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Helium retention properties of plasma facing materials

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Abstract

In a fusion reactor, the continuous removal of helium from the core plasma is needed in order to sustain the ignition condition. For this purpose, it has been proposed to place helium selective pumping metals, which can trap more helium than hydrogen, in the vicinity of the divertor. In this study, the helium and hydrogen trapping properties of nickel, tungsten, molybdenum, SS 304 and Inconel 625 were examined. Namely, the dependencies of irradiation temperature on the amount of trapped helium and hydrogen were obtained by thermal desorption spectroscopy (TDS), after helium or hydrogen plasma irradiation. In those metals, nickel showed the most suitable selective pumping capability. Nickel had the helium selective pumping property above 100°C. The maximum amount of trapped helium was $(2-3)\times 10^{16}$ He/cm^2 at an irradiation temperature of 200°C and 600°C. The optimum temperature becomes about 600°C when nickel is used for a selective pumping material.

Keywords: Wall particle retention; High Z wall material

1. Introduction

In a fusion reactor, high energy helium produced by D–T reactions heats D–T fuel particles and maintains the burning state. But, too much helium ash level in the core plasma makes it difficult to sustain the ignition condition due to helium ash causes fuel dilution and enhancement of radiation loss. If the helium ash level is high, the energy confinement time has to be lengthened to compensate for the reduction of α-heating power. In the design of the International Thermonuclear Experimental Reactor (ITER) [1], the size of the plasma has to be increased significantly when the helium concentration increases from 10 to 20%. So, the reduction of helium ash concentration is very important. Although helium ash is pumped by the divertor or the limiter, additional pumping of helium is required when the pumping efficiency of helium by the divertor is not enough. As one of the additional pumping methods, the use of metals such as nickel, which may be able to trap more helium than hydrogen, has been suggested [2–4]. If such selective pumping material is placed near the divertor or limiter, the helium recycling flow into the core plasma is suppressed and the helium concentration can be largely reduced [4]. If this material is not used in the vicinity of the limiter but the divertor, it has been suggested that this method becomes more effective [5]. For the selective pumping material, nickel, vanadium and so on have been proposed [2,3]. For nickel, vanadium and aluminum, fluence and energy dependencies for retained helium were examined in the fluence range from 10^{15} to 10^{21} He/cm^2, and in the energy range below a few keV [3,6–8]. In addition, in the limiter of TEXTOR, nickel was used and the effect of reduction of helium concentration was confirmed [9–11]. For nickel and tungsten, irradiation temperature dependency for trapped helium has been examined [8,12]. But, for other divertor or first wall materials, irradiation temperature dependency for the amount of trapped helium, and the selective pumping property have not been

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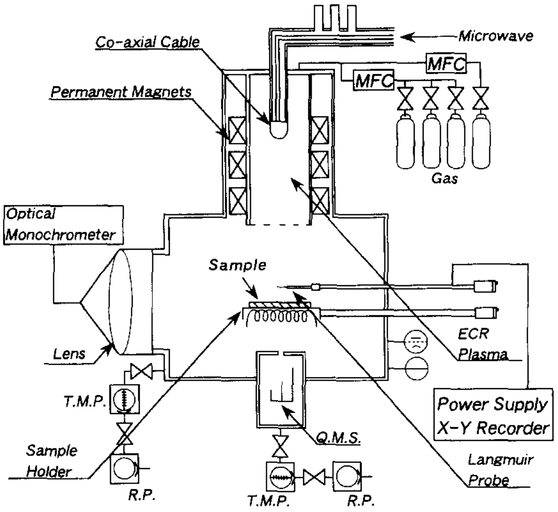

Fig. 1. ECR plasma irradiation apparatus.

investigated. So, in this study, in order to obtain these data, helium or hydrogen plasma irradiation was carried out for nickel, tungsten, molybdenum, SS 304 and Inconel 625, and the pumping properties were examined.

2. Experiments

2.1. Samples

Polycrystalline plates of nickel (purity: 99.9%), tungsten (purity: 99.95%), molybdenum (purity: 99.95%), SS 304 and Inconel 625 were used. The samples were polished mechanically and cleaned in an ultrasonic bath with ethanol.

2.2. Plasma irradiation

Fig. 1 shows the schematic diagram of the ECR plasma irradiation apparatus [8,12] used for the plasma irradiations. There are two chambers, the ECR plasma chamber and the irradiation chamber. In this apparatus, the plasma state was monitored both by an electrostatic probe and optical emission spectroscopy. Helium or hydrogen plasma was produced in the ECR plasma chamber. In the irradiation chamber, the sample was placed on the sample holder. Before plasma irradiation, the sample was degassed at 800°C for 2 h. After this treatment, helium plasma or hydrogen plasma was irradiated to the sample which was negatively biased at -1 kV. The discharge pressure was 5 Pa. The helium or hydrogen ion fluence was $\sim 4.5 \times 10^{18}/\text{cm}^2$. The samples were irradiated by changing the irradiation temperature of the sample from RT to 700°C.

2.3. Desorption of trapped helium

After the plasma irradiation, the sample was moved to the thermal desorption spectroscopy (TDS) apparatus [8,12–14] for measurement of the trapped amount of helium or hydrogen. Fig. 2 shows the schematic diagram of the TDS apparatus which was used in this experiment. The sample was directly spotwelded on the end of thermocouples directly. Typical pressure before the TDS measurement was about 1×10^{-6} Pa. The sample was linearly heated from RT to 1000°C and kept at 1000°C for 30 min. The heating rate was 10°C/min. During the heating, the

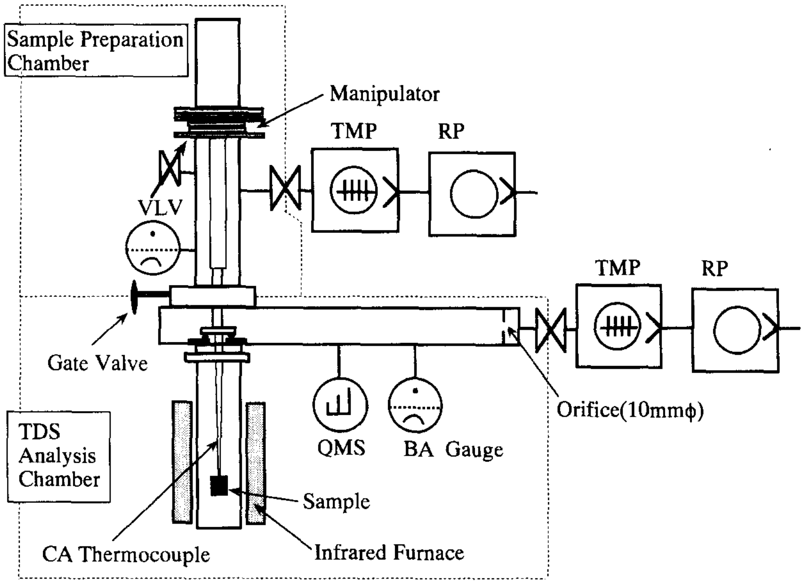

Fig. 2. Thermal desorption spectroscopy (TDS) apparatus.

amount of desorbed helium or hydrogen was measured by a quadrupole mass spectrometer (QMS).

3. Results and discussion

Fig. 3 shows the amount of trapped helium in nickel after helium plasma irradiation and the amount of trapped hydrogen in nickel after hydrogen plasma irradiation when the irradiation temperature was changed from RT to 700°C. Hydrogen trapping was not observed when the irradiation temperature was higher than 100°C. In the case of helium, there were two peaks, 200°C and 600°C, at the irradiation temperature. The amount of trapped helium was $(2-3) \times 10^{16}$ He/cm^2 at these temperatures. It is presumed from our previous experiments [12] that at 600°C the trapped helium may diffuse into the bulk. And if the temperature is higher than this temperature, self-diffusion of the bulk shall take place [15]. So, the occurrence of this peak may result from helium diffusion into the bulk and the disappearance of helium trapping sites by nickel self-diffusion [16]. The present data showed that nickel had the selective pumping capability for helium when the temperature was higher than 100°C.

Fig. 4 shows the irradiation temperature dependences of the trapped helium and hydrogen in tungsten. For tungsten, the amount of trapped helium did not exceed that of trapped hydrogen in the range from RT to 700°C. The amount of trapped helium was almost the same value, 1×10^{16} He/cm^2, in the temperature range from RT to 700°C. From these results, it was seen that the tungsten did not have the selective pumping capability, although a considerable amount of helium (1×10^{16} He/cm^2) was trapped.

Fig. 5 shows the irradiation temperature dependences for the amounts of trapped helium and hydrogen in molybdenum. For molybdenum, the hydrogen was not trapped at more than 300°C. The amount of trapped helium in molybdenum was about half that of nickel. From these results, it was found that molybdenum trapped the helium selectively at a temperature range higher than 300°C.

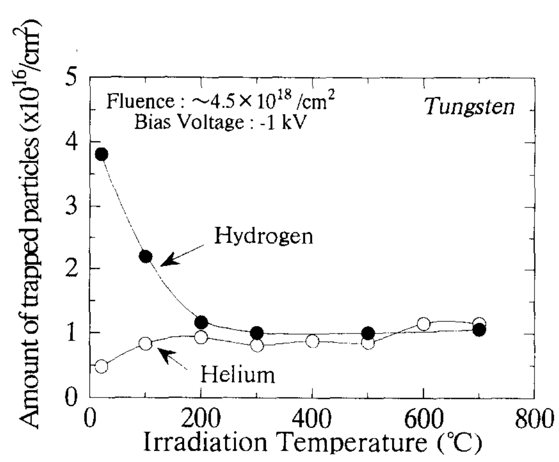

Fig. 4. Total amount of trapped helium or hydrogen in tungsten as a function of irradiation temperature, after helium or hydrogen plasma irradiation.

Fig. 6 shows the irradiation temperature dependences of the trapped helium and hydrogen in SS 304. For SS 304, the hydrogen was not trapped at above 300°C. For the case of helium, the trapped amount was almost constant from RT to 300°C, but there was a peak at the temperature of 500°C. SS 304 had roughly the same tendency with nickel, with respect to the existence of the absorption peak. From Fig. 6, it was observed that SS 304 could pump helium selectively above 300°C.

Fig. 7 shows the irradiation temperature dependences for the amounts of trapped helium and hydrogen in Inconel

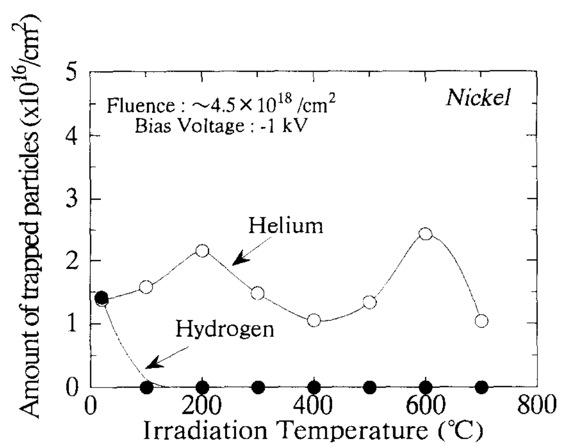

Fig. 3. Total amount of trapped helium or hydrogen in nickel as a function of irradiation temperature, after helium or hydrogen plasma irradiation.

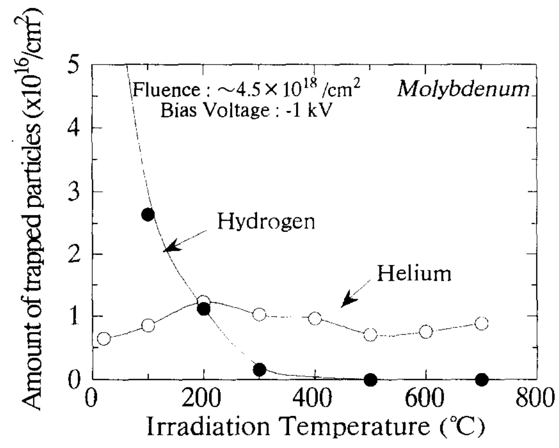

Fig. 5. Total amount of trapped helium or hydrogen in molybdenum as a function of irradiation temperature, after helium or hydrogen plasma irradiation.

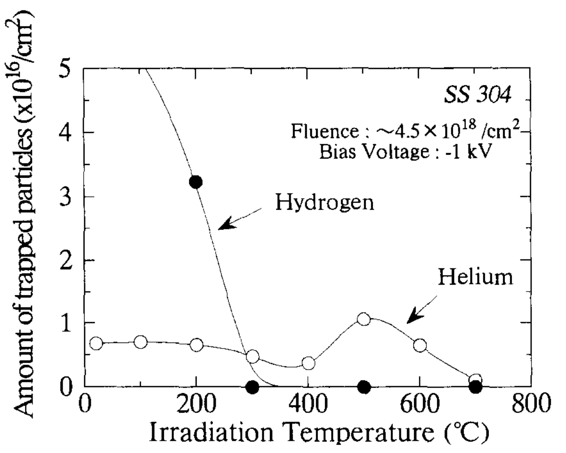

Fig. 6. Total amount of trapped helium or hydrogen in SS 304 as a function of irradiation temperature, after helium or hydrogen plasma irradiation.

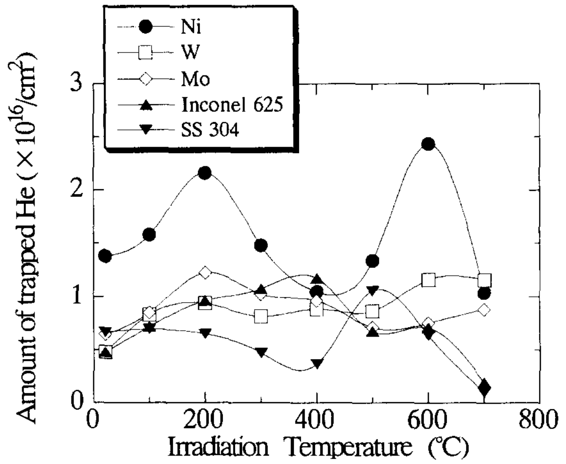

Fig. 8. Amounts of trapped helium for nickel, tungsten, molybdenum, SS 304 and Inconel 625 versus irradiation temperature.

625. For Inconel 625, the hydrogen was not trapped above 100°C. On the other hand, the maximum amount of trapped helium was about 1.2×10^{16} He/cm^2 at 400°C. Inconel 625 showed the selective pumping capability for helium above 100°C, similar to the case of nickel.

In Fig. 8, the amounts of trapped helium among nickel, tungsten, molybdenum, SS 304 and Inconel 625 are compared. In these metals and alloys, the amount of trapped helium in nickel, SS 304 and Inconel 625 largely depended on the irradiation temperature. However, in the cases of tungsten and molybdenum, obvious dependency of the irradiation temperature for the trapping amounts was not observed. The melting points of nickel, SS 304 and Inconel 625 are approximately 1400°C and those of tungsten and molybdenum are above 2600°C. These difference of melting points may be one reason for the different dependencies of trapping on irradiation temperature. Nickel showed the largest amount of trapped helium. The maximum amount of trapped helium was $(2\text{–}3) \times 10^{16}$ He/cm^2 both at 200°C and 600°C.

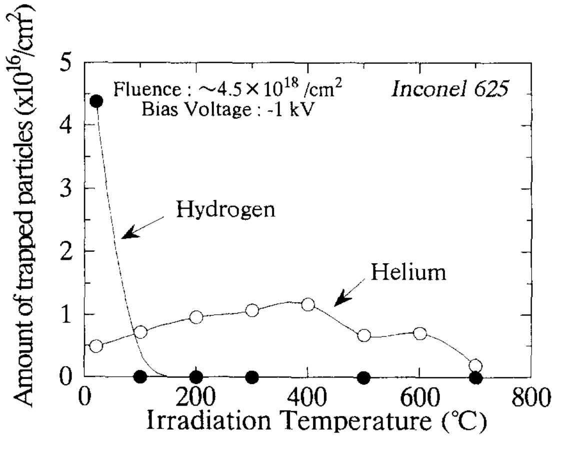

Fig. 7. Total amount of trapped helium or hydrogen in Inconel 625 as a function of irradiation temperature, after helium or hydrogen plasma irradiation.

As a helium selective pumping material, nickel seems to be suitable because of the large amount of trapped helium and the selective pumping property of helium above 100°C. Based on the above results, we can consider using nickel as a helium pumping material. According to the condition of ITER, the temperature of the wall in the vicinity of divertor may be around 300°C if the gas target divertor scheme is used [17]. So, if nickel is used in such a place at 600°C, it is possible to pump helium most efficiently. At such a temperature, the nickel can pump the helium up to $(2\text{–}3) \times 10^{16}$ He/cm^2 if the helium ion energy is about 1 keV. Since the trapping amount of nickel saturates, the refreshment of the surface such by evaporation of nickel is required. If the saturation amount is $(2\text{–}3) \times 10^{16}$ He/cm^2, the periodic refreshment is needed every several 10 s [4].

In the present experiment, the energy of helium ion was as high as 1 keV. In the case of ITER, the energy of helium may be much lower than 1 keV. Thus, the saturation amount of nickel becomes much lower than the value obtained in the present experiment, because of the low range of helium in nickel. In order to pump such a low energy helium, the continuous evaporation of nickel is required. In the present experiment, the trapping ratio of nickel for helium was approximately 0.5 He/Ni. The net throughput of helium in ITER is estimated at 2 Pa m^3/s. For example, in order to trap 10% of the net throughput, the evaporation rate required becomes approximately 10 mg/s.

4. Summary

In this study, nickel, tungsten, molybdenum, SS 304 and Inconel 625 were irradiated by helium plasma or hydrogen plasma with the various irradiation temperatures in the range from RT to 700°C. The trapping amount of helium and hydrogen were measured by TDS. From these results, the irradiation temperature dependency for trapped helium or hydrogen, selective pumping property were examined. The obtained results are summarized in the following.

1. Among nickel, tungsten, molybdenum, SS 304 and Inconel 625, nickel showed the highest helium selective pumping capability. Two peaks of the helium amount for the irradiation temperature appeared at 200°C and 600°C. At those temperatures, the amount of trapped helium was (2–3) × 10^{16} He/cm^2.
2. The amount of trapped helium in tungsten, molybdenum, SS 304 and Inconel 625 was 1/2–1/3 times of that in nickel.
3. Both nickel and Inconel 625 had the helium selective pumping capability above 100°C. Molybdenum and SS 304 showed the helium selective pumping capability above 300°C. However, tungsten did not have such capability in the temperature range from RT to 700°C.
4. For the case in which nickel is used as a helium pumping material, a suitable temperature may be around 600°C. If the helium energy is about 1 keV, the amount of trapped helium becomes (2–3) × 10^{16} He/cm^2.

Acknowledgements

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