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HIGH GRADIENT EXPERIMENT BY ATF

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Abstract

High gradient experiments at S-band frequency have been carried out using disk loaded structures with the length of 0.6 m which are the traveling wave constant gradient type. An accelerating gradient up to 90 MV/m has been obtained and the field emission current at the high field has been studied.

A Hot Isostatic Pressing (HIP) diffusion bond of OFHC and Titanium was successfully achieved to eliminate the micro pores of the material for accelerating structures and reduce the field emission current at the high accelerating fields.

Introduction

The accelerating gradient of the Japan Linear Collider(JLC) is 100 MV/m for the X-band main linac and 40 MV/m for the S-band injector and the pre-accelerator. We have already carried out the acceleration of the electron beam with the peak current of 0.9 A and pulse width of 0.2 μsec by the S-band structure of 0.6 m long at the gradient of 85 MV/m [1]. At this gradient, however, the dark current is very large and breakdown occurs frequently. On the other hand, at 70 MV/m, the beam acceleration is so stable that it seems feasible to operate at this gradient for the practical use after a reasonable processing period. It is confirmed that the operation of the S-band structure at 50 MV/m is quite promising. This level corresponds to 100 MV/m at X-band which meets requirement of the JLC.

Experimental studies on the upper limit of the electric field strength in conventional disk loaded structures and single cavities have been reported from several laboratories [2, 3]. From these studies, there found many factors to be discussed concerning rf breakdown phenomenon with dark current such as surface finish, micro dusts, electron multiplications and vacuum conditions, etc. However, the fundamental mechanism of the rf breakdown is not yet clear. The recent experiments are focused to study the correlation between the rf breakdown phenomena and the dark current. The origin of the dark current from disk edges is the dielectric material such as dust and machine-oil remained on the copper surface inside the structure. To study the effect of these impurities, a clean structure has been fabricated by improving the manufacturing processes such as brazing, tuning of each cell and so on.

Furthermore, it has been found that the electron multiplications at disk edges is one of the main reasons for limiting the accelerating gradient [4, 5]. In order to reduce the electron multiplications from disk edges in a traveling wave structure at high field gradient, a new type of disk has been proposed which comprises of a part made of Titanium around the beam hole area and a part made of OFHC. Since the secondary electron emission coefficients of Titanium is less than unity, the beam hole of a disk has been designed to be made of Titanium. We applied diffusion bonding by a hot isostatic pressing, HIP, to join Titanium to OFHC [6].

This paper describes the upper limit of the field gradient at S-band structure and the preliminary results concerning the characteristics of HIP diffusion bonded OFHC-Titanium metals.

Experimental Procedure

Set-up

The schematic diagram of the experimental set-up is shown in Figure 1. The waveguide system, the structure and the beam ducts are pumped down to 5×10^{-7} Pa by four 60 l/s ion pumps and two 160 l/s ion pumps. The vacuum pressure is monitored by the cold cathode gauges (CCG) and the B-A gauges. Signals of the CCG are used for the interlock system of the vacuum pressure during the rf operation. The partial pressure of residual gases during the processing of the structure is monitored with a mass-spectrum analyzer.

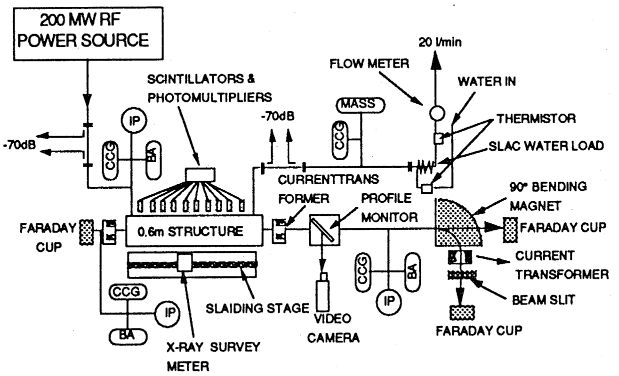

Figure 1 Schematic diagram of the experimental set-up

The rf-output from two klystrons (SLAC 5045 and TOSHIBA E3712) are combine with a -3 dB directional coupler. The maximum power of 200 MW with a pulse width of 1 μsec and repetition rate of 50 Hz can be fed into the structure. The rf power of both the forward and reflected wave was monitored by dual Bethe-hole couplers with a coupling ratio of -70 dB. The transmitted power through the test structure of 0.6 m long was monitored by also a Beth-hole coupler and terminated by the rf water load which was developed at SLAC.

The field gradient was evaluated by measuring the energy spectrum of electrons generated by the field emission from the structure. For this purpose, a magnetic spectrometer of 90° bending angle was put behind the structure and electrons were captured by a Fraday cup. The peak current and pulse shape of the beam were monitored by two current transformers at the upstream and downstream of the structure. A beam profile monitor using a luminescent ceramic is mounted downstream of the structure.

The microscopic field enhancement factor, β, was estimated from the modified Fowler-Nordheim plot (F-N plot) according to the following formula:

$$\frac{I_f}{E_s^{2.5}} = C \cdot \exp\left(-\frac{2.84 \times 10^9 \times \phi^{1.5}}{\beta E_s}\right) \qquad (1)$$

where I_f is the field-emission current dumped to the Faraday cup on the beam axis at the down stream of the structure, E_s is the maximum surface field which appears around the beam hole at the disk, C is the constant and ϕ is the work function of the copper.

Structures

Two structures were manufactured by brazing method in a hydrogen atmosphere and another one was manufactured by an electroplating method.

As for two brazed structures, the surface roughness of the beam hole is approximately 0.8 µm and that of the flat surface is less than 0.8 µm. One of the brazed structures was fabricated in the usual environment and another one was fabricated carefully to avoid the contamination of immunities as mentioned in the previous section.

In the electroplating structure, the vacuum tightness was obtained by the electroplated layer of copper without using any brazing process. The surface roughness of the beam hole is approximately 0.3 µm and that of the flat surface is less than 0.02 µm.

Table 1
Parameters of the 0.6 m structure

Phase Shift/Cell	$2\pi/3$	Constant Gradient
Structure Length	66.5	cm
Iris Diameter 2a		
input	1.8998	cm
output	1.5900	cm
Cavity Diameter 2b		
input	8.172	cm
output	8.124	cm
Resonant Frequency f	2856	MHz at 36.5°C, VAC
Quality Factor Q	11600	
Shunt Impedance r	62	MΩ/m
Attenuation Constant α	0.48	Neper/m
Peak Surface Electric Field (Es) / Axial Electric Field (Ea)	1.9 ~ 2.1	
Average Group Velocity vg/c	0.00445	
Filling Time Tf	0.475	µsec

These three structures have a same geometry as a $2\pi/3$ traveling wave constant gradient type with 17-cells, input and output couplers. The structures are designed to obtain the gradient of 100 MV/m at the input rf power of 195 MW and the parameters are given in Table 1. From these values, the accelerating field E_a without beam is expressed as follows:

$$E_a\,(\mathrm{MV/m}) = 7.16 \times \sqrt{P_{in}\,(\mathrm{MW})} \qquad (2)$$

where E_a is the accelerating gradient in MV/m and the P_{in} is the input rf power in MW. The SUPERFISH calculation gives the result that the maximum surface field at the disk edges E_s is 2.1 times of E_a.

Application of HIP

A forged OFHC generally involves a large number of micro pores with dimension of a few µm at the grain boundary. This is one of the origins of dark current, since dielectric material such as machine oil remains in the micro-pores of the copper surface. Furthermore, it can give micro-pits on the surface of the disk edges after the machining. We applied HIP to join Titanium to OFHC and to reduce the micro-pore inside the OFHC. HIP is a thermo-mechanical process for materials that makes use of applied gas pressure in order to achieve high density and diffusion bonding in the treated material. HIP subjects generally a material to pressures as high as 2,000 kgf/cm^2 and temperatures up to 2,000 °C in a pressure vessel. The source of the heat is a furnace within the pressure vessel, holding temperatures well below the melting point of the material being processed. This method can be used for a wide range of materials such as metals, ceramics and composites.

Experimental Results

High gradient experiments

We have been already tested two brazed structures which are the normal structure and the clean structure. The experiment on the electroplated structure is now under way. In the conditioning, the rf pulses with a width of 0.8 µsec and repetition rate of 50 Hz were applied to the structure. During the conditioning, the rf power applied to the structure was controlled by a computer to keep vacuum pressure below $1\text{x}10^{-5}$ Pa although the interlock level is set at $1\text{x}10^{-4}$ Pa. Normally the vacuum pressure of the structure was around $5\text{x}10^{-6}$ Pa during the rf processing at any rf power level. Occasionally it rose up to $5\text{x}10^{-5}$ Pa or even higher as rf breakdown took place inside the structure. The vacuum pressure when the structure was not fed by the rf power was $4\text{x}10^{-7}$ Pa.

In case of the normal structure, the maximum gradient of E_a= 91 MV/m was attained after 800 hours rf processing which corresponded to the rf power level of 160 MW. The β was evaluated to be 44 as indicated in Figure 2-(a). In case of the clean structure, the maximum gradient of E_a=73 MV/m was achieved after only 200 hours of rf processing and ß was evaluated to be 57 as shown in Figure 2-(b). As for the electroplated structure, also the maximum gradient of E_a= 83.6 MV/m and ß=53 has been achieved after 200 hours of rf processing which is still under way as shown in Figure 2-(c). We hope that the field gradient of the electroplated structure would be increased by continuing the rf processing.

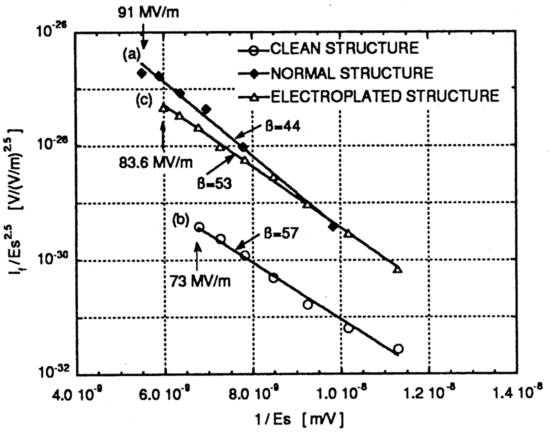

Figure 2 Fowler-Nordheim plots for the three structures.

As can be seen in Figure 2, the amount of the dark current of the clean structure is order of magnitude lower than the normal and electroplated structures, and the three F-N lines in this figure have almost the same tangent of slope. Considering that only the difference between the clean and normal structures is the amount of impurities on the surface of the structure, we conclude that the reduction of the impurities could affect drastically to reduce the field emission current. On the other hand, the upper limit of field gradient is determined with other factors which should be studied by the further systematic experiments.

HIP process

The quality of HIP was studied with metallographical measurements which are optical microscope and scanning electron microscope, and mechanical tests. At three different HIP temperatures (700, 750 and 800 °C) with an isostatic pressure of 1,200 kgf/cm^2 for 2 hours, all samples took on a fine, homogeneous micro stricture. In experiments at these three different temperatures no grain growth of the whole OFHC and Titanium was observed.

The micro structures of a HIP sample and a forged OFHC are shown in Figure 3 in which the micro pores disappear. In addition, HIP-processed OFHC is much more homogeneous than the forged OFHC.

The tear strength was measured using a plates with a thickness of 2 mm which were JIS standard tear test specimens. We obtained the tear strength of 6.4 kgf/mm^2 in average for the three different HIP temperatures. The minimum value of strength was 4.9 kgf/mm^2. The tear strength of all the specimens, which does not depend on HIP temperature as shown in Figure 4. All of the test specimens were fractured at inside of reaction zone where the concentrations of OFHC and Titanium were equal. The vacuum leak rate of the reaction zone is well blow than 10^{-7} Pa•l/sec.

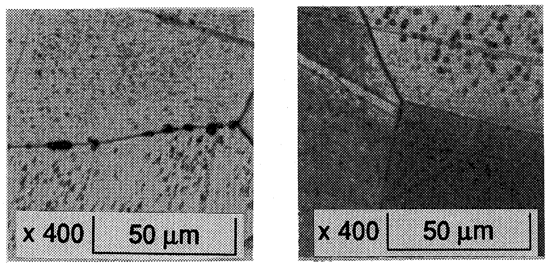

Figure 3. Optical micrograph showing forged OFHC (left) and HIP-OFHC (right) at a temperature of 800 °C and an isostatic pressure of 1,200 kgf/cm^2 for 2 hours.

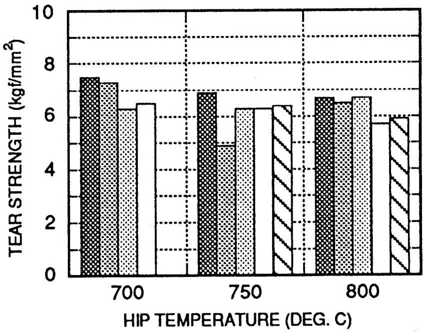

Figure 4 Tear strength according to the JIS standard test.

Acknowledgment

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