PERFORMANCE CHARACTERISTICS OF HBC-FOILS BY 650 KeV H^- AND DC HIGH INTENSITY ION BEAM IRRADIATION

I. Sugai*[,1)], A. Takagi[1)], Y. Takeda[1)], Y. Irie[1)], M.Oyaizu[1)], H. Kawakami[1)], Y. Yamazaki[2)], M. Yoshimoto[2)] and M. Kinsho[2)]
[1)] KEK, Oho1-1, Tsukuba-shi, Ibaraki, 305-0801, Japan
[2)] JAEA, Tokai-mura, 319-1195, Japan

Abstract

Newly developed Hybrid type of Boron mixed Carbon stripper foils (HBC-stripper foil) are extensively used for not only J-PARC for but also PSR of LANL.

In order to know further characteristics of the HBC-stripper foils, we measured following parameters; foil lifetimes, thickness reduction, uniformity before and after beam irradiation, and foil deformation using 650 keV, H^- and DC light ion beam KEK-Cock Croft type accelerator, which are adjustable the same energy deposition as well as the J-PARC. For looking for the reason why the HBC stripper foils are high durability against high intensity beam irradiation, we measured following physical properties; the density, thermal conductivity, electric resistivity, sputtering yield by ion beams and we compared these values with other tested carbon stripper foils such as commercially available carbon best foils(CM-foil), nano-crystalline diamond (nDM-foil), high purity synthetic diamond (DM-foil), diamond like carbon(DLC-foil) and nano-tube carbon foils (NTC-foil).

INTRODUCTION

The newly developed HBC-stripper foils have been extensively used without any problem for RCS of J-PARC and PSR of Los Alamos National laboratory since September of 2007[1-3]. These foils have no any problem because of very low foil temperature due to low beam power of 300 kW at stripping of H- ion beam at first stage of 180 MeV at present. However, the final goal of the beam power is scheduled to be much more 1MW at second stage of 400 MeV in a few years, and thus the foil temperature at MW class accelerator power becomes higher than 2000K.

Therefore, in order to develop of the HBC stripper foils with further high durability higher than 1800K, we are going on comprehensive research, development and production with high reproducibility about the HBC stripper foils.

Further, in order to know the characteristics of the HBC-stripper foils by a 650 keV, H^- and DC light ion beam irradiation, we measured following parameters; lifetime, thickness reduction, uniformity before and after beam irradiation, and deformation. And also in order to understand for the reason why the HBC stripper foils are high durability even at the high temperature of 1800K, we measured following parameters: density, thermal conductivity, electric resistivity, and sputtering yield against hydrogen ion beam and compared these values measured with other tested foils such as the CM foils, the DLC-foil, the nDM-foils and the NTC-foil.

EXPERIMENT

Foil preparation: HBC-Foil for the J-PARC

The preparation method of the HBC stripper foils was identically the same as the previous one of Ref.[3] and we have used the Controlled DC Arc-Discharge (CDAD) method [4]. The cathode electrode used a boron-mixed (20%) carbon rod of 10 mm diameter and 70 mm long while the opposite anode electrode was a pure graphite rod of 15 mm diameter and 30 mm long. The carbon discharge arc-evaporation source was installed in a vacuum chamber of EBX-2000C.

The distance between the evaporation arc-source and the substrate was 350 mm. The deposition thickness onto the substrate was monitored using two quartz thickness gauges to reduce error deposited thickness and the weight was measured after deposition by using a microbalance. As mentioned in Ref.[5-7], the lifetime of the foil was found to be correlated to the expression R = Wc /(Wc + Wa) calculated in % where Wc and Wa are the carbon source weight losses due to ablation from the cathode and the anode electrodes, respectively. In the present preparation, the ratio R was kept between 70 and 80 %.

Lifetime measurement

The experimental set up for lifetime measurements is identically the same as show in Fig.1of Ref.[2]. The H^- beam from ion source is injected from the right-hand side of the figure, and is converted to H^+ beam after stripping two electrons through the carbon stripper foils. The Faraday-cup monitored the H^+ beam current. The average beam current was 110± 20 μA, and the beam size was 3.5 ± 0.5 mm in diameter controlling by using the upstream quadrupole magnets. During the experiments, the beam current was kept approximately stable although the beam fluctuated occasionally in the vertical direction. The lifetime of the foils was defined as an irradiated time (hours) until the foil shows large deformation or ruptures. Surface conditions of the foil were monitored by a video camera looking through a viewing port shown in Fig.1 of Ref.[3].We tested other different carbon stripper foils of the CM-foil, nDM-foils, DLC-foil and the NTC-foil, for comparisons. Figure 1 shows the results of the lifetime

*Isao.sugai@kek.jp

measurements for the HBC-foils and other tested various types of foils.

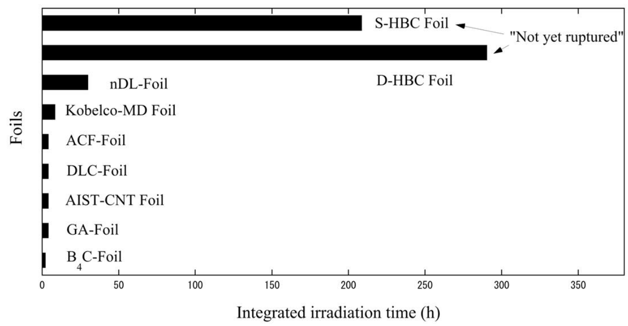

Figure 1: Histograms of lifetimes of the single and double-layered HBC-foils and the other tested foils.

The lifetimes of the single and double layered HBC-foils showed 210h and 280h, respectively. The both foils were not yet ruptured due to the limited beam time. The lifetimes of the nDM foil from the SNS and the Kobelco DM foil with a Si frame were 30h and 15 h, respectively. Originally, the color of the DM foils was transparent. However, the irradiation spot turned black as the irradiation proceed. These foils did not show shrinkage like the CM and DLC-foils, but showed rather strong bending toward the beam direction at the blackened area with the irradiation time. This area was fragile, and easily tore off in the handling process after the experiments. The DLC and CM-foils, however, showed large deformation within half an hour and then were broken within a few h.

Measurement of physical properties of the HBC-Stripper foils

Next, in order to investigate the physical properties of the HBC stripper foil, we measured following three parameters: density, thermal conductivity and electric resistance. Table 1 shows the values obtained including the other tested foils for comprising with the HBC-stripper foils.

The density (ρ) was obtained by division of surface density (g/cm^2) / depth (cm) of the foil by following procedure. The depth of the foil was measured with a Dektak V-200Si surface profile measuring system of ULVAC Co., Ltd and surface density was measured using ultra-electronic balance. The density of the foil was 1.10±0.20 g/cm^3, about half of 2.26 g/cm^3 of the density of a single crystal graphite, which was lowest value compared with other tested materials as shown in Table. The resistivity of the HBC-foil was measured by using a 4-pin probe method Lorester-GP of Mitsubishi-kagaku Co., Ltd. The value was 2.34 Ω·cm and the value is considerably higher than that of the CM-foil and it is corresponded to about 2 times that of the cluster foil. The thermal conductivity (λ) was obtained by following procedure that first thermal diffusivity (d) was measured with a light alternating method of Laser PIT of ULVAC Co., Ltd and the value of the density (ρ) of the HBC foil was used for the calculation, and the specific heat(s) was derived from Ref.[8]. The thermal conductivity (λ) can be obtained by (ρ) x (s) x (d). The value obtained was 0.24 (W/m·K) as shown in Table. Among them, the value showed smallest value compared with other foil's values.

Table 1: Physical properties of HBC-foil and other tested foils

Sample	Density(g/cm^3)	Resistance(Ω・cm)	Thermal conductivity(w/m・k)
Syntactic diamond	3.5	>10^{16}	2000
Carbon nano-tube	~2.2	4.7 x 10^{-4}	2,000-4,000
Boron	2.36	1.5 x 106	27.4
Boron carbide(B_4C)	2.51	0.5	20
Poly graphite	1.8-2.3	1.4 x 10^{-3}	50-130
ACF-foil	1.94	1.5 x 10^{-2}	1.41
Cluster-foil	1.85±0.20	1.26	3.95
HBC-foil	1.10	2.34	0.24
DLC-foil	2.5	>10^9	200

RESULTS AND DISCUSSION

Foil deformation

As shown in Table 1, the density of the HBC-foil showed lowest value of 1.10±0.20 g/cm^3 in the other measured foils. We speculate that the low density of the HBC stripper foil plays a vital role in the foil lifetime. Here, we roughly discuss about the foil deformation. The foil deformation considers to be cause through following process. First, the amorphous carbon foil at the irradiated area crystallizes due to heat by the ion beam irradiation [5-7]. Second, the crystallized areas produce volume shrinkages. Third, the volume shrinkage makes the foil deformation though pull to a radial direction along the beam spot. The foil deformation is strongly dependent on the speed of the volume shrinkage and the speed of the volume shrinkage may be strongly dependent on the foil temperature and the carbon particle sizes of the foil. Here, as we mentioned above the Wc is composing of large carbon particles (300±100 nm) emitted from the cathode electrode in DC arc-discharge play important roles of the high durability (long lifetime) against high intensity ion beam irradiation, while the Wa is composing of small particles of 3± 2 nm emitted from anode one play a roll of the mechanical flexible of the foil but very weak against ion irradiation as mentioned in Ref. [5-7]. The cluster foils (without boron-doped) of composing of both combination (R = 60-80 %) of the Wc and the Wa demonstrated to be very long-lived and a few deformation due to the large carbon particles in the foils against high intensity beam [5-7]. From the obtained data mentioned above, the foil deformation might be strongly dependent on the carbon particle size. Therefore, the large particles in carbon foils play an important role of the mitigation in the rapid foil shrinkage speed.

Next, we discuss about the thickness reduction by the sputtering. The thickness reduction of carbon foils as main reason is considered due to the evaporation and the sputtering due to the ion beam irradiation at the irradiated beam spot area. Here, it should be noted concerning the vapour pressure of the B_4C target material, the B_4C material is noticeably very low of about 10^{-11} Torr at the 2000K [9]. As mentioned above our used carbon evaporation source was made by mixing with the B_4C (20%) powder in poly-graphite powder, the HBC-foils is considered to be had low vapour pressure compared with the 10^{-5} Torr for the poly-graphite and 10^{-4} Torr for the boron materials at the same temperature of 2000K [9].

It is well known that the sputtering yield in maximum beam energy is well known around 10-15 keV sputtering voltage [10]. The sputtering yield decreases with increasing further higher than 10-15 kV sputtering voltage and after then the implantation effect appears with the voltage increases. Therefore, in order to investigate the sputtering yield by difference gas ion mass, we measured the sputtering yield of each carbon target materials at sputtering voltage of 10 kV. We used following target materials; poly-graphite, boron, boron carbide, synthetic diamond and boron (20%) doped graphite. The gas ion sorts were used hydrogen, neon and krypton. The result obtained shows in Table 2. From the table, the sputtering yield by the hydrogen gas ion showed significantly very low values of 0.007 for the boron-(20%) doped graphite carbon nearly to 0.004 for the boron carbide, respectively and these values corresponds to about 1/5 of the graphite and synthetic diamond target materials.

Table 2: Sputtering yield of various target materials by hydrogen, neon, krypton gas ion bombardment at 10kV sputtering voltage

Sputter material	Sputtering yield(atoms/ion) for hydrogen gas ion	Sputtering yield(atoms/ion) For neon gas ion	Sputtering yield(atoms/ion) for krypton gas ion
Poly-graphite	0.030	0.42	0.58
Boron	0.070	0.26	0.36
Boron carbide	0.004	0.04	0.09
Synthetic diamond	0.050	0.30	0.70
Boron doped (20%) graphite	0.007	0.26	0.36

SUMMARY

We measured the lifetimes of single and double-layered HBC-foils including other different carbon foils by using 650 keV H^- and DC high intensity ion beam irradiation, and the single and double-layered HBC-foils showed following great improvements;

1) The lifetimes of single and double layered HBC-foils showed the same tendency to have the long lifetimes as obtained with a 3.2 MeV Ne^+ and DC heavy ion beam irradiation. Although the single-layered HBC-foils produced some pinholes, the lifetime showed a long lifetime of 210 h, which is about 180 times longer than that of the best CM-foil. The double-layered HBC-foils also showed a long lifetime of 280h, and we could not observe any pinholes if seen through a light.

2) We also measured three physical properties of the density, thermal conductivity and electric resistivity of the HBC-foil and other tested foils. Among them, the values of the density and thermal conductivity of the HBC-foil showed noticeably different values of 1.10± 0.20 g/cm^3 and 0.24 (W/m·K) for the HBC-foils compared with other tested and untested carbon foils and materials.

3) We found that HBC-foils showed very low sputtering yield of 0.007 near 0.004 (atoms/ion) of the B_4C material from the result measured with H^+ beam at the sputtering voltage of 10 kV.

4) Noticeable low thickness reductions less than 26 % for the double and 30 % for single layered HBC-foils due to low vapour pressure and low sputtering yield even after long time irradiation at the high temperature of 2000K and high intensity beam irradiation.

From these great positive results, therefore, the HBC-foils could be applicable for not only use in much more 1MW class like the J-PARC, for but also heavy ion accelerators with high energy power.

REFERENCES

[1] T. Spickermann, et al., Nucl. Instr. and Meth. A590 (2008) 25.
[2] T. Spickermann, et al., HB-2008, Albuquerque, NM, USA
[3] I. Sugai, Y. Takeda, M.Oyaizu, H. Kawakami, T.Hattori, K. Kawasaki, Nucl. Instr. and Meth. A561 (2006) 16.
[4] I. Sugai, M.Oyaizu, H. Kawakami, C. Ohmori, T.Hattori, K. Kawasaki, N. Hayashizaki, Nucl. Instr. and Meth. A 480 (2002)191.
[5] I. Sugai, T. Hattori, H. Suzuki, H. Kinoshita, H. Kato, K.Yamazaki, Nucl. Instr. and Meth. A 251(1986) 596.
[6] I. Sugai, T.Hattori, H. Suzuki, H. Kinoshita, H. Kato, K.Yamazaki. Nucl.Instr. and Meth. A 263(1988)376.
[7] I. Sugai, T.Hattori, H. Kato, Y. Takahashi, H. Muto, K.Yamazaki. Nucl. Instr. and Meth. A 282(1989)164.
[8] Chronological Scientific Tables (in Japanese) Maruzen Co. Ltd.
[9] THIN FILM EVAPORATION SOURCE REFERENCE, THE R.D Mathis Company, 2840 GUNDRY AVENUE・LONG BEACH, CA 90806
[10] G. Sletten, P. Knunudsen, Nucl. Instr. and Meth. 102(1972)485.