doi.org/10.15407/tpwj2017.12.04

APPLICATION OF EXPLOSION WELDING FOR MANUFACTURE OF TRIMETALLIC TRANSITION PIECES OF CRYOMODULES OF LINEAR COLLIDER

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An original design of transition piece for joining cryomodules of linear collider was proposed, providing necessary strength, helium and vacuum tightness at relatively low cost. The modes of explosion welding of plane titanium–stainless steel–titanium workpieces, at which intermetallics in the joining zone are almost absent, were developed. The modes of electron beam fillet welding of niobium branch pipe with titanium of a transition disc were selected experimentally. The experimental samples of transition pieces were manufactured which successfully passed tests on thermocycling and helium tightness. 8 Ref., 11 Figures.

Keywords: *collider, explosion welding, helium tightness, transition piece, nuclear research*

The unique international project of the linear collider, being developed at the present time, has a great importance for fundamental research in the field of nuclear physics and power engineering [1]. Its peculiarity consists in the fact that accelerated particles will collide in vacuum space at the temperature, close to absolute zero. The length of the collider will be more than 50 thou m. It should consist of separate cryomodules of 1 m length, joined between each other by transition pieces.

The joined elements of the cryomodule are a niobium superconducting resonator, which should be welded-on by electron beam welding (EBW) to the niobium branch pipe and casing of stainless steel (type 316L) coaxially located with respect to the niobium resonator, welded-on to the disc of the transition piece manufactured of the same stainless steel. The vacuum niobium resonator is located inside the stainless steel casing, a liquid helium is filled under the casing (Figure 1). Thus, the transition piece should provide a vacuum and helium tightness. and serviceability of the unit under the conditions of high-frequency electromagnetic loads at cryogenic temperatures [2].

It is known that the most quality welded joints are produced in welding of homogeneous materials. Thus, the transition piece should provide producing welded joints of niobium with niobium and stainless steel with stainless steel, i.e. the transition piece should consist of at least two metals: niobium and stainless steel. The use of any methods of fusion welding, including EBW, for producing joints of niobium with stainless steel, is unacceptable for solving the specified problem in connection with the formation of intermetallics of type Nb_xFe_y, which do not allow providing the required tightness of the transition pieces.

We manufactured a transition piece by explosion welding-on of a niobium branch pipe directly to the disc of stainless steel. It was expected that much less intermetallics would be formed due to absence of high-temperature heating in explosion welding and they would not violate the tightness due to a large area

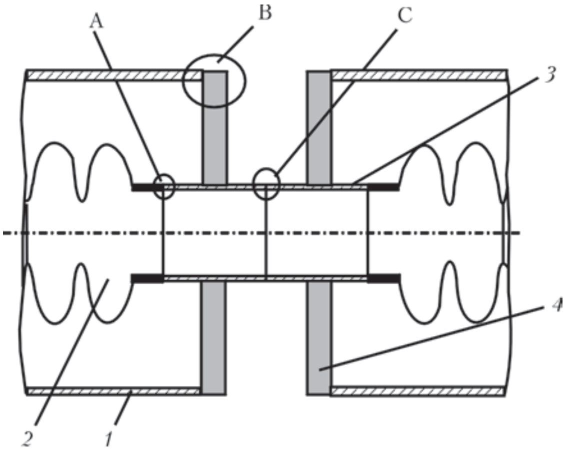

Figure 1. Scheme of cryomodules joining: *1* — casing of stainless steel; *2* — niobium resonator; *3* — niobium pipe; *4* — disc of stainless steel; A — joining of resonator with niobium pipe by EBW; B — joining of casing with the disc of transition piece by EBW or argon-arc welding; C — joining of niobium pipes of transition pieces by EBW

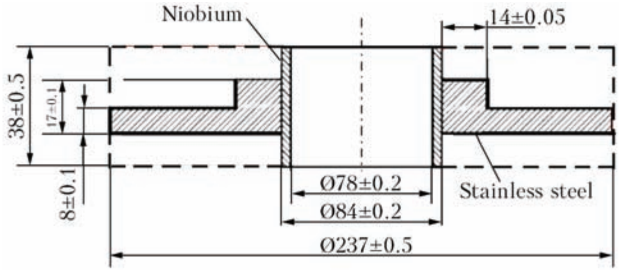

Figure 2. Scheme of manufacture of transition piece, using the explosion welding of niobium with stainless steel

of the joint [3]. Moreover, in order to preserve the integrity of the niobium pipe at the moment of explosion, the width of steel workpiece should be not less than the width of the niobium pipe. In Figure 2 the dotted line indicates the dimension of steel workpiece before the explosion.

To provide the required geometric dimensions of the transition piece, taking into account the inevitable deformations of niobium from explosion, it is necessary to use a niobium pipe with a smaller outer diameter and a larger wall thickness so that after explosion welding a transition piece with the necessary dimensions can be manufactured using machining. During machining a part of niobium and a significant part of stainless steel will make chips. Therefore, this method is not suitable for industrial application because of a high labor consumption, high cost and high consumption of scarce niobium. The helium tightness of the joint was not investigated.

The earlier carried out experiments showed, that in electron beam welding of niobium with titanium the intermetallics were not formed and the necessary tightness of joints was provided as to helium and vacuum. In this regard, the following variant of manufacturing the transition piece was proposed.

At first the disc of stainless steel is cladded with titanium on both sides applying explosion welding, then, after giving the necessary shape to trimetal (by straightening and turning to size), a hole is cut out for a niobium branch pipe. The branch pipe is inserted into the hole and welded-on to the titanium applying EBW (Figure 3). The possible formation of intermetallics in the joint of titanium with steel produced by explosion welding does not affect the transition piece

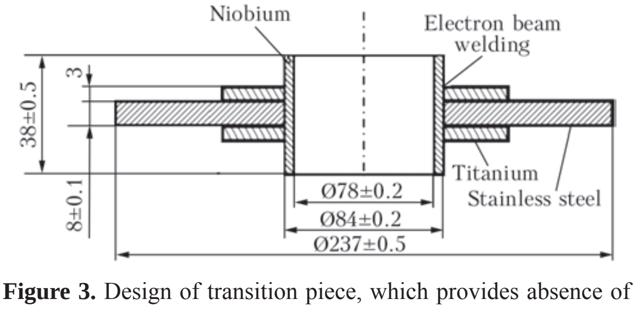

Figure 3. Design of transition piece, which provides absence of formation of niobium intermetallics during welding

serviceability, since helium can not enter the niobium pipe cavity through it.

The advantages of the proposed variant of manufacturing the transition piece:

- helium .tightness is provided by welding niobium with titanium, which have a good weldability;
- the hole in the flange is made according to the niobium pipe size, moreover, the branch pipe of the resonator can be welded-in instead of the pipe-transition piece;
- the possible formation of intermetallics in the joint area of steel with titanium during explosion welding does not affect the helium tightness;
- technologically, the explosion welding of plane specimens is much easier than welding of pipe billets and allows producing joints with the maximum possible stability of quality, which reduces the probability of rejection;
- after explosion welding, if necessary, the cheaper steel-titanium workpieces will be rejected;
- steel-titanium flange can be subjected to heat treatment to reduce residual stresses in a conventional (non-vacuum) furnace;
- the consumption of steel and niobium is reduced.

The titanium-steel joint is rather difficult to weld by explosion due to the fact that these metals form brittle chemical compounds during welding and subsequent heat treatment. It should be noted that titanium forms intermetallics with almost all metals except of niobium, tantalum and vanadium. In particular, during welding of titanium with steel the brittle intermetallic compounds Fe_2Ti and FeTi are formed. In case of formation of significant amount of intermetallics (in the form of solid interlayer), the joint strength is reduced to zero. The separate rare spot inclusions do not affect the static strength of the joint [4].

For the growth of intermetallic phase, the necessary condition is not only a high temperature, but also a certain time when high temperatures exist, i.e. a latent period. The explosion welding, being a very rapid process, provides a minimum time for staying the contact zone under the influence of high temperatures. This is the advantage of using explosion welding for creating the similar combinations of metals and alloys [5].

Experimentally, the modes for explosion welding of the titanium-steel-titanium trimetal were selected. Thickness of titanium was 3 mm and that of steel was 8 mm. The plates of 250×250 mm and 300×700 mm were welded. The straightening of plates after the first explosion and after manufacture of trimetal was carried out in industrial roll mills, at first in three-roll (the workpiece was given an arched shape) to eliminate local deformations, and then in nine-roll mills to

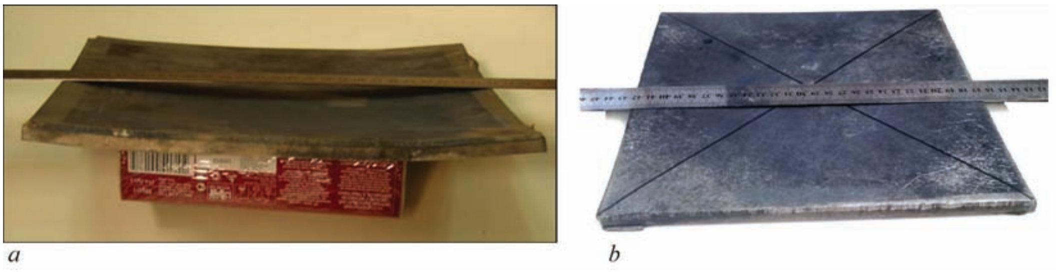

Figure 4. Appearance of workpiece produced by explosion welding: *a* — before straightening; *b* — after straightening

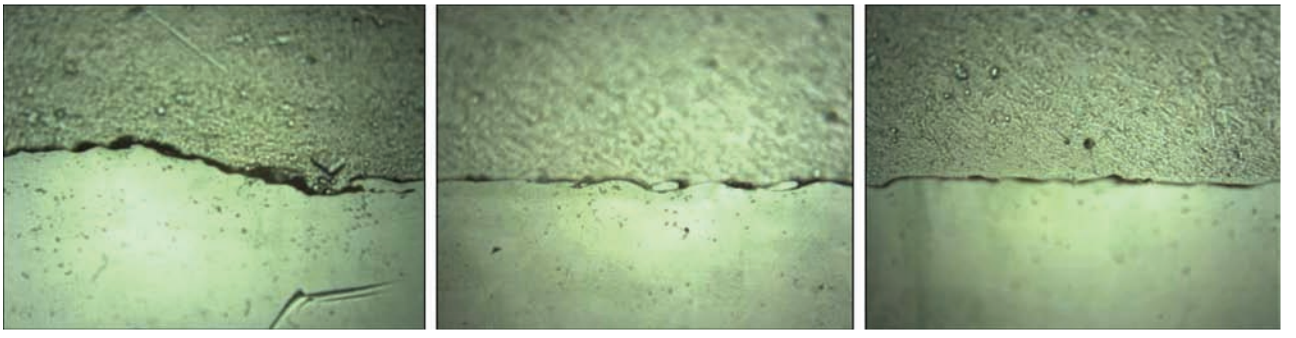

Figure 5. Microstructure (×400) of steel-titanium joint produced by explosion welding

make the plane.workpiece. The need in straightening is shown in Figure 4.

The discs of 237 mm diameter with a central hole for niobium branch pipe of 84 mm diameter were cut out of trimetallic workpieces. The maximum residual deflection of the disc was 0.5 mm.

In Figure 5 the photos of microsections with characteristic areas of the steel-titanium joint are given, produced in the selected welding modes. The waviness formation is almost absent, which evidences about the selection of the optimal mode for this case with the minimum power input, which reduces the number and size of the forming intermetallics.

On the microsection along the boundary of the joint, the elongated dark bands and also white spots of a small size can be occasionally, seen, which can be intermetallics.

To determine the nature of bands and spots, the investigations of microhardness were carried out applying Vickers method. The results of hardness measurements at a load of 100 g are shown in Figure 6.

The width of dark bands was of the order of 10 μm. Near the boundary of the joint the microhardness was measured by the dark bands. The hardness of the original titanium was 1300–1600 and that of the initial steel was 1700–1900 MPa. It is known that the hardness of intermetallics of type Fe_xTi_y is .above 9000 MPa. It is seen from Figure 6 that titanium and steel undergone a significant hardening as a result of collision during explosion welding, the titanium has its initial hardness already at a distance of 300 μm from the boundary, the steel is hardened to a greater depth. The achieved hardening can not affect the operating properties of the transition piece [6]. The absence of sharp hardness jumps near the boundary evidences that the dark bands are not intermetallics.

In the process of investigation it was established that there is a step on the boundary of the joint, which could have formed as a result of etching during the manufacture of a section or for other reasons. Apparently, the dark bands represent either contaminations accumulated along the step during grinding, or a shadow from the step, formed as a result of the section illumination by the microscope lamp.

Measurement of the microhardness of white spots and steel around them at a load of 10 g showed their equivalence and indicates that they are not intermetallics.

The quality of the titanium–steel joint produced by explosion welding was evaluated by standard test methods: on bending, on separation and shearing of layers [7].

Figure 7 shows the specimen after the bend test.

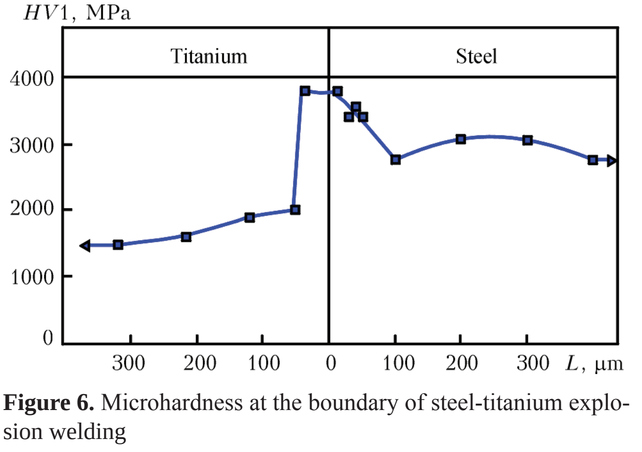

Figure 6. Microhardness at the boundary of steel-titanium explosion welding

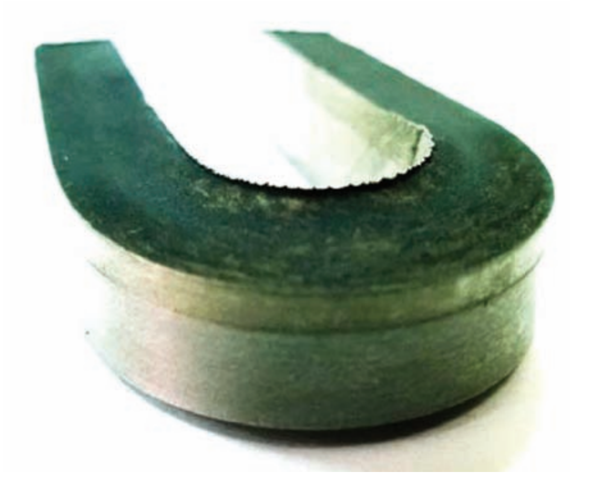

Figure 7. Specimen of steel-titanium bimetal after bending test

During bending at the angle of 180°, the specimen preserved its integrity, the delamination did not occur. This is a rather rigid type of tests, during low-quality welding the boundary of the joint of metals is destroyed.

Figure 8 shows the scheme of test for tear of bimetal layers and the general appearance of specimens.

The fracture of specimens occurred at the, steel-titanium interface, which is typical for this pair of metals [8]. The rupture strength amounted to 375 MPa. The tensile tests of sheet titanium in the initial state showed that the yield strength amounts to 390 MPa and that of tensile strength is 430 MPa. The strength of the joint is not too much inferior to the strength of the less strength metal among the those being joined.

The shear tests of layers (Figure 9) showed the strength at the level of 350 MPa. Such a high shear strength, which is comparable to the tear strength, is achieved due to the wavy boundary of the steel-titanium joint.

The service conditions of the transition piece do not imply the application of loads to it, leading to shear or tear of the layers, the strength of the joint can be considered satisfactory.

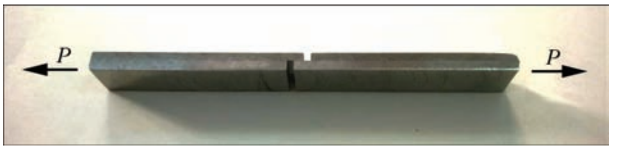

Figure 9. Scheme of test of specimen for shear strength of the layers

Thus, the carried out investigations allow stating that the developed mode of welding the trimetallic workpiece of the transition piece is close to optimal.

The cold working of metals and residual stresses in the produced trimetal can be removed by heat treatment. The safe heating for this composition is the heating of up to 600 °C. During heating above 700 °C, the intensive formation of intermetallics and carbides begins [4].

In case of welding titanium with stainless austenitic steels, the problem of need in heat treatment should be separately examined, as far as during heating and cooling the austenite can be transformed into martensite, which changes the properties of steel, including its magnetization, which reduces the efficiency of the collider.

The efficiency of applying heat treatment for improving mechanical properties of trimetal was investigated on specimens after heat treatment of workpiece at the mode of 600 °C, holding — 1 h, cooling in air. The tear strength of the layers was 325 MPa (375 MPa without heat treatment), the shear strength of layers was 345 MPa (350 MPa without heat treatment). The significant differences in the microstructure of metals in the joint zone as compared to the specimen without heat treatment, manufactured of the same trimetal workpiece, were not revealed. The Vickers microhardness at a load of 10 g amounted to: for steel — 2500 MPa (2600 MPa without heat treatment), for titanium — 2600 MPa (2150 MPa without heat treatment). On microsections at the joint boundary, a greater number of white spots was detected which have microhardness of 2300 MPa and are not intermetallics. They are, most likely, the areas of met-

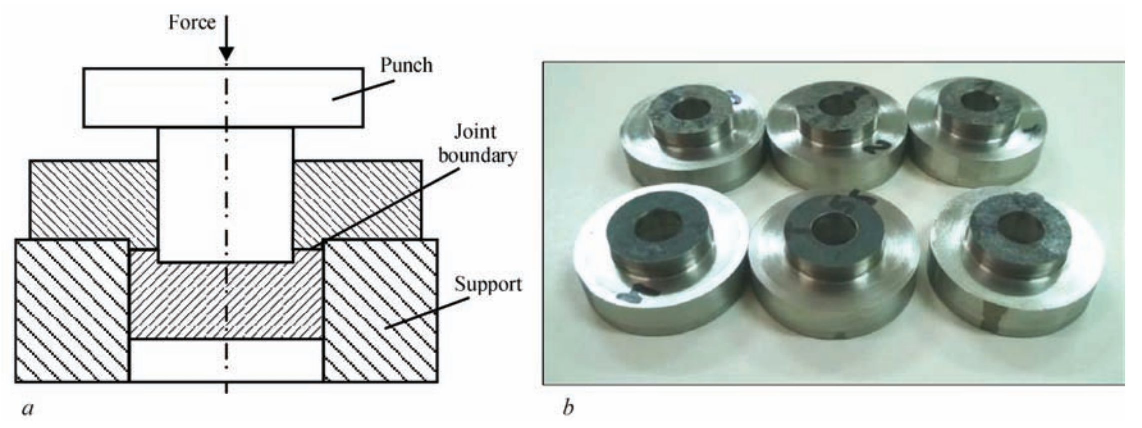

Figure 8. Scheme of tear test of bimetal layers (*a*) and general appearance of specimens (*b*)

al micro-overlaps, formed during explosion welding. The intermetallics in the investigated sections were not found. Thus, the heat treatment according to the mode mentioned above did not affect the properties of the trimetal required in the work. An increase in the annealing temperature is undesirable, as far as it can lead to appearance of intermetallics and a change in the properties of austenitic steel. Preliminarily, it can be concluded that it is not reasonable to perform heat treatment of trimetal billets, as it only increases the cost of the transition piece.

Selection of EBW modes. The use of high-purity niobium for manufacture of resonators demands for the performance of any thermal operations with it, including welding in vacuum. EBW is the most suitable for our case, since the process occurs in a chamber with a high degree of evacuation.

To perform EBW, the parts being welded should adjoin each other as close as possible. Since the niobium pipe has an initial ovality, along the circumference of adjoining the niobium branch pipe to the edge of the hole in the trimetallic disc, there are places with a larger gap not suitable for EBW. To eliminate this drawback, a device was manufactured, which fixes the branch pipe in the hole of the disc. The disc with the clamped branch pipe was inserted into the cartridge of the turning lathe, the roller was fixed instead of the cutter. By rolling the niobium branch pipe from the inside, its tight adjoining to the edges of the disc hole was achieved.

During manufacture of the experimental transition piece, the preliminary EBW mode was applied. The investigations of structure of the joint showed that the penetration depth of titanium was approximately 1 mm. According to statement of EBW experts, having a large experience in producing tight welds, including by helium, such penetration is rather sufficient to provide helium tightness. At the same time, the transition piece can be influenced by the loads generated from the excessive pressure inside the cryomodule due to the presence of vacuum on the outer side of the transition piece, as well as due to the possible heating of liquid helium from the elements of the cryomodule design during its filling with liquid helium and thermal conductivity of the transition piece, contacting the casing around the contour. In this connection, it seems rational to produce the weld as much strong as possible while, at the same time, preventing the full penetration of titanium and niobium by electron beam. On the model specimen the niobium branch pipe was welded-in to the titanium disc of 3 mm thickness using four EBW modes. Figure 10 shows the sections of the produced joints and the welded joint width is indicated.

The largest penetration was achieved at the modes 3 and 4. These modes will be used in manufacture of the subsequent transition pieces. The specific choice will depend on thickness of titanium, remaining after machining during manufacture of the disc of a trimetallic workpiece.

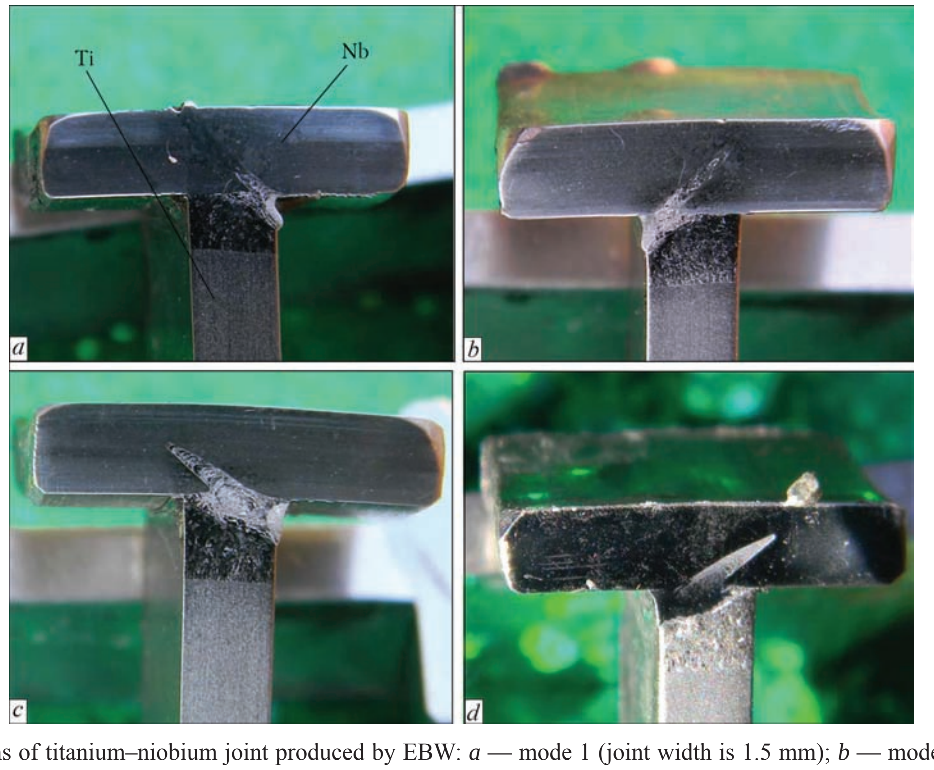

Figure 10. Sections of titanium–niobium joint produced by EBW: *a* — mode 1 (joint width is 1.5 mm); *b* — mode 2 (joint width is 1.9 mm); *c* — mode 3 (joint width is 2.75 mm); *d* — mode 4 (joint width is 2.1 mm)

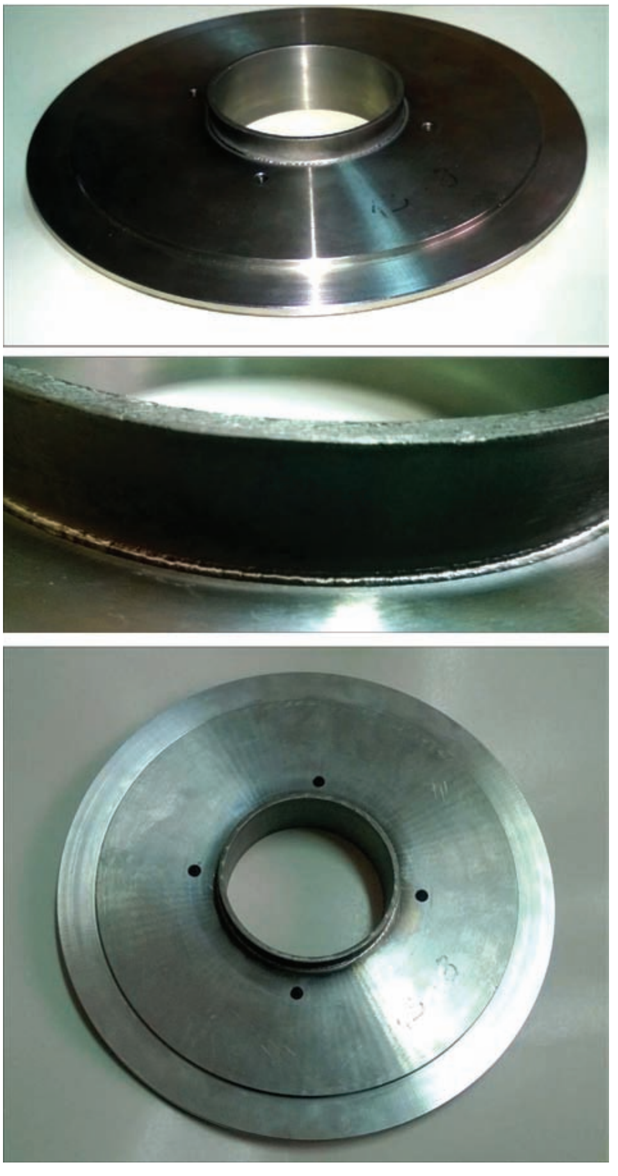

Figure 11. Appearance of manufactured transition piece

For today, two transition pieces were manufactured, one of which was subjected to heat treatment. Both transition pieces were tested for thermal cycling in liquid nitrogen and then in liquid helium. After each type of thermal cycling, the transition pieces were tested for helium tightness. In all the cases the positive results of tests were obtained.

Figure 11 shows the variants of appearance of the transition piece. The holes were made to carry out some investigations, the real transition piece will have no holes.

Conclusions

1. The design of transition piece, suitable for manufacture of cryomodule of a linear collider was developed which allows excluding welding-on of niobium to steel.

2. The technology of explosion welding the trimetallic workpiece for manufacture of transition piece was developed, providing the absence of intermetallics at the boundary of the steel-titanium joint.

3. The modes of EBW of niobium with titanium were selected, which, according to the preliminary evaluations, should meet the service requirements of the transition piece.

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Received 27.11.2017