Development of multi-channel high power rectangular RF window for LHCD system employing high temperature vacuum brazing technique

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Abstract. A 3.7 GHz., 120 kW (pulsed), lower hybrid current drive (LHCD) system is employed to drive non-inductive plasma current in ADITYA tokamak. The rf power is coupled to the plasma through grill antenna and is placed in vacuum environment. A vacuum break between the pressurized transmission line and the grill antenna is achieved with the help of a multi (eight) channel rectangular RF vacuum window.

The phasing between adjacent channels of 8-channel window (arranged in two rows) is important for launching lower hybrid waves and each channel should have independent vacuum window so that phase information is retained. The geometrical parameter of the grill antenna, like periodicity (9mm), channel dimensions (cross sectional dimension of 76mm x 7mm), etc. is to be maintained. These design constraint demanded a development of a multi channel rectangular RF vacuum window. To handle rf losses and thermal effects, high temperature vacuum brazing techniques is desired. Based on the above requirements we have successfully developed a multi channel rectangular rf vacuum window employing high temperature vacuum brazing technique. During the development process we could optimize the chemical processing parameters, brazing process parameters, jigs and fixtures for high temperature brazing and leak testing, etc. Finally the window is tested for low power rf performance using VNA. In this paper we would present the development of the said window in detail along with its mechanical, vacuum and rf performances.

1. Introduction

A 3.7 GHz., 120 kW pulsed lower hybrid current drive (LHCD) system [1] on ADITYA tokamak [2], employs 8-channel grill type antenna. It consists of two rows, each having 4 rectangular channels having 76mm x 7mm cross sectional dimension, separated by 2mm thin septa (periodicity of 9mm). The antenna is placed in vacuum environment whereas the transmission line is pressurized. Thus a vacuum break between the pressurized transmission line and the grill antenna is required. This is achieved with the help of a multi channel rectangular RF vacuum window. High temperature vacuum brazing technique is employed to realize the said window. Similar kind of windows, having different base material and configurations have been developed for LHCD systems on different tokamaks [3, 4]. In realizing the window several major technological issues are considered, processes are optimized and the window is successfully fabricated.
The paper is organized as follows: The design constraints and technological challenges (like accommodating uniform periodicity, precise dimensions, rectangular geometry, rf losses, thermal effects, etc.) are addressed in section-1, whereas optimization of various processes is discussed in section-2. The results obtained (mechanical, vacuum and low power rf performance) from the developed window are discussed in section-3, followed by conclusion in the last section.

2. Design constraints and technological challenges
The fabrication of window posed several critical issues. The most challenging one was the brazing of several ceramic (99.5% alumina) rectangular bricks within a single metal frame (titanium alloy 6Al, 4V) in a single process. This demanded the development of a reliable, repeatable and a robust process to accomplish brazing in a single shot. Failure of brazing in any of the ceramics means complete failure and was not acceptable. Further the rectangular geometry of the ceramic bricks was a bottleneck to obtain leak tight joints at the edges. However with careful planning and optimization of chemical processing parameters, specially designed jigs and fixtures, profiling of each ceramic and wire cutting the slots in the metal frame, the development of the window was successfully realized. Each of these methods is described in details in the following subsections.

2.1. Profiling and wire cutting
In this process the profile measurements of each of the ceramic was carried out. Using these measurements the dimensions and tolerances of each of the slots in the metal frame was defined. Wire-cut techniques in two steps (one coarse cutting followed by fine cutting) were employed to prepare the metal frame. Special care was adopted at the slot corners to match the profile around the edges of each ceramic. The photograph of the wire-cut frame is shown in figure 1.

2.2. Metallized ceramic
The four surfaces of the ceramics, which would get brazed with the metal frame, were metallized using molybdenum-manganese coating followed by galvanic deposition of nickel (~50μm thick). Additional silver-plating of ~60μm thickness was done on the metallized surface for cushioning effect during high temperature brazing. The four corners of the ceramics were rounded (radius ~100μm) to avoid sharp edge effects and assist in easy flow of brazing material at the edges during brazing. The photograph of the ceramic bricks is shown in figure 2.

2.3. Chemical processes
After the mechanical process, the metallic frame is degreased with acetone and/or trichloroethylene. It is thoroughly cleaned using solution of RO water (1000 by part), hydrochloric acid (830 by part), hydrofluoric acid (60 by part) and orthophosphoric acid (80 by part) at temperature of 20-25°C. Further it is water washed with de-ioized water (5MΩ) and rinsed in methanol. Finally it is dried using hot air blower. The ceramics are degreased using acetone and/or trichloroethylene.
2.4. Heat treatment
After chemical processing, the titanium block is fired in vacuum furnace at about 800°C, maintaining a pressure below \(10^{-5}\) torr, to remove the stresses and surface finishing. During firing of titanium, often pressure used to rise due to degassing from titanium block and so the temperature is increased slowly to maintain pressure within prescribed limit. The metalized ceramic is also fired at 900°C in dry H\(_2\) atmosphere to remove any oxide layer on metallic surface. Slow cooling is employed (@ about 30°C per 5 minutes), in both the cases, to avoid stress building.

2.5. Forming of brazing alloy
Copper silver brazing alloy CuSil (M.P. 780°C) is used for brazing of titanium alloy with metalized ceramic. Brazing alloy is formed in rectangular shape so as to fit into the individual rectangular slots in the metal partner. Typical formed alloy is shown in figure 3. The formed brazing alloy is chemically cleaned with Acetic acid solution (5% v/v) and then it is fired in dry H\(_2\) up to 450°C (5 minutes holding at 450°C) to form it in the exact shape.

2.6. Assembly of rectangular window
After firing of the parts, ceramic pieces are fitted into the rectangular slots of the titanium block. Brazing alloy is put into exact shape of the slot. Figure 4 shows the window assembly along with formed brazing alloy.

2.7. Brazing
The assembled window is put in vacuum furnace and brazing is done at the pressure below \(5 \times 10^{-5}\) Torr. The profile of temperature versus time during brazing is shown in figure 5. It can be observed from the graph that brazing is completed at 790°C temperature and then cooling is done at the rate of 6°C per minute up to 500°C. Thereafter heaters are switched off and natural cooling is allowed. The total brazing process took about 9-10 hours for the completion of the job. Figure 6 shows the photograph of window loaded in the vacuum furnace.
3. Results and discussions

After brazing, the window is subjected to qualification tests. Visual inspection is carried out for any cracks, deformation or for any gross leaks. The mechanical measurements are carried out and are found within reasonable limits. The narrow dimension being very critical (because additive tolerances may lead to change in periodicity) shows a typical variation of about 30 microns. The typical measurement of the narrow dimension for all the channels is shown in figure 7. Later helium leak detector (HLD) test is carried out to establish its UHV compatibility. Proper jigs, fixtures and O-rings are prepared and used for leak testing as shown in figure 8. Figure 9 shows a leak testing process using a helium leak detector. Leak rate better than $4.66 \times 10^{-9}$ mbar-lit/sec is observed against HLD background signal of $3.97 \times 10^{-9}$ mbar-lit/sec. The window is then pressurized to 4.5 bar using dry nitrogen gas and kept under pressure for few hours. With one side under pressure, the other side is subjected to HLD test and the measurements confirm UHV compatibility of the window with other side pressurized to 4.5 bar. Finally the window is tested for its RF performance. An assembly is prepared to make rf measurement. The assembly converts the non-standard rf channel to standard WR284 waveguide and is calibrated using VNA by putting two of them back to back, such that input and output ports remain as of standard (WR284) type. Two waveguide to coaxial adapters are used to connect the assembly with VNA ports. The insertion loss obtained from our measurements for each of the channels is shown in figure 10. The measured insertion loss is better than -0.3 dB and average return loss is ~16 dB.
4. Conclusion
A rectangular eight ceramic RF window has been developed successfully. Two prototypes of the window have been developed to establish the reliability, repeatability and robustness of the development process. The details of development process are described and challenges involved are addressed. The mechanical, vacuum and rf measurements have been made and results obtained are in agreement with the desired results.

5. References
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