Stainless steel to titanium bimetallic transitions

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Abstract. In order to use stainless steel piping in an LCLS-II (Linac Coherent Light Source Upgrade) cryomodule, stainless steel to titanium bimetallic transitions are needed to connect the stainless steel piping to the titanium cavity helium vessel. Explosion bonded stainless steel to titanium transition pieces and bimetallic transition material samples have been tested. A sample transition tube was subjected to tests and x-ray examinations between tests. Samples of the bonded joint material were impact and tensile tested at room temperature as well as liquid helium temperature. The joint has been used successfully in horizontal tests of LCLS-II cavity helium vessels and is planned to be used in LCLS-II cryomodules. Results of material sample and transition tube tests will be presented.

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1. Introduction
The connection to the two-phase helium line and the cooldown helium supply lines for the dressed cavities within the LCLS-II cryomodule have a transition joint from titanium grade 2 to stainless steel 316L. The bimetallic transition tube is machined out of explosion welded material. The material consists of two plates with a very thin layer (0.010” or 0.254 mm thick) of tantalum between the two metals. The

Figure 1: Close up of polished explosion welded sample showing three different metals: Stainless Steel 316L (top), Tantalum (middle), and Titanium (bottom).
Table 1: Typical values of the base materials within the explosion weld at room and cryogenic temperatures. [1] [2] [3] [4] [5]

| Ultimate strength of base materials | Room Temperature (around 295 K) | Cryogenic Temperature |
|-------------------------------------|----------------------------------|-----------------------|
| SS316L                              | 558 MPa                          | SS316L (4 K annealed)  |
| Ti gr.2                             | 481 MPa                          | SS316L (4 K 20% cold worked) |
| Tantalum                            | 276 MPa                          | Ti gr.2 (4 K)         |
|                                     |                                  | Tantalum (70 K)       |

explosion welded material is manufactured by High Energy Metals, Inc. Case 2493 of the ASME Boiler and Pressure Vessel Code is used to qualify the butt joint transitions for cryogenic applications, which can then be welded using conventional processes to adjacent similar metals.

Similar transition joints have been developed and used at Jefferson Lab in the Spallation Neutron Source. The original Jefferson lab design did not have a tantalum layer and had a length of base metal extending 0.38” (9.7 mm) from the joint. This short length allowed the joint to get too hot during welding. The solution that was tested and implemented included adding a layer or tantalum to increase the allowed temperature and lengthening the base metal to reduce the temperature during welding. Additional welding restrictions such as heat sinking and waiting times were put in place to keep the

Figure 2: Equivalent stress of the transition joint for the vessel two-phase pipe connection at a temperature of 2 K and pressure of 0.4 MPa. The tube transition is shown with the stainless steel half on the top and titanium half on the bottom.
2. Samples

A block of the material used to machine the transitions was EDM (Electric Discharge Machining) cut into 24 samples. Some of these samples were sent to St. Louis Testing Laboratories to be tested at ambient temperature and liquid helium temperature. The tests are described in 2.1 and 2.2. The samples sent for these tests had a 10 mm square cross section, and the tensile samples were machined round by the testing lab.

2.1. Tensile Test

The ultimate strength of the joint was measured at 295 K and 4 K pulling six specimens with the methodology described in ASTM A370-14, see Table 2. The samples tested at 295 K had a ductile

| Tensile Test - Bond Ultimate Strength |
|-------------------------------------|
| Test temperature - 295 K            |
| Sample #4                          | 789 MPa |
| Sample #5                          | 788 MPa |
| Sample #7                          | 774 MPa |
| Test temperature - 4 K             |
| Sample #12                         | 1138 MPa |
| Sample #13                         | 1259 MPa |
| Sample #18                         | 1328 MPa |

joint at reduced temperatures. The new lengths for the Jefferson lab transition were 0.5” (12.7 mm) for the titanium and 1.0” (25.4 mm) for the stainless steel [6]. The lengths for the Fermilab transition are 1.0” (25.4 mm) on each side of the joint. The Fermilab transition also has an increased surface area at the joint to provide extra strength.
(a) Samples tested at 295 K. (b) Samples tested at 4 K.

Figure 4: Charpy impact test samples. The samples are shown with the titanium half on the top and stainless steel half on the bottom of the image.

Table 3: Charpy test results of the stainless steel-titanium explosion bonded joint at 295 K and 4 K.

| Charpy Test | Test temperature - 295 K | Test temperature - 4 K |
|-------------|--------------------------|------------------------|
| Sample #9   | 9.5 ft-lbs (12.9 J)      | 2.0 ft-lbs (2.7 J)     |
| Sample #10  | 6.0 ft-lbs (8.1 J)       | 2.0 ft-lbs (2.7 J)     |
| Sample #14  | 7.5 ft-lbs (10.2 J)      |                         |
| Sample #15  |                          |                         |
| Sample #19  |                          |                         |
| Sample #20  |                          |                         |

break in the titanium away from the joint, see Figure 3(a). This means the joint at room temperature has an ultimate strength larger than the values listed in Table 2. At 4 K, the three samples had a brittle break around the joint interface, see Figure 3(b). There was also slight necking in the stainless steel during the 4 K tests. Sample 13 broke in the titanium near the joint at a titanium-titanium boundary that seems to be created during the welding process.

2.2. Charpy Impact Test
Six samples were Charpy V-notch tested to measure the ability of the joint to absorb energy. Table 3 lists the results at 295 K and 4 K. The energy absorbed by the samples at room temperature is about five times larger than at 4 K. A similar ratio, around three, was measured impact loading titanium grade 2 samples at 290 K and 4 K reported in [7]. This is due to the transition from ductile to brittle fracture, already noticed in the tensile test. Similar to the tensile test, one of the samples tested at 4 K, sample 19, broke in the titanium near the joint. The surface of this break was significantly different than the typical break at the stainless steel-tantalum boundary. The difference can be seen in Figure 5 where 5(a) is the mostly tantalum face and 5(b) is the titanium face.
(a) Sample 14 mostly showing tantalum layer with some of the tantalum layer missing.

(b) Sample 19 showing the surface of a titanium-titanium break near the weld joint.

Figure 5: Faces of Charpy samples looking toward the titanium half of the sample. For reference, the samples are 10 mm square.

(a) Side 1 of polished sample.

(b) Side 2 of polished sample.

Figure 6: Sample polished to show metal interfaces around joint. The samples are shown with the titanium half on the top and stainless steel half on the bottom of the image. The dark layer slightly below center is the tantalum layer.
2.3. Polished Sample
One of the samples that was not tested was polished at Fermilab. Polishing the sample revealed the wave pattern typically seen in explosion welding. The wave pattern is most obvious between the stainless steel and tantalum, and is shown in Figure 1. The sample was polished on two perpendicular sides and the two sides are shown in Figure 6. Figure 6 also shows a vague line in the titanium above the tantalum layer. This looks to be the joint that broke on sample 13 and 19 in the tensile and Charpy tests.

3. Machined Transition Tube
A transition was designed and machined from the explosion welded material. The shape of the design can be seen in Figure 2. The machined transition was then welded to a tube for tests. Finite element analysis was done on the design, and tests were done on the welded tube.

3.1. Finite Element Analysis
Finite element analyses were performed in order to quantify the von-Mises equivalent stress for the two transition joints at the two operating conditions, 290 K with a pressure of 0.2 MPa and 2 K with a pressure of 0.4 MPa. Figure 2 shows the map of von-Mises equivalent stress of the transition joint with the highest stress. The stresses are a result of internal pressure and differential thermal contraction.

Figure 7: Stainless steel-titanium transition test tube. The joint is near the top in the section that is flared out. A plate was welded to the titanium side on the top, and a tube was welded to the stainless steel side on the bottom.
3.2. Transition Tube Tests
A machined transition was welded into an assembly that has been put through a variety of tests. Before welding, the transition was radiographed and no defects were seen. A cap was TIG (tungsten inert gas) welded to the titanium side, and a tube was orbitally TIG welded to the stainless steel side. After welding, the transition tube was again sent for radiography with no defects found. The assembly was then cold shocked with liquid nitrogen 12 times, and leak checked finding no leaks on a sensitivity of $10^{-9}$ mbar-liters/sec. The tube was radiographed again and no defects were found. Overall, there was no sign of leaks or degradation of the joint during the tests. The tube was not leak checked at superfluid helium temperatures, but similar transitions have been used to hold superfluid during horizontal tests of dressed cavities.

4. Conclusion and Future Work
Explosion welded stainless steel to titanium transitions are planned to be used in the cavity helium vessel assembly for LCLS-II. Analysis and tests have been done to show that the joint is able to withstand the conditions expected. The joint has been used successfully in 2K horizontal tests of dressed cavities at Fermilab and Jefferson Lab.

Additional tests could be done on the material. One test that could be done is to tensile and Charpy test on the base material before and after the explosion welding process. This would give the ability to look for a change in material properties due to the explosion welding process as well as the strength of the joint in comparison to the base materials. More investigation could also be done on the the titanium near the joint where an additional boundary seems to exist. This could determine the cause of the boundary as well as the difference between the titanium on either side of the boundary.

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