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The response of ZrB_2 to simulated plasma-facing material conditions of He irradiation at high temperature☆

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ABSTRACT

Zirconium diboride (ZrB_2) has many potentially beneficial properties for fusion plasma-facing component application, but almost no data exist on the response of ZrB_2 to ion irradiation. In this work, ZrB_2 samples were irradiated with 30 keV He^+ to fluences of 8.4×10^{21} and 5.0×10^{22} He/m^2 at temperatures of 920, 1020, and 1120 K in the Materials Irradiation Experiment (MITE-E) at the University of Wisconsin Inertial Electrostatic Confinement (UW-IEC) Laboratory to simulate some of the conditions of plasma-facing components in fusion reactors. The samples irradiated to the higher fluence developed surface morphology changes in the ion irradiated zone including rough, porous, and ripple structures. The ZrB_2 had similar mass loss as W irradiated to similar conditions. Additionally, the ZrB_2 samples did not exhibit flaking as did the SiC samples previously irradiated to similar conditions. This first look at ZrB_2 behavior under ion irradiation is promising and justifies further testing of this emerging ultra-high temperature ceramic material for fusion applications.

1. Introduction

For a plasma-facing material (PFM) to survive in a fusion reactor, it should possess a high melting temperature, high thermal conductivity at high temperatures, low sputtering yield, resistance to He-induced nanostructure formation, thermal shock resistance, high strength at high temperatures, high fracture toughness, and low hydrogen isotope retention. Additionally, the material should be easily machinable, form robust joints with relevant structural and cooling materials such as copper and steel, and maintain these beneficial properties after intense 14 MeV neutron irradiation without becoming highly radioactive. None of the previously investigated materials for PFMs matches this long list of requirements. Tungsten (W) and carbon (graphite or various carbon composites) have been the leading candidates because each meets several of the requirements. Carbon materials were favored in tokamaks because of their ease of use and long history of operating data from many tokamak experiments around the world. However, as machines advance toward the power reactor scale, the high amount of tritium retention in carbon and carbon co-deposits [1] was determined to be more detrimental than the benefits of carbon. SiC has a similar drawback as graphite; the C within SiC easily bonds with hydrogen and likewise causes high tritium retention. Because of this, SiC is not generally considered a leading candidate for PFMs, but has been studied for this purpose in the past [2,3]. SiC is referenced here as one example of a ceramic PFM to compare with ZrB_2. ITER, the large international experimental reactor, is being built with an all W divertor [4] because it could not safely operate with the amount of tritium that was estimated to be retained in the carbon materials. Thus, W is now essentially the only material considered for divertors with any significant research history.

While W has several benefits, such as high thermal conductivity,

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low sputter yield, and lower hydrogen isotope retention than carbon materials [5], its main drawbacks include having a high ductile to brittle transition temperature, a low recrystallization temperature, and becoming more brittle after neutron irradiation [6]. In contrast to the main concern with carbon materials, which was retention of hydrogen, the main concern with W is that it will not survive the intense stress from thermal gradients within the component or the sudden stresses of a plasma off-normal event. The recent focus has been on W-based composites to try to make a more fracture resistant W but with varying levels of success [7–9].

Because no perfect PFM has been found to simultaneously satisfy all of the requirements, options for finding a solution include (a) change the plasma conditions in such a way that the ion and heat flux on the PFMs are less intense; (b) change the geometry of the divertor such that the heat flux and stress on the materials can be reduced; (c) explore new materials; or (d) some combination of these. In this paper, we consider option (c) by exploring the novel material zirconium diboride (ZrB_2) for its potential use as a PFM.

The focus of this first test of ZrB_2 is on its response to He implantation at elevated temperatures to simulate plasma-material interactions it might encounter as a divertor material in a tokamak or first wall material in an inertial fusion device. For this initial irradiation study, ZrB_2 ceramics produced using commercial ZrB_2 powder with natural B were irradiated with 30 keV He^+ in the Materials Irradiation Experiment (MITE-E) at the University of Wisconsin (UW) Inertial Electrostatic Confinement (IEC) Laboratory. The results of ZrB_2 are compared with past experiments in the IEC Laboratory with He-implanted W and SiC [10–13]. These results offer a first look at the behavior of ZrB_2 under ion irradiation.

2. Motivation for investigating ZrB_2 as a PFM

ZrB_2 is one of the ultra-high temperature ceramics (UHTCs), a group of materials with melting temperatures above 3000 K that includes carbides, nitrides, and diborides of early transition metals. Because of their high melting temperatures, high temperature strength, chemical resistance, high hardness, and relative insensitivity to O and N, UHTCs are candidates for many applications including hypersonic flight, plasma arc electrodes, and refractory linings [14,15]. Refractory coatings, including certain diborides, were considered as PFMs previously, and a few permeation and retention tests were done, for example with TiB_2 [16,17]. Only limited neutron irradiation studies have been conducted on ZrB_2 [18,19]. Neutron irradiation of ZrB_2 with natural B caused swelling and catastrophic cracking because of the He accumulation from the $^{10}B(n, \alpha)^{7}Li$ reaction [18]. The concept of ZrB_2 as a PFM is reconsidered here because modern production techniques have allowed the fabrication of high purity and high thermal conductivity ZrB_2 using isotopically separated ^{11}B [20]. Modern ZrB_2 has several properties, including high melting temperature, high thermal conductivity, and some indication of resistance to plasma erosion, which make it attractive for investigation as a PFM.

The high melting temperature of ZrB_2, ~3520 K, is attractive because many future PFMs are expected to operate at extreme temperatures. For example, the ARIES tokamak reactor design with a W tile divertor was modeled to have a peak temperature during steady state operation of 2234 K [21]. In addition, the High Average Power Laser (HAPL) laser fusion reactor design was modeled to have peak temperatures on the surface of the W PFM in the range of ~2270–2770 K for different shot and buffer gas conditions [22]. While these examples were modeled specifically with W, it is expected that the temperature on a ZrB_2 PFM would be similar or higher. Transient temperatures on a PFM can be higher and may lead to melting of W [23]. Melting of a PFM can lead to catastrophic failure of the PFM and possibly the fusion system. The possibility of ZrB_2 sublimating before melting is another positive feature.

Thermal conductivity is another important property for a PFM. Fig. 1 compares thermal conductivities for W, SiC, and ZrB_2. For each of these materials, thermal conductivity depends on the processing method, grain size, impurities and more, so the data presented in Fig. 1 are representative examples and do not capture the range of possible values. The W data are for high purity and annealed W [24], and the SiC data are for single crystal SiC [25]. For ZrB_2, reactive hot pressing with no sintering additives results in the highest thermal conductivity values [26], and even trace levels of impurities such as Hf decrease the thermal conductivity of ZrB_2 [27]. A range of thermal conductivities have been reported for ZrB_2, mostly lower than shown in Fig. 1 because of impurities or other extrinsic factors. For example, a room temperature thermal conductivity of 0.24 W/cm/K is reported in Ref. [28] and 0.56 W/cm/K is reported in Ref. [29]. The values chosen for the present comparison from Ref. [26] are among the highest reported because the ZrB_2 was intentionally fabricated to minimize transition metal impurities dissolved in the ZrB_2 lattice. At the highest tested temperature of ~2273 K, the ZrB_2 fabricated by Lonergan et al. had a thermal conductivity of ~0.8 W/cm/K [26], which is similar to the value of 0.95 W/cm/K reported for W at this temperature [24] and higher than the value of 0.25 W/cm/K for SiC [25].

The values in Fig. 1 are for unirradiated materials, but a PFM would be subjected to neutron irradiation, which can degrade thermal conductivity. Both electron and phonon transport contribute to thermal conductivity [24]. During neutron irradiation, the collision cascades displace atoms from their lattice sites. This disrupts phonon transport, but has little effect on the electron component of thermal conductivity. In addition, neutron irradiation causes transmutation which can change the thermal conductivity of the material. SiC, like many other electrically insulating ceramics, has essentially all of its thermal conductivity from the phonon contribution, so after neutron irradiation, its thermal conductivity is severely reduced [30,31]. However, metals, such as W, have a more significant portion of their thermal conductivity from the electron component [32,33]. Neutron irradiation disrupts the phonon transport in W and causes transmutation to Re and Os which reduces the thermal conductivity. The electron component remains, so the thermal conductivity of W is less affected by

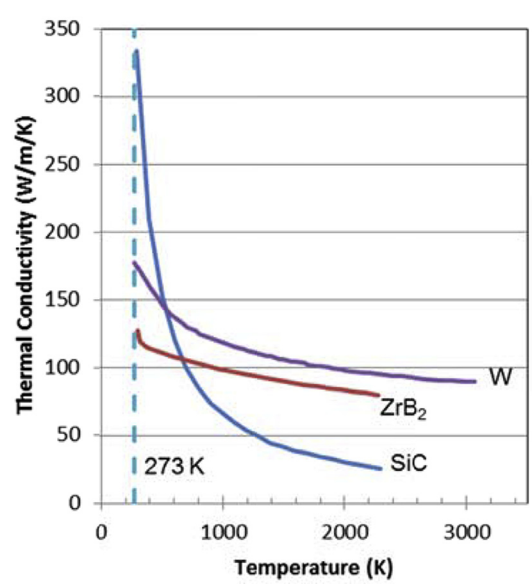

Fig. 1. Comparison of the thermal conductivities of three candidate PFMs: SiC [25], ZrB_2 [26], and W [24].