DROPLET FORMATION AT THE W-MACROBRUSH TARGETS UNDER TRANSIENT EVENTS IN ITER

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Most important mechanisms of melt splashing and melt bridge formation under ITER transient heat loads are analyzed. Approximate criteria for droplet ejection are used to find the range of transient events where the droplet injection is absent. The critical radius of brush edges rounding which prevents the bridge formation at the macrobrush edges is determined.

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INTRODUCTION

Tungsten in form of a macrobrush structure is one of candidate materials for ITER divertor. In the tokamak ITER even for moderate and weak ELMs with a rather weak evaporation rate, when the vaporized material does not protect the armour surface from the impacting plasma, the main mechanisms of metallic armour damage is surface melting and melt motion erosion caused by direct action of dumped plasma which moves with the velocities of $10^4 – 10^5$ m/s along the target surface. In case of strong transient events such as the Type I ELMs and the disruptions the heat loads of GW/m^2 range result in melting and a violent evaporation at the surface of metallic divertor armour. Due to formation of an ionized vapor shield the exposed target is essentially protected from the main heat load, and the evaporation is mainly caused by the radiation from the plasma shield. Due to finite width of the shielding layer, an inhomogeneous distribution of plasma pressure along the target surface forms. The pressure gradient generates a rather intense plasma motion along the surface [1] with plasma velocities of $10^3 – 10^4$ m/s.

Earlier the melt motion erosion at the surface of bulk and W-macrobrush brush tungsten armour caused by single and multiple transient events (TE) was numerically investigated using the code MEMOS [2-4] without accounting the droplet formation and melt splashing under the high heat loads. However, formation of droplets and the splashing of melt layer anticipated during ITER ELMs and disruption thermal quench phase may be substantial for the erosion of W armour. Under typical ITER TE the droplet formation may be caused by rapid growth and further breakaway of liquid at the peaks of the waves generated at the liquid – incident plasma interface (in case of weak ELMs), or the liquid-plasma shield interface (in case of essential evaporation during intense TE), or at the interface between moving melt layer and background solid surface. Depending on the intensity of TE, different mechanisms may be responsible for those perturbations. In the case of weak ELMs the direct action of the plasma stream impacting on the target surface under a rather low angle of 2-5 degree produces the perturbation of Kelvin-Helmholtz type (KH) at the liquid-plasma interface. In the case of strong TE with developed plasma shield, small initial perturbations of the surface heat loads together with a rather rapid vapor flow along the target surface are responsible for the liquid-vapor interface perturbations of different types, like the instabilities by Kelvin-Helmholtz, Rayleigh-Taylor, and the capillary wave instabilities. The Rayleigh-Taylor instability may also generate the perturbations growing in the melt layer at the macrobrush edges which may lead to the formation of the bridges between the brushes.

Droplet splashing of thin liquid films was investigated mainly for three cases: a gas-liquid flow in channels (annular flow) [5], droplet formation under intense laser heat loads and laser welding (for instance [6,7]), and the impact of either droplets or liquid spray on the solid walls [8,9]. The case of annular flow is the most investigated case, the experimental data on droplet formation, their size distribution and droplet velocities in annular gas-liquid flows and several models of droplet formation are reviewed in [5]. The most developed model is based on the Kelvin-Helmholtz instability mechanism. In case of the droplet impact at the solid surface the Rayleigh-Taylor (RT) instability plays a major role which can be also relevant to the melt layer splashing occurring during the melt motion caused by the plasma stream.

In this study two most important mechanisms of melt splashing and melt bridge formation under ITER TE heat loads are analyzed, namely the growth of the bridges between neighbor brushes and droplet splashing at the brush edges due to the RT instability, the growth of surface waves due to the KH instability caused by the impacting plasma stream, and a simplified phenomenological model for practical estimations of mass loss rate due to the droplet formation. The conditions of intense droplet formation in the QSPA experiments [10], in typical ITER weak ELMs, and ITER Type I ELMs (giant ELMs) are analyzed. It is assumed that the droplets are formed due to the breakaway of liquid at the peaks of unstable waves. An approximate criterion for the droplet ejection is applied based on comparison of surface energy of a droplet with the kinetic energy of the surface layer element of the velocity equal to that in unstable wave [6]. The critical radius of the brush edges rounding is determined which prevents the growth of the RT instability and bridge formation at the macrobrush edges.

1. ESTIMATION OF SPLASHING THRESHOLD AND DROPLET FORMATION DUE TO THE RAYLEIGH-TAYLOR INSTABILITY AT THE MACROBRUSH EDGES

For droplet formation, the brush edges are the critical points of macrobrush geometry. The macrobrush edges are assumed as convex corners rounded with a radius *R*.

The sharp brush corners can be considered as convex edges having a small radius R << 1 cm. There are two main mechanisms of the melt splashing at the brush edges. The first one is the separation of the liquid from the solid surface and the second one is the Rayleigh-Taylor instability. Both effects are caused by the centrifugal force of longitudinal melt motion along the convex corner.

Separation of melt as a splashing mechanism.

The motion of the liquid film along the macrobrush edge of a radius R is stable if the centrifugal force is smaller than the capillary force. The balance of these forces gives the stability criterion:

$$\rho \frac{V_{\max}^2}{R} h = \frac{2\sigma}{R} \qquad (1.1)$$

The centrifugal force is in the left side and the capillary force in the right hand side of Eq.(1.1). The surface tension σ , the liquid density ρ and the melt thickness h . The equation gives the Taylor criterion on the maximum splashing free velocity of the fluid [11]:

$$V < V_{\max} = \sqrt{\frac{2\sigma}{\rho h}} \qquad (1.2)$$

The liquid film separation from the convex corner and further splashing of the melt layer occurs as soon as velocity of melt motion exceeds $V_{\max}$.

For the tungsten armor (σ = 2200 din/cm, ρ = 17 g/cm^3) and ITER transient events the maximum velocities estimated from the Taylor criterion are:

For typical disruptions h~400 μm, $V_{\max}$ = 0.8 m/s. For typical ELMs h~40 μm $V_{\max}$ = 2.5 m/s. Typical averaged melt velocities $\tilde{U}$ obtained for W targets with the MEMOS are below 1.5 – 2.0 m/s for the bulk target, and $\tilde{U}$ < 0.5 m/s for the W macrobrush armour. In the frame of the "shallow water" approximation [2-4] used in the code it is assumed that the velocity of melt motion is zero at the liquid - solid interface. The velocity reaches a maximum value at the liquid - plasma interface. If neglecting the influence of surface temperature gradient upon the melt motion, $\tilde{U}$ and the velocity at the liquid plasma interface $V_{\max}$ are related as $V_{\max} = 1.5 \cdot \tilde{U}$.

Thus the velocities of melt motion in the thin surface layer do not exceed 2-3 m/s for the bulk target and are below 0.75–1 m/s for the W-brush armour. Therefore at the macrobrush edges the separation of melt layer from the solid surface and violent melt splashing may occur for the disruptions and not in case of ELMs. In the case of the bulk target the melt separation from the solid surface may occur both for the disruptions and the ELMs.

The RT instability as a cause of melt splashing.

A rapid liquid motion in the melt layers along a convex edge of W-brush can produces growing waves at the plasma-liquid interface, named the Rayleigh-Taylor instability [12] which in the rotating rest-frame of the fluid is caused by the centrifugal acceleration in the melt layer (see Fig. 1). The RT instability generated at the liquid-plasma interface can lead to the extension of the melt layer until the next macrobrush, thus producing the bridges between the brushes after the resolidification as it is seen in the experiments [10] (see Fig. 2). Also the droplets may form in perpendicular direction to the convex surface splashing into the plasma shield.

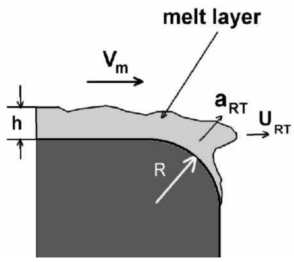

Fig. 1. Sketch of droplet formation for the Rayleigh-Taylor instability

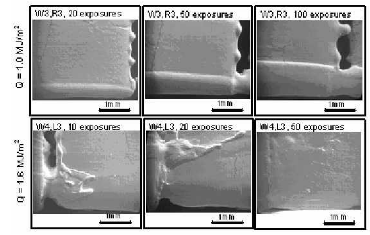

Fig.2. The view of the tungsten tile surface obtained by means of electron microscope [10]

Let's assume that the melted material moves along the top surface of the macrobrush with the convex brush edges of a radius R. The velocity of melt motion along the surface is V_m , the melt density ρ_m , and the surface tension σ . The centrifugal acceleration is given by $a_m = V_m^2 / R$. The dispersion equation that describes the RT perturbations of stationary moving melt stream in linear approximation with the frequency ω of sinusoidal perturbations and the wave number k on the liquid surface has the following form:

$$\omega^2 = a_m k - \frac{\sigma k^3}{\rho_m} = \frac{V_m^2}{R} k - \frac{\sigma}{\rho_m} k^3 \qquad (1.3)$$

When Eq.(1.4) has complex roots, the perturbations grow exponentially, which establishes the stability criterion:

$$\frac{V_m^2}{R} k < \frac{\sigma}{\rho_m} k^3 \qquad (1.4)$$

The perturbations with k larger than the critical wave number k_{cr} are unstable. The k_{cr} is given by

$$k_{cr} > \sqrt{\frac{\rho_m V_m^2}{\sigma R}} \qquad (1.5)$$

The surface tension stabilizes the perturbation with the wave length $\lambda = 2\pi/k$ shorter than the critical wavelength $\lambda_{cr} = 2\pi / k_{cr}$ given by

$$\lambda_{cr} = \frac{2\pi \sqrt{\sigma R}}{\rho_m^{1/2} V_m} \qquad (1.6)$$

The maximum instability increment follows as

$$\gamma_{RT} = \frac{0.62 V_m^{3/2} \rho_m^{1/4}}{R^{3/4} \sigma^{1/4}} \qquad (1.7)$$

The increment γ_{RT} corresponds to the wave with the wavelength $\lambda_{RT} = 2\pi / k_{RT}$

$$\lambda_{RT} = \sqrt{3}\lambda_{cr} = \frac{2\pi\sqrt{3\sigma R}}{\rho_m^{1/2} V_m} \qquad (1.8)$$

In assumption of exponential growth of RT the critical edge convex radius R_{RT} can be found. At $R > R_{RT}$, essential growth of instability and the bridges between the brushes during the intense melt motion period τ_m do not occur. We assume that the growth of RT waves is negligible if $\gamma_{RT}\tau_m < 1$, from which the inequality follows:

$$\frac{0.62 V_m^{3/2} \rho_m^{1/4} \tau_m}{R_{RT}^{3/4} \sigma^{1/4}} \le 1. \qquad (1.9)$$

The critical edge convex radius R_{RT} follows from the Eq. (1.9) as

$$R_{RT} \ge \frac{0.53 V_m^2 \rho_m^{1/3} \tau_m^{4/3}}{\sigma^{1/3}}. \qquad (1.10)$$

With sufficiently rapid growth of RT-waves the liquid is likely to splash normally to the convex surface. We assume that the radius of droplets formed in this process is $r_{RT} = \lambda_{RT}/4$, so that the volume of the droplets is $Y = (4/3)\pi(r_{RT})^3$. The condition for the breakaway of droplet with the given volume may be found in the assumption of equality of the kinetic energy E_k of the given liquid volume to the surface energy of the droplet E_S:

$$E_k = \frac{1}{2}\rho_m\left(\frac{\partial\xi}{\partial t}\right)^2 \mathrm{Y}, \quad E_S = 4\pi r^2\sigma .$$

Here $\xi = \xi_0\exp(\gamma_{RT}t)$ is a growing perturbation of the melt surface. Thus the breakaway condition for the RT waves is given by:

$$\frac{1}{2}\rho_m\left(\frac{\partial\xi}{\partial t}\right)^2 \mathrm{Y} \ge 4\pi r^2\sigma . \qquad (1.11)$$

After substitution of droplet volume Y the inequality acquires the form:

$$\rho_m\left(\frac{\partial\xi}{\partial t}\right)^2 \ge \frac{6\sigma}{r_{RT}}. \qquad (1.12)$$

Substituting $\frac{\partial\xi}{\partial t} = \gamma_{RT}\xi$ the breakaway condition is reduced as

$$\xi \ge \frac{1}{\gamma_{RT}}\sqrt{\frac{6\sigma}{r_{RT}\rho_m}}. \qquad (1.13)$$

For the droplets to break away it is required that the RT-wave's amplitude reaches the value in the right hand side of Eq. (1.13) during the time of intense plasma motion along the surface. In the assumption of exponential growth of capillary waves Eq. (1.13) may be rewritten as:

$$\xi_0 \exp(\gamma_{RT}\tau) \ge \frac{1}{\gamma_{RT}}\sqrt{\frac{6\sigma}{r_{RT}\rho_m}}, \qquad (1.14)$$

where ξ_0 is the amplitude of the incipient melt-surface perturbation at the wavelength. It can be assumed that $\xi_0 \cong h$ where h is the thickness of melt layer at the brush edge. Then the characteristic time interval τ_{RT} for the wave breaking is estimated:

$$\tau_{RT} = \ln\left(\frac{1}{\gamma_{RT} h}\sqrt{\frac{6\sigma}{r_{RT}\rho_S}}\right)/\gamma_{RT}. \qquad (1.15)$$

The rate of droplet production caused by the RT instability (the number of droplets generated from the unit surface per unit time) can be estimated using the following assumptions:

a) the wavelength of RT waves with maximum instability increments has to be less than the thickness of the melt layer h (otherwise the wave breaking will not occur):

$$\lambda_{max}/2 \le h \qquad (1.16)$$

b) The characteristic time interval τ_{RT} for the wave breaking (see Eq.(1.15)) has to be significantly less than the time τ_{res} of intense plasma motion above the melt layer.

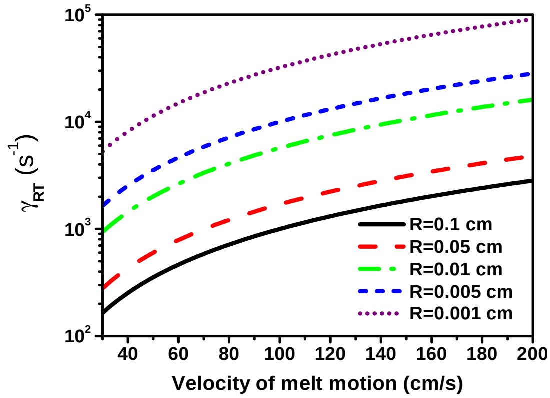

Fig. 3. Dependence of γ_{RT} growth increment of RT instability as function of the melt velocity for different edge convex radius

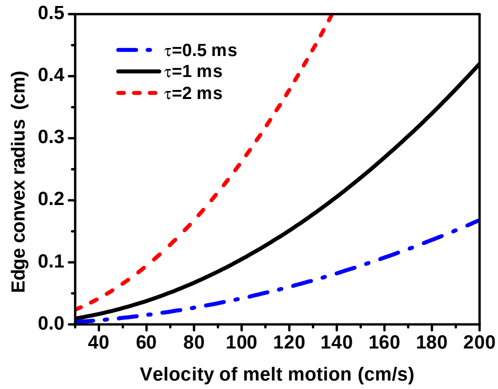

Fig. 4. Dependence critical edge convex radius preventing intense bridge formation as function of the melt velocity for different values of characteristic time of intense melt motion

For tungsten armor (σ = 2200 din/cm, ρ = 17 g/cm^3) the growth increment varies in the range 200–2000 s^{-1} for convex edge radius R=0.1 cm and in the range 5000-10^4 s^{-1} for R=0.001 cm (V_m varies in the range 0.4-2 m/s); see Fig.3 in which the dependence of growth increment as a function of melt velocity is shown for different values of convex edge radius. For instance when $R \cong 0.1$ cm and $V_m \approx 100$ cm/s, we obtained for $\lambda_{RT} = 0.39$ cm that $\gamma_{RT} \cong 10^3$ s^{-1}. This value of λ_{RT} is much larger than typical melt layer thickness expected after ITER ELMs. If $R \cong 0.005$ cm, the increment increases up to 10^4 s^{-1} for the RT with wavelength λ_{RT} = 0.087 cm. If $R \cong 0.001$ cm the increment reaches $4{\cdot}10^4$ s^{-1} for RT with the wavelength λ_{RT} = 0.039 cm. In this case the wavelength becomes comparable with the expected melt layer thickness. That demonstrates that in case of violent melt motion with the melt velocity V_m =100 cm/s the sharp edge leads to a fast RT instability and the droplet splashing can occur at the brush edges with $R < 0.001$ cm, for which the increment γ_{RT} >$4{\cdot}10^4$ s^{-1} with the wavelength λ_{RT} < 0.039 cm.

In the opposite case the RT instability leads to the bridges between neighbor brushes, but a large radius of edge convex can prevent fast formation of bridges. The dependences of critical edge convex radius as a function of melt velocity are shown in Fig.4 for different values of characteristic time of intense melt motion τ_m (0.5 ms, 1 ms, and 2 ms). From Eq. (1.10) and Fig. 4 it for example follows that in case of ITER like ELMs (or at the conditions of the QSPA facility in Troitsk) with typical time of melt layer existence τ_m =1 ms and the melt velocity $V_m \approx 100$ cm/s, the edge convex radius that prevents the growth of RT instability and formation of the bridges between brushes should exceed 0.12 cm.

In the experiments at the Troitsk facility QSPA with the heat loads Q in the range 1.0~1.6 MJ/m^2, carried out for the tungsten macrobrush targets with sharp bush edges, overlapping the gaps between brushes and bridge formation was observed with insignificant droplet injection after several first shorts [27], which is in qualitative agreement with the model described.

2. ESTIMATION OF DROPLET SPLASHING CONDITIONS FOR *QSPA* EXPERIMENTS AND *ITER* ELMS

A rapid plasma flow along a thin melt layer film produces growing waves at the plasma-liquid interface, which is called the Kelvin-Helmholtz instability. The KH instability generated at the liquid-plasma interface can lead to the droplets formation in perpendicular direction to the liquid surface and splash the droplets into the plasma shield. The KH dispersion equation for frequency ω of sinusoidal perturbations with the wavenumber k on plane liquid surface has the following form

$$\omega^2 = \frac{2\rho_{pl}}{(\rho_{pl}+\rho_S)} kV_{pl}\omega - \frac{\rho_{pl}}{(\rho_{pl}+\rho_S)}(kV_{pl})^2 + \frac{\sigma k^3}{(\rho_{pl}+\rho_S)}, \quad (2.1)$$

where ρ_{pl} is the vapor density of the plasma near the melt layer surface, V_{pl} the velocity of the plasma along the liquid surface, ρ_S and σ are the density and the surface tension coefficient of the melt layer, respectively.

According to the model of the KH instability growth described in Ref. [12] the maximum instability increment γ_{max} and wavelength corresponding to it λ_{max} are:

$$\gamma_{max} = \frac{2(\rho_{pl}V_{pl}^2)^{3/2}}{3\sigma\sqrt{3\rho_S}}, \quad \lambda_{max} = \frac{3\pi\sigma}{\rho_{pl}V_{pl}^2}. \quad (2.2)$$

As it was done in previous section for a sufficiently rapid growth of the KH-waves, it can be assumed that the radius of droplets formed in this process is $r_{KH} = \lambda_{max}/4$. The condition for breakaway of droplet may be found in assumption of equality of the kinetic energy of the given liquid volume to the surface energy of the droplet. For the droplets to break away it is required that the KH-wave's amplitude reaches this value during the time of intense plasma motion along the surface and the wavelength of the KH waves with maximum instability increments has to be less than the thickness of the melt layer (otherwise the wave breaking will not occur). Thus in assumption of exponential growth of the wave amplitude the characteristic time interval τ_{KH} for the wave breaking can be estimated as:

$$\tau_{KH} = \ln\left(\frac{1}{\gamma_{max}\xi_0}\sqrt{\frac{6\sigma}{r_{KH}\rho_S}}\right)/\gamma_{max}, \quad (2.3)$$

where ξ_0 is the amplitude of the incipient melt-surface perturbation at the wavelength.

In the case of weak ELMs expected in ITER (Q< 2.5 MJ/m^2) the velocity of impacting plasma along the divertor surface is to be $V = 10^5$ m/s, the density of impacting plasma is assumed to be $N = 10^{19} - 10^{20}$ m^{-3}. The time of intense plasma motion above the melt layer is expected as $\tau_{res} < 3{\cdot}10^{-4}$ s. The thickness of melt layer calculated for the W targets remains between 40 and 80 μm. The KH instability analysis demonstrates that in this case the plasma impacting on the target surface does not cause growth of the KH instability waves therefore the melt splashing would not expected.

For the experiments at the QSPA-T with the heat loads 1.0< Q <1.6 MJ/m^2 the following parameters of the plasma are expected: $10^4 < V < 10^5$ m/s, $N < 10^{22}$ m^{-3}, the time of intense plasma motion above the melt layer negligible for Q < 1 MJ/m^2 and less than 3x10^{-4} s for 1< Q <1.6 MJ/m^2. The melt layer thickness calculated for the W brush targets are about 10 μm for Q =1.3 MJ/m^2 and increases up to 40 μm for Q =1.6 MJ/m^2. The KH instability analysis demonstrates that in this case the plasma impacting on the target with velocities along the surface $V > 2{\cdot}10^4$ m/s can produce the KH instability waves with the wave length less than the melt layer thickness (H<40 μm) and the time of wave breaking below 10^{-4} s. Thus for the rather high heat load Q ~ 1.5-1.6 MJ/m^2 intense droplet formation with $r_{KH} = \lambda_{max}/4$ ~ 10 μm may occur and mass loss from the melt surface during τ_{res} =3x10^{-4} s are expected to be more then 15 mg/cm^2. In the experiments intense droplet splashing was observed at Q > 1.3 MJ/m^2. Estimated mass losses due to the droplet injection are in a reasonable agreement with the experimental data obtained at the QSPA facility [10].

CONCLUSIONS

The Rayleigh-Taylor instability at the macrobrush edges, the capillary-wave instability caused by violent evaporation, and the Kelvin-Helmholtz instability due to high speed plasma motion along the target surface lay in the background of melt splashing phenomenon. It is concluded that for the ITER ELMs with the heat loads below 2.5 MJ/m^2 the melt splashing due to droplet formation would not be expected, but in case of ITER disruptions a violent melt splashing may occur. It is demonstrated that in the experiments at the QSPA facility with heat loads exceeding 1.5 MJ/m^2 a violent melt splashing caused by the KH instability may also occur. It is also demonstrated that rounded macrobrush edges prevents intense bridge formation between the brushes.

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ФОРМИРОВАНИЕ КАПЕЛЬ НА ПОВЕРХНОСТИ ВОЛЬФРАМОВЫХ МИШЕНЕЙ ТИПА «MACROBRUSH» В ПЕРЕХОДНЫХ РЕЖИМАХ ИТЭРа

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Проанализировано развитие неустойчивостей Рэлея-Тейлора и Кельвина-Гельмгольца, как механизмов разбрызгивания расплава при воздействии переходных тепловых нагрузок на диверторные пластины в ИТЭРе. Приближенные критерии для эжекции капель были использованы для нахождения диапазона переходных режимов, не сопровождающихся капельной эрозией, и определения критического радиуса закругления границ элементов диверторных пластин типа «macrobrush».

ФОРМУВАННЯ КРАПЕЛЬ НА ПОВЕРХНІ ВОЛЬФРАМОВИХ МІШЕНЕЙ ТИПУ «MACROBRUSH» У ПЕРЕХІДНИХ РЕЖИМАХ ІТЕРу

Б.М. Базилєв, І.С. Ландман

Проаналізовано розвиток нестійкостей Релея-Тейлора і Кельвіна-Гельмгольца, як механізмів розбризкування розплаву при впливі перехідних теплових навантажень на диверторні пластини в ІТЕРі. Наближені критерії для ежекції крапель були використані для знаходження діапазону перехідних режимів, що не супроводжуються краплинною ерозією, і визначення критичного радіуса заокруглення границь елементів диверторних пластин типу «macrobrush».