materials for the future 700 °C power plants. This project is fully funded by the VGB E_{MAX}–Power Plant Initiative with the funding members E.ON Energie, RWE Power, EnBW Kraftwerke, Vattenfall Europe Generation, Electricite de France, Elsam Kraft and ENERGI E2.

1. ESBJERG TEST RIG

The Esbjerg Test Rig is located in the unit 3 of the Esbjerg Power Plant.

The Esbjerg Power Plant was designed as a pulverized coal-fired power plant with supercritical steam parameters, single reheat and a high efficiency. The maximum continuous net output is approximately 385 MW. A block efficiency of approximately 45 % can be achieved with pure condensing operation. The unit was commissioned in July 1992.

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Fig. 2 shows the boiler, which was built by ALSTOM Power Boiler. It is a once-through boiler of tower type design. The steam conditions are: live steam pressure 251 bar, live steam temperature 560 °C, hot reheat temperature 560 °C. As fuel world-market coal is used. More details about the boiler and the power plant are included in [2].

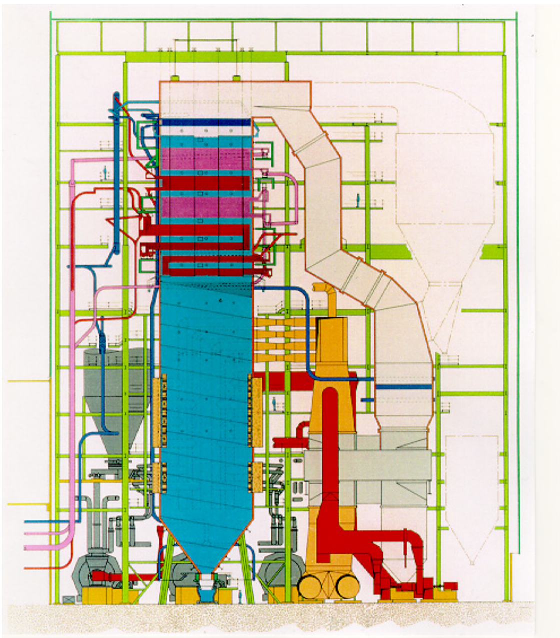

Fig. 2: Esbjerg Power Plant - Boiler unit 3

A first test rig was originally built in the framework of the Brite-Euram project in 1995 [3]. In this test rig, totally three different test superheaters can be installed in the boiler. Fig. 3 shows the steam side integration of the test rig in the power plant. The steam is taken from the connecting pipe between IT-superheater and HT-superheater of the existing boiler before the last spray water injection with a steam temperature of approximately 495 °C. In the test loop, the steam is heated up to the desired outlet temperature. The mass flow through the test loop is controlled by a control valve at the inlet of the test loop. After the test loop, the hot steam is cooled down to 560 °C by a mixing piece where the hot steam is mixed with a cold bypass steam. This steam flows finally to the hot standby pipe of the high-pressure bypass system of the existing boiler.

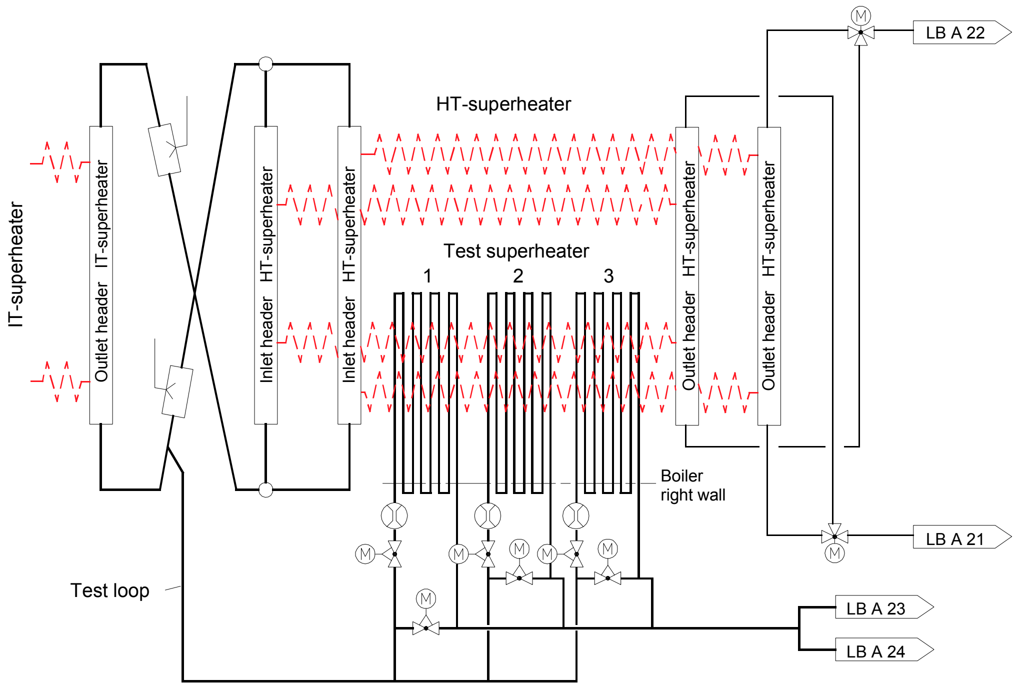

Fig. 3: Esbjerg Test Rig for investigations of advanced materials

On the flue gas side the test superheater is located in the boiler between the HT-superheater and the HT-reheater at a flue gas temperature of approx. 920 °C. At one side, the testing tubes are connected to the boiler water wall by means of sleeves. The tube coils lie transversely on the HT-

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superheater tubes of the existing boiler which ensures a free heat expansion of the test tubes. Fig. 4 shows the test superheaters installed in the boiler and the tube samples after dismantling of the test loops from the boiler.

Fig. 4: Test superheaters before and after dismantling

An overview of the operating data, which are recorded is shown in Table 1. Data on the water/steam side and flue gas side conditions, fuel data and the special situations of the power plant operation are registered. The data can be used for the evaluation of the test results after the dismantling.

Parameter		**Components**	**Measuring or Analysis Interval**
Flue gas	Flue gas mass flow		2 h average value
	Flue gas temperatures		2 h average value
	Flue gas compositions	O_2, NO_2, CO_2, SO_2, ect.	2 h average value
Steam and feedwater	Steam mass flow		2 h average value
	Steam pressure		2 h average value
	Steam temperatures		2 h average value
	Steam quality	Conductivity, SiO_2, Fe, Cu ect.	once a week
	Feedwater quality	Conductivity, SiO_2, Fe, Cu, pH value ect.	once a week
Material	Surface temperature		2 h average value
	Analysis of the ash deposit at the surface	K_2O, Na_2O, CaO, MgO ect.	after the removal of a test superheater
Coal and ash	Coal analysis	Calorific value, H_2O and ash content, S, HCl ect.	average weekly value
	Ash analysis	K_2O, Na_2O, CaO, MgO ect.	monthly average value
Operation	Operating time		
	Start-up and shut-down processes		
	Load changes		

Table 1: Parameters to be measured during the operating test

Since the first commissioning of the test rig in 1995, various test loops have been installed. Fig. 5 shows the operating time of the former test loops in the Esbjerg Test Rig and the planned operating time for the current 720 °C test loop. During the Brite-Euram project, which was partly funded by the European Commission, three test superheaters were installed in 1995 in the existing boiler with

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a steam temperature at outlet of 620 °C. The three test superheaters have been dismantled, each after a one-year, a three-years and a seven-years exposure time. In the subsequent project, which was a cooperation between Elsam, EDF and ALSTOM Power Boiler, a test superheater with a steam temperature at outlet of 635 °C was installed in 1998 and has been dismantled in 2001. The last test loop, which was fully funded by ALSTOM Power Boiler had an outlet steam temperature of 700 °C. This test superheater was installed in 2000 and has been dismantled in 2004.

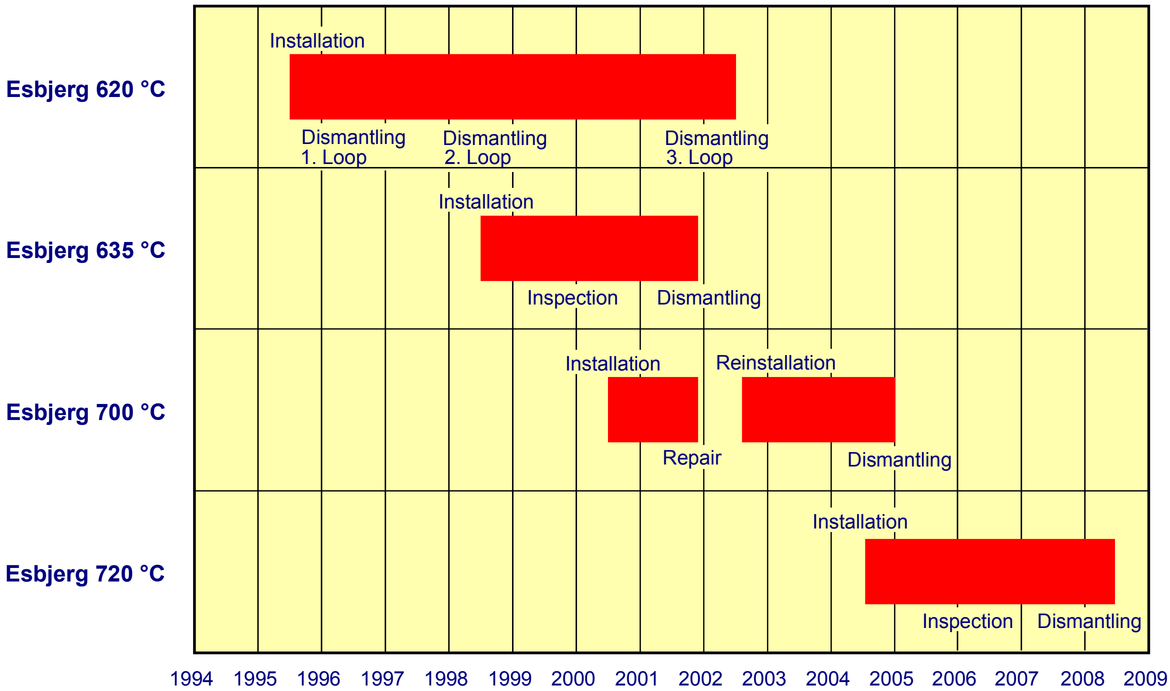

Fig. 5: Test superheaters installed in Esbjerg Test Rig

For the current 720 °C test loop, most parts of external piping from the former test loops including the control valve could be reused. The test superheater and the high temperature parts of the external piping including the mixing piece and a T-piece had to be replaced. The work was distributed to the participating partners according to Table 2. Fig. 6 shows the detailed time schedule for the test loop. After a period of less than one year for engineering, material procurement and component manufacturing, the test loop has been installed in the boiler in the summer of 2004. The planned operating time is four years (approximately 30000 h exposure time). After dismantling of the test loop, the material samples will be investigated extensively concerning the changes of microstructure, the mechanical properties and especially the corrosion and the oxidation behaviour. Not only base materials but also similar and dissimilar welds will be investigated.

Task	Parties involved
Project management	VGB Power Tech e.V. and Elsam Engineering A / S
Design and engineering of the test loop	ALSTOM Power Boiler
Manufacturing	ALSTOM Power Boiler
Erection and commissioning	Elsam Engineering A / S and ALSTOM Power Boiler
Operation of the test loop	Elsam Engineering A / S
Examination of material samples	Babcock Hitachi Europe

Table 2: Distribution for the works of the 720 °C test loop

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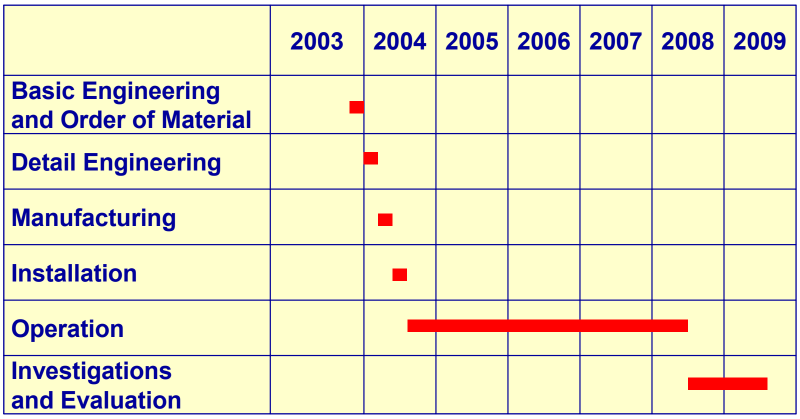

Fig. 6: Time schedule for the 720 °C test loop

2. MATERIAL SELECTION

The purpose of the Esbjerg Test Rig is to test potential candidate materials for the superheater and reheater tubes at high temperatures. Table 3 shows the materials, which have been tested in former test loops. From the group of ferritic steels, martensitic steels, austenitic steels and Ni-based alloys, different representative materials have been tested at different temperature levels.

Ferritic steels (Steam temperature 500 - 525 °C)	T 23, T 24
Martensitic steels (Steam temperature 500 - 580 °C)	X 20, T 91, T 92, HCM 12, HCM 12A, NF 12
Austenitic steels (Steam temperature 510 - 690 °C)	1.4988, TP 347HFG, SUPER 304H, SUPER 304H (SB), NF 709, NF 709 R, Tempaloy A 3, Tempaloy AA 1 (SB), SAVE 25, TP 310 N, HR3C
Ni-based alloys (Steam temperature 635 - 700 °C)	Alloy 617, Alloy 4020

Table 3: Materials tested in former test loops

In the current 720 °C test loop, the main focus lies on the advanced materials, which can be used for critical components of a 700 °C power plant. Therefore, only austenitic steels and Ni-based alloys have been selected. One important criterion for the material selection is also the commercial availability and the delivery time of the materials.

Table 4 lists all selected materials, which have been installed in the current 720 °C test loop. The chemical composition of the materials is shown in Table 5. Fig. 7 shows the average 100 000 h creep rupture values which are indicated in different codes (if available) or expected by the tube manufacturer.

Austenitic steels (Steam temperature 565 - 650 °C)	TP 347HFG, SUPER 304H (SB), TP 310N, HR3C, Alloy 174 (Sanicro 25), HR6W
Ni-based alloys (Steam temperature 650 - 720 °C)	Alloy 617 mod., Alloy 740

Table 4: Materials tested in the 720 °C test loop

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Steel	Cr	Ni	Mo	Nb	Ti	Others
TP 347 HFG	17.0 - 20.0	9.0 - 13.0	-	max. 1.0	-	-
SUPER 304 H	17.0 - 19.0	7.5 - 10.5	-	0.30 - 0.60	-	Cu, N
TP 310 N	24.0 - 26.0	17.0 - 23.0	-	0.20 - 0.60	-	N
HR 3 C	24.0 - 26.0	17.0 - 23.0	-	0.20 - 0.60	-	N
Alloy 174	22.5	25.0	0.02	0.48	-	Cu = 3.0 N, Al, W, Co
HR 6 W	21.0 - 25.0	35.0 - 45.0	-	< 0.40	< 0.20	W = 4.8 – 8.0
Alloy 617 mod.	20.0 - 23.0	Rem.	8.0 - 10.0	-	0.20 - 0.50	Co = 10.0 - 13.0 Al = 0.80 - 1.30, B
Alloy 740	25.0	Rem.	0.5	2.0	1.8	Co = 20.0 Al = 0.9

Table 5: Chemical composition of tested materials

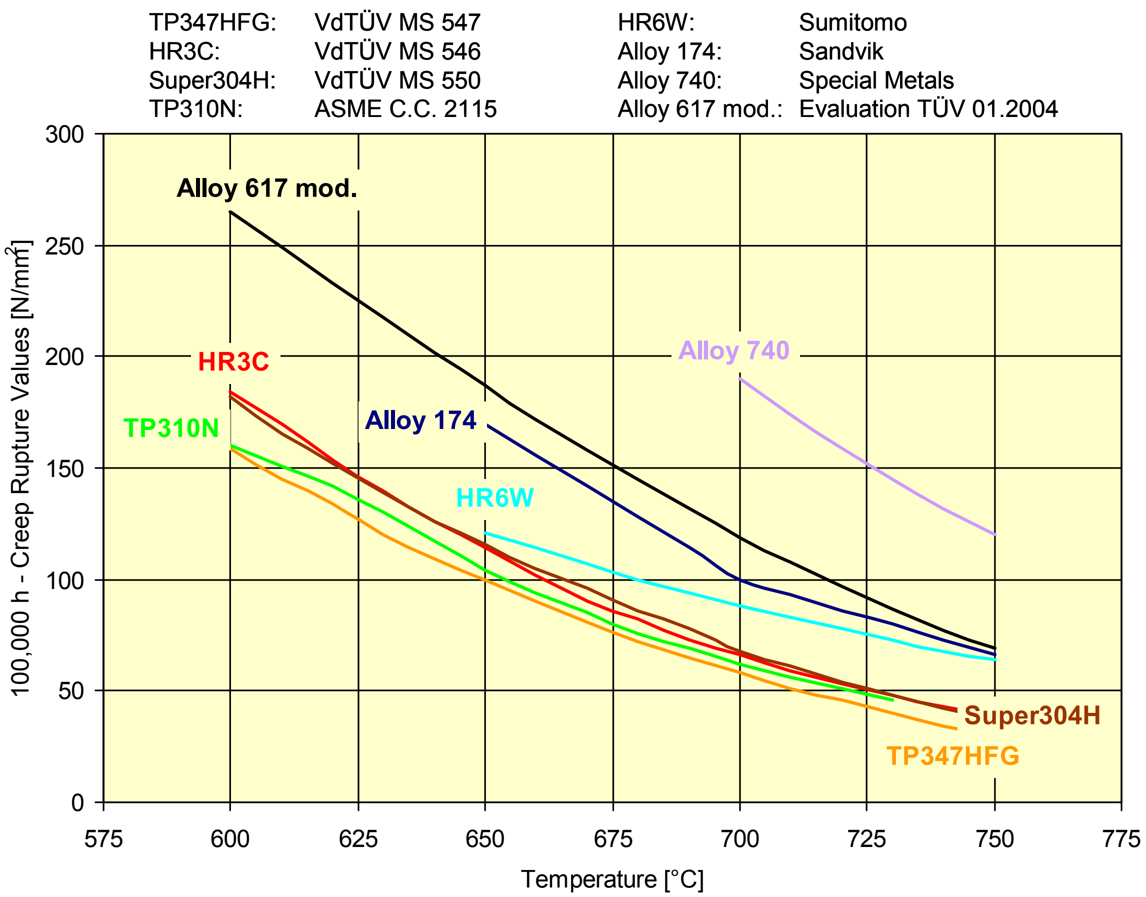

Fig. 7: 100,000 h - creep rupture values of selected materials

It is well known that the chemical composition has the most important influence on the corrosion and oxidation behaviour of the materials. The most important parameter here is the chrome content. Additionally, but only affected on the steam side, the oxidation resistance can be improved largely by other methods, especially by the reduction of grain size and by application of a surface treatment (shot-blasting).

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In the group of the 18 % Cr steels, the fine-grained austenitic steel TP 347HFG and the short-blasted austenitic steel SUPER 304H (SB) have been selected. In the group of the 25 % Cr steels, the austenitic steel TP 310N from DMV and HR3C from Sumitomo have been selected which have been already used in industrial applications. The new developed Alloy 174 (Sanicro 25) with a composition of 23Cr-25Ni is a development from Sandvik during the AD 700 project. The new material HR6W with a composition of 23 Cr-43Ni-6W is a development of Sumitomo. These two materials should have higher creep rupture strength values at high temperatures than other austenitic steels mentioned above. All austenitic steels will be tested at the temperature levels of 565 °C to 650 °C.

In the group of Ni-based alloys, the material Alloy 617 mod. (in the version of modified composition, developed from the German R & D programme Marcko DE2) and Alloy 740 have been selected. While the Alloy 617, at least with the conventional composition, has been investigated in a wide range, the material Alloy 740 has been just recently developed by Special Metals during the AD 700 Project and has only limited creep rupture design values.

3. DESIGN ASPECTS OF THE TEST LOOP

The test superheater comprises four tube coils consisting of a number of material samples, which are welded together as short tube sections (Fig. 8). The total tube length is determined by heat transfer characteristics, which have been measured in former test loops. At the test superheater inlet, outlet and the three external locations outside the boiler, the metal temperatures are registered and these correspond to the steam temperatures in these positions. Based on theses data together with the registered steam flow and pressure, steam temperature profiles through the test superheater can be calculated exactly. The capability to determine exactly the metal temperatures at each tube section is a big advantage of the Esbjerg Test Rig in order to evaluate the temperature influence on the material properties [4].

In order to ensure a safe operation of the test loop and the existing power plant, the mechanical design has been done on a very conservative basis. The tube dimensions are determined according to allowable stresses which are based on an operating time of 200 000 h (100 000 h average creep rupture values divided by a factor of 1.5). If the materials are standardised in codes, the design values in the codes have been used for the mechanical calculation. If such design values are not available, the values from the manufacturer´s specifications have been used. In this case, the creep rupture strength values are extrapolated.

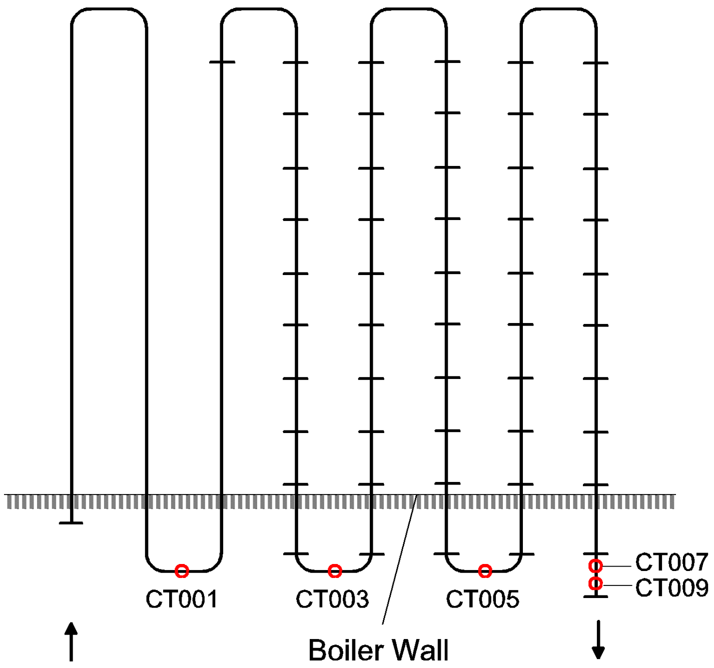

Fig. 8: Design of the test superheater

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Fig. 9 shows the temperature profile of the test superheater. Based on the steam temperature values, sufficient margins haven been added to get the design temperatures (refer to mid wall temperatures).

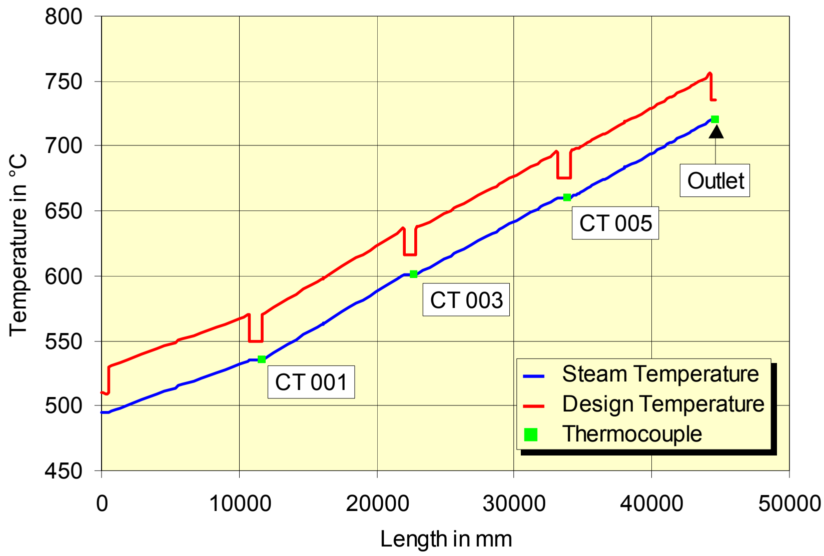

Fig. 9: Temperature profile of the test superheater

4. MATERIAL CERTIFICATES AND WELDING PROCEDURE QUALIFICATIONS

The programme for fabrication of the new 720 °C test loop including the test superheater, the mixing piece and a T-piece as well as the high temperature part of external piping is described in Table 6. Components fabricated from well-known materials are not treated here.

Component	Material	Dimension [mm]	Program of Work: Workshop	Program of Work: Site
Superheater	TP347HFG, HR3C, SUPER304H (SB), TP310N, Alloy 174, HR6W, Alloy 617 mod., Alloy 740	OD 38.8 x 8.8(6.3)	Machining, Bending, Welding, Heat treatment of bends, Mechanical testing of bends of Alloy 617 mod.	Welding of butt welds on return bends and to external piping
Mixing Piece and T-Piece	Alloy 617 mod.	OD 136 x 36 OD 108 x 30 OD 100 x 20 OD 80 x 21	Machining, Welding of butt welds and stubs	Welding of butt welds to external piping
External Piping	Alloy 617 mod.	OD 38.8 x 8.8	Machining, Bending, Heat treatment of bends, Mechanical testing of bends of Alloy 617 mod.	Welding of butt welds

General at workshop and at site: NDT and Pressure Test

Table 6: Esbjerg 720 °C test superheater - extent of fabrication

Because the test loop is installed in an existing power plant, it was agreed with the responsible Authorities to apply the TRD code. With regard to future applications, all qualifications have been done also based on the EN code and the Pressure Equipment Directive (PED) in order to demonstrate that the requirements of other standards can be fulfilled in the same way.

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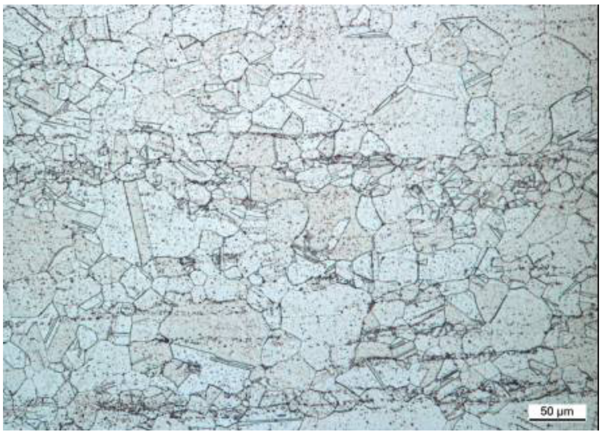
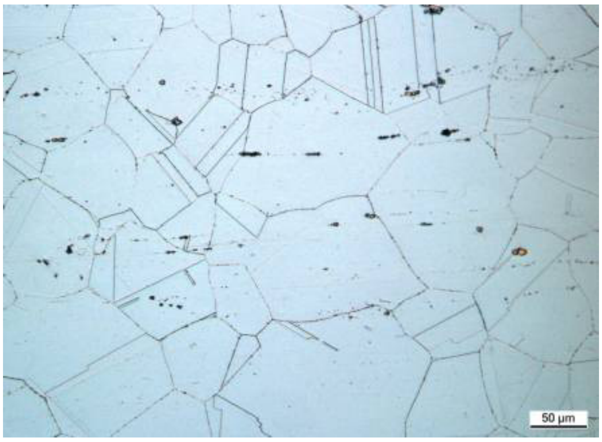
Requirements for the used base materials have been specified within the framework of Material Certificates. Based on this, the materials have been supplied with the 3.1A-Certificates according to TRD, issued and confirmed by the Notified Body (TÜV). Because the most of the materials are not covered by the TRD code, the Material Certificates have been issued based on Particular Material Appraisals (PMA). That means that besides the standard code requirements related to the mechanical tests additional requirements have been proved. This includes in detail the following tests:

- Warm tensile test,
- Investigation and documentation of microstructure with specified grain size for TP 347 HFG and SUPER 304H (SB),
- Impact tests,
- Documentation of heat treatment parameters,
- Ongoing creep tests in parallel for materials not covered by the code.

All base materials have been delivered as specified. Typical microstructures of the advanced materials Alloy 174 and Alloy 740 are shown in Fig. 10.



Alloy 174 M 200 : 1



Alloy 740 M 200 : 1

Fig. 10: Microsections of superheater materials: Alloy 174 – Alloy 740

Welding Procedure Qualifications (WPQ) have been done based on the TRD, the PED and the EN code. For all weld connections, Alloy 617 mod. was used as filler material. It was the first practical application for this kind of filler material, which was developed within the framework of the German R&D project Marcko DE2. This filler material has elevated creep rupture values compared with the standard version of Alloy 617 [5]. The chemical composition of the used filler material with the elevated Al-content in comparison with the standard version is shown in Table 7.

Name	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Co	Ti	Al	Fe
GTAW welding	0.058	0.10	0.03	0.002	0.002	21.2	8.55	56.88	0.01	11.15	0.3	1.28	0.4
SMAW welding	0.05	0.82	0.03	0.003	0.002	21.59	8.37	56.1	0.03	10.27	0.26	1.41	0.36

Table 7: Chemical composition of wire from Alloy 617 mod..

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Because the most of the base materials and the filler metal are not covered by the TRD, PED and EN code, all conditions of the WPQ have been mutually agreed and specified with the Notified Body (TÜV) in the form of Particular Material Appraisals (PMA).

The qualification works can be distinguished between thick-walled parts and tubes. For the thick-walled mixing piece and T-piece from a pipe of OD 400 mm x WT 50 mm, butt welds are qualified. For the external piping and weld connections in the test superheater from a tube of OD 38 mm x WT 8.8/6.3 mm, similar butt welds are qualified for each advanced material.

For the qualification welds, GTAW (Gas Tungsten Arc Welding) was applied for the tubes. For the pipe covering the mixing piece and T-piece, GTAW for the root pass and SMAW (Shielded Metal Arc Welding) was specified. Details of the Welding Procedure Specifications (WPS) are shown in Table 8.

Component	Pipe	Tube
Base material	Alloy 617 mod.	TP347 HFG, TP 310N, HR3C, SUPER 304H (SB), HR6W, Alloy 174, Alloy 617 mod., Alloy 740
Dimension	OD 400 x 50 mm	OD 38 x 8.8/6.3 mm
Welding process	GTAW/SMAW	GTAW
Filler metal	Alloy 617 mod.	Alloy 617 mod.
Weld position	Tube axis horizontal fixed	Tube axis horizontal and vertical fixed
Type of joint	Butt weld	Butt weld
Weld preparation	U-groove on V-root	V-groove
Backing gas	Yes	Yes
Heat treatment	No	No, except Alloy 740 at 800 °C / 4h

Table 8: Details of Welding Procedure Specification

At the welds Non-Destructive Tests (NDT) have been performed. For all butt welds Radiographic Test (RT) and Penetration Test (PT) were applied after welding. For the butt welds on the thick-walled pipe, additional RT and PT were carried out during the welding process, when the groove has been filled by one third and two thirds of depth. All tests showed acceptable results. Failures like cracks or lack of fusion did not occur.

For the butt welds mechanical tests and micro/macro investigations have been performed. For the material Alloy 740, all tests and investigations have been carried out after the precipitation hardening process after welding. A summary of tests is shown in Table 9.

The mechanical tests are specified according to the TRD and PED code as well as PMA. Short-term properties like tensile test at room temperature and elevated temperature have been determined. Test results showed that the requirements for the relevant base materials have been clearly fulfilled. Bend tests and impact tests to obtain toughness and ductility values were also carried out. The results demonstrated a high ductility (180 °C without incipient crack) and a toughness level much higher than the specified minimum values. The micro and macro investigations were done for the structure of the weld and the heat-affected zone (HAZ). The macro sections showed a homogenous build-up of layers without any failures and imperfections. The micro sections demonstrated the typical structure with dendritic solidification for the weld. The heat-affected zone of base materials showed austenitic structure without precipitations. Micro cracks have not been detected.

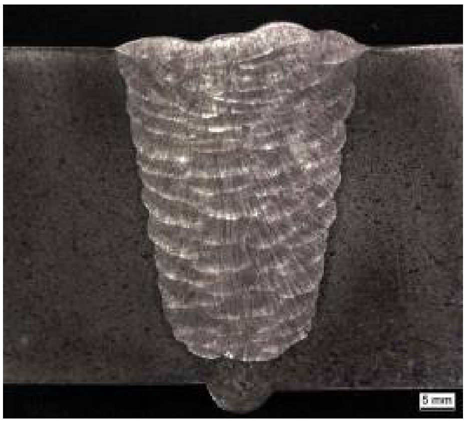
Component	Pipe, Butt weld	Tube, Butt weld
Base material	Alloy 617 mod.	TP347 HFG, SUPER 304H (SB), HR3C, TP 310N, HR6W, Alloy 174, Alloy 617 mod., Alloy 740
Dimension	OD 400 x 50 mm	OD 38 x 8.8 mm
Tensile test at RT	2 x cross to the weld	2 x cross to the weld
Tensile test at elevated temp.	2 x cross to the weld	2 x cross to the weld
Bend test	2 x root pass at extrados 2 x cover pass at extrados	2 x root pass at extrados 2 x cover pass at extrados
Impact test at RT	1 set of weld 1 set of HAZ	1 set of weld 1 set of HAZ
Micro/macro section	Weld and HAZ	Weld and HAZ

Table 9: Mechanical tests and micro/macro sections

Table 10 shows the results of mechanical tests of similar welds of Alloy 617 mod. during the WPQ. Examples of macro sections are given in Fig. 11.

Result		Pipe	Tube		Requirements acc. to VdTÜV (PED)
			Tube axis horizontal	Tube axis vertical	
Dimension		OD 400 x 50 mm	OD 38 x 6.3 mm		
Tensile Test at RT	$R_{P0.2}$ (MPa) R_{Pm} (MPa)	381 / 393 747 / 736	327 / 329 723 / 719		300 700
Tensile Test at 650 °C	$R_{P0.2}$ (MPa) R_m (MPa)	285 542	227 / 202 532 / 513		187 460
Impact Test at RT	Notch: Weld Notch: HAZ	105 J/cm^2 258 J/cm^2	207 J/cm^2 213 J/cm^2	194 J/cm^2 212 J/cm^2	75 (34) J/cm^2 75 (34) J/cm^2
Bend Test	2 x root pass 2 x cover pass	180 °C without incipient cracks	180 °C without incipient cracks		

Table 10: Results of mechanical tests


Pipe OD 400 x 50 mm – Butt weld
GTAW/SMAW

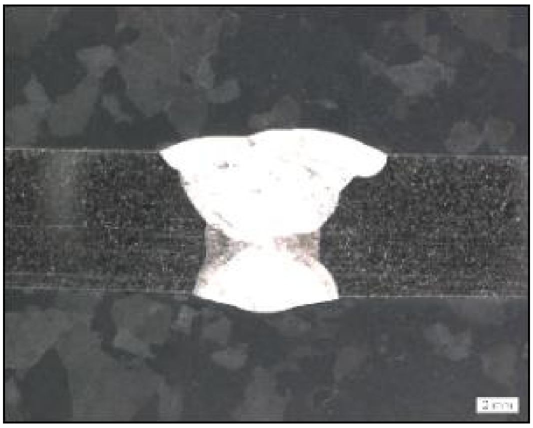

Tube OD 38 x 6.3 mm – Butt weld
GTAW

Fig. 11: Macro sections of the Alloy 617 mod. material

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5. MANUFACTURING AND ERECTION

The manufacturing of the test superheater took place at the workshop of ALSTOM Power Boiler. All welds at workshop and at site were done according to the WPS (see Table 8). For each of similar and dissimilar welds, detailed WPS have been made based on the corresponding WPQ. In order to fulfil the code requirements, all WPS have been approved by the Notified Body. An overview of the weld connections on pressure parts, material combinations, dimensions and number of welds at workshop and site is summarized in Table 11.

Component	Similar	Dissimilar	Dimension [mm]	No. of Welds	
				Workshop	Site
Superheater	TP347HFG, TP310N, HR3C, SUPER304H (SB), HR6W, Alloy 174, Alloy 617 mod., Alloy 740	Alloy 174 - HR6W, Alloy 617 - Alloy 740, HR3C - Alloy 174, HR6W - Alloy 617, HR6W - HR3C, HR6W - SUPER304H (SB), HR6W - TP347HFG, SUPER304H (SB) - TP310N, TP310N - HR3C, TP347HFG - SUPER304H (SB)	OD 38.8 x 8.8 (6.3)	63	7
Mixing Piece	Alloy 617 mod.	-	OD 136 x 36 OD 108 x 30	4	-
T-Piece	Alloy 617 mod.	-	OD 100 x 20 OD 80 x 21	1	-
External Piping	Alloy 617 mod.	Alloy 617 mod. – 10CrMo9-10 TP347HFG – Alloy 617 mod.	OD 38.8 x 8.8 OD 38.8 x 8.8	4	10

Table 11: Extent of pressure part welds

As usual praxis for the welding during the erection of boiler components, all welds have to be done in fixed position. That means to apply vertical-up welding for butt welds, starting in the overhead position. In order to demonstrate the aptitude of the used filler material under typical boiler erection conditions, welding in fixed position was also applied at the workshop.

As a special feature for the material Alloy 740 which was delivered in solution heat treated condition, all similar and dissimilar welds have been welded at workshop in order to apply the necessary precipitation hardening process for the welded area and the total tube length. During the precipitation hardening process, the microstructure was transferred in the condition corresponding to the characteristic mechanical properties specified for this alloy.

Impressions during the manufacturing at the workshop are shown in Fig. 12.

All bends for the test loop have been carried out by cold bending process at workshop. An overview about the bends which have been fabricated for the test superheater and for the external piping is shown in Table 12.


Welding in fixed position


Dissimilar weld
Alloy 740 – Alloy 617 mod.


Alloy 740 - heat treatment

Fig. 12: Manufacturing at the workshop

Component	Base Material	Dimension [mm]	Radius [mm]	No. of Bends	Heat Treatment
Superheater	TP347HFG	OD 38 x 8.8	100	6	-
	Alloy 174	OD 38 x 8.8	100	6	-
	Alloy 617 mod.	OD 38 x 8.8	100	4	Solution heat treatment
External Piping	Alloy 617 mod.	OD 38 x 8.8	100	5	Solution heat treatment

Table 12: Extent of cold bending

Before fabrication of the bends, the Bending Procedure Qualification (BPQ) was carried out in presence of the Notified Body for each material. The evaluation of quality requirements for the BPQ and for fabrication was done as specified according to the TRD code, the VGB-Directive and the specifications of tube manufacturers. For the material Alloy 617 mod., following the requirements of VdTÜV-Sheet 485 for conventional Alloy 617 material, solution heat treatment with renewed proof of mechanical properties have been done for each heat and heat treatment lot, because the deformation rate was more than 10 % (see Fig. 13).


Alloy 617 mod. - heat treatment


Alloy 617 mod. - cold bended


Alloy 174 - cold bended

Fig. 13: Superheater bends

HOME

As results, all bends have been fabricated without any problems. The requirements in regard of out-of roundness, corrugation and wall thickness have been met. For Alloy 617 mod. bends, mechanical tests demonstrated results appropriate to the specified properties.

Fig. 14 shows the test superheater after the fabrication at workshop. Fig. 15 shows the mixing piece after erected in the test rig.

Fig. 14: Test superheater after fabrication

Fig. 15: Mixing piece after erection in the test rig

For all butt welds during the manufacturing and erection process, 100 % RT and 100 % PT were applied. As practiced in the WPQ, additional RT and PT were carried out during the welding for the mixing piece, once the weld was filled by one third and two thirds of depth. For the stub welds at the mixing piece and T-piece, 100 % PT was done. All NDT-tests demonstrated results without distinctive features.

Final inspections with the Notified Body have been successfully performed without problems. In this context, both at workshop and at site hydro tests were carried out. Therefore, all specified demands based on code requirements and PMA have been completely fulfilled.

6. COMMISSIONING AND OPERATING RESULTS

The commissioning of the test loop has taken place in September 2004.

Since commissioning of the test loop, the test rig has been operated without any problems (operating time approximately 7000 h up to August 2005). The maximum steam temperature at outlet has reached 720 °C.

7. SUMMARY AND PROSPECTIVE

It can be summarised that the knowledge on the material properties, especially the high temperature corrosion rate on the flue gas side and the oxidation behaviour on the steam side need to be further deepened in order to allow a safe plant conception of a 700 °C power plant. The installation of the test superheater in the boiler of Esbjerg Power Plant ensures the realization of realistic operating conditions for the examination of the material properties up to a steam temperature of 720 °C, both for base materials and for different kinds of welds.

The engineering, manufacturing and erection, as well as the commissioning works have been successfully completed. During the manufacturing of the test superheater, extensive experiences for the material processing, especially the welding and bending could be gained for the new developed advanced materials.

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