

Enhancement of Arc Ignition on Tungsten in Helium Plasmas with Impurity Gases^{*)}

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Arcing was ignited on deformed tungsten (W) surfaces, where W fuzz and/or nano-tendrils bundles (NTBs) were grown, by steady state helium (He) plasma exposures with impurity gas seeding. At the same sample potential of -250 V, the presence of NTBs enhanced the frequency of arc ignition, whereas no arc ignition appeared on typical fuzz surfaces without NTBs. After a series of arc ignitions on a sample surface with NTBs, the aspect ratio of NTBs decreased, indicating that protruded NTBs with larger aspect ratio tend to trigger arcing easily.

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1. Introduction

Tungsten (W) has been chosen as a material of the ITER divertor due to its high thermal and mechanical properties. The fuzzy nanostructure, also called *fuzz*, is formed on W under helium (He) plasma exposure [1]. The high porosity of fuzz decreases the sputtering rate of W [2] and the secondary electron emission [3], which are favorable properties for plasma facing materials (PFCs). However, fuzz is also known to be brittle and fragile under transient heat loads [4]. Moreover, the formation of fuzz increases the occurrence of unipolar arcing [5], which erodes the PFCs and degrades the performance of fusion devices. Previous studies reported that the sheath potential needs to be lower than -50 V for arc ignition on fuzzy W with a transient heat load [6], while the arcing hardly occurs on fuzzy W by the steady He plasmas exposure without the transient heat load even when the sheath potential is higher than -300 V [7].

Seeding of impurity gases like neon (Ne), argon (Ar) and nitrogen (N_2) are considered to be used in the divertor region of ITER to decrease the heat load impacting divertor plates [8]. Isolated bundle-like nanostructures called *nano-tendrils bundles* (NTBs) are found to form when a W surface is exposed to He plasmas in addition to the impurity seeding raised above [9]. This implies that there is a possibility of NTBs formation on the ITER divertor. The field electron emission measurements from NTBs showed that the NTBs can be a trigger of arc ignition with greater possibility compared to fuzz [10], whereas detailed conditions for arc ignition on such NTBs surfaces have not been investigated.

In this paper, several W samples with NTBs on their surfaces are prepared to demonstrate if arcing is more easily triggered when NTBs are formed on W surfaces. By changing the sample potential and impurity gases such as Ne and Ar, the conditions for arc ignition are investigated in detail. In addition, the effects of impurity gas types and NTBs shapes to the arc ignition property are discussed.

2. Experiment Setup

Experiments were conducted in the linear magnetized divertor simulator NAGDIS-II. A schematic of experiments is shown in Fig. 1. A steady state plasma was produced at the magnetic field strength of 0.1 T. The electron density, n_e , and the electron temperature, T_e were $\sim 10^{18} \text{ m}^{-3}$ and ~ 3 eV, respectively. He gas was injected from upstream at a constant flow rate of 200 sccm, while the secondary gas was injected from downstream at a constant flow rate of 30 sccm. In this experiment, He, Ne and Ar were used as secondary gases. When Ne or Ar was used, the total gas pressures before/after the secondary gas injection were separately measured by capacitance manometers, giving the partial pressure of impurity gas to be $\sim 18 \pm 2\%$.

A W sample ($10 \times 10 \times 0.2 \text{ mm}^3$) was installed at the radial boundary of the He plasma column and its axial position was 1.4 m away from the plasma source. The surface normal was perpendicular to the magnetic field line. A negative bias was introduced to the sample and adjusted in the range of $-100 \sim -250$ V by a power supply (Matsusada, HAR-1R1200-LJIS). Note that the plasma potential at the boundary of plasma column is ~ -3 V [11], and the sheath potential is determined by the difference between the bias and plasma potential.

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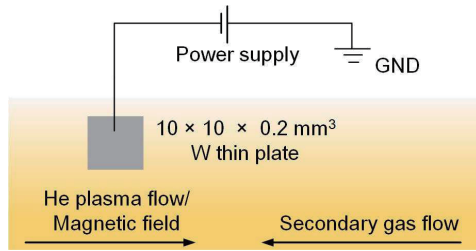


Fig. 1 Schematic of the experiment.

The sample was heated by the ion bombardment, and the surface temperature was determined from the balance between ion impact heating and radiation cooling. The surface temperature was measured by an infrared pyrometer at the wavelength of $1.6 \mu\text{m}$ at the beginning of the He plasma exposure and was approximately $1500 \pm 50 \text{ K}$, except for one sample which was exposed with a temperature of 1300 K because of relatively low incident ion energy (100 eV).

During the plasma exposure, the sample potential and the current to the sample were monitored by an oscilloscope (Yokogawa, DL850E) with a sampling rate of 10 kHz . When an arc occurred, a sudden large spike of the potential and current appeared due to the electron emission. The power supply changed from constant voltage (C.V.) mode to constant current (C.C.) mode after the arcing initiated. In this study, the period when the sample potential became greater than -100 V was defined as arc ignition period. After the exposure, a scanning electron microscopy (SEM) was performed to observe the surface morphology and the damage recorded on the surface due to the arcing. A confocal laser scanning microscopy (CLSM) was used to obtain the three-dimensional surface profile of the samples.

3. Results and Discussion

3.1 Arc ignition on NTBs-abundant surfaces

Figure 2 shows SEM micrographs of a sample exposed to a He plasma with Ne impurity seeding at the bias voltage of -250 V . In Fig. 2 (a), NTBs appear to be distributed broadly and randomly on the surface. The formation mechanism of NTBs has yet to be understood fully, but the sputtering and re-deposition of W atoms are thought to be related [12]. In Fig. 2 (b), an eroded arc trail can be seen, starting from an NTB. This trail implies that an arc was ignited from the NTB.

According to the previous research [7], arcing hardly ignited on fuzzy W without an aid of transients when the bias was higher than -300 V . However, in this study, the arcing easily occurred on W even without transient heat loads. It is considered that this easiness of arc ignition is related to the formation of NTBs.

In [9], it was reported that, under the same incident ion energy condition of 150 eV , NTBs seemed favorable

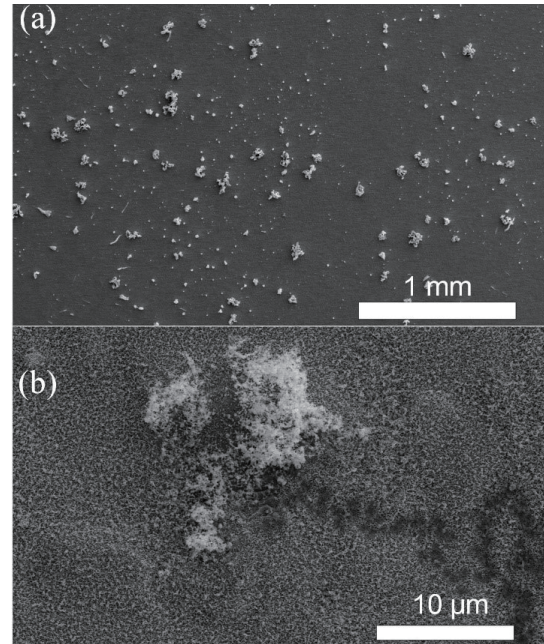


Fig. 2 (a) SEM micrograph of W sample surface, in which white dots represent the NTBs. (b) Magnified view of (a) showing a typical arc trail near an NTB.

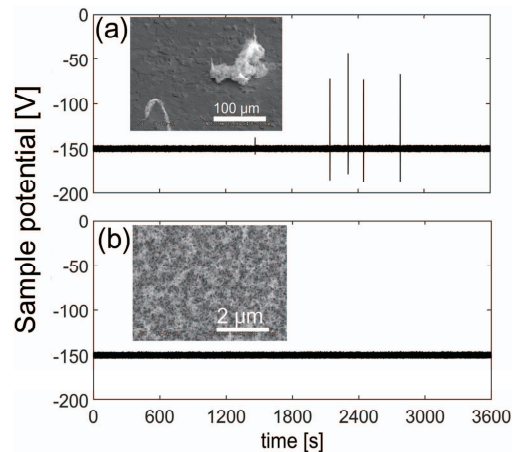


Fig. 3 The temporal evolutions of the sample potential during the exposure to He plasmas with (a) Ar and (b) Ne seeding at -150 V . The insets present SEM micrographs of each surface, presenting (a) NTBs and (b) fuzz on the surfaces.

to grow with Ar seeding, but not with Ne seeding. To confirm whether the arc ignition without the transients is attributed to the NTBs formation, two W samples were exposed to He plasmas at the same bias of -150 V . One of the samples experienced Ne seeding, and the other Ar seeding. Figures 3 (a) and (b) show the temporal evolutions of the potentials of the samples with Ar and Ne seeding, respectively. The insets represent SEM images of each sample surface. In Fig. 3 (a), arcing started occurring at $\sim 2000 \text{ s}$ and ignited four times during one hour of plasma exposure

with Ar seeding, whereas no arcing was triggered with Ne seeding, as seen in Fig. 3 (b). From the surface observations, NTBs were found on the Ar-seeded surface, while only a uniform fuzz was observed when the surface was treated with Ne impurity seeding. This result clearly indicates that the NTBs can trigger arcing even without a transient heat load. In addition, the arcing started occurring at ~ 2000 s after the beginning of plasmas exposure. From the previous study [12], it is thought that certain time (ion fluence) is required for NTBs to grow. The ion fluence was not enough for the NTBs formation at the initial phase, thus arc ignition did not appear before ~ 2000 s.

3.2 Frequency of arc occurrence at various conditions

Figure 4 shows the frequency of arcing, f_{arc} , defined as the number of arc occurrence per an hour as a function of the bias voltage for different plasma conditions. When samples were exposed to a pure He plasma without any pre-treatment, f_{arc} was always 0 at the bias voltage range of -150 to -250 V. When Ne was seeded, arcs were not detected at -150 V, but triggered at -200 V and f_{arc} became greater as the bias voltage deepened to -250 V. It is thought that the field emission from the tip of NTBs was enhanced, hence increased chance in transit to breakdown [10]. When Ar was seeded, the arcing occurred at -150 V, likely due to the presence of NTBs on this condition.

To investigate the dependence of arc occurrence on the shape of NTBs, two samples were exposed to the same He-Ne mixed plasma for 60 min at the same bias voltage of -250 V to generate identical NTBs on their surfaces. $100\ \Omega$ resistor was installed between the power supply and the sample to prevent arcing and preserve NTBs formation during the exposures. After that, the resistor was removed and one sample was exposed to a pure He plasma at the bias of -250 V, while the other at -100 V to trigger arcing.

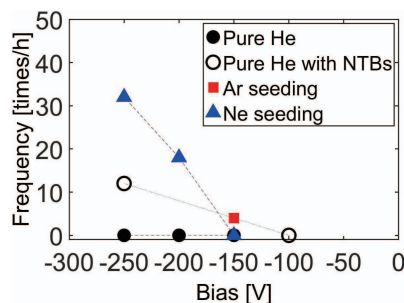


Fig. 4 The frequency of arcing as a function of the sample bias voltage during an hour of plasma exposures for various conditions. The circle, square, and triangle markers represent pure He, Ar seeding, and Ne seeding cases, respectively. The open markers show the sample was pre-treated with NTBs before the plasma exposures for arcing.

Before and after a series of arc ignitions, the surfaces were observed by SEM and CLSM to compare the morphology changes induced by arcing.

As depicted with black open circles in Fig. 4, the arcing was triggered on a sample at the bias of -250 V with the pure He plasma. Note that no arcs occurred at the same bias of -250 V when the initial surface is bulk with no NTB (closed circles in Fig. 4). Considering that no NTB formation is anticipated on a surface with a pure He plasma exposure, this also suggests that NTBs, which have already grown on the surface, trigger arcing with ease. It is known that the onset of field electron emission on NTBs is on the order of ~ 1 kV/mm depending on their shapes [10], which is much lower than that on fuzzy surface (~ 7 kV/mm) [13]. It implies that the breakdown could be initiated by the onset of field electron emission from the tip of NTBs and lead to arcing.

On the other hand, there were no arcs at the bias of -100 V, indicating that the sheath potential threshold for arc ignition exists under -100 V. The sheath electric field would be 1.18 kV/mm at the bias of -250 V and 0.94 kV/mm at -100 V at the given plasma parameters ($n_e = \sim 10^{18} \text{ m}^{-3}$, $T_e = \sim 3 \text{ eV}$) [14]. It could be thought that the less field emission and thermionic emission due to lower sheath electric field and surface temperature (1300 K) prevented the arc ignition at the bias of -100 V.

3.3 NTBs morphology changes after arcing

When the already-grown NTBs with He-Ne plasma exposure were exposed to successive pure He plasma exposure at the bias of -250 V, as shown with black open circles in Fig. 4, not only arcs but also surface morphological changes occurred. Figure 5 shows the SEM micrographs of the sample surface viewed from 45° . Figure 5 (a) shows SEM micrographs of the sample surface after the He-Ne pre-exposure to generate NTBs on it. NTBs appear to be distributed in a random manner. With a closer view in Fig. 5 (b), it is seen that each NTB has different size and aspect ratio. These NTBs' shape altered after the successive pure He plasma exposure. Figures 5 (c) and 5 (d) show the same surfaces after the successive pure He plasma exposure with Figs. 5 (a) and 5 (b), respectively. First, it is obvious that the number of NTBs decreased. This is likely due to the ignition of arcing exploding on sharp-shaped NTBs, for example, one in the mid-right in Fig. 5 (b). In addition, remaining NTBs showed morphology changes and tended to become short and round.

To evaluate the morphology changes of NTBs in detail, the aspect ratio distribution of the NTBs were investigated using CLSM. The aspect ratio was defined as $2\pi h/l$, where the h and l are the height and perimeter of NTB, respectively [12]. Figure 6 (a) shows the distribution of the aspect ratio of the NTBs on the surface after the He-Ne plasma exposure (1st irradiation), and after the successive pure He plasma exposure (2nd irradiation). Before the 2nd

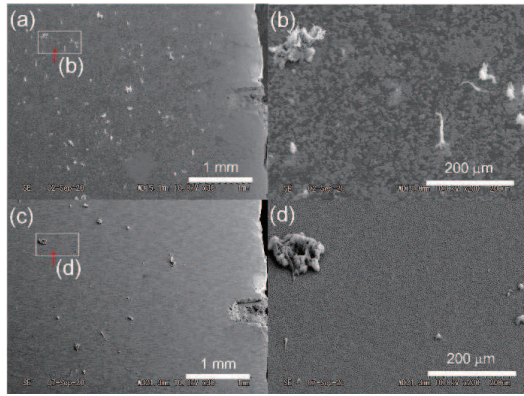


Fig. 5 (a) SEM micrograph of a sample surface exposed to a He-Ne mixed plasma and (b) a magnified view of the same surface marked in (a). (c) The same surface with (a) after the exposure to a pure He plasma and (d) a magnified view of the same surface with (b).

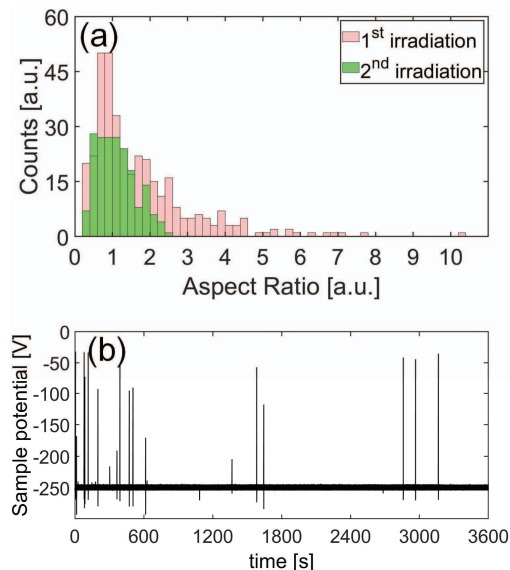


Fig. 6 (a) The distributions of the number of NTBs as a function of the aspect ratio of NTBs. Pink represents NTBs formed after the first irradiation of the He-Ne plasma with the arc preventing resistor. Green represents NTBs remained after the second irradiation of the pure He plasma without the resistor. (b) The temporal evolution of the sample potential during the second irradiation at the bias of -250 V.

irradiation, the aspect ratio of NTBs ranged 0 - 10, and the peak of the distribution appeared at ~ 1 . The total number of NTBs was 364. These are regarded as the already-grown NTBs, as mentioned above.

After the 2nd irradiation, the range of aspect ratio distribution was narrowed to 0 - 3, and the total number of NTBs decreased to almost a half, 191. It is notable that the NTBs with high aspect ratio were preferentially disappeared. These disappearances would result from the explosion of NTBs by arcing, as was discussed above. On

the other hand, the number of NTBs at the aspect ratio of $\sim 1 - 2$ decreased, and a slight increase was identified at the aspect ratio of ~ 0.5 . This indicates that some portion of remaining NTBs were deformed during the 2nd irradiation. This was probably induced by annealing, sputtering and/or re-deposition, all of which could contribute to the changes of the aspect ratio without arc occurrence.

Figure 6 (b) shows the temporal evolution of the sample potential during the 2nd irradiation. The arcing occurred 8 times during initial 600 s, then only occurred 4 times during following 3000 s. The frequency of arcing obviously decreasing. It is probable that the relatively sharp NTBs were preferentially eroded by arcing at the initial phase of exposure, and the other NTBs remained and were gradually deformed. This indicates that more protruded NTBs with larger aspect ratio tend to trigger arcing more easily.

4. Conclusion

The arcing was found to be easily occurred when a W surface was exposed to an impurity mixed He plasma, in which NTBs were developed on the surface. The occurrence of arc ignition was strongly dependent on the existence of NTBs, indicating that the NTB structure could be a trigger of arc ignition on W owing to its lower onset field electron emission. The sheath potential threshold for arc ignition was found to be below -100 V on the NTB surfaces. The number of NTBs decreased after arcing due to the explosion of NTBs, and the aspect ratio of remaining NTBs decreased. The frequency of arcing appeared to decrease with decreasing the aspect ratio, suggesting that the NTBs with larger aspect ratio tend to trigger arcing more easily. Since the presence of NTBs can greatly enhance the erosion of PFCs by arcing, the possibility of NTBs formation on the ITER divertor as well as the evaluation of eroded amount by arcing with NTBs should be carefully investigated to clarify the potential effect of NTBs to the ITER divertor.

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