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RECENT OPTIMIZED DESIGN OF **ILC** CRYOMODULE WITH EXPLOSION WELDING TECHNOLOGY

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Сабиров Б. и др. E9-2017-23
Новая оптимизированная конструкция криомодуля ILC, полученная с использованием технологии сварки взрывом

В статье суммированы результаты тестов усовершенствованных компонентов криомодуля международного линейного коллайдера (ILC), полученные коллаборацией ОИЯИ (Дубна), INFN (Пиза/Генуя, Италия) и ИЭС им. Е. О. Патона (Киев, Украина). Первоначально конструкция сверхпроводящего радиочастотного резонатора, разработанная в DESY как резонатор ТЕСЛА 1,3 ГГц, состоящий из 9 ячеек, была изготовлена из ниобия и помещена в титановый дьюар, имеющий титановый патрубок для подачи и удаления двухфазной гелиевой смеси. Для удешевления проекта ILC было предложено заменить титановые компоненты на компоненты из нержавеющей стали (SS), используя уникальный метод сварки взрывом, открывающий возможность создания криомодулей нового поколения для ускорителей частиц. Эти компоненты криогенной системы работают при сверхнизких температурах сверхжидкого гелия — 1,8 К. В результате поэтапной модернизации этих компонентов получена финальная версия переходника Nb/Ti/SS, которая привела к эволюционному улучшению криомодуля ILC. Благодаря этому новому элементу решается проблема остаточных напряженностей и предотвращаются возможные специфические сдвиги, обусловленные разностью коэффициентов линейного расширения составляющих металлов. При испытании на гелиевую течь не обнаружена течь из испытуемых образцов при величине фоновой течи $\approx 0{,}4 \cdot 10^{-10}$ атм $\cdot$ см$^3 \cdot$ с$^{-1}$.

Результаты тестов весьма обнадеживающие. Новая конструкция триметаллического Nb/Ti/SS образца обещает более технологическое и более дешевое производство. Исследования показали, что триметаллические компоненты могут быть использованы в ускорительной технике, в исследовательском оборудовании, а также в гражданских инженерных задачах.

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Sabirov B. et al. E9-2017-23
Recent Optimized Design of ILC Cryomodule with Explosion Welding Technology

This paper summarizes the test results of modified components for the cryomodule of the International Linear Collider (ILC) obtained by the international collaboration of JINR (Dubna), INFN (Pisa/Genova, Italy), and PWI (Kyiv, Ukraine). Initially, the baseline design for the superconducting RF cavities of the ILC is the TESLA 1.3 GHz cavity design developed at DESY consisting of a 9-cell cavity structure of Nb sheet material and Ti for the surrounding helium vessel and for the biphase He gas return pipe. To make the ILC project even cheaper, it is proposed to replace titanium cryomodule components with stainless steel (SS) ones using a unique method based on explosion welding, opening up the possibility to develop a new generation of cryomodules for particle accelerators. These cryogenic system components operate at superlow temperatures, as niobium cavities are contained in a stainless steel vessel filled with superfluid liquid helium at 1.8 K. Stepwise upgrading of these components to the latest version of the Nb/Ti/SS transition element has led to an evolutionary improvement of the ILC cryomodule. This new component resolves problems of residual stress, and its peculiar design prevents the possibility of a shift due to the difference in the linear expansion coefficients of the constituent metals. Helium leak testing found no leaks at the background rate of $\approx 0.4 \cdot 10^{-10}$ atm $\cdot$ cm$^3 \cdot$ s^{-1}.

The results of these tests are very encouraging. The newly developed design of triple-metallic Nb/Ti/SS samples promises more technological and cheaper manufacture. Investigations have shown that explosion welding allows unique trimetallic components to be made for cryogenic units of accelerators, research equipment, and civil engineering tasks.

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

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INTRODUCTION

Over the recent years, we have made a great progress in developing and demonstrating the enabling technology needed for a linear collider for the modernization of the cryomodule for the International Linear Collider (ILC) in the framework of collaboration between JINR (Dubna), INFN (Pisa/Genova, Italy), and PWI (Kyiv, Ukraine) [1, 2].

Based on our experience [3], the collaboration got down to creating a transition specimens between the steel shell of the cryomodule vessel and the niobium cavity (Fig. 1). Trimetallic Nb + Ti + SS specimens were produced using the explosion welding and successfully tested at liquid nitrogen and liquid helium temperatures. This version deserves special attention for its manufacturability, simpler design, guaranteed strength and reliability of the joint, and above all for an appreciably lower cost. It is a promising new transition joint technology based on cladding side surfaces of a steel flange by titanium using explosion bonding and welding a Nb pipe to titanium by electron beam welding (EBW) [4].

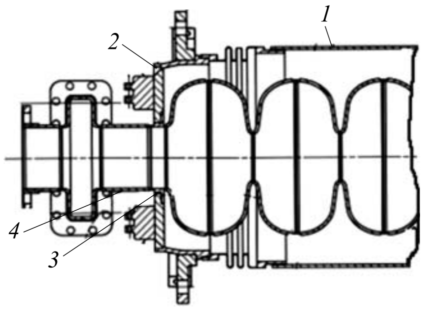

Fig. 1. Scheme of combined adapter connection with a cryogenic module: *1* — steel shell; *2* — electron beam welding or argon arc welding connection of shell with steel flange of adapter; *3* — steel flange; *4* — niobium tube

PROBLEM DEFINITION

It is known that welding of similar materials gives the best results. The adapter should consist of at least two metals — niobium and stainless steel. No fusion welding, including electron beam welding, is suitable for joining niobium and stainless steel because it results in formation of intermetallic compounds like Nb_xFe_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.

Previous 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. 2). 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.

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.

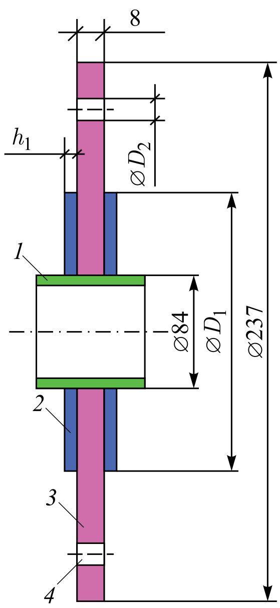

Fig. 2. The design of the adapter, ensuring the absence of niobium intermetallic formations during welding: *1* — niobium tube; *2* — titanium claddings; *3* — stainless steel plate; *4* — holes

— 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 welded 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 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. 3). In optimum explosion welding regimes the heat-affected zone is very small, as is the existence time of high temperature.

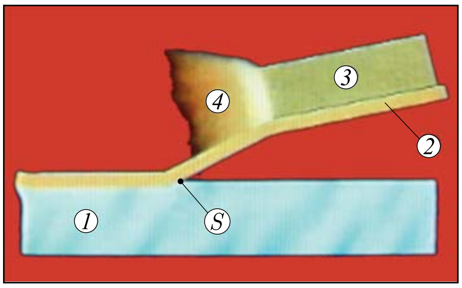

Fig. 3. Principal scheme of explosion welding process with an angle between metal sheets: *1* — base plate; *2* — cladding plate; *3* — explosive; *4* — detonation products; *S* — point (line) of contact of surfaces during welding

The surfaces of the metals to be joined suffer plastic deformation creating a wave pattern bond line. An increase in the welding energy (collision energy of plates) increases wave parameters.

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 explosion 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 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 [5].

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. Plates with dimensions 250×250 and 300×700 mm were welded. After the explosion and the fabrication of the trimetal, the planishing was performed on an industrial rolling mill to eliminate local deformation to make the billet flat. The necessity of planishing is demonstrated in Fig. 4.

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 5 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.

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

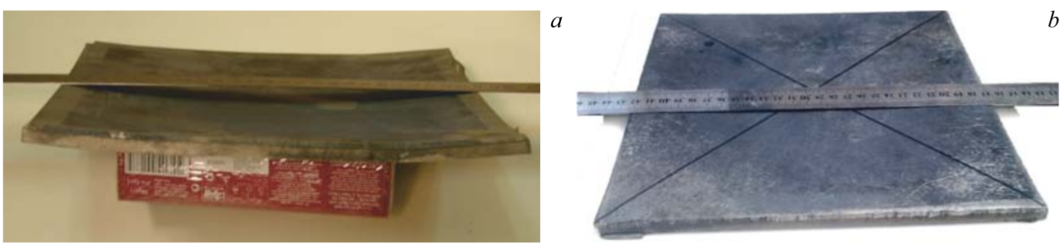

Fig. 4. View of the billet after explosion welding: *a*) before planishing; *b*) after planishing

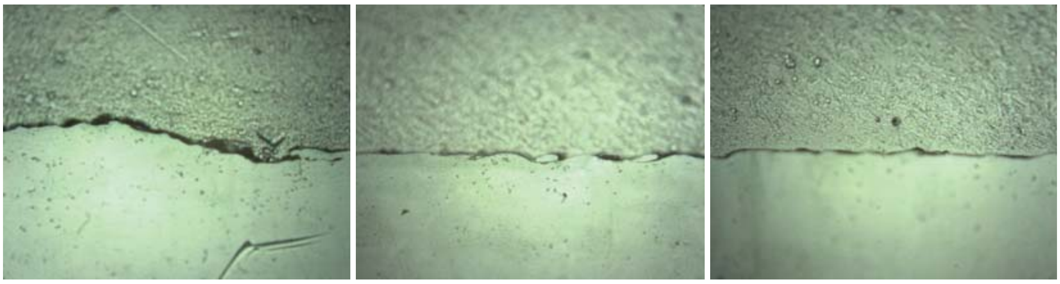

Fig. 5. Microstructure of steel–titanium joint obtained by explosion welding (magnification $\times 400$)

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. 6.

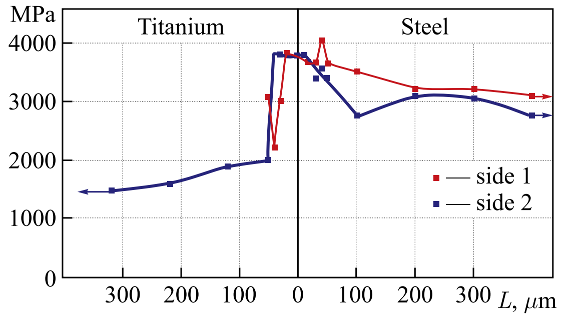

Fig. 6. The microhardness of the steel–titanium boundary after explosion welding

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 one of initial steel is 1700–1900 MPa. It is known that hardness of intermetallic compounds like Fe_xTi_y is above 9000 MPa. It is evident from Fig. 6 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 quality of the titanium–steel joint made by explosion welding was tested using the standard bending, layer separation, and layer shear tests.

Figure 7 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.

Fig. 7. Bimetal steel–titanium sample after bending test

Figure 8 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.

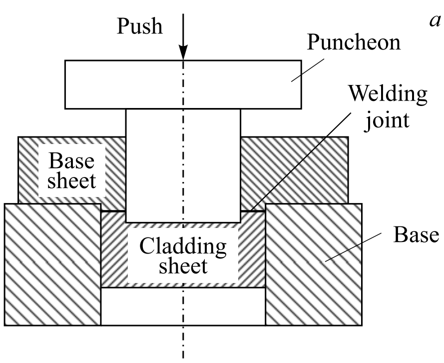

Fig. 8. Scheme of layer tear test (*a*) and the general view of the samples (*b*)

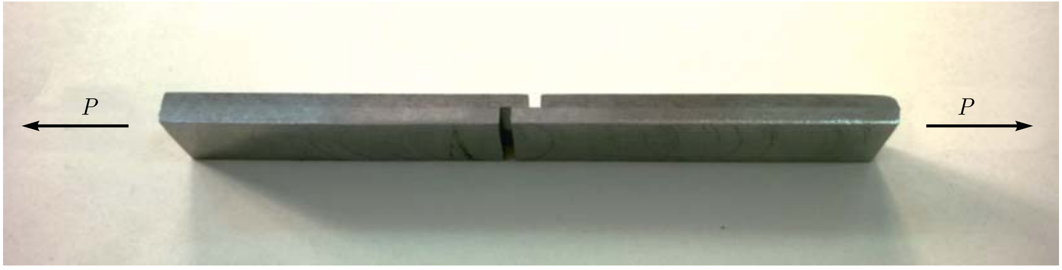

Fig. 9. Scheme of layer shear test

The layer shear tests (Fig. 9) 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.

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. To increase the annealing temperature is undesirable because it can cause formation of intermetallics and change the properties of austenite steel.

Electron beam welding (EBW) process of niobium tube with titanium clad occurs in a high-vacuum chamber in the deepest penetration regime. To date, two adapters have been made (Fig. 10), one of which was thermally treated.

The test results are rather optimistic and encouraging: the strength of joining characterized by power of share ∼250 MPa; the joining density characterized by absence of leak at background leak rate $\sim 4.7 \cdot 10^{-9}$ mbar $\cdot\, l \cdot s^{-1}$, measured at variety extreme conditions: thermocycles at temperature 77 and 2 K, at pressure 6.5 atm; test at high temperature thermoload; exposure to ultrasonic radiation. The developed technology for a trimetallic billet for manufacturing an adapter is 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.

In all cases the test results were positive: helium leak measurements performed in Pisa after the thermal cycling of two adapters in liquid nitrogen and helium revealed no leaks at a background leak rate of $0.4 \cdot 10^{-10}$ atm $\cdot$ cm$^3 \cdot$ s^{-1} [6].

The next test is the *crucial* one: for imitation of using transition sample in real working position, connected with Nb cavity, Nb rings were joint with Nb pipe of samples by EBW. 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

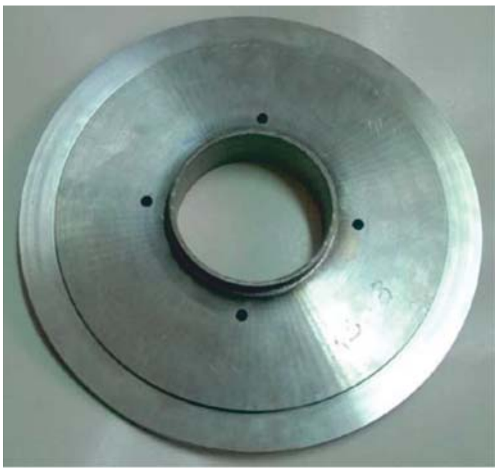

Fig. 10. View of a combined adapter

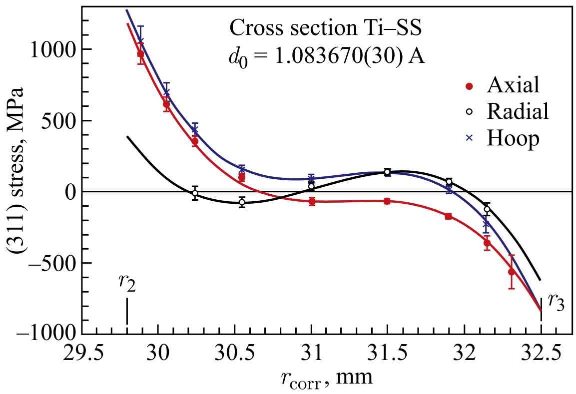

Fig. 11. Measured (points) and fitted (curves) radial dependence of the stress tensor components obtained for the peak (311) in the Ti + SS cross section

2460 °C), and ultimately due to the thermal load at an extremely low helium temperature of 4 K. Superposition of all these residual stresses may result in plastic deformation, failure of welds, and consequently, occurrence of a leak. Electron beam welding of Nb rings to Nb pipe were made at ZANON company, Milano. Test result issued absence of leak at background leak rate of $\approx 0.5 \cdot 10^{-10}$ atm $\cdot$ cm$^3 \cdot$ s^{-1}. The results showed the full eligibility of the suggested design Nb + Ti + SS transition sample [6].

We have measured residual stresses in Ti + SS joint using the neutron diffraction method. Measurements were carried out with the POLDI stress diffractometer on the neutron beam from the ISIS reactor of the Paul Scherrer Institute (Switzerland) [7].

Measured and fitted radial dependences of the stress tensor components were obtained for the peak (311) in the Ti + SS cross section ultimate result of residual stress measurements in the bimetallic Ti + SS joint in the process of scanning the titanium-to-stainless steel joint (Fig. 11). As is evident from the plot, the residual stress is quite considerable, amounting to ≈ 1000 MPa. Considering that additional thermal loads may arise from the electron beam welding or the deep cooling in liquid helium, their superposition can make titanium turn into the state which corresponds to the deep plastic region. This may cause local microcracks in the Ti + SS (or Nb + SS) joint, which in turn may adversely affect tightness of the transition element when it is used in the cryomodule.

CONCLUSIONS

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

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, which tentatively meet the adapter operation requirements, are chosen.

4. The results showed the full eligibility of suggested design Nb + Ti + SS transition sample not only for Linear Collider but for any cryogenic system.

5. Research-based results allow to get patent of the Russian Federal Service for Intellectual Property [8].

REFERENCES

1. *Sabirov B.* Explosion Welding: New Design of the ILC Cryomodule. JINR News. 2010. No. 3. P. 16.
2. Electric Welding Technology of Metals and Alloys by Melting / Ed. by B. E. Paton. M.: Mashinostroenie, 1974 (in Russian).
3. *Sabirov B. et al.* Recent Advances in Ti and Nb Explosion Welding with Stainless Steel for 2 K Operating (ILC Program) // Proc. of the Intern. Workshop on Future Linear Colliders (LCWS11), Spain, Granada, Sept. 26–30, 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, Oct. 6–10, 2014.
5. *Lisak V. I., Kuzmin S. V.* Explosion Welding. M.: Mashinostroenie, 2005. 511 p. (in Russian).
6. *Basti A. et al.* Optimization of ILC Cryomodule Design Using Explosion Welding Technology // Intern. Particle Accelerator Conference (IPAC'15), Richmond, Virginia, May 3–8, 2015.
7. *Taran Yu. V. et al.* Residual Stresses in an Explosion Welding Titanium–Steel Bilayer Pipe by Neutron Diffraction // JINR News. 2011. No. 4. P. 16.
8. *Sabirov B. et al.* Method of Adapter Manufacturing to Connect Resonator with Casing of Collider Cryomodule, RU2540978C1, FIPS Moscow, Feb. 10, 2015.

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