THERMAL SIMULATIONS OF CHARGE-EXCHANGE STRIPPER FOILS FOR HIGH-MELTING-POINT MATERIALS

Y. Takeda#, KEK, Tsukuba, Japan
M.Plum, ORNL/SNS, Oak Ridge, TN, USA

Abstract

Charge-exchange stripper foils can be very quickly broken by high-current beams. Hence, a long-lived foil that can withstand prolonged beam irradiation is eagerly awaited. It is well known that the maximum temperature of the foil plays an important role in the foil lifetime. Therefore, the temperature distribution map and the maximum temperature of the foils were investigated in detail by using simulation software of the finite element method and applications with ANSYS. Moreover, the heating properties of several kinds of high-melting-point materials were researched. According to the results, stripper foils of the same effective thickness showed drastically different maximum temperatures, differing by up to about 200 K. From these results, we show that the emissivity and specific heat of the foil considerably influences its maximum temperature.

INTRODUCTION

At present, high-intensity proton accelerators that are being produced or operated use charge exchange injection method in injecting beam from linear accelerator into circular accelerator such as synchrotron. With charge exchange injection, it is necessary to convert negative hydrogen beam (H^- beam) into Proton beam (H^+ beam) so as to inject high-intensity beam effectively into circular accelerator. Therefore foil is installed at the injection point of circular accelerator, incident beam passes through the foil, in that way electrons of H^+ beam are torn off and charge exchange is conducted.

In Japan Proton Accelerator Research Complex (J-PARC) built in Tokai-village in Ibaraki prefecture, H^- beam is converted into H^+ beam by the carbon charge exchange foil installed at the injection point of 3-GeV Synchrotron [1],[2]. Also in Oak Ridge National Laboratory / Spallation Neutron Source (ORNL/SNS) in the USA, as much as 1-MW H^- beam can be converted with charge exchange foil [3]. This foil for charge exchange, which is called charge stripper foil, is exposed not only to injection but also to circulating beam, and it heats up to 1800K because of energy loss by the particles passing through it. The difference of temperature between heated parts and unheated parts, and change of temperature caused by the pulsed beam as time passes, do great damage to the carbon foil. Also elements move and evaporate due to high heat, which leads to pinholes and transformation. If the foil is damaged, it must be exchanged, whereupon radiation exposure to workers is inevitable, so a new foil that won't be broken for a long time is desired. At present, Hybrid Boron mixed Carbon foil (HBC-foil) mixing amorphous carbon and boron, which is strong against heat damage is being developed in J-PARC. Also in SNS, a nanocrystalline diamond foil is being developed (Figure 1). In this way, although long-lifetime carbon foils are being developed all over the world, a satisfying foil hasn't yet been developed. Therefore in order to make accelerators effective and lessen foil-worker's exposure, early development of long-lifetime foil is desired.

Figure 1: Left: HBC-foil at KEK, Right: Diamond foil at SNS.

EFFORT TO MAKE LONG-LIFETIME FOIL

As it is said above, amorphous carbon in J-PARC, and diamond in SNS, are put in the center to develop stripping foil. In J-PARC, Dr. Sugai and others of High Energy Accelerator Research Organization (KEK) have developed a new method to produce more than 200 μg/cm^2 thickness foil that contains carbon and boron. This HBC-foil is strong against heat damage and it doesn't cause a lot of thickness change under irradiation for many hours, although it often makes pinholes, it is very fragile, and since it has stress in the direction of thickness, it sometimes curls. They are searching for conditions of producing foil that doesn't make pinholes, but they haven't realized it yet.

On the other hand, in SNS they have developed long-lifetime diamond foil that uses CH_4 gas by plasma-enhanced chemical vapor deposition (CVD). They are researching the difference of its long-lifetime by changing the proportion or sort of the support gas that is added to CH_4 gas and changing the grain size of diamond (it is called nanocrystalline-diamond foil when the grain size is on the nanometer scale, and it is called microcrystalline-diamond foil when the grain size is on the micrometer scale). Also various corrugation patterns are used so that curling is less likely to occur. In the diamond foil, since each grain is connected firmly, it is much easier to handle than the amorphous carbon foil. Also, since the foil is produced by CVD, it has no pinholes, and the surface is very plain. Diamond, however, has a fault that its composition changes into that of graphite when it is exposed to high heat for hours. If it becomes graphite, transformation is likely to occur due to the difference of density and composition, therefore it is a concern how to prevent diamond from becoming graphite.

THE PATH TOWARD LONG-LIFETIME FOILS

Beam irradiation lessens the thickness of the foil, makes pinholes and curling, and makes it become graphite (in the case of diamond foil). If these influences become larger, it won't work as stripper foil, and it must be exchanged. Therefore how to suppress these things is the point toward long-lifetime foil.

As the foil becomes hotter, it is likely to become thinner. Since the sputtering rate of carbon is small, it is thought that the foil becomes thin due to evaporation by high heat. Curling is likely to occur when the structure or composition of the materials changes, or when the temperature gradient is large. Pinholes are considered to caused by the space generated when the consisting elements are rearranged because of high heat. Diamond becomes graphite under high heat, and the higher the heat, the faster it becomes graphite. In this way, the root cause of many of the foil issues is based in the temperature of the foil, and the path to long-lifetimes is through suppressing the temperature.

Therefore we conducted analysis of foil's heating by using Finite Element Method Analysis Software (ANSYS). We minutely examined how the temperature evolves how the heat conducts when a beam irradiates a foil, and the tendency of heat generation by a pulsed beam, as to materials whose melting point is high, as well as diamond foil and graphite.

CONDITION OF CALCULATION OF HEAT GENERATION

We conducted simulations of heat generation by a beam with six materials such as diamond, graphite, boron, boron carbide (B_4C), h-boron nitride (h-BN), and c-boron nitride (c-BN) under the condition of beam that the thickness of foil was 400 μg/cm^2, beam was 1.0 GeV, 1.5e14 ppp injected over 1 ms, 60 Hz. Table 1 shows properties of each material, and Table 2 shows the details of the conditions of the simulations.

Table 1: Properties of each material (SH: Specific Heat, TC: Thermal conductivity, RT: Room temperature)

	Diamond	Graphite	Boron	B4C	h-BN	c-BN
Density (g/cm3)	3.5	2.28	2.08	2.52	2.1	3.45
TC@RT (W/mK)	1800	178	27	28.5	600	740
SH@RT (J/kgK)	516	718	1048	836	791	791
Emissivity	0.3	0.8	0.8	0.85	0.55	0.55

Table 2: Conditions of the simulations

Foil	Size	45x17mm
	Thickness	400ug/cm2
Beam	Spec.	1GeV, 1.5e14ppp injected over 1ms (Max) 60Hz, 1ms pulse beam
	Spot size	Like Gaussian beam
Model	Form	Very simple (Foil only)
	Element	Shell
	TC	Temperature depend
	SH	Temperature depend

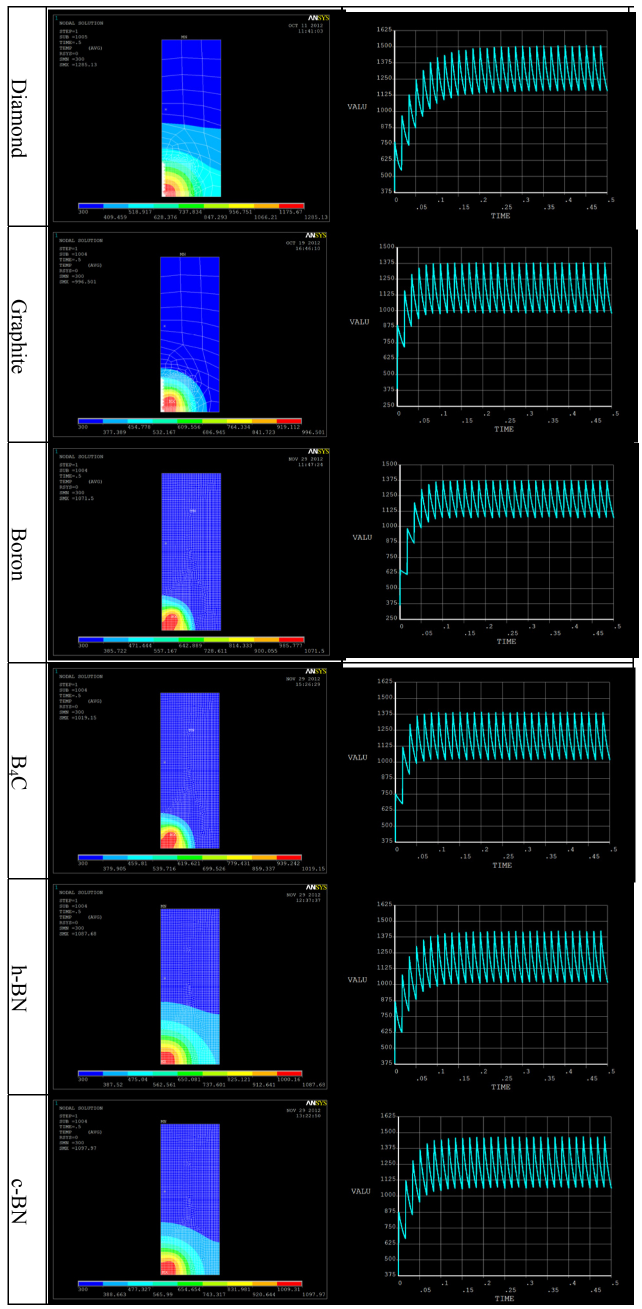

Figure 2: Temperature distribution 0.5ms after irradiation of beam (left) and change of temperature toward time (right).

ISBN 978-3-95450-122-9

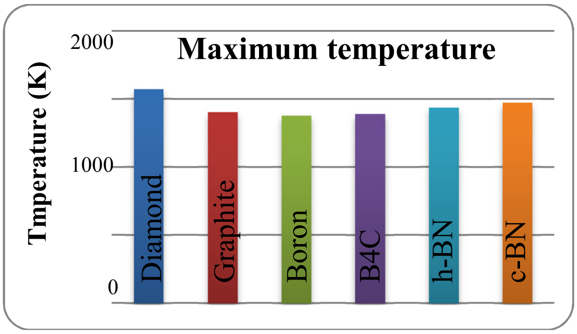

Figure 3: Comparison of the maximum temperature.

We assumed that the foil was a sheet, restricted the top end at normal temperature (300K), and early temperature of atmosphere at normal temperature (300K). Also we modelled the heat at the surface of foil that was transferred to the outside in radiation.

RESULT

Figure 2 shows the temperature distribution 0.5 ms after irradiation of beam and the change of temperature over time, and Fig. 3 shows the result of plotting the maximum temperature. As a result, diamond foil's temperature at 1572K, which was the highest, and boron at 1377K, which was the lowest, the difference between them was 200K. This shows that the material whose specific heat is higher can suppress the temperature of heat generation. Namely, when we use materials whose specific heat and radiation rate are larger, we can suppress the temperature due to heat generation. On the contrary, we find that thermal conductivity doesn't affect the temperature much.

A thin foil that is used for charge exchange cools little by thermal conductivity, but instead radiates most of the heat. Therefore the amount of heat generation using DC beam in steady state analysis is shown by the formula

$$q = \varepsilon\sigma A(T_1^{\ 4} - T_2^{\ 4}),$$

(q: energy deposition, ε: emissivity, σ: Stefan–Boltzmann constant, A: area of beam, T_1: foil temperature, T_2: temperature of scattering chamber)

As this formula shows, the specific heat of materials is not involved with the maximum temperature. In unsteady state analysis such as heat generation by a pulsed beam, however, it is clear by the result above that the specific heat greatly affects the temperature of due to heat generation. The reason of this is considered that the rising rate in temperature per unit of time has an effect on it. Namely, when the foil is heated by pulsed beam, the heat generation ends before the foil reaches its maximum temperature, and since it is cooled by radiation, material whose rising rate in temperature per a unit of time is low — whose specific heat is high— can suppress the temperature due to heat generation.

Figure 4 shows the result of the temperature simulation for one pulse, which was calculated as to only specific heat value transferred into boron's physical property based on the condition of diamond and graphite. As it shows, if the specific heat is high, the amount of temperature increase is small, and also the change of temperature is small when the beam pulse is on or off. Stress damage of foil is small if change of temperature is little when pulse is on or off, therefore we can expect that foil is unlikely to be broken. As a result, we can hopefully expect that using material as stripping foil whose specific heat is high not only lowers temperature of heat generation, but also lessens stress damage.

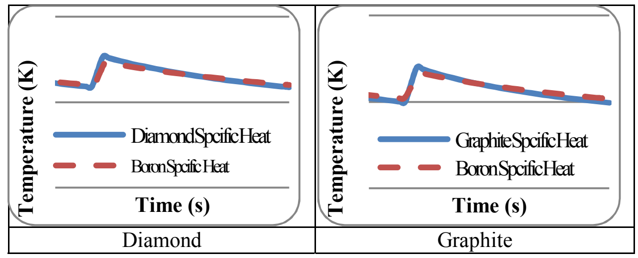

Figure 4: Temperature inclination per a pulse.

CONCLUSION

As a result of the examination and comparison among high-melting temperature materials, we found that the specific heat capacity and the radiation of material had a big influence on the maximum temperature. The boron was the most effective one among the pure materials. However, the foil-forming of the boron foil is quite difficult and also the handling of such material isn't as easy as the other materials. In addition, because there are many unknown matters regarding the heat physical property value (probably, the heat conductivity of the foil is quite low, because foil is made by evaporation), it is difficult for us to judge categorically which material is the best. However, based on the experience of foil foil-forming in the past, B_4C foil can be thought of as the best one because its foil-forming is easier and the generation of heat is also lower. However, we still don't know what will happen in the case of the beam irradiation. So, we need to investigate to find the best foil by doing the beam irradiation test with which we can observe the exothermic temperature and the process of the damaging.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number 25400306.

REFERENCES

[1] I. Sugai, Y. Takeda, et. al., "Development of thick hybrid-type carbon stripper foils with high durability at 1800 K for RCS of J-PARC," Nucl. Instrum. Meth. Phys. Res. A vol. 561, pp. 16–23, February 2006.
[2] Y. Takeda, M. Kinsho, et. al., "Exchange and observation system for charge stripper foils at the J-PARC 3GeV-RCS," Nucl. Instrum. Meth. Phys. Res. A vol. 590, pp. 213–220, March 2008.
[3] M.A. Plum, J. Holmes, et .al. "SNS stripper foil development program" Nucl. Instrum. Meth. Phys. Res. A vol. 590, pp. 43–46, March 2008.