Fusion Engineering and Design 128 (2018) 154–157

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Shape evolution of surface molten by electron beam during cooling stage

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ARTICLE INFO

Keywords:
Divertor
Tungsten
Pulsed heat load
Melt motion

ABSTRACT

A number of experimental studies of melt motion and droplet ejection caused by pulsed plasma load include the measurements of the shape of surface after the solidification of target. The measured shape may be different from the one during the heating stage because of melt motion. In present paper the evolution of this perturbations is treated as capillary waves on the melt surface. The dispersion relation for capillary waves taking into account viscosity and limited depth of liquid was used. The numerical estimations for the melt surface behavior are done for tungsten samples irradiated at BETA facility.

1. Introduction

The powerful heat loads on the first wall and divertor plates are expected at the next generation of the experimental fusion reactors [1]. Tungsten will be used as a material of the divertor surface because of the high melting point [2]. However, even the tungsten surface melts under the heat loads supposed to be in fusion reactor [3]. The melting significantly increases the erosion of irradiated materials and the growth rate of surface roughness. It could lead to the formation of droplets and their emission from the surface to plasma and other harmful to the plasma confinement and heating events [4]. The Kelvin–Helmholtz instability is one of the most discussed mechanism on the above mentioned phenomena [5–8]. Burst of bubbles during boiling is another common hypothesis [9,10].

The dynamic observation of the surface during the irradiation is complicated by the short duration of the events, low magnitudes and typical wave lengths of the surface shape perturbations and the flare of the heated material or the plasma. The most of the experimental measurements of the irradiated surface shape are carried out by the “post mortem” analysis, while the shape may be drastically changed during the cooling stage before the solidification [11,12]. The main subject of the paper is theoretical study of the evolution of the molten surface shape during the cooling stage. We will make the numerical estimations for tungsten as one of the promising material for divertor plates.

2. Capillary waves

We suppose that at the cooling stage there is no significant plasma or gas near to the material surface. Perturbation excited during electron beam irradiation can be expanded on set of eigenmodes of melt tungsten, which are surface and volumetric (sound) waves. The sound waves emanate through substrate and not influence on the surface shape. The surface tension is the main force driving surface wave (see below) so such waves are the capillary waves. So the dynamics of the small perturbations of the melt surface could be described as the superposition of capillary waves. Let's get the dispersion relation of the capillary waves to calculate the dynamics. Assuming the smallness of the perturbation amplitudes we will linearize all equations. The surface tension, viscosity and the finite depth of the molten layer will be taken into account. We assume that the surface tension coefficient, the viscosity and the depth of the molten layer are constant. Besides that we neglect the influence of the magnetic field to the melt motion. Let's estimate the volumetric Ampere's force ($\vec{f} = \vec{j} \times \vec{B}$, here j is the current density) using the Maxwell equation $\nabla \times \vec{H} = 4\pi\vec{j}/c$ (we neglect the displacement current because melt velocity is small in compare with speed of light [13]):

$$f \sim jB_0 \sim \frac{B_0 \delta H}{\lambda} \approx \frac{B_0 \delta B}{\mu_0 \lambda}, \tag{1}$$

where B_0 is the constant magnetic field, μ_0 is the vacuum permeability, λ is the perturbation wavelength and δB is the magnetic field perturbation (hereinafter the SI units are used). The perturbation of the

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https://doi.org/10.1016/j.fusengdes.2018.01.027
Received 23 October 2017; Received in revised form 9 January 2018; Accepted 10 January 2018
Available online 09 February 2018
0920-3796/

magnetic field may be estimated using the induction equation [13]:

$$\frac{\partial \delta \overrightarrow{B}}{\partial t} = \nabla \times (\overrightarrow{V} \times \overrightarrow{B_0}) + \frac{1}{\mu_0 \sigma} \Delta \delta \overrightarrow{B}, \tag{2}$$

where t is the time, $\overrightarrow{V}$ is the melt velocity, σ is melt conductivity. Let's suppose that the left part of the equation is much less than the second term of the right part. The condition is expressed by the following formula:

$$\frac{\lambda^2}{\tau} \ll \frac{1}{\mu_0 \sigma}, \tag{3}$$

where τ is the oscillation period. Further, it will be shown that the condition (3) is satisfied for the discussed experiments. Using the formula (2) the magnetic field perturbation may be estimated:

$$\delta B \sim \mu_0 \sigma \lambda V B_0. \tag{4}$$

Using the expressions (1), (4) the condition of the smallness of the Ampere's force in comparison with the rate of impulse density change:

$$\frac{\rho V}{\tau} \gg \sigma V B_0^2, \tag{5}$$

where ρ is the melt density. The simplified expression follows:

$$\mu_0 \sigma \tau V_A^2 \ll 1, \tag{6}$$

where $V_A = B_0/\sqrt{\mu_0 \rho}$ is the Alfvén velocity.

The linearized Navier–Stokes equation and continuity equation describe the capillary wave [14]:

$$\frac{\partial \overrightarrow{V}}{\partial t} = -\frac{1}{\rho} \overrightarrow{\nabla} p + \nu \Delta \overrightarrow{V}, \tag{7}$$

$$(\overrightarrow{\nabla}, \overrightarrow{V}) = 0, \tag{8}$$

where p is the pressure and ν is the kinematic viscosity coefficient. Here we assume that the liquid is incompressible. The sticking to the bottom and the absence of momentum flux through the fluid free surface are used as boundary conditions [14]:

$$\overrightarrow{V} = 0 \text{ at } z = -h_0, \tag{9}$$

$$\frac{\partial V_x}{\partial z} + \frac{\partial V_z}{\partial x} = 0 \text{ at } z = 0, \tag{10}$$

$$p + \alpha \frac{\partial^2 \xi}{\partial x^2} + 2\nu\rho \frac{\partial V_z}{\partial z} = 0 \text{ at } z = 0, \tag{11}$$

where z is the axis perpendicular to the surface, x and y are the parallel ones, h_0 is the depth of the molten layer, α is the surface tension coefficient, ξ is the perturbation of surface. We consider 2-dimensional motion of a liquid, as is commonly assumed for capillary waves ($V_y = 0$ and the functions do not depend on the y). The ξ could be calculated using the following expression:

$$\frac{\partial \xi}{\partial t} = V_z \text{ at } z = 0. \tag{12}$$

The complex amplitude method allows to use the following dependence on x and t:

$$\overrightarrow{V}, p, \xi \sim e^{i\,kx - i\omega t}, \tag{13}$$

where k is the wave number and ω is the frequency. The dispersion relation for the capillary wave follows:

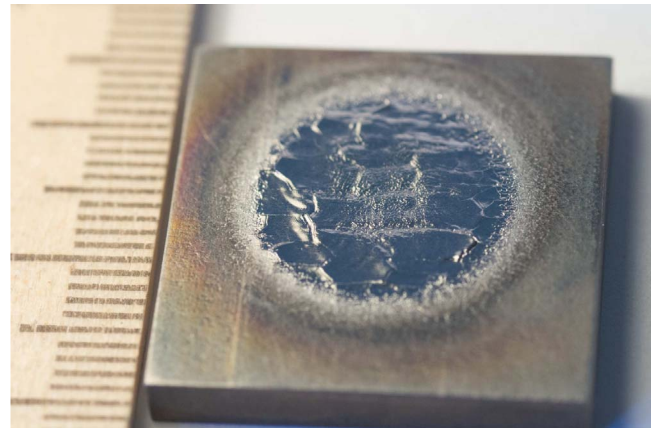

Fig. 1. The tungsten sample irradiated at the BETA.

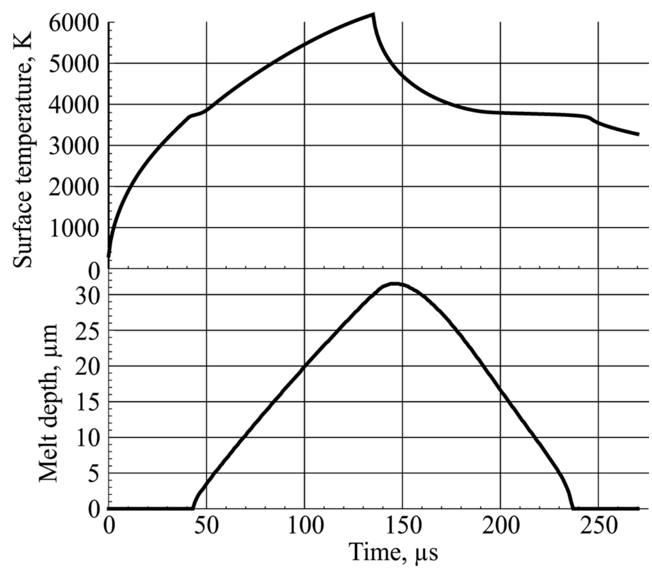

Fig. 2. The calculated tungsten surface temperature and melt depth vs. time. The heating surface power is 8 GW/m^2, the irradiation duration is 130 µs.

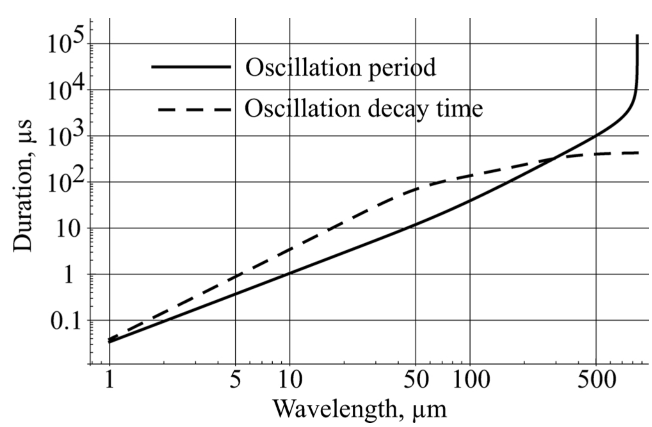

Fig. 3. The oscillation period and decay duration of the capillary wave vs. wave length at 15 µm-depth melt.