18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-C03-2

DEVELOPMENT OF WELDED JOINTS FOR STEEL AND ZIRCONIUM TUBES AT NUCLEAR POWER PLANTS

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ABSTRACT

The design of transition joints and the technique of joining dissimilar materials by solid-phase vacuum diffusion welding are discussed, using as an example joints between tubes made of stainless steel 06X18H10T and tubes of zirconium alloy with 2.5 % (mass) of niobium (transition joints of RBMK pressure tubes). The results of tests demonstrating the performance of diffusion-welded joints and of studies on the transition joints are presented, and the results of calculating the stressed-strained states of a transition joint are described, covering the range from the fabrication stage (residual stresses) through operation (residual and operational stresses). Detailed structural analysis has been performed for the zirconium-steel bonding layer. The long operation history of transition joints in RBMK reactors is summarized.

Keywords: channel tube, zirconium, steel, welding technique, test, operation.

INTRODUCTION

The zirconium tubes present in the reactor core of nuclear power plants have to be joined to steel tubes. Steel and zirconium belong to the category of materials that present great difficulties for joining them with the use of traditional fusion welding techniques, which is explained by the serious difference in their thermal, physical and chemical properties.

Review of techniques for joining zirconium to steel, such as rolling, co-extrusion, soldering, explosive welding, and diffusion welding, has shown that the most acceptable one among them is solid-phase joining of steel tubes and zirconium tubes in vacuum under the action of high temperature and welding pressure.

Drawing on its experience, NIKIET has addressed the problem of RBMK fuel channels by developing the design and the process of producing transition joints between zirconium alloy with 2.5 % Nb and stainless steel 06X18H10T (of type 18-8).

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Transition joint design and fabrication

The RBMK fuel channel is a core component operating at high temperature (~300 ^oC), pressure (~8 MPa) and irradiation (max $2{\cdot}10^{17}$ n/m^2 · s, E ≥ 1 MeV).

A fuel channel is a 17-metre component which has in its centre an 8-metre tube made of zirconium alloy with 2.5 % (mass) of niobium and measuring ∅ 88 × 4 mm, with steel tubes welded to it via transition joints at both ends (Fig. 1).

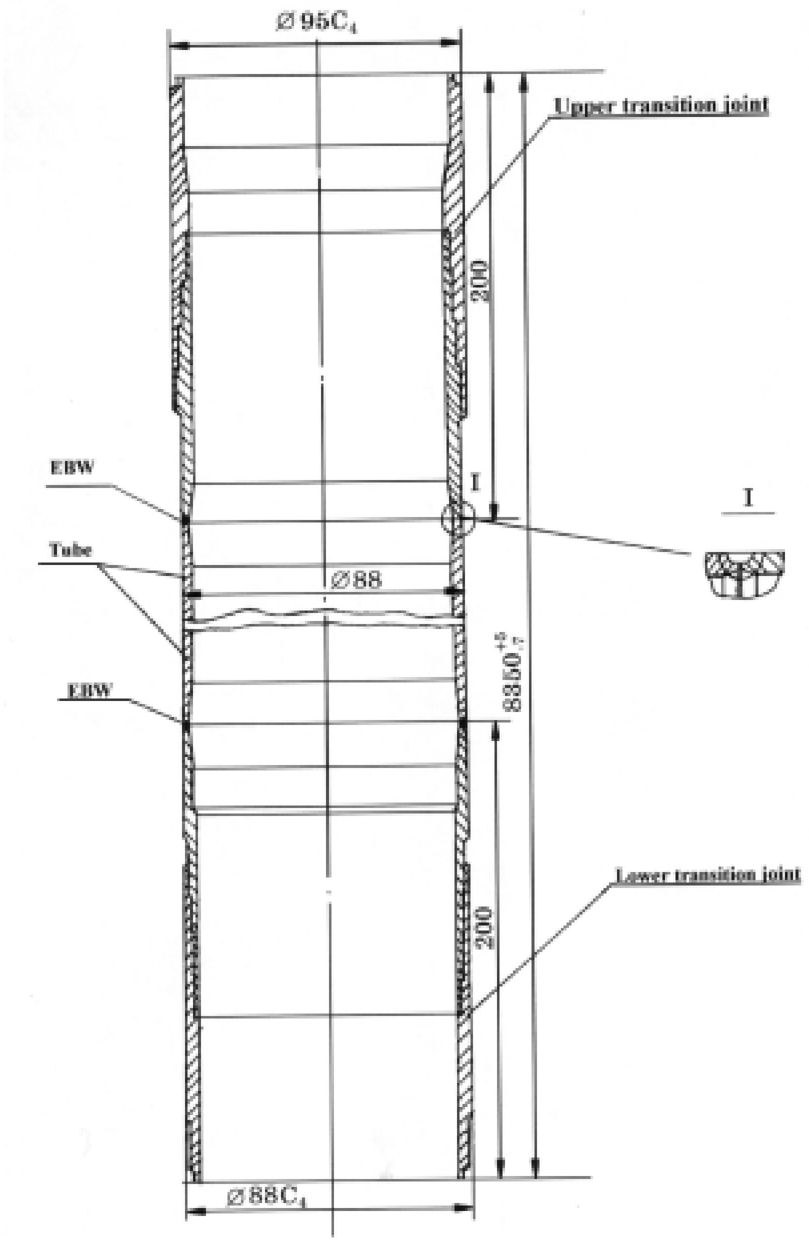

Fig. 1. Central part of the RBMK channel tube

The transition joint is produced separately, with its zirconium part joined subsequently to the zirconium tube by electronic beam welding and its steel part connected to the steel tube by argon-arc welding.

Figure 2 presents schematically the design of a Zr-2.5% Nb – 06X18H10T steel transition joint for RBMK fuel channels.

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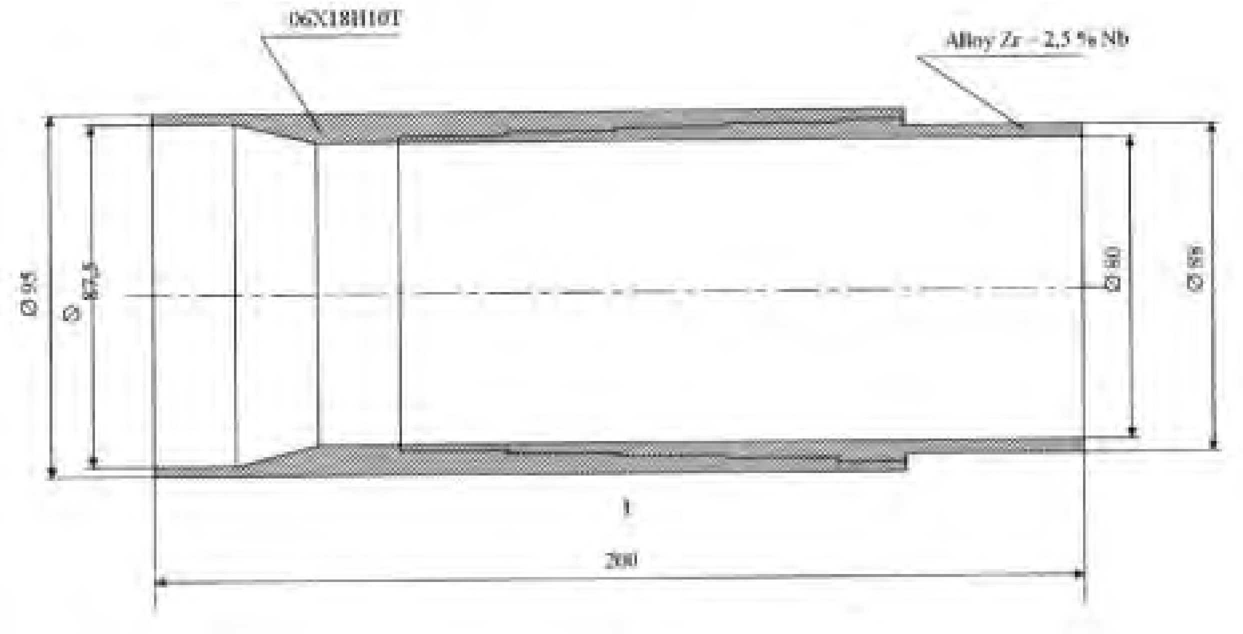

Fig. 2. Steel-zirconium transition joint

The inner part is made of Zr-2.5 % Nb alloy and the outer part is fabricated from steel 06X18H10T.

The surface of welded parts has a threaded profile to increase the contact area and to provide mechanical engagement between steel and zirconium.

Besides, with the diameters of joined parts varying stepwise, stresses are smoothly distributed along the joint.

Figure 3 shows the way zirconium-steel transition joints are produced by diffusion welding.

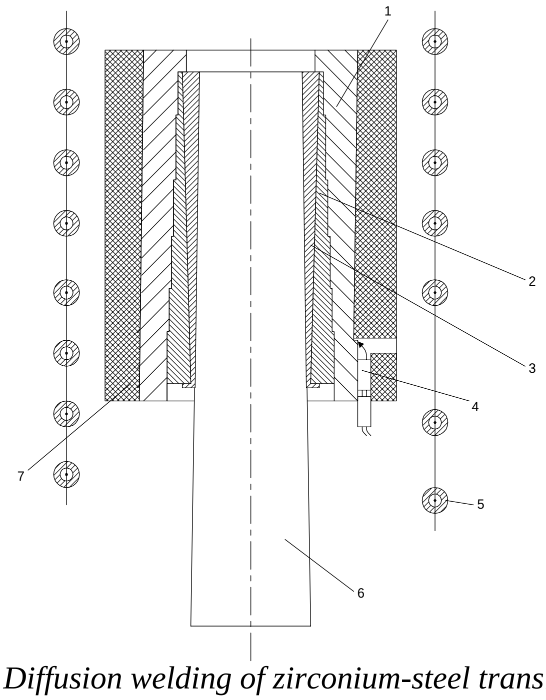

Fig.3. Diffusion welding of zirconium-steel transition joints

1 – SS part of joint; 2 – Zr - 2,5 % part of joint; 3 – intermediate sleeve; 4 – thermocouple; 5 – high frequency induction coil; 6 – press-in mandrel; 7 – binding band

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The transition joint welding process involves heating an assembly of steel and zirconium parts to the temperature (~ 900 ^{o}C) of vigorous interaction between the joined metals and ensuring a tight contact in the connection zone. Welding pressure is set up by a special mandrel pressed into the assembly to a specified depth. The welding parameters, such as temperature, pressure and time, were tried out and developed in experiments.

The transition joint design and its fabrication process allow using a joining technique which combines mechanical engagement and metallurgical bonding of joined materials. All thermal and working stresses in such a joint are almost completely taken up by mechanical engagement, while welding (metallurgical bonding) fulfils the function of sealing.

The stepped connection of welded parts makes it possible, by varying the length, height and number of the steps, to obtain a welded joint of any length and to change the stiffness of the connected tubes as smoothly as may be required.

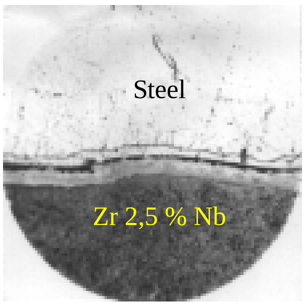
The stepped design allows reliable checking of the welding quality by cutting a test ring from a welded piece.

Mass production of transition joints and fuel channels is arranged at the Chepets Mechanical Factory in the town of Glazov, Udmurtia, Russia.

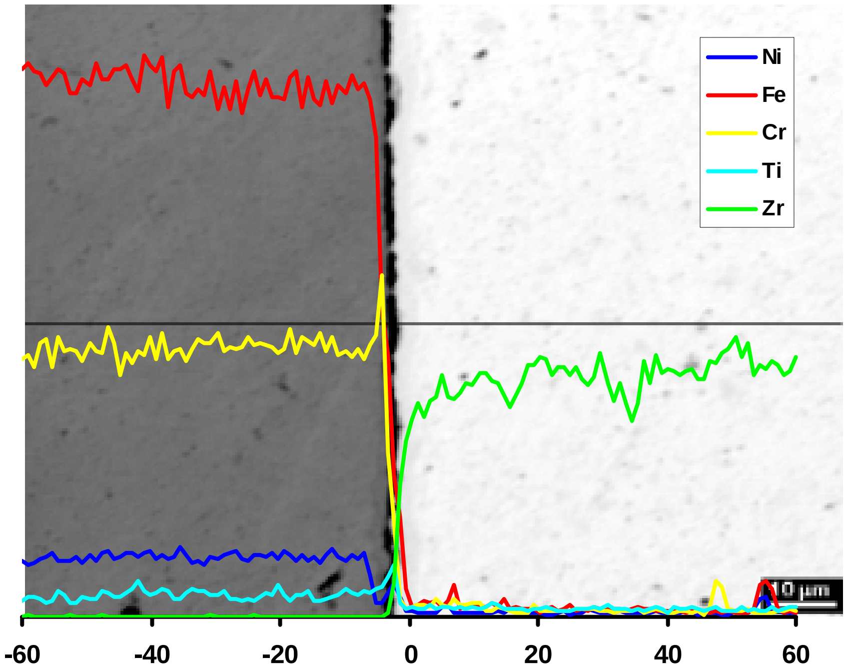
Structure of the steel-zirconium bonding zone

The welding process under discussion involves interdiffusion of the steel and zirconium alloy elements, with formation of transition zones. The strength and corrosion resistance properties of the transition joint and its general performance depend largely on the composition of such transition zones.

The microstructure of a transition zone in a steel-zirconium joint is presented in Figure 4.



a)



b)

Fig.4. Transition zone structure

a) Microstructure of the bonding zone b) Distribution of alloying elements

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The transition zone in a joint consists of 4 layers with a thickness of ~1, 0.5, 0.5 and 3.5 μm, respectively, counting from the steel side. The chemical composition of each layer was determined with the use of X-ray microspectrum analysis.

The first layer from the steel side, 1.0 μm in thickness, has shown magnetic properties. According to test findings, this layer contains 21-25 % of chromium, ~4-5 % of nickel, 60-70 % of iron, and as much titanium as found in steel. It has been established that steel-zirconium interaction in the welding process leads to appearance of a ferritic layer on the austenitic steel surface through $\gamma \rightarrow \alpha$ transformation, and that this layer is lower in nickel and higher in chromium as compared to the steel.

The second layer carries 0.5-0.7 % of titanium, with variable content of the other elements.

The third layer consists of iron (~35 %), chromium (~15 %) and zirconium (~50 %) and is a mixture of intermetallic chromium and iron compounds with zirconium.

The fourth layer, adjacent to the Zr-2.5% Nb alloy, contains nickel, iron and zirconium. At the welding temperature, it appears as a uniform intermetallic Fe-Ni-Zr layer, with Ni making ~ 9 %, Fe reaching ~ 25 %, and zirconium accounting for the rest.

The results of tests and studies show that the best stability in structure and chemical composition and higher corrosion resistance are achieved in steel-zirconium bonding layer up to 5 μm in thickness.

This value (≤ 5 μm) is a criterion for assessing the quality of each transition joint by its test ring.

Stress-strain analysis of transition joints

The stress-strain states of the transition joint were analyzed in elastic-plastic terms by the finite element method, including simulation of the residual stresses arising in the transition joint fabrication process and the effect of stresses from operating loads.

The following loading conditions were adopted. It was assumed that stresses undergo complete relaxation at the temperature of 600 ^{o}C. Subsequent cooling brings the temperature down to 20 ^{o}C. The stresses obtained for this condition are residual stresses. With the aim of finding the distribution of stresses in normal operating conditions and assessing possible redistribution of residual stresses, the stresses in the first two cycles of reactor power rise and fall were calculated. The temperature was assumed to be uniformly distributed across the wall.

Stress distribution analysis leads to the following conclusions:

- On the whole, the residual stresses in the manufactured transition joint produce compression of the steel-zirconium bonding layer, which is a favorable factor.

These stresses are reduced through relaxation, but the bonding layer will still be compressed.

- Cyclic stresses are incapable of causing opening of the steel-zirconium connection in the process of operation (with the corrosion effect of coolant disregarded).

Susceptibility of the zirconium part of the transition joint to delayed hydride cracking

During operation, hydrogen uptake in water, steam and steam-water mixtures may give rise to development of crack-like flaws in zirconium alloy components through delayed hydride cracking (DHC).

The criteria for possible occurrence of this process are the threshold stress intensity factor (SIF) and the hydrogen solubility limit at working temperatures.

The experience of in-pile operation of transition joints shows that crack-like microflaws are likely to appear in the zirconium part of the transition joint due to material corrosion. In this regard, it appears important to study the susceptibility of the zirconium joint portion to DHC.

To this end, studies were performed on samples of transition joints after a full fabrication cycle, covering all thermal impacts on the metal. Before the tests, fatigue cracks were grown in the specimens, whereupon they were subjected to hydrogenation to the hydrogen content of 100 ppm.

The tests were carried out under isothermal (T = 300 ^{o}C) and thermocyclic (20-300-20 ^{o}C) loading conditions, with the duration of 5000 hours and 400 cycles, respectively.

The studies established that the threshold value of the stress intensity factor, K_{1H}, during isothermal tests was ~ 14 MPa $\sqrt{\mathcal{M}}$, with the rate of crack growth by the DHC mechanism never exceeding ~ 4x10^{-12} m/s. During thermal cycling, K_{1H} was found to vary between 12 and 12.5 MPa $\sqrt{\mathcal{M}}$, while the crack growth rare reached 0.0035 mm per cycle.

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Analysis made with allowance for the stresses existing in the transition joint showed that crack development through DHC is unlikely.

Testing of mock-up fuel channels

Much attention was devoted to studies on cyclic strength and long-term corrosion resistance of the diffusion-welded zirconium-steel joint, since under operating conditions it experiences significant cyclic variation of stresses in excess of the yield stress.

Extensive (up to 10 000 hours) rig tests were performed at inner pressure and operating temperature (300 ^{o}C), involving short zirconium parts of pressure tubes (mockups), i.e. tubes made of Zr-2.5% Nb alloy, zirconium-zirconium welds and zirconium-steel transition joints.

The corrosion resistance of the mockup components was assessed by their appearance and by the oxide film condition. During the tests, both the zirconium and the steel parts of the transition joint showed high corrosion resistance. It was established that the titanium-to-carbon ratio should be greater than 6 to ensure proper corrosion resistance of the steel in an aggressive environment, at high operating stresses.

According to the cyclic strength assessment, the specified service life of fuel channels is assured for a given number of transients for RBMKs.

The most vulnerable point of the transition joint is the area of the zirconium-steel weld exposed to the coolant. Inspections revealed individual cases of opening of such welded joints due to corrosion processes. But even in those instances, with the bond broken (joint opening), no further degradation occurred if the steel had the required resistance to intergranular stress corrosion cracking (Ti/C ratio > 6).

The operating record of transition joints in RBMK fuel channels

More than 40 000 steel-zirconium transition joints have been manufactured and installed, as part of RBMK fuel channels, since 1973.

Their successful in-pile operation for almost 30 years is testimony to the correct choice of the engineering approaches underlying the design and technology of producing diffusion-welded steel-zirconium joints.

Individual cases of transition joint seal failure were observed in the process of operation, such as opening of the steel-zirconium weld exposed to the water coolant (lower transition joints), development of cracks in steel by the IGSCC mechanism and leak initiation. Complete failure of transition joints has never been experienced. The total number of failed transition joints (about 40) makes a very small percentage of all the transition joints in operation. The adopted design modifications (increased thickness of the steel part with the ensuing stress reduction) and improvements in the steel inspection processes have almost entirely eliminated the possibility of transition joint damage during operation.

Transition joints of this type, varying from 10 mm to 150 mm in diameter, are successfully operating in various research reactors.

Conclusion

1. Diffusion-welded transition joints between tubes made of steel 06X18H10T and tubes fabricated from zirconium alloy with 2.5 % Nb, are described from the viewpoint of their design and production process.
2. The structure of the steel-zirconium joint is discussed. It is shown that a bonding layer between steel and zirconium alloy up to 5 μm in thickness has the greatest stability in terms of its structure and chemical composition and higher corrosion resistance.
3. The elastic-plastic analyses of stress-strain states covering the whole cycle of transition joint fabrication show that the post-fabrication residual stresses are able to provide compression of the steel-zirconium bonding layer. Despite their certain relaxation during operation, their positive effect is retained.
4. The characteristics of the zirconium alloy with 2.5 % Nb after the whole cycle of transition joint fabrication are such that, with regard to the existing stresses, they practically rule out the possibility of delayed hydride cracking occurrence.
5. Experiments performed to study the cyclic strength and long-term corrosion resistance of transition joints have confirmed their adequate performance.

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6. More than 40 000 transition joints have been operating successfully in RBMK reactors for almost 30 years. Individual cases of their damage (about 40) account for a very small percentage of their total number in operation, and this rate may be further reduced by the design and technological improvements that are in place already.

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