COMPLEX EVALUATION OF STRUCTURE AND MATERIAL PROPERTIES OF SELECTED WELDING JOINTS

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Abstract

The National Action Plan for the Development of Nuclear Energy in the Czech Republic envisages the preparation for the construction of two new blocks of the nuclear power plant in the location of Dukovany and the location of Temelín. Although the final supplier of these units is not clear yet, there are good prospects that some components could be produced by the local producers. The paper presents the principal results of development and verification of production technology of weld joints of pressure vessels components for primary circuits of the nuclear power plants of MIR 1200 type. Attention was focused to the influence of welding technology SAW and SMAW including post weld heat treatment on the final mechanical and fracture properties of welded joints of large forgings. Homogeneous weld joints were made of 10GN2MFA low-alloy steel while heterogeneous weldment was prepared from 10GN2MFA and 08CH18N10T stainless steel. The welded joints were subjected to a comprehensive evaluation of the material properties, especially the evaluation of macro and microstructure, tensile test and impact bending test as well as unconventional mechanical properties such as initial value of the J-integral, the stress intensity factor and low cycle fatigue limit. The effect of welding technology on the transition temperature (T_{k0}) of the weld joint was evaluated, too.

Keywords: Steel 10GN2MFA, corrosion resistant steel 08CH18N10T, nuclear power plants of type MIR 1200, welded joints, mechanical and fracture properties

1. INTRODUCTION

The main aim of the solution was to develop and verify the production technology of welding joints for MIR 1200 nuclear power plant components. These weld joints are of high thickness and their design is technologically demanding with regard to safe operation. The given welding technology must ensure that many requirements for weld joints according to PN AEG-7-009-89 [1] and PN AEG -7-010-89 [2] regulations, such as the mechanical properties of both the weld joint and the weld metal and microstructure requirements, meet the requirements of non-destructive inspection regulations, achieve the required level of low cycle fatigue, exhibit sufficient resistance to stress corrosion cracking, and many more. Given the assumed lifetime of these weld joints of at least 60 years, many of the above requirements, especially in the case of unconventional properties, are not easy to achieve, especially in the case of heavy forgings. [1] An example of such a welded joint of a heavy forging is shown in **Figure 1**.

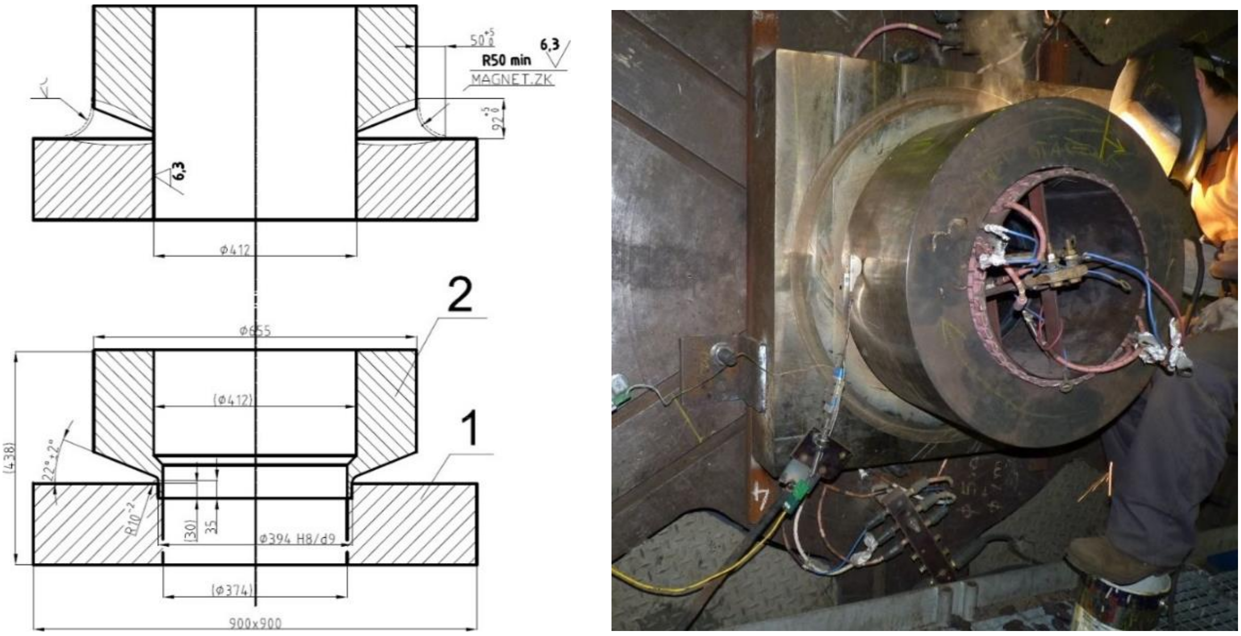


Figure 1 Drawing of real components used in nuclear power plant MIR 1200, corresponds to welds 2 and 3, photographic image from the welding process

2. EXPERIMENTAL PROCEDURES

Weld joints were selected for the experimental program:

- weld 1 represents the circumferential weld joints of the vessel ring, this weld was made of 10GN2MFA steel using SAW technology in a narrow gap **(Figure 2),**
- weld 2 represents the weld of heavy socket joints of 10GN2MFA steel using SAW technology (**Figure 3),**
- weld 3 represents the weld joints of heavy socket SMAW **(Figure 4),**
- weld 4 represents the weld of heavy socket joints of 10GN2MFA steel provided with an austenitic weld deposit on the inner surface again performed by SAW technology **(Figure 5)**,
- weld 5 represents heterogeneous weld joint made of 10GN2MFA and 08Ch18N10T steels with dissimilar weld **(Figure6)**.

The indicative chemical composition of this steel grade is given in **Table 1** and the required mechanical properties at + 20 °C and at elevated temperature, together with the T_{k0} transition temperature prescription, are given in **Table 2**.

Table 1 Guide chemical composition of steel 10GN2MFA, (wt%).

Element	**C**	**Mn**	**Si**	**P**	**S**	**Cu**	**Ni**	**Cr**	**Mo**	**V**	**Ti**	**Al**
Min.	0.08	0.80	0.17	-	-	-	1.80	-	0.40	0.03	--	0.005
Max.	0.12	1.10	0.37	0.008	0.005	0.30	2.30	0.30	0.70	0.07	0.015	0.035

Figures 2 to **5** shows macrostructure of homogenous 10GN2MFA – 10GN2MFA type of welded joints prepared for experimental programme (narrow gap, SAW, SMAW, SAW + austenitic base). **Figure 6** then shows macrostructure of dissimilar weld with two-layer buttering and two-layer cladding made of a corrosion resistant steel. It is possible to observe all areas of the weld joint, i.e. the parent materials 08Ch18N10T, 10GN2MFA, buttering layers and corrosion resistant cladding, fusion lines and individual weld metal beads.

Table 2 Required mechanical properties

Mechanical properties										**Transition Temperature**
+20 °C					+350 °C				-10 °C	
$R_{p0.2}$ (MPa)	**R_m** (MPa)	**A** (%)	**Z** (%)	**KCV** (J·cm^2)	**$R_{p0.2}$** (MPa)	**R_m** (MPa)	**A** (%)	**Z** (%)	**KCV** (J·cm^2)	**T_{K0}**
345-590	540-700	18	60	59	min. 295	min. 490	15	55	39	max. –10 °C

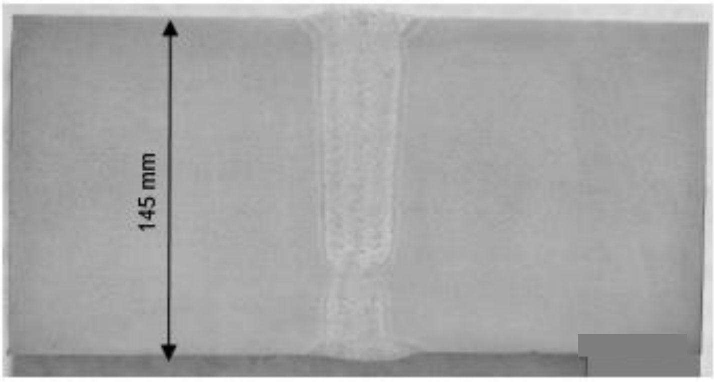


Figure 2 Macrostructure of weld1

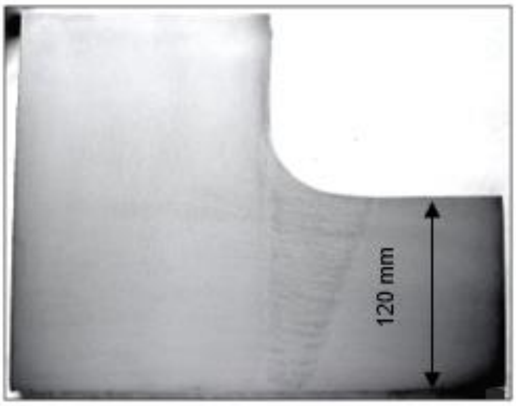


Figure 3 Macrostructure of weld 2

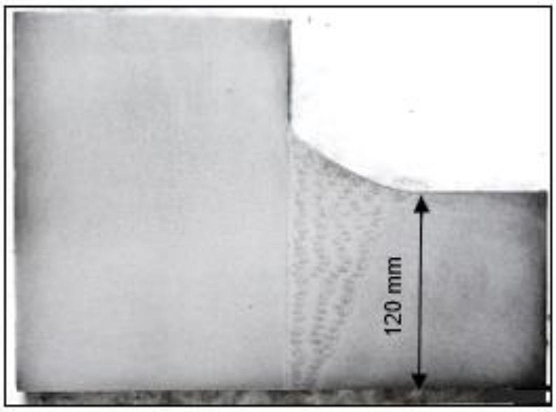


Figure 4 Macrostructure of weld 3

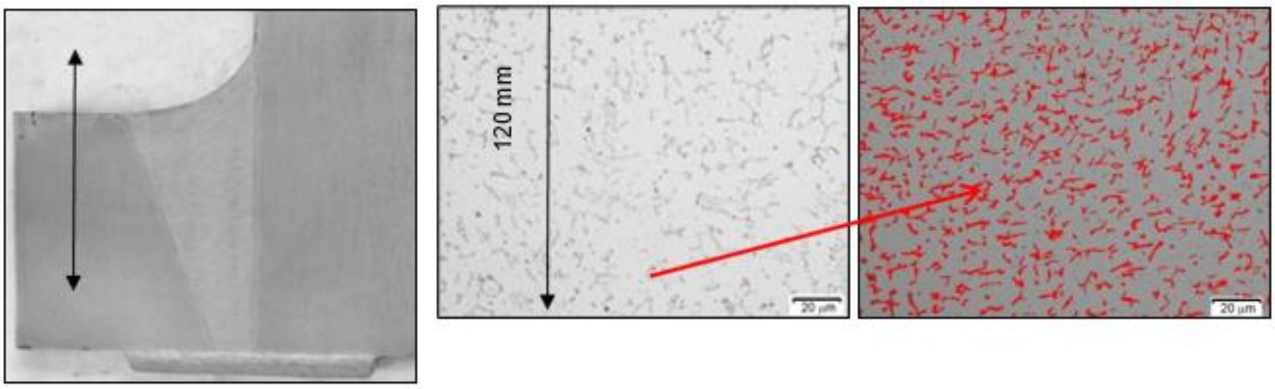


Figure 5 Macros of weld 4 with evaluation of delta ferrite content using image analysis in austenitic weld deposit

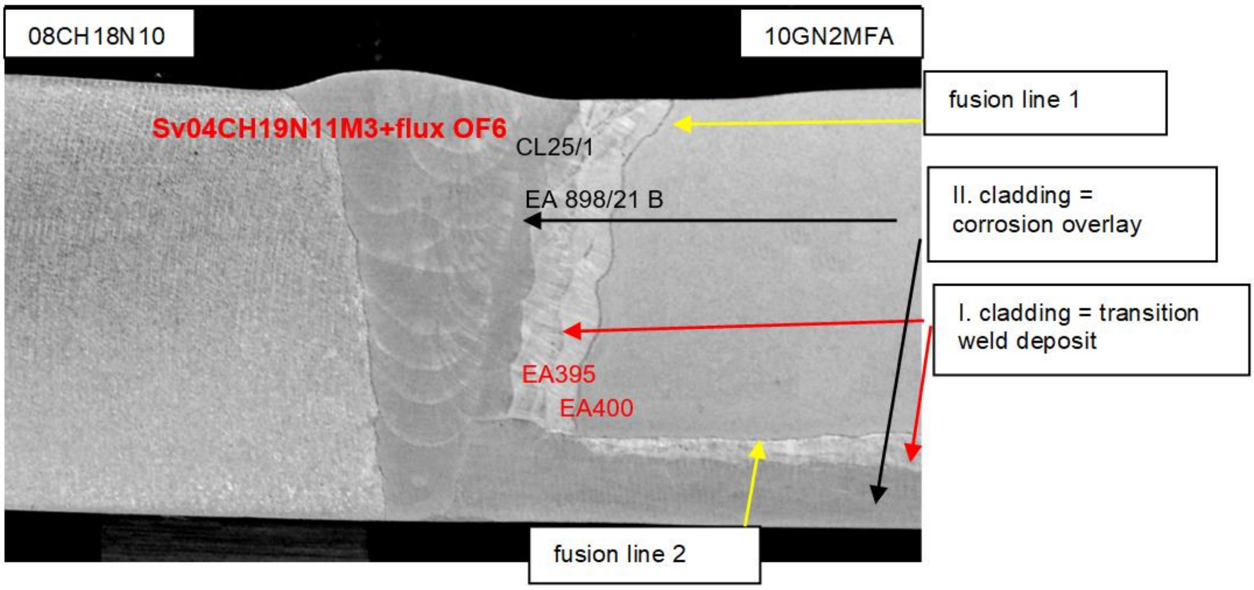


Figure 6 Macrostructure of heterogeneous weld joint made of 10GN2MFA and 08Ch18N10T steels with transition overlay

Specimens were cut out from each area of the weld joint to perform metallographic analysis of the microstructure. **Figure 5** shows the macro and microstructure of weld metal in the weld axis. The basic microstructure is austenitic with contains amount of δ-ferrite.

Table 3 Chemical composition of welded-joint areas, buttering layer and parent material (wt%)

	Experimental				**Standard requirement PNAEG-7-010-89**			
Area of weld	**A_1- weld**	**A_2 - transition weld deposit 2. layer**	**A_3 - transition weld deposit1. layer**	**A_4- parent material**	**A_1- weld**	**A_2 - transition weld deposit 2. layer**	**A_3- transition weld deposit 1. layer**	**A_4- parent material**
	Sv04CH19-N11M3+flux OF6	EA400/10T	EA395/9	10GN2MFA	Sv04CH19-N11M3+flux OF6	EA400/10T	EA395/9	10GN2MFA
Si	0.4 - 0.6	0.3 - 0.7	0.6 - 0.8	0.0 - 0.4	0.3 - 1.2	0.3 - 0.7	1.0	0.17 - 0.30
Cr	18.1 - 22.3	16.1 - 18.4	12.9 - 16.3	-	16.0 - 20.0	16.1 - 18.4	14.0 - 17.0	0.3
Mn	1.4 - 2.0	1.3 - 1.8	1.4 - 2.5	0.8 - 1.0	0.8 - 2.0	1.3 - 1.8	0.8 - 2.0	0.8 - 1.0
Fe	64.4 - 66.5	61.0 - 66.3	54.0 - 65.9	96.2 - 97.5	-	61.0 - 66.3	-	-
Ni	7.3 - 12.4	9.2 - 13.1	12.7 - 19.7	1.6 - 2.3	9.0 - 12.0	9.2 - 13.1	23.0 - 27.0	1.8 - 3
Mo	2.2 - 3.7	3.0 - 5.50	3.1 - 8.9	-	1.5 - 3.0	3.0 - 5.5	5.0 - 7.0	0.4 - 0.7
V	-	0.3 - 0.5	-	-	-	0	-	-

The evaluation of welded joints was performed in accordance with the PN AEG -7-010-89 regulation for mechanical properties - tensile test at room and elevated temperatures and impact test in bending.

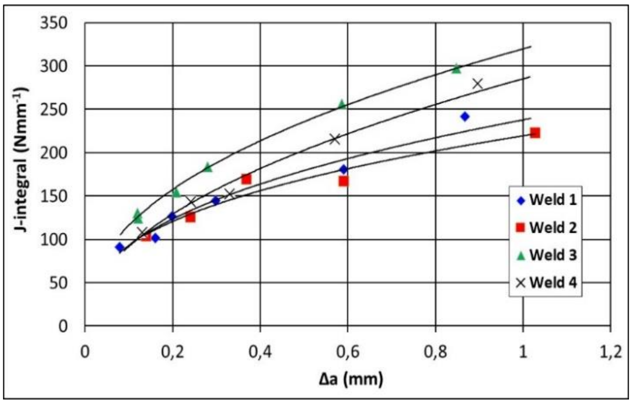
Furthermore, the evaluation of unconventional properties was performed, namely fracture toughness tests and low-cycle fatigue tests, both at room and working temperatures, stress corrosion cracking resistance in water environment at working temperature and metallographic evaluation using light optical microscopy. Non-destructive testing as well as metallographic analysis did not reveal any defects related to the welding process. The mechanical properties, including the transition temperature of all examined welds, met the requirements given in **Table 2.** In fact, the level of mechanical properties of the evaluated welded joints far exceeded the values prescribed by the standard [1]. The evaluation of the fracture behavior of welded joints is stated here as an example of performed material analyses. The evaluation was based on the fracture toughness parameters at a hot collector operating temperature 290 °C. The concept of the so-called R-curves interpreting the dependence of the fracture toughness parameter (J-integral, δ-critical crack opening) on the stable crack increment Δa was used for the evaluation. The obtained results are shown in **Table 3**. The evaluation of the fracture behaviour of weld joints at the working temperature in the form of R-curves is evident from the graph in **Figure 8** and **9.** The graph clearly shows the influence of welding technologies on the fracture behavior. The highest initial value of fracture resistance (corresponds to the value of the J-integral at the place of stable crack growth of 0.2 mm) was measured in weld 3 (welded by SMAW technology) in comparison with other welds produced by SAW method, see **Table 3**. However, it must be stated that the initial values of the J-integral are very high for all monitored welds and indicate a high toughness of the studied materials [3, 4].

Table 3 Initial value of the J-integral or (δ) and the stress intensity factor $K_{J0.2}$ or ($K_{\delta C}$)

Weld	**$J_{0.2}$ (N·mm^{-1})**	**$K_{J0.2}$ (MPa·m$^{1/2}$)**
1	125.5	166.1
2	121.8	163.6
3	160.0	187.5
4	128.0	167.7
5	δ (mm) = 0.18	$K_{\delta C}$ (MPam$^{1/2}$) = 150

Table 4 Mechanical values of welds and corrosion resistant welds

		Measured values		**PNAEG-7-010-89**	
Testing temperature	**Weld area**	**Weld 1**	**Anti-corrosion cladding 1**	**Weld**	**Anti-corrosion clading**
	Filler material	**Sv04Ch19N11M3** **+ flux OF6**	**EA898/21B**	**Sv04Ch19N11M3** **+ flux OF 6**	**EA898/21B**
+20°C	R_m (MPa)	597 - 12	649 - 670	min. 491	min. 539
	$R_{p0.2}$ (MPa)	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	R_m (MPa)	408 - 418	477 - 487	min. 343	min. 441
	$R_{p0.2}$ (MPa)	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



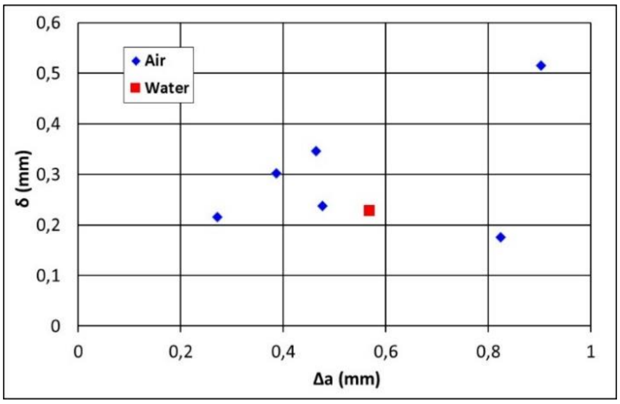


Figure 8 R-curves at working temperature 290 °C welds under investigation

Figure 9 Evaluation of fracture behavior of heterogeneous weld joint at 290 °C

3. CONCLUSIONS

The experimental program performed on five weld joints of heavy forgings intended for modern nuclear power plant components demonstrated that the welded joints completely fulfilled all requirements on mechanical properties, macrostructure, microstructure, fracture toughness and stress corrosion cracking in hot water. All obtained results were in accordance with the respective requirements stated in PNAEG-7-010-89. It can therefore be concluded that the manufacturer is able and ready to produce the weldments in question of the prescribed quality and the required conventional and unconventional properties.

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