

METHOD OF ASSESSMENT OF METAL STATE OF WWER-1000 REACTOR WELDED BODY

The reactor body is a welded structure. The safe service of the reactor unit depends on many factors and is defined mainly by the reliability of the reactor body (RB), which has to preserve the integrity at a normal service, violation of service conditions and at design accidents.

The effect of service factors (neutron irradiation, increased temperature, cyclic loading) on metal of RB (base metal and weld metal) leads to change in metal properties, first of all, to reduction in the brittle fracture resistance. Therefore, the data about the developing of the radiation embrittlement process of RB metal are important from the point of view of safe service of the NPP.

The control of RB metal state is realized by testing the witness specimens (WS), mounted into the reactor, using the nondestructive and destructive methods. The results of the WS testing are representative for the assessment of RB metal properties only in that case, if the conditions of irradiation of specimens in the reactor and RB itself are known with a necessary accuracy, which requires making a thorough dosimetry of the neutron irradiation.

Test results of WS are the main source of information about RB metal state. Using the witness specimens the change in mechanical properties and characteristics of brittle fracture resistance is controlled. This information is required for justification of safe service life of the nuclear power unit.

Basic materials

In the nuclear power engineering of Ukraine 13 reactor units of WWER-1000 type are in service. Rated heat power of the reactor is 3000 MW, pressure of working medium (borated water) at the output of active zone is 160 kgf/cm², temperature is 320 °C, consumption of a coolant is 84000 m³/h. The bodies of reactors WWER-1000 are manufactured of low-carbon low-alloy steel of ferrite-pearlite class of chrome-nickel-molybdenum-vanadium composition. The nickel-free steel 15Kh2MFA, used earlier for bodies of the WWER-440 reactors, was not suitable for manufacture of RB of WWER-1000 by strength and technological properties. In particular, it was necessary to decrease the temperature of preliminary and concurrent heating in welding, as well as to eliminate subsequent tempering after completion of welding works with account for possibility of some lowering the tempering temperature. In this connection the bodies of reactors WWER-1000 are manufactured of 15Kh2NMFA grade steel. To manufacture the upper and bottom shells, located opposite the active zone, steel 15Kh2NMFA-A of the same composition is used, but with more strict requirements as to content of harmful impurities (phosphorus, copper and sulphur).

The reactor body consists of 7 shells, welded together by the circumferential welds. For each element of RB, an ingot of a definite weight is produced by casting, from which a proper forging is manufactured. Weight of forgings for RB of WWER-1000 is from 70 up to 115 tons. The thick-walled shells are manufactured from ingots in the hydraulic presses. An ellipsoid segment for a bottom is manufactured by a stamping method. Forgings for RB are subjected to hardening and tempering. After full heat treatment of initial billets a sample is cut out from each of them for mechanical and technological tests. Then billets are subjected to the preliminary mechanical treatment and edge preparation for welding of circumferential welds.

Welding consumables

In manufacture of RB of WWER-1000 different welding consumables are used for welding of circumferential welds: wire Sv-08KhGNMTA with flux 48NF-18M or wire Sv-10KhGNMAA and Sv-12Kh2N2MAA with flux FTs-16A. As the use of these consumables was permitted by the valid standard documentation, then the plant-manufacturers (Izhora and Atomash) performed welding of circumferential joints on the same type of RB by using different technological variants. Later, to reduce the radiation embrittlement factor, the solution was taken to refuse the applying of welding consumables with nickel content of more than 1.5 % for welds, located opposite the active zone. However, this was not already important for the power units of the NPP of Ukraine, as the bodies of reactors were manufactured earlier.

After the completion of welding of each circumferential weld the heat treatment by a high tempering mode is performed. The anti-corrosion surfacing is made inside by the automatic welding with a strip electrode of Sv-07Kh25N13 grade (first layer) and Sv-08Kh19N10G2B (second and third layers) under the flux layer at rotation of RB in a special tilter. This operation requires also the post heat treatment (additional tempering), therefore, the tempering after welding is performed together with a tempering after surfacing.

Manufacture of witness specimens

WS of base metal (BM) of RB are manufactured at the plant-manufacturer of the reactor bodies from tolerances of one of the shells, located opposite the active zone, for which the content of harmful impurities by a sum (10P+Cu) is highest, and in case of an equality of this value it is manufactured from a shell for which the content of arsenic, antimony and tin (As + Sb + Sn) is highest.

WS of weld metal (WM) and heat-affected zone (HAZ) are manufactured of an industrial reference welded joint, made at the same groove preparation, the same modes and methods of welding, using the welding consumables of the same batch as the welded joints of RB shells, located in the active zone region, passed the complex of heat treatments, as the RB itself.

In accordance with the requirements of PNAE G-7-002 and PNAE G-7-008 the control of change in properties of BM, WM and HAZ is envisaged in specimens of Charpy, Charpy with a crack and tensile specimens, namely:

- proportional ten-fold cylindrical specimens of 3 mm diameter test part for the tensile tests (T);
- test specimens for impact bending of type II by GOST 9454 for BM and type IX by GOST 6996 for WM and HAZ (Charpy specimens) (Ch);
- specimens of COD type for determination of crack resistance (Charpy with a crack) (C).

The witness specimens are placed into airtight containers, manufactured from stainless steel 08Kh18N10T. Heat removal from WS, heated by a neutron flux and gamma-irradiation, is provided by means of fillers and gaskets of aluminium of aluminium alloys. At the present time, two types of containers are used. The regular container is a cylindrical container with thick walls, withstanding the operating medium pressure without deformations. These containers are supplied by a plant-manufacturer in a set with RB. The main drawback of regular container assemblies (CA) with cylindrical containers is the high scattering of value of neutrons fluence on the WS test parts due to a high gradient of the neutron flux around the perimeter and height of regular CA. In the updated programs it is rational to use plane containers, which allow decreasing greatly the gradient of neutron flux to WS test parts, irradiated in the same container, at optimum orientation of CA.

At all the power units of WWER-1000 of the NPP of Ukraine the container assemblies with irradiated WS are mounted into a space between the upper edge of a compartment and the lower edge of a block of protective pipes into special pipes, welded-on to the upper edge of the compartment. Containers with WS are arranged into container assemblies which are mounted at the upper and lower tiers.

Results of the WS testing are representative for evaluation of RB metal properties only in that case, if the conditions of specimens irradiation in reactor and RB itself are known at a required precision. To determine the conditions of WS irradiation (fluence of rapid neutrons of energy $E \geq 0.5$ MeV and irradiation temperature) in the container with WS, the neutron-activation indicators (NAI) and irradiation temperature indicators (ITI) are mounted. NAI represent foils (thin discs) or wires of metals (chemically pure iron, niobium, copper), which are placed into the aluminium alloy capsule. As ITI, the indicators on the base of a diamond powder and fusion-type monitors of temperature, based on fusible eutectics with a melting temperature, close to a temperature of the coolant, are used. The indicators are placed in holes, made in WS or in the fillers.

Arrangement of containers with WS in CA provides the irradiation of containers of the upper tier by the neutron flux, approximately equal to the neutron flux to the inner surface of RB, and that of the lower tier is irradiated by the neutron flux of approximately 2.5 times higher, which allows determining the metal properties at the present moment and predicted period until the fuel unloading.

The terms of withdrawal of sets of witness specimens are determined from the results of investigations of specimens of the previous sets of WS, analysis of accumulated fluence of rapid neutrons at the inner surface of RB

since the service beginning and value of a critical temperature of brittleness for the predicted period. Evaluation of results of WS investigations are carried out by the comparison of predicted properties of RB materials, obtained during the WS testing, with limited admissible values, established in RB design documentation. From the results of this comparison the conclusion is made about the feasibility of safe service of RB before the unloading and testing the next set of WS or about the need in carrying out the compensating measures in case, if it is expected that during the period of time, for which the prediction is made, the controllable values of base and weld metals will come out beyond the safe limits.

In case of emergency stop of the reactor operation and its filling with a cold water (at thermal shock), the high stresses are occurred in RB. The state of RB metal is evaluated mainly by a critical temperature of brittleness T_{cr} , at which the body integrity is provided. In some cases, to avoid the brittle fracture the constant preheating of a water container up to temperature above the critical one is used.

If it is revealed during the process of reactor service that RB is subjecting to embrittlement more intensively than the metal of other similar bodies, then it is possible either to decrease the neutron flux in a preset point of RB due to, for example, change in procedure of fuel loading, or to perform a special heat treatment of the body («annealing»). In this case a powerful programmable heat source (based usually on electric heaters and filament lamps) is used. The body is heated slowly approximately up to 500 °C, held at this temperature not less than 20–40 h and then cooled slowly. Time of heating and cooling is not less than 4–20 h, maximum heating temperature is determined by the strength of concrete and structures of the reactor support elements. The cooling rate is usually lower than that in heating for decreasing stresses in the anti-corrosion inner surfacing of the body.

During metal irradiation with a neutron flux the defects are formed in a crystalline lattice. The value of defects depends on energy of the moving neutron. During decay of uranium nuclei the neutrons emission is occurred with a wide energy spectrum. At metal annealing the defects of the crystalline lattice are annihilated («dissolved») due to energy of heating, and the energy spectrum of lattice atoms is comparatively narrow and determined by the metal heating temperature. It is evident, that the probability of annihilation is higher in small defects, formed by neutrons with a low energy. Consequently, during heating the low-energy defects are most intensively dissolved in the lattice, and the defects from neutrons with a high energy are preserved. Thus, the annealing purifies the lattice mainly from low-energy defects. Moreover, the total density of defects is decreased and the values of metal ductility are increased.

Effect of brittleness decrease as a result of annealing can occur to be comparatively short. At the above-mentioned parameters of annealing the brittle fracture resistance is not recovered completely up to the initial state of the non-irradiated metal. From the system point of view, during the process of reactor operation the annealing is a comparatively short-time disturbance and the system is gradually returned into a normal state.

It should be noted that the metal heating during annealing contributes also to decrease in concentration of atoms of harmful impurities, in particular, phosphorus at the grain boundaries and increases the metal resistance to the brittle fracture.

The definite difficulties in control of the reactor body properties may be connected with insufficient number of WS, in particular, for doubling the measurements in evaluation of current and accumulated fluence of rapid neutrons. In this case, it is possible to apply the method of specimens reconstruction. It consists in the following. To the fragments (halves) of irradiated specimens after tests for impact and three-point static bending the tail pieces are welded-on, they are cut by a required size and a proper notch is made in the middle of the obtained specimen. As a result we have a specimen with a notch in the test part of the irradiated material. The main requirement to welding is a minimum power of welding to avoid the specimen overheating and violation of its properties. The electron beam welding is usually used.

In general, the accepted system of control of metal properties of the reactor body and its welds allows evaluating and predicting their properties at an acceptable accuracy and reliability. The certain drawback is the WS arrangement in the reactor. It would be more logic to place them on the body inner wall, however, it is connected with the change in design and sizes of the reactor body.

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