Visco-elastic model of the “fuzz” growth (P64B)

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Abstract
The visco-elastic model of fuzz growth is presented. Model describes main features of fuzz observed in experiments and gives the estimates of important data close to experimental ones.

I. Introduction
Plasma-wall interactions (which include many different aspects including plasma transport, wall erosion and surface modification, formation of bubbles and blisters, dust formation, hydrogen retention, etc.) are the key issues for fusion reactors like ITER (e.g. see Ref. 1 and the references therein). Unfortunately we still do not understand many important phenomena associated with plasma-wall interactions. For example, recent experiments on the irradiation of Tungsten with helium-hydrogen plasma have shown the formation of “fuzz” [2] (see Fig. 1) on the front surface of the sample. The fibers of the “fuzz” are filled with nano-bubbles, which, presumably, contain helium at a very high pressure. The “fuzz” growth was observed for the energies of impinging ions above ~20 eV and sample temperatures in the range from T~1000 to T~2000 K [3]. In case of rather long exposure of the sample, the thickness of “fuzz” in linear devices, L_f, can easily reach ~ ten microns (e.g. see Ref. 4). The rate of “fuzz” growth depends on the temperature of the sample as well as on the rate of helium ion flux. However, at relatively large helium fluxes the rate of “fuzz” growth saturates and the thickness of the “fuzz” increases as a square root of the time of the irradiation

$L_f(t) \propto \sqrt{t}$ [4]. This square root time dependence of the "fuzz" growth was interpreted in Ref. 3 as if the process of the "fuzz" formation "is dominated by diffusion", so that $L_f(t) = \sqrt{D(T)t}$, where $D(T)$ is the effective diffusion coefficient. Assuming Arrhenius-like temperature dependence, $D(T) = \overline{D}\exp(-E_D/T)$, the fitting of experimental data gives $E_D = 0.71\,eV$ and $\overline{D} = 10^{-8} cm^2/s$ [4].

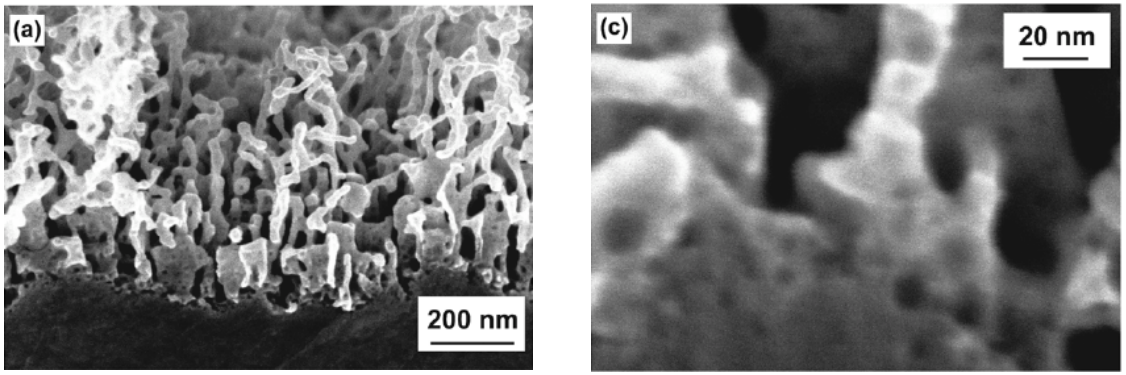

Fig. 1. Cross-sectional micrograph of the nanofibers (taken from Ref. 2)

In Ref. 5 it was found that nano-scale structures could also grow on the grain boundaries 100 μm deep into the sample. The heat treatment of "fuzz" in vacuum was studied in [5] by ramping up the temperature from T~300 K to 1450 K and 1900 K in 45 min. The outcome of these experiments was practically complete extinction of nano-structures with, however, no measurable Tungsten mass loss (although, heat treatment of "fuzz" at 900 K did not cause the change of "fuzzy" nano-structures). The main peaks or helium release was observed at the temperatures in the vicinity of 1000 K and 1500 K. The TDS analysis of helium release from tungsten samples irradiated by He ions with different energies gives similar peak temperatures [6], which are also consistent with the data published by Kornelsen and Gorkum [7].

In spite of a large interest to the physics of the “fuzz” from fusion material community and potential importance of “fuzz” related issues for reactor (e.g. an impact of “fuzz” on optical reflectivity and heat conductivity of invessel components, modification of surface morphology, dust generation, etc. [8-10]) so far there is no even qualitative explanation of the most important effects related to “fuzz” growth process. In what follows we present the physics based model, which in ballpark describes main features of “fuzz” dynamics. The main component of our model [11] is the visco-elastic properties of tungsten, which, we advocate, it acquires under the combination of a strong helium irradiation and elevated temperature.

II. Model of “fuzz” growth

It is well known that the irradiation of many metals with ions of different gases results in the formation of clusters/bubbles, which can trap the majority of implanted gas atoms. The trapping energy, E_{tr}, can be very substantial and for the case of tungsten irradiation by helium ions E_{tr} can reach 3-5 eV depending on the size of the cluster/bubble (e.g. see Ref. 7).

Due to high rate of helium self-trapping in tungsten He clusters/bubbles are formed within the implantation depth (e.g. see Ref. 12 and the references therein). For the case where He ion energy is ~100 eV and the bubble formation depth is $\sim 100\,\mathrm{nm}$ [12]. Due to asymmetry in material stress caused by proximity of the surface, bubbles with the radius ~tens of nanometers will experience large force pushing them toward the boundary. As a result dynamic process of cluster seeding, transport, growth and coalescence some size spectrum of clusters/bubbles will be formed. We notice that the formation of bubbles depends somewhat on the orientation of the crystal and the method of fabrication [13] but in our consideration we will disregard these effects.

The evolution of He clusters/bubbles as well as the morphology of the interface depends on the temperature of the sample, which can strongly affect the visco-elastic properties of irradiated tungsten. We notice that the material mechanics usually considers two major groups of the creep

theories [14]: a) models related to the grain boundary phenomena (e.g. Nabarro-Herring and Coble models) and b) more relevant for our case, the mechanisms of the creep related to the lattice effects and which do not depend on grain size (e.g. “dislocation creep”, “dislocation glide” models). Even though these models (except “dislocation glide” model) predict very strong Arrhenius-like increase of the creep with temperature (activation energy ~ 6 eV [14]), within the temperature range of interest 1000-2000 K an impact of the creep, according to these models, “fuzz” related phenomena should be negligible. However all existing creep models assume that the dislocations, which finally cause the creep, appear in material only due to applied stress. Meanwhile in our case very large stresses and related dislocations always present in tungsten due to the presence of helium clusters/bubbles caused by irradiation (e.g. see Ref. 15 and the reference therein). Moreover, one can easily imagine that there is a hierarchy of the scale-length of the stresses related to different sizes of clusters/bubbles. Therefore, it is plausible that the creep in a strongly irradiated material is much larger than standard models [14] predict.

Being focused more on creep then on elastic deformation we will use a simple model describing relatively large spatial scale material flow under impact of the stress:

$$\frac{\partial \sigma_{ij}}{\partial x_j} = \mu(T) \frac{\partial}{\partial x_j} \left\{ \frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \nabla \cdot \vec{V} \right\}, \qquad (1)$$

where σ_{ij} is the stress tensor, $\vec{V}$ is the material velocity, $\mu(T) = \bar{\mu} \exp(E_\mu / T)$ is the effective viscosity, $\bar{\mu}$ is the normalization constant, and E_μ is the activation energy.

At low temperature effective viscosity is very large and there is, practically, no large-scale material flow. Experimental data from Ref. 16 on irradiation of tungsten by hydrogen-helium plasma (fluence $\sim 5 \times 10^{21} \mathrm{cm}^{-2}$, temperatures 573 K and 775 K, the energy of impinging ions ~100 eV) show formation at the interface of the foam-like structure of the thickness ~ 10-50 nm, which contain ~ 1nm radius clusters.

At relatively high temperature the effective viscosity becomes low enough so that the creep starts to be important. In this case bubbles will be able to move from the bulk close to the surface to reduce their potential energy. However, due to flux of helium ions, newly seeded bubble starts to grow on the tope of old one (see Fig. 2a) causing additional stress and, correspondingly, the flow of tungsten resulting in the formation of nano-fiber (see Fig. 2b).

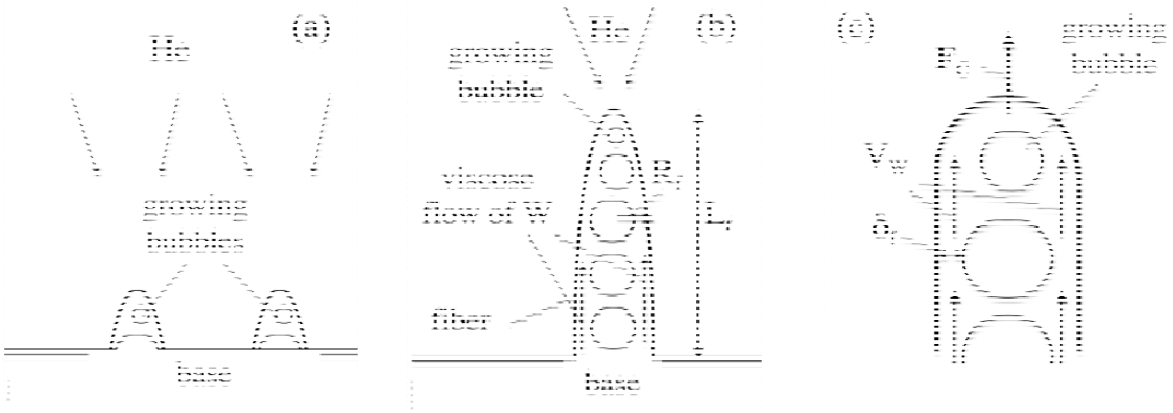

Fig. 2. Schematic views of: (a) initial stage of the fiber growth; (b) developed fiber; (c) viscose flow of W to the tip of the fiber due to the force caused by the pressure of the He in the growing fiber.

In general case the fiber growth depends on both helium and tungsten supplies to the newly growing bubble. However, it is obvious that in practice the slower process determines the fiber growth rate. Since experiments shows that for the fixed helium flux, the growthrate of the fiber decreases with time (recall $L_f(t) \propto \sqrt{t}$ [4]) it indicates that the tungsten supply limits the growth. In what follows we will assume that this is the case and corresponding estimates for applicability of such assumption will be made below.

Then, we can estimate the rate of the fiber growth by considering force balance at the very tip of the fiber (see Fig. 2c) and then find the flow velocity of the tungsten in the fiber's "skin" by using equation (1). From Fig. 2c one easily sees that the force on the cap of fiber, F_C, can be estimated as

$$F_C = P_{He}\pi R_f^2, \qquad (2)$$

where P_{He} is the helium pressure in the bubble of radius R_f, which we will assume to be large the thickness of the fiber "skin", δ_f. Helium pressure in the growing bubble can be estimated as

$$P_{He} \sim 2\gamma / R_f, \qquad (3)$$

where γ is the tungsten surface tension coefficient.

As a result, the magnitude of the stress in the "skin" can be evaluated as

$$\sigma_0 \sim \frac{F_C}{2\pi R_f \delta_f} \sim \frac{2\gamma}{2\delta_f} \ . \qquad (4)$$

Then substituting expression (4) in Eq. (1) we have

$$\frac{\partial \sigma_{ll}}{\partial l} \sim \frac{\sigma_0}{L_f} = \mu_W \frac{V_W}{\delta_f^2}, \qquad (5)$$

where L_f is the length of the fiber and V_W is the flow velocity of tungsten (see Fig. 2c). Then taking into account that $dL_f/dt = V_W$ from Eq. (5) we find:

$$L_f(t) = \sqrt{\frac{2\gamma\delta_f}{\mu_W} t} \ . \qquad (6)$$

As we see from Eq. (6), similar to experimental results [4], our model predicts $L_f(t) \propto \sqrt{t}$ growth of length of the fibers, strong temperature dependence (through $\mu_W(T)$) of fuzz growth rate. By fitting experimental data from Ref. 4 with expression (6) we find $E_\mu = 0.71\,\text{eV}$, and $\bar{\mu} \sim 10^4\ \text{Pa}\cdot\text{s}$ (following Ref. 17 we take $\gamma \sim 3\,\text{J/m}^2$, which was measured at ~2000 K).

Now we discuss at want conditions tungsten transport to the tip of the fiber can be considered as a limiting process of fuzz growth. Since fuzz is filled with helium bubbles the helium flux to the sample, Γ_{He}, should satisfy inequality

$$\Gamma_{He} \tilde{>} n_{He} \frac{dL_f}{dt} = \frac{\gamma n_{He}}{\mu_W} \frac{\delta_f}{L_f(t)}, \qquad (7)$$

where $n_{He} \sim 10^{29} m^{-3}$ is the helium particle density in the bubbles; deriving Eq. (7) we used Eq. (6). Since expression (6) is only valid for $L_f \tilde{>} R_f$, from Eq. (7) we find an estimate

$$\Gamma_{He} > \Gamma_{He}^{min} \sim \frac{\gamma n_{He}}{\mu_W(T)} \frac{\delta_f}{R_f}. \qquad (8)$$

For ~1500 K from Eq. (8) we find $\Gamma_{He}^{min} \sim 10^{22} m^{-2} s^{-1}$, which is in a reasonable agreement with experimental data [4].

So-far we ignore thermal de-trapping of helium from the bubbles. This is acceptable for relatively modest temperatures, since trapping energy is high $E_{tr} \sim 3 \div 5\,eV$. However, at higher temperatures, thermal de-trapping will cause so fast degradation of the bubbles and fiber structure located close to the base and, therefore, lucking the source of energetic helium ions, that the growth of the bubbles at the very top of the fibers will not be able to compete with it. Taking into account that the degradation rate is $\sim V_{th} \exp(-E_{tr}/T)$ ($V_{th} \sim 10^3 m/s$ is the helium atoms thermal speed) and comparing it with the growth rate (6) we find that the fuzz growth stops at temperatures

$$T \tilde{>} T_h \sim \left(E_{tr} - E_\mu\right) \Big/ \ln\left(\frac{V_{th}\bar{\mu}}{\gamma} \frac{R_f}{\delta_f}\right), \qquad (9)$$

where we assumed that $L_f \sim R_f$. For $E_{tr} \sim 4\,eV$ from Eq. (9) we find $T_h \sim 2000\,K$, which is in a good agreement with experimental data from Ref. 3.

III. Conclusions

We present theoretical model describing all main features observed in experiments. The main idea of the model can be described as follows. Newly glowing bubble (see Fig. 2) having high helium pressure inside creates an excessive force on surrounding tungsten “skin” of the fiber and forming pressure difference between base and top of the fiber. As a result, tungsten “flows” through the “skin” from the base to the top. This model predicts $t^{1/2}$ growth of length of the fibers, strong

temperature dependence of the growth rate, the saturation of the growth with ion helium flux to the substrate for $\Gamma_{He} > \Gamma_{He}^{min} \sim 10^{22} m^{-2} s^{-1}$, and the termination of fuzz growth at the temperatures $T \tilde{>} T_h \sim 2000$ K. All these features seen in experiments and experimental values of Γ_{He}^{min} and T_h are close to theoretical estimates.

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