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Mechanics of tungsten blistering II: Analytical treatment and fracture mechanical assessment

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ABSTRACT

Since a decade the blistering of pure tungsten under hydrogen implantation has been one of the major research topics in relation to the plasma–wall interaction of tungsten-armored first wall. Overall blistering may reduce the erosion lifetime of the wall. Mature blisters grown by high internal pressure are likely to burst leading to exfoliation of the surface. Therefore, the control and suppression of blistering is an important concern for sustainable operation of the tungsten-armored plasma-facing components. In this context, a quantitative assessment of the mechanical conditions for blister bulging and growth is an important concern.

In this article a theoretical framework is presented to describe the bulging deformation of tungsten blisters and to estimate the mechanical driving force of blister growth. The validity of the analytical formulations based on the theory of elastic plates is evaluated with the help of finite element analysis. Plastic strains and *J*-integral values at the blister boundary edge are assessed by means of numerical simulation. Extensive parametric studies were performed for a range of blister geometry (cap aspect ratio), gas pressure, yield stress and hardening rate. The characteristic features of the blistering mechanics are discussed and the cracking energy is quantitatively estimated for the various combinations of parameters.

1. Introductions

Blistering is an irreversible surface damage phenomenon of a solid occurring often under hydrogen or helium ion bombardment and characterized by the formation of microscopic blisters filled with high-pressure gas [1]. Since a decade the blistering of pure tungsten under hydrogen implantation has been one of the major research topics in the plasma–wall interaction community in relation to the physical compatibility of tungsten-armored first wall with fusion plasma.

Depending on the fluence of incident hydrogen and surface temperature, significant blistering may develop on the surface of tungsten [2,3]. Since the solubility of hydrogen in tungsten is extremely low, the excessive hydrogen solutes are populated beneath the surface and readily trapped at crystal defects, where the solutes precipitate as tiny gas bubbles and subsequently agglomerate together forming a blister of larger size ranging between one and hundreds of μ m [3]. Fig. 1 shows a typical blister on tungsten [1]. Blisters can accommodate a considerable amount of fuel gas thus raising the issue of tritium retention [4].

Overall blistering may reduce the erosion lifetime of the wall. Mature blisters grown by high internal pressure are likely to burst leading to exfoliation of the surface [1,5]. The loss of material by such exfoliation could be far more significant than that of physical sputtering that is very small for tungsten. Therefore, the control and suppression of blistering is an important concern for sustainable operation of plasma-facing components. In this context, quantitative assessment of the mechanical conditions for blister growth is as important as the understanding of physical mechanism. The knowledge on the impact of blister geometry, pressure and material properties on the driving force of blister growth would provide deeper insight into the blistering behavior.

In literature, there are several mechanics-based studies on the deformation and growth of a (already formed) blister. These works can be categorized into analytical [6–8] and numerical [9,10] studies. The analytical studies were mostly focused on adapting the closed elastic stress solutions of a pressurized thin plate to a blister cap on the basis of plate theories and studying blister growth which was modeled as a crack extension event in the framework of

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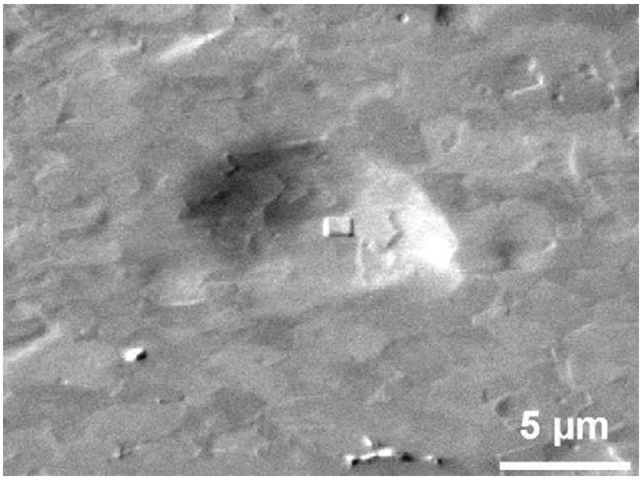

Fig. 1. Scanning electron micrograph of a typical blister on a tungsten sample irradiated by deuterium ions [1].

linear elastic fracture mechanics. The numerical studies aimed at quantitative computation of stress and strain fields of a three-dimensional blister system for various loading parameters and boundary conditions by means of finite element analysis (FEA).

In this paper, a comparative study of blister mechanics is presented, where the deformation and the growth of a tungsten blister are modeled and compared on the basis of plate theories, analytical linear elastic fracture mechanics (LEFM) and FEA-based LEFM and elasto-plastic fracture mechanics (EPFM) simulations, respectively. The validity of the analytical models is discussed with reference to the computational prediction. Emphasis is placed on rigorous and systematic evaluation of the methodologies. In addition, the results of parametric investigation are presented for a range of yield stress, size, thickness and hardening behavior of the tungsten blister.

2. Theoretical background for analytical models

2.1. Thin plate

In the analytical study of blistering mechanics, the theory of elastic thin plates is often applied (e.g. [7,8]). In this approach, a blister cap is modeled as a thin circular plate where its edge section is assumed to be fully restrained along the periphery by cantilever boundary condition. In Fig. 2, an axi-symmetric plane model of a pressurized blister is schematically illustrated. Uniform gas pressure is applied onto the lower (i.e. inner) face of the plate to produce the deformation of the cap.

The analytical solution derived by Timoshenko can be used for

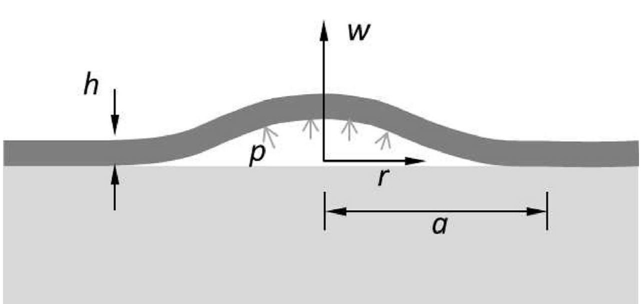

Fig. 2. A schematic drawing blister model based the assumption of thin plate. p is the gas pressure in the blister, a is the blister radius and h is the thickness of the blister cap.

pressurized thin circular plates [11]. In the following Timoshenko's thin plate theory is briefly summarized.

The plate is assumed to be thin and the vertical deflection is small compared to the thickness of the plate. When the edge is fully clamped, the slope of the vertical deflection must be zero at $r = 0$ and $r = a$. At the edge of the plate ($r = a$), the deflection is zero as well. Applying these boundary conditions, the vertical deflection, w, is given by

$$w = \frac{p}{64D}\left(a^2 - r^2\right)^2, \tag{1}$$

where $D = Eh^3/12(1-\nu^2)$ is bending stiffness, E is the Young's modulus and ν is Possion's ratio. The maximum deflection, w_{max}, at center of the plate is then,

$$w_{max} = \frac{pa^4}{64D}. \tag{2}$$

The small deflection assumption is valid, when the maximum deflection is smaller than one fifth of the thickness. From this condition following constraint is derived:

$$\frac{a}{h} < \left(\frac{64E}{12p(1-\nu^2)}\frac{1}{5}\right)^{0.25}. \tag{3}$$

The strain energy of bending, V, has the form [11].

$$\begin{aligned} V &= \frac{1}{2}\int_0^{2\pi}\int_0^{a}(M_r\kappa_r + M_t\kappa_t)\,\mathrm{r}\mathrm{d}\mathrm{r}\mathrm{d}\theta \\ &= \frac{D}{2}\int_0^{2\pi}\int_0^{a}\left[\left(\frac{\partial^2 w}{\partial r^2}\right)^2 + \frac{1}{r^2}\left(\frac{\partial w}{\partial r}\right)^2 + \frac{2\nu}{r}\frac{\partial^2 w}{\partial r^2}\frac{\partial w}{\partial r}\right]\mathrm{r}\mathrm{d}\mathrm{r}\mathrm{d}\theta \\ &= \frac{32\pi}{3}\frac{w_{max}^2}{a^2}D. \end{aligned} \tag{4}$$

where M_r and M_t are the bending moments, and κ_r and κ_t are their curvatures. Hence, the strain energy release rate, G, is given by

$$G = \frac{\mathrm{d}V}{\mathrm{d}\pi a^2} = \frac{32Dw_{max}^2}{a^4}. \tag{5}$$

If the deflection is not small enough so that the small deflection assumption is not valid any more, the membrane strains at the mid-plane needs to be considered. Taking the radial displacement into account, the strain energy due to the stretching of the mid-plane, V_1, is given by ($\nu = 0.3$)

$$V_1 = \frac{\pi E h}{1-\nu}^2 \int_0^{a}\left(\varepsilon_r^2 + \varepsilon_t^2 + 2\nu\varepsilon_r\varepsilon_t\right)\mathrm{r}\mathrm{d}\mathrm{r}. \tag{6}$$

where ε_r and ε_t are the radial and the tangential strains. ε_r and ε_t are related respectively to the radial displacement, u, and the vertical deflection, w, respectively, by

$$\varepsilon_r = \frac{\mathrm{d}u}{\mathrm{d}r} + \frac{1}{2}\left(\frac{\mathrm{d}w}{\mathrm{d}r}\right)^2, \tag{7}$$

and

$$\varepsilon_t = \frac{u}{\mathrm{r}}, \tag{8}$$