Towards fracture toughness measurements of MPA CVD diamond in nuclear fusion devices

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***Abstract*—Optical quality polycrystalline diamond is the only window material allowing transmission of high-power microwave beams in nuclear fusion devices. Failure to fracture is the main failure mode for diamond, which is integrated in the shape of disks in the so-called window units. This paper reports on the path to measure the fracture toughness of this diamond for a later potential structural integrity assessment of the disks based on fracture mechanics.**

I. Introduction and Background

THE electron cyclotron (EC) systems [1] are required in nuclear fusion devices for heating and control of the instabilities in the plasma. These systems feature diamond window units acting as safety confinement and/or vacuum barriers for the transmission of MW-class, mm-wave radiation (1-2 MW) [2]. Thanks to its properties, diamond is the only window material to use in high power continuous wave operation. Optical grade chemical vapor deposition (CVD) diamond is produced by microwave plasma assisted (MPA) reactors in the shape of disks, which are then integrated in the metallic housing of the window units. The diamond disks are generally qualified for their integration in the units by measuring their loss tangent (tanδ), i.e. the parameter describing the microwave absorption in the material [3]. For instance, this is the case for the 60 diamond disks produced by Diamond Materials (DM) GmbH & Co. KG [4] for the ITER EC torus window units [5]. These disks feature a resonant thickness of 1.11 mm and a diameter of 70 mm.

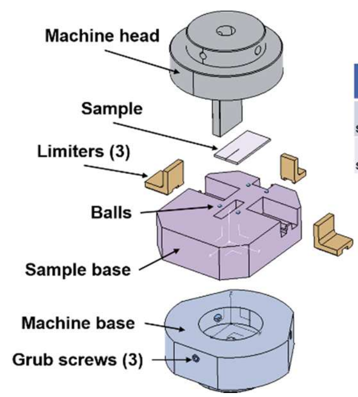
However, the failure to fracture, i.e. failure due to crack propagation, represents the main failure mode of the disks. Generally, when growing in the MPA CVD reactors, microcracks appear in the diamond wafers, especially in the outer region of the disks. Despite the design philosophy of the window aims to minimize the loads propagation to the disks, beyond operational loads, off-normal events like overpressure are to consider. Keeping in mind the safety role of MPA CVD diamond in fusion and the very limited body of work in literature for such a diamond [6, 7], there is thus the need to characterize the disks from the mechanical perspective by fracture toughness (the parameter describing the resistance to crack extension of a material) measurements and consequent structural integrity assessment based on fracture mechanics.

In this paper, the path to measure the fracture toughness in the same diamond as used in the ITER torus windows is described, together with the numerical analyses and microscopy activity aiming to provide information on stresses and microcracks in the disks. For the very first time, the toughness measurements will be carried out in a diamond to be previously characterized by tanδ measurements.

II. Experimental Setup and Samples

With respect to other techniques, the double-torsion (DT) method was selected for the diamond fracture measurements, mainly because of two key factors: the planar geometry of the samples and its intrinsic simplicity [8]. Optical diamond samples are quite expensive, and it is important to reduce as much as possible the failure risk, that for instance might be introduced by the need of a particular sample preparation. In addition, the thickness of the samples (1.11 mm) is dictated by the resonant condition of the ITER EC disks [2]. The DT method consists in a symmetric four-point loading applied around a notch/pre-crack on one side of a rectangular shaped sample. Torsional deformation occurs and leads to crack propagation across the sample which is finally divided into two halves. However, it is of fundamental importance to have a well aligned loading fixture. An experimental setup was designed on purpose (Fig. 1) and drawings are in preparation for the parts to be manufactured. This setup will be then mounted in a classical testing machine where compression load can be applied.

The DT method has been not standardized yet. However, the dimensions of the samples (Fig. 1) were selected by achieving a compromise among high cost of diamond, recommendations from literature and variables to investigate in this work. The samples will be extracted by a diamond disk to be produced by DM as in the case for the ITER EC system. For in-depth understanding, thermal grade diamond samples will be also used in the measurements. In fact, thermal grade diamond is used for thermal applications, and it grows in the MPA CVD reactors much faster than the optical one with a resulting greater density of microfeatures.



	t (mm)	W (mm)	L (mm)	L/W	W/t
Big samples	1.11	15	30	2.0	13.5
Small samples	1.11	12	22	1.8	10.8

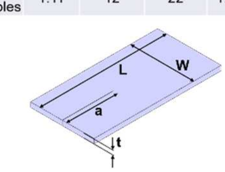


Fig. 1. Exploded view of the experimental setup design to measure fracture toughness of diamond by double torsion technique (left side) and dimensions of the diamond samples to use in the measurements (right side).

Preliminary optical and thermal quality diamond small size samples have been kindly provided by DM for an initial characterization of the diamond to use in the fracture toughness measurements. Raman, electron backscatter diffraction (EBSD), X-rays and neutron diffraction measurements are planned in these preliminary samples to investigate the role of microstructure on the diamond fracture toughness.

III. Numerical Analyses and Microscopy Activity

The ITER EC window design [9] developed at Karlsruhe Institute of Technology (KIT) has been further advanced by Fusion for Energy and the current design was considered for the stress assessment in the disk (Fig. 2). The worst load scenario of the disk consisting in 2 bar overpressure during normal operation (NO) was taken into account. First, steady-state computational fluid dynamics (CFD) conjugated heat transfer analyses were performed to investigate the cooling and thermal performance of the window. The code ANSYS 2021 R1 was used. A reference case was initially analyzed with an absorbed power in the disk of 346 W (design beam power of 1.31 MW, tanδ = 2.0E-5). Then, analyses were run for higher values of tanδ (up to 3.5E-5) to check the sensitivity of the window design against a potential degradation of such an important parameter, which rules the power absorption in the disk.

The heat generation load was applied to the disk by the Bessel function of order zero which describes the power pattern of the HE_{11} mode beam inside the waveguide line. Finally, the temperature distribution obtained in the reference case was applied as load, with 2 bar pressure acting on the disk and copper cuffs on the plasma side, in a plastic steady-state structural analysis of the window. Fig. 2 shows the resulting stresses in the disk, with the maximum in the range 88-102 MPa in the central area on the gyrotron side. These stresses can be safely accepted, if compared to the allowable stress limit of 150 MPa assumed for diamond (safety factor of 2).

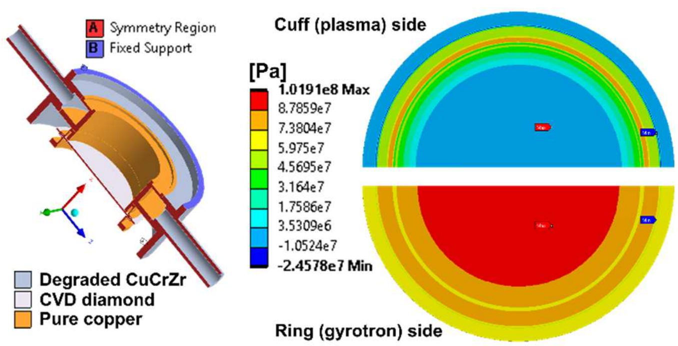


Fig. 2. Geometry of the ITER EC torus diamond window unit used in the numerical analyses (left side) and maximum principal stress distribution in the diamond disk for the worst load scenario (right side).

The manufacturing of 60 diamond disks for the ITER EC torus windows by DM is ongoing and their qualification by tanδ measurements at KIT has started. This offers a unique opportunity to collect information on microcracks over a large amount of disks, produced by the same manufacturer and same growth conditions. The investigation of the disks by the high-resolution Olympus BX53M digital light microscope [10] has started to detect, measure and classify the microcracks in each disk at the end of the manufacturing phase. Each disk is scanned at different vertical position across the thickness and then all the scans are combined in the so-called EFI (extended focal imaging) image. The dark spots in the image are microfeatures generated during the CVD process. They appear both as single microcracks and discrete clusters of microcracks. The image is then segmented by a threshold value to separate the foreground, consisting in the dark microfeatures, from its background. The microcracks are so detected, counted and measured by different ways in specific areas of the disk, as shown in Fig. 3. These areas correspond to the ones where high stresses are expected.

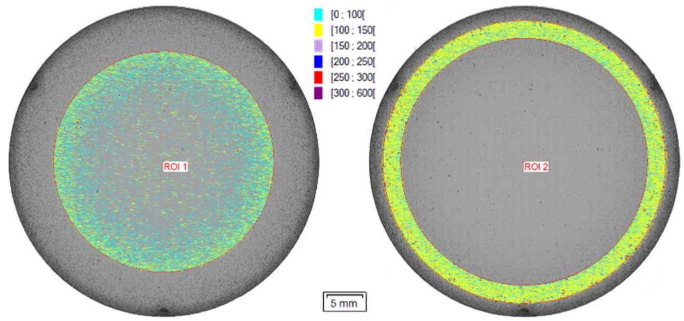


Fig. 3. Typical segmentation of the EFI image of the ITER diamond disks obtained by the microscope to detect the microcracks and classify them in the area related to the window aperture (left side, 50 mm diameter area) and to the brazing region (right side, annulus with inner and outer diameters of 56 mm and 64 mm). A threshold value of 8000 was adopted for the segmentation and the equivalent circle diameter object (diameter of a circle with the same area as the microfeature, excluding any hole) was used in this case for the classification of the microcracks. The selected crack size ranges are also shown.

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