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Investigation of the high temperature erosion of nickel under 5 keV neon irradiation

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Abstract

The erosion behaviour of Ni has been investigated in the temperature range up to 1500 K under 5 keV Ne ion irradiation at a flux density of $\approx 1.5 \times 10^{19}$ Ne/m^{2}s. The amount and velocity distribution of thermally or ion released Ni-atoms (mass 58) has been determined by means of time of flight analysis in a differentially pumped line of sight mass spectrometer. It was found that the amount of physically sputtered atoms was constant within the experimental accuracy in the investigated temperature range. Also, no noticeable enhancement of thermally emitted particles exceeding the normal evaporation fluxes could be detected in this temperature range within the accuracy of the measurement. The accuracy amounts to about 5% of the thermally evaporated atom flux, determined mainly by the temperature stability of the target with and without ion irradiation.

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1. Introduction

The majority of the plasma facing components in ITER and in particular future fusion devices will be made out of metals, in ITER from Be (700 m^2 first wall) and tungsten in the divertor region (about 100 m^2) and most probably from tungsten or other high Z materials in a Demo fusion reactor. Erosion of these plasma facing components will occur by physical sputtering due to particle impact and possibly by evaporation and melt layer loss in transient power loads during disruptions or large ELMS. Erosion in transient events due to evaporation and melt layer loss are the most serious concerns for the use of metals in fusion devices, calling for a strict control of the ELM power loss and in particular of disruptions.

Very recently, an enhanced physical erosion rate was observed for beryllium at elevated temperatures exposed to high particle fluxes at low impact energies by a deuterium plasma [1]. The Be erosion rate in a certain temperature range exceeds significantly (≈10 times) the sum of physical sputtering and normal thermal sublimation. This effect appears similar in some features to the Radiation-Enhanced-Sublimation (RES) of graphite at high temperatures [2–5] both in the temperature behaviour but also from the fact that in both cases the particles are released with a thermal energy distribution instead of a fast distribution characteristic of physical sputtering. The authors of [1] proposed a universal mechanism

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attributing this additional temperature dependent erosion to the sublimation of radiation-activated ad atoms which occurs in form of thermally released atoms, somewhat similar to the RES model which is based on the production and thermally activated diffusion of radiation produced Frenkel pairs (interstitials and vacancies) in graphite. Such a mechanism could have serious consequences for the erosion of metals in fusion devices at high target temperatures. Besides this, these phenomena are also of basic interest for the understanding of surface and solid state physics under energetic particle bombardment. In this contribution this effect has been analysed under ion beam conditions under the impact of 5 keV Ne on Nickel at flux densities of about 1.6×10^{19} Ne/m^{2}s. These conditions are very similar to those for Radiation-Enhanced-Sublimation of graphite (RES) that has been discovered 1982 in two independent ion beam facilities [2,3]. Interestingly, under the high flux and low energy conditions at the edge of TEXTOR plasmas, a negligible or very small contribution of RES has been found, compared with the ion beam conditions under which RES-erosion enhances the carbon release by about a factor of ten before normal thermal sublimation dominate at higher temperatures [6]. Within the present RES model, this behaviour has been explained by a flux dependent decrease of the yield, due the simultaneous increase of the density of the recombination sites (vacancies) that are produced simultaneously with the moving interstitials, while physical sputtering remains constant with increasing particle fluxes. The results in this paper show, however, that an RES-like effect does not exist for Ni under the present, low flux ion irradiation conditions. If an enhancement of the erosion of Ni with temperature exists, as indicated from PISCES [1] and other [7] results, this effect must increase in relation to physical sputtering with increasing flux and decreasing impact energy, opposite to the behaviour of RES.

2. Experimental

The scheme of the experimental set-up is shown in Fig. 1. Details of how to determine the energy distribution of sputtered and thermally released particles by time-of-flight (TOF) are described in previous papers [8]. Metals stripes ($3\,\text{mm} \times 0.05 \times 50\,\text{mm}$) of Ni were bombarded by 5 keV Ne ions with a flux density of about 1.6×10^{19} Ne/m^{2}s under an angle of 15° with respect to the normal. All the emitted particles (ion induced or thermally evaporated) were periodically chopped by a motor driven disc with a trapezoidal transmission pulse (FWHM 19 μs). The chopped particle are directly detected after a flight path lengths of 15 cm by a differentially pumped line-of-sight quadrupole mass spectrometer under an angle of 45° with respect to the direction of the ion beam. Neutral emitted particles are ionized and extracted from the ionizing regions with a bias voltage. The signals were collected in a multichannel counting device (2 μs channel width) which directly records the TOF spectra. To determine the energy of particles by TOF with QMS technique, some uncertainties can occur [9], mainly due to the influence of extracting the ions from the ionising region of the QMS and the transmission of the ionised particles in the QMS on the TOF. In fact, a relatively high ion energy of 60 eV was used. But for a better mass resolution the ions were decelerated to 20 eV in the mass analyser. However, in this experiment the TOF spectra were only used to distinguish between thermally released and physically

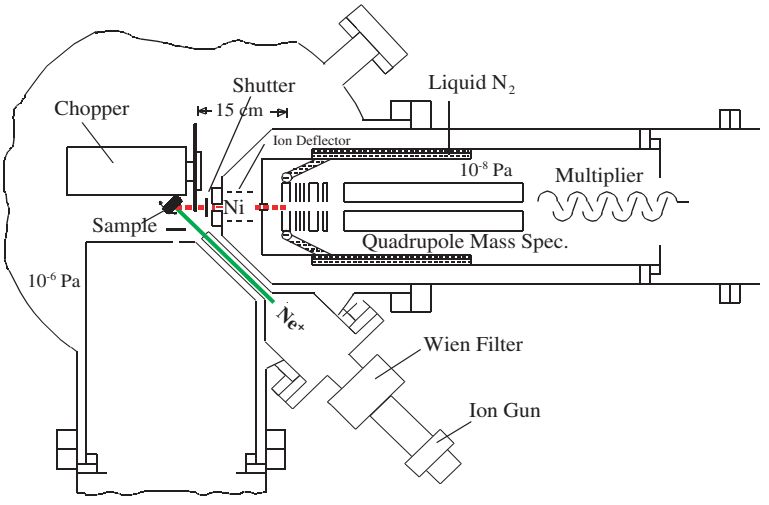

Fig. 1. Schematic view of the experimental set-up.

sputtered Ni atoms. There was no intention to make an exact determination of the velocity distribution of the sputtered Ni atoms. The zero intensity line of the TOF spectra was obtained by averaging the noise at large TOFs. The Ni targets were mechanically clamped in a water cooled holder and heated by direct current. Temperatures were determined by an optical pyrometer assuming an emission probability of 0.19 for Ni. The power deposited by the ion beam on the target represents about 0.3% of the ohmic heating power at a temperature of about 1300 K and cause thus a temperature increase of about 2 K. The Ni temperature was not feedback stabilized in these experiments and measurements were done therefore sometimes under conditions were the temperature of the target drifted in the course of the measurements in a range of typically 10 K. To minimize this, some measurements have been done under conditions where a given temperature was used for long times to bring the system in equilibrium. However, the overall accuracy of the absolute temperature is estimated to be not better than about ±30 K (due to uncertainties in the emission coefficient) but the relative stability of the temperature between different measurements is better, estimated to about ±5 K.

3. Results

Fig. 2 shows a typical time of flight spectrum of ^{58}Ni ions obtained by heating a Ni target to 1355 K with and without Ne ion impact and at 300 K with Ne-irradiation. The full triangles show the thermally evaporated Ni species (ion beam off) at the isotope mass 58 and the solid curve shows calculated TOFs based for a Maxwell–Boltzmann velocity distribution of evaporated ^{58}Ni at the given target temperature of 1355 K. The absolute amount of the evaporated flux of Ni atoms, N, at the target temperature can be calculated by $N = \alpha \times 4.75 \times 10^{24}(MT)^{-0.5} \times P$ with α the sticking probability of Ni on Ni, assumed to be 1, M the mass (here for the Ni isotope of 58), T the temperature in K and P the vapour pressure in Pascal, which amounts to 1.8×10^{18} ^{58}Ni/m^2 sec at 1355 K [10]. This corresponds to an absolute Ni flux of 1.1×10^{13}/s using the effective area seen by the QMS of about 6 mm^2 and considering only the Ni-isotope at mass 58. The open triangles show the detected signal with the Ne-ion beam on. At low TOF, centred at around 35 μs, sputtered Ni atoms appear now with a maximum peak height similar to that of the evaporated atoms. The solid line represents a TOF spectrum calculated by a Thompson energy distribution, $f(E) \sim E/(U + E)^3$ with U the surface binding energy of Ni. With the measured absolute ion beam flux of 3×10^{13} Ne/s and a sputter yield of 1.7, as taken from sputter data [11], the total amount of sputtered ^{58}Ni amounts to 3.4×10^{13} Ni/s. It can be shown (more details in [8,12] that the ratio of the fluxes of sputtered and evaporated particles can be determined comparing the maximum peak height of the TOF spectra for sputtered and evaporated species, using $F_{\text{sputter}}/F_{\text{Maxwell}} = 1.83\ \text{Max}_{\text{sputter}}/\text{Max}_{\text{Maxwell}}$, with $F_{\text{sputter}}/F_{\text{Maxwell}}$ the fluxes of sputtered and evaporated atoms and $\text{Max}_{\text{sputter}}/\text{Max}_{\text{Maxwell.}}$ the peak heights of the corresponding TOF spectra. Thus, comparing the peak heights of the sputtered and thermally released particles and using the Ni-sputter flux as a calibration, an evaporated Ni-flux of 1.85×10^{13} Ni/s results compared with a value of 1.1×10^{13}/s calculated based on the measured temperature. The QMS signals are thus in reasonable agreement taking into account the uncertainties in determining the absolute target temperature and the sensitivity of the evaporated fluxes on the temperature. The figures shows also that the sputter flux does not differ noticeable between 300 K and 1400 K irradiation temperature.

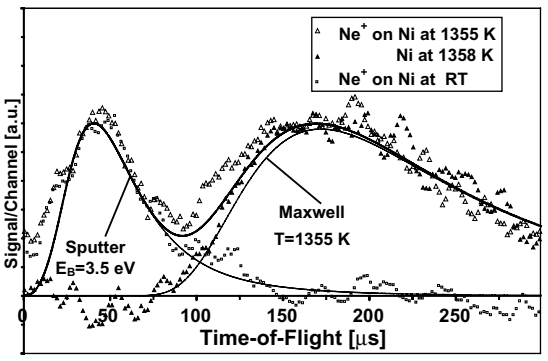

Fig. 2. Typical TOF spectra of Ni at 1355 K with and without Ne bombardment of 5 keV Ne ions and at 300 K with ion beam on. Also shown are the calculated TOF spectra from a Maxwell–Boltzmann distribution according to the irradiation temperature and a velocity distribution according to the Thompson formula using a binding energy of 3.5 eV.

Fig. 3 shows similar spectra for three different Ni target temperatures, always with the ion beam on and off. For large TOF corresponding to thermally emitted particles, the spectra with and without ion beam on show no noticeable enhanced emission of thermally released Ni atoms with the ion beam on. Note that the temperature of the target with and without Ne beam in the figure differs slightly which is the main cause of the small differences in the TOF spectra with and without Ne-irradiation. Even under the best stabilized temperature conditions, a systematic slight increase of the detected Ni signal has been observed with compared to without the ion beam for all the measuring conditions. This is partly attributed to a slight increase of the temperature due to the ion beam on, which is about 2 K which has not been compensated in the present set-up. A temperature rise of 2 K at 1300 K corresponds to an increase of

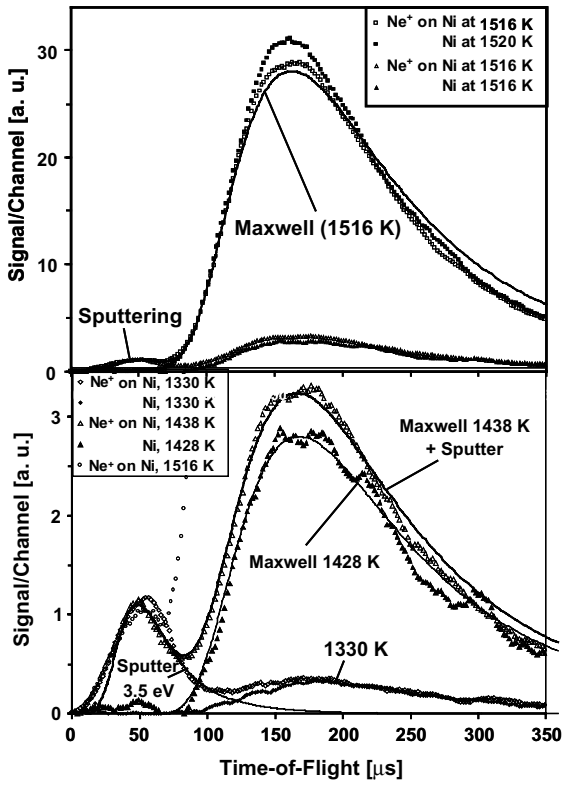

Fig. 3. TOF spectra from Ni at three different target temperatures with and without Ne irradiation. Also shown are the calculated Maxwell velocity distributions (solid lines).

the evaporated Ni flux of about 6%. In general, we estimate for the accuracy of the present measuring system that a possible increase of the Ni flux at 1400 K of about 5% due to the Ne-ion bombardment can not be ruled out. Fig. 4 shows a summary of all the data for the different temperatures in comparison with the expected fluxes from thermal sublimation, confirming again that, under these conditions, no noticeable enhancement of the released Ni flux due to the Ne bombardment occurs.

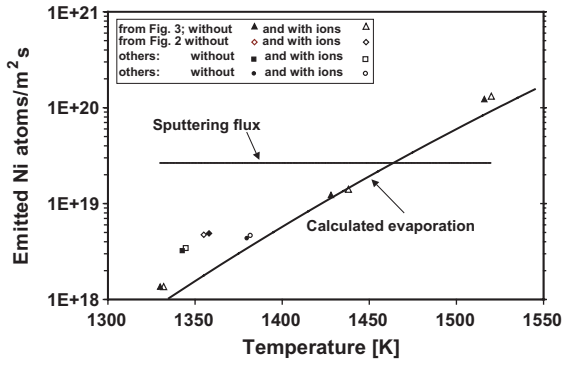

Fig. 4. Comparison of the measured Ni release at high temperatures with (open symbols) and without (full symbols) Ne irradiation and with the theoretically expected Ni evaporation taken from the literature [10].

4. Discussion

For comparison, Fig. 5 shows the temperature dependence of the RES flux of graphite under 5 keV Ar bombardment. At 2000 K, the carbon release is exclusively attributed (about 99% of the released C-atoms) to the Radiation-Enhanced Sublimation of graphite (RES) and disappears consequently with the ion beam off. In case of Ni, an enhancement of the released Ni flux due to the Ne bombardment is absent over all the temperature range investigated, or below the resolution of the measuring system, which is estimated to about 5% of the thermal evaporation flux. We have thus to conclude that a graphite-like RES mechanism does not exist for Ni under these ion flux and energy conditions. In the RES model, the RES flux is explained by those interstitials produced in the near surface region which survives recombination with vacancies and diffuse to the surface where they evaporate. The effective depth from which the interstitials can reach the surface is determined by the mean free path and in the order of 10–15 nm at 1800 K for Ar-ion beam irradiation of graphite. The RES flux increases with temperature since the recombination rate decreases due to the increasing mobility of the defects and the flux yield decreases with increasing ion flux density [13] (with $\theta^{-0.25}$ with θ the ion flux density), since recombination becomes more probable at higher defect densities. A detailed spectroscopic study of the carbon release from TEXTOR limiters at high temperatures under the TEXTOR edge plasma conditions (ion impact energy typically 200–300 eV and flux densities up to several $10^{23}/m^2s$) [6] showed only a

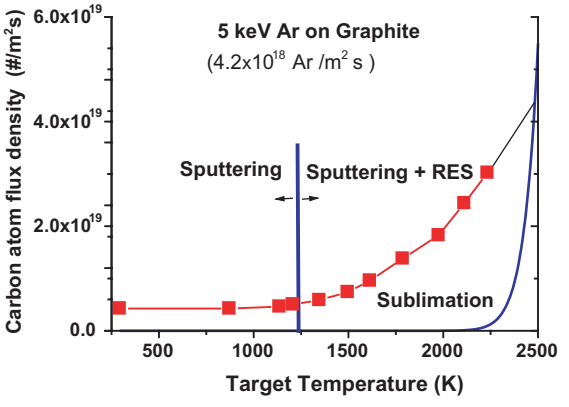

Fig. 5. Carbon release under 5 keV Ar bombardment as function of the surface temperature. Also shown is the calculated carbon sublimation rate (for C atoms only).

minor contribution of carbon release which could be attributed to the RES effect. The majority (>80%) of C release seen by spectroscopy at the RES important temperatures (1600–2400 K) could be explained by physical sputtering and normal sublimation, while the possible contribution from RES was estimated below about 15% of the sputter flux.

For Ni, no equivalent RES-like behavior could be found in this work. However, the production of interstitials and vacancies occurs in Ni very similar to graphite from which part will arrive at the near surface (similar than on internal surfaces, responsible e.g. for the growth of irradiation induced voids), but obviously a similar evaporation of the Ni- interstitials from the surface does not appear. However, in [1], a significant enhancement of the Be-release with increasing temperature has been reported under high flux and low energy conditions. The authors claim a universal mechanism, the 'adatom' model, for all materials causing this enhanced ion-induced evaporation. It is based on subthreshold energy transfer by collisions to surface atoms such that they are transformed to 'adatoms' which then can either recombine at surface sites or thermally desorb. The increase with temperature is due to increasing desorption while the recombination sites remain constant. Production of such adatoms will also occur (in parallel to physical sputtering) significantly in the present experiment, since the collisional energy transfer in the top surface layer by 5 keV Ne^+ in Ni is significant. In the overall, the adatom process, must be much weaker compared to physical sputtering and RES such that this effect becomes measurable (in comparison to normal sublimation) only at high flux densities and only near the threshold impact energies for physical sputtering.

5. Summary and conclusions

No enhancement of the release of Ni-atoms exceeding physical sputtering and normal thermal sublimation under 5 keV neon bombardment of Ni could be found in the temperature range up to 1400 K within the accuracy of the measurements. This is estimated to about 5% of the thermal sublimation flux, measured without ion irradiation on. The Ne-ion flux density was 1.6×10^{19} Ne/m^2s. This shows that the mechanism responsible for the Radiation-Enhanced Sublimation of graphite (RES), which has been observed under very similar irradiation conditions is not effective for Ni. This is thought to be due to stronger binding of interstitials arriving at the Ni-surface compared with graphite. A significant enhancement of thermally released Ni at high temperatures under conditions of higher fluxes and lower impact energies, as reported from other experiments, would include that this effect significantly increases in relation relative to normal sputtering under these conditions.

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