SUPERCONDUCTING RF CAVITY DEVELOPMENT WITH UK INDUSTRY

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Abstract

As part of a STFC Industrial Programme Support Scheme (PIPSS) grant Daresbury Laboratory and Shakespeare Engineering Ltd have fabricated, processed and tested a single cell 1.3 GHz superconducting RF cavity, in collaboration with Jefferson Laboratory. The overall aim of the project through a knowledge exchange programme was to develop the capability of UK industry to fabricate and process a single cell niobium superconducting cavity, as part of a long term strategy to enable UK industry to address the large potential market for superconducting RF structures. As a means of measuring the performance of the fabrication and processing an objective of the programme of work was to achieve an accelerating gradient of greater than 15 MV/m at an unloaded quality factor of 1.0 x 10^{10} or better. Three cavities were fabricated by Shakespeare Engineering, and electron beam welded at Jefferson Laboratory in the USA. Processing and testing of the cavities was then performed both at Jefferson Laboratory and at Daresbury Laboratory. The fabrication and process methods are discussed in this paper along with the results obtained from the testing performed in the vertical test facilities.

INTRODUCTION

Three single cell 1.3 GHz niobium superconducting RF cavities have been manufactured by Shakespeare Engineering Ltd [1] as part of a joint programme of work between ASTeC (Accelerator Science and Technology Center) Department at Daresbury Laboratory and Shakespeare Engineering Ltd. The work has been performed in collaboration with Jefferson Laboratory in the US, who has provided their technical expertise throughout all the stages (design, manufacture, processing and testing) of the project. The machining and forming of the cavities was performed by Shakespeare Engineering whilst the electron beam welding of the cavities was performed at Jefferson Laboratory. The Buffered Chemical Polish (BCP) etching and High Pressure Rinse (HPR) and testing of the first cavity were performed at Jefferson Laboratory, whilst all preparations for the second cavity were performed at Daresbury Laboratory. The third cavity is presently awaiting qualification. The tests on the first cavity were performed to provide a benchmark for the processing and testing performed at Daresbury Laboratory.

CAVITY DESIGN & MANUFACTURE

The cavity design utilised the standard TESLA geometry incorporating steps at the equator and beam-pipe interfaces to ensure easy interlocking and location of adjacent parts. Tooling was designed and manufactured using tool steel to ensure durability for repeated processes and to reduce the likelihood of stray material being picked up, thus minimising the transfer of impurities to the surface of the niobium sheets.

Successful trials using a 60 tonne press to produce cavity half cells were performed firstly using copper, as its malleability is similar to that of niobium. The forming dies were polished, to ensure that there was no contamination of the niobium parts. However, the first attempt to produce a niobium cavity half cell was unsuccessful, as the niobium sheet dragged in the press producing a deformed half cell. An investigation determined that the cause was due to the fact that the material thickness was greater in places than the pressing tools had been initially designed for; 3.26 mm compared to 3.1 mm. Modifications were made to the tooling to account for the extra material thickness. The dies were then re-polished and a second attempt to produce a niobium half cell was subsequently successful.

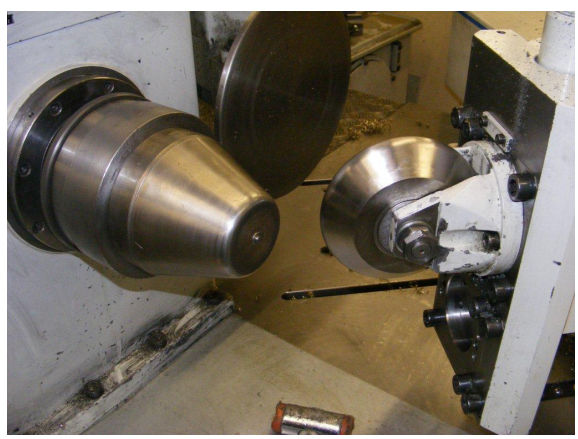

Figure 1: Beam-pipe spinning at Shakespeare Engineering

The beam-pipes were spun on a CNC (computer numerical control) lathe to eliminate the need for performing an electron beam (EB) weld along the seam of a rolled sheet of niobium, as is typically performed. The niobium sheet was spun into a cone (Figure 1), and with successive heat treatments and spinning operations, the cone was eventually transformed into a cylinder and formed on a mandrel. A thickness reduction in the

material of approximately 0.75 mm was observed along the beam-pipe section. The machining of the parts to length and of the weld edges were all performed on a CNC machine. Adjustments to the tool geometry set-up were necessary to take account the variation in material properties of niobium compared to copper.

The welding of the cavities was performed on a EB welder (Figure 2) at Jefferson Laboratory, which has 6-axis of freedom providing the required capability to perform welds both on the outside as well as the inside of the cavity sections (apart from the equator weld).An ultrasonic degrease and a light BCP etch was performed on each of the weld areas prior to EB welding. The welding of the parts was then performed within a couple of hours of the parts being cleaned, to minimise the likelihood of contamination of the weld preparation surfaces.

Figure 2: Cavity half cell welding at Jefferson Laboratory.

No issues were encountered in the EB welding of the first cavity. However, on the final equator weld for the second cavity, there was a lot of debris seen flying from the joint as the cavity was rotated around its horizontal axis, which culminated in a big 'flash' as the weld came to an end. It is suspected that contamination was trapped in between the two steps at the equator interface which was then pushed around the weld joint by the electron beam. In certain circumstances this can often result in a puncture due to the build up of the contamination levels. A visual examination of the cavity externally and internally indicated that the weld appeared to be leak tight. Thus a consideration for future geometry designs will be to avoid step interfaces and to preferentially include butt joints, to minimise the risk of producing punctures during the welding process, though this type of geometry requires greater care and attention with regards to component alignment to ensure optimum success.

CAVITY PROCESSING

In order to ensure that there are no impurities or inclusions on the internal surfaces of the cavity, which potentially could have been formed during the machining and welding processes, it is normally standard to remove between 100 and 150 μm of the surface using a chemical etching process [2]. For the two cavities evaluated, a conventional BCP etch was performed using an acid mixture of HF (49%), HNO_3 (65%), H_3PO_4 (85%), with a 1:1:1 mixture, which was performed in the vertical orientation. To ensure a uniform amount of material was removed from the surfaces, the BCP process was performed for equal lengths of time with the cavity seated on opposite flanges.

Cavity #01 was processed at Jefferson Laboratory and was ultrasonically degreased with a detergent (Micro-90®) and ultra pure water for 30 minutes, so as to remove any surface contamination due to handling. The cavity then underwent a number of BCP etches to remove in total around 100 μm from the niobium surface. The process was performed in a number of stages as it needed to be turned over to ensure uniform etching; and as the process is exothermic the temperature needs to be controlled to minimise the absorption of hydrogen produced during the reaction and to control the reaction rate. After each etch process the cavity was thoroughly rinsed with ultra pure water for 30 minutes and then dried with methanol and filtered nitrogen, so that a frequency measurement could be performed to determine more accurately the thickness of niobium that had been removed.

Cavity #02 was processed at Daresbury Laboratory. For this purpose a dedicated fume cupboard was modified to allow the BCP etch process to be performed. Prior to BCP etching, the cavity was ultrasonically degreased for 40 minutes. The cavity was then BCP etched twice removing a total of around 85 μm from the niobium surface.

Both cavities were then HPR rinsed with ultra pure water for more than 45 minutes to remove particulates from the interior surfaces incurred during etching process and subsequent handling. The cavities were then allowed to dry in an ISO4 class cleanroom before being assembled onto vertical test inserts in readiness for testing. Normally a vacuum bake for 10 hours at 600ºC would be performed, however time limitations during the visit to Jefferson Laboratory meant this process was missed out initially, and at Daresbury Laboratory, a fault with the vacuum furnace meant the process could not be performed here either.

CAVITY TESTING

The testing of Cavity #01 was performed at Jefferson Laboratory in their vertical test facility. Numerous test runs were performed. The first was done after it had undergone its initial BCP etch followed by a HPR, but without any vacuum processing. The results obtained (shown in Figure 3) show that the cavity reached an accelerating gradient of 15.7 MV/m with a Q_0 of 1.15 x 10^{10} at a temperature of 2K, thus exceeding the required target specification for this first test. However, multipactor was exhibited above this level which CW and pulsed conditioning was not able to overcome, though gradients of 17.6 MV/m with a Q_0 of 2.17 x 10^9 were achieved. Further processing on the cavity was performed in an attempt to improve its performance, via another

BCP etch, removing an additional 41 μm from the surface. The cavity was then re-tested (Test #02), with no real improvement observed in the accelerating gradient and multipactor was still present, and so a vacuum furnace bake at 600°C for 10 hours was performed, including an additional BCP etch (28 μm removed) and a HPRA subsequent test (Test #03) showed an improvement in the gradient, though multipactor was still present. Finally a further HPR was performed and the cavity had its final test performed (Test #04) highlighting an accelerating gradient of 22.94 MV/m with a Q_0 of 1.06 x 10^{10} at 2K, and a maximum gradient achieved of 28.05 MV/m with a Q_0 of 2.93 x 10^9. However, multipactor was still present at around 16 MV/m.

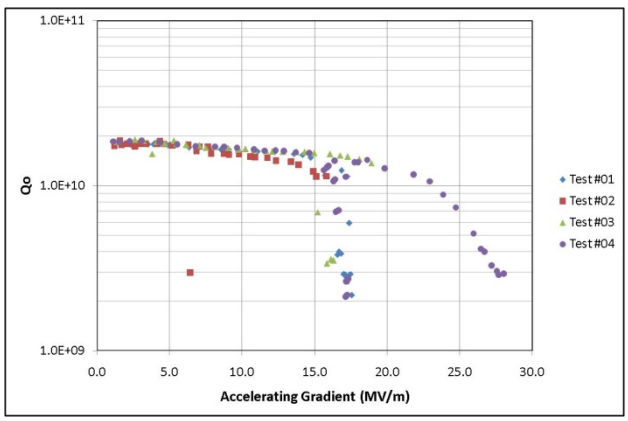

Figure 3: Performance results for Cavity #01 tested in a vertical test facility at Jefferson Laboratory.

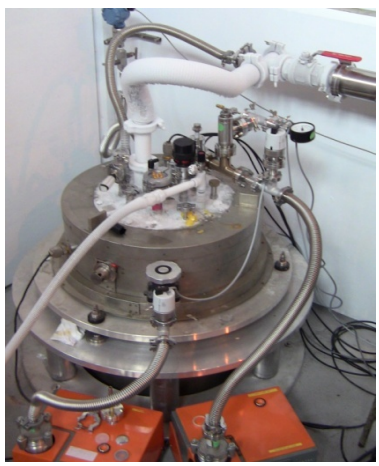

Figure 4: Vertical test facility at Daresbury Laboratory

The second cavity (Cavity #02) was tested at Daresbury Laboratory in a newly installed vertical test facility [3]. The system incorporates a test cryostat located in concrete within the ground (Figure 4), in which the vertical test insert with the cavity sits. The RF system uses a phase lock loop (PLL) system which is controlled by a Field-Programmable Gate Array (FPGA) controller. A phase detector is used to compare the sampled cavity RF with that of the RF source. The change in output voltage is used to drive the DCFM (DC-coupled frequency modulation) input to the signal generator ensuring that the frequency of the RF source is always locked to the frequency of the cavity. A solid state amplifier is then used to amplify the signal to the cavity. In addition, the RF system incorporates a frequency counter as a means of monitoring the frequency of the RF source. Initially tests were performed on the system at 4K to ensure that the system was working correctly. The calibration of the couplers and the cavity pick-up probe were measured and performance of the cavity was verified at 2K (Figure 5).

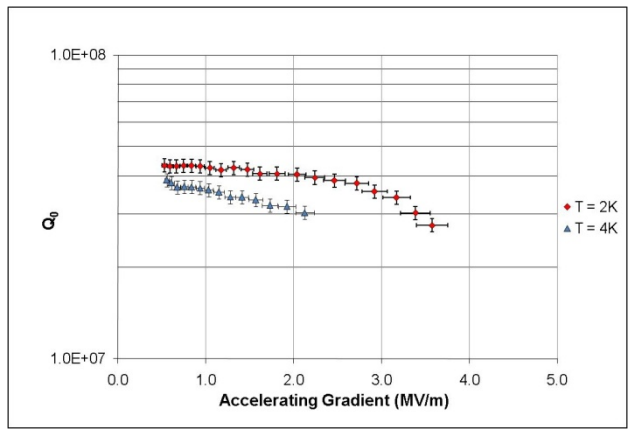

Figure 5: Cavity #02 vertical tests at 4K and 2K.

The results obtained for this preliminary test were quite poor, with strong 'Q-disease' and low field Q_o performance observed. It is believed that the 'Q-disease' caused by hydrogen in the bulk material of the cavity could have been caused by poor temperature control during the BCP process or due to the fact that insufficient material was removed. Further preparations to re-process Cavity #02 are currently underway, to enable additional testing which are hoped to replicate or even exceed levels reached for Cavity #01 at Jefferson Laboratory.

SUMMARY

Tests performed demonstrate that UK industry has the capability to fabricate SRF components to the required standards. The first cavity tested at Jefferson Laboratory, exceeded the required success criterion and verification of a purpose built test facility at Daresbury Laboratory was successfully performed on the second cavity. Further processing and testing of the second cavity is planned.

REFERENCES

[1] Shakespeare Engineering Group, Unit 91, Haltwhistle Road, Western Industrial Area, South Woodham Ferrers, Essex, CM35ZA, UK.

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[3] R.K. Buckley et al, "Vertical Test Facility for Superconducting RF Cavities at Daresbury Laboratory", SRF 2011, Chicago, TUPO008.