

Development of the Heat Sink Structure of a Beam Dump for the proton accelerator

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Abstract

The beam dump is the essential component for the final treatment of the beam produced in proton accelerator. Reliable performance of the beam dump depends on the function of heat sink structure in the beam dump. The large amount of the heats and radioactivity produced in the beam dump should be removed by a proper heat sink structure. The heat sink structure of a beam dump for a 20 MeV proton accelerator was designed and manufactured in this study. Heat and stress analysis were carried out to evaluate the reliability of the various designed structures. The heat sink structure was made by placing two heat sink plates at an angle so as that the maximum heat flux on the surface of the plate is lowest (12°). The heat sink plates were fabricated by a brazing of graphite and copper plate. One step brazing process for the joining of Cu-graphite plate was established during this research. The mechanical soundness of the joined heat sink plates was confirmed by the thermal fatigue tests of the brazed specimens of the graphite-copper tile components.

Key words : Beam Dump, Proton accelerator, Heat Sink

1. Introduction

The energy of 20 MeV, 20 mA proton beam produces very large amount of heats (96kW, duty factor: 24%) when the beam collides with heat sink structure of beam dump. Average heat flux of the beam of 1 cm diameter is about 1.223×10^3 MW/m². The power density of the proton beam in graphite is about 532kW/cm³. Comparing this value with the power density of PWR fuel of 0.21kW/cm³, the power density of the proton beam is extremely high.

It is necessary to design the heat sink structure to have enough cooling capacity and to withstand the thermal stresses induced by the heats. It is also required that the materials of the structure have little radio-activation characteristics. The heat sink structure of the beam dump that satisfies the requirements was designed, fabricated and verified in this study.

2. Design of heat sink structure of beam dump

2.1. The structure of heat sink structure

The heat sink structure is composed with two heat sink plates as shown in Fig. 1. A heat sink plate is composed of the graphite and the Cu plate. The graphite and the Cu plate were joined by brazing.

The angle between the two plates was determined so as that the maximum heat flux on the surface of graphite plate is lowest in the range of angle between $0^\circ \sim 60^\circ$. The maximum heat fluxes on the surface of graphite plate as a function of plate angle were calculated and shown in Fig. 2. The heat sink plate angle was decided as an angle of 12° where the lowest maximum heat flux is achieved. The heat flux distribution on a surface of graphite plate of the heat sink structure of plate angle of 11.5° is shown in Fig. 3. This distribution is used for the thermal and stress analysis.

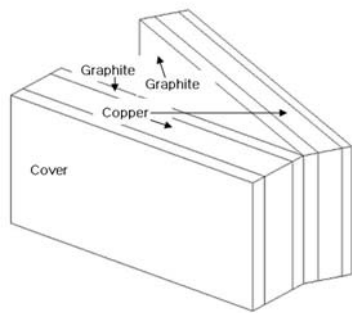


Fig. 1 Heat sink structure of beam dump

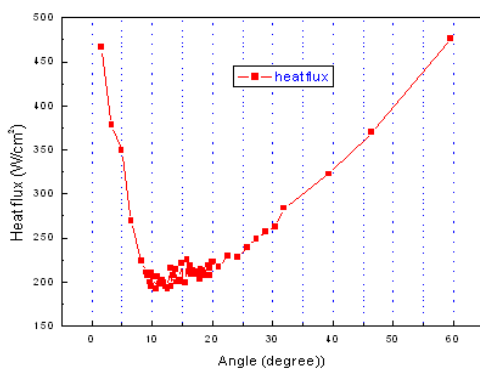


Fig. 2 The maximum heat flux on the surface of graphite plate as a function of plate angle.

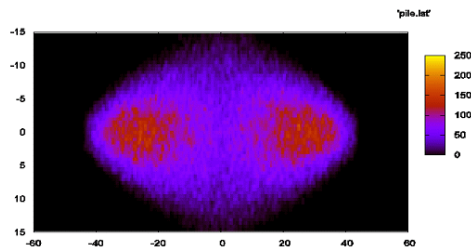


Fig.3 The heat flux distribution on a surface of graphite plate of the heat sink structure of plate angle of 11.5°

2.2. The assessments of radioactivity

The assessments of radioactivity of the composed materials are essential procedure for the design of the heat sink structure of a proton beam dump because the residual radioactivity influences the operation mode of the proton accelerator itself as well as the safety of operator.

The graphite was chosen as the front face of the heat sink plate because the materials have the advantages of the activity reduction and the high stopping power.

The amount of the residual radioactivity of the Graphite and the Cu after the proton beam (20MeV, 4.8mA) irradiation on the graphite-Cu heat sink structure for 3 hours is shown in Fig. 4. The residual radioactivity in the Cu is 400 times higher than that in graphite.

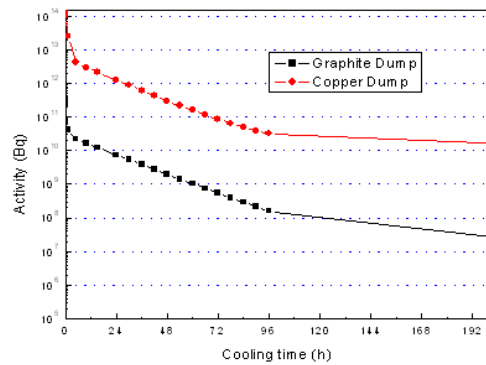


Fig. 4 Residual radioactivity after the proton beam (20MeV, 4.8mA) irradiation on the graphite-Cu heat sink structure for 3 hours

2.3. The cooling design

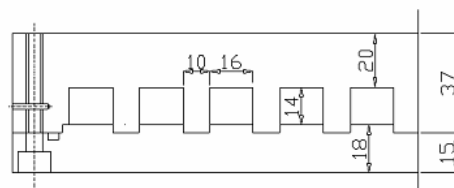
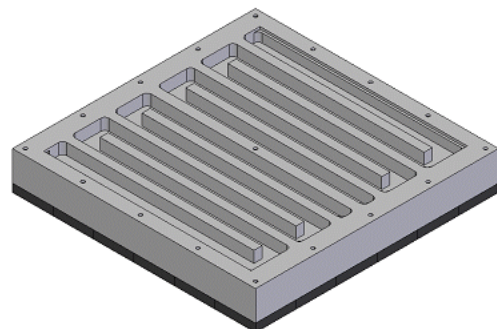


Fig. 5 Shape of cooling jacket

The schematic shape of the Cu cooling jacket (30cm x 30 cm) that is joined with graphite front face is shown in Fig. 5. The Cu cooling jacket has two parts (1) part facing graphite, 2) part facing water). Average heat flux (q'') from the water contacting surface of the cooling jacket (of the part facing graphite) to the cooling water is calculated as this equation.

$$q'' = 2(\text{safety factor}) \times 24 \text{ kW}/(30 \times 30) \text{ cm}^2 = 53.33 \text{ W/cm}^2$$

The maximum heat transfer coefficient can be estimated if we suppose that the ΔT (Temperature difference between Cu surface and water) is 30° ;

$$H = q'' / \Delta T(30^\circ) = 17,778 \text{ W/m}^2\text{K}$$

The heat transfer coefficient for the cooling jacket shown in Fig. 5 is calculated as $20,666 \text{ W/m}^2\text{K}$. So it is considered that the designed cooling system has enough cooling capacity.

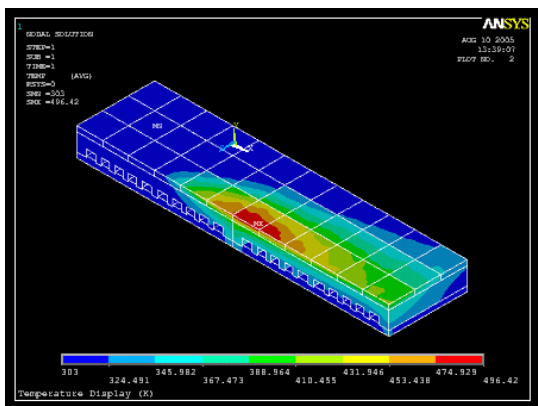


Fig. 6 Temperature distribution of the cooling jacket

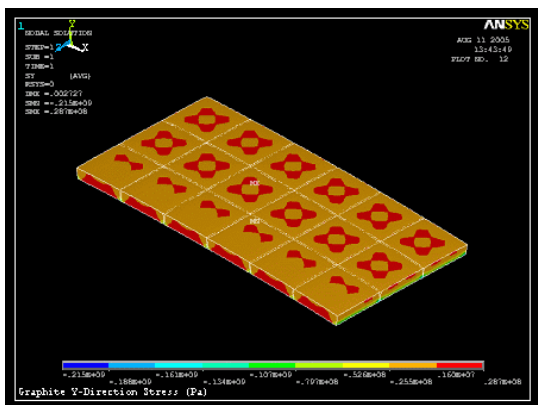


Fig. 7 Stress distribution of graphite in y direction after brazing

The results of heat transfer analysis are shown in Fig. 6. The highest temperatures of the graphite, copper, and copper faced by cooling water were evaluated to be 223 , 146 , and 85 , respectively when the velocity of cooling water was 3 m/sec .

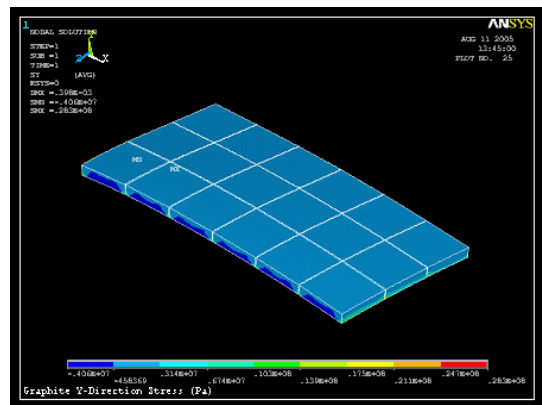


Fig. 8 Stress distribution of graphite in y direction during operation condition

2.4. The stress analysis

Stress analysis of the heat sink structure was carried out for the two case of stress situation: 1) the stress analysis after brazing, 2) the stress analysis during operation. The results of the stress analysis are shown in Fig. 7 and Fig. 8. The stress in the y direction is about 75% of tensile strength as shown in Fig. 7 (stress distribution after brazing). The operation stress analysis also shows similar results in Fig. 8. The tensile stress of the graphite was less than 75% of a maximum tensile stress during the accelerator operation based on the analysis.

3. Fabrication of heat sink structure

Heat sink structure is made with two heat sink plates placed at an angle of 12° . A heat sink plate is manufactured by brazing graphite tiles (36 tiles) to a copper plate (30 cm x 30 cm x 4 cm). The size of a graphite tile is 5 cm (w) x 5 cm (l) x 1 cm (t).

3.1 The materials

The graphite used for front facing material is IG-430 of Toyo Tanso. The copper plate for the cooling jacket material is made with OHFC (Oxygen Free High Conductivity Copper, ASTM B170 Grade 1). The filler material for the brazing is TiCuSil alloy (4.5%Ti-27.7%Cu-68.8%Ag, Wesgo Metals).

3.2 The brazing procedure

The brazing of Cu and graphite requires careful consideration for the good bonding strength and reliable mechanical properties of the brazed

assembly. A brazing procedure for the joining of the Cu with the graphite was established successfully in this study. In the case of conventional brazing, the surface of graphite should be properly modified, because conventional brazing filler metals generally do not wet graphite materials. The modification is carried out by plating or CVD. In this study, attempts have been made to join graphite to metal through a one-step brazing process without any surface modification of graphite by selecting the proper filler materials and heat treatments.

Pretreatments were carried out to remove residual gas and impurities in base materials. The brazing face of graphite was polish with 600 grit sand paper. The graphite and the Copper were cleaned with ultrasonic wave in isopropyl alcohol for 10 minutes to remove surface impurities. The graphite was baked up to 950°C to eliminate the residual gas or water vapor in the pore of the material. This step is crucial for the sound joining because the residual water vapor or gases deteriorate the wetting layer of the filler alloy during the brazing heat treatment.

The base material (the graphite and the Cu) and the filler materials (the TiCuSil alloy) are placed in vacuum furnace for brazing process as shown in Fig. 9. These assemblies are heat-treated in vacuum furnace of $\sim 10^5$ torr. Tight atmospheric control is necessary because the graphite easily oxide in high temperature. The above materials slightly slipped on the surface of the bottom material by it's own weight of the above material. So it is necessary to be cautious to prevent this kind mismatch in the joining process.

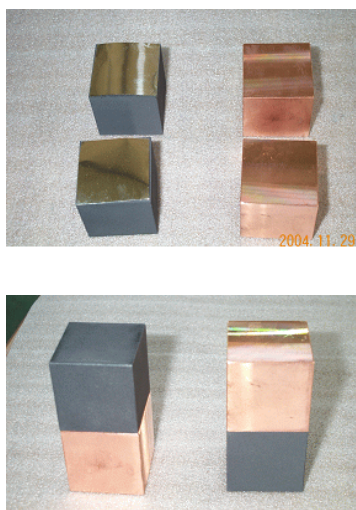


Fig. 9 The base materials and the filler alloy for brazing

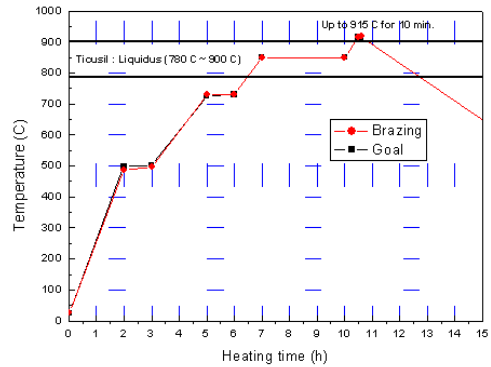


Fig. 10 The brazing heat treatment curve for Cu and graphite joining.

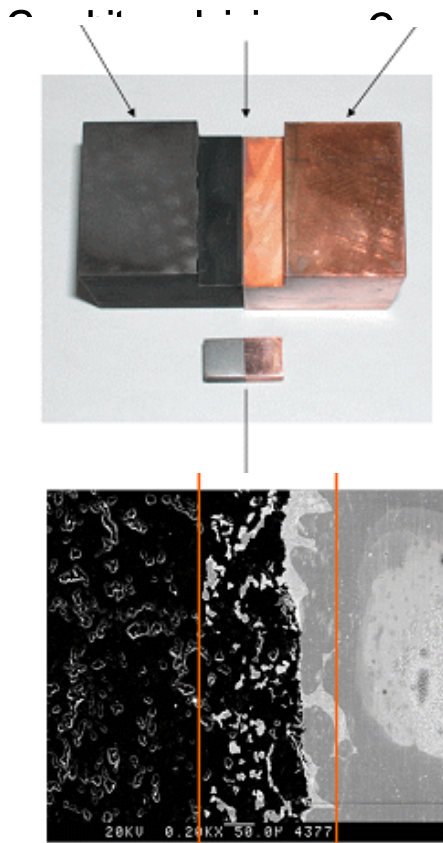


Fig. 11 Microstructure of the joining interface of graphite and copper.

The curve for the brazing heat treatment is shown in Fig. 10. The solidus temperature of the TiCuSil filler alloy is 780°C, and the liquidus temperature is 900°C. Both solid and liquid phases of the filler alloy exist in the temperature range between the solidus and the liquids. The assembly slowly heats up to 730°C and

maintained for 3 hours to promote the diffusion bonding between filler alloy and Cu. To have enough wetting of the filler materials to the base materials, the assembly was hold for 2 hours at 850°C. The assembly was heated up to above the liquidus to 915°C for a short time (10 min.) to fully impregnate the filler alloy into the base materials.

Brazing results is shown in Fig. 11. The filler alloy wetted well into the base materials. The filler alloy flowed into the pore of graphite and made a sound mechanical bonding. An active reaction of Ti component of the filler alloy can increase the bonding strength between the filler and the graphite. A diffusion bonding strengthens the joining of the filler alloy and the copper metal.

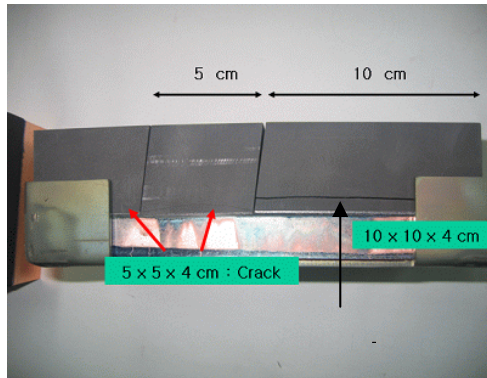


Fig. 12 Cracks in the various size of graphite and Cu tiles.

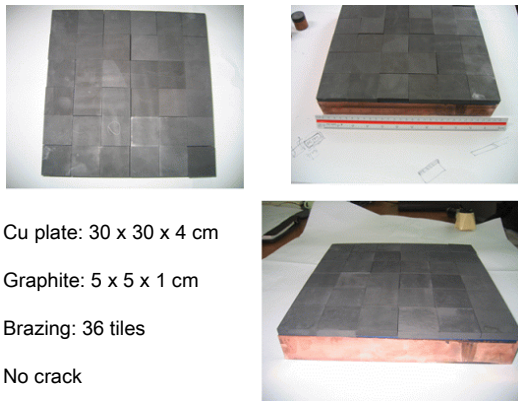


Fig. 13 The developed heat sink structure of beam dump for 20 MeV proton accelerator.

Various size of brazed assemblies were prepared and investigated to evaluate the mechanical reliability of the assemblies. We found that a severe long crack occurred on the surface of the graphite in the assembly which size are 10(w) x 10(l) x 4(t) cm, 5(w) x 5(l) x 4(t) cm

(Fig. 12). No crack was found in the assembly of the graphite tile of size of 5 x 5 x 1 cm. So we used the tiles of that size as our heat sink structure materials. One heat sink plate which was manufactured by brazing the graphite tiles (36 tiles) to a copper plate (30 cm x 30 cm x 4 cm) is shown in Fig. 13. No crack was found in the heat sink plate. We used the plate as one plate of our heat sink structure of beam dump.

4. Verification tests

The soundness of the heat sink structure of the beam dump was checked by the thermal fatigue tests of the brazed specimens of the graphite-copper tile components with the repetitive heating and cooling between 50C to 200C. It was confirmed that there is no crack in the tested specimens.

5. Summary

We designed and manufactured a heat sink structure of a beam dump for a 20 MeV proton accelerator. The stress, the heat and the radioactivity analysis confirmed the reliability of the heat sink structure. The heat sink structure was manufactured by brazing the graphite tile to copper plate. One step brazing process was established during the development. The mechanical soundness was confirmed by the thermal fatigue tests. The heat sink structure developed can be applied to various components, such as plasma facing components, collimators of accelerator and dumps for resolving high heat loads and high radioactivity.

Acknowledgement

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