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Brazing of photocathode RF gun structures in Hydrogen atmosphere: Process qualification, effect of brazing on RF properties and vacuum compatibility

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Abstract. In this paper, we report on the development of a brazing process for an ultra-high vacuum (UHV) compatible photocathode RF gun structure developed at our Centre. The choice of brazing alloy and its form, brazing clearance between parts to be joined and the brazing cycle adopted have been qualified through metallographic examination of identical joints on an OFE copper prototype that was cut open after brazing. The quality of brazed joint not only affects the UHV compatibility of the gun, but also influences the RF parameters finally achieved. A 2-D electromagnetic code, SUPERFISH, was used to predict the variation in RF parameters before and after brazing considering actual brazing clearances provided between the parts to be joined. Results obtained from low power RF measurements on the brazed gun structure confirm the integrity of the brazed joints and show good agreement with those predicted by electromagnetic simulations. The brazed gun structure has been leak-tested and pumped down to a vacuum level limited by the vacuum compatibility of the flange-fittings employed in the setup.

1. Introduction

Laser driven photocathode RF guns are used to generate ultra short pulses of electrons with high peak currents and low emittances required for advanced accelerator applications such as Free Electron Lasers (FELs), colliders, ERLs, Inverse Compton Scattering, Plasma Wake field accelerators, etc. [1]. In a Laser photocathode RF gun, electrons generated by shining a laser beam on a cathode are accelerated to high energies by an electromagnetic field setup in the gun by feeding high radiofrequency (RF) power to the structure. A typical design of photocathode RF gun is the 1.6 cell BNL/SLAC/UCLA type S-band gun, consisting of two cells- a full-cell and a half cell, each of which has ports for different use. The two cells and the ports are machined from Oxygen Free Electronic (OFE) grade copper and AISI Stainless Steel (SS) 316L respectively, and brazed together after tuning of RF properties of the independent cells to form a photocathode RF gun structure. The requirement of a good quality electron beam from a photocathode gun imposes stringent conditions upon the RF parameters, and consequently on the geometrical features of the gun, and a small variation in RF parameters due to different possible reasons can seriously affect the quality of electron beam from the gun[2,3]. Variation in geometrical dimensions of gun cells due to brazing is one of the most important contributors to the deterioration in RF parameters of a tuned gun structure. Therefore, adequate care has to be taken while designing the brazed joints and finalizing the brazing cycle to minimize such deleterious effects of distortion due to brazing.

Hydrogen atmosphere is preferred for brazing copper since the oxides of copper can easily be removed by reactive hydrogen at brazing temperatures. The issue of hydrogen diffusion in copper during the brazing process can be resolved by subsequent baking of the brazed component in a vacuum baking furnace. Brazing of a photocathode RF gun structure involves joining of two RF cavities (full-cell and half-cell) and one rectangular waveguide made of Class 1 OFE Copper (Cu), six cylindrical ports and two seal plates made of AISI SS 316L. Since brazing of a photocathode RF gun involves joining of copper to SS, gold based alloys are usually employed worldwide at brazing temperatures of ~ 1000^{o} C. In order to avoid such high brazing temperatures, all SS components of the photocathode RF gun were electroplated with copper and Eutectic Copper-Silver (72%-28%) filler alloy (BVAg8) was used in the brazing. Before brazing of the actual gun structures, similar joints were qualified by brazing of multiple dummy samples with SS to copper joints.

Brazing of a photocathode RF gun structure is complex as the profile, cross sectional area and angle of various joints are different. The requirement of minimization of variation in RF parameters of gun due to distortion caused by brazing makes the task further challenging. To minimize these distortions and to achieve UHV compatibility, proper fixtures were designed and brazing cycles were finalized after testing over multiple full-scale gun prototypes made of Electrolytic Tough Pitch (ETP) copper before brazing the final gun structures [4]. The volume of brazing filler required was determined by calculating the volume of joints to be filled and care was taken to minimize the flow of filler inside the gun cells, since this can seriously compromise the high electric field gradient supporting capability of the gun. This has been confirmed by metallographic test of brazed joints of a gun prototype which was brazed by employing the same brazing cycle with the same amount of filler alloy as was used in the final gun structures. The brazing procedure adopted and calculations of brazing joint and filler volumes for the photocathode RF gun is given in section 2. Section 3 discusses the metallographic evaluation of the brazed joints, which is followed by a discussion of predicted and measured variation in RF parameters of the gun structure due to brazing in section 4. UHV compatibility of the brazed gun structure is discussed in section 5 followed by conclusion and discussions in section 6.

2. Brazing procedure and filler requirement estimation

Brazing of photocathode gun was carried out in two brazing cycles in a hydrogen furnace (HT 1800 G, Linn, Germany) having hot zone of 30cmx28cmx30cm. The same filler alloy (BVAg8) was employed for both cycles. In the first cycle, the two cells were brazed together and 6-ports were simultaneously brazed on the two cells. The second cycle involved brazing of the waveguide at the RF port on the full cell. All joints brazed together in the first cycle were tubular butt-lap joints. The second cycle involved brazing of a rectangular butt-lap joint. While achieving the required brazing clearance in the butt joint was relatively easy, care had to be taken during machining of the port openings on the gun cell and the ports themselves to ensure brazing clearance of the order of 30-50 μm in the tubular lap joint region. This was ensured by inspection of each component after machining and after electroplating. After each brazing cycle, leak test of all brazed joints were performed using helium leak detector [4].

The different butt and lap joints involved in brazing of the photocathode gun structure are shown in Fig.1 and 2. The formula used to calculate volume of brazing joints and respective filler volumes required for each joint are given in table I. Copper silver eutectic (Cusil, BVAg8) was used as brazing alloy, in form of a ring of 0.1 mm thick foil for the butt joints and a ring of wire of 1mm diameter for lap joints. From practical considerations 30-50 % extra volume of filler alloy was taken.

The brazing cycle and fixtures used during the brazing are important to ensure UHV compatibility of the joints. Since the first cycle involves brazing of six orthogonal joints and two joints at 22.5 degree, proper fixturing is a crucial element of the brazing process. Fixtures used were machined out of AISI SS 304 and the tuner ports were held in position using tungsten wire. More details of the fixtures and the brazing cycle employed are discussed in Ref. 4.

Table 1: Calculations of volume of brazing joints.

Joint	Formula used to calculate joint volume	Volume of joint (mm^3)
Half cell - seal plate	$\pi\left(\frac{OD_{lip}^2-OD_{half\ cell}^2}{4}\right)t+\pi\left(\frac{OD_{lip}^2-ID_{seal\ plate}^2}{4}\right)\times h_{seal\ plate}$	449.76
Full cell – half cell	$\pi\left(\frac{OD_f^2-ID_f^2}{4}\right)t-\left(\frac{OD_f-ID_f}{2}\right)b_{wo}t+d*b_{wo}t+\pi\left(\frac{ID_f^2-OD_{iris}^2}{4}\right)L_{iris},.$	401
Full cell – tuner port	$\pi\left(\frac{ID_h^2-ID_p^2}{4}\right)t+\pi\left(\frac{ID_h^2-OD_p^2}{4}\right)L,$	25.30
Full cell - vacuum port		62.47
Full cell – beam exit port		27.52
Full cell - half cell		401
Half cell – laser port		35.63
Gun - Waveguide	$2(B_f-B_{wi})\times(A_f-A_{wi})\times t+2(B_f-B_{wo})\times(A_f-A_{wo})\times h$	401.45
Waveguide – RF port flange	$2(B_f-B_{wi})\times(A_f-A_{wi})\times t+2(B_{Rf}-B_{wo})\times(A_{Rf}-A_{wo})\times h$	365.58

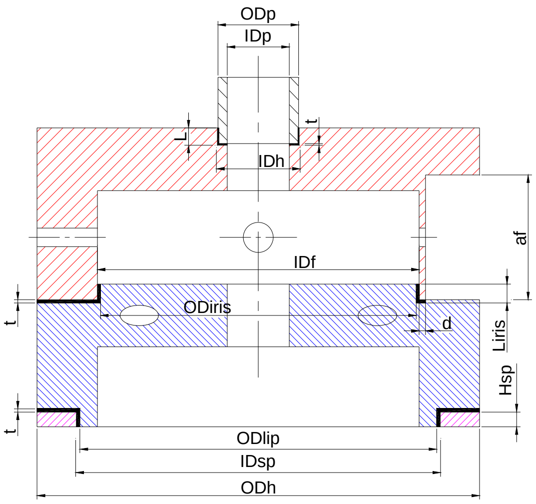

Fig.1: Details of different brazing joints in photocathode gun brazed in first cycle.

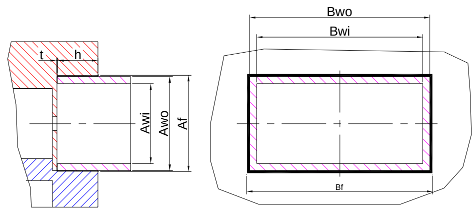

Fig. 2: Details of photocathode gun to waveguide brazing.

3. Evaluation of brazed joints

The photographs of gun assembly after first and second cycles are shown in Fig. 3 (a) and (b), while a cross-section of a prototype gun cut open for metallographic evaluation is shown in Fig. 3 (c). This section includes Cu-Cu as well as Cu-Cu plated SS joints which were examined under a microscope at 20X and 50 X to evaluate the depth of penetration of brazing alloy and the micro-structure of the joint interface. Micrographs of Cu-Cu and Cu-SS brazed cross-sections are shown in the Fig. 4. Full penetration of the brazing alloy, confined to joint interface is seen in Cu-Cu joint, while in the case of Cu-SS joint penetration is observed along the grain boundaries into the copper matrix. All the joints were found to be micro-structurally sound and free of defects like porosity and lack of wetting. Thickness of braze joint in the case of Cu-Cu is in the range of 20 μm with some excursions up to 60 μm, while in the case of Cu-SS joint it is in the range of 25 μm with some excursions up to 40 μm. Figure 4B clearly shows penetration of the filler alloy into the copper matrix along the grain boundaries for Cu-SS joint.

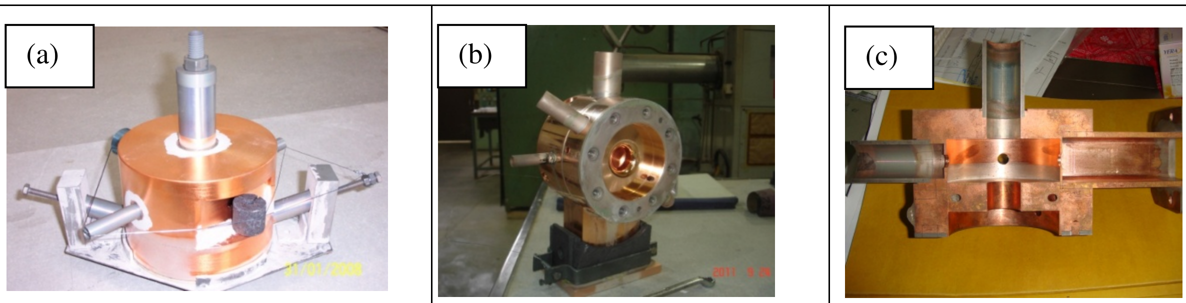

Fig. 3: Gun assembly after: (a) first brazing cycle, (b) second brazing cycle and (c) cross section of a brazed gun prototype

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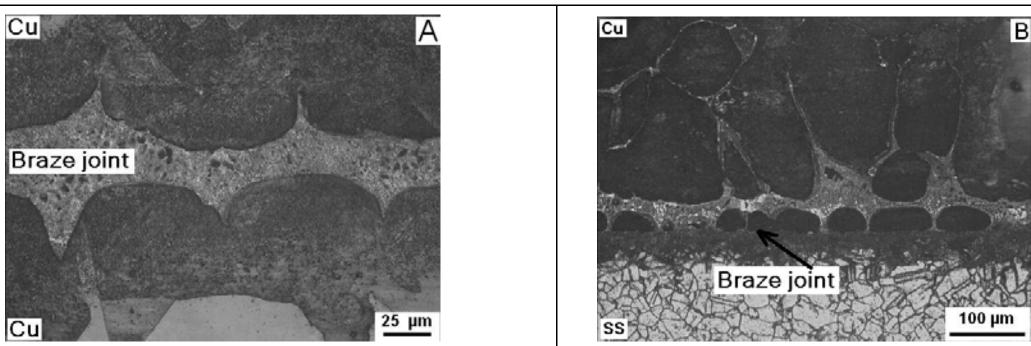

Fig. 4: Micrographs of: (A) copper to copper and (B) copper to SS brazed joint

4. Effect of brazing on RF properties

From brazing considerations, a clearance of ~ 25-50 µm is usually maintained at the location of the joint between the full and half-cells of a photocathode gun as shown in Fig. 5. This clearance is present during tuning, but gets filled up with the brazing filler after brazing, which causes a change in independent full cell frequency (f_f) and waveguide to independent full cell coupling coefficient (β_f) before and after brazing. SUPERFISH simulations show that f_f decreases linearly with brazing clearance with a gradient of -0.127 MHz/10 µm, while β_f after brazing becomes 1.17 times its value before brazing [3]. This change is like a step and is independent of variations in the value of the brazing clearance. Low power RF measurements on the brazed gun structure confirm that experimentally measured variation in RF parameters is very close to the predictions as given in table II, which further confirms that the brazed joints show good RF continuity, distortion due to brazing is nominal, and calculation of filler volumes is appropriate.

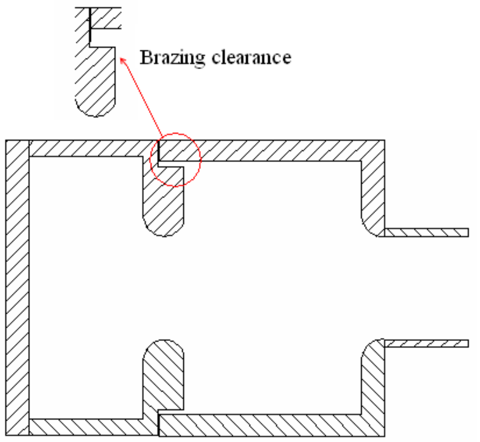

Fig. 5: Brazing clearance between the full-cell and half-cell

Table II: Comparison of variation in RF properties of photocathode gun due to brazing.

Variation in Parameters	Prediction		Experimentally measured	
	Gun 1	Gun 2	Gun1	Gun 2
$\Delta\beta_f$	1.17	1.17	1.26	1.27
Δf_f (MHz)	0.457	0.457	0.54	0.44

5. Testing of UHV compatibility

Before brazing of final gun structures, all brazed prototypes were subjected to leak testing using a Mass Spectrometer Lead Detector (MSLD) (Alcatel, ASM 142) using Helium. The measured leak rate at all joints was ≤ $5x10^{-10}$ mbar l/s, which was acceptable. Figure 6 shows the photocathode gun being leak-tested and a test setup where a Sputter Ion Pump of 140 l/s is employed backed by a turbo-molecular pump [Pfeiffer, TSU 260D] of 210 l/s to ultimately achieve a vacuum level of $3x10^{-8}$ mbar within 48 hours.

6. Conclusion

A technique to braze a photocathode RF gun in hydrogen furnace with predicted variation in RF parameters along with UHV capability has been developed, qualified and successfully used to braze multiple photocathode RF gun structures. Metallographic examination confirms that all joints are micro-structurally sound and free of defects. Further study to qualify the brazing joints is presently underway.

Fig.6: Photocathode RF gun being leak tested, and on the vacuum test setup

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