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Development and experimental study of beryllium window for ITER radial X-ray camera

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HIGHLIGHTS

- The thickness of the beryllium foil is chosen as 80 μm to guarantee its safety under high pressure differential in accident events.
- Using low purity of beryllium as the transition material, the effect of thermal stress caused by diffusion bonding process can be reduced.
- Sealing ring and honeycomb-like supports are designed and used in the mechanical clamped beryllium window to enhance its sealing and safety performance.
- The beryllium windows have good performance under severe working conditions like high temperature baking, vibration or impact load.

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ABSTRACT

Radial X-ray camera (RXC) is a diagnostic device planned to be installed in the ITER Equatorial Port #12. Beryllium window will be installed between the inner and outer camera of RXC, which severs as the transmission photocathode substrate and also the vacuum isolation component. In this paper the design and manufacture process of two types of beryllium windows were introduced. Although 50 μm thickness of beryllium foil is the best choice, the 80 μm one with X-ray threshold of 1.34 keV was selected for safety consideration. Using the intermediate layer (low purity of beryllium) between the beryllium foil and the stainless steel base flange is an effective strategy to limit the welding thermal deformation and thermal stress of the thin foil caused by bonding between different materials. By using ANSYS software, the feasibility of the aperture design was analyzed and validated. Metal sealing ring was applied in the mechanical clamped beryllium window for its good stability under high temperature and neutron radiation. Although both of the hollow metal sealing ring with 0.03 mm silver coating and the pure silver sealing ring can satisfy the sealing requirement, the later one was chosen to produce the final product. Two hours 240 °C high temperature baking test, two hours 3.3 Hz vibration test and fatigue test were performed on the two types of beryllium windows. Based on the tests results, the two types of beryllium windows could stand the high temperature baking during the wall conditioning phase of ITER tokamak and the vibration during transportation without causing large leakage. Both of the two types of beryllium windows could bear impact load (0.1 MPa pressure difference) for many times without failure.

1. Introduction

Radial X-ray camera (RXC) is one kind of diagnostics which will be applied and arranged on Equatorial Port #12 of ITER tokamak. The ITER RXC is designed to measure the poloidal profile of the plasma X-ray emission with high spatial and temporal resolution [1]. In order to enhance the maintainability of the diagnostics on the port, all of them are installed in a port plug which can be assembled or disassembled easily. There are three vertical drawers in the Port #12 plug and the RXC located in the middle one. With the "drawer" design of the port plug, the diagnostics including the RXC can be maintained separately by remote handling device which also provide an upgrade path for future advanced detectors. ITER RXC has two main components: the inner camera which is installed in the vacuum vessel (VV) of ITER and the outer camera [1,2]. The inner camera and the big flange are cooled by cooling water system to remove the heat load generated by nuclear radiation. The interfaces of the inner camera and the outer camera are beryllium

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windows which are two Knife-edge flanges with beryllium foils on them. For safety consideration, the outer camera is pumped to a secondary vacuum (about 10^{-2} Pa) to reduce the pressure difference of the two sides of beryllium window. In addition to optical component the beryllium window also acts as vacuum isolation component.

The key optical function of the beryllium window is X-ray transmission; the X-ray transmission threshold which is the minimum energy of the X-ray to penetrate the beryllium filter should be as low as possible. Besides, the safety of the beryllium window is another critical issue related to its design. The failure of beryllium window can cause serious consequences, such as the rapid increase of the gas pressure in VV and the neutron diffusion from the inner camera to the outer camera. The design requirements of the ITER beryllium window are summarized as follows: the X-ray transmission threshold of the window should be 1 keV; reliable support with acceptable light-blocking area; good sealing performance with leak rate less than 6×10^{-10} Pa m^3 s^{-1} during normal operating phase; bearing impact load with one atmospheric pressure difference many times and static load of 0.2 MPa pressure difference without causing broken or excessive leakage; easy to be manufactured, fabricated and maintained.

2. Engineering design of beryllium window

2.1. Bonding method consideration of beryllium window's assembly

Just like the beryllium windows used on other equipments, the ITER RXC beryllium window has a structure base (CF-150) made by SS316L, the thin beryllium foil is fixed in the middle of it. Epoxy bonding, brazing and diffusion bonding are three common methods to connect the foil with the substrate material of the base. Using epoxy as bonding material can simplify the manufacture process of the beryllium window, but as a critical component used on fusion reactor which is baked under high temperature (240 °C in the outgas process) and working in the condition of high dosage of neutron radiation which can reach to 3×10^9 n/cm^2 s in D–T operating phase [2], the epoxy is not stable in those situations. Vacuum brazing has been performed successfully on the beryllium window for CESR-C (Cornell Electron-Positron Storage Ring) [3]. There are two vacuum braze steps on it: two stainless steel tubes which were brazed to each end of a copper ring at 955 °C with BAu-4 (82%Au–18%Ni) alloy wires, then the 75 μm thick beryllium disk is vacuum brazed onto the copper ring using Bag-18 (60%Ag30%Cu10%Sn) alloy at 719 °C [3]. One of the big challenges of the window's assembly when beryllium foil is being brazed onto the substrate, however, is the coefficient difference of thermal expansion caused by different materials, and during cool down from brazed temperature the thin foil would become pre-stressed [4,5]. Extreme care must be taken to avoid sudden pressure changes cross the window aperture, either during the pumping or venting process to atmosphere pressure. Diffusion bonding is an available method for different types of materials' bonding. Under a temperature of 70% of the material's melting point and apply pressure on the workpieces, the two parts will be connected by the process of atomic diffusion. The material properties of the bonding joint changed slightly after diffusion bonding process. In the R&D phase, one diffusion bonded beryllium window was designed and manufactured successfully. Besides, a new type of beryllium window called mechanical clamped beryllium window on which the sealing ring was used to realize vacuum tight has also made significant progress.

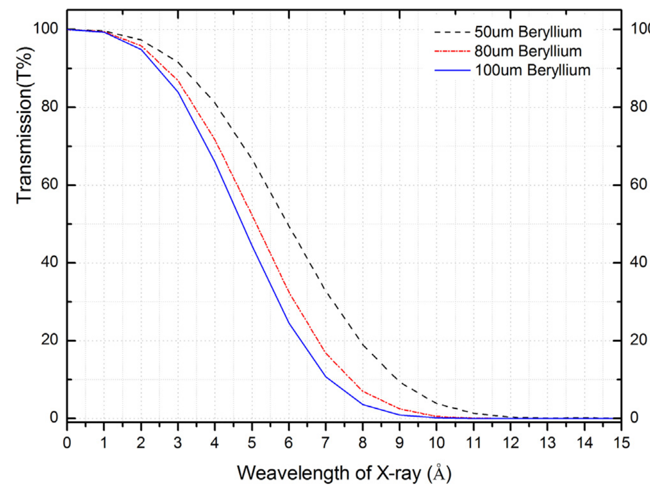

Fig. 1. Transmittance of beryllium foils with different thicknesses.

2.2. The thickness selection of the beryllium filter

Thick beryllium foil benefits to the beryllium window's safety under high pressure, meanwhile, such a window strongly absorbs soft X-ray, which limits the sensitivity of the diagnostic device [6]. The effective energy range of X-ray measured by ITER RXC is from 1 keV to 200 keV with the wavelength of 12.4–0.062 Å [2]. The transmittance of the beryllium filters with three different thicknesses was studied as Fig. 1 shows. 50 μm thick beryllium foil has the X-ray threshold of 1 keV and can meet the function requirements perfectly. Taking the strength and safety into consideration, the 80 μm thick beryllium foil was selected finally.

2.3. Engineering design of two types of beryllium windows

Two types of beryllium windows based on different connection methods were designed and manufactured during the R&D process. For the brazed one, a transition part made by low purity of beryllium was added to decrease the welding stress remained in the beryllium foils; dividing the big aperture into small ones can strengthen the beryllium foils to stand high pressure differential. For the mechanical clamped window, by applying the metal sealing ring, good vacuum sealing performance was realized; special support was designed to prevent the large deformation of the foil under high pressure which can improve its safety performance.

2.4. Structure design and analysis of the diffusion bonded beryllium window

2.4.1. Aperture size design

The aperture that the ITER RXC needs is a rectangle whose size is 60 mm × 25 mm. Big aperture is benefit to improve the light transmittance of the window, however, big aperture can cause big deformation of the beryllium foil in the middle area and also cause extra high stress concentration at the edge region. Big deformation and high stress increase the risk that the beryllium window would be destroyed when being exposed to high pressure. Adding auxiliary supports (bars) is a useful method to strengthen the beryllium foil which can prevent it from large deformation and also cut down the light transmittance of the RXC accordingly. In the design of ITER RXC beryllium window the light transmittance is required larger than 0.7. In order to find the best solution of the aperture size for beryllium window support design, ANSYS software was used for stress simulation.