Latest developments for the flexible high efficient power plant of the future

Gregor Gierschner[(1)],Christian Ullrich[(1)], Helmut Tschaffon[(2)],
[(1)] E.ON New Build and Technology GmbH
[(2)] VGB PowerTech e.V.

IEA CCC Workshop

Advanced ultrasupercritical coal-fired power plants

19-20 September 2012 in Vienna

Abstract

Increasing the live steam parameters of coal fired power plants to 700 °C and 350 bar leads to an improved efficiency. State of the art steel does not have the ability to resist these parameters in power plants. Therefore, the application of nickel-base alloys is necessary. Within the last 10 years several projects have been launched to identify the challenges of these materials during fabrication and operation. Apart from comprehensive laboratory investigations, test facilities such as COMTES700 were installed in commercially operated power plants. First it was demonstrated that fabrication of such components is possible. During operation new problems have emerged. Therefore, it was decided to initiate further projects such as COMTES+ which includes the high temperature test rigs HWTII and ENCIO to solve open problems. One important issue is the verification of a repair concept which was developed after the dismantling of COMTES700. This concept will be verified by reinstalling service exposed material from COMTES700 in a 700 °C test facility. Different welding procedures will be applied to illustrate the ability to simulate repairs in a 700°C power plant in the future. Another example is the test of a large scale valve which was initially designed for a 500 MW demonstration plant and redesigned for the use in a test rig. Final results of the current projects are expected by the end of this decade. It is planned to generate all the knowledge necessary to construct and operate a 700 °C demonstration power plant after finalization of the above mentioned projects.

It has to be shown within the next years that:

1. The technical risk for a 700 °C power plant can be minimised
2. The manufacturing costs can be reduced
3. A 700°C power plant matches the demands in terms of flexibility due to the increasing influence of renewable energy production in Europe

1 Introduction / Motivation

The political and social demand to reduce the CO_2 emissions for modern coal power plant stations has risen considerably within the last years.

To reach the aim of reduction of CO_2 emissions of a coal-fired power plant, there are two technical attempts. On the one hand the capture and storage of CO_2 can prevent its output to the atmosphere. The other possibility is by raising the efficiency with technical measures to reduce the necessary quantity of coal and the CO_2 amount for each generated kilowatt hour. It is necessary to raise the steam parameters (temperature and pressure) for the new generation of plants to increase the efficiency and to reduce the emissions. The steam temperature of high efficient coal power stations under construction reaches about 600 °C. These stations have an efficiency of about 46 %.

The increase of efficiency to 50 % results in 700 °C steam temperature and 350 bar pressure combined with further measures. At the same time an increase of the plant flexibility in comparison to state of the art plants is required due to the increasing influence of renewable energy production in Europe.

The strength and corrosion values of iron based materials do not satisfy the requirements of a 700 °C plant. In the areas with corresponding temperatures within the power plant materials are used based on nickel like the A617 B.

In order to test these materials, which are not applied in existing power stations, different product types of nickel based alloys were tested in particular the alloy A617B.

The first test plant with large components from A617 B was implemented in the E.ON power plant Scholven. The component test facility COMTES700 is an European cooperation project, is funded by European Commission “Research Fund for Steel and Coal” and is supported by well known European suppliers and utilities.

At first it was demonstrated that a manufacture of such components is possible. During operation problems with thick-walles nickel based components arose. Therefore, it was decided to initiate further projects such as COMTES+ which includes the high temperature test rigs HWTII and ENCIO.

	Project	Public Funding	Partner
	COMTES700	European Commission (Research Fund for Coal and Steel)	VGB, E.ON, EDF, Electrabel, EnBW, ENEL, DONG, PPC, RWE, Vattenfall, Alstom, Hitachi, B&W, Siemens
COMTES+	HWTII	BMWi	GKM, ABB, Babcock Borsig Service GmbH, BASF, BGH, BHR, Böhler, Bopp und Reuther, E.ON, EagleBurgmann, EnBW, Fraunhofer IWM, RWTH Aachen, Kraftanlagen München, KSB, Lisega, MPA Stuttgart, MVV, Saarschmiede, SMST, SLV Mannheim, IFW Darmstadt, ThyssenKrupp VDM, TÜV Süd, VGB, V&M, Welland & Tuxhorn, Wrede & Niedecken
	ENCIO	European Commission (Research Fund for Coal and Steel)	VGB, ENEL, Hitachi, Centro Sviluppo Materiali, CEZ, EDF, EnBW, ENEL, E.ON, Eskom, EVN, Evonik, GDF Suez, GKM, RWE, Vattenfall, HORA, Sandvik, Sempell, V&M, ThyssenKrupp VDM, VoestAlpine, Siemens, Böhler

Figure 1: Public funding and partners of COMTES700, HWTII and ENCIO

Utilities and manufacturers have to face many challenges during the development of a 700 °C power plant. The following chapters deal with the results of former investigation such as from COMTES700 and current activities, for example HWTII. The topics high temperature valves, repair concept for thick-walled A617 B components, flexibility and costs of nickel based alloys are focus of the following text.

2 High temperature valves

Different valves were tested in the COMTES700 facility such as gate valves, a safety valve and a high pressure bypass valve. These valves were in operation for four years from 2005 until 2009. Some of the valves were investigated afterwards. The experiences were transferred to the follow-up projects HWTII and ENCIO. The high pressure bypass valve of COMTES700 and the high pressure bypass valve of HWTII are described in detail in this chapter as an example.

2.1 Experience from COMTES700 high pressure bypass valve

The planned operation parameters for the high pressure (hp) bypass valve were 100 to 500 hours of operation and 10 to 20 times operation in bypass mode at maximum temperature. In contrast to that theory, the real operation conditions in the power plant during operation led to a much higher load factor. The valve was during start-up and shut-down times from July 2005 to August 2009 in daily operation due to changed load profiles of the host power plant

Scholven Unit F. In addition, the valve was in full operation since the test facility was switched to complete bypass operation during April 2008 to August 2009.

The experience from operation and from the valve investigations after the dismantling showed that full functionality of the hp bypass valve was given during the four years of operation and that graphite and metallic gaskets are applicable for 700 °C applications. Only slight but reasonable indications of erosion at seat area and at throttle bores could be detected.

But the investigations of the valve body and the temperature profiles from operation exposed cracks in the valve body and high temperature gradients during operation. These items did not lead to a breakdown of the valve during operation, but the formation of cracks and high temperature gradients have to be avoided in future applications by design optimisations and optimised operation modes.

Figure 2 shows a part of the hp bypass valve close to the steam outlet. Two perforated discs for the pressure reduction were installed in this part of the component.

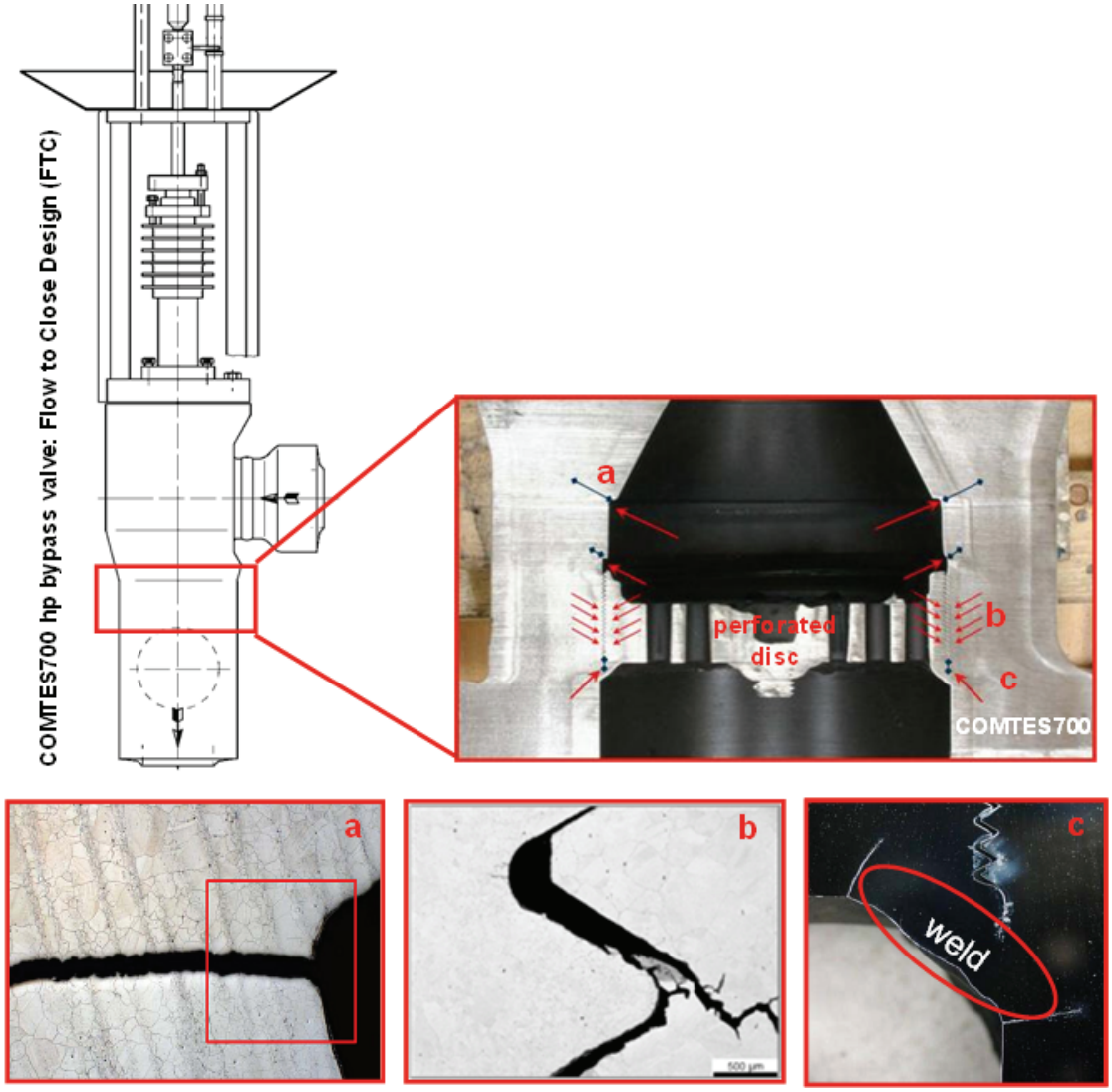


Figure 2: Investigation of COMTES700 high pressure bypass valve after 4 years of operation

The pictures a, b and c in figure 2 lead to required modifications within future designs.

Small radii shall be avoided to reduce notch effects and therefore stress peaks. Favourable are large radii and smooth transitions in geometry. In addition, a good surface quality avoids notch effects. Specific designs which lead to high temperature differences and to high thermal stresses in the component shall be avoided wherever possible.

Threads shall be avoided in pressure bearing parts by other design solutions as far as possible since notch effects and differences in temperature can lead to high local stresses.

Welds shall be avoided inside the valve body if possible. Notch effects in the root can be reduced by an optimised geometry of the root area. Notch effects at the outer surface of the weld can be eliminated by grinding. The welds shall be located in parts of the component where thermo mechanical stresses are low.

The formation of cracks was encouraged by high temperature gradients which occurred sometimes during operation. Figure 3 shows temperature curves from one specific day of operation as an example. Graphs of the live steam temperature, the steam temperature after the hp bypass valve, the material temperature of the valve and the mass flow through the valve are parts of the diagram.

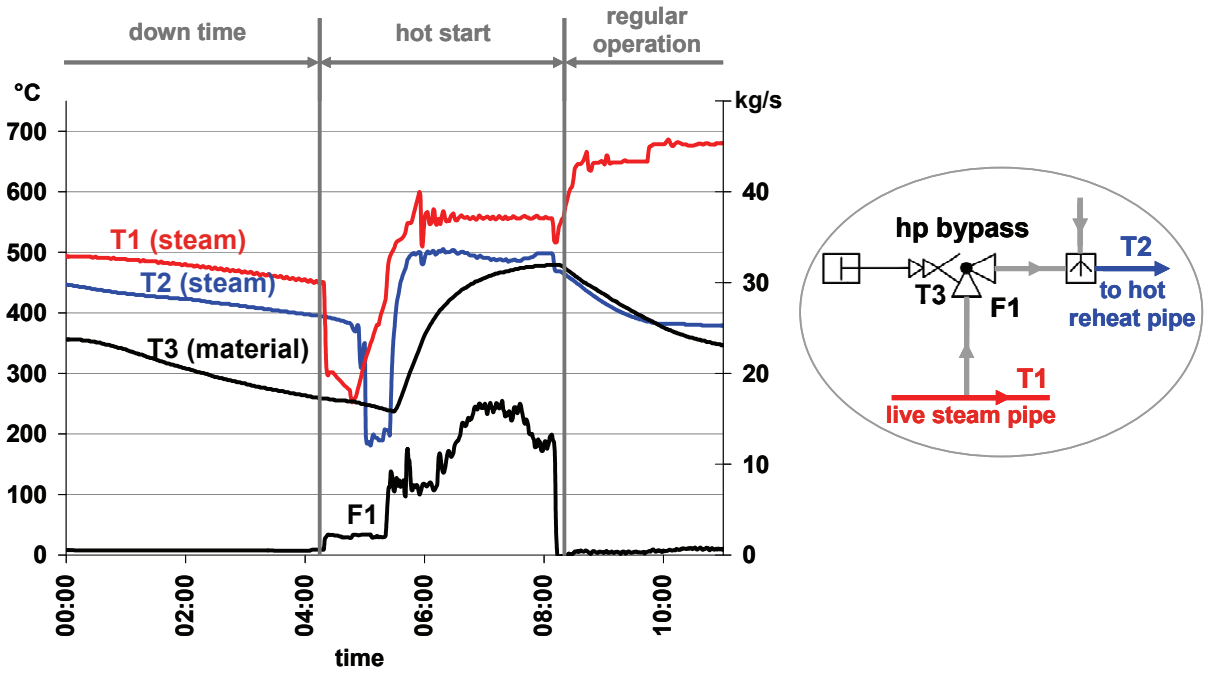


Figure 3: Evaluation of measuring data from COMTES700

Obviously, the hp bypass valve had to suffer high temperature gradients sometimes, which will lead to increased thermal stresses and to a reduction of life time.

High temperature gradients have to be avoided in general, their impact on Ni-base alloys is not fully investigated up to now.

In addition to the above mentioned suggestions, further recommendations for high temperature valves regarding pre-heating, heat treatment and seals can be derived.

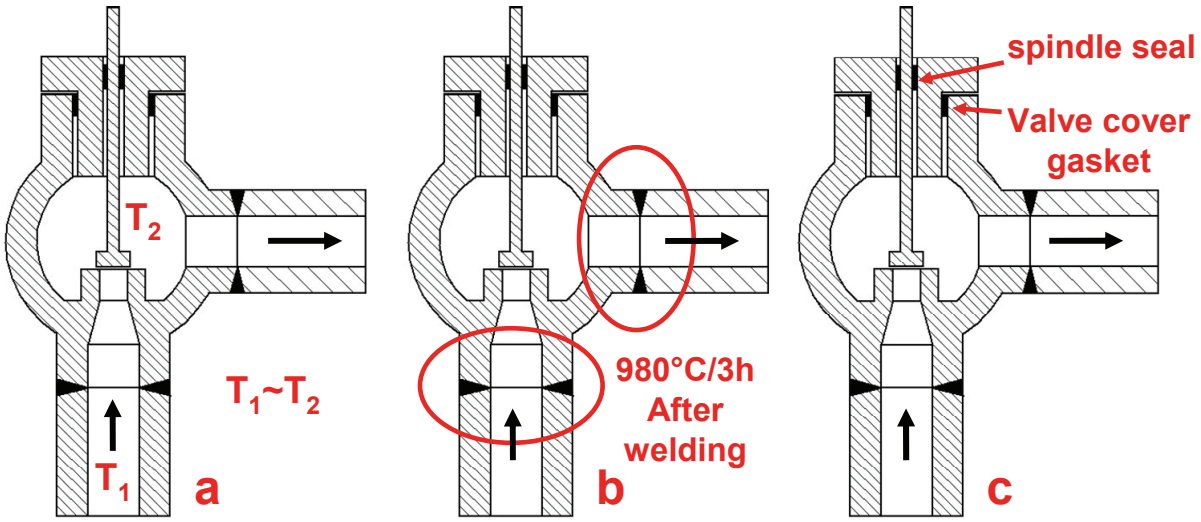


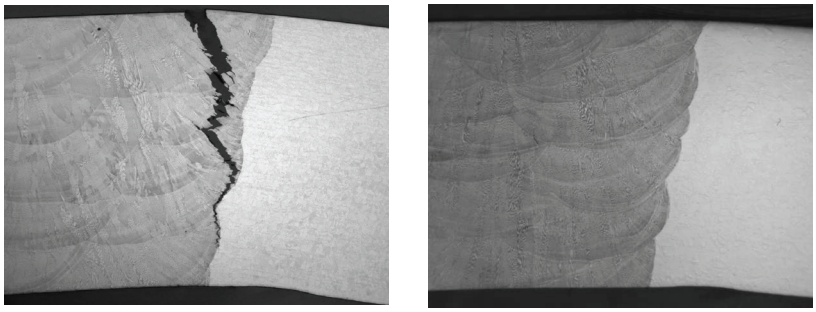
Figure 4: Recommendation for high temperature valves design

2.1.1 Preheating system

A well-engineered preheating system for the valve is essential. The preheating temperature shall be similar to the operation temperature before the valve entry (Figure 4a). It is important that the preheating steam advice affects all parts of the valve, but especially the seat area. A good insulation can help to avoid heat losses during preheating.

2.1.2 Heat treatment of welds

Thick welds can not be avoided for the connection from the valve body to the inlet and outlet pipes. Residual stresses in the weld can cause ductility dip or relaxation cracking during operation since the grain inside does not have the capability to plastically deform in the hardened condition and the grain boundary itself is not strong enough to bear the stresses or reduce them by very localized deformation (Figure 4b). A heat treatment of the weld by oven or heating mats at 980 °C for 3 h reduces the residual stresses. Figure 5 shows the results of two bending relaxation tests at 700 °C. The weld sample of the left hand side is not heat treated and broken during the tests. A second sample from the same weld but with a heat treatment at 980 °C for 3 h did not show any cracks.



No heat-treatment of the weld before test

With heat-treatment of the weld before test (980°C/3h)

Figure 5: A617 B weld after bending relaxation test at 700 °C

2.1.3 Seals

Seals based on graphite cannot withstand temperatures of 700 C°. Problematic seals are the spindle seal and the valve cover gasket (Figure 4c). The distance from the flown valve body to the seals shall be align with the requirements and therefore larger to have a lower temperature in the sealing part. Another possibility is the implementation of cooling fins between the flown valve body and the spindle sealing to increase the dissipation by convection and therefore to a reduced temperature at the seal.

2.2 High pressure bypass valve for HWTII

E.ON and HORA supply a large scale high pressure bypass valve for the project HWTII. The valve was originally planned to be one of four valves for the 700°C demonstration plant 50+ with a steam mass flow of 83 kg/s. Therefore, the valve had to be adapted to the new requirements.

The valve body is made of forged A617 B. The steam temperature is 725 °C. A Flow to Open design (FTO) was chosen since the valve takes over a safety function and has to be in open position in case of a safety incident. A three stages pressure reduction with parabolic plug containing two concentrical cages was installed. The spindle is driven by a hydraulic cylinder and sealed with a graphite stem packing. The 2.6 t valve has an inlet diameter of 245 mm with a wall-thickness of 65 mm and an outlet diameter of 168.3 mm with a wall-thickness of 10 mm. The following steam cooler is a steam assisted water injection cooler.

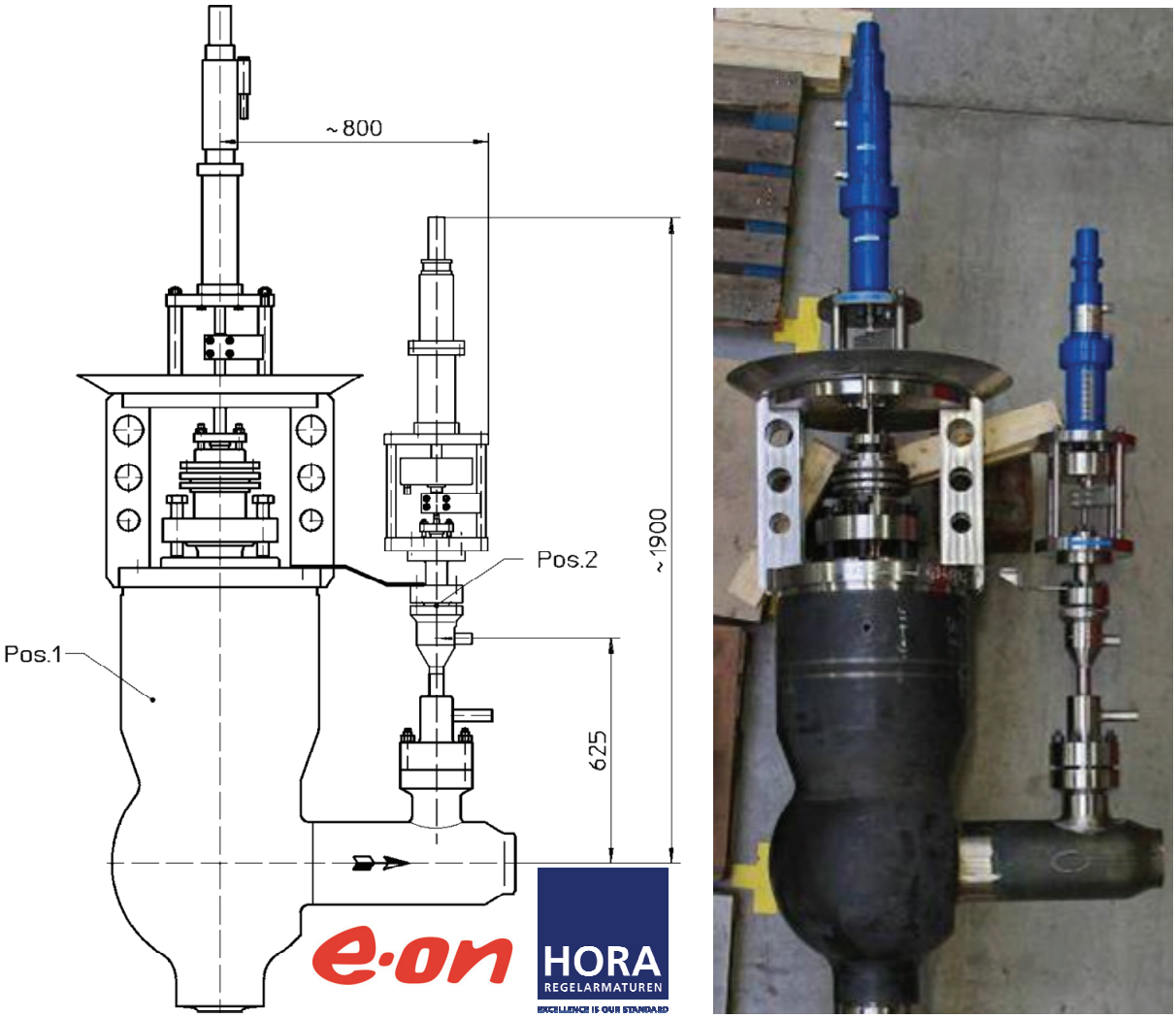


Figure 6: hp bypass valve with Flow to Open design (FTO) for project HWTII

The most difficult design adaptation was the reduction of the valve seat. A diameter of 105 mm was designed for the E.ON project 50plus. It had to be reduced for HWTII to 25 mm due to the mass flow decrease from 83 kg/s to 2.75 kg/s. Many concepts were discussed in order to bring about a decision. A build-up weld in the seat area was decided to be the best solution.

Figure 7: Valve seat adaptation by build-up weld

Figure 7 shows the electrode build-up weld on the right hand picture. The weld surface was machined after welding and the complete valve body was heat treated at 980°C for 3 hours duration to reduce the internal welding stresses. The left hand picture shows the result of a penetration test of the completed weld.

The completed valve was installed in the HWTII test facility and starts operation in October 2012.

3 Repair concept for thick-walled A617B pipes

Repair welds in the thick-walled A617B steam pipe part of COMTES700 posed a major challenge during the operation of the facility.

Some welds from the erection time whose quality was fulfilled had do be welded again or had to be replaced with fitting pieces during operation since samples were taken or repairs of components had to be undertaken. These repair welds were conducted according to the weld procedure specification from the facility erection time. These repair welds caused to problems since small cracks appeared in the weld affected zone along the grain boundaries (Figure 8). The wall-thickness in the 700°C steam piping part was 50 mm. Potential improvements such as switching from electrode to tungsten inert gas welding or changes in the bead sequence did not lead to the desired result.

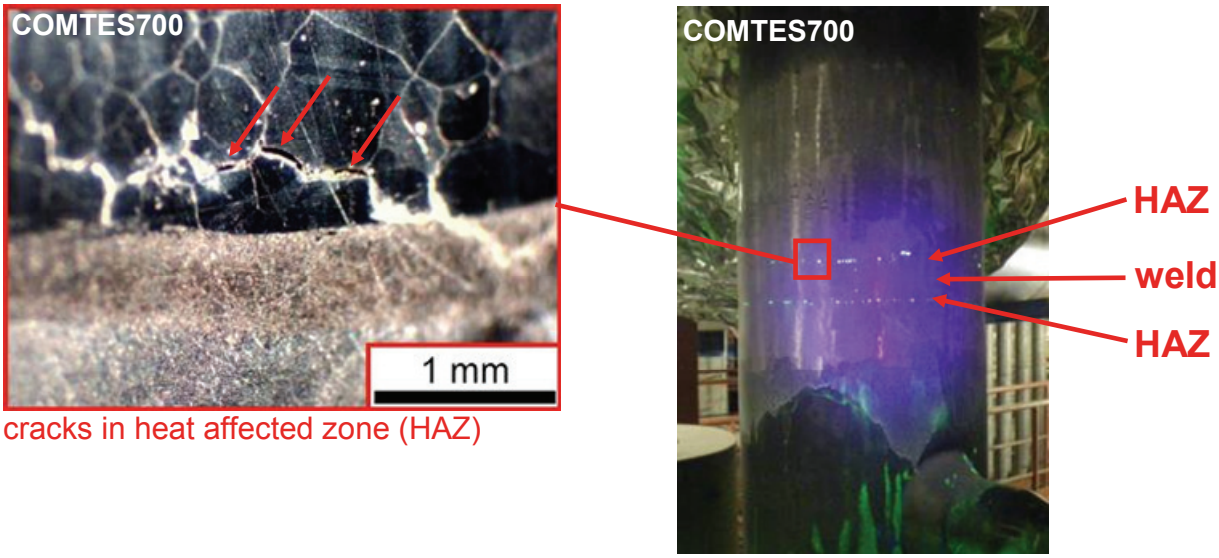
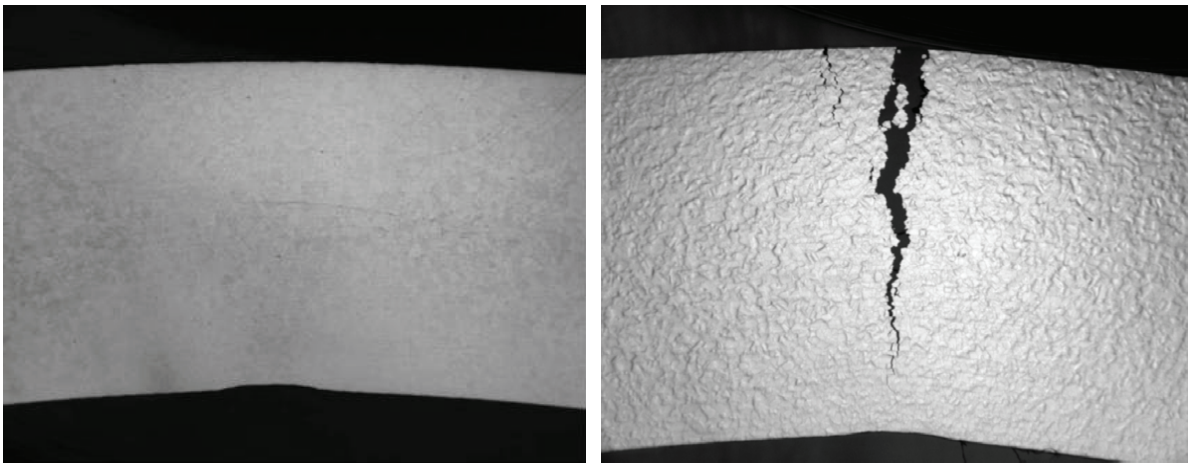


Figure 8: Repair welds of COMTES700

Three point bending relaxation tests at 700°C were done to understand the behaviour of the service exposed material. The left hand picture in figure 9 shows the result of a three point bending test applied on new A617B material which is in solution annealed condition. The material was able to bear and to reduce the stresses by plastic deformations during the relaxation time in the test. The right hand picture shows the same material, but after 3 years of operation. The material in this condition is not able to bear and to reduce the stresses by plastic deformation since a crack was formed. Obviously, the microstructure and therefore the mechanical properties of the material changed. The material hardened during operation and lost the ductility.



New A617B
after 3-point relaxation bending test

Service exposed A617B
after 3-point relaxation bending test

Figure 9: Three-point relaxation bending tests on new and service exposed A617B

SEM and TEM investigations were carried out in order to understand the changes in the microstructure. Figure 10 shows an SEM and TEM picture of new solution annealed A617B material. Some Cr carbides are visible at the grain boundaries but the inside of the grain is generally free of precipitations.

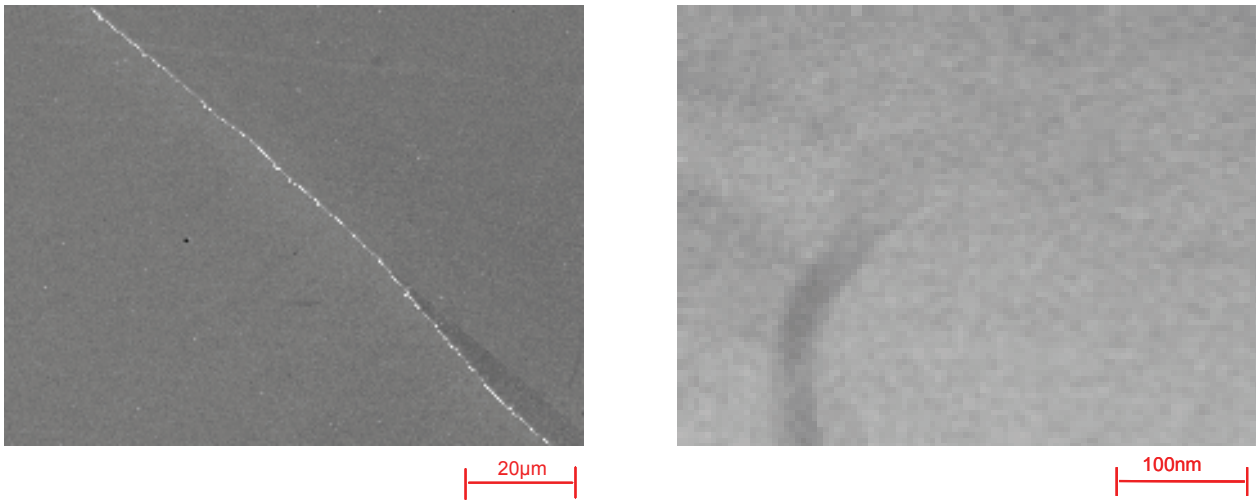


Figure 10: SEM and TEM investigations of new A617B

Contrary to these pictures service exposed material shows a series of Cr carbides at the grain boundaries and inside the gain (see figure 11). In addition formations of γ‘ were found inside the grain. These precipitations found will lead to a significant hardening effect .

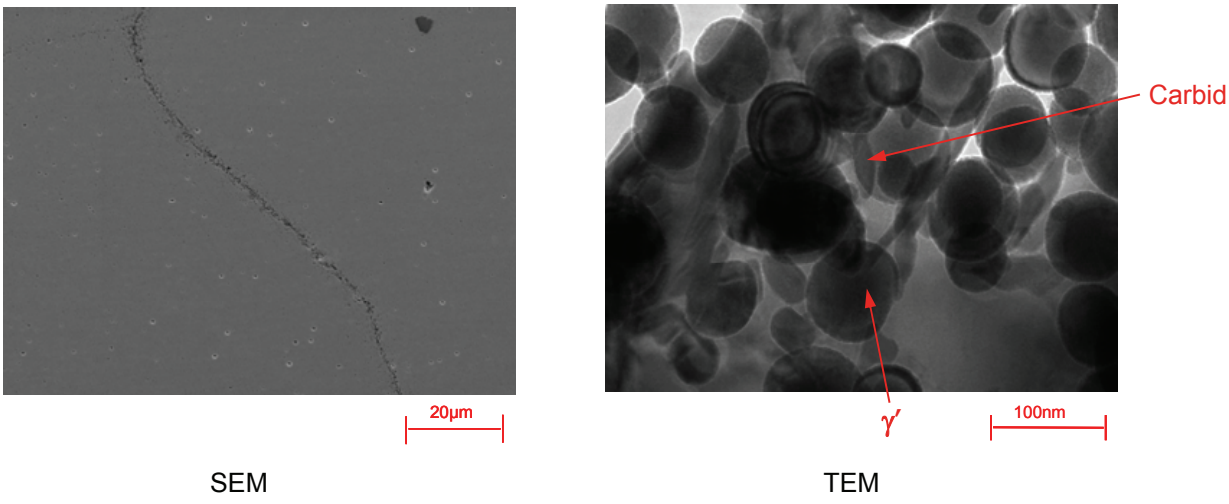
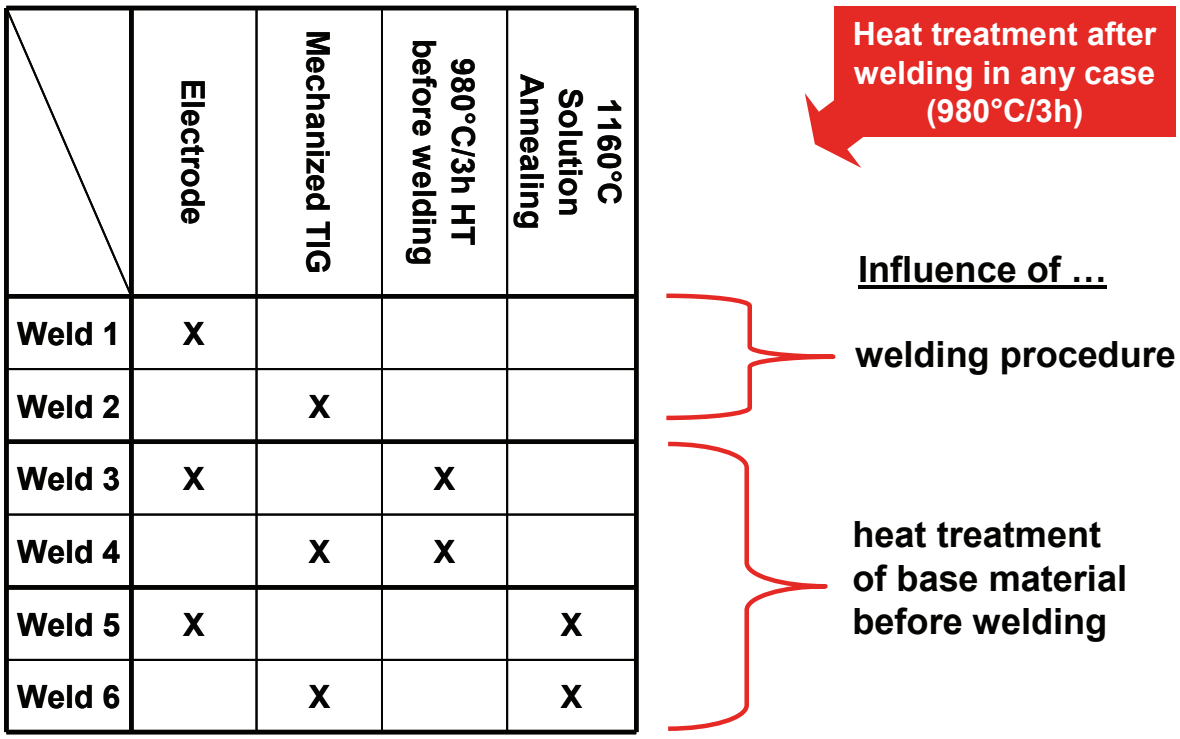


Figure 11: SEM and TEM investigations of service exposed A617B

Welding tests with service exposed pipe material from COMTES700 (219x50mm) were initiated after the dismantling of COMTES700 to develop a repair concept for thick-walled

A617B components. The test revealed the influence of the welding procedure and the influence of a heat treatment of the base material before welding (see figure 12). The heat treatment was made at different temperatures, 980 °C for 3 hours and 1160 °C for 1 hour which correspond with the solution annealing parameters. A post weld heat treatment at 980 °C for 3 hours was carried out in any case to reduce to the internal welding stresses.



	Electrode	Mechanized TIG	980°C/3h HT before welding	1160°C Solution Annealing
Weld 1	X			
Weld 2		X		
Weld 3	X		X	
Weld 4		X	X	
Weld 5	X			X
Weld 6		X		X

Figure 12: Welding tests of COMTES700

It was expected that the mechanised TIG welds will deliver better results than the electrode welds since the bead sequence and the heat input is more homogeneous. In addition the mechanised TIG technique lead to a significant reduction in weld size. Internal stresses are therefore reduced (see figure 13).

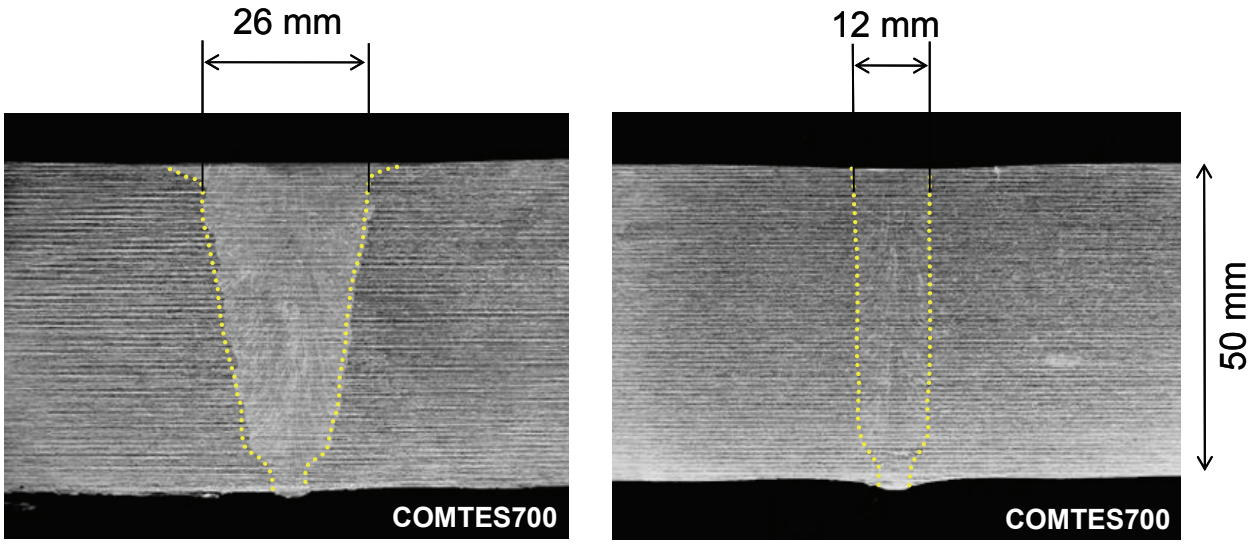
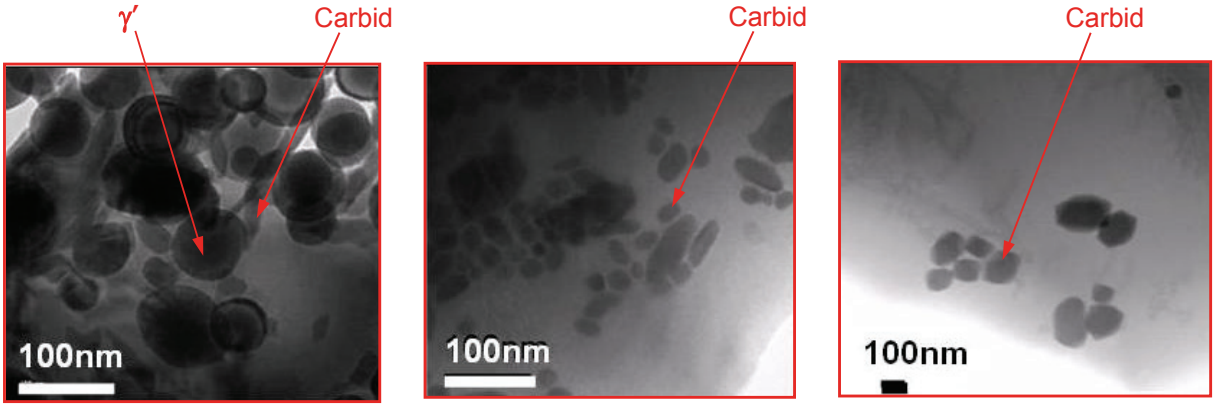


Figure 13: Comparison between electrode weld and mechanised TIG weld

An improved result with increasing heat treatment temperature was expected in addition to that. Service exposed A617 contains a high number of carbides and γ‘ precipitations (see figure 14). The γ‘ precipitations can be solved with a 980°C heat treatment for 3 hours. Carbides being present can not be solved either at 980 °C or 1160 °C. But their number and size changed significantly at 1160 °C which has an influence on the ductility of the material.



A617B service exposed (22kh)

A617B service exposed (22kh) plus 980°C / 3h

A617B service exposed (22kh) plus 1160°C / 1h

Figure 14: Precipitations in A617B depending on heat treatment

The results of the metallographic weld investigation correspond with the assumptions regarding weld technique and heat treatment (see figure 15).

The mechanised TIG technique leads to better results. The welding tests on service exposed material without heat treatment before welding showed quite large widening effects along the grain boundaries in the heat affected zone. A heat treatment of the service exposed material

before welding has a positive influence on the results. The widening effects could be reduced significantly with a heat treatment at 980 °C. No defects could be realized with a heat treatment at 1160 °C.

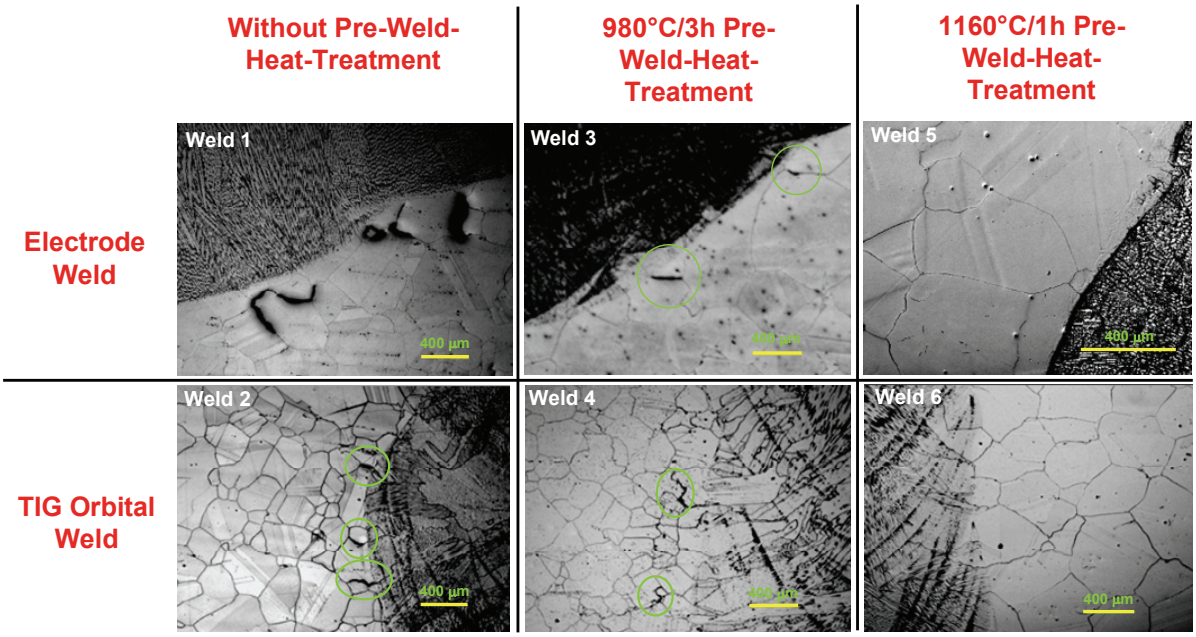


Figure 15: Metallographic results of COMTES700 test welds

The best results could be achieved with the parameters applied for the welds 4, 5 and 6. These welds will be reproduced and tested in a weld test rig at MPA Stuttgart. The welds will be heated up to 700 °C and stressed with internal pressure and external forces.

Furthermore, the repair concept will be verified in the project ENCIO, where repair welds produced with COMTES700 material will be tested in a power plant test rig.

To verify that heat treatment at temperatures above 1000 °C is applicable under site conditions simulation of this heat treatment at these conditions was performed. In comparison to a typical heat treatment at 1160 °C in a workshop, only equipment which can be applied in a power plant was used. Quenching in water, which is usually applied after the solution annealing in a workshop, is not possible in a power plant. The temperature has to be reduced to a temperature of 700 °C as rapid as possible. A spray water device was manufactured for this task.

An experimental test heat treatment was done, in order to investigate:

- If a temperature of 1160 °C can be reached by using heating mats
- If a rapid cooling is possible
- How the temperature decreases next to the heat treated part.

Figure 16 shows the experimental setup. A service exposed Alloy 617 B pipe (219,1x50mm) from COMTES700 was used for the test.

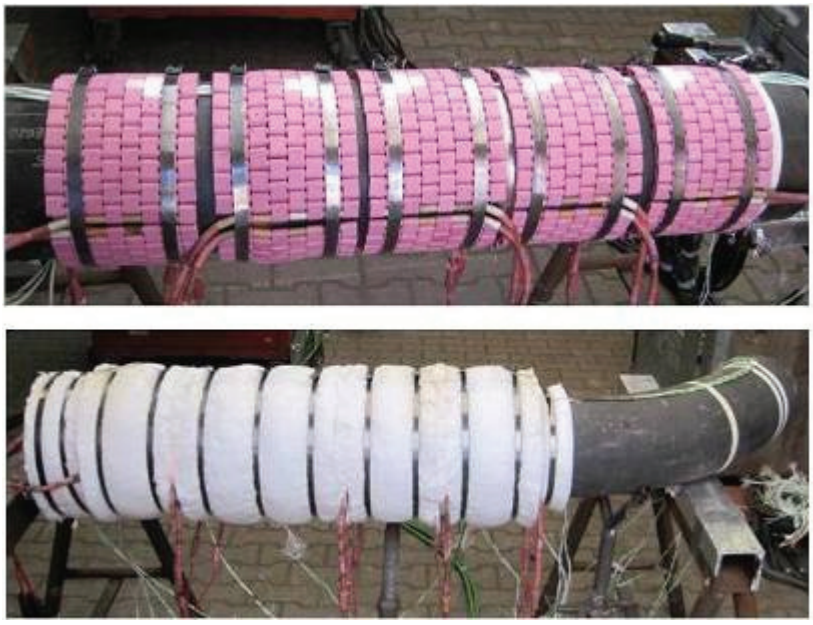


Figure 16: COMTES700 1160 °C heat treatment test – experimental setup

The pipe was heated with a maximum rate of 150 °C/h. The temperature of 1160 °C could be reached at the outer and inner surface of the pipe. A defects of the heating mats were not observed. The holding time at 1160 °C was one hour. The pipe was cooled down as rapidly as possible after the holding time of one hour at 1160 °C was reached. Two spray water cooling devices were manufactured for this task (see figure 17)

Figure 17: COMTES700 1160 °C heat treatment test – heating and cooling down

The cooling rate is illustrated in figure 18 based on the data from two temperature measurements fixed at the internal pipe surface. The cooling rate of the upper thermocouple TE11 is higher than the cooling rate of TE12. The spray water device was preferably applied from above. This is the reason for the temperature difference. A temperature of 700 °C was achieved in about 11 minutes in case of TE11 and in about 15 minutes in case of TE12. The maximum cooling rate achieved at the inner surface was 53 K/min.

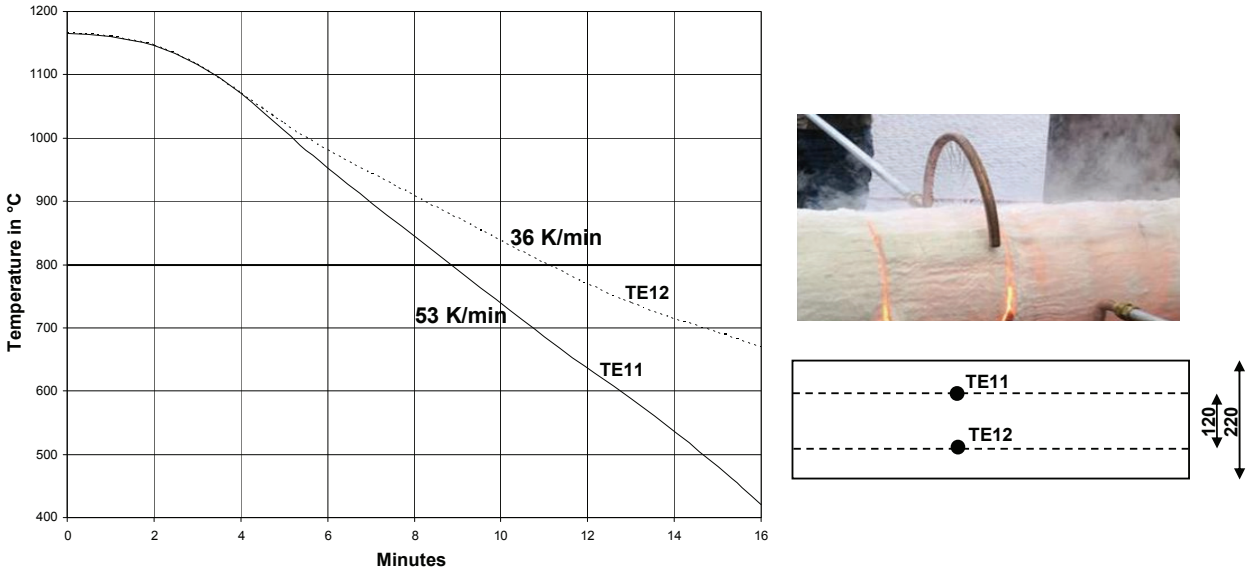


Figure 18: COMTES700 1160°C heat treatment test – cooling rates

A good limitation of the heat treated part is possible since the temperature reduction with increasing distance from the heat treated part is very high due to the low thermal conductivity of nickel based alloys (see figure 19).

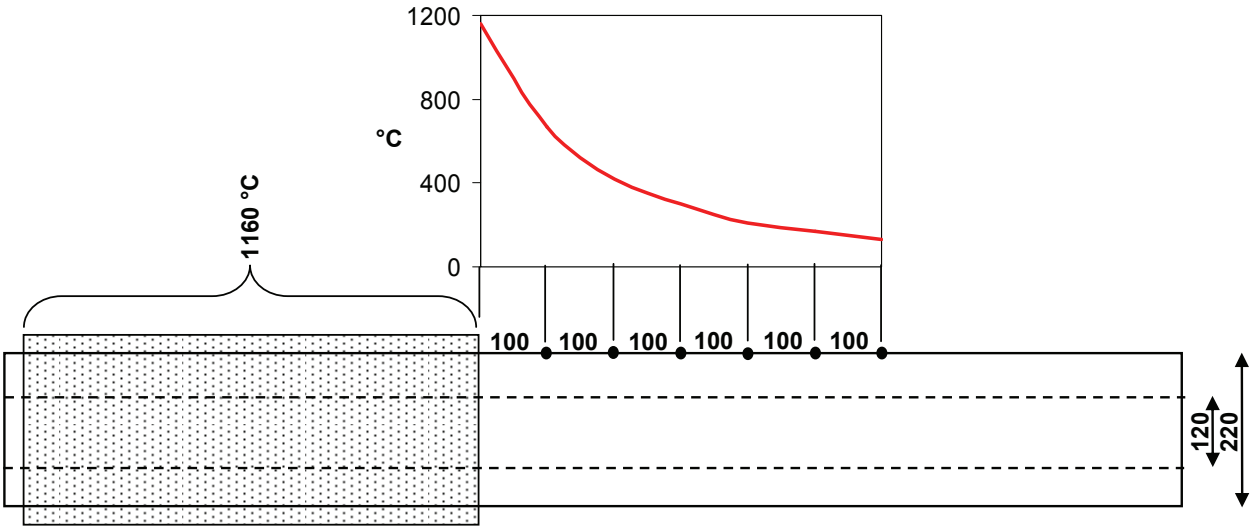


Figure 19: COMTES700 1160 °C heat treatment test – temperature reduction with increasing distance

4 Challenges on the way to the 700 °C power plant

COMTES+ with the projects HWTII and ENCIO is intended to be the final step before realization of the first 700 °C demonstration power plant. There are still some challenges. Some of the technical challenges were described in the previous chapters. In addition there are financial challenges and challenges regarding flexibility.

4.1 Financial challenges

The price for nickel based alloy is much higher compared to conventional ferritic and martensitic steels (see figure 20).

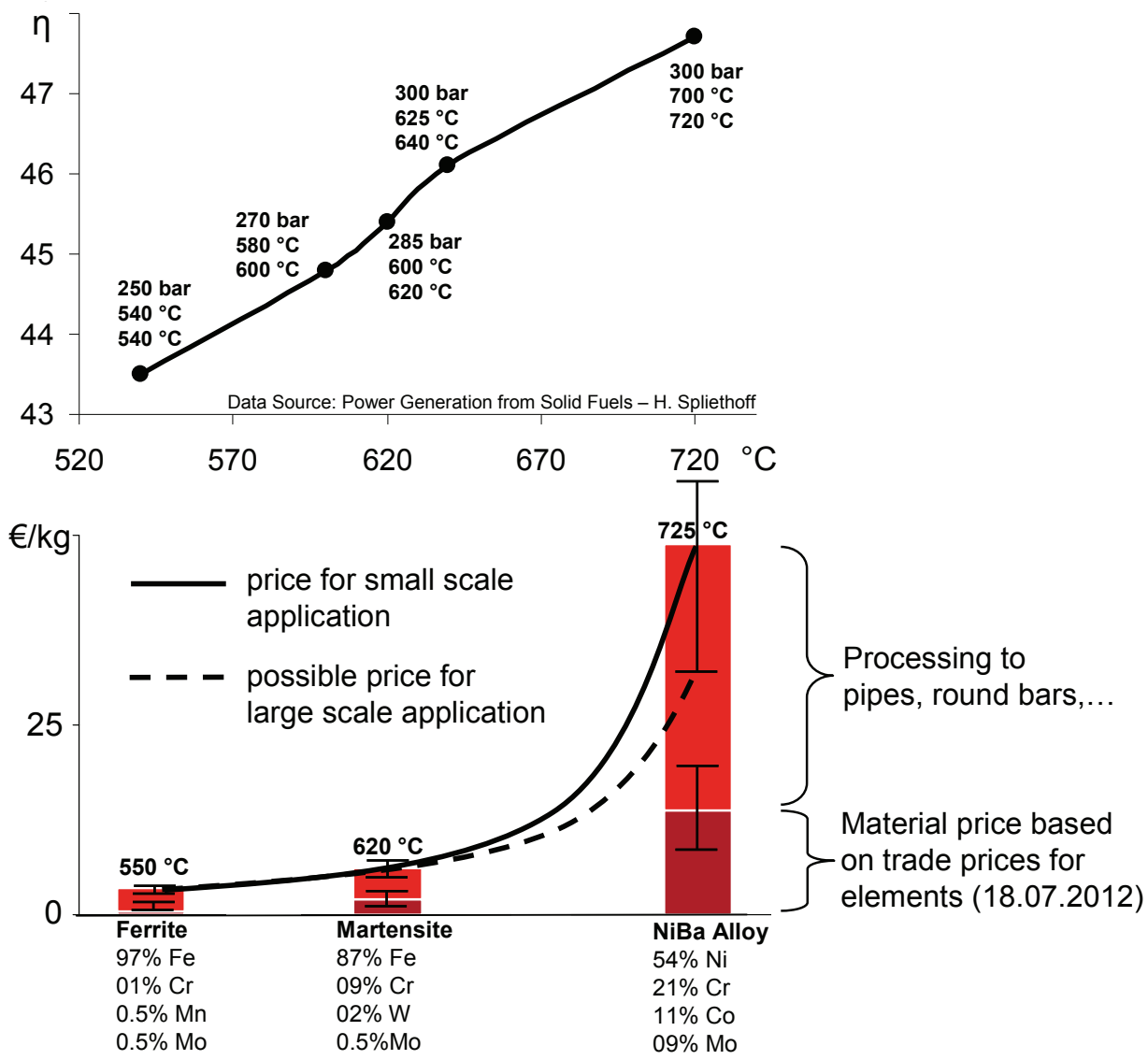


Figure 20: Costs of nickel based alloys in comparison to martensitic steels

The efficiency increase is more or less proportional to the temperature in the considered range. But in contrast to this, the raise of the price for materials is exponential to the

temperature. But the price might decrease for a large scale application in future. Further additional costs arise from the subsequent processing of material such as turning or milling. These costs are much higher in comparison to conventional steels due to the difficult machineability of nickel based alloys.

The price for nickel based components has to be reduced as much as possible among others by novel manufacturing methods which will be tested in COMTES+.

4.2 Flexibility challenges

Increased flexibility capability is required in Europe due to the increasing influence of renewable energy production. Coal fired power plants need to change their load very fast in the future. For economical reasons it is necessary to guarantee high load gradients, minimum shut-down and start-up time, minimum down time, minimum min. load and an increased number of starts (see figure 21).

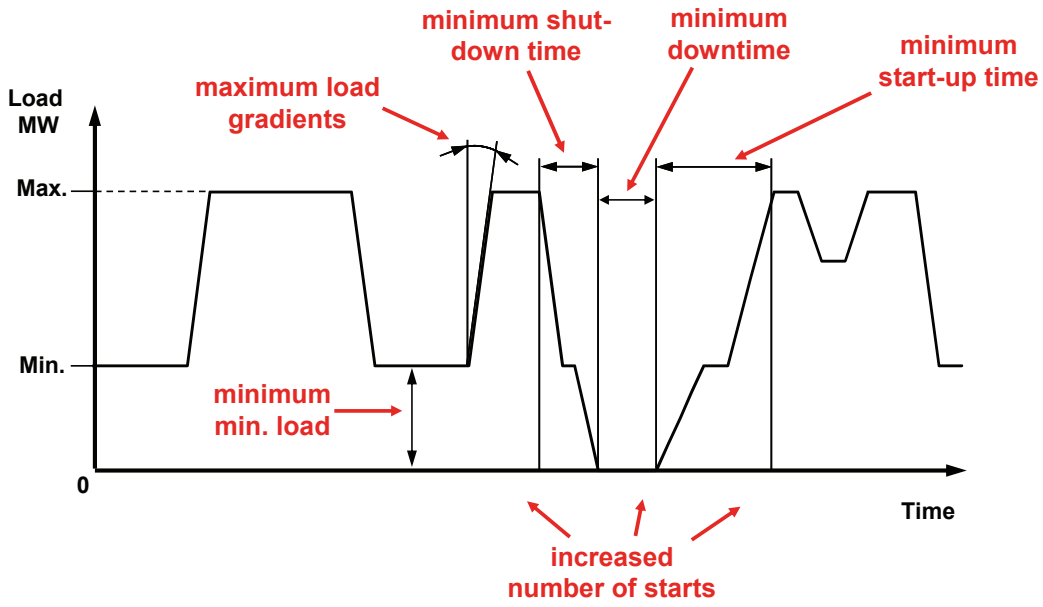


Figure 21: Flexibility requirements for future power plants

From the first point of view, nickel based alloys do not have good characteristics in terms of thermal flexibility due to their low thermal conductivity and their high thermal expansion.

The low thermal conductivity in comparison to martensitic steels leads to a late equilibrium of the temperature in a component in case of temperature changes in the steam system (Figure 22). That results in higher thermal induced stresses. The high thermal expansion of nickel based in comparison to martensitic steels is disadvantageous since higher thermal induced stresses can be expected during changes of the steam temperature (Figure 23).

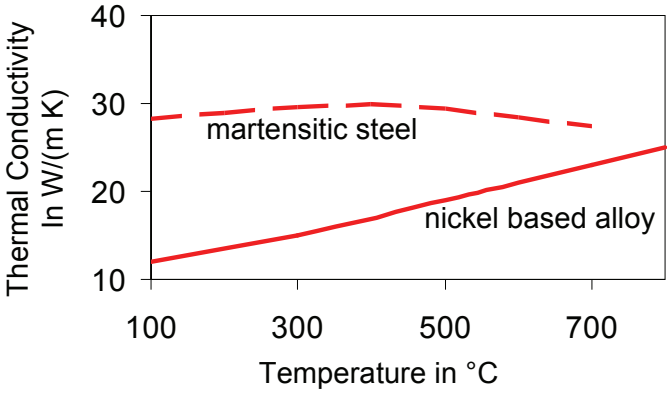


Figure 22: Thermal conductivity of nickel based alloys in comparison to martensitic steels

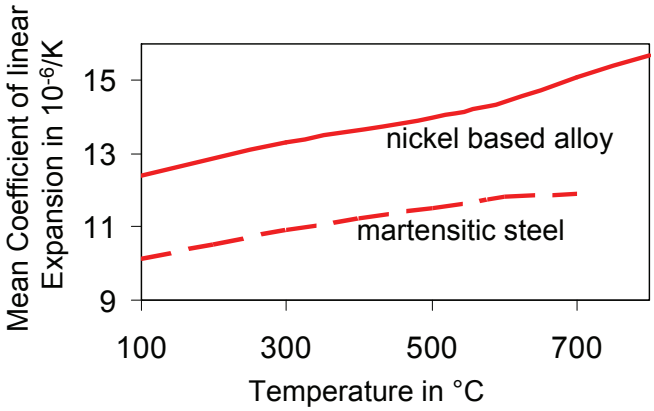


Figure 23: Thermal expansion of nickel based alloys in comparison to martensitic steels

This behaviour of nickel based alloys has to be considered in the design of the components and in the modes of operation for the power plant. The current projects have to show that nickel based components fulfil the flexibility requirements of the future.

5 Summary and Conclusion

Many hurdles have been overcome and solutions have been developed on the way to the first 700 °C power plant in the last years. For example, design optimisations were identified for high temperature valves, heat treatments were adopted for thick welds to reduce internal stresses and pre-heating optimisations reduce thermal stresses in thick-walled valve bodies.

The understanding of nickel based material microstructure was improved, especially of service exposed and heat treated material. A repair weld concept was developed and it has been demonstrated that at 1160 °C heat treatment is applicable in a power plant.

But there are hurdles left in terms of technique, finance and flexibility. The remaining technical challenges have to be solved so that the technical risk for a 700 °C demonstration plant can be reduced even more. Material and processing costs have to be minimised. Last but not least it has to be shown that nickel based components can withstand the required thermal flexibility.

6 Acknowledgement

A special thank you goes to all partners of COMTES700 and COMTES+, which were involved in some of the illustrated activities as well as to the funding of BMWI and the Research fund for Coal and Steal of the European Commission.

EUROPEAN COMMISSION

Research Fund for Coal & Steel

Gefördert durch:

Bundesministerium für Wirtschaft und Technologie

aufgrund eines Beschlusses des Deutschen Bundestages

In Zusammenarbeit mit:

ptj Projektträger Jülich Forschungszentrum Jülich