WELDING REPAIR OF DEFECTS IN WWER REACTOR PRESSURE VESSELS

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ABSTRACT
Reactors pressure vessels are components that are practically not replaceable and thus they determine lifetime of the whole nuclear power plant (NPP).
Lifetime of reactor pressure vessels are determined by level of material degradation as well as by existence of defects found during in-service inspection and their size and location.

According to some codes, it is necessary to have a procedure for repair of potential defects found during in-service inspection that can be non-acceptable from point of view of assurance of required RPV lifetime.

A wide experimental program was realized to propose, check and approve a procedure for repair of potential defects in underclad region of WWER-440 MWe (PWR type reactors of Russian design) reactor pressure vessels during operation.

Experimental program was realized on as-received materials as well as on materials subjected to simulated ageing to level representing expected material embrittlement after design reactor lifetime.

Main requirements for this procedure were: RPV will not be pre-heated during repair welding, and no post-weld heat treatment will be applied. Maximum repair depth will be 40 mm including austenitic cladding thickness (8 to 10 mm).

Such procedure was developed and checked by series of mechanical testing (hardness, fracture toughness, impact notch toughness as well as by detailed metallography studies).

1. INTRODUCTION
The main objectives of the project were to establish a simplified qualification program for materials not listed in the construction rules applied during manufacturing of components for WWER type reactors and to implement this program for some materials selected as the most suitable to be used for further repair or replacement.

The qualification program is intended to provide generic material data for new material grades. The manufacturer qualification and materials tests required by those rules are fully applicable when the qualified material is produced for a repair or a replacement.

Components of WWER type reactors were designed and manufactured in accordance with old soviet rules issued in 1973 or 1989.

Those rules specify lists of materials and welding consumables that only can be used for manufacturing or repairing the components. Any other material is defined as a new material and must be qualified before its use according to requirements given in Soviet “Rules for Safe Operation of Components and Piping in Nuclear Power Plants”.

Reactor pressure vessel is the only pressure boundary component that operates in the field of a strong reactor radiation, mostly of fast neutron type. Thus, requirements for qualification of such materials must also include tests characterized their resistance against radiation damage in operation conditions.

Proposed material for the defect repair – ALLOY 52 – is a nickel based alloy of austenitic structure, i.e. without any clean transition between brittle and ductile failure, on the contrary, only ductile failure could be supposed for the whole operation temperature region. Thus, dynamic Charpy notch impact tests have only limited importance as a measure of resistance against ductile tearing. On the contrary, such weld repair should be realized without any post-weld heat treatment, thus knowledge of residual stresses is becoming important for any life calculations. It was decided that such repair should be applicable to the total depth up to 40 mm including austenitic cladding – weld material must also serve as a protection against corrosion of the base ferritic material.

As most of reactor pressure vessels are now in operation...
between 10 and 15 years, any potential repair will be realized in aged/embrittled materials; extent of this embrittlement will depend on the age of the vessel and on the location of repair weld. In any case, qualification program should also include tests of heat affected zone in a material artificially aged to values similar as after 20 years of operation that practically represents their remaining life. Irradiation tests were performed only on repair weldments performed on unirradiated non-aged material; irradiation was done at temperature + 270 °C by a fluence equal to approx. 1x10^{24} m^{-2} (E>0.5 MeV).

2. ACCEPTANCE TEST PROGRAM – MATERIALS AND TESTING

Realization of test coupons for Acceptance as well as for Qualification Test Programs was preceded by a very broad research and technological program that included the following principal steps:
- feasibility study of repair welding in RPVs
- choice of a potential suitable welding materials and welding technology
- welding tests with different welding parameters
- microstructural study and hardness measurements for individual tests with different welding parameters
- analysis of these data with the aim to find the optimal welding parameters from point of view of weld integrity, heat affected zone hardness and strength and residual stresses

Following technical documentation have been prepared before the welding:
- Drawings of test coupons and cutting plans
- Qualifications of welders [in accordance to EN 287-1]
- Welding procedures
- Certificates of welding materials and base metal

2.1. WELDING MATERIAL

INCONEL 52 Filler Metal (AWS AS.14 ERNiCrFe-7) is used for gas-metal-arc and gas-tungsten arc welding (GMAW/GTAW) in general. This Ni-Cr welding material has been developed to meet the needs of requirements for nuclear components to avoid problems with stress corrosion cracking in the nuclear, pure water environment by optimizing the chemical composition of welding metal, first of all. With respect to the INCONEL 52 properties this welding material is intended to replace the original Soviet welding materials.

2.2. TEST COUPONS

Experimental materials have been prepared with respect to the qualification program on the same material (BM) and welding wire (0.9 mm dia) basis used for the INCONEL 52 qualification.

As the base material, the 15Kh2MFA (2 1/4Cr-1 Mo-V type) steel in embrittled state was used with the original anticorrosive submerged strip cladding of WWER 440 RPV that represents a part of a WWER 440 RPV smooth ring. The grooves were machined from both surfaces of the test piece to a shape and dimensions in accordance with Fig.1 (depth 30 mm, width 30 mm at the bottom and 70 mm at the surface). Total number of beads was approximately one thousand for each groove. These grooves were filled-in without preheat and post-weld heat treatment by BOKI BSV 1500 automatic welding equipment using GTAW Fronius 2000 Magic Wave welding current source under real welding conditions.

Acceptance test programme includes the following tests:
- Chemical analysis of weld metal
- Tensile test from weld metal (L-orientation) 2 specimens at RT, 2 specimens at 350 °C
- V-notch Charpy from weld metal (T-orientation) – 3 specimens at RT
- Macrostructure of weld section
- Microstructure of weld metal and heat affected zone including “triple” point (repair weld, heat affected zone, austenitic cladding) in aged base metal
- Hardness measurement through the weld
- Non-destructive tests

3. QUALIFICATION TESTS

The Qualification program of welding materials must be performed in accordance with existing rules, i.e. with Czech code ASI (Association of Mechanical Engineers), Section I - WELDING OF EQUIPMENTS AND PIPING IN NPP OF WWER TYPE and with the Slovak documents BNS II.5.1, II.5.2, II.5.3/1999. These documents are based on original Russian similar materials – PN AE G 7-008, -009, and –010. For ERNiCrFe-7 nickel base material a simplified Qualification Test Program was proposed and preliminary accepted by Czech Institute of Technical Inspection.

The 15Kh2MFA steel base material is used in an embrittled state. The welding material to qualify INCONEL 52 type (AWS AS.14 ERNiCrFe-7) is deposited by automatic TIG (GTAW) welding without preheating and without post-weld heat treatment according to the same Welding Procedure Specification.

Qualification program contains, in complement to the Acceptance program the following tests:

**ERNiCrFe-7 Nickel base weld metal**
- Tensile tests from weld metal (L-orientation) 3 specimens at RT, +100, +200, +270, +350 °C in initial condition 3 specimens at RT, +100, +200, +270 °C in irradiated condition
- Static fracture toughness tests from weld metal (T-orientation) temperature dependence between RT and + 350 °C:
  - 15 specimens for un-irradiated and 15 specimens for irradiated conditions
- Low-cycle fatigue from weld metal (T-orientation)
  - 15 specimens at RT and 15 specimens at +350 °C
- Crack growth rate from weld metal (T-orientation) at PWR operation conditions 6 specimens 0.5CT
- Slow strain rate test from weld metal (L-orientation) at PWR operation conditions 6 specimens – tensile type

**15Kh2MFA Heat Affected Zone**
- Static fracture toughness tests from heat-affected zone in base metal
15 specimens for un-irradiated condition from aged material +
15 specimens for un-irradiated condition from non-aged material +
15 specimens for irradiated condition from non-aged material
• Charpy V-notch impact tests from heat affected zone in aged base metal
15 specimens for un-irradiated condition from aged material +
15 specimens for un-irradiated condition from non-aged material +
15 specimens for irradiated condition from non-aged material

The results from the Qualification program have informative character to be used in RPV integrity and lifetime evaluation for potential welding repair of the RPVs.

4. RESULTS

4.1 Nickel Base Alloy (Inconel) Qualification

4.1.1 Acceptance tests results

Results from chemical analysis as well as from mechanical tests are shown in tables 1 and 2. The macrostructure examination confirm the defects free weld and thus the acceptable results including the anticorrosive SS cladding & INCONEL 52 weld metal interface area which could be more sensitive to "hot cracks" creation. The microstructure of this typical area shows a good structural homogeneity as confirmed on figure 2.

Three areas of HV 0.1 hardness were tested
• in the "triple point" area along solid line direction,
• in 0.5 mm melting line direction and
• in the weld metal perpendicular to the melting line direction in several distances from this line up to 10 mm.

The lowest hardness value (209 HV) was found in the vicinity of the melting line crossings in heat affected zone both under anticorrosive cladding and repair weld.

On the contrary, the highest hardness value (254 HV) was usually measured in the narrow band approx. in 0.5 mm distance from the melting line of TIG (GTAW) repair weld as a result of this steel type/ chemical composition and the cooling rate after welding.

The radiographic examination of the welds was performed within the framework of welding staff qualification. The results of tests were acceptable in agreement with the original Russian standard PNAE G-7-010-89; no particular indication was detected.

4.1.2 Qualification tests results

• Static tensile testing of Nickel base weld metal was performed in un-irradiated and irradiated conditions in the temperature range between 20 and 350 °C.

Results of testing are shown in Figure 3.

The applied neutron fluence has a small effect on both tensile and ductile properties of weld metal that was expected in relation to the weld metal structure and chemical composition. Decrease of tensile values as a result of temperature increase from room temperature to 350 °C is also limited.

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• Static fracture toughness tests were performed on ERMiCrFe-7 weld metal in un-irradiated and irradiated conditions.

Testing was performed in accordance with standard ASTM E813-87, but for evaluation also the following standards were used: ASTM E399-90, ESIS P2/91D, IAE 443.56-86 and ÈSN 420347, if appropriate.

Tests of ERMiCrFe-7 weld metal in un-irradiated as well as irradiated conditions gave no valid results, i.e. its fracture toughness was much higher than validity limits for these type and size of specimens.

• Low-cycle fatigue tests were carried out at design temperature + 350 °C with a asymmetry coefficient r = -1, frequency f = 0.1 Hz with control strain in specimens.

The results and data obtained with ERMiCrFe-7 weld metal will be used for potential evaluation of repair weld effect on RPV lifetime.

• The corrosion fatigue tests – crack growth rate - were performed in simulated PWR environment without oxygen at temperature 300°C using IT CT specimens and active loading.

After the test the specimen was opened by cycling in air and crack length measurement was performed by using light microscope (LM). The crack length measured by reverse direct current potential drop (RDCPD) was corrected in accordance to the LM measurement and crack growth rates da/dn and da/dt was calculated.

Fractography analyze documents the fracture surfaces and determines the fracture mechanism.

The results of environmentally assisted crack growth increments per fatigue cycle are plotted versus the applied total stress intensity factor ∆K and are compared to the corresponding ASME XII, Case N643 reference fatigue crack growth curves in figure 4.

There was found no stress corrosion cracking (SCC) for ERMiCrFe-7 (Inconel) weld metal in primary circuit VVER water environment at temperature 300°C.

No significant areas of transgranular or intergranular fracture have been found.

The tested weld metals shows usual resistance to fatigue crack propagation. The crack growth rate measured in WWER water environment are a little bit higher comparing to CGRs in air and are in a good agreement with the range given in ASME Code Case N643 for PWR water. The fracture mechanism is mostly transgranular ductile fatigue fracture.

Susceptibility to SCC was examined by slow strain rate tests (SSRT) with different strain rates in primary circuit water environment without oxygen at temperature 300°C. The tests were curried out at the autoclave loops Golem I and II. The smooth cylinder tensile specimens with diameter 6 mm, working length 30 mm and orientation L were used.

The tensile test results of ERMiCrFe-7 weld metal are
shown in figure 3 as a graph of stress versus strain for different strain rates. The tested Inconel 52 type material shows no susceptibility to SCC in primary circuit environment at elevated temperature (300°C).

- Tests of 15Kh2MFA Heat Affected Zone were performed in three conditions:
  - final heat treatment of RPV in base metal
  - simulated heat treatment (artificial ageing) of base metal
  - irradiated heat affected zone made on base metal with final heat treatment

Static fracture toughness data were evaluated using "Master Curve" approach in accordance with ASTM E1921-02. Calculated Reference Temperatures $T_0$ are shown in the following table 4.

Shift in transition temperatures can be predicted using the soviet Standard and the formula

$$\Delta T_k = A_F \cdot \left( F \cdot 10^{-22} \right)^{1/3}$$

where $A_F$ is neutron embrittlement coefficient, for the steel 15Kh2MFA:

$$A_F = 18 \degree C$$

and $F$ is a neutron fluence with energies larger than 0.5 MeV. Thus, shift in transition temperature $T_k$ is smaller than predicted for impact notch toughness tests.

Impact notch tests with specimens of Charpy V-notch type were performed for all three conditions similarly as with heat affected zone. Results are summarised in Table 5. In this table, the following abbreviations are used:

- TT_KCV50 - $KCV = 50 \text{ J cm}^{-2}$
- TT_41J - $K = 41 \text{ J}$
- TT_KCV60 - $KCV = 60 \text{ J cm}^{-2}$
- TT_68J - $K = 68 \text{ J}$
- TT_LE - $L = 0.89 \text{ mm}$
- TT_SF - $S = 50 \%$
- $T_{k0}$ - critical temperature of brittleness in accordance with Soviet Standard.

as these criteria are commonly used either for WWER or PWR type RPVs.

Initial transition temperature, close to $T_{k0}$, is $TT_{KCV60}$: Technical specification for 15Kh2MFA material required that $T_{k0}$ of base metal should be lower than 0 $\degree C$. Thus, this heat affected zone is fairly well below this requirements in all tested conditions. Moreover, there is practically no shift due to irradiation or simulated ageing which shows to the fact that repair welding practically do no create any dangerous zones within the welding joint.

5. CONCLUSIONS

Acceptance tests results fulfilled required criteria values and conditions for all type of tests.

Qualification programme was performed in whole required volume – all required type of tests were realised.

Impact notch tests in heat affected zone showed a very high toughness fully comparable with properties of base metal of 15Kh2MFA type of steel. Properties of this zone are practically not changed either if performed on simulated aged condition or in irradiated condition.

Static fracture toughness tests also showed very high resistance against fast failure. Effect of irradiation on transition temperature of heat affected zone is smaller than predicted by soviet standard for base metal, i.e. it is more resistant against radiation embrittlement.

Low-cycle fatigue results were collected for potential evaluation of repair weld effect on RPV integrity and lifetime.

Weld metal show usual resistance to fatigue crack propagation, this material has also sufficient resistance against corrosion crack initiation.

All test results from Acceptance as well as Qualification Test Programmes showed that this type of repair weld using INCONEL 52 filler material showed required and/or sufficiently high properties comparable with original RPV materials.

Thus, this type of repair weld with INCONEL 52 filler material can be used for WWER-440 RPV repairs of defects during operation.

REFERENCES

Standards for Strength Calculations of Components and Piping in NPPs, PNAE G-7-002-86, Energoatomizdat, Moscow, 1989

Equipment and piping in nuclear power plants. Weld joints and cladding. Rules for examination, PNAE G-7-010-89, Energoatomizdat, Moscow, 1989
Figure 3: Temperature dependence of tensile properties of ERNiCrFe-7 weld metal in unirradiated and irradiated conditions where Rp0.2 is yield strength and Rm is ultimate tensile strength.

Table 1: Results of chemical analysis

<table>
<thead>
<tr>
<th>Melting Line Distance [μm]</th>
<th>HV 0.1 Hardness</th>
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<tbody>
<tr>
<td>0</td>
<td>254</td>
</tr>
<tr>
<td>600</td>
<td>223</td>
</tr>
<tr>
<td>10 000</td>
<td>223</td>
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</tbody>
</table>

Table 3: Microhardness of weld metal

<table>
<thead>
<tr>
<th>Melting Line Distance [μm]</th>
<th>HV 0.1 Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>254</td>
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<tr>
<td>600</td>
<td>223</td>
</tr>
<tr>
<td>10 000</td>
<td>223</td>
</tr>
</tbody>
</table>

Table 4: Comparison of reference temperatures \( T_0 \) for different conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>( T_0 ) °C</th>
<th>( \Delta T_0 ) °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unirradiated</td>
<td>-132.4</td>
<td>-</td>
</tr>
<tr>
<td>Simulated ageing</td>
<td>-116.3</td>
<td>+16.1</td>
</tr>
<tr>
<td>Irradiated</td>
<td>-71.0</td>
<td>+61.3</td>
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<tr>
<td>Prediction</td>
<td>-</td>
<td>+76.1</td>
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</table>

Table 5: Transition temperatures and their shifts for heat affected zone in different conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>( T_{T_K} ) °C</th>
<th>( T_{T_{AV}} ) °C</th>
<th>( T_{T_{LE}} ) °C</th>
<th>( T_{T_{SF}} ) °C</th>
<th>SHIFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unirradiated</td>
<td>-112.6</td>
<td>-111.9</td>
<td>-106.0</td>
<td>-91.5</td>
<td>-5.4</td>
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<tr>
<td>Simulated ageing</td>
<td>-108.4</td>
<td>-108.3</td>
<td>-107.7</td>
<td>-106.3</td>
<td>-5.8</td>
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<tr>
<td>Irradiated</td>
<td>-118.0</td>
<td>-117.7</td>
<td>-114.8</td>
<td>-108.1</td>
<td>-8.8</td>
</tr>
<tr>
<td>SHIFT</td>
<td>-5.4</td>
<td>-5.8</td>
<td>-8.8</td>
<td>-16.6</td>
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<td></td>
<td>-</td>
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<td>-15.3</td>
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Table 2: Results of mechanical properties

<table>
<thead>
<tr>
<th>Deposited weld metal</th>
<th>Room temperature (20°C)</th>
<th>Elevated temperature (305°C)</th>
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<tbody>
<tr>
<td></td>
<td>( R_y )</td>
<td>( R_m )</td>
</tr>
<tr>
<td>INCONEL 52 on product</td>
<td>416</td>
<td>671</td>
</tr>
<tr>
<td></td>
<td>403</td>
<td>650</td>
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<tr>
<td></td>
<td>186</td>
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</table>

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Figure 4: Effect of loading conditions on cycle based CGR and comparison with current ASME XI Code Case N° 643 for ERNiCrFe-7 weld metal.