Vacuum Brazing of Accelerator Components

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Abstract. Commonly used materials for accelerator components are those which are vacuum compatible and thermally conductive. Stainless steel, aluminum and copper are common among them. Stainless steel is a poor heat conductor and not very common in use where good thermal conductivity is required. Aluminum and copper and their alloys meet the above requirements and are frequently used for the above purpose. The accelerator components made of aluminum and its alloys using welding process have become a common practice now a days. It is mandatory to use copper and its other grades in RF devices required for accelerators. Beam line and Front End components of the accelerators are fabricated from stainless steel and OFHC copper. Fabrication of components made of copper using welding process is very difficult and in most of the cases it is impossible. Fabrication and joining in such cases is possible using brazing process especially under vacuum and inert gas atmosphere. Several accelerator components have been vacuum brazed for Indus projects at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore using vacuum brazing facility available at RRCAT, Indore. This paper presents details regarding development of the above mentioned high value and strategic components/assemblies. It will include basics required for vacuum brazing, details of vacuum brazing facility, joint design, fixturing of the jobs, selection of filler alloys, optimization of brazing parameters so as to obtain high quality brazed joints, brief description of vacuum brazed accelerator components etc.

1. Introduction

Indus-1 and Indus-2 are two storage rings presently operational at RRCAT. In these machines, electron beam from an injector microtron is accelerated to rated energies (450 MeV for filling Indus-1 and 600 MeV for filling Indus-2) in a booster synchrotron before being used to fill up Indus-1 and 2 synchrotrons to rated currents. In Indus-2, beam energy is further ramped up after filling to ultimately achieve the design energy of 2.5 GeV. Synchrotron Radiation (SR) from Indus-1 and Indus-2 is extracted through the different beamlines on these machines and used for a wide range of experiments in different areas of science and technology. The components and assemblies used between points of beam extraction and experimental area are called Front-End components. These include collimator, water cooled shutter, fixed mask, water cooled safety shutter etc made of stainless steel and OFHC copper. Main requirements of the above components are either removal of the heat or to check/contain radiation produced by travelling beams. These components have SS-to-copper and copper-to-copper joints. In most of the cases vacuum
brazing of the joints of these components is carried out using Cusil BVAg-8 brazing alloy in the vacuum atmosphere of $5 \times 10^{-5}$ mbar at temperatures ranging from 830°C to 860°C.

A Plane Wave Transformer (PWT) linac structure is another accelerating structure that has been brazed in the Vacuum Brazing Furnace at RRCAT. It involves brazing of copper to copper and copper to SS joints with minimum distortion and good electrical conductivity. Eight and twelve cell PWT linac structures have been successfully developed indigenously using Vacuum Brazing.

OFHC Copper is main engineering material used in the accelerators. It has relatively less strength which results into selection of its higher thicknesses. Glidcop is a new material to be used in lieu of OFHC/OFE Grade copper. It is similar to OFHC copper in all respects but with higher strength as compared to OFHC copper. Brazing process has been developed for the above material using Cusil BVAg-8 brazing alloy vacuum atmosphere. Brazed joints are developed using test samples.

2. Working Principle of Brazing Process
Joining of two pieces of base metal is performed when melted filler alloy flows across a very thin gap or clearance between them and on cooling it forms a solid bond. Brazing creates an extremely strong joint, usually stronger than the base metal pieces themselves, without melting or deforming the components. The principle by which the filler alloy is drawn through the joint to create this bond is capillary action. In a brazing operation, the heat is applied to the entire base material. The filler alloy automatically comes in contact with the heated parts. The filler alloy melts instantly by the heat available in the base metals and on melting it is drawn by capillary action completely through the joint. Thus, a brazed joint is made. In Vacuum brazing process all gases are essentially removed from the area surrounding the job. For this reason it is an expensive process. No reaction or oxidation takes place of the components being brazed as gases present removed vacuum pumping. Flow, wetting and spreading of liquid filler is affected by the presence of oxides and impurities present at the surfaces to be brazed. For removing the oxides proper cleaning methods are used. Most of the impurities and the remains are generally of volatile nature detrimental to joining and are cleaned by physical and/or chemical methods. Their presence in traces is easily removed by evacuating the surroundings of the job. Thus the surfaces are maintained clean. In some cases oxide present on the surfaces of the components being brazed dissociate themselves during heating cycles under vacuum environment. This results into self- cleaning of the components. Gases are desorbed from the components during heating cycles and these are also removed completely. In this way in vacuum brazing an environment is created for carrying out joining process in ideal conditions. The components are uniformly heated. All of the above factors in vacuum brazing result into several advantages which are not possible to get in other methods of joining and brazing.

3. Vacuum Brazing Furnace
The above facility consists of a double walled water cooled vacuum chamber having demountable type door ends with provision of vertical bottom loading. Job loading is motorized. The above furnace can accommodate jobs of 700mm diameter x 2000mm long sizes with job weight of 500kgs. The furnace was designed for a maximum temperature of 1250°C at a vacuum of $5 \times 10^{-5}$ mbar. At present the furnace is in regular use for temperatures upto 1000°C with vacuum of order of $2 \times 10^{-5}$ mbar. Oil diffusion pumping system with a combination of rotary and mechanical booster pump have been employed for obtaining vacuum. Molybdenum heating elements, radiation shield of molybdenum and Stainless Steel Grade 304 have been used. The above furnace is computer controlled with manual over-ride facility. PLC and Pentium PC are integrated together to maneuver steps of operation and safety interlocks of the system. Closed loop water supply provides cooling to the system, Figure 1 [4].

4. Main Steps in Vacuum Brazing
Following are the main steps to be followed in vacuum brazing –
4.1 Clean and Compatible Vacuum Furnace

The vacuum furnace in which vacuum brazing of components is scheduled should be absolutely clean. If it is a new furnace the hotbox assembly is required to be carried out in a dust free clean room with control on humidity. High humidity may spoil molybdenum components of hotbox assembly. In case the furnace is old and has been in use for a long time it requires cleaning of the hotbox and vacuum chamber surfaces exposed to vacuum. Vacuum degassed materials and oxides formed deposit on hotbox components. They are required to be removed chemically or by using mechanical methods. Thick black tar layer of contaminants deposited on the hotbox also requires its removal. Hydrogen purging at elevated temperature is also employed for removal of metal oxides from surfaces of the hotbox components. To know and ascertain the health of the vacuum furnace from cleanliness viewpoint it will be ideal to identify the level of various contaminants by using Residual Gas Analyzer (RGA). The above practice has been followed in present facility.

4.2 Cleaning of the components/Assemblies

Proper cleaning of the components is equally important. Capillary action works properly if the surfaces are clean. The surfaces contaminated with oil, grease, rust, scale or dirt will form a barrier between base metal surfaces and the molten filler alloys. An oily base metal will result into poor wetting and spreading of the filler. The molten filler that oxidizes due to heat results into voids and in imperfect joint. Oils and grease carbonize the parts when heated and form a film over which the filler metal will not flow. Similarly brazing filler cannot bond rusty surfaces. Hence cleaning is essential part of vacuum brazing. Cleaning of base metals and non metals is a complex process. In general, most of the impurities are cleaned and washed with water and detergent soaps. Further cleaning is done with organic solvents. Rough surfaces are smooth buffed and acid pickling is done to remove buffing compounds from the surfaces. Good quality joints have been obtained following the above practices.

4.3 Joint Design and Types of Joints

Many types of joints are used in brazing similar to other brazing methods. However, two basic types of joints are commonly used. These are butt and lap types. Butt joints do not provide as much strength as lap joints. This is because more area is available for brazing in lap type joints. Main consideration in designing a joint is given to the strength of the joint. If high strength is required lap or scarf type joint is preferred rather than a butt. Strength depends on area of brazing of faying surfaces of the components. The joint design can further be improved by adopting a joint which can re-distribute stresses. This will reduce stress concentrations in the areas nearer to the joints, Figure 6. It also depends on gap or clearance between the components[4]. The recommended clearance for typical furnace brazing is given the Table 1 for particular type of brazing filler metals. Necessary care has been taken in designing of the components which had been vacuum brazed.

4.4 Good Fit and Proper Clearance

For getting a quality joint it is necessary to provide and maintain proper clearance between components of the base metal to allow capillary action to work most effectively. A close clearance is maintained during the brazing operation as the tensile strength of the brazed joint varies with the amount of clearance between the parts being joined. Joint strength is reduced if the clearance is either reduced or increased than a value which is specific to a particular base metal in given set of conditions. Figure 9. Typically these clearances range from 10 microns to 100 0f microns [4]. In joining dissimilar metals thermal coefficient of expansions should also be considered once deciding for the clearances. For this reason manufacturing tolerances and allowances in the design of the individual components and an assembly as a whole are required to be specified so as to meet the brazing process requirements, Figure 2.

4.5 Assembly and Loading of the Job

On accomplishment of cleaning and oxide removal the components are assembled in a clean room. Assembly of components requires holding in position. This is achieved by using fixtures. Filler
metals/materials are cut or formed to the required sizes and are placed/sand witched between the components. It shall be ensured that the assembly remains in required position till it is taken out of the chamber on completion of the heating and cooling cycle. It should further be ensured that the assembly remains in correct and aligned position throughout the cycle. The simplest way of doing this is to hold the components together by gravity. For easy and successful brazing the joints surfaces are kept in horizontal plane for effective working of capillary action. Joints inclined to the horizontal plane are also brazed by holding fillers in position using special holding fixtures. For brazing several joints and/or subassemblies multi-stage brazing is carried out. The components received after cleaning should immediately be assembled and loaded in the vacuum furnace with minimum time gap so that the surfaces to be brazed are joined in clean and oxide free condition.

![Vacuum Brazing Furnace](image1)

![Variation of Strength with thickness of joints](image2)

### 4.6 Heating Cycle of Furnace/Job

Once the job is loaded into the furnace, it is ready for starting the heating cycle. Cooling water, compressed air and power supply are checked before starting the furnace. Vacuum pumping system and all other sub-systems are also checked for their proper working. Initially the heating rate High purity alumina ceramics are kept from 3 deg. C to 5 deg. C per minute. For achieving temperature uniformity in the hot zone temperature soaking of adequate durations are given. For achieving a quality brazed joint heating is carried out to a temperature of 50 deg. C above the melting point of the filler alloy with duration of few minutes. Very low voltages Thyristor/SCR controlled power supply are used in the furnace. Operation & control of the furnace is computer controlled with manual over ride facility. PLC and SCADA are also used in the vacuum brazing furnaces to make them operator and user friendly. Operation and safety interlocks are provided for safe operation of the furnaces. Closed loop clean and cooled water supplied is used. Periodic maintenance and timely up-keeping of the sub-systems reduced down time to the minimum.

### 5. Brazing of Accelerator Components

Various components have been vacuum brazed successfully at RRCAT, Indore. These components as mentioned below are explored as better and suitable alternatives to the available components. Some of them are new developments. Brief description of brazed components is given below -

#### 5.1 Brazing of a PWT linac structure

In order to support high electric field gradients $\geq 20$ MV/m, linac structures are operated under high vacuum $\leq 1 \times 10^{-7}$ mbar. Further, all joints should have very good electrical/rf conductivity to minimize losses. A 12-cell PWT linac structure that is capable of accelerating electron beam to $> 10$ MeV energy consuming ~ 8 MW of RF power has been successfully brazed and leak-tested to a leak rate $\leq 5 \times 10^{-10}$
mbar l/s. The brazed disk-array of the linac has 101 joints that are brazed in a single cycle. The disk array of the linac, at the axis of which the accelerating electric field is generated, has twelve disks machined from Class I Oxygen-free Electronic (OFE) Grade Copper, which are supported on four tubes of AISI Stainless Steel (SS) 316L plated on the outside surface with copper. These tubes serve the dual purpose of support and cooling since they carry water from a reservoir at one end of the array to all the disks. The total number of joints to be brazed in a single cycle is 101. The outer vacuum envelope of the linac (tank), into which the disk array is inserted, is made of AISI SS 316L and it has the necessary ports for vacuum pumping and for feeding RF. The RF port made of Class I OFE copper is brazed to the outer surface of the tank. In all these brazing cycles, the filler alloy used is eutectic Copper-Silver (72-28) and all brazed SS surfaces are electroplated with copper before the brazing cycle. Appropriate fixtures are employed during the brazing cycles to ensure alignment and precise spacing between the disks of the array. Figure 3 shows the brazed disk array and figure 4 shows the tank envelope of the 12-cell PWT linac structure.

5.2 Brazing of an S-band pre-buncher structure:
An S-band pre-buncher structure has been designed to bunch an electron beam from a sub-harmonic pre-buncher before injection into the PWT linac structure for acceleration to rated energy. This pre-buncher is a single-cell RF structure with a geometry identical to the full cell of the standard BNL/SLAC/USLA type of laser photocathode RF guns. The half cell part of a photocathode RF gun has been modified to accommodate a beam port. The structure has two beam ports, two tuner ports, one vacuum pumping port and one RF port with a rectangular wave-guide section. Excepting the RF port, all ports are made of AISI SS 316L and electroplated with copper before brazing of the assembly using eutectic copper-silver/Cusil (72-28) filler/brazing alloy. The complete assembly has been vacuum brazed in two cycles with appropriate fixtures to maintain precise alignment of the ports. Figure 5 shows the S-band pre-buncher after the final brazing cycle. The above has been vacuum and leak tested to a leak tightness of 2x10^{-10} mbar-lit/sec with excellent quality brazed joints.

5.3 Front End Components

5.3.1 Collimator (CM)
Collimator is a beam-defining aperture made of OFE Copper solid block with rectangular tapered hole along its central axis. Collimator receive Synchrotron Radiation (SR) Beam of around 24 mrad horizontal divergence out of which only 7 mrad SR beam will pass through it resulting in heating the collimator. The water cooled copper block is vacuum brazed with Cu tube and two S.S. conflat flanges such that the water cooling is done inside UHV beam line chamber. Vacuum brazing is done by using BVAg-8 silver copper
eutectic filler metal in foil form as per SFA-5.8 of ASME boiler and pressure vessel code Section II part C at the above mentioned vacuum brazing facility.

5.3.2 Water Cooled Shutter

Water-cooled shutter is used to completely intercept the SR beam and absorb the full thermal power of the beam to isolate downstream components from the thermal load. The shutter is made of a water cooled Cu plate which can be moved up & down pneumatically inside a vacuum chamber. The Cu tube is vacuum brazed with Cu plate and the conflat flange such that there is no direct vacuum to water joint. Vacuum brazing is done by using BVAg-8 silver copper eutectic filler metal in foil form as per SFA-5.8 of ASME boiler and pressure vessel code Section II part C.

5.3.3 Fixed Mask (FM)

Fixed mask is a final beam-defining aperture made of OFE Copper solid block with rectangular tapered hole along its central axis. Fixed mask receive S.R. beam of 7 mrad horizontal divergence. The purpose of FM is to provide the required beam size for a particular beam line. The water cooled copper block is vacuum brazed with Cu tube and two S.S. conflate flanges such that there is no direct vacuum to water joint. Vacuum brazing is done by using BVAg-8 silver copper eutectic filler metal in foil form as per SFA-5.8 of ASME boiler and pressure vessel code Section II part C at the above mentioned facility.

5.3.4 Safety Shutter

The purpose of safety shutter is to absorb Bremsstrahlung gamma radiation generated from electron beam scattering, absorb the SR beam and absorb the thermal load. The safety shutter is consist of a radiation absorber head made of densimet, a tungsten alloy, and a water-cooled copper plate which can be moved up & down inside a vacuum chamber by pneumatic cylinder. The Cu tube is vacuum brazed with Cu plate and the conflat flange such that there is no direct vacuum to water joint. Vacuum brazing is done by using BVAg-8 silver copper eutectic filler metal in foil form as per SFA-5.8 of ASME boiler and pressure vessel code Section II part C.

6. Water-cooled Four Blade slit system of XRF Microprobe Beamline

Water cooled four blade slit system will be used to precisely define the white beam size. Slit system is 4 blade type which is housed in UHV chamber. Each blade is independently actuated by linear motion system. The cooling of slit blade is done through a water-cooled Cu plate. The above copper plate is vacuum brazed to copper tube carrying cooling water. The Cu tube is vacuum furnace brazed with Cu plate and the conflat flange using BVAg-8 silver copper eutectic filler metal in foil form as per SFA-5.8 of ASME boiler and pressure vessel code Section II part C.
7. Vacuum Brazing of Glidcop® to OFE Cu for application in Photon Absorbers of Indus-2

Indus-2, a 2.5 GeV synchrotron radiation (SR) source emits 187 kW of SR power from bending magnet source at the design current of 300 mA. Only 15% of this power is channeled in beam lines while the rest is absorbed by 64 water-cooled photon absorbers installed on 16 numbers of bending magnet chambers. The normal incident SR power density on the exposed surface ranges from 10 to 12 kW/cm². In the upgraded design of photon absorber, the bottom part facing SR is made of low oxygen (LOX) grade Glidcop AL-15 (UNS C15715) while the intermediate part is made of oxygen-free electronic copper (OFE Cu - UNS C10100) which is to be joined to the bottom part. The dissimilar joint between Glidcop and OFE Cu is required to be hermetically sealed (helium leak rate < 2 x 10⁻¹⁰ mbar.lit/s), bakeable up to 150°C and reasonably strong to withstand high pressure of cooling water. The experimental study was done to standardize brazing process to obtain helium leak tight, bakeable and strong brazed joint between Glidcop® to OFE Cu. Vacuum brazing joint thus produced yielded helium leak tight and bakeable joints with acceptable shear strengths and the joints were comparable to the joints made using gold-50%-copper-50% alloy using hydrogen atmosphere in some other furnace[6].

Fig. 8. Details of specimen used for brazing experiments.

8. Conclusion

Vacuum brazing of hundreds of components and assemblies have been successfully done using the vacuum brazing facility available at RRCAT, Indore. The vacuum compatible brazing assemblies are leak tested by using Helium leak detector. All the brazing joints are found leak tight with leak rate better than 10⁻¹⁰ mbar liter/sec. The above process of joining will be highly useful for developing UHV compatible accelerator components and systems in the future.

References

[1] Giles Humpston and David M. Jacobson, 1993, ASM International.
[2] D. Apelian, Introduction to Furnace Brazing, 2001, APD.
[3] Handy & Harman Brazing Book, 2001.
[4] Singh R, Development of Vacuum Brazing Techniques, Invited Talk 2005 Proc. Int. Conf. IVSNS (Gandhinagar, India).
[5] Singh R, Yedle K, Jain A K, Development of Vacuum Brazing Furnace, 2005 Proc. Int. Conf. IVSNS (Gandhinagar, India).
[6] Yadav DP, Vacuum Brazing of of Glidcop® to OFE Copper, unpublished.