Evaluation of Material Properties of Welded Joint of Component for Nuclear Power Stations of the type MIR 1200

Hodnocení vlastností svarového spoje pro komponenty jaderných elektráren typu MIR 1200

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Material & Metallurgical Research Company Ltd. has been working on the project focused on the evaluation of metallurgical and mechanical properties of both homogeneous and heterogeneous weld joints used in the recent type of nuclear power stations MIR 1200. The main goal of the project is to verify welding technology, filler materials and heat treatment from the point of view of mechanical properties, structure and also unconventional materials (stress corrosion cracking, low-fatigue tests etc.). Numerical simulation of fracture behaviour and modelling of the critical condition of crack growth is also included in the project. The paper summarizes results of experimental work and numeric simulation carried out within the project TA04021746 "Research, development and verification of production technology of selected welded joints for pressure vessels of the primary circuit of nuclear power plants of the type MIR 1200". Effect of welding technology, both for homogeneous, as well as for heterogeneous weld joints including simulation of heat treatment soaking time on mechanical, fatigue and fracture properties, has been studied. Heterogeneous weld joint 08Ch18N10T – 10GN2MFA has been prepared for the experimental program and this paper deals with the results obtained for this type of weld since the results obtained for homogeneous welds were already published elsewhere. Conventional mechanical properties, as well as unconventional mechanical properties (fracture mechanics in the terms of R-curves in the air and in a water environment, low-cycle fatigue and stress corrosion cracking in water environment at elevated temperature), have been studied. Effect of elevated working temperature on structure, material properties, and corrosion resistance has been evaluated. Resistance against stress corrosion cracking in real water environment at working temperature has been studied. Experimental data have been compared with a numerical simulation using FEM.

***Key words**: MIR 1200; heterogeneous weld joint; low cycle fatigue; fracture behaviour; stress corrosion cracking*

Článek shrnuje výsledky experimentálních prací a numerických simulací provedených při řešení projektu TA04021746 Výzkum, vývoj a ověření výrobní technologie vybraných svarových spojů pro tlakové nádoby primárního okruhu jaderných elektráren typu MIR 1200. Zabývá se studiem konvenčních a nekonvenčních vlastností heterogenního svarového spoje 08Ch18N10T – 10GN2MFA. Hlavním cílem provedených experimentů bylo posouzení výrobní technologie těchto komplikovaných heterogenních svarů a ověření jejich užitných vlastností vzhledem k předepsaným podmínkám. Rovněž bylo provedeno ověření nekonvenčních vlastností (lomová houževnatost, nízkocyklová únava, náchylnost ke koroznímu praskání při pracovní teplotě). Získané výsledky byly porovnány s numerickou simulací metodou konečných prvků.

***Klíčová slova**: MIR 1200, heterogenní svarový spoj; lomové chování; korozní praskání; nízkocyklová únava*

In connection with the increasing consumption of electricity, the building of additional blocks of our nuclear power plants, especially in Temelín, is becoming more and more important to. Although the topic of completion of nuclear power plants is a topic that raises the public debate and becomes a pre-election issue for many politicians, it is indisputable that in the near future the realization of a central and stable source of electric power that will not burden the transmission system with sudden peaks, as is the case of supplies from renewable sources, will be necessary. The increase in the output and efficiency of nuclear power plants is currently realized by the MIR 1200 design, which approved itself at the power plant built in Novovoronezh. The MIR 1200 design is a follow-up design of reactor of the type VVER 1000, but it eliminates some technical deficiencies and includes new technical solutions. **The primary circuit** has 4 loops and it includes a reactor, 4 horizontally positioned steam generators (type PVG-1000MKP), 4 main circulation pumps (type GCNA-1391) and a volume compensation system. The safety systems comprise, for example, the passive system of emergency cooling of the active zone and the emergency gas discharge system. The pressure in the primary circuit is 16.2 MPa and the flow rate is 86,000 $m^3 \cdot h^{-1}$. The inlet water temperature in the

 Hutnické listy č. 4/2017, roč. LXX
ISSN 0018-8069

primary circuit is 298.2 °C and output 328.9 °C. **The secondary circuit** consists of steam generators, turbine, condensers, the system of low pressure and high pressure reheating of condensate water, feed and condensate pumps. The steam generator has an output of 1,602 tons of steam per hour. The turbine consists of one high-pressure and four low-pressure parts. The steam escapes from the steam generator under a pressure of 7 MPa, its dryness is less than 0.2%. Tab. 1 shows a comparison of the main technical parameters of the existing VVER 1000 reactors after modernization and MIR 1200 [1]. The work is based on the experiments already carried out on several model homogeneous weld joints [2 - 4].

Tab. 1 Combination of evaluated welds
Tab. 1 Kombinace hodnocených svarových spojů

Parameter	VVER-1000	MIR.1200	Change (%)
Heat output (MWt)	3,000	3,200	+ 6.7
Electrical output (MWe)	1,070	1,200	+ 10.8
Average duration of shutdown (days)	40	25	- 37.5
Annual production of electric power (TWh)	7.5	9	+ 20.0
Coefficient of utilization of the installed power	0.8	0.92	+ 15.0
Volume of spent nuclear power (t/TWh)	5.5	3.5	- 36.4
Project service life of nuclear power plant (years)	30	60	+ 100

Experimental methods

The research working site (MATERIAL AND METALLURGICAL RESEARCH Ltd.) received for material analyses, two identical model heterogeneous weld joints No. 5 (Fig. 1). Both pieces were welded at the project co-researcher (VÍTKOVICE POWER ENGINEERING, a.s.) and they were inspected visually and subjected to other NDT (capillary tests and X-ray inspection).

Fig. 1 Welded joint No. 5
Obr. 1 Svarový spoj č. 5

Austenitic sockets were made from forgings made of CrNi stabilized steel 08Ch18N10T with dimensions ø 450/ø 300 × 160 mm. The forgings were for testing in the state after solution annealing.

Sockets from the steel 10GN2MFA with dimensions ø 660/ø 340 × 300 mm were in the state after hardening and tempering. A 2-layer transient weld deposit was welded after machining on both sockets by the method ROS (SMAW) with the use of the electrodes EA 395/2 and EA 400/10T (positions 2, 3). Subsequently, a 2-layer anti corrosive weld deposit was welded on the inner diameter by the method ROS (SMAW) with the use of the electrodes CL-25/1 and EA 898/21B (positions 4, 5). After welding, the sockets with weld deposits were heat treated by the mode a 650 °C/10h. The detailed execution with positions is presented in drawing 3-N-804-096.

Weld joints of the sockets were made by the APT method using the wire Sv04Ch19N11M3 with the welding flux OF-6.

The framework process for the production of both model welds is the following:

- Mechanical machining of the sockets, incl. flaw detection of welding and weld deposit edges.
- Overlaying of the transition layers 1 and 2 on the socket 10GN2MFA by the ROS method with application of the prescribed heat treatment mode, incl. measurement.
- Flaw detection and repair of the layers 1 and 2 of the weld deposit.
- Welding of the layers 1 and 2 of anti corrosive welding on the socket 10GN2MFA sleeve by the ROS method with application of the prescribed heat treatment mode, incl. measurement.
- Flaw detection and machining of layers 1 and 2 of the weld deposit.
- Heat treatment of the overlaid sockets 10GN2MFA with the use of the mode 650°C/10h with controlled heating and cooling, incl. measurement.
- Welding of the sockets 08Ch18N10T with overlaid sockets 10GN2MFA, weld root by MIG (GMAW), method, weld joint filler by APT (SAW) method.
- Flaw detection of the weld joint.

Within the frame of the experimental program, the chemical composition of the heterogeneous weld joint along its width was also verified in individual layers of weld deposits (Fig. 2). The results of tests of mechanical properties are summarized in Tab. 2.

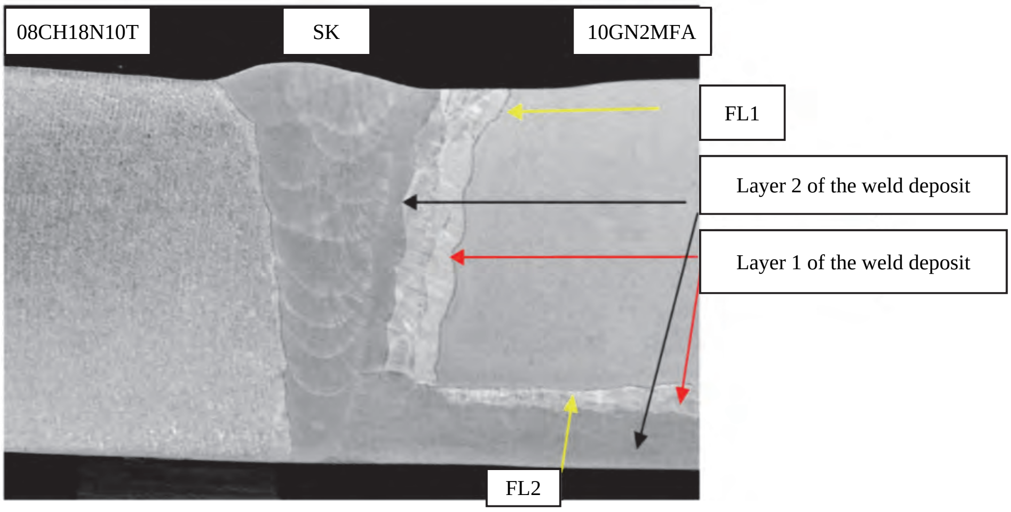

Fig. 2 Welded joint - detail
Obr. 2 Svarový spoj - detail

Tab. 2 Results of testing of mechanical properties of the welded joint and of weld deposit
Tab. 2 Výsledky zkoušek mechanických vlastností svarového spoje a návaru

		Measured values		PNAEG-7-010-89 resp. RTD 2730.300.02-91	
		Weld joint	**Anti-corrosive weld deposit**	**Weld joint**	**Anti-corrosive weld deposit**
	Filler material	Sv04Ch19N11M3 with welding flux OF 6	EA 898/21B	Sv04Ch19N11M3 with welding flux OF 6	EA 898/21B
20 °C	Rm	597 – 612	649 – 670	min. 491	min. 539
	Rp0.2	406 – 471	449 – 479	min. 245	min. 343
	A %	28.0 – 38.0	33.6 – 40.4	min. 25	min. 16
	Z %	59.8 – 64.1	39.8 – 42.8	min. 35	min. 30
350 °C	Rm	408 – 418	477 – 487	min. 343	min. 441
	Rp0.2	286 – 336	352 – 379	min. 196	min. 245
	A %	18.8 – 25.2	16.8 – 20.8	min. 15	min. 10
	Z %	65.7 – 75.2	28.6 – 35.6	min. 25	min. 20

Intercrystalline corrosion

The evaluation of the complex properties of the heterogeneous weld joint comprised also the assessment of its resistance to intercrystalline corrosion, which was tested according to GOST 6032-2003 by AM method.

A total of 4 corpuscles were always removed from the weld joint surface and from the anticorrosive weld deposit, which were then subjected to an initiation of the intercrystalline corrosion according to the above-mentioned norm in a defined acid solution, and which were consequently bent on the mandrel and checked for the presence of cracks. No cracks were detected.

All test corpuscles met the requirement for resistance to intercrystalline corrosion (Fig. 3).

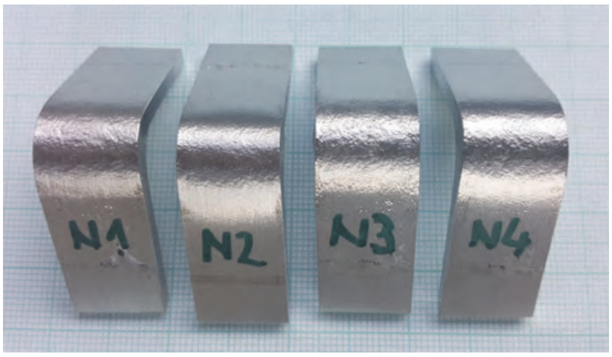

Fig. 3 Samples after IGC test
Obr. 3 Vzorky po zkoušce MKK

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ISSN 0018-8069

Low cycle fatigue

For evaluation of resistance to low cycle fatigue, smooth test specimens with "button end" with a diameter of the loaded section of 8 mm were manufactured (Fig. 4). The test specimens were taken in the transverse or in the tangential direction of the base materials and across the weld joint.

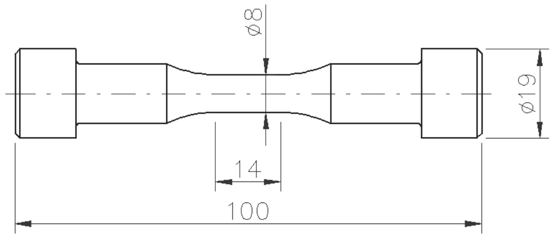

Fig. 4 LCF specimen
Obr. 4 Zkušební těleso pro zkoušky NCÚ

Test specimens for determination of the Manson-Coffin curve and of the strain hardening curve were manufactured from the experimental material. The tests of low cycle fatigue were conducted in accordance with the standard ASTM E 606 [5] at the laboratory temperature and at the temperature of 350°C on the MTS 100 kN servo-hydraulic testing device in the mode of control of axial deformation by an alternate load tension-compression. During these tests, the constant amplitude of the total strain ε_{ac} was maintained. Low cycle fatigue tests were performed at a constant velocity of the total strain $\varepsilon_{ac} = 4.10^{-3}\ s^{-1}$. Longitudinal deformation of the test bodies was read by a sensor with the 12 mm base. For a complex assessment of the material response to a plastic deformation, a cyclic stress-strain curve characterizing plastic response of material for major part of the fatigue service life was determined in the form

$$\sigma_a = k \cdot \varepsilon_{apl}^n ,$$

Where k is the cyclic reinforcement factor and n is the cyclic strain hardening exponent.

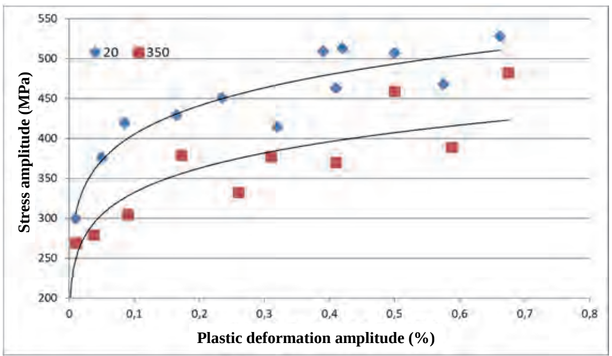

Fig. 5 Effect of temperature on cyclic stress-strain curve
Obr. 5 Vliv teploty na cyklickou křivku napětí-deformace

In this way, it was possible to construct the Manson-Coffin curve of service life and the cyclic curve of the strain hardening from the saturated values (Fig. 5), which characterize the deformation behaviour of the material over the major part of its fatigue service life, and which are therefore material characteristics.

Evaluation of fracture behaviour and corrosion cracking

Evaluation of fracture behaviour of the steel 10GN2MFA-A was made on the basis of fracture toughness parameters at 290°C in accordance with the ASTM E1820-09 [6]. For this purpose, test specimens of type C (T) were taken with thickness B = 12.5 mm and width W = 25 mm so that the fatigue crack would propagate through the interface 10GN2MFA – weld deposit layer 1. The test specimens were then loaded at a constant speed of movement of the piston rod of the servo-hydraulic testing machine of 0.5 mm·min^{-1}. The heating was ensured by a three-zone furnace. The specimen temperature was measured with a NiCr-Ni thermocouple spot welded to the test specimen in the area of the fatigue crack. During each test, it was possible to detect a crack opening in the load axis using a specially developed jig.

For each test specimen, a record of the force-notch opening in the load axis was thus obtained. The fracture behaviour of the steel 10GN2MFA at 290°C is characterized by a steady growth of a ductile crack. To describe this behaviour, it is appropriate to use the concept of the so-called R-curves interpreting the dependence of the fracture toughness parameter (J - integral, critical opening of the crack δ) on a stable increment of the crack Δa. After unloading, the test specimens were fully broken in a liquid nitrogen and the initial length of the fatigue crack a_0 and its stable increment Δa were measured on the fracture areas using a microscope.

Figure 6 shows the R-curve determined at the calculation temperature, or at a temperature corresponding to the operating state on the hot collector. Remote points are caused by swerving of a crack, which should have been located at the interface of the material 10GN2MFA and the first weld deposit layer. After testing, all test specimens were subjected to fractography analysis of fracture areas in order to determine precisely the location, in which the crack propagated.

Corrosion cracking is defined as the process of initiation and subcritical growth of the macroscopic crack due to the simultaneous action of tensile stress (from external strain or stress) and corrosive environment. Learning of the regularities of corrosion cracking and corrosion fatigue consists therefore in understanding the complex interaction between the properties of the material, the properties of the environment and the manner of strain. Corrosion cracking occurs only if the stress level, properties of the corrosion environment and material properties achieve simultaneously the limit values necessary for its occurrence.

Special attention is during experiments devoted to the stage of sub-critical growth of the macro-crack, mainly because it is based on practical experiments performed on materials of really manufactured components where it is no longer possible to influence the manufacturing process itself or the technology or operating conditions that are dictated by the technical conditions of the operation of the given nuclear power plant.

Due to the fact that the sub-critical growth of cracks takes place with respect to the operating conditions (temperature) and material parameters (tough steel) by the mechanism of stable growth of the ductile crack, it is necessary to quantify it by the relevant parameters of the fracture mechanics. Stable growth of cracks can be described on the basis of the parameters of linear fracture mechanics, which is usually the stress intensity factor K (MPa·m$^{1/2}$) or the elastoplastic fracture parameter δ (mm) - the opening of the crack face or J-integral (N·mm^{-1}).

In principle, two methods are used for assessment of corrosion cracking. The first one is based on slow tests in the uniaxial tension of cylindrical test specimens when the factor used for the assessment is the value of contraction. The second method uses a slow loading of test specimens with crack for evaluation of the fracture behaviour when the effects of the environment and temperature are reflected by a reduction of the initiation value for stable growth of the crack, or by the occurrence of an intercrystalline fracture on fracture surfaces.

Evaluation of resistance of the material of a heterogeneous weld joint made of low-alloyed bainitic steel 10GN2MFA and austenitic steel 08Ch18N10T to corrosion cracking was made on the test specimens of type C(T) with thickness $B = 12.5$ mm and width $W = 25$ mm with initial fatigue crack. Test specimens were loaded at a constant speed of movement of the piston rod $1.8\cdot10^{-4}$ mm·s^{-1}, while even in this case, the evolution of the force- piston displacement was recorded. After loading to the selected value of the piston displacement, the test specimens were fully broken in liquid nitrogen and the lengths of the initial fatigue cracks and their stable increments were measured with the use of the measuring microscope. For the evaluation of the results, the concept of the fracture mechanics was used and the opening of the crack face δ (mm) was chosen as its parameter.

Fig. 6 shows the effect of the aquatic environment with elevated temperature and pressure on the change in fracture behaviour in comparison with the air. The change, especially in the area of the R-curve, which illustrates an intense ductile growth of the crack, is well noticeable in Fig. 6.

What is significant, however, is that the initiating values for the realisation of the ductile growth are relatively close to each other. For the value of stable increment of 0.2 mm, the value of opening of the crack on air at 290°C is equal to $\delta = 0.17$ mm. In the aquatic environment, the crack opening is then reduced to the value $\delta = 0.15$ mm, which, expressed by the stress intensity factor K, means a drop from the value of 171 MPa·m$^{1/2}$ for air to the value of 158 MPa·m$^{1/2}$ for the aquatic environment.

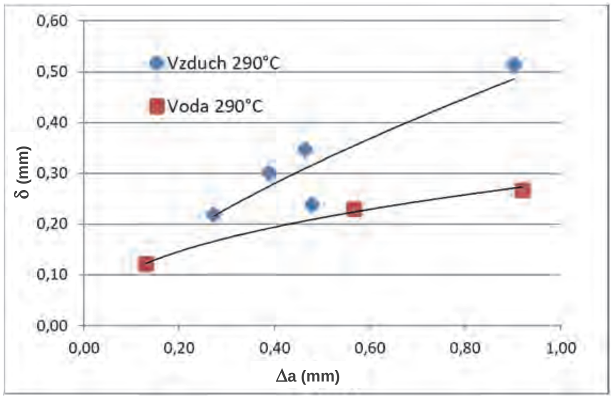

Fig. 6 Effect of water environment and working temperature on fracture behaviour of heterogeneous welded joint

Obr. 6 Vliv vodního prostředí a pracovní teploty na lomové chování heterogenního svarového spoje

The finding, that fractographic analysis of fracture surfaces of the specimens exposed to corrosion in an aquatic environment at elevated temperature and pressure did not confirm an occurrence of intercrystalline fracture, is also of great importance. It can be therefore assumed that the technological and material execution of the evaluated weld joint has a high resistance to corrosion cracking in the environment of boiler water.

Conclusions

This paper deals with the study of conventional and unconventional properties of a heterogeneous weld joint made from low alloyed bainitic steel 10GN2MFA and from austenitic stainless steel 08Ch18N10T intended for pressure vessels of the primary circuit of nuclear power plants of the type MIR 1200. The paper summarizes the results of the basic mechanical properties and compares them with the requirements of the PN AEG directive.

It follows from the obtained values that both the yield strength and the strength limit are significantly higher than the requirements, while the plastic properties (ductility and contraction) also met.

It follows from the performed chemical analyses of individual layers of the heterogeneous weld joint, that the requirements for chemical composition in the individual layers of the weld joint are also met. What concerns the unconventional properties, special attention was paid mainly to the assessment of the low cycle fatigue at the project temperature, to which the nuclear power plant components are dimensioned, as well as to the assessment of the fracture behaviour at

Hutnické listy č. 4/2017, roč. LXX
ISSN 0018-8069

operating temperature and to the assessment of resistance to corrosion cracking in an aquatic environment.

The experiments have shown that the chosen material and the technological process for producing a heterogeneous weld joint can be considered optimal from the point of view of the structure and material properties.

Acknowledgements

This work was created within a solution of the project ´TA04021746 Research, development and verification of production technology of selected welded joints for pressure vessels of the primary circuit of nuclear power plants of the type MIR 1200´ funded by the Technology Agency of the Czech Republic.

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[5] ASTM E 606

[6] ASTM E 1820

Začíná se nedostávat oceli

Die Welt *11.04.2017*

Radost a žalost leží v ocelářském odvětví často blízko sebe. Ještě před několika málo měsíci se výrobci oceli kvůli přílivu oceli z Číny a pádu cen viděli krátce před propastí. Nyní se situace naprosto otočila. Alespoň německé hutě pracují s vytížením přes 90 % na hranici svých možností, navíc EU svými antidumpingovými opatřeními dovozy oceli z Dálného východu omezila, a tím se postarala o zvýšení cen. Zotavení ocelářského průmyslu vhání ovšem do problémů jiné odvětví: zpracovatelské. „Vývoj cen oceli žene do likviditních problémů první subdodavatele“, varuje například průmyslový svaz tváření plechů (IBU). „Situace je dramatická,“ podtrhuje jednatel IBU Benhard Jacobs v rozhovoru s novinami „Die Welt“. Ohrožuje to mimo jiné velké výrobce automobilů. Další problém vzniká u ploché oceli, přesněji řečeno u širokých pásů, válcovaných za tepla, u níž v uplynulých několika měsících stoupla cena o téměř 75 %. Na spotovém trhu stojí dnes za tepla válcované plechy kolem 570 € za tunu a to je o 240 € víc, než před rokem. Ceny zde příkře stoupají od listopadu 2016 na nejvyšší hodnotu za posledních 6 let. Zatížení pro mnohé subdodavatele jde tak do milionů. Kupuje-li dnes podnik například 7000 tun za tepla válcovaných plechů, leží vícenáklady u 1,8 mil. €. Pro středostavovské podniky je to dramaticky mnoho. Cenové skoky zvyšují požadavky na likviditu a přetěžují úvěrové limity. Výsledkem jsou insolvence. Postiženo je zatím kolem 500 firem, které dodávají tvářené díly z oceli především výrobcům automobilů a systémovým dodavatelům, ale také elektrotechnickému průmyslu, strojírenství a výrobcům lékařské techniky, praček, ledniček, zámků a kování.

Schoeller Werk vyrábí přímé roury o délce 36 m

marketsteel.de *18.04.2017*

Chladicí systém je centrální součástí elektrárny. Horká pára, která je nutná pro výrobu proudu, musí být za turbínou ochlazena a následně znovu přivedena do systému. Se stoupajícím výkonem elektráren se zvětšuje také sekundární okruh k chlazení systému a tam používané roury jsou delší. Ty musí současně odolávat zvýšeným požadavkům, protože jsou vystaveny silným zátěžím vysokých teplot a tlaku a každý defekt může vést ke škodám na zdraví, životnímu prostředí a věcným škodám. „Větší efektivita a větší výkonnost při maximální bezpečnosti. Tato devíza platí v energetickém odvětví již dlouho. My s našimi cennými řešeními problémů trub podporujeme naše zákazníky při optimalizaci funkční bezpečnosti jejich elektráren“, říká Markus Zimmermann, šéf týmu u Schoeller Werk. „Podle specifikace zákazníka mají naše roury průměr od 15 do 25,4 mm a sílu stěny od 0,8 do 2,11 mm. Pro jejich výrobu se používá široká paleta austenitických a feritických ocelí. Ty jsou nejen obzvlášť korozivzdorné, ale také odolné proti vysokým teplotám.“