LIFETIME MEASUREMENT OF HBC-FOIL AND NANOCRYSTALLINE DIAMOND FOIL BY USING KEK-650 KEV HIGH INTENSITY H^- DC BEAM

I. Sugai#, A. Takagi, Y. Irie, Y. Takeda, M. Oyaizu, H. Kawakami
High Energy Accelerator Research Organization, Oho 1-1, Tsukuba-shi, Ibaraki 305-0801, Japan
R. W. Shaw, M. A. Plum, ORNL, Oak Ridge, TN 37831, USA
C. S. Feigerle, University of Tennessee, Knoxville, TN 37996, USA

Abstract

At the 39th ICFA HB2004 and the EPAC-2006, we reported the lifetime and properties of the newly developed HBC-foils measured by using the 3.2 MeV Ne^+ ion beam. Here, superior durability was shown against high temperature damages by foil deformation, thickness reduction and pin holes production compared with the cluster foils made by the CADAD method. In this report, we compared the lifetime of the HBC-foils with that of other foil types such as high quality nanocrystalline diamond foil by using the KEK-650 keV high intensity H^- and DC beam. The beam can deliver the same energy depositions as those in the MW class accelerators such as the J-PARC and the SNS.

INTRODUCTION

In high intensity proton synchrotrons, the temperature of the stripper foils becomes about 2000K at peak due to the energy loss of the incoming H^- beam and the circulating proton beam. Commercially available foils (CM-foil) are then ruptured in a very short time with thickening, twist and shrinkage. In order to overcome this problem, we have developed the Controlled AC/DC Arc-Discharge (CADAD)method [1]. Although this method has an advantage of long lifetime of the foils, we have found the following several negative aspects. The first one is that maximum obtainable foil thickness is 140 ±30 μg/cm^2. The second one is the thickness reduction by -75% on average and the third one is the generation of pinholes [2]. We have then developed the Hybrid Boron mixed Carbon stripper foil (HBC-foil) [3], which is prepared using a boron mixed graphite rod. The HBC foil has strong adhesion to the substrate and thus the foils could be made with thickness up to 700 μg/cm^2. High temperature damages of the foil were also mitigated significantly even at approximately 1700 K. However, when the foil temperature reaches higher than 1800 K, foil damage was always observed at and around the irradiated area.

Lifetime measurement of the foils were performed by using the KEK 650 keV H^- and DC beam, which is the same ion species as those in the J-PARC and SNS, and can deliver the same energy depositions as these in the those machines by adjusting the beam current. We have tested various types of stripper foils, for example, HBC-foils, micro and nanocrystalline diamond foils with corrugated pattern, microcrystalline diamond foils, multi-layered diamond-like foil (MDLC-foil), carbon nano tube (CNT) foil and commercially available (CM) foils. Comparisons of these foils are given in this report from the view point of lifetime.

EXPERIMENT

Foil Preparation: HBC-Foil for the J-PARC

The preparation method of the HBC-foils was almost the same as the previous one in ref. [2]. We have used the Controlled DC Arc-Discharge (CDAD) method [4]. The cathode used a boron-doped (20%) carbon rod of 10 mm diameter while the opposite electrode was a pure graphite rod of 15 mm diameter. The carbon discharge arc-evaporation source was installed in a new vacuum chamber (EBX-2000C). The distance between the evaporation source and the substrate was 220 mm. The deposition thickness onto the substrates was monitored using a quartz thickness gauge and the weight was measured after deposition by using a microbalance. The self-supporting foils were obtained by applying an annealing technique. Namely, the deposited layer with substrate was heated at 573 K for 6 h using a Ta filament heater in vacuum chamber. Then, foils were peeled off from the substrate, keeping a flat shape. Pinholes were observed in some parts of the annealed foils which could be identified by seeing light pass through the foil. Reason for this pinhole formation is not clear yet and it is a serious problem to be solved in the near future. For the beam test, we used the foils with no pinholes.

Single (417 μg/cm^2) - and double (210 μg/cm^2 × 2) -layered HBC foils have a shape of 24 mm (W) × 40 mm(L) and are suspended at one edge with two Stainless steel-304 holder (48 mm (W) × 80 mm (L)). The SiC fibers of approximately 10 μm in diameter are used to sandwich the foil to prevent from curling during irradiations.

Isao.sugai@kek.jp

Micro and Nanocrystalline diamond foils for the SNS

These foils were produced by Chemical Vapor Deposition (CVD) from a microwave driven plasma [5]. The micro and nanocrystalline diamond foils were mechanically stronger and easier to handle than the commercially available diamond foils: nanocrystalline diamond foil has a grain size of 5-50 nm, and was made using CVD Ar gas content (> 90%). Corrugating lines on the foils prevent curing of the foil when it is released from the Si growth substrate. The free standing portions of these foils were 12 mm in width and 25 mm in length. Two types of micro and nanocrystalline foils with corrugated patterns were prepared. One was 349 μg/cm^2 sandwiched by SiC fibers and the other 439 μg/cm^2 without SiC fibers. Another nanocrystalline diamond foil had a shape of circle with 18 mm in diameter and was 541 μg/cm^2. The foil is supported by an unetched part of Si wafer along the circumference.

For comparisons, we have also obtained a microcrystalline diamond foil (DM-foil) of 540 μg/cm^2 from the Kobelco [9] in Japan, a multi-layered diamond-like foil of 480 μg/cm^2 (MDLC foil) from TRIUMF [6], carbon nano-tube foils of 450 μg/cm^2 from Prof. I.Yamane of KEK [7-8] in Japan and a commercially available foil of 425 μg/cm^2 from Arizona Carbon Foil Company [10] in the USA.

Lifetime Measurement

The experimental set up for lifetime measurements is shown in Fig.1. The H^- beam is injected from the right-hand side of the figure, and is converted to H^+ beam after passing through the carbon stripper foils. The Faraday cup monitored the H^+ beam current. The average beam current was 90±20 μA, and the beam size was 3.5±0.5 mm in diameter. The foil holder can accommodate four foils: one of them, called HBC-monitor foil of 360 μg/cm^2, was used to check and adjust the beam profile. The vacuum was 1.3×10^{-5} Pa without beam and 5.3×10^{-5} Pa during beam irradiation. The foil lifetime in this paper is defined as the irradiation time (hours) until the foil shows large deformation or ruptures. During the experiments, the beam current was kept approximately stable although the beam fluctuated occasionally in the vertical direction. Surface conditions of the foil have been monitored by a video camera looking through a viewing port shown in Fig.1.

RESULTS AND DISCUSSION

Table 1 shows the results for the lifetime measurements for various types of foils. The foil temperature was measured on the hottest spot of the foils using a digital optical pyrometer of model IR-AHU, CHINO Corp. in Japan. In this measurement, the emissivity of the carbon surface was taken to be 1.0 for all cases, because we do not know the actual emissivity on the test samples. The measurement error due to the unknown value is believed to be ~120 K for a measured temperature of 1900 K: the true temperature of the foil should be 2020 K at most. The thickness reduction of the foils was measured by using alpha-ray thickness gauge [11].

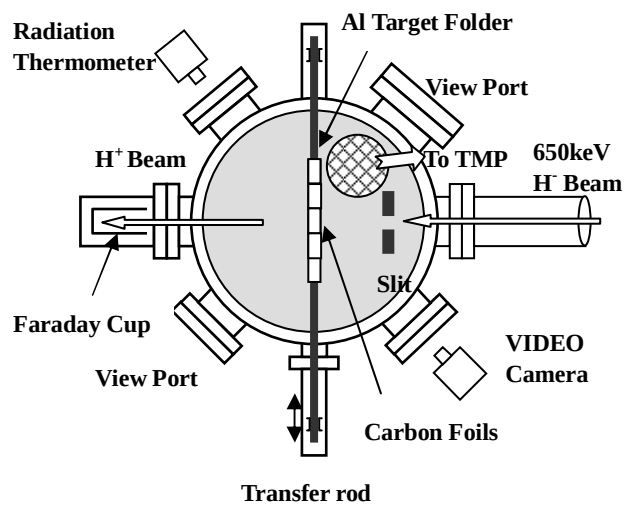

Figure 1: Experimental apparatus for lifetime measurement of various carbon stripper foils by using KEK 650-keV.

Fig. 2 (a) and (b) show the thickness reduction in the single and double–layered HBC-foils irradiated. In Fig. 2(a), the single-layered HBC-foil did not show noticeable deformations even after 250 h at the temperature of 1900±100 K, which corresponds to about 171 times longer lifetime than that of the CM-foil. The double-layered HBC-foil also showed a long lifetime of 203 h. The thickness reductions at the irradiated area showed considerably low value of 30% for the single- and 26% for the double-layered foils as shown in Fig. 2, respectively. However, we could clearly see the production of pinholes for the single-layer foil, while no pinholes could be observed for the double-layered HBC-foil.

The lifetimes of the micro and nanocrystalline diamond foils were 10.5 h and 21.0 h, respectively. Originally, the color of the diamond foil was transparent. However, the irradiation spot turned black as the irradiation proceed. These foils did not show shrinkage like CM-foils, but showed 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 diamond foils from the SNS and the Kobelco with a Si frame showed rather long lifetime of 60 h. The MDLC and CM-foils, however, showed large

deformation within half an hour and then were broken within 1~1.5 h.

We should also note that any kind of diamond foils with a Si frames were ruptured when the irradiation to the foils was stopped during irradiation due to thermal expansion.

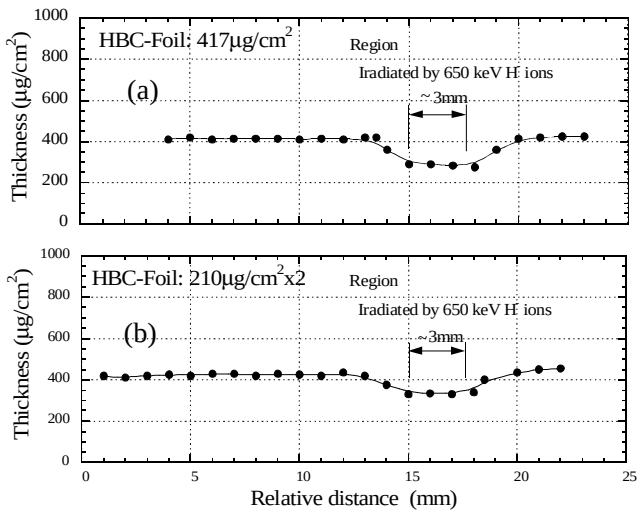

Figure 2: Thickness reduction in the single (a) and double (b)-layered HBC-foils irradiated for 256.5 h and 203.5 h by using 650 keV H^- and DC ion beam.

SUMMARY AND CONCLUSION

We measured various types of stripper foils of HBC-foils, micro and nanocrystalline diamond foils, multi-layered DLC foils, carbon nano-tube foils and CM-foils at the high temperature of >1800K by using the KEK 650 keV, H^- and DC beam. Although the single-layered HBC-foils produced some pinholes, the lifetime showed 256 h, which is 171 times longer than that of the CM-foil. The double-layered HBC-foils also showed a long lifetime of 200 h, and we could not observe any pinholes if seen through a light. For both the HBC-foils, there were no large deformations such as those that could be observed for the single layered CNT, MDLC and CM-foils. The micro and nanocrystalline diamond foils for the SNS with and without the SiC fibers showed a lifetime of 20 h on average. However, these foils tend to bend toward the beam direction at a temperature higher than 1800 K. The foils with a Si frames showed a very long lifetime of about 60 h at 2000 K. From these results, the single- and double-layered HBC foils are very promising for use in the MW class accelerators like the J-PARC.

Table 1: Lifetime Results of Various Foils

Type of foil	Lifetime (h)	Initial thickness (μg/cm^2)	Thickness Reduction (%)	Foil conditions	Incident Beam Current (μA)	Foil Temperature (K)
Uncertainty		±10 %			±10	±100
Single HBC sandwiched by SiC fibers (KEK)	256.5 reusable	417	30.0	No deformation, but pinholes	90	1970
Double-Layer HBC sandwiched by SiC fibers (KEK)	203.5 reusable	210 x 2	26.0	Small shrinkage and no pin-holes	90	1950
Microcrystalline diamond sandwiched by SiC fibers (SNS)	10.5	349	3.0	Back bending and pin-holes	110	1930
Nanocrystalline diamond without SiC fibers (SNS)	21.0	439	6.5	Back bending and no pin-holes	130	1950
Nanocrystalline Diamond with Si Frame(SNS)	62.0	541	2.1	Cracks inside frame corner and no pin-holes	90	2100
Multi-DLC (TRIUMF)	1.0	480	Non measurable Due to a big hole	Broken	110	2260
Carbon nano-tube(AIST)	9.0	450	Non measurable Due to a big hole	Broken	90	1880
CM (Arizona) sandwiched by SiC fibers	1.5	425	Non measurable Due to a big hole	Broken	90	1920
Micro diamond with Si frame (Kobelco)	61.5	540	5.7	Cracks inside frame corner and no pin-holes	90	2080

REFERENCES

[1] I.Sugai, M.Oyaizu, H. Kawakami, C. Ohmori, T.Hattori, K. Kawasaki, M.J.Borden , R.J. Macek, Nucl,. Instr. and Meth. A 362 (1995)70.

[2] I.Sugai, Y. Takeda et al., Nucl. Instr. and Meth. A521(2004) 192.

[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. Hasyashizaki, NUcl. Instr. and Meth. A 480 (2002)191.

[5] R. W. Shaw et al., PAC '05, 16-20 May 2005, Knoxville, TN, United States, p 2152.

[6] S. Zeisler, V. Jaggi, Nucl. Instr. and Meth. A590(2006) 18.

[7] I.Yamane et al., KEK Report 2007-5 January 2008.

[8] T. Saito, S. Ohshima et al., J. Phys. Chem.. B 109(2005) 10647.

[9] T. Tachibana et al., Nucl. Instr. and Meth. A590(2006) 22.

[10] J. Stoner et al., Nucl. Instr. and Meth. A590(2006) 57.

[11] I. Nonaka and I.Sugai INS-J-132.