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Analysis of J-HBC stripper foil for the J-PARC RCS

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Japan Proton Accelerator Complex (J-PARC) 3-GeV Rapid Cycling Synchrotron (RCS) adopts the Hybrid type Boron-doped Carbon (HBC) stripper foil, which was developed in the High Energy Accelerator Research Organization (KEK) to improve the lifetime. Recently, the deposition apparatus for the HBC foils has been relocated from the KEK Tsukuba-site to the Japan Atomic Energy Agency (JAEA) Tokai-site, where a new foil called J-HBC foil, has been fabricated since 2017. Because deposition parameters between the original HBC foil and the J-HBC foil are different, the performance of the latter was evaluated against the former by ion beam bombardment in the Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) of the National Institutes for Quantum and Radiological Science and Technology (QST) laboratory. The experiments revealed that the J-HBC foil has similar toughness to the original one. Therefore, the authors of this study have stared utilizing the the J-HBC foil for the user operation in J-PARC.

KEYWORDS: J-PARC, High Power Proton Beam, Stripper Foil

1. Introduction

The multi-turn charge-exchange H^- beam injection scheme with stripper foils is one of the key techniques to achieve a MW-class high-power proton beam. Japan Proton Accelerator Complex (J-PARC) 3-GeV Rapid Cycling Synchrotron (RCS) adopts a Hybrid type Boron-doped Carbon (HBC) stripper foil, which was developed in the High Energy Accelerator Research Organization (KEK) to improve its lifetime [1].

Several beam studies have been conducted to examine the characteristics of HBC foils. These include stripping efficiency measurement and long-term observation with an H^- beam in J-PARC RCS [2, 3], foil analysis by means of Rutherford backscattering spectrometry and particle induced X-ray emission, and scanning electron microscope and transmission electron microscope (TEM) observation after ion beam irradiation in Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) of National Institutes for Quantum and Radiological Science and Technology (QST) [4, 5].

Recently, the deposition apparatus for the HBC foils has been relocated from the KEK Tsukuba-site to the Japan Atomic Energy Agency (JAEA) Tokai-site, where the fabrication of a new HBC foil, known as J-HBC foil, was introduced in 2017 [6]. The TIARA equipment has been utilized to determine the lifetime of the new foil against beam irradiation as compared to the original foil, prior to its use for high-power beam user operation in J-PARC. Details of the recent analysis for the J-HBC foil are presented in this paper.

2. HBC stripper foil

2.1 Foil characteristics

The HBC foil is fabricated with an arc-discharge method having carbon electrodes doped with boron carbide (B_4C) powder. It was developed primarily for cluster carbon foils using the controlled AC/DC arc-discharge (CADAD) method [7]. Thus, the basic principle of foil deposition between HBC and CADAD foils is the same. A schematic description of the foil deposition process using CADAD is shown in Figure 1. Separation of the two electrodes after a large-current energization creates an arc discharge in a strong electric field between the two electrodes, thereby causing ionization of residual gas in the deposition apparatus. The strong electric field accelerates the motion of the generated ions and electrons, and facilitates their collisions with the cathode and anode. As a result, the cathode emits large carbon clusters of a few hundred nanometers due to intense bursts by ion bombardment, whereas the anode emits small carbon clusters of a few nanometers due to evaporation by electron bombardment heating. The deposited foil is thus mixed with the large and small clusters. Based on the study results of the cluster carbon foil by the CADAD method, the mixing rate of large and small clusters is a key parameter of the foil lifetime [7], which is correlated to the ratio $Rc = Wc/(Wc + Wa)$, where Wc and Wa are the carbon source weight losses due to arc-deposition from the cathode and anode, respectively. For the purpose of this study, Rc is termed “cathode ratio.” Herein, the optimum condition for long-lived carbon foils signifies Rc values from 0.6 to 0.8. Additionally, the cathode ratio was considered an important parameter for the HBC foil [8].

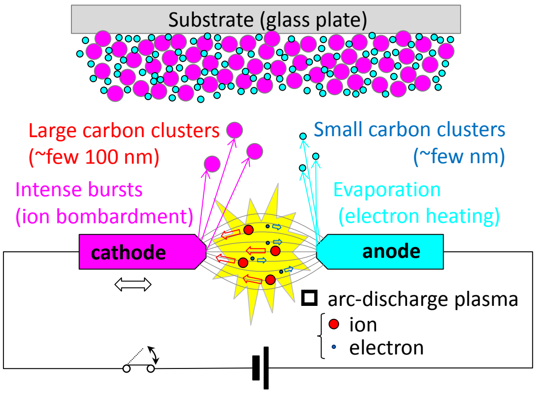

Fig. 1. Arc-discharge foil deposition process

2.2 Fabrication of J-HBC foil

HBC foil fabrication in KEK ceased operation in 2016 due to the sudden retirement of Dr. Sugai. After a series of careful consultations between KEK and JAEA, the deposition apparatus for HBC foil was relocated from KEK to JAEA, and the HBC foil fabrication was transferred to the JAEA staff [6]. Hereon, a new foil fabrication process was studied according to the fragmentary information of Sugai's method, whereas the experimental setup for foil deposition was changed to consider machine maintenance, replacement, and overhaul of the deposition apparatus. Accordingly, the new HBC foil was called J-HBC foil to distinguish it from the original HBC foil. Currently, deposition parameters between the original HBC foil and J-HBC foil are significantly varied as shown in Table I. More specifically, the cathode ratio *Rc* for J-HBC foil ranges from 0.1 to 0.4 as compared with that from 0.6 to 0.8 for the original foil. The reason for such smaller values of *Rc* will be explored in this study, of which one probable cause is reduction in ion bombardment for much lower pressure in the vacuum chamber and enhancement of the heating efficiency for the smaller anode size. After relocation of the deposition apparatus, a base pressure in the vacuum chamber might have gradually decreased while the foil deposition was repeated, thereby decreasing the *Rc*. The cathode ratio is expected to recover as the vacuum pressure is increased during arc-discharging by gas feeding scheme; however, there is no effective procedure found yet to increase the cathode ratio. Therefore, it is necessary to determine the lifetime of the J-HBC foil before a high-power beam user operation in J-PARC.

Table I. Deposition parameters of the original HBC foil and J-HBC foil.

	Original HBC (@KEK)	J-HBC (@JAEA)
Vacuum pressure	$\sim\times10^{-4}$ [Pa]	$\sim\times10^{-6}$ [Pa]
Arc current	500 [A]	500 [A]
Type of arc discharge	AC/DC	DC only
Discharge time	~few seconds	One second
Cathode electrode	C(0.8)+B(0.2), φ10mm	C(0.8)+B(0.2), φ10mm
Anode electrode	C(1.0), φ15mm	C(0.8)+B(0.2), φ10mm
Rc ratio	0.6–0.8 (Controllable)	0.1–0.4 (Not controllable)

3. Investigation of J-HBC foil lifetime

Various items in the TIARA were used to investigate the factors for the very long lifetime of the original HBC foil on QST-Takasaki. For comparison, the same procedure was carried out to determine the performance of the J-HBC foil. The primary concern was to compare the lifetimes of J-HBC foil and original HBC foil against beam irradiation. Accordingly, the HBC foils were beam-irradiated with a 400-keV ion implanter in TIARA. Subsequent microstructure modifications in J-HBC foil were then studied by TEM observation.

3.1 Ion beam irradiation tests

Beam irradiation test focused on the thermal effect on radiation damage. Thus, an energy deposition upon the foil due to the irradiating particle should be estimated as a critical parameter. In the experiment, an ion implanter of the TIARA was used to irradiate 20-μg/cm^2-thick HBC foils with an argon ion (Ar$^+$) beam of 300-keV energy, so that energy deposition in the foil per unit area is comparable to the user operation of the RCS where the 333-μg/cm^2-thick HBC stripper foil was irradiated with the negative hydrogen ion (H^-) and proton (H^+) beam of 400-MeV energy. The stopping powers of the proton and argon in the thin carbon foil were calculated respectively at 2.70 and 4.15×10^3 MeV/(g/cm^2) by using the SRIM simulation code [9]. The RCS was operated at a repetition rate of 25 Hz for a beam irradiation period of 0.5 ms. Meanwhile, the time structure for the Ar^+ beam was constant; thus, this irradiation test was not able to simulate the heat cycle as the pulsed beam irradiation in the RCS. In the user operation of 500 kW however, thermal radiation in visible light from the irradiation spot on the stripper foil was hardly observed, which suggests that the foil temperature may not reach 600 °C, and the heat cycle may not affect the foil damage. The average current at 500 kW was 0.166 mA, but the foil hit number considering the circulating proton was about seven and the foil hit area about 20 × 20 mm^2. Accordingly, the energy deposition at the RCS was estimated at 0.306 W/cm^2, which includes the energy deposition from the two electrons in the H^-. Meanwhile, the beam condition in the TIARA included an Ar^+ beam current of 500 nA and a beam diameter of about 5 mm, which gave an energy deposition at the TIARA at approximately 0.212 W/cm^2, roughly close to that for RCS.

Figure 2 shows pictures of the original HBC foil and the J-HBC foil before and after the beam irradiation. Irradiation times were 15 and 5 min. with a beam current of 200 and 500 nA, respectively. In the former, the irradiation areas of both HBC foils gradually became flat, like a mirror surface, with radial wrinkles clearly and simultaneously appearing at the peripheral parts. Beam irradiation caused a change in the crystal structure as described in the next subsections. Such a structure change caused volumetric contraction and generated tensile stress in the foil toward the irradiation area. In the latter, both HBC foils finally broke as shown in Figure 2. Similar foil deformation in the 200-nA beam irradiation occurred and the foils were torn suddenly at the hole edge of the holder plate just before the completion of the beam irradiation. Nevertheless, the foil at the irradiation area was not broken, which suggests that higher beam currents

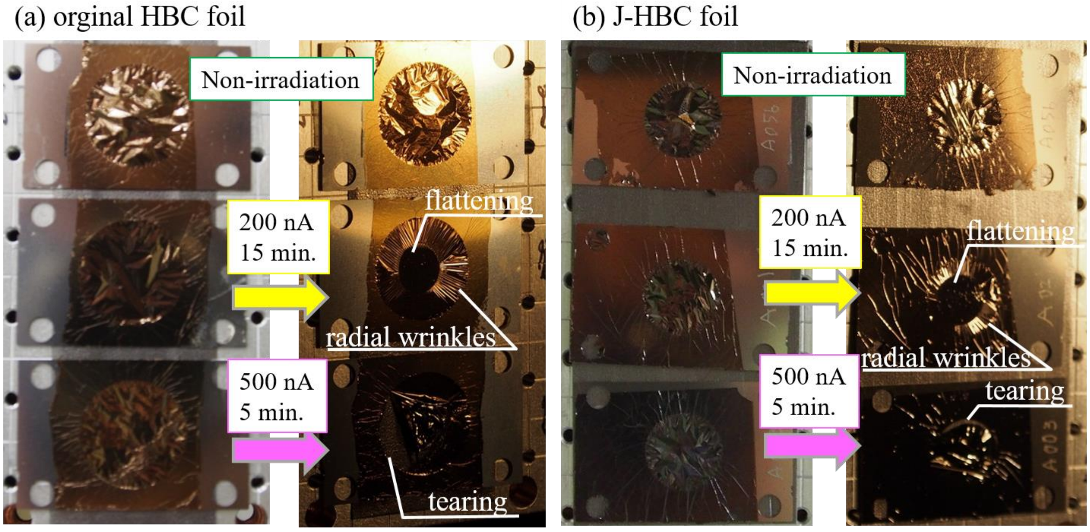

Fig. 2. Photographs of ion beam irradiation tests comparing with (a) original-HBC foil and (b) J-HBC foils; thickness of both HBC foil is about 20 μg/cm^2; Beam condition as follows: ion species is Ar^+, energy of 300 keV, and beam size of 5-mm diameter.

would likely to generate stronger tensile stress. Most importantly, in the experiments, the changing process of the J-HBC foil due to beam irradiation was just the same as that with the original HBC foil. This means a long-lived stripper foil could be achieved for J-PARC user operation.

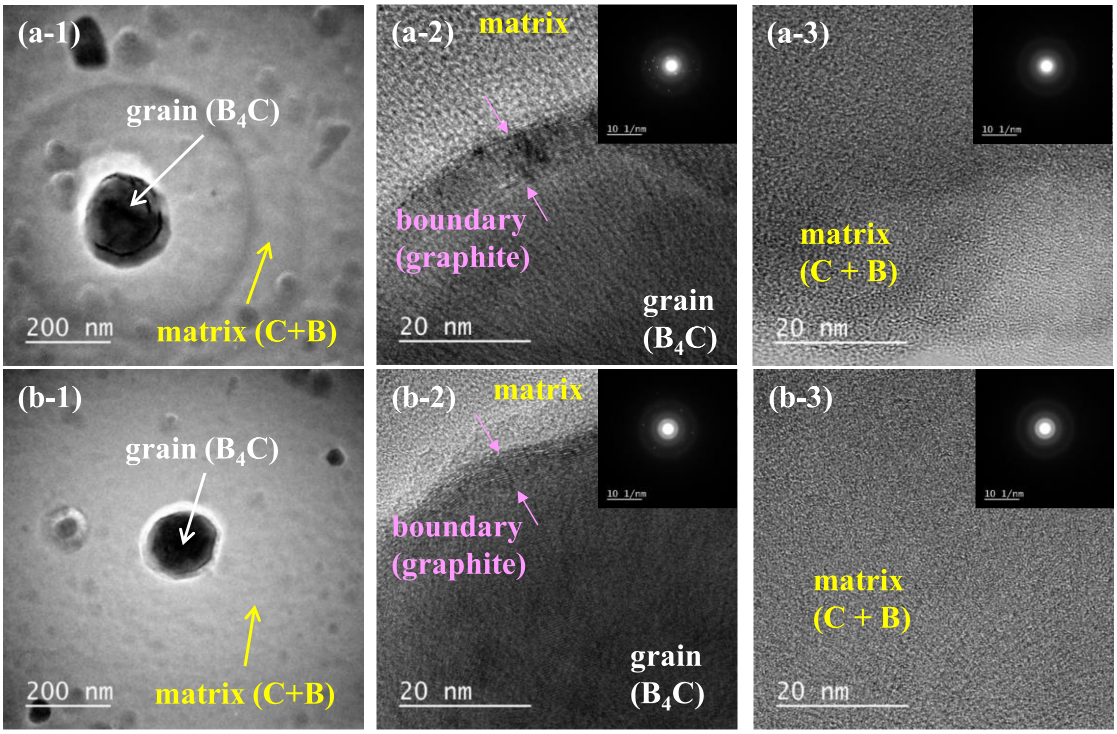

Fig. 3. Typical TEM images and SAED patterns of J-HBC foil for (a) non-irradiation and (b) after irradiation of Ar^+ beam with 200 nA for 15 min. —(-1): Low magnification, (-2): high-resolution TEM image and the diffraction pattern of the grain area, and (-3): high resolution of the matrix area

3.2 Microstructural observation

Figure 3 shows typical TEM images and selected area electron diffraction (SAED) patterns of J-HBC foils for the cases with non-irradiation and after irradiation of Ar^+ beam. From the low-magnification TEM image, grains few hundred nm in size and derived from the B_4C powder in the cathode, were embedded into the amorphous carbon and boron matrix. From the high-resolution TEM images and SAED patterns, shell layers of graphite forming onion-like structure [10] could be observed on the grain boundaries. These graphitic layers should be generated at foil deposition. In addition, the B_4C grains and the onion-like graphitic layers did not change significantly due to the beam irradiation in this experiment. Meanwhile, SAED patterns of the matrix area exhibited a drastic change from a bright and broad ring (a typical halo pattern arising from amorphous structures) to several coaxial circles (Debye–Scherrer rings characteristic of polycrystalline structures). These results indicate that the amorphous carbon and boron were crystallized with beam irradiation. Indeed, the high-resolution TEM image after irradiation of J-HBC foil at matrix area reveals a mixture of amorphous and nano-sized crystalline structures as shown in Figure 3 (b-3). Previous works reported that amorphous carbon stripper foils such, as HBC foils and CADAD foils, were crystalized by the ion beam irradiation [11, 12]. Similar structure changes were confirmed to have taken place in the J-HBC foil.

3.3 Conclusion

With respect to the investigated physical properties of the HBC foil, its density with 1.1 g/cm^3 is rather significantly small [11]. As a result, the beam irradiation easily induced the amorphous-to-crystalline transition. The crystallization allows the volumetric contraction, while the structure reconstruction creates the flat-out surface. At the same time, the volumetric contraction generates the tensile stress anew that highlights the flat surface to look like a mirror and creates clear radial wrinkles under the fixed boundary condition. The beam-induced crystallization is an important issue to clarify the macro-scale specific phenomena of stripper foil.

4. Summary and outlook

As discussed above, fabrication of J-HBC foils in J-PARC started after relocation of the deposition apparatus from KEK Tsukuba-site to JAEA Tokai-site. Deposition parameters were different in the original HBC and the J-HBC foils. In J-HBC, the cathode ratio is very small. However, the ion beam irradiation tests demonstrated that its performance is as good as the original foil. Moreover, as shown experimentally, the cathode ratio may not be important for the HBC foil. Microstructure observations with TEM indicated that the amorphous structure in the HBC foil is changed into a nanocrystal structure due to the beam irradiation. Such beam-induced crystallization should be a key issue in the mechanism of foil deformation and breakage. As the results were commendable, the authors of this study have started utilizing the J-HBC foil for the J-PARC user operation.

As future direction, the authors intend to measure the foil temperature in-situ by using an infrared camera. The first test will be carried out at the ion beam irradiation test in the TIARA. Furthermore, the authors aim to achieve a highly dense and pulsed structure ion beam to simulate a high-intensity beam operation in J-PARC RCS.

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