FEM analyses of a CVD diamond Brewster window

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***Abstract*—The Brewster window is a broadband window solution for H&CD applications. Its geometry is quite complex and involves brazing of diamond and copper, which have very different thermal expansion coefficients. In this paper, a study of its feasibility was carried out by FEM structural analyses.**

I. Introduction and Background

CHEMICAL vapor deposition (CVD) diamond windows are used as confinement barriers in the transmission of high power mm-wave beams such as, for instance, in the ITER electron cyclotron H&CD system [1]. The thickness of the diamond disc must match the desired beam wavelength in order to minimize the amount of reflected power, thus moveable mirrors are necessary to deploy the beam at different positions in the plasma. However, looking beyond ITER, the higher heat loads and neutron fluxes could make the use of moveable parts close to the plasma difficult.

A promising alternative might be the use of gyrotrons able to tune the beam frequency to the desired resonance, but this concept requires transmission windows that work in a given frequency range (e.g. 105-140 GHz) [2], such as the Brewster window [3]. It consists of a CVD diamond disc brazed to two oxygen-free high conductivity (OFHC) copper cuffs at the Brewster angle (67.22°). The brazing process is carried out at 800°C and then the temperature is decreased down to room temperature. Diamond and copper have very different thermal expansion coefficients (ratio of 1 to 16 at 20°C, respectively), therefore high stresses build up during the cool down phase that might eventually lead to failure of the disc. Considering also the complex geometry of the window with the skewed position of the disc, the cool down phase was hence simulated in ANSYS for several geometric and constraint configurations of the window. A study of an indirectly water-cooled configuration was also performed, considering the power absorption in the diamond disc due to a HE_{11} mode beam.

II. Methods

A FEM model of the Brewster window was set up as reference case and it is shown in Figure 1. The diamond disc has an elliptical shape with major axis of 160 mm, minor axis of 80 mm and thickness of 1.9 mm. The cuffs are cylindrical with inner diameter of 50 mm, thickness of 1 mm and total length of 200 mm. Symmetry was assumed along the major axis of the disc allowing the analysis of half structure. Constant, temperature dependent and non linear material properties were used [4, 5, 6]. A fixed support was applied to the two ends of the cuffs as boundary condition. Stresses and deformations were first calculated in a structural analysis by decreasing the temperature from 800°C to 20°C.

A parameters impact analysis was subsequently carried out by varying the thickness of the cuffs and the disc and the aspect ratio of the disc. The thickness varies from 0.8 to 2 mm for the cuffs and from 1 to 2.5 mm for the disc. The disc has an aspect ratio of 2 with major axis of 160 mm which is maybe too big for a real manufacturing of the disc. Other two aspect ratios, 1.4 and 2.33, were so considered with major axis of 140 mm and minor axis respectively of 100 mm and 60 mm. Other two constraint configurations were also investigated with respect to the reference case. One configuration (named configuration 1) has one end free to move along only the axis of the cuffs while the other configuration (named configuration 2) has one end without constraints.

Finally, adding an indirect cooling copper circuit to the reference geometric model, a thermal analysis of the window was performed by applying a 0.4 kW heat load to the disc according to the HE_{11} pattern and applying the profile of the heat exchange coefficient calculated by CFD analysis to the cooling interface. The resulting temperature distribution was then applied to the window in a second load step of the structural analysis of the reference case.

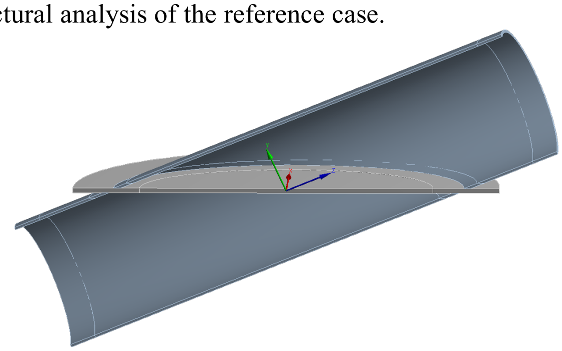

Fig. 1. Reference configuration of the Brewster window.

III. Results

The first principal stress in the reference case, shown in Figure 2, is generally in the range 30-75 MPa along the contact region between the disc and the cuffs and has a maximum of 137.4 MPa, located at the tip of the disc in the contact region with the longer side of the cuffs. The cuffs experience plastic behaviour, in fact the equivalent stress varies between 50 and 75 MPa (yield stress of OFHC copper is 45 MPa at 20°C [6]) in the most part of the cuffs and has maxima values in the range 103.1-110.6 MPa, located close to the area of maximum principal stress and to the support. However, the maximum principal stress is below the permissible stress of diamond which is 150 MPa (ultimate stress is 450-500 MPa [7]) and the maximum equivalent stress is below the ultimate stress of OFHC copper (250 MPa at 20°C [6]).

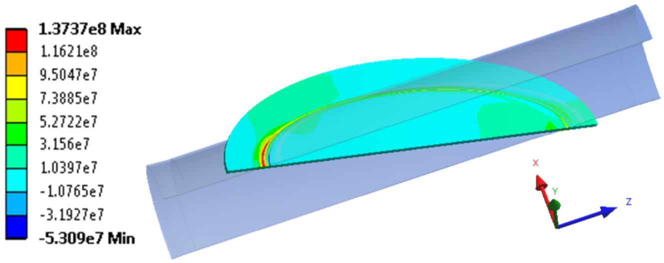

Fig. 2. First principal stress distribution on the top side of the diamond disc in the reference case. Values are in Pa.

Figure 3 shows the maxima stresses as functions of the thickness of the cuffs and the disc. The first principal stress grows significantly as the cuff thickness increases or the disc thickness decreases, reaching values well above the permissible stress. Values of cuff thickness above 1.2 mm and of disc thickness below 1.7 mm are not recommended. On the contrary, the equivalent stress is not affected by the variation of the thickness since the cuffs are in plastic field. Then, the aspect ratio of the disc affects the first principal stress profile by less than 3%.

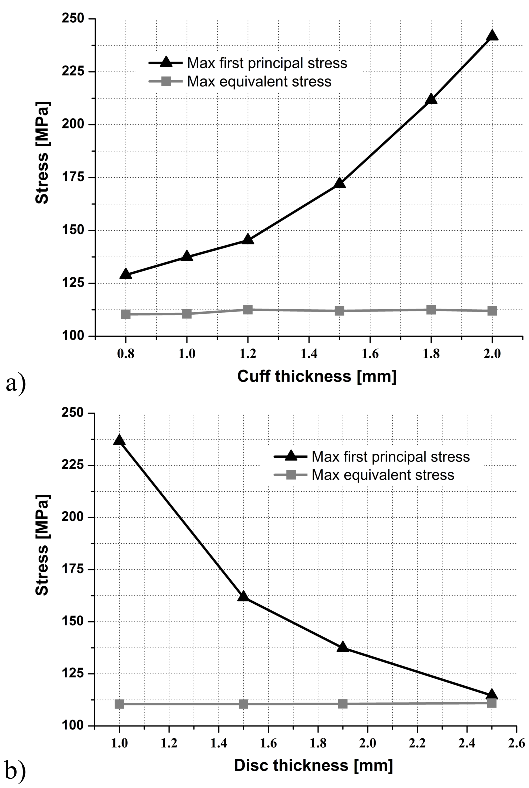

Fig. 3. Maxima first principal stress and von-Mises stress as functions of cuff thickness (a) and disc thickness (b).

The constraint configurations 1 and 2 lead to a maximum stress in the disc of 181 MPa, greater than that obtained in the reference case. This difference might be explained looking at the Figure 4a. In configuration 1, because of the boundary condition, the plastic deformation occurs only in the part of the cuffs near the disc but the deformation is big (maximum is 2.83 mm) and the deformation mechanism would lead to severe stresses in the disc. In contrast, in the reference case due to the fixed support, the deformation is more limited (maximum is 1.23 mm), occurring in the plane perpendicular to the axis, but the cuffs are wholly plastically deformed. This would result in a more relaxed stress profile in the diamond disc of the reference case. The considerations done for the configuration 1 are also valid for the configuration 2, but here the maximum deformation amounts to 3.32 mm.

Finally, when the temperature distribution, corresponding to the absorbed power of 0.4 kW in the disc, is applied to the window in a second load step of the structural analysis of the reference case, the stress profile shown in Figure 4b is obtained for the disc. The maximum first principal stress decreases from 137.4 to 98.7 MPa but, the stress along the contact region between the disc and the cuffs is now in the range 60-75 MPa for the most part and an area with stresses in the range 30-50 MPa appears in the outer side of the disc. In conclusion, the stress field generated in the disc by the cool down phase of the brazing process and the applied temperature distribution is well below the permissible stress of diamond.

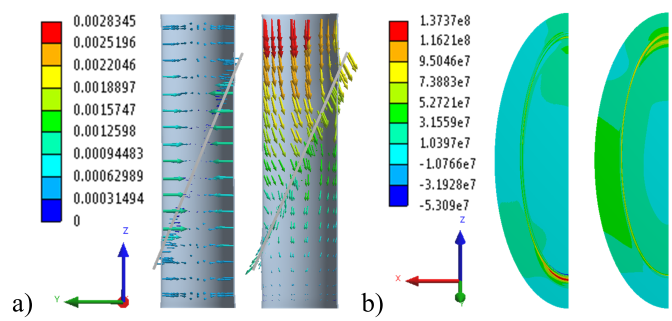

Fig. 4. Comparison (a) of the deformation mechanism between the reference case on the left and the configuration 1 (upper cuff end free to move along the axis of the cuffs) on the right. Values are in m. Comparison (b) of the first principal stress distribution on the top side of the disc between the reference case on the left and the reference case with the applied second load step on the right. Values are in Pa.

IV. Conclusion

FEM structural analyses showed that the CVD diamond Brewster window is a feasible solution to achieve resonance in a plasma by frequency tuning. Values of the cuff thickness greater than 1.2 mm and of the disc thickness less than 1.7 mm are not recommended.

References

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