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COMBINED ADAPTER FOR THE UPGRADED CRYOMODULE OF THE LINEAR COLLIDER

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Комбинированный переходник для модернизированного криомодуля
линейного коллайдера

В рамках работ по проекту ILC были развернуты исследования по модернизации криомодуля, основного элемента линейного ускорителя, с целью достижения его надежности и удешевления производства. В существующем ILC TDR, оболочка гелиевого дьюара и гелиоподающая трубка изготовлены из дорогостоящего титана, единственного материала, сваривающегося с ниобием с помощью электронно-лучевой сварки. В статье описываются конструкция и характеристики переходного элемента, полученного сваркой взрывом, который соединяет ниобиевый резонатор с оболочкой дьюара из нержавеющей стали, что уменьшает огромные затраты титана. Созданный переходник содержит минимальное количество титана в качестве промежуточного слоя. Предварительные тесты продемонстрировали большую сопротивляемость к шоковым температурным перепадам от сварки ЭЛС и до криогенной температуры. Технология триметаллического связующего элемента ниобий–титан для производства переходника исключает образование интерметаллидов и влияние разности коэффициентов линейного расширения компонентов ансамбля.

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Combined Adapter for the Upgraded Cryomodule of the Linear Collider

As part of work on the ILC Project, research was performed on the development of techniques to simplify and make reliable and cheaper the construction of the cryomodules that are core of the main linac. In the current ILC TDR design both the helium vessel surrounding the niobium RF cavities and the connected pipes which channel the exhaust helium gas are made of expensive titanium, one of the few metals that can be welded to niobium by the electron beam technique. In this paper we describe the construction and performance of transition elements, obtained by explosion welding, that can couple the niobium cavity with a stainless steel helium vessel, thus saving large amounts of titanium. A new design, including a minimal titanium intermediate layer, has been built. Preliminary tests yielded a very strong resistance of the bond to extreme temperature shocks from electron beam welding to exposure to cryogenic temperatures. The developed technology allows a trimetallic billet for manufacturing an adapter to be made such that the niobium–titanium bond is free of intermetallic compounds and the effect of the difference in the linear expansion coefficients of the ensemble components is eliminated.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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INTRODUCTION

To reduce the cost of the ILC cryomodule, possible replacement of its titanium shell with a stainless steel (SS) shell is considered [1]. For this purpose, an adapter is proposed to join the niobium cavity to the stainless steel cryomodule shell.

The cryomodule elements to be joined are the superconducting niobium cavity, which should be electron-beam welded to the niobium pipe of the adapter, and the shell of stainless steel (grade 316 L), which is arranged coaxially with respect to the niobium cavity and should be welded to the adapter disc made of the same stainless steel. The niobium cavity is inside a stainless steel shell, which is pumped to vacuum and liquid helium is poured in (Fig. 1). Thus, the adapter must ensure vacuum and helium tightness and operability of this unit under radio-frequency electromagnetic loads at cryogenic temperatures.

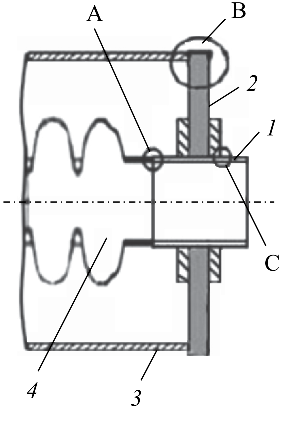


Fig. 1. Scheme of combined adapter connection with a cryogenic module: *1* — niobium tube; *2* — steel flange; *3* — steel shell; *4* — niobium cavity; A — electron beam welding connection of niobium tube with cavity; B — electron beam welding or argon arc welding connection of shell with steel flange of adapter; C — electron beam welding connection of niobium tube with titanium plate of adapter

It is known that welding of similar materials gives the best results. Thus, the adapter must ensure that niobium is welded to niobium and stainless steel to stainless steel; i.e., the adapter should consist of at least two metals, niobium and stainless. No fusion welding, including electron beam welding, is suitable for joining niobium and stainless steel because it results in formation of intermetallic compounds like $\mathrm{Nb}_x\mathrm{Fe}_y$, which do not allow the required adapter tightness to be obtained. In addition, this compound does not withstand the thermal load at cryogenic temperatures and fails.

We began with making an adapter by explosion welding of the niobium pipe directly to the stainless steel (SS) disc. It was expected that much fewer intermetallics will be formed because explosion welding is not accompanied by high-temperature heating, and they do not affect the tightness due to a large joint area. To maintain integrity of the niobium pipe at the moment of explosion, the width of the steel billet must be no smaller than the width of the niobium pipe. In Fig. 2 the overall dimensions of the billet before the explosion are shown in red and the dimensions of the adapter in black.

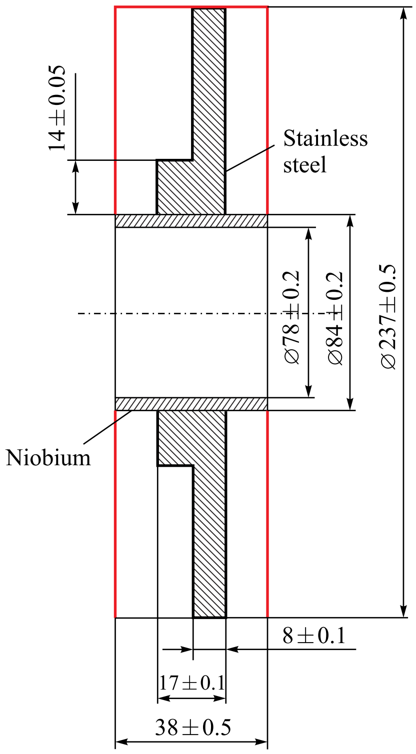


Fig. 2. Scheme of adapter manufacturing by means of explosion welding of niobium with stainless steel

In view of unavoidable explosion-induced deformation of niobium, a niobium pipe with a smaller outer diameter and thicker walls must be used to allow machining the adapter to the required size after the explosion welding. A part of niobium and a large part of stainless will be cut during the machining, so this method is unsuitable for industrial manufacture because of laboriousness, high cost, and expenditure of scarce niobium.

Six adapters were made to investigate helium, mechanical, and vacuum tightness under various extreme conditions [2]. Thermal cycling tests at the liquid nitrogen temperature (77 K) and liquid helium temperature (2 K) revealed no leakage at the background leak rate $0.7 \cdot 10^{-10}$ atm · cc/s in five samples; one sample showed a leak of $2.6 \cdot 10^{-6}$ atm · cc/s. Two samples were subjected to tests with imitation of their installing to the working position. To this end, niobium rings were electron beam welded to both ends of the niobium pipes. One of the samples was tempered before and after the welding, and the other sample was not tempered. In the nontempered sample a large leak occurred in several places of the Nb–SS joint after the first 3–4 thermal cycles in liquid nitrogen. This is because the welded joint experienced various internal stresses, first, due to the explosion welding, then due to the thermal load from the electron beam welding (niobium melting point is 2460°C), and ultimately due to the thermal load at a very low helium temperature of 2 K.

Superposition of all these residual stresses resulted in plastic deformation, failure of welds, and consequently occurrence of a leak [3].

Earlier experiments showed that electron beam welding of niobium and titanium did not result in formation of intermetallic compounds and ensured the required helium and vacuum tightness. In this connection the following adapter manufacture procedure was proposed [4]. First, the stainless steel disc is clad with titanium on both sides by explosion welding, the resulting trimetal is shaped as required (by planishing and turning to the size), and a hole is cut for the niobium pipe. The pipe is inserted in the hole and electron-beam welded to titanium (Fig. 3). Possible formation of intermetallic compounds in the titanium–steel joint made by explosion welding does not affect the operability of the adapter because helium cannot penetrate the niobium pipe through it.

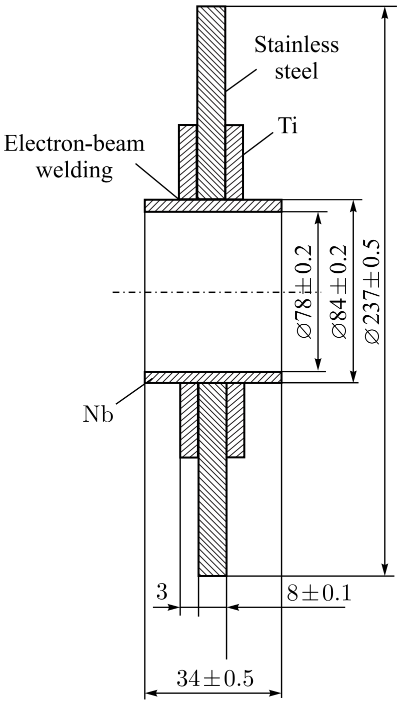


Fig. 3. The design of the adapter, ensuring the absence of niobium intermetallic formations during welding

Advantages of this adapter manufacture procedure are as follows:

— electron beam welding of niobium and titanium did not result in formation of intermetallic compounds and ensured the required helium and vacuum tightness;

— the hole in the flange is made to the size of the niobium pipe, and the cavity pipe can be welded in it instead of the adapter pipe;

— possible formation of intermetallic compounds in the explosion weld steel–titanium joint does not affect helium tightness;

— explosion welding of flat pieces is technologically much simpler than welding of pipes and allows joints with quality as much stable as possible, which reduces the probability of rejects;

— cheaper steel–titanium pieces will be rejected, if necessary, after explosion welding;

—to reduce residual stresses, the steel–titanium flange can be thermally treated in an ordinary (not vacuum) furnace;

— expenditure of steel and niobium decreases.

EXPLOSION WELDING OF METALS AND ITS MAIN PARAMETERS

Explosion welding is a process of making a permanent joint through metallic bonding [5]. It does not require a heat source because the energy comes to the joint area from the collision of the plates (Fig. 4). In optimum explosion welding regimes the heat-affected zone is very small, as is the existence time of high temperature.

The surfaces of the metals to be joined suffer plastic deformation creating a wave pattern bond line (Fig. 5). An increase in the welding energy (collision energy of plates) increases wave parameters. A waveless bond can also be made by choosing a welding regime with the minimum energy deposition.

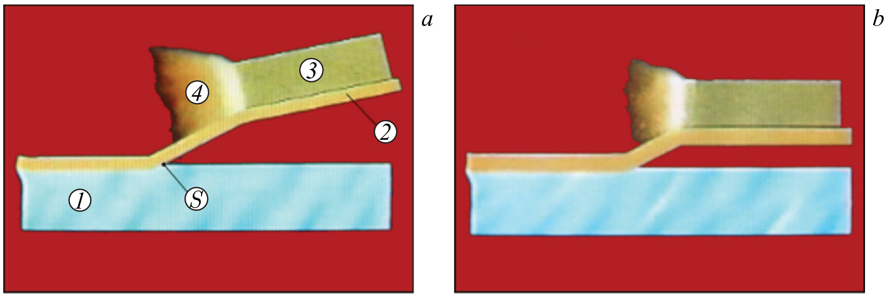


Fig. 4. Principal schemes of explosion welding process: with an angle between metal sheets (*a*); parallel (*b*): *1* — base plate; *2* — cladding plate; *3* — explosive; *4* — detonation products; S — point (line) of contact of surfaces during welding

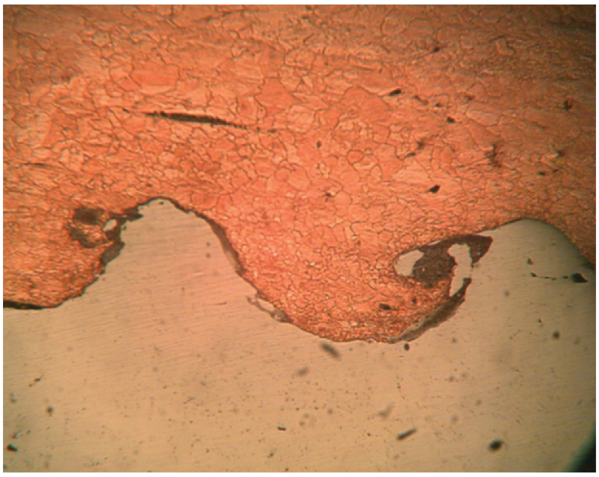


Fig. 5. The microstructure of the copper–stainless steel joint, magnification × 100

Since explosion welding is a complicated and high-velocity process, there is so far no universal mathematical model capable of precisely describing all its details.

It is very difficult to join titanium and steel by exposition welding because both metals form brittle compounds during the welding and subsequent thermal treatment. It is worth noting that titanium forms intermetallic compounds with almost all metals except niobium, tantalum, and vanadium. In particular, when titanium and steel are welded, intermetallic compounds Fe_2Ti and FeTi are formed. When a large amount of intermetallic compounds is formed (as a solid layer), the strength of the joint reduces to zero. Rare individual inclusions do not affect the static strength of the joint.

A necessary condition for the growth of intermetallic phase is not only the high temperature but also the time for which high temperature exists — the latent period. Explosion welding as a very high-velocity process keeps the contact zone under high temperature for the minimum time which makes it advantageous for producing similar combinations of metals and alloys.

Explosion welding regimes for fabricating the titanium–steel–titanium trimetal were selected experimentally. The titanium was 3 mm thick and the steel was 8 mm thick. Plate swith dimensions 250×250 mm and 300×700 mm were welded. Planishing of the plates after the first explosion and after the fabrication of the trimetal was performed first on an industrial rolling mill, first with three rolls (making the billet U-shaped) to eliminate local deformation and then with nine rolls to make the billet flat. The necessity of planishing is demonstrated in Fig. 6.

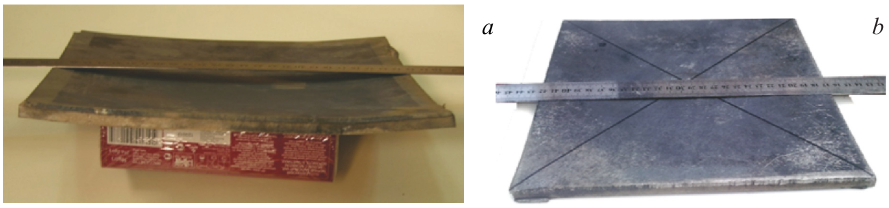


Fig. 6. Appearance of the billet after explosion welding: *a*) before planishing, *b*) after planishing

Discs 237 mm in diameter with a central hole 84 mm in diameter for the niobium pipe were cut from the trimetallic billets. The maximum residual deflection of the disc was 0.5 mm.

Figure 7 shows photos of microsections with characteristic areas of the joint made by welding in the chosen regimes. There is practically no wave pattern, which indicates that minimum energy deposition regimes were chosen.

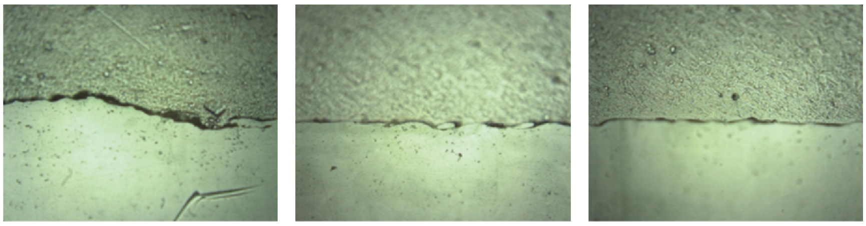


Fig. 7. Microstructure of steel–titanium joint obtained by explosion welding, magnification × 400

Along the bond line, extended dark stripes are seen, and small white spots sometimes occur, which can be intermetallic compounds.

To find the nature of the stripes and spots, the Vickers microindentation test was performed. The results of measuring microhardness at a load of 100 g are presented in Fig. 8.

The dark stripes were about 10 μm wide. Near the bond line microhardness was measured by dark stripes. The hardness of initial titanium is 1300–1600 MPa, and the hardness of initial steel is 1700–1900 MPa. It is known that hardness of intermetallic compounds like Fe$_x$Ti$_y$ is above 9000 MPa. It is evident from Fig. 8 that the collision caused by the explosion added much to the titanium and steel hardness. Titanium has its initial hardness as far as 300 μm away from the bond line, and steel is hardened to a greater depth. The resulting hardening cannot affect the operational properties of the adapter. Absence of abrupt hardness changes near the bond line indicates that dark stripes are not intermetallic compounds.

The investigations revealed a step at the bond line, which could result from the etching during the preparation of the microsection or from anything else.

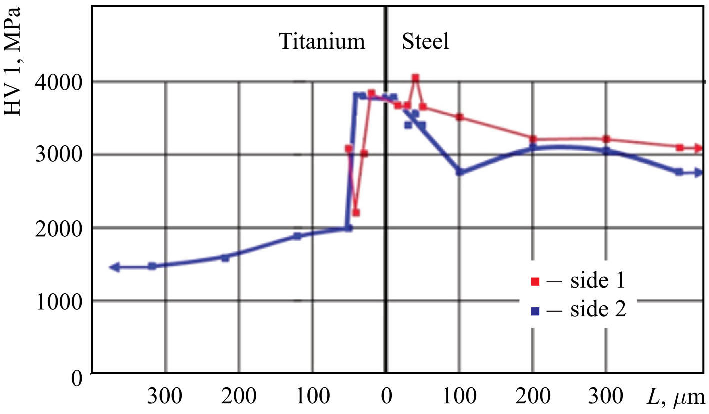


Fig. 8. The microhardness of the steel–titanium boundary after explosion welding

The dark stripes are probably either dirty accumulated along the step during the polishing or the shadow of the step resulting from illumination of the section by the microscope lamp.

The microhardness measurement of the white spots and steel around them at a load of 10 g showed their equivalence, indicating that they were not intermetallic compounds.

The quality of the titanium–steel joint made by explosion welding was tested using the standard bending, layer separation, and layer shear tests.

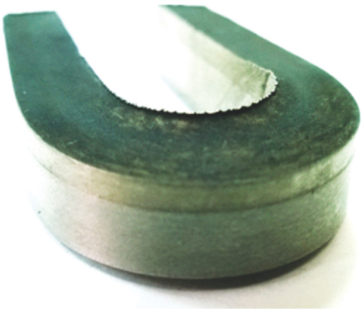


Fig. 9. Bimetal steel–titanium sample after bending test

Figure 9 shows a sample after the bending test.

Bent at an angle of 180°, the sample retained integrity and no layer separation occurred. It is quite a severe test, and if the welding is of poor quality, the bond line is broken.

Figure 10 shows the scheme of the bimetal layer separation test and the general view of the samples.

The samples were broken along steel–titanium interface, which is typical of this pair of metals. The breaking strength was 375 MPa. The tension test of the titanium sheet in the initial state showed that the yield point was 390 MPa and the breaking point was 430 MPa.

The layer shear tests (Fig. 11) showed the strength at a level of 350 MPa. This high shearing strength comparable with the peel strength is obtained due to the wavy steel–titanium bond line.

The operation conditions of the adapter do not imply application of loads leading to layer shearing or peeling, and the bond strength can therefore be considered satisfactory.

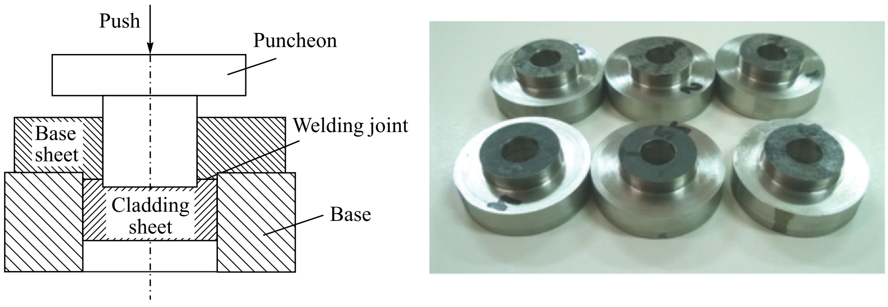


Fig. 10. The scheme of layer tear test and the general appearance of the samples

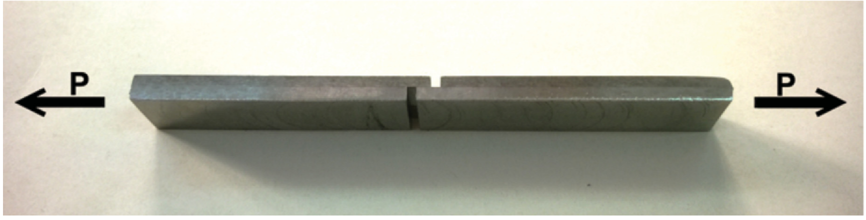


Fig. 11. The scheme of layer shear test

Thus, the investigations allow stating that the developed regime for welding a trimetallic billet for the adapter is close to optimum.

Work hardening of the metals and residual stresses in the resulting trimetal can be relieved by thermal treatment. It is safe to heat this composition to 600°C. Heating above 700°C causes intensive formation of intermetallic compounds and carbides.

When titanium is welded to austenite steels, the necessity of thermal treatment should be carefully considered because austenite, when heated and cooled, can transform to martensite, which changes properties of steel, including its magnetization.

Effectiveness of using thermal treatment to improve mechanical properties of the trimetal was investigated in the samples thermally treated by heating to 600°C, holding up for 1 h, and cooling in the air. The layer peel strength was 325 MPa (375 without thermal treatment), and the layer shear strength was 345 MPa (350 without thermal treatment). No significant difference in the microstructure of the metals in the bond area was found between the thermally treated and untreated samples of the same trimetallic billet. Microhardness obtained by the Vickers test at a load of 10 g was 2500 MPa for steel (2600 without thermal treatment) and 2600 MPa for titanium (2150 without thermal treatment). In the microsections, a lot of white spots observed at the bond line had microhardness of 2300 MPa and were not intermetallics. They are most likely to be metal micromelts resulting from the explosion welding. No intermetallic compounds were found in the microsecitons. Thus, the above thermal treatment regime did not affect properties of the trimetal. To increase the annealing temperature is undesirable because it can cause formation of intermetallics and change the properties of austenite steel. A tentative conclusion is that thermal treatment of the trimetallic billets is unreasonable because it only increases the cost of the adapter.

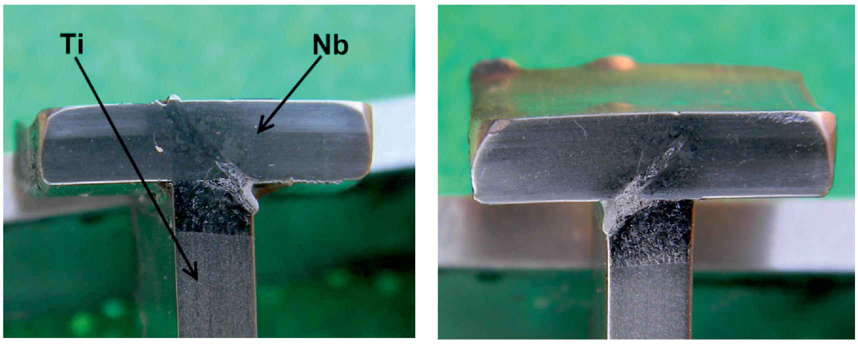
CHOICE OF ELECTRON BEAM WELDING REGIMES

Highly pure niobium used for manufacturing the adapter requires that all thermal operations, including welding, be carried out in a vacuum environment.

Electron beam welding (EBW) suits best to our purposes because the process occurs in a high-vacuum chamber.

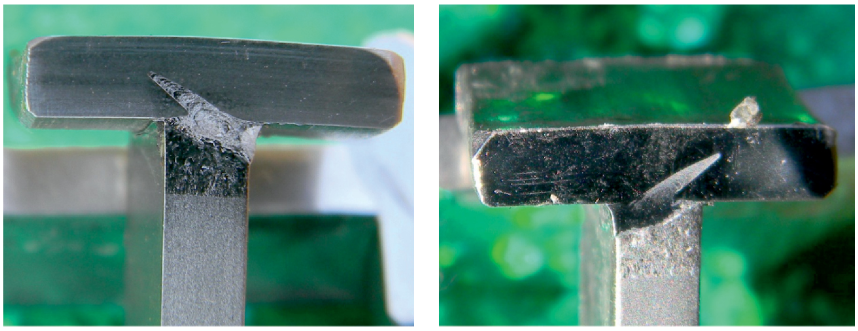
The parts to be welded by the electron beam should be in as close a contact as possible. Since the niobium pipe has initial out-of-roundness, the gaps between the niobium pipe and the edge of the hole in the trimetallic disc are in some places unsuitably large for EBW. To eliminate this fault, a device was made for fixing the pipe in the hole of the disc. The disc with pipe in it was chucked in the lathe, and the cutter was replaced with a roll. By rolling the niobium pipe from inside, it was brought to a tight contact with the edges of the hole in the disc.

The prototype adapter was made using the preliminary EBW regime. Investigation of the bond structure showed that titanium penetration depth was about 1 mm. According to the EBW experts with broad experience in making tight, including helium-tight, welds, this penetration depth is quite enough for ensuring helium tightness. At the same time the adapter can be affected by loads arising from the excess pressure inside the cryomodule due to the vacuum on the outer side of the adapter, possible heating of helium by structural elements of the



Regime 1. Width of joint 1.5 mm

Regime 2. Width of joint 1.9 mm



Regime 3. Width of joint 2.75 mm

Regime 4. Width of joint 2.1 mm

Fig. 12. Niobium–titanium joints microsections obtained by electron beam welding

cryomodule as it is filled with liquid helium, and heat conduction of the adapter which is in contact with the shell through the loop. In this connection is seems reasonable to make a maximum thick weld while avoiding complete penetration of titanium and niobium by the electron beam. In the model sample, the niobium pipe was welded in the 3-mm-thick titanium disc using four EBW regimes. Figure 12 shows microsections of the resulting joints, and their widths are given.

The deepest penetration was obtained in regimes 3 and 4. They will be used to manufacture further adapters. The particular choice will depend on the thickness of titanium after machining in the process of making the disc from the trimetallic billet. To date, two adapters have been made, one of which was thermally treated. Both adapters were tested by thermal cycling in liquid nitrogen and then in liquid helium. The thermal cycling in liquid nitrogen was performed at the INFN, Pisa, Italy. The adapter was cooled by liquid nitrogen in a Dewar flask with a sufficiently wide opening. Attainment of temperature of 77 K was determined by visually observing termination of liquid nitrogen "boiling" around the adapter (Fig. 13).

Fig. 13. Cooling in liquid nitrogen

Fig. 14. Heating with heat guns

Then the adapter was taken out and heated to room temperature by a heat guns (Fig. 14). This procedure was repeated six to seven times. Thermal cycling with liquid helium was performed at the INFN, Genoa, Italy. A Dewar flask with a wide opening was also used. Attainment of temperature of 4.2 K was determined by thermal sensors attached to the adapter. The cooling–heating procedure was carried out only twice due to its complexity and for helium saving. After each type of thermal cycling the adapters were tested for helium leak. In all cases the test results were positive: helium leak measurements performed in Pisa after the thermal cycling of two adapters in liquid nitrogen helium revealed no leaks at a background leak rate of $0.4 \cdot 10^{-10}$ atm · cc/s [6].

In the nearest plans there is an adapter–cavity joining test, which consists in electron-beam welding of niobium rings to niobium pipes in the adapters, and

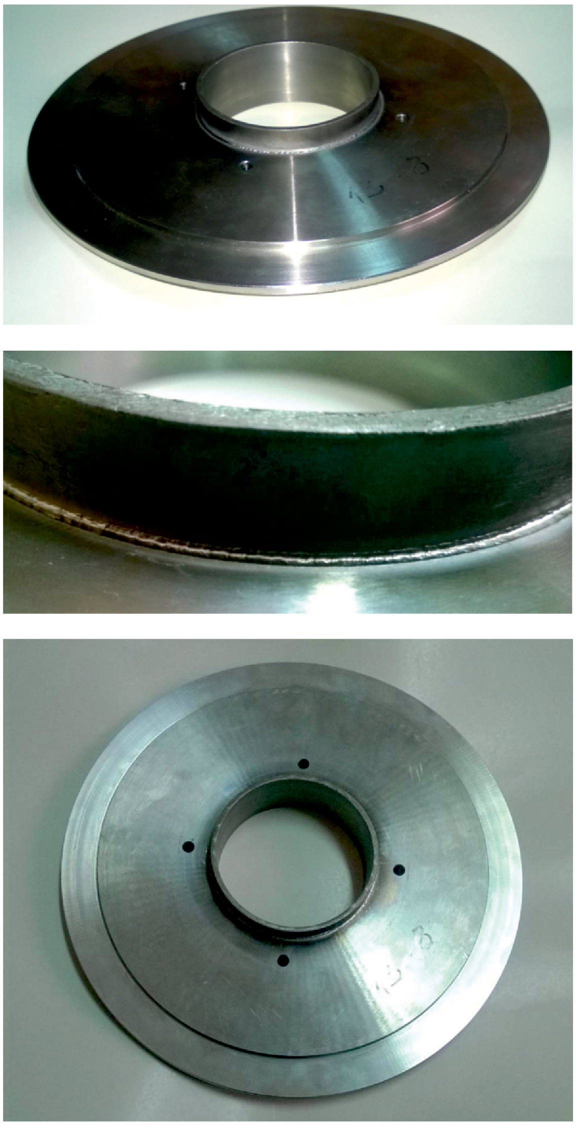


Fig. 15. Appearance of combined adapter

subsequent thermal cycling tests with liquid nitrogen and liquid helium. The tests are planned to be performed in Pisa and Genoa.

Figure 15 shows the appearance of the adapter. The holes are made for performing some investigations, while actually there will be no holes in the adapter.

CONCLUSIONS

1. The adapter is designed which is suitable for manufacturing a linear collider cryomodule and eliminates the necessity to weld niobium to steel.

2. An explosion welding technology is developed that allows a trimetallic billet for manufacturing an adapter to be made such that the niobium–titanium bond is free of intermetallic compounds and the effect of the difference in the linear expansion coefficients of the ensemble components is eliminated.

3. Regimes for EBW of niobium to titanium are chosen which tentatively meet the adapter operation requirements.

REFERENCES

1. Sabirov B. *“Explosion Welding: New Design of the ILC Cryomodule”*. JINR News, 2010, No. 3, p. 16.
2. “*Electric Welding Technology of Metalls and Alloys by Melting”* (Rus.). Ed. by B. E. Paton. Moscow: Mashinostroenije, 1974.
3. Sabirov B. et al., “*Recent Advances in Ti and Nb Explosion Welding with Stainless Steel for 2K Operating (ILC Program)”*, Proceedings of the International Workshop on Future Linear Colliders (LCWS11), Spain, Granada, 26–30 September, 2011, arXiv:1201.3472.
4. Sabirov B. et al.,*”Modernisation of the ILC Cryomodule Using High-Tech Technology — Explosion Welding*”, XXIV Russian Particle Accelerator Conference (RuPAC’2014), Obninsk, Russia, 6–10 October, 2014.
5. Lisak V. I., Kuzmin S. V. “*Explosion Welding*” (Rus.). Moscow: Mashinostroenie, 2005, 511 p.
6. Basti A. et al.,”*Optimization of ILC Cryomodule Design Using Explosion Welding Technology”*, International Particle Accelerator Conference (IPAC’15), Richmond, Virginia, 3–8 May, 2015.

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