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SUPERFLUID HELIUM TESTING OF A STAINLESS STEEL TO TITANIUM PIPING TRANSITION JOINT

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Басти А. и др. E13-2009-175
Тестирование в сверхтекучем гелии трубных переходников
нержавеющая сталь – титан

Изготовлены биметаллические (нержавеющая сталь – титан) переходники методом взрыва. Эта оригинальная методика соединения реализована в Российском федеральном ядерном центре (Саров) на основе договора с Объединенным институтом ядерных исследований (Дубна). Биметаллические переходники предполагается использовать в будущих сверхпроводящих радиочастотных резонаторах в конструкции криомодулей. Такое применение требует криогенных испытаний образцов для демонстрации факта, что эти переходники остаются герметичными при контакте с жидким гелием. Для моделирования соединения сервисной трубы из нержавеющей стали и титанового дьюара с резонатором внутри биметаллические трубки были соединены для создания трубных ансамблей. Ансамбли были протестированы в условиях сверхтекучего гелия на испытательных стендах Национальной ускорительной лаборатории им. Ферми (FNAL). Дано описание программы тестов переходников, а также представлены созданная методика и результаты тестов.

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Superfluid Helium Testing of a Stainless Steel to Titanium
Piping Transition Joint

Stainless steel-to-titanium bimetallic transitions have been fabricated with an explosively bonded joint. This novel joining technique was conducted by the Russian Federal Nuclear Center (Sarov) working under contract for the Joint Institute for Nuclear Research (Dubna). These bimetallic transitions are being considered for use in future superconducting radio-frequency cavity cryomodule assemblies. This application requires cryogenic testing to demonstrate that this transition joint remains leak-tight when sealing superfluid helium. To simulate a titanium cavity vessel connection to a stainless steel supply pipe, bimetallic transition joints were paired together to fabricate piping assemblies. These piping assemblies were then tested in superfluid helium conditions at Fermi National Accelerator Laboratory (USA) test facilities. The transition joint test program has been described. Fabrication experience and test results have been presented.

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

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INTRODUCTION

International research and development to support the International Linear Collider (ILC) is underway. The issue considered here is the joining of dissimilar metals during Superconducting Radio-Frequency (SRF) cryomodule construction, specifically the feasibility of techniques that would allow a titanium (Ti) SRF vessel to join to a stainless steel (SS) supply tube. Since SS and Ti cannot be welded by conventional electron-beam welding methods, alternative methods are under investigation. This has been successfully done for other SRF accelerator components [1]. A joint program involving JINR (Dubna, Russia), FNAL (Batavia, USA), INFN (Pisa, Italy), and RFNC (Sarov, Russia) was conducted for further study [2].

Stainless steel-to-titanium bimetallic transitions have been fabricated with an explosively bonded joint, with a stainless steel sleeve covering the junction (see Fig. 1). This novel joining technique was conducted by the Russian Federal Nuclear Center (Sarov) working under contract for the transition piece fabricators at Joint Institute for Nuclear Research (Dubna, Russia). The design, fabrication, and characteristics of these bimetallic transitions are discussed elsewhere [3–6]. See Table 1 for description and geometry. All tubes were made with the same explosion-bonded joining procedure, with a stainless steel collar explosion bonded onto the external surface of the 316L SS and Ti Grade 2 tubes.

Fig. 1. SS-to-Ti transition joint tubes

Project requirements have established the maximum integral leak rate for the transition tubes. It is not to exceed $1 \cdot 10^{-10}$ Pa $\cdot$ m^3/s at room temperature and $1 \cdot 10^{-9}$ Pa $\cdot$ m^3/s at LN_2 temperature. The goal is to test the transition tubes in

Table 1. Ti–SS bimetallic tubes for test program

Assembly designation	Fabrication year	Tube designation	OD, mm	Wall thick, mm	Length, mm
I	2008	5A, 6A	47	1.95	190
II	2008	8A, 9A	47	1.95	190
III	2008	3N, 7N	47	1.95	190
IV	2009	5N, 6N	60	2.5	170
V	2009	9N, 11N	60	2.5	170

superfluid helium conditions at Fermilab to see how well they seal under actual service conditions.

ASSEMBLY FABRICATION EXPERIENCE

The final assembly of test articles was completed at Fermilab. Five bimetallic transition joint test assemblies were made for attachment to the cryogenic test system, each with a pair of transition tubes (See Fig. 2). Also noted in Table 1, two versions of this size transition joint are available: non-annealed (N) or annealed (A) (after the explosion-bonding procedure).

Fig. 2. The transition joint test assemblies, 47 mm OD version. Each has a pair of transition joints

Initial Leak Checking. Before a bimetallic transition tube was shipped to Fermilab for a final assembly, it was qualified as leak-tight at various conditions and multiple thermal cycles at INFN (Pisa) and at JINR (Dubna) [7, 8]. These successful initial results were repeated at Fermilab. See Table 2 for initial values.

Note, some transition samples were rejected because they did not pass the initial leak check after the joining process. For the tubes made in 2009, five out of thirteen total passed. It is believed that better tolerancing of the Ti wall thickness may help improve this acceptance percentage [8].

Welding Temperature. Transition joint test article assembly titanium tubes were welded inside a LABCONCO glove box at argon atmosphere. Even though no specification on a temperature limit for the explosion-bond exists, means to minimize the temperatures on the stainless steel collars during welding were investigated. Water-cooled copper heat sinks were fabricated. When cooling water was used, peak temperature was $< 50\,^{\circ}$C. When welded without water cooling, peak temperature was $< 70\,^{\circ}$C. The mild temperature increase with gas cooling only suggests that these bimetallic tubes can be welded in real condition without any special cooling, without any risk. The use of active cooling had been important to the success of other bimetallic transition usage in cryomodules [1].

Post-Fabrication Ambient Leak Checks Effect of Ultrasonic Cleaning. Since the transition joint test assembly will be installed for testing on a vacuum system that normally is used for SRF cavity beam tubes, they have to be particulate free. They received ultrasonic water cleaning. Note, none of the 47 mm transition tubes available in 2008 had previously been cleaned ultrasonically. Post-fabrication and cleaning leak check results are shown in Table 2. In both cases in which a leak was found, the leak was at the Ti end of the explosion joint on transition tube.

Table 2. Leak check results after ultrasonic cleaning

Assembly designation	He leak rate ambient at 77 K, initial, $\mathrm{Pa\cdot m^3/s}$	He leak rate at at ambient temp after ultrasonic clean, $\mathrm{Pa\cdot m^3/s}$	Comment	Tube with leak
I	$< 5\cdot10^{-11}$	$< 5\cdot10^{-11}$	OK, no leak	None
II	$< 5\cdot10^{-11}$	$\sim 1\cdot10^{-7}$	Leak	8A
III	$< 5\cdot10^{-11}$	$\sim 5\cdot10^{-11}$	Slight leak	7N
IV	$< 3\cdot10^{-11}$	$< 3\cdot10^{-13}$	OK, no leak	None
V	$< 3\cdot10^{-11}$	$< 4\cdot10^{-13}$	OK, no leak	None

For tube 8A and 7N, the hypothesis is that the bimetallic explosion-joint may have been damaged during the ultrasonic cleaning. The concern is that, at the explosion-joint, one can destroy the structure of the diffusion layer, which is only 50–100 microns thick. The leak on tube 7N actually meets the room temperature leak rate requirement. However, a positive leak indication is seen, and at ambient temperature the leak is worse than what had been seen previously at 77 K.

Based on this experience, some 60 mm transition tubes shipped in 2009 underwent extensive ultrasonic cleaning at Pisa before shipment to Fermilab. Three total samples (9, 11 and 18) were ultrasonically cleaned. Two (9, 11) were cleaned in cold distilled water — the normal procedure — and proved to have their leak-tightness unaffected. The third sample (18), was aggressively cleaned with $100\,^{\circ}$C water and afterwards showed a slight leak detected at $\sim 5 \cdot 10^{-11}$ $\mathrm{Pa \cdot m^3/s}$ sensitivity, similar to what was experienced with tube 7N [8]. However, the drastic change in leak rate, as observed for tube 8A, was not repeated. The 60 mm versions of the transition joint test assemblies were ultrasonically cleaned by Fermilab in preparation of installation and cooldown. Afterwards, both assemblies (all four tubes) proved to be leak-tight.

There have been no changes to the explosion-joint design to specifically address this issue. However, future joints will be tested for this condition and design tolerances to improve the fabrication acceptance rate may help.

SUPERFLUID TEST FACILITIES FOR ASSEMBLY LEAK CHECKS

Two different test beds are available to cool a SS-to-Ti transition joints assembly to superfluid temperatures: the A0 Vertical Test Dewar (A0 VTD) and the Meson Detector Building Horizontal Test System (HTS) [9, 10]. The general test plan is to confirm that at room temperature the assembly is initially leak free, then continuously monitor leak-rate during cooldown and superfluid operation.

Fig. 3. Transition joint test assembly, prior to installation into the A0 Vertical Test Dewar (VTD)

The primary test bed for a transition joint test assembly is the A0 Vertical Test Dewar (A0 VTD) (see Fig. 3). The major benefit of this is that the interior of the transition joint can be connected to a high vacuum residual gas analyzer for a direct leak-rate measurements while the exterior is cooled down and bathed in superfluid. Any positive He leak indication would be from the transition joint test assembly. The A0 VTD is cooled by a transient dewar-fed supply of helium.

The secondary test bed is the Meson Detector Building Horizontal Test System (MDBHTS). A benefit of this installation is that the transition joints would be tested in actual service condition: superfluid helium on the interior while surrounded by insulating vacuum. However, the main problem is that leak-rate checks must be made on the entire cryomodule system's insulating vacuum, something for which it was not designed. The HTS insulating vacuum can have a relatively high He background, is a relatively large volume, and has many frequently assembled cold connections which could be potential, small leak sources. These factors would make it difficult to make a straightforward leak-rate assessment of the bimetallic explosion-bond.

SUPERFLUID TEST RESULTS

The transition joint test assemblies have been cooled down with superfluid helium on various occasions. There was continuous monitoring for leaks, with A0 VTD using a residual gas analyzer while HTS uses a helium leak detector. Overall results are given in Table 3.

Table 3. Bimetallic transition joint assembly leak check results at superfluid conditions

Assembly designation	Test system	Intial He leak rate, ambient, $Pa \cdot m^3/s$	Duration of 2 K conditions, h	He leak rate, superfluid, $Pa \cdot m^3/s$	Final He leak rate, ambient, $Pa \cdot m^3/s$	Conclusion
I	A0 VTD	$< 5 \cdot 10^{-10}$	0.3	$< 5 \cdot 10^{-10}$	$< 2 \cdot 10^{-11}$ on different leak detector	No leak observed. Test system had low sensitivity
I	MDB HTS	$< 7 \cdot 10^{-11}$	30	$< 3 \cdot 10^{-11}$	$< 3 \cdot 10^{-11}$	No leak observed
I	A0 VTD	$< 6 \cdot 10^{-13}$	1.5	$< 6 \cdot 10^{-13}$	$< 10^{-12}$	No leak observed
I	A0 VTD	$< 2 \cdot 10^{-11}$	21	$1 \cdot 10^{-8}$ was $< 6 \cdot 10^{-12}$ for 15 h	$1 \cdot 10^{-12}$	No leak, initially. But then cold leak. Slight leak detected at room temperature

The initial test indicated no leak, yet it was performed in the presence of some new Vertical Test Dewar (VTD) hardware, which subsequently was baked-out to improve sensitivity. The second test, at MDBHTS, was successful and showed no leak for many hours. This test was terminated when a suspected cryomodule component cold leak (into the common insulating vacuum and thus leak detector) occurred during the second day of the test; this flange leak was identified and

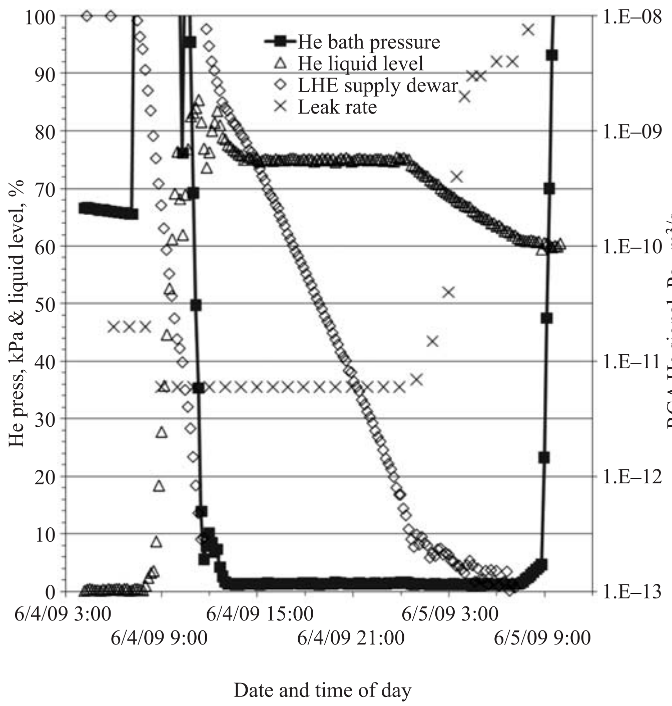

Fig. 4. The SS–Ti transition test assembly at superfluid conditions, long duration test in VTD

repaired during a subsequent warmup. MDBHTS scheduling prevented further transition joint tests here. The third test went well with no observed leaks, although it was of limited duration. The fourth test, shown in Fig. 4, revealed no leak for over 15 h, but then the RGA responded to a leak. This leak appearance coincided with the supply dewar running empty and reduction in the bath pressure about 0.1 kPa. Furthermore, the subsequent ambient temperature leak-check after this warmup confirmed the presence of a small leak.

CONCLUSIONS

JINR (Dubna) delivered bimetallic Ti–SS tubes to Fermilab to assess their ability to contain superfluid helium. Seven 47 mm tubes and five 60 mm tubes were delivered as test articles. These bimetallic tubes were verified as being initially leak-tight.

The tubes were fabricated into five assemblies by having the tubes welded in pairs for installation into a cryogenic test system. Three assemblies (six tubes) were fabricated with no change in its leak rate. However, two assemblies, of the earlier generation, had ambient condition leaks developed at a bimetallic joint, which was attributed to an ultrasonic cleaning process. For future fabrication, design tolerances to improve the fabrication acceptance rate may help.

On several occasions, a pair of tubes was cooled down and operated in a superfluid environment. The explosion-bonded SS-to-Ti transitions joints successfully contained superfluid, especially during short duration tests. One long duration test indicated a leak, however. This demonstrates that the design could be feasible for superfluid helium service, but more testing and development is required. Future superfluid leak testing still remains for the four most-recently fabricated transition tubes. These results will contribute to this further development.

While long duration testing was limited during this program due to test bed schedule requirements, we see the importance of such testing. So a future test program should emphasize longer term tests. Also, these results suggest that several thermal cycles with superfluid are valuable.

This program has been working with Ti-to-SS transitions. Future SRF cryomodule designs are considering the use of Nb-to-SS transitions. The cryogenic testing experience gained here will be useful for future superfluid testing of this concept. Facilities and methods developed here will be useful to support a test program for future transition piece assessments.

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