NEW TECHNIQUE AND RESULTS OF LASER WELDED SCRF CAVITY DEVELOPED AT RRCAT

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Abstract

A new technique to fabricate SCRF cavities with the help of laser welding process has been developed at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, Department of Atomic Energy, India. In this technique, an Nd:YAG laser has been used and welding was performed in inert gas environment in a specially designed welding rig. The advantages of this technique are reduced cost, small heat affected zone, no necessity to weld in vacuum and an enhanced rate of production. The paper describes the technique and fabrication method of a single-cell 1.3 GHz SCRF cavity which was fabricated at RRCAT with this new technique. It also discusses the test results of this cavity which was processed and tested at Fermi Lab, USA (FNAL). The cavity reached an E_{acc} of 17MV/m with a Q_0 of 1.4 $x10^{10}$ at 2K after buffered chemical and electro-polishing processing sequence. The cavity was then barrel polished to remove a small weld defect and then electro-polished. In the next test the cavity achieved a quench field of 31.6 MV/m with a Q_0 of 1.0 $x10^{10}$.

INTRODUCTION

Raja Ramanna Centre for advanced Technology (RRCAT) has taken up a program for development of SCRF technology. It is aimed at setting up a high intensity superconducting proton linac, which is the next major project being planned at the centre. The necessary infrastructure required for this project is in an advanced stage of commissioning [1]. Under this major project, the Cryomodule Engineering Lab (CMEL) of RRCAT had initiated an effort to develop a new technique for the fabrication of SCRF cavities made of niobium (Nb) [2]. The novelty of this technique is the use of laser beam welding (LBW) for fabrication of SCRF cavities instead of electron beam welding (EBW). A special feature of the technique is the use of an inert gas environment instead of vacuum.

The effort is directed towards reducing the cost (both capital and operating) of fabricating the cavities. Another objective is to increase the rate of production. An attempt has also been made to reduce the energy incident on the Nb parts being welded, so that the heat affected zone (HAZ) and corresponding shrinkage and distortion are reduced. It is expected that such a reduction may make SCRF cavities easier to fabricate, thereby increasing the probability of fabricating high performance cavities.

A large number of experiments (>150) were carried out over 3 years to develop the technique and then arrive at an optimum process for fabrication of SCRF cavities. A specially designed welding rig was fabricated with the help of Indian industry. A laser system for the task was tailor-made by the Solid State Laser Division (SSLD) of RRCAT, subsequent to the assessment of requirements.

After process finalization, based on this technique, a 1.3GHz, Tesla type, single cell cavity was fabricated. This cavity (see Fig.1) has been surface processed & tested at FNAL. The very first cavity fabricated by this process has shown encouraging results. The cavity reached an E_{acc} of 31.6 MV/m with a Q_0 of $1.0x10^{10}$ at 2K in the rest (see Fig. 2). Further processing is being done for improving the performance.

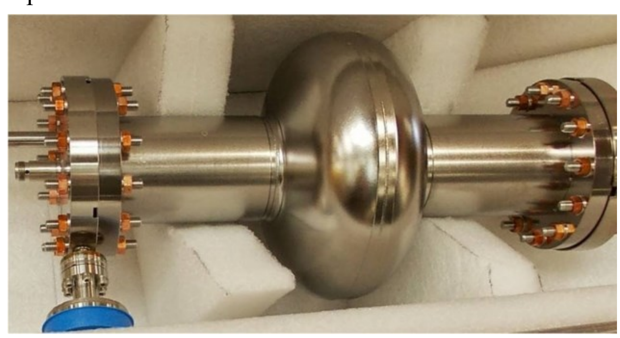

Figure 1: First laser welded 1.3 GHz SCRF cavity.

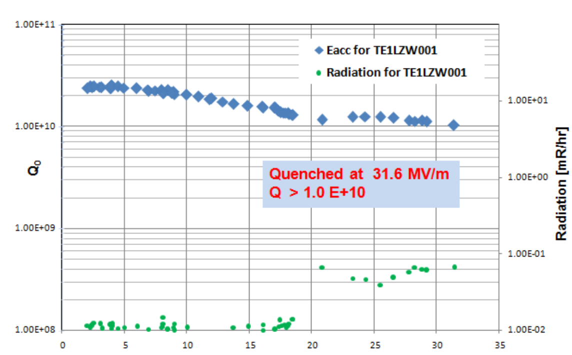

Figure 2: Q_0 v/s E_{acc} for laser welded 1-cell 1.3 GHz cavity.

ADVANTAGES OF NEW TECHNIQUE

The new technique based on LBW has many advantageous features compared to the standard EBW based technique as listed below:

- No necessity of vacuum environment. Gas jet to assists in driving away evaporated material.
- Low capital cost, as laser system is ~25 times cheaper than EB welding system.
- Lower operating cost (LBW cheaper by 4-5 times)
- Weld energy can be easily manoeuvred to any place, as the laser energy can travel through an optical fiber. Intricate joints can be easily welded. It imparts flexibility for new cavity designs (low, medium or high beta).
- Better control on energy deposition (frequency, pulse shape, duration etc.). Lesser energy can be deposited to get the same joint. This results in
  - Lower HAZ (~500 µm on both sides of bead)
  - Less shrinkage and distortion (5-6 times less)
- Higher production rate as
  - Multiple joints are possible in a single setting.
  - One laser can feed many welding rigs using Multiport fibre optic beam delivery (see Fig.3)

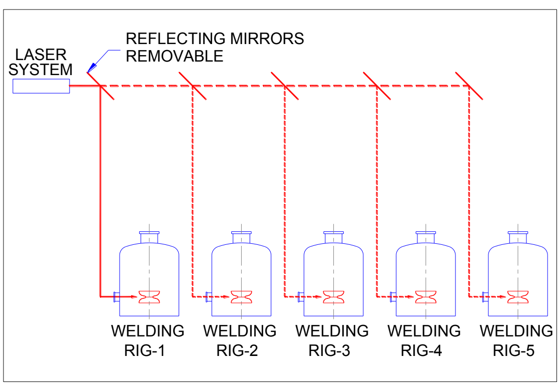

Figure 3: A schematic diagram showing multi-port fiber optic beam delivery by same laser.

DEVELOPMENT OF LBW TECHNIQUE FOR SCRF CAVITY FABRICATION

Laser welding experiments were carried out on niobium (Nb) samples using Nd:YAG (1.064 µm) laser system. The absorption of this wavelength is just ~10% for Nb. Welding parameters were developed and optimized for full penetration in Nb samples (1.7mm, 2.1mm, 3 mm thickness). These parameters were fine tuned for reliability in depth of penetration and vacuum leak tightness. Parameters were developed for smoothing the bead by laser, to get a smooth surface finish.

Metallography

Metallographic analysis was performed for most of the samples. Laser welded specimens exhibited a ~2.5 mm wide weld bead with a smooth ripple pattern (see Fig. 4).

A cross-sectional metallographic examination of laser welded niobium specimens did not reveal any defects. The laser welded metal displayed coarse columnar grains, growing from the two sides of the melt pool to meet axial grains at the weld centre line as shown in Fig. 5. Due to the low heat input associated with the laser welding process, the laser welded joint developed a very narrow HAZ of about 500 µm on both sides of the weld bead. None of the weld samples made from the final parameters showed any micro cracks or voids.

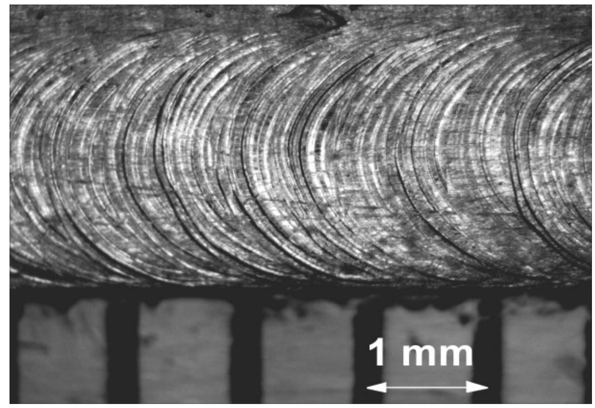

Figure 4: Laser weld bead with smooth ripple pattern.

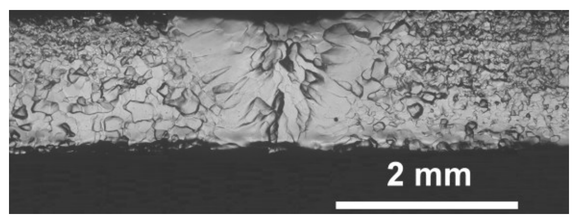

Figure 5: Cross-sectional view of Nb specimen.

Tensile Test

The weld samples were tested for tensile strength. The results of these tests (Table 1) appear satisfactory.

Table 1: Tensile Test Results of Nb Samples

LBW sample	UTS 170 MPa YS 100 MPa
Original substrate	UTS 180 MPa YS 100 MPa

Vacuum Leak Tightness

To qualify the weld joint, vacuum leak tightness was checked for the laser welded Nb sample, using a mass spectrometer leak detector having minimum detectable leak rate of $< 1\text{x}10^{-11}$ mbar.ltr./sec. The sample was a Nb disk welded along diameter. It was found that the vacuum leak rate was of the order of $1\text{x}10^{-10}$ mbar.ltr./sec.

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Optimizing Inert Gas Environment & RRR Measurement

The above mentioned experiments were followed by experiments on optimizing the welding environment. Taking advantage of the fact that a laser can travel through gases (unlike an EBW electron beam), a recipe was developed which could ensure high RRR of the welded samples subsequent to welding. After a certain number of experiments, it was found that high purity argon gas with 99.9999% purity could be used for the task. A gas jet was used to assist the laser welding process, to drive away the evaporated material and weld spatter from the sensitive region. Gas jet parameters (flow rate, orifice diameter, incident angle, etc.) were optimized so that any evaporated material and spatter are not allowed to deposit on the cavity surface, while keeping the weld pool undisturbed. Subsequent to parameter finalization, RRR measurement was carried out and results were very satisfactory. The RRR value for the pristine Nb sample was 314 and for the welded sample, it was 296, a reduction of just 6%, which is acceptable.

A 3.9 GHz SCRF cavity (Fig. 6) made of low RRR Nb was laser welded with optimized parameters in an argon environment for testing the functioning of all subsystems as a single unit.

This exercise provided two important inputs. The first input was about weld shrinkage and the second was about gas flow regulation through nozzle for assisting in muck removal when a circumferential joint is welded. This trial also showed how much weld overlap has to be there.

Figure 6: 1st Laser welded 3.9 GHz SCRF cavity.

INFRASTRUCTURE DEVELOPMENT FOR SCRF CAVITY FABRICATION

A specially developed SCRF cavity welding rig was designed and fabricated (see Fig. 7). The vacuum vessel of the rig can achieve the vacuum level of the order 10^{-6} mbar. The rig is comprised of motion feed through, optical fiber feed through, and gas feed through to carry out welding in an inert gas atmosphere. A stepper motor based target manoeuvring system was also developed.

A tailor-made, indigenously developed Nd:YAG laser was used for the task with average output power of 500W (Fig. 8). Laser beam power is delivered to weld joints by means of an optical fiber and lens arrangement passing via an optical feed through, into the vessel, which was developed specifically for the task.

Figure 7: Photograph of laser welding rig.

1.3 GHz SCRF CAVITY FABRICATION

The process to weld the cavity was conceptualized, experimented and finalized. This was the logical next step after the welding samples were qualified on all accounts including RRR measurement.

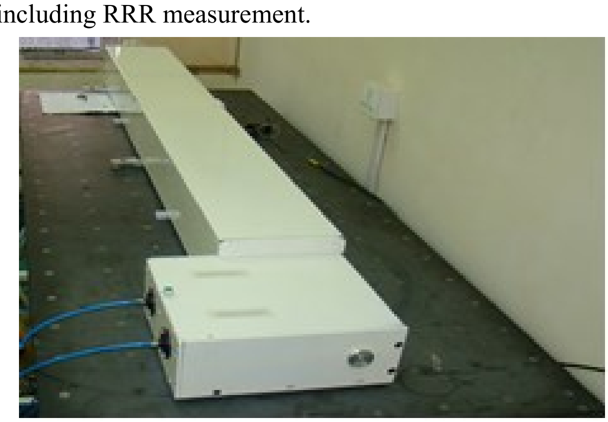

Figure 8: A photograph of Nd:YAG laser system.

The weld sequence for cavity components, weld overlap and other such aspects were ascertained and thus the process was finalized. Suitable fixtures were developed for welding Nb components of a single cell 1.3 GHz Tesla-shape cavity. The first cavity was fabricated at RRCAT and initial tests like vacuum leak test, resonant frequency measurement and vacuum integrity test subsequent to cold shock at 80K were performed at RRCAT. Test results are summarized in Table 2.

Table 2: Room Temp. Test Results of 1.3 GHz SCRF Cavity

Test	Result
Vacuum leak tightness	1 x 10^{-10} mbar. litre./sec.
Room temp. frequency	1.2962GHz
Quality factor	9542
Overall length	393 mm
Vacuum. leak tightness (after cold shock)	2 x 10^{-10} mbar. litre/sec

PROCESSING AND TESTING OF 1.3 GHZ LASER WELDED SCRF CAVITY

Laser-welded 1.3 GHz cavity was shipped to FNAL for surface processing and RF testing at 2K in the Vertical Test Stand (VTS). On its arrival at FNAL, it was once again tested for vacuum leak tightness at room temperature and was optically inspected (see Fig. 9(a)).

It was observed that a very narrow weld bead (~ 2.5 mm) and HAZ was visible in optical inspection. A standard approach was taken to process the cavity as reported in references [3] and [4]. As a first step, buffer chemical polishing (BCP) was done to remove 120µm of material. A solution comprising of 1:1:2 HF (48%), HNO_3 (65%), and H_3PO_4 (85%) was used, and the bath temperature was kept around 12^0C.

BCP was followed by a bake at 800^0C for 2 hrs. at 10^{-6} mbar of vacuum. A second optical inspection was performed which showed a small HAZ and weld bead. After second optical inspection, a light EP for 40 µm material removal was carried out. The temperature was around 24^0C near equator while average cavity temperature was kept below 30^0C.

As a next step, ultrasonic cleaning and high pressure rinsing (HPR) of cavity was carried out. The cavity was assembled in Class 10 clean room. First testing was then carried out at 2 K in Vertical Test Stand (VTS).

The laser-welded 1.3 GHz SCRF cavity developed at RRCAT reached an acceleration gradient (E_{acc}) of 17 MV/m with a quality factor (Q_0) of 1.4×10^{10} at 2 K in its maiden test (see Fig. 10). At this gradient, there was a hard quench. No field emission was observed.

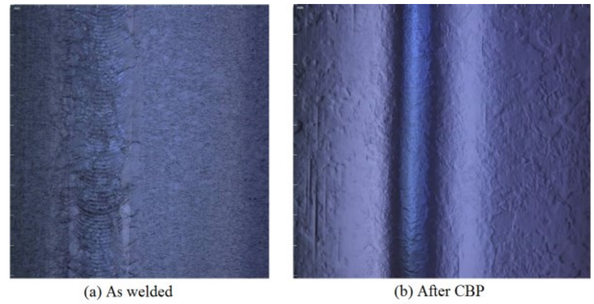

Figure 9: Images of inner surface of SCRF cavity.

A small weld defect was likely the cause of the early quench in the first test. A repair process was implemented that included > 100 um of centrifugal barrel polishing to remove any surface morphological defects. The CBP process was continued through the mirror finish stage prior to light EP and high temperature bake [5]. Fig. 9 shows inner surface of cavity after CBP. The cavity received a 15 um EP prior to the 800^0C 3-hour plateau hydrogen degasification bake. No post-bake electro-polishing occurred as this step has been successfully eliminated at Fermilab [6]

The cavity was again tested in VTS at FNAL. The cavity reached an accelerating gradient (E_{acc}) of 31.6 MV/m with a quality factor (Q_0) of 1 $x10^{10}$ at 2 K.

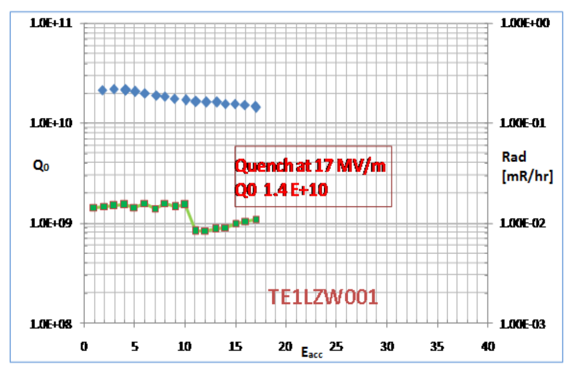

Figure 10: Q_0 v/s E_{acc} plot of First test.

CONCLUSION

A new technique has been developed for fabricating SCRF cavities. This technique uses laser beam welding to join Nb components in inert gas environment. There are significant advantages which are foreseen from this technique. The process and infrastructure have been developed. The very first 1.3 GHz Tesla-shape SCRF cavity fabricated at RRCAT, using this new technique, reached an acceleration gradient (E_{acc}) of 31.6 MV/m with a quality factor (Q_0) of 1.0×10^{10} at 2K. This is a very encouraging result, as the cavity has been welded with LBW, which is significantly economical process compared to EBW. Furthermore the process is carried out without vacuum, thereby mitigating complications associated with it. These advantages make the new technique of SCRF cavity fabrication an attractive choice for future accelerator projects. To the best of our

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knowledge, these are the first high quality test results of an SCRF cavity, which has both, RF sensitive and non RF sensitive joints, made with laser beam welding process. Efforts are being made at our centre to further improve the performance of cavities. Attempts are also being made to take the technique to production level, so that SCRF cavities can be fabricated at low cost with high production rate for future projects.

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