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Determination of the temperature dependence of tungsten erosion

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ABSTRACT

We present the results of erosion measurements on actively cooled tungsten samples at quasi-constant surface temperature conditions performed in the high heat flux facility GLADIS. The samples were exposed to a H beam at a central power density of 10 MW/m^2 up to a fluence of 10^{26} m^{-2}. We observe a weak temperature dependence of the erosion yield. The data are compared with similar data obtained from loading with a H beam with He admixture. Both datasets are analysed in a probabilistic approach. We obtain activation energies of 0.04 eV and 0.06 eV for the cases with and without He, respectively.

1. Introduction

Tungsten is considered to be the most viable armour material for the plasma-facing components of a fusion reactor, especially for divertor components [1–3]. The most important reason for this is the long lifetime of tungsten under erosion by physical sputtering, which is due to its high atomic mass and high surface binding energy. In the literature it is usually assumed that physical sputtering is a process, which is insensitive to the target temperature, see e.g. [4]. Temperature dependent erosion yields of liquid and solid metals have, however, been reported in the past, e.g. [5–7], and also very recently [8]. As the sputtering process is based on binary collisional energy transfer there should not be any principal difference between solids and liquids in this respect.

The behaviour of tungsten materials under a variety of heat and particle loads has been investigated in various devices, e.g. [9–13]. In the special case of He impingement on tungsten it is well known that this leads to the formation of complex surface morphologies (see the review [14] and also [15]).

Using our high heat flux facility GLADIS [16] we investigate actively water-cooled tungsten samples under high heat flux loading with H/He mixed neutral beams at quasi-stationary surface temperatures. We have recently devised a method to measure erosion in the μm range on such samples [17] and a thorough data analysis revealed an Arrhenius-like temperature dependence in the case of loading with a H beam with a 6 atomic percent He admixture [18]. A temperature dependent erosion behaviour was reported recently in the case of bombarding tungsten with a He plasma [9], which would in principle be in line with our findings cited above. The results even indicated erosion below the sputtering threshold energy. However, high temperature tungsten erosion measurements in the TEXTOR edge plasma were well explicable by a combination of temperature independent physical sputtering by carbon impurities and thermal sublimation [19]. No further enhancement of atomic tungsten release was observed up to 3600 K. Therefore one might speculate that the presence of He and/or its influence on the morphology formation has an influence on the reported temperature dependences in [9,18]. For this reason we have employed our erosion measurement method to investigate the case of loading with a pure hydrogen beam.

In this contribution we present a comparison of the new experimental results on loading with pure H with the published results on loading with a H/6% He mixture. We present a thorough data analysis based on maximum-likelihood considerations (see e.g. [20]) with error estimates. Finally we extend our maximum likelihood considerations to compute the full probability distribution for the activation energy of the temperature dependent erosion data.

2. Experiment and results

The experiments were performed on actively water cooled samples under quasi-stationary surface temperature conditions in the high heat flux test facility GLADIS, which is described in [16]. Commercially available tungsten from Plansee SE with a purity of 99.97% was employed to manufacture the samples. The surfaces were mechanically polished. The design of the employed mockup as well as the sample preparation and analysis was identical to the procedures described in detail in [17]: For the erosion measurements markers are engraved into the side of the samples by focussed ion beam milling. The distance of these markers to the beam-exposed surface of the respective sample is measured by electron microscopy before and after exposure. The difference of these two distance measurements gives the amount of eroded material. This procedure results typically in a precision of

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100 nm to 1 μm, depending on the amount of erosion. During the erosion process additionally a roughening of the surfaces occurs. This is mainly caused by the grain orientation dependence of physical sputtering and increases with fluence. Since our erosion measurement is local this effect introduces an additional uncertainty. This is taken into account by measuring the surface topography using confocal scanning laser microscopy. The mean square deviations from the average height level are then used as additional error for the individual erosion data points. For most data points this is the dominating contribution to our error estimate.

The surface temperatures of the samples ranged from 600 °C to 2000 °C. The samples were exposed to a neutral hydrogen beam with a Gaussian beam profile at a central power density of 10.5 MW/m^2 with individual pulses lasting 30 s each. The local flux varies between 3.7 and 4.1×10^{21} H/m^2s. The acceleration voltage was 29 kV resulting in an average particle energy of 16 keV per atom, see e.g. [17].

Samples were removed after total fluences of 1×10^{25} H/m^2 and 1×10^{26} H/m^2, respectively. Depending on the individual position of the respective sample the above fluences have to be scaled with 0.98 for 600 °C, 1.03 for 1000 °C and 1500 °C and 1.08 for 2000 °C.

The results of the erosion measurements are given in Fig. 1 together with the total error estimate. The low temperature data are consistent with published physical sputtering yields [21].

Fig. 2 shows a comparison of cross-sections prepared by focussed ion beam (FIB) from samples loaded at a surface temperature of 2000 °C with pure H (top) and H/6% He (bottom), respectively. The figure clearly shows that the pronounced morphology formation, which is observed in the presence of He, is absent in the case of irradiation with pure H. The presence of He in the GLADIS beam causes a complex three-dimensional surface structure (see [17,18]), which yields a strong contribution to the surface roughness contributing to the uncertainty mentioned above. In addition the bottom sample shows a bubble-rich layer extending nearly half a micron below the surface. There are bubbles visible in the subsurface cross-section in the hydrogen case as well, however on a comparably sporadic level.

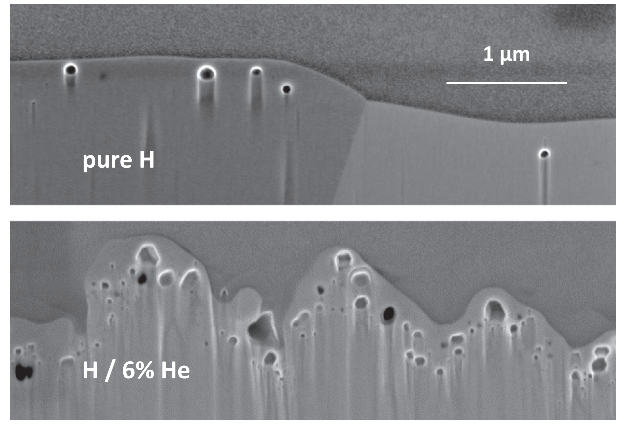

Fig. 2. FIB cross sections from samples loaded at a surface temperature of 2000 °C with a fluence of approximately 1×10^{26} m^{-2} with a pure H beam (top) and H with 6% He (bottom, see [18]). The vertical structures below the pores are due to sample preparation (curtaining effect).

3. Data analysis and discussion

3.1. Erosion yields

As already pointed out in [18] a careful choice of the analysis method is required in an analysis based on very few data points the quality of which is unknown. If a measurement yields a large number of data points, outliers are easily identified and can be treated e.g. by median filtering. Our situation, however, is the opposite.

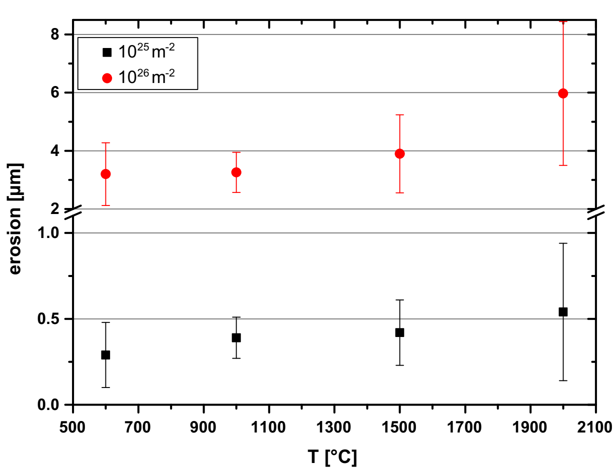

Fig. 1. Experimental results of erosion with pure H for the four different temperatures and the two different fluence steps. The exact fluence values are given in the text. The error bars are total errors including also the surface roughening (see text).

Since the usual least squares analysis scheme is rather sensitive to outlier data points because of their large contribution, we chose a "robust estimation" method: We minimize the sum of the absolute deviations instead of the squares to determine the model parameter which maximises the likelihood of our data. The concept of robust estimation is described in [20].

The model we want to use to describe our data is:

$$Y = \boldsymbol{a} \cdot X \tag{1}$$

Here X is the fluence, Y the amount of erosion and $\boldsymbol{a}$ represents the erosion yield. To find the maximum likelihood erosion yield $\boldsymbol{a}$ we determine

$$\min_{\boldsymbol{a}} \sum_i \frac{|Y_i - \boldsymbol{a} \cdot X_i|}{\sigma_i} \tag{2}$$

Here Y_i are the individual erosion values at fluences X_i and σ_i are the corresponding error estimates. This procedure yields a value of the erosion yield for each of the investigated sample surface temperatures. This kind of analysis was performed for the present case of loading with a pure H beam. In [18] the same kind of analysis was described for the case of loading with a H beam containing 6% of He admixture. Fig. 3 shows the erosion yields determined for both cases as a function of the sample surface temperature. The error bars in the figure are set such that they correspond to the usual 1σ standard deviation error of Gaussian statistics, i.e. they cover a 68% probability interval.

In Fig. 3 it can be seen that both data sets show a trend for the erosion yield to increase with temperature. The trend, however, barely exceeds the error margins. So the question arises whether or how definitely the data really represent the presence of a temperature dependent mechanism in the erosion process. In the case of a thermally activated process with a Boltzmann-like temperature dependence the traditional way is to analyse the data by performing a linear fit in an Arrhenius representation as shown in [18]. Here we want to proceed instead with a probabilistic approach, which is presented in the next section.

3.2. Activation energy

The procedure described above yields maximum likelihood values for the erosion yield at each temperature. An extension of the