The explosion welding of Ti and Nb with stainless steel and full-scale tests of joints (the world first samples)

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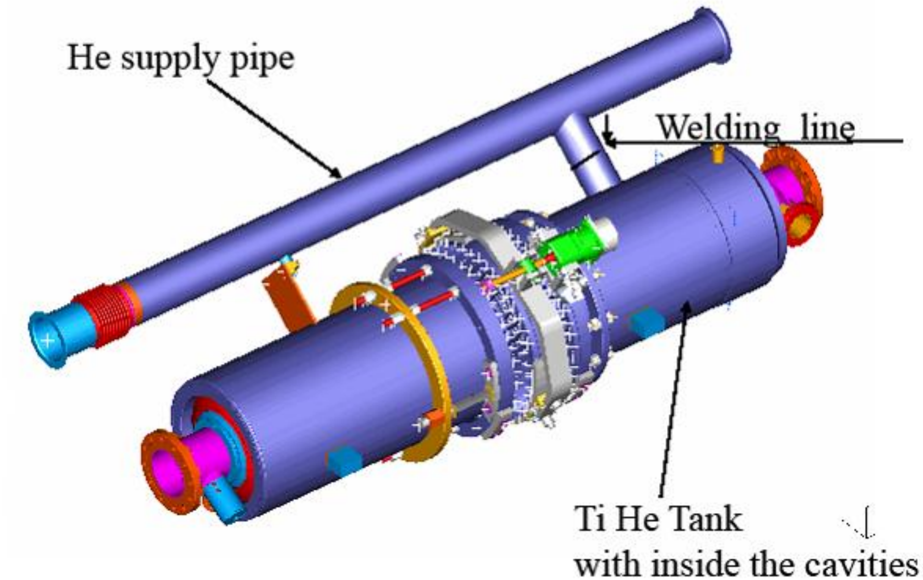
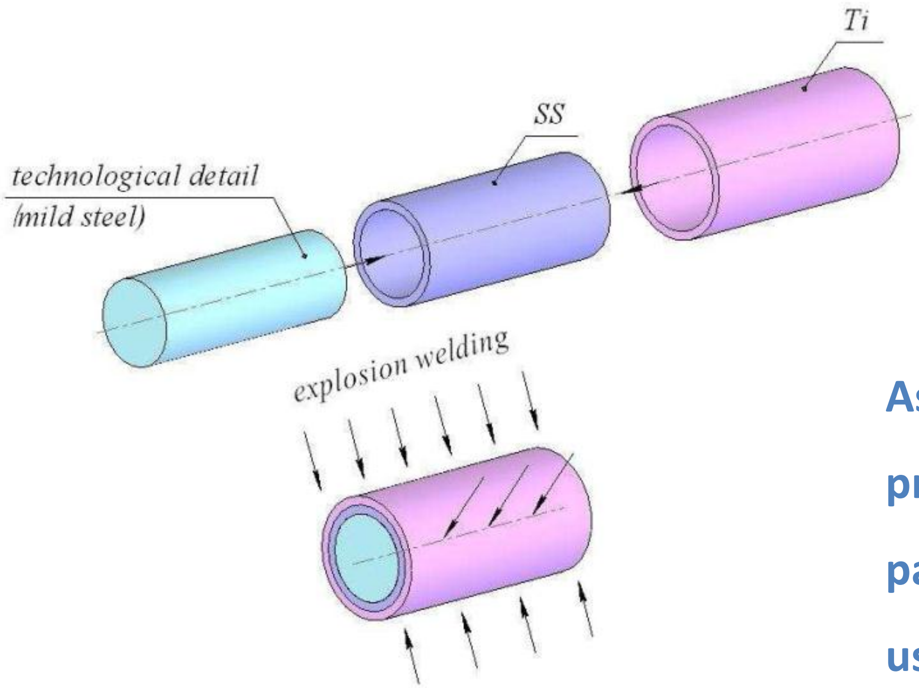
JINR group in the frame of collaboration JINR-FNAL-INFN- RFNC joined the ILC topic in 2006 and proposed to use the explosion welding technique for making bimetallic titanium–stainless steel (Ti + SS) and niobium–stainless steel (Nb + SS) joints.

ILC T4 Cryomodule



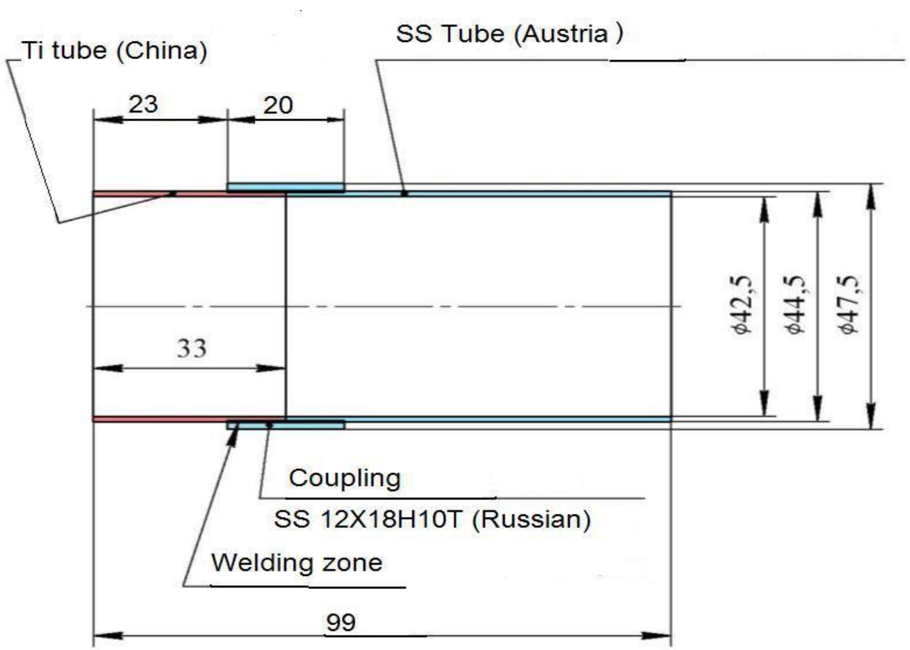
The first stage task was to make a bimetallic transition from the helium supply pipe of stainless steel (SS) to the cryomodule shell of titanium. This would appreciably lower the cost of the accelerator. It was a nontrivial problem: Ti and stainless steel cannot be welded by conventional welding techniques. We came into contact with the Russian Federal Nuclear Centre (RFNC, Sarov), where, as we knew, they have mastered a method of welding dissimilar materials by explosion.

B.Sabirov, *"Production of Bimetallic Transition Tube Elements for the ILC Cryomodule",* in JINR News, 4/2008, p.19, Dubna, Russia, 2008



As starting of technological research to produce bimetallic billets of tube type parallel circuit for explosion welding was used.

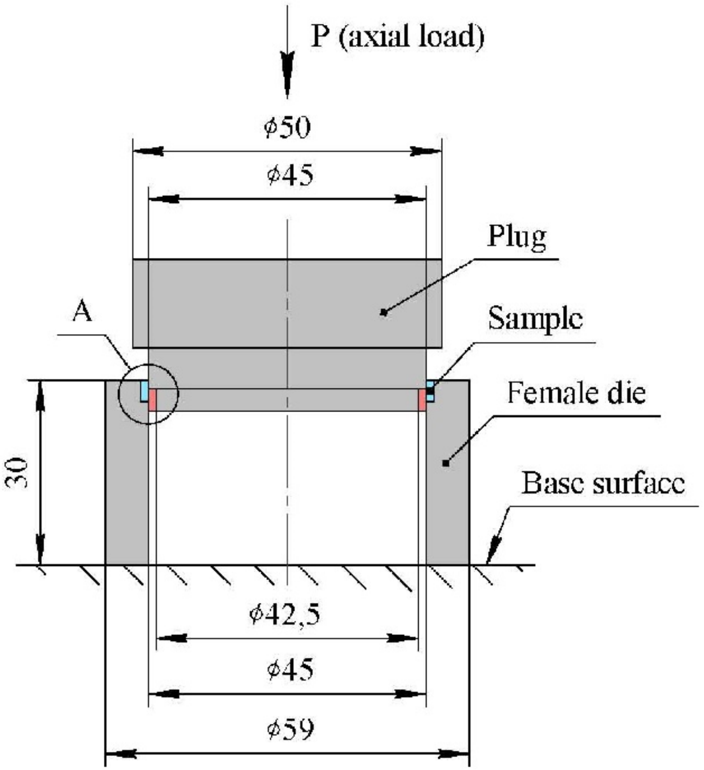
•US Patent 5190831 - *Bonded titanium/steel components;* US Patent Issued on March 2, 1993, USA.
•K.Szymlek, “*Review of Titanium and Steel Welding Methods*”, Ship Materials, Corrosion and Environment Protection Division Gdansk, Poland, DOI:10,2478/v10077-008-0023-4

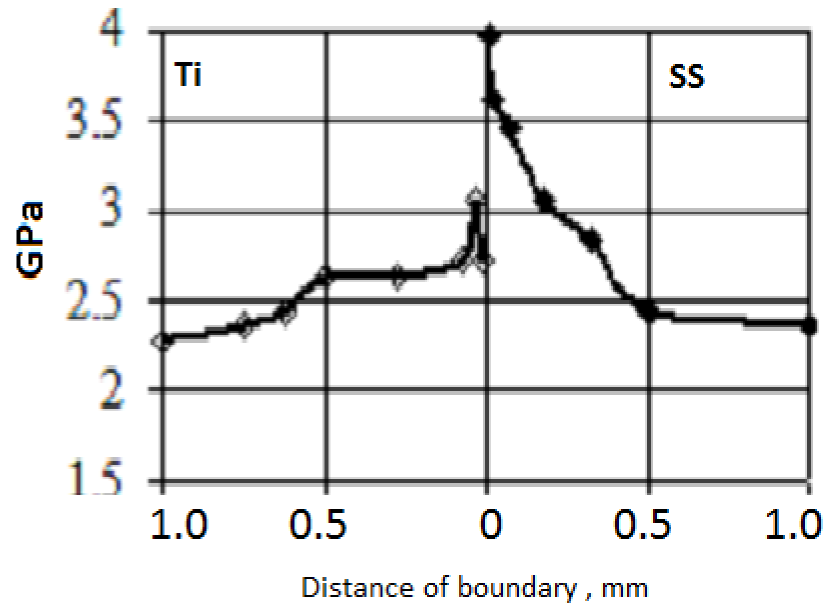


Analysis of tube bimetal billet shows that this variant is not optimal according to material capacity and design. Therefore we chose the technology that assumed production of bimetal billet of tube type of Grade 2 titanium (China) and stainless steel TP316/TP316L (Austria) applying joint sleeve from stainless steel 12Cr18Ni10Ti (Russia).

To produce this variant of bimetallic transition sample we used parallel scheme of explosion welding as in the first case .

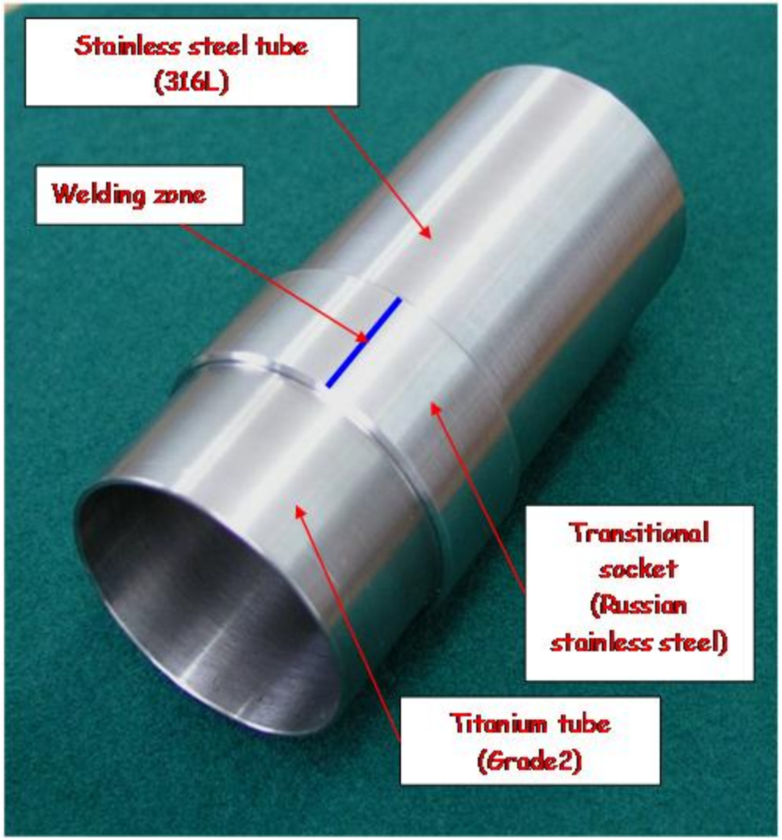
•I.Malkov et al., *"Investigation of the Possibility of Production the Bimetallic Tube Transition Element by Explosion Welding for the Cryomodule of the International Linear Collider"*, JINR, E13-2008-109, Dubna, 2008, Russia.





Measurement of the welded joint shear strength was carried out. An impressive result is obtained: $\zeta_{sh} \approx 250$ MPa.

Metal strengthening is observed in the welded joint area. The highest material strengthening occurs in a narrow area ~0.5 mm wide near the titanium-steel interface; beyond this area strengthening decreases.

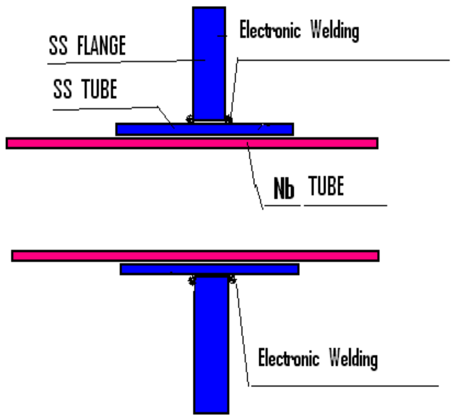


The pilot specimen was severely tested for strength and leakage. The tests were carried out in Sarov and Dubna (Russia), Pisa (Italy), and Fermilab (USA) under various shock conditions: thermal cycling in liquid nitrogen, cooling to 2K, pressure up to 6 atm inside the specimen. The leak test showed absence of leakage at the leak detector background indication ≈10^{-10} atm·cm^3·s^{-1}. To verify the results, we manufactured and tested another 24 Ti + SS transition elements. The tests for leakage and strength of the joints yielded similar results.

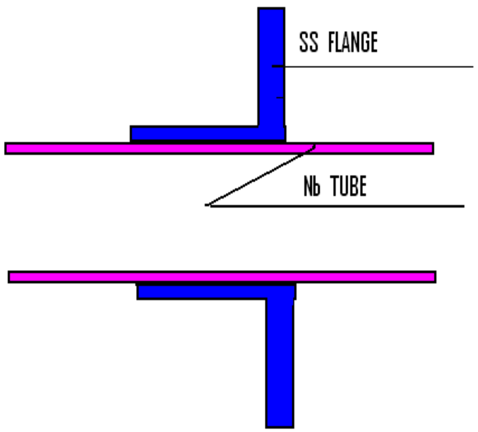
- A.Basti et al., *"Characterization measurements of Ti-SS Bimetallic transition joint samples"*, ILC-NOTE-2008-044, May 2008;   JINR, E13-2008-111, Dubna,2008.
- W.Soyars et al., "*Superfluid Helium Testing of a Stainless Steel to Titanium Piping Transition Joint", «*Cryogenic Engineering Conference», 2009 at Tuscon, Arizona, USA.

Based on the experience gained with the Ti + SS specimens, we got down to solving the next problem set to us by the ILC management: to make the ILC project even cheaper, it was proposed to consider a possibility of replacing titanium with stainless steel in the shell of the helium cryostat. Thus, it was necessary to develop a transition from the stainless-steel shell to the niobium cavity—the main acceleration element of the accelerator.

Four Nb + SS elements were produced at RFNC (Sarov, RUSSIA) using two explosion welding schemes – external and internal :



External cladding scheme



Internal cladding scheme

Sabirov B. "Explosion welding: New Design of the ILC Cryomodule". JINR NEWS, 3/2010, p.16, Dubna,2010.

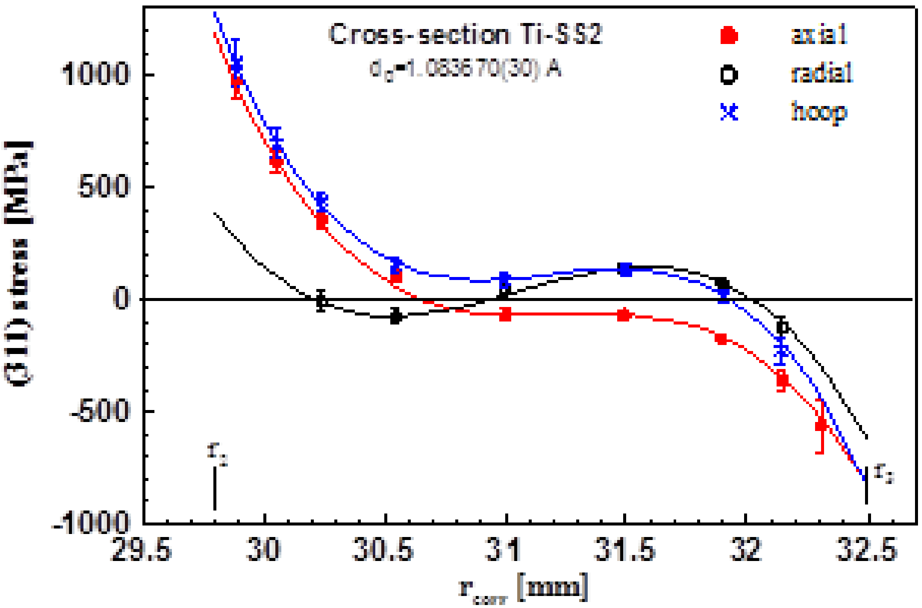
Leak tests by thermal cycling in liquid nitrogen carried out with all Nb–stainless steel joint in samples made by both internal and external cladding showed rather good results: after six thermal cycles and ultrasonic cleaning no leakage was found in the specimens at the background leak detector indication $2 \cdot 10^{-9}$ atm·cm^3/s (gaseous He was used for vacuum testing).

As far as NB + SS transition elements could be used in cryomodules of the ILC, the niobium tube from Nb+SS transition should be welded to the niobium cavity. Since the niobium melting temperature is 2460^{o}C, the question arises as to how the Nb + SS joint will withstand this high thermal load.

Niobium rings of the size corresponding to the size of the niobium tube were welded to the tube on both sides by electron-beam welding at the Sciaky Company (Chicago). The very first leak measurement at room temperature revealed large leaks at two points on the joint of niobium and stainless steel. The holes were stopped with the Apiezon-Q vacuum paste, and the test was continued in the LN_2 thermal cycling regime. After the third cycle one more leak appeared.

It is well known that in result of machining, forging, welding, etc. may give rise of residual internal stresses inside the material or product due to its plastic deformation. Destruction of mechanical components or structures results not only from stresses arising in the course of their use but also from the superposition of the former stresses on the residual stresses.

For residual stress measuring we used results from nondestructive neutron diffraction measurements .



Measurements were carried out with the POLDI stress diffractometer on the neutron beam from the ISIS reactor of the Paul Scherrer Institute (Switzerland). The residual stresses in the bimetallic Ti + SS tube measured during the scanning of the titanium–stainless steel joint are shown in the picture.

As is evident from the plot, the residual stress is quite considerable, amounting to ~1000 MPa. Since additional thermal stresses may arise from electron-beam welding or deep cooling in liquid helium, their superposition can make titanium turn into the state corresponding 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.

Yu.V.Taran, B.M.Sabirov et al, *"Residual Stresses in an Explosion Welding Titanium-Steel Bilayer Pipe by Neutron Diffraction ", JINR NEWS, 4/2011, Dubna, Russia (in press)*

It was decided to subject other Nb + SS transition elements to annealing for relaxation of residual stresses both before and after the electron-beam welding. The leak test was carried in the six LN_2 thermocycling regime using the Dupont (Ametek upgrade) leak detector

The table presents the measurement results for one of the cycles.

Cycle 2	Specimen 1	Specimen 2
Background leak at room temperature	$1.0 \cdot 10^{-9}$ atm·cc/s	$5.3 \cdot 10^{-9}$ atm·cc/s
Background leak at 77 K	No change	No change
Specimen in polyethylene package, gaseous He injected, 77 K	$1.2 \cdot 10^{-9}$ atm·cc/s	$5.0 \cdot 10^{-9}$ atm·cc/s
Specimen heated to room temperature, gaseous He injected	No change	$4.9 \cdot 10^{-9}$ atm·cc/s

One-hour long measurements with the Residual Gas Analyzer (RGS) after evacuation down to 10^{-9} Torr at the temperature 2 K and background level $4.6 \cdot 10^{-9}$ atm·cc/s did not reveal any leak in specimens.

Conclusion

The samples of Ti+SS and Nb+SS joints were manufactured by an explosion welding technology demonstrating a high mechanic properties and leak absence at 2K with background leak level of $4.6 \cdot 10^{-9}$ atm·cc/sec. Residual stresses resulting from explosion welding are quite high and may cause plastic deformation and destruction of bonding of the materials. The annealing of explosion-welded Ti + SS and Nb + SS specimens leads to complete relaxation of internal stresses in Ti, Nb + stainless steel joints and makes the transition elements quite serviceable. Investigations have shown that explosion welding allows unique bimetallic components to be made for cryogenic units of accelerators, research equipment and for other civil engineering tasks.

To optimize the explosion welding technique and gain statistics, we plan to produce ten more Nb+SS transition elements using both welding schemes, external and internal cladding. This work will be done by the world-known Paton Electric Welding Institute (Kiev, Ukraine), which has great experience in welding various materials using a great variety of welding techniques, including explosion welding. We plan to conduct these investigations within the year 2012.