ELECTRON BEAM WELDING AND VACUUM BRAZING CHARACTERIZATION FOR SRF CAVITIES

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Abstract

In the framework of the SPL R&D effort at CERN, development design efforts study the joining of dissimilar metals: bulk niobium for the superconducting RF cavities and stainless steel (316LN) or titanium alloys (Ti-6Al-4V and Nb55Ti) for the cryostats. Joining techniques of electron beam welding (EBW) and vacuum brazing are particularly important for these applications. These processes have been used in the accelerator community and developed into generally accepted "best practice". Studies were performed to update the existing knowledge, and comprehensively characterise these joints via mechanical and metallurgical investigations using modern available technologies. The developed solutions are described in detail, some currently being applied uniquely at CERN.

INTRODUCTION

One of the main objectives of the SPL R&D effort at CERN is to develop 704 MHz bulk niobium β=1 elliptical cavities operating at 2 K with an accelerating gradient of 25 MV/m and to test a string of four cavities in a cryo-module [1]. The 5-cell cavities are made up of bulk niobium (RRR>300) and are equipped with SS flanges. The half-cells are shaped by spinning and assembled together with the cut-off tubes via EB welding.

VACUUM BRAZING

Stainless steel (316LN) Conflat flanges are joined to the niobium cavity by vacuum brazing. This technique was developed at CERN [2] and it has been proven as a successful solution for many years. The main challenges to attain a sound joint are shown here.

Procedure

The Nb tube and the stainless steel flange are machined for vacuum brazing with a 20 µm gap between them for its correct filling once the Cu brazing filler metal (BFM) is in molten state. In addition, one or two grooves (depending on the thickness of the flange) have to be machined in the flange where the Ø1 mm Cu-OFE will be placed. A SS insert has to be introduced inside the Nb tube to ensure that thermal expansion mismatch between Nb and SS does not increase the 20 µm clearance at brazing temperature. Brazing is performed under vacuum (10^{-5} mbar) at a temperature slightly above the melting temperature of the copper for a short period of time (< 5 min). Once finished, the insert is machined away.

Validation Campaign 1

For the first validation campaign, a Nb tube of 100 mm internal diameter (ID) and 2.2 mm wall thickness was brazed to a SS (316LN) DN100 flange. The brazed joint was submitted to the same processes to which the cavity will be, consisting of a hard electropolishing (200 µm material removal), heat treatment (600 ºC/ 24h) and a light electropolishing (20 µm material removal). Between those steps, ultrasonic examination and leak test were performed to check the soundness of the joint. In addition, thermal shocks in liquid nitrogen and a shear test reaching 30 kN (10 times higher than the mechanical stresses that the joint will suffer during operation) were accomplished. Fig. 1 shows a metallographic observation of a cross section of the brazed joint after the test campaign.

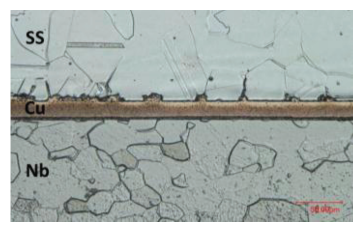

Figure 1: Metallographic observation of the brazed joint stainless steel (316LN) - niobium with copper as BFM.

Scanning electron microscopy (SEM) and energy disperse x-ray spectroscopy (EDS) analyses (detailed in [1]) showed a layer rich in chromium and iron in the niobium - copper interface, displaying brittle rupture surfaces after fractographic analysis. Nevertheless the shear test has proven they do not jeopardize the mechanical integrity of the cavity. This test campaign proved that for the dimensions above described, the brazing procedure gives a robust joint which fulfills the requirements for the SPL cavities.

Validation Campaign 2

The second campaign was intended to study the consequences on the brazed joint when submitting the assembly to a chemical polishing treatment. During fabrication of the SPL cavities, Nb pieces have to be chemically polished within 8 hours before EBW to avoid the readily formed oxide layer getting inside the weld seam [3]. For this campaign, Nb and SS plates were brazed and cut into 10 samples. They were introduced in the chemical polishing bath (40% HF, 60% HNO_3, 85% H_3PO_4 (1:1:2)) with different conditions of temperature and time. They were microscopically observed afterwards in order to determine the amount of

BFM removed. On the sample submitted to the most extreme conditions (temperature between 21 °C and 25.4 °C during 20 min), the bath removed 300 µm of the BFM (each side). Such a small quantity of material removal does not endanger a good performance of the brazed joint, but it has been decided to protect it during chemical polishing with a polymer resistant to the chemical agents present in the bath.

Validation Campaign 3

One of the main concerns after cavity design was the presence of an EBW in the vicinity of an Nb – SS brazing, as extremely high temperatures could be reached in the joint. Thus, the third campaign was envisioned to study if the brazed joint was weakened by the heat produced during EBW. A SS flange with an external diameter of 249.5 mm and 12 mm thickness (simulating the cryostat connection flange where the tuner leans against) was brazed to a Nb tube 100 mm ID and 2.6 mm thickness. After brazing, ultrasonic examination and leak test were performed. Then the assembly was EB welded to a Nb tube 100 mm ID and 2.4 mm thickness. Distance from the brazing to the weld seam is 4.5 mm.

The welding procedure was the same as for welding the irises of SPL cavities: tack welding followed by one welding pass from the outside and a second smoothening pass from the inside. After EBW, ultrasonic examination and leak test were repeated and it was concluded that the brazed area was not affected. Finally the test probe was submitted to a compressive shear test, where the Nb tube buckled before the brazed joint started to fail. Ultrasonic testing is foreseen to determine the state of the interface after the above mentioned test where a maximum compressive load of 380 kN was applied to the Nb tube.

EFFECT OF EBW VACUUM LEVEL ON RRR VALUE

A commonly used parameter to determine the purity of Nb (and by extension, the performance of the cavity) is the RRR value. It is defined as the ratio of the electrical resistivity at 293 K to the resistivity at 4.2 K. Bearing in mind the changes in material properties taking place after welding operations, it was decided to study the impact of EBW on the RRR.

Being Nb a superconductor at temperatures lower than 9.3 K, RRR measurements presented in this paper have been obtained by dividing the resistivity at 293 K by the resistivity at ~10 K (the resistivity was measured at three temperatures between 9.3 K and 10 K and the average was calculated). The data was not extrapolated to 4.2 K and therefore the values are 8 - 10 % smaller compared to an evaluation at 4.2 K [3].

As welding under vacuum better than $5x10^{-5}$ mbar is recommended for welding SRF cavities [5], such an EBW machine was commissioned at CERN 2 years ago. Welding tests have been performed on it at $4.8x10^{-5}$ mbar (60kV, 12 mm/s, 45 mA) and on a second welding machine at $2.8x10^{-4}$ mbar (60 kV, 12 mm/s, 37 mA) to confirm that the degradation of RRR during welding depends on vacuum level.

Sample Preparation

The material adopted for these measurements is high purity niobium (RRR > 300) with 3.6 mm thickness, which was reduced to 1.7 mm thickness by milling. Samples were chemically polished within 8 hours before welding.

The welding procedure was the same as for welding the equators of SPL cavities (butt weld 1.7 mm): tack welding followed by a single pass full penetration weld.

After welding, 7 RRR samples have been cut parallel to the weld bead at different distances (0, 2.5, 5, 10, 15, 20 and 40 mm away from the weld) by wire electrical discharge machining, Samples were then chemically polished to remove the superficial oxide layer.

RRR Measurement Results

Fig. 2 shows the RRR of each sample relative to the RRR at 40 mm from the weld seam (reference). There is a slight reduction of the RRR value in the weld area in both cases, always less than 5 %. As expected, the reduction of the RRR is lower when welding in the $5x10^{-5}$ mbar vacuum range. Further tests to improve statistics and with different vacuum levels are ongoing. This will finally allow assessing the trade-off between welding costs (equipment, pumping time to achieve vacuum level) and RRR quality.

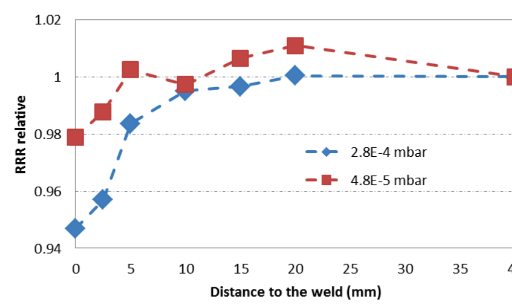

Figure 2: RRR variation from the weld to the bulk metal.

EBW OF DISSIMILAR METALS

In case it is decided to fabricate the cryostat in titanium, several different transitions are being studied.

Three EBW joints have been characterised:

- Nb to Nb55Ti alloy
- Nb55Ti alloy to Ti grade 5 (Ti6Al4V)
- Nb to Ti grade 5 (Ti6Al4V)

All welds are butt joints with 3 mm thickness, starting with tack welding followed by a single pass. Special considerations have to be taken when welding dissimilar materials with different physical properties [6]. As niobium has higher thermal conductivity than titanium, the EB was offset from the joint towards the niobium side. The welding parameters are presented in Table 1.

After welding, the samples were heat treated (600ºC / 24h) in order to simulate the same heat treatment of the

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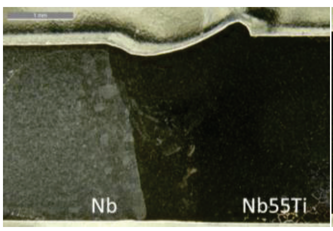
cavity. Mechanical properties of the joint have been studied by means of micro-hardness profiles on the cross section of the weld and via tensile tests. The macrographs of the cross section of the welds are shown in Fig. 3, Fig. 4 and Fig. 5.

Table 1: Welding Parameters

	Nb-Nb55Ti	Nb-Ti6Al4V	Ti6Al4V-Nb55Ti
HV	60 kV	60 kV	60 kV
Beam current	34 mA 15 mA tack	33 mA 18 mA tack	18 mA 12 mA tack
Offset	0.5 mm in Nb	0.4 mm in Nb	0.3 mm in Nb55Ti
Speed	16.7 mm/s	16.7 mm/s	12 mm/s



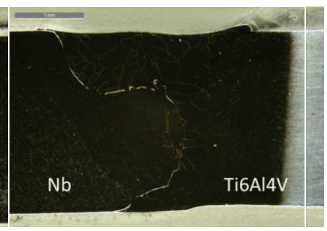


Figure 3 (left): Macrograph of the EB weld Nb-Nb55Ti.
Figure 4 (right): Macrograph of the EB weld Nb-Ti6Al4V

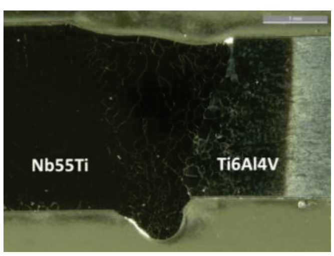


Figure 5: Macrograph of the EB weld Nb55Ti-Ti6Al4V.

Macrograph of the EB weld Ti6Al4V-Nb55Ti presents an excess penetration of 0.3 mm. Nb-Nb55Ti shows an asymmetrical surface causing a sagging of 0.1 mm which could be improved with a beam deflection pattern. For the intended application all macrographs are acceptable.

After tensile testing, all specimens broke away from the welding area and always in the material with lower ultimate tensile strength (either Nb or Nb55Ti) as expected. The average tensile strength was 219 ± 4 MPa with and average elongation at break of 30.5 % for the Nb-Nb55Ti weld. For the weld Ti6Al4V-Nb55Ti, the average tensile strength was 488 ± 10 MPa with and elongation at break of 19.4%. The results of the tensile tests of Nb to Ti6Al4V are detailed in [6].

HV0.05 hardness measurements were performed at 0.75 mm from the root (green), 0.75 mm from the top (blue) and in the middle of the cross section (red). Results are presented in Fig. 6, Fig. 7 and Fig. 8.

From the mechanical point of view, all three welds show a robust mechanical behaviour and with the improved parameter selection which is undergoing, defects could be corrected.

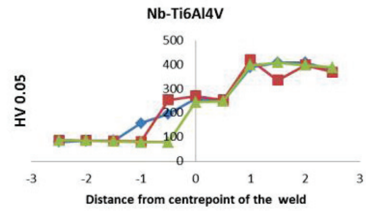


Figure 6: Hardness profile in the weld Nb-Ti6Al4V.

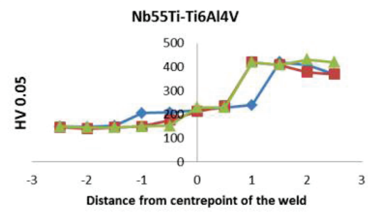


Figure 7: Hardness profile in the weld Nb55Ti-Ti6Al4V.

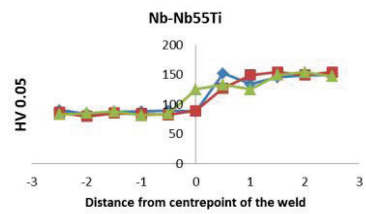


Figure 8: Hardness profile in the weld Nb-Nb55Ti.

CONCLUSION

The parameters for effectively vacuum braze stainless steel (316LN) and Nb have been reviewed and updated. Metallurgical and mechanical tests have proven it to be a successful and reproducible solution for SRF cavities.

RRR degradation in the weld area has being studied, measuring a lower reduction at the highest vacuum level.

The 3 different EBW transitions have shown operative weldability (parameters given) and acceptable mechanical properties. Nb-Ti6Al4V weld (done exclusively at CERN) has proven to be as robust as the other two.

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