FABRICATION OF FERRITE-COPPER BLOCK BY SPARK PLASMA SINTERING (SPS)

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Abstract

Ferrite is a well-known material for effectively absorbing electromagnetic waves, and ferrite blocks are used in accelerators as higher-order modes (HOM) absorbers in vacuum beam pipes. However, one of difficulties in using ferrite for this purpose is its weak bonding to the metal beam pipes, leading to a poor heat transfer rate. Herein we report the fabrication of ferrite-copper blocks using the spark plasma sintering (SPS) technique in which the ferrite powder is directly sintered on the copper block. This ferrite-copper block fabricated via SPS can be directly brazed or welded to other desired metals or directly to the beam pipes.

INTRODUCTION

Higher-order modes (HOM) absorbers are indispensable components for recent high-power accelerators in order to prevent beam instabilities or the overheating of vacuum components. Several kinds of absorber materials, such as SiC, ferrite and Kanthal, have been investigated and applied in accelerators [1-3]. Among these materials, ferrite has been found to be superior to others because of its higher HOM absorbing efficiency. However, because of its low tensile strength and small thermal expansion rate, it cannot be easily bonded to other metals thus limiting its use as a HOM absorber.

We are currently developing a HOM absorber chamber (beam pipe) based on ferrite blocks for the SuperKEKB [4]. A schematic proposed design of the HOM absorber chamber is shown in Fig.1. The chamber has a complicated cross section with antechambers at both sides of the beam channel. Some ferrite-metal blocks or ferrite tiles will be surrounding this chamber. For ferrite-metal adhesion, several bonding methods such as brazing, soldering, and hot isostatic pressing (HIP) were investigated. It was finally found that the SPS technique is more promising than other methods. In the SPS process, the ferrite powders are directly sintered on a copper substrate under high temperature and pressure conditions in vacuum, leading to strong bonding of ferrite with the copper substrate. The results of the analysis of on the ferrite-copper block fabricated by the SPS method will be discussed herein.

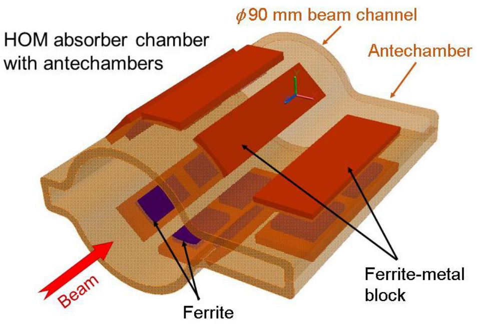

Figure 1: Concept of the HOM absorber chamber for Super KEKB.

BONDING METHODS STUDY

Various bonding methods studied here are schematically illustrated in Fig. 2. The results and features of these methods are summarized in Table 1. The ferrite used was NMB84 (powder) or IB004 (sintered block) available from TDK Co. Ltd, Japan, which was adopted for the HOM absorbers of the superconducting RF cavities in KEKB [3]. We considered a copper-based HOM absorber chamber, and our focus was on the fabrication of 30–50 mm ferrite-copper block and on ensuring a ferrite thickness of more than 5 mm. These blocks will be finally bonded to the chamber at last, as shown in Fig. 1.

The conventional method for bonding ceramics to metals is brazing. However, in case of ferrite, the wettability was poor for the available brazing filler materials. As for the soldering method, the melting temperature of a typical solder was much lower than those for the brazing filler materials. As a result the thermal stress during the process reduces and the generation of cracks was avoided [5]. However, the low melting temperature of solders also limits the allowable HOM power. Also, the high gas desorption of solder is an issue for ultra-high vacuum applications. Since ferrite is available in a powder form, a thermal spray is possible. However, the thickness of the

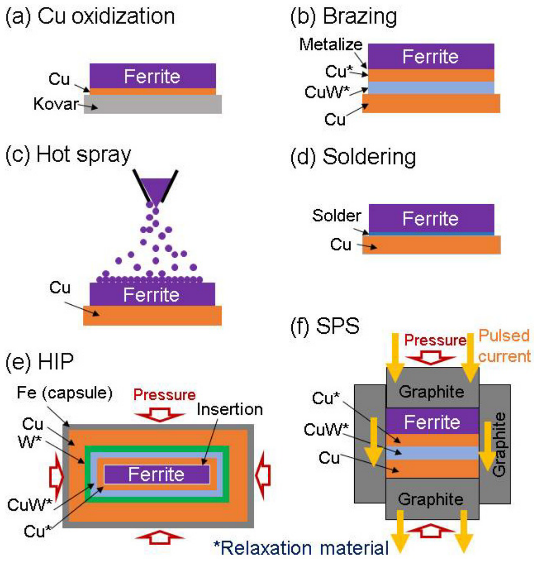

Figure 2: Schematic of several bonding methods.

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ferrite layer formed on a copper substrate was limited to 0.5 mm due to the crack generation. In addition, the density of the ferrite layers was found to be small.

In the HIP method, the ferrite powder is sintered in a capsule under high temperature and pressure conditions, leading to its simultaneous bonding to copper [3]. The adhesive force is strong and the density of the sintered ferrite is comparable to that in the case of commercially available ferrite blocks. However, the size of obtainable ferrite-copper blocks was limited to 25 mm due to the cracks generated during capsule cutting. Also the cost of this process is relatively high. In contrast, the SPS method sinters the ferrite powder in a graphite container under a high pressure in a vacuum environment via high pulsating currents, leading to strong bonding of the ferrite with the copper substrate. The graphite container can be reused and the cost can be decreased as a result compared to the case of HIP. In SPS, the ferrite-copper blocks with a diameter larger than 30 mm were obtained. Also, the density of the obtained ferrite was comparable to that of commercially available ferrite, approximately 5 g cm^{-3}.

It was found in the study that the SPS is the best method for fabricating the ferrite-copper block for our purpose. Figure 3 shows the ferrite-copper blocks with a diameter of 30 mm and 50 mm and a ferrite thickness of 5 mm fabricated by SPS. Note that the copper-tungsten layer was inserted as a relaxation material. The conventional machining techniques can be used for cutting the block into the arbitrary shapes.

Table 1: Comparison of the Bonding Methods (a)–(f) in Fig. 1, where ○: Good, ◊: Moderate and ●: Bad

Property	(a)	(b)	(c)	(d)	(e)	(f)
Bonding strength	●	◊	●	○	○	○
Ferrite thickness	○	○	●	○	○	○
Area available	●	●	○	○	●	○
Heat transfer rate at bonding plane	●	◊	●	○	○	○
HOM absorbing	○	○	●	○	○	○
High power HOM	●	◊	●	◊	○	○
Bakable temperature	○	○	●	●	◊	○
Direct bonding to chamber	●	●	○	○	●	●
Outgassing rate	○	○	●	●	○	○
Cost	○	◊	◊	○	●	◊

PROPERTIES OF FERRITE-COPPER BLOCK FABRICATED BY SPS

Heat Transfer Rate at the Bonded Plane

The heat transfer rate at the bonded plane between the ferrite and the copper substrate was estimated by heating the ferrite surface, and measuring the temperatures of the ferrite surface and the copper substrate. The measured heat transfer rate was approximately 1000 W K m^{-2}.

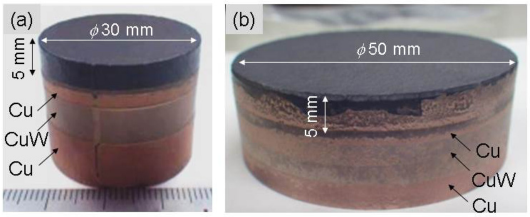

Figure 3: Ferrite-copper block fabricated by SPS method, with a ferrite thickness of 5 mm and a diameter of (a) 30 mm and (b) 50 mm.

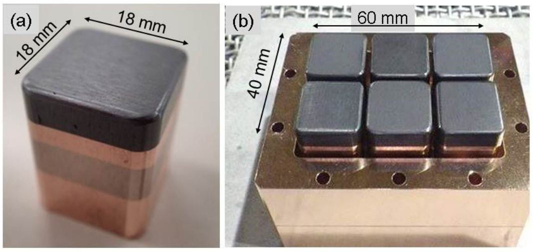

Figure 4: (a) A square ferrite-copper block machined from the cylindrical one in Fig. 3 (a), and (b) the assembly of six ferrite-copper blocks brazed to a copper block.

Gas Desorption Rate

Using two ferrite-copper blocks with a diameter of 40 mm and a ferrite thickness of 5 mm, the thermal gas desorption rate was measured at 25 °C. After evacuation for 100 h, the gas desorption rate was approximately 1×10^{-7} Pa m^3 s^{-1} m^{-2}. For reference, the gas desorption rate of a commercial ferrite block was 1×10^{-8} Pa m^3 s^{-1} m^{-2}. Thus the ferrite-copper block fabricated by SPS showed higher gas desorption rate, and some kind of countermeasures for reducing the gas desorption rate would be required for the ultra-high vacuum application. It is reported that the gas desorption rate of the ferrite fabricated by HIP reduced by one order of magnitude after baking up to 200 °C [3].

Bonding of Ferrite-Copper Block to Copper Plate

For applying the ferrite-copper block to the copper chamber, the bonding of the block to the copper plate is required. In this study, both the electron beam welding and the brazing of the copper substrate of the block and copper plates were successful. Considering the ferrite cooling, however, brazing is preferable because of its greater contact area. One observed problem in brazing, however, was the generation of cracks. Careful control of the brazing parameters, such as the heating rate, filler material used (one with a low melting point of 700 °C, for example), and pre-baking of the ferrite powder lead to a significant reduction in the number of cracking. Figure 4 (a) shows a square ferrite-copper block for the brazing test with an area of 18 mm × 18 mm machined from a cylindrical block in Fig. 3(a). Figure 4 (b) shows the assembly of 6 ferrite-copper blocks brazed to a copper block.

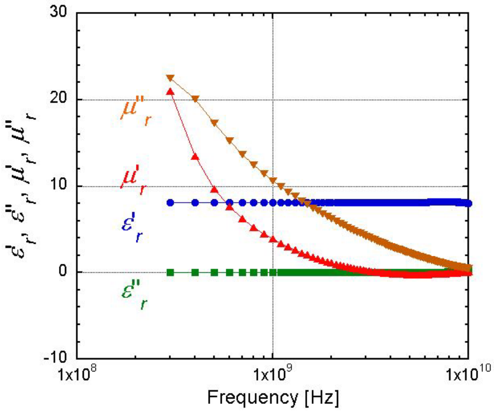

Figure 5: Complex dielectric constant and permeability of the ferrite fabricated by the SPS method.

Complex Dielectric Constant and Permeability

The complex dielectric constant and permeability were measured using a sample obtained by machining the ferrite-copper block. The results are shown in Fig. 5: the values are quite comparable to those for the commercially available IB004 bock.

S_{11} *Measurements Using a Wave-Guide*

A ferrite-copper block with a diameter of 50 mm was set on the H plane of a waveguide of the 2856 MHz microwave. The block was attached near a short-circuited end of the waveguide line, and the S_{11} parameters were measured. S_{11} decreased by 5–10 dB as compared to those of the blocks having no ferrite. This decrease was consistent with the values expected using the parameters in Fig. 5.

S_{21} *Measurement Using a Test Cavity*

A test cavity with the same aperture as that of SuperKEKB beam pipes (see Fig.1) was fabricated for measuring the S_{21} parameters. The cross section consists of a circular beam channel with a diameter of 90 mm at the center and two ante-chambers at both sides as shown in Fig. 6 (a). The length of the chamber is 143 mm. The experimental setup is presented in Fig.6 (b). Both ends of the cavity were short-circuited with aluminum plates. Two small antennae were inserted from the end plates for determining the S_{21} parameter for different excitation frequencies. The ferrite blocks, as shown in Fig. 4 (b), were attached only on the antechamber side as also shown in Fig. 6 (a). The typical frequency spectrum with and without the ferrite blocks are presented in Fig. 7. It is clear that the resonant peaks of the TE modes are strongly damped by the ferrite blocks. On the other hand, the resonant peaks of TM modes remained unaffected. The result is reasonable since the magnetic field does not exist in the antechamber for the TM modes. The changes in the measured resonant frequencies and the external Q values were quite close to the simulation results obtained using the parameters in Fig. 5.

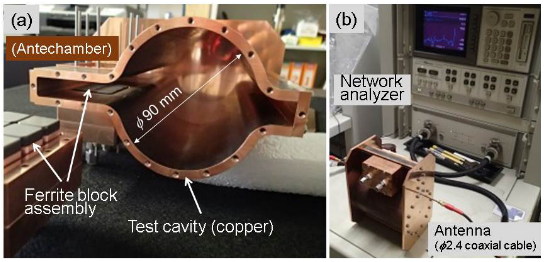

Figure 6: (a) Test cavity and (b) setup for S_{21} measurement.

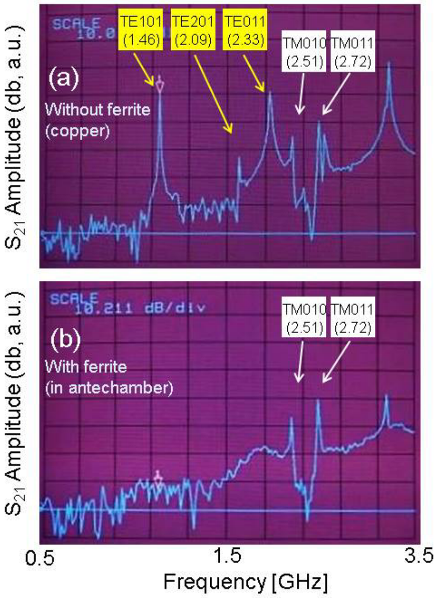

Figure 7: Frequency spectrum of S_{21} (a) without and (b) with ferrite-copper block at the antechamber.

CONCLUSION

The SPS method is quite promising for the fabrication of ferrite-copper blocks. The physical and RF properties of these blocks are quite satisfactory for their application as HOM absorbers. Testing with a high-power RF source is planned as the next step. Also any countermeasures for decreasing the gas desorption rate should be studied for the ultra-high vacuum application. A prototype of the HOM absorber chamber for SuperKEKB will be manufactured soon.

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REFERENCES

[1] Y. Takeuchi, T. Abe, T. Kageyama and H. Sakai, in *Proc. PAC'05*, pp. 1195-1197.

[2] F. Miyahara et al., in *Proc. IPAC'13*, pp. 2744-2746.

[3] T. Tajima et al., in *Proc. PAC'97*, pp. 3090-3092.

[4] Y. Suetsugu et al., "Construction status of the SuperKEKB vacuum system", *Vacuum*, vol. 121, p. 238-244, 2015.

[5] H. Hahn, I. Ben-Zvi, L Hammons and W. Xu, in *Proc. SRF'09*, pp. 625-629.