Calculation of heat sink around cracks formed under pulsed heat load

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Abstract. The experimental and numerical simulations of the conditions causing the intensive erosion and expected to be realized infusion reactor were carried out. The influence of relevant pulsed heat loads to tungsten was simulated using a powerful electron beam source in BINP. The mechanical destruction, melting and splashing of the material were observed. The laboratory experiments are accompanied by computational ones. Computational experiment allowed to quantitatively describe the overheating near the cracks, caused by parallel to surface cracks.

1. Introduction
The plasma-facing components (PFC) of the reactor tokamak prototype ITER will be subjected to intense heat load during the discharge [1]. The load will consist of continuous and pulsed parts. The continuous one is result of plasma flow along scrap off layer (up to 20 MW/m²) and the pulsed loads are results of type I ELMs, breakdowns, etc. The energy release of the pulsed heat load can be about 80 MJ/m² during 1 µs. Currently experimental facilities cannot produce the conditions of the pulsed plasma loads. So the quasi-stationary plasma accelerators [2,3], electron beam sources [4,5] and lasers [6] are used for experimental simulations of the pulsed heat loads. The obtained experimental data on the erosion of materials become basis of the computational models for predictions of the tokamak operational regimes.

The proper operation of fusion reactor assumes the heat sink from the surface of the PFC. The formation of the parallel to surface cracks can make significant obstacle for the heat sink and excessively increase the surface temperature (see Figure 1a). The crack formation was observed by post-mortem analysis in many experimental works [7,8], although numerical modeling of the surface overheating above the cracks was not carried out. The overheating near cracks was measured at the BETA facility in BINP. The tungsten samples were heated by submillisecond powerful electron beam and were measured by in-situ optical diagnostics at the experiments [9].
2. Statement of the problem

The cracks form in the surface layer of tungsten in a result of thermal expansion during pulsed heat load. It was found experimentally that not only perpendicular to the surface cracks appear after pulsed heating, but also the parallel to the surface cracks form. The latter may significantly affect the heat sink from the irradiated surface of material. The aim of this work is to calculate the heat sink at pulsed heat loads near parallel to the surface of the material crack. In particular, we attempt to reproduce the measured temperature distribution on the surface and to predict the typical dependencies of the suppression of the heat sink on the geometry of cracks.

The computational domain is the rectangular area of the sample cross-section with a subsurface crack (see Figure 1a). The photo demonstrates the parallel to surface crack at the depth of ~250 microns. The left part of the sample surface had a weak mechanical contact with a deeper part of material and was lost during the preliminary cutting. On the boundary the heat flux is specified. The perpendicular to heated surface crack is located on the boundary of the computational region \( x = 0 \) and transits to the parallel to surface crack (see Figure 1b).

![Figure 1](image)

**Figure 1.** Cross-section of the tungsten sample made with the electron microscope (a). Scheme of the computational domain (b).

The thermal conductivity equation (1) was solved in the area using method [10].

\[
c(T)\rho(T) \frac{\partial T}{\partial t} = \text{div} \lambda(T) \text{grad} T + Q,
\]

where \( T \) is the temperature, \( c(T) \) is the specific heat capacity, \( \rho(T) \) is the density, \( \lambda(T) \) is the thermal conductivity, \( Q \) is the heat source.

The initial and the boundary conditions are of the form:

\[ T(0, x, y) = T_0, \quad \left( n, \nabla T \right)|_y=0 = 0, \quad \frac{\partial T}{\partial y}|_{y=0} = \frac{W(t, x)}{\lambda(T)}, \]

where \( W(t, x) \) is the heat flow power (see Figure 2a), with a duration of 100-200 \( \mu s \).

The subsurface crack set condition \( \left( n, \nabla T \right)|_{y=0} = 0 \). The typical run time is of 1000 \( \mu s \). The following characteristic values were used:

\[ t = 1 \mu s, \quad x = 10^{-2} \text{ mm}, \quad T = 10^3 \text{ K}, \quad \lambda = 10^{-2} \frac{\text{ W}}{\text{ mm} \cdot \text{ K}}, \quad \rho = 10^{-5} \frac{\text{ kg}}{\text{ mm}^3}, \quad c = 10^3 \frac{\text{ W} \cdot \mu \text{ s}}{\text{ kg} \cdot \text{ K}}, \quad W(t, x) = 10^3 \frac{\text{ W}}{\text{ mm}^2}. \]

Measurement of thermal characteristics of refractory metals is rather a difficult task. So generally reference books and articles present approximated or theoretically predicted dependencies with the accuracy about 10% or worse. Thermal conductivity and specific heat of solid tungsten are taken from [11]. The thermal conductivity of liquid tungsten is estimated from [12-14]. In the temperature range of density, specific heat capacity and thermal conductivity are specified as dependencies on the temperature (2-4).
Figure 2. Distribution of the surface power of heat flow (a) and temperature (b): experimental data (solid line) and calculated results (dotted line).

The density (see Figure 3a):

\[
\rho(T) = \begin{cases} 
19.25 - 2.66207 \cdot 10^4 \cdot (T - 273.15) \\
-3.0595 \cdot 10^9 \cdot (T - 273.15)^2 \\
-9.5185 \cdot 10^{12} \cdot (T - 273.15)^3 
\end{cases} \cdot 10^{-6} \text{ kg/mm}^3, \\
300K \leq T \leq 3695K, \quad (2)
\]

The thermal conductivity (see Figure 3b):

\[
\lambda(T) = \begin{cases} 
149.441 - 45.466 \cdot 10^3 \cdot T + 13.193 \cdot 10^6 T^2 - \\
-1.484 \cdot 10^9 T^3 + 3.866 \cdot 10^6 T^2 
\end{cases} \cdot 10^{-3} \frac{\text{W}}{\text{mm} \cdot \text{K}}, \\
300K \leq T \leq 3695K, \quad (3)
\]

The specific heat capacity (see Figure 3c):

\[
c(T) = \begin{cases} 
21.868372 + 8.068661 \cdot 10^3 \cdot T - \\
-3.756196 \cdot 10^6 T^2 + 1.075862 \cdot 10^9 \cdot T^3 + \\
+1.406637 \cdot 10^4 T^2 
\end{cases} \cdot 10^6 \frac{\text{W} \cdot \mu \text{s}}{0.186 \text{ kg} \cdot \text{K}}, \\
300K \leq T \leq 3080K, \quad (4)
\]

\[
c(T) = \begin{cases} 
2.022 + 1.315 \cdot 10^2 \cdot T 
\end{cases} \cdot 10^6 \frac{\text{W} \cdot \mu \text{s}}{0.186 \text{ kg} \cdot \text{K}}, \\
3080K \leq T \leq 3695K, \quad (4)
\]

\[
c(T) = \begin{cases} 
51.3 \cdot 10^6 \frac{\text{W} \cdot \mu \text{s}}{0.186 \text{ kg} \cdot \text{K}}, 
\end{cases} \\
3695K \leq T \leq 6000K,
\]
Figure 3. Plots of the temperature-dependent density (a), thermal conductivity (b), specific heat capacity (c) capacity and the energy losses caused by evaporation (d).

3. Melting and evaporation processes

The enthalpy of the phase transition $L_m$ [15] is added in equation (1) to take into account the melting (see Figure 4) and the evaporation:

$$
\left( c(T) \rho(T) + L_m \delta(T, \Delta) \right) \frac{\partial T}{\partial t} = \text{div}(\lambda(T) \text{grad}T) + Q,
$$

$$
\delta(T, \Delta) = \begin{cases} 
\frac{1}{2\Delta}, & |T - T_m| \leq \Delta, \\
0, & |T - T_m| > \Delta,
\end{cases}
$$

$$
x_m = \eta_m(t), \quad \left[ \frac{\partial T}{\partial x} \right] = -L_m \frac{\partial \eta_m}{\partial t},
$$

where the melting temperature $T_m = 3695$ K, and the melting heat $L_m = 51.1 \cdot 10^5 \text{ W} \cdot \mu \text{s} \text{ mm}^{-1}$.

The following expression was taken for the energy losses caused by evaporation: $N(T_v) = L_v \cdot \frac{1}{S} \frac{dm}{dt}$ (see Figure 3d). The complete heat flux is $W_c(t, x) = W_v(t, x) - N(T_v)$, where $P(T)$ - saturated vapor pressure, $\frac{1}{S} \frac{dm}{dt}$ - the rate of mass losses caused by evaporation:
\[ L_c = 4.482 \cdot 10^{12} \frac{W \cdot \mu s}{kg}, \]
\[
\frac{1}{S} \frac{dm}{dt} = P(T) \sqrt{\frac{M}{2\pi RT}}|_{y=0} = \exp \left( 26.19104 \cdot \frac{83971.3}{T}|_{y=0} \right) \sqrt{\frac{0.184}{2\pi 8.314T}|_{y=0}} 10^{-12} \frac{kg}{mm^2 \cdot \mu s}. 
\]

To take into account the deep heating the possibility of the change of the heat flow through the boundary for the heat source inside a thin layer within the region is provided:

\[
Q = \begin{cases} 
0, & y \leq y^w_0, \\
\frac{W_c(t, x, y)}{y^w_0 \epsilon(T) \rho(T)}, & 0 \leq y \leq y^w_0, \\
0, & y^w_0 \leq y.
\end{cases}
\]

\[
\frac{\partial T}{\partial y}|_{y=0} = \frac{W_c(t, x, y)}{\lambda(T)}, \quad \frac{\partial T}{\partial y}|_{y=0} = 0.
\]

**Figure 4.** Temperature distribution on cross-section at time 200 µs (a) 230 µs (b). Area of the melt is grayed out. Step between temperature level lines is 500 K, \( W_c = 2.5 \cdot 10^3 \frac{W}{mm^2} \).

### 4. Results of numerical simulation

The results of computational experiments match measurement data (see Figure 2b). Calculation parameters: the duration of exposure of the beam 186, ISS, time of measurement 200 µs from the beginning of beam exposure time - 10 µs, the left crack depth of about 0.12 mm, the left crack length of about 0.2 mm, the right crack depth of about 0.15 mm, the right crack length of about 0.145 mm.

The heating was assumed to be uniform \( W_c = 3 \cdot 10^3 \frac{W}{mm^2} \).

Given the isotherms on the cross section at the time of measurement 200 µs and 400 µs from the start of the beam (see Figure 4) for exposure of a beam of 400 µs. In the case of duration of exposure of the beam 186 of ISS at time 400 microseconds from the start of the beam material have time to cool down and the temperature reaches the melting point.

The calculations confirmed the hypothesis that nonuniformity of the surface temperature of tungsten associated with the presence of subsurface cracks.

The extension of the model involves the inclusion of thermodynamic coordinated conservation equations for solid, liquid and gas phases of a substance [16-18] in the axisymmetric statement of the problem with the purpose of studying the processes happening during melting and evaporating of the substance.

### 5. Conclusions

The experimental and numerical simulations of the conditions causing the intensive erosion and expected to be realized infusion reactor were carried out. The influence of relevant pulsed heat loads to tungsten was simulated using a powerful electron beam source in BINP. The mechanical destruction,
melting and splashing of the material were observed. The laboratory experiments are accompanied by computational ones. Computational experiment allowed to quantitatively describe the overheating near the cracks, caused by parallel to surface cracks.

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