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Modeling and simulation of melt-layer erosion during a plasma disruption

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Abstract

Metallic plasma-facing components (PFCs) e.g. beryllium and tungsten, will be subjected to severe melting during plasma instabilities such as disruptions, edge-localized modes and high power excursions. Because of the greater thickness of the resulting melt layers relative to that of the surface vaporization, the potential loss of the developing melt-layer can significantly shorten PFC lifetime, severely contaminate the plasma and potentially prevent successful operation of the tokamak reactor. Mechanisms responsible for melt-layer loss during plasma instabilities are being modeled and evaluated. Of particular importance are hydrodynamic instabilities developed in the liquid layer due to various forces such as those from magnetic fields, plasma impact momentum, vapor recoil and surface tension. Another mechanism found to contribute to melt-layer splashing loss is volume bubble boiling, which can result from overheating of the liquid layer. To benchmark these models, several new experiments were designed and performed in different laboratory devices for this work; the results are examined and compared. Theoretical predictions (A*THERMAL-S and SPLASH codes) are generally in good agreement with the experimental results. The effect of in-reactor disruption conditions, which do not exist in simulation experiments, on melt-layer erosion is discussed.

Keywords: Plasma–wall interaction simulator; Energy deposition; Plasma disruptions; Erosion and particle deposition; Vaporization and melting

1. Introduction

Several distinct mechanisms cause material erosion and consequently shorter plasma-facing component (PFC) lifetime due to the high energy deposited during various types of plasma instabilities. These mechanisms include surface vaporization, loss of melt layer, material cracking and spallation and, in some cases, explosive erosion due to sudden and large volumetric heat deposition. However, the most serious erosion mechanisms relevant to future tokamak machines during plasma instabilities are believed to be due to surface vaporization and melt-layer erosion of metallic PFCs.

Most studies predicting material erosion lifetime of PFCs during plasma energy deposition as a result of instabilities have considered only surface vaporization losses as the main erosion mechanism. This is partly because carbon-based materials, which do not melt, were the favorite choice as plasma-facing materials (PFMs) in most previous reactor design studies. Metallic PFCs, such as beryllium and tungsten, will, however, be subjected to severe melting during various plasma instabilities such as disruptions, edge-localized modes (ELMs) and high power excursions. Because of the much greater thickness of the resulting melt layer relative to that of the surface vaporization, melt-layer loss can significantly shorten the lifetime of these components, severely contaminate the plasma in subsequent operation and potentially prevent successful and reliable reactor performance.

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Mechanisms that are responsible for melt-layer loss during a disruption are modeled and evaluated. Of particular importance are hydrodynamic instabilities developed in the liquid layer due to various forces such as magnetic forces, plasma impact momentum, vapor recoil and surface tension. Another mechanism that contributes to melt-layer splashing loss is volume bubble boiling due to overheating of the liquid layer. The presence of impurities, gas content and surface inhomogeneity can accelerate bubble growth and bubble splashing. To check the validity of these models, several experiments were designed and performed on different laboratory devices (MK-200UG, QSPA at TRINITI, VIKA at Efremov, GOL-3 at the Budker Institute and others). Theoretical predictions (A^*THERMAL-S and SPLASH codes) are generally in good agreement with the results of these experiments. The effect of in-reactor disruption conditions, which do not exist in simulation experiments, on melt-layer erosion and their implications are discussed. Under certain conditions it is predicted that disruption erosion losses will exceed the calculated surface vaporization losses and the stationary melt layer combined, therefore significantly reducing metallic PFC lifetime.

2. Erosion of metallic plasma-facing materials

During shorter plasma instabilities such as hard disruptions, most recent theoretical calculations have shown that surface vaporization losses are small (a few μm) for a wide range of plasma conditions [1]. This is due to the self-shielding mechanism in which the materials own vapor stops and absorbs most of the incoming plasma energy, therefore significantly reducing the net energy flux to the disruption area to $< 10\%$ of its original value. This reduced energy flux is, however, large enough to cause significant melting of metallic PFCs. The resulting melt-layer thickness can be one to two orders of magnitude higher than surface vaporization losses. During longer plasma instabilities, however, significant self-shielding is not expected and depending on the amount of energy deposited and the deposition time, both vaporization and melting thicknesses can be very large.

During a disruption, the melt layer is subject to various forces such as electromagnetism, gravitation, mechanical vibration, plasma momentum, surface tension and ablation recoil [2]. Several mechanisms can cause melt-layer loss during the thermal quench phase of the disruption [1]. One mechanism is melt-splashing from overheating of the melt-layer due to the formation, growth and boiling of gas bubbles. Another mechanism is splashing due to absorption of plasma momentum. A further important erosion-causing mechanism is from instabilities that develop in the liquid layer because of various forces acting on the free surface of the liquid. Models for studying melt-layer erosion due to such mechanisms are implemented in the SPLASH computer code [1].

Among the mechanisms that cause melt-layer erosion during plasma instabilities, two have been demonstrated experimentally and studied theoretically in more detail. Contributing significantly to melt-layer erosion at high heat loads is melt splashing due to the formation, growth and boiling of volume bubbles inside the liquid layer. This results from the continuous heating and overheating of the liquid layer during energy deposition. The surface temperature of the liquid layer will exceed the equilibrium vaporization temperature during the course of the disrupting plasma and this overheating will result in the growth and the explosion or vaporization of the volume bubbles, in turn leading to ejection and loss of parts of the melt layer. The amount and rate of melt-layer erosion depends on many parameters, such as degree of overheating, impurity and gas content, material properties and disrupting plasma parameters.

A second mechanism in melt-layer erosion is the development and growth of hydrodynamic instabilities. Such forces can occur, during the thermal quench phase of a disruption, from plasma impact momentum (plasma wind) at the liquid surface. Part of the deposited plasma momentum will accelerate a thin surface layer of the liquid metal to very high velocities. As a result, hydrodynamic instabilities such as the Kelvin–Helmholtz instability (K-H) will arise and form liquid droplets that will be carried away by the plasma wind.

Several laboratory experiments are designed and performed to study melt-layer erosion in plasma gun facilities such as the MK-200UG and QSPA at TRINITI and the VIKA device at Efremov Institute. Most of these facilities can generate a low-temperature plasma ($T < 1$ keV) with high energy flow of up to 30 MJ/m^2 deposited in pulsed durations of < 1 ms [3,4]. Most results from these facilities have demonstrated significant losses and erosion of the developed melt layers of metallic samples due to various erosion mechanisms.

3. Experimental results

Fig. 1 shows the eroded thickness of an aluminum target (a beryllium-like material i.e. low melting temperature, high vapor pressure etc.) as a function of the incident plasma energy density at two different plasma gun facilities (VIKA and QSPA). The maximum erosion depth measured by surface profilometry of samples in the VIKA facility is also compared with the average depth inferred from mass-loss measurements. The mass-loss calculations yield an erosion depth that is shallower by a factor of about 3 to 5 than the maximum depth recorded by surface profilometry. Such a discrepancy is not unusual and can be due to factors such as gun beam profile, melt layer movement and possible redeposited material (particularly near the edges) which was clearly shown in the VIKA facility [4]. At high plasma energy densities (> 10 MJ/m^2), the average eroded thickness is much higher than the predicted thickness from only the surface vaporization [1]. In fact, at higher energies the eroded thicknesses can significantly exceed (2–3 times) the sum of the calculated surface vaporization and the stationary melt layer thicknesses. This implies that part of the evolving melt layer is lost while it is being developed. More recent lifetime analyses of reactor components have only assumed small parts (10–50%) of the stationary melt layer to be lost during disruptions [5]. This work will clearly have serious implications on reactor PFCs lifetime, plasma contaminations and other safety issues as a result of plasma instabilities. Other plasma gun facilities have yielded much higher aluminum erosion thickness (> 200 μm) at a much lower energy density ($E \approx 3.3$ MJ/m^2) deposited in 100 μs [6]. Such differences among various plasma gun facilities can be attributed to many uncertainties in energy calibration and diagnostic methods, mass-loss versus surface profilometry of exposed samples, sample geometry and the incident plasma dynamic pressure.

Preliminary analysis of the microstructure of the exposed aluminum surface in the QSPA facility clearly shows the formation of volume bubbles at high bubble densities. Aluminum targets in the MK-200UG facility have also shown the formation of volume bubbles during intense energy deposition (Fig. 2). Similar behavior was shown for other materials such as B_4C in the VIKA plasma gun [7] and a tungsten sample in the GOL-3 electron beam facility [8]. Traces of melted aluminum metal were found at locations in the QSPA facility up to 1 m from the aluminum target area. Splashes of molten metal and metal droplets are observed in tokamaks with metal limiters as well [9,10].

Careful analysis of the irradiated surface has also suggested the possibility of hydrodynamic instability to be a melt-layer erosion mechanism, in addition to volume bubble vaporization. Near central areas where the velocity of the incident plasma stream along the sample surface is close to zero, one can clearly see the volume bubbles. Near the sample preferral areas, however, one can see liquid droplets with long tracks formed because of the high plasma stream velocity, which may suggest the existence of K-H instability [3]. These droplets are transported by the plasma wind whose higher velocities are along the edges of the sample surface because of plasma flow around the more intense central vapor cloud.

A third mechanism of melt layer movement and possible erosion of PFCs that was clearly shown in laboratory experiments such as those at the VIKA facility and in other electron beam experiments [11], is the non-uniform incident beam dynamic pressure that causes the centered liquid layer to flow around the sides of the exposed sample. This liquid flow can be estimated by solving the liquid hydrodynamic Navier–Stokes equation, with the appropriate boundary conditions [2].

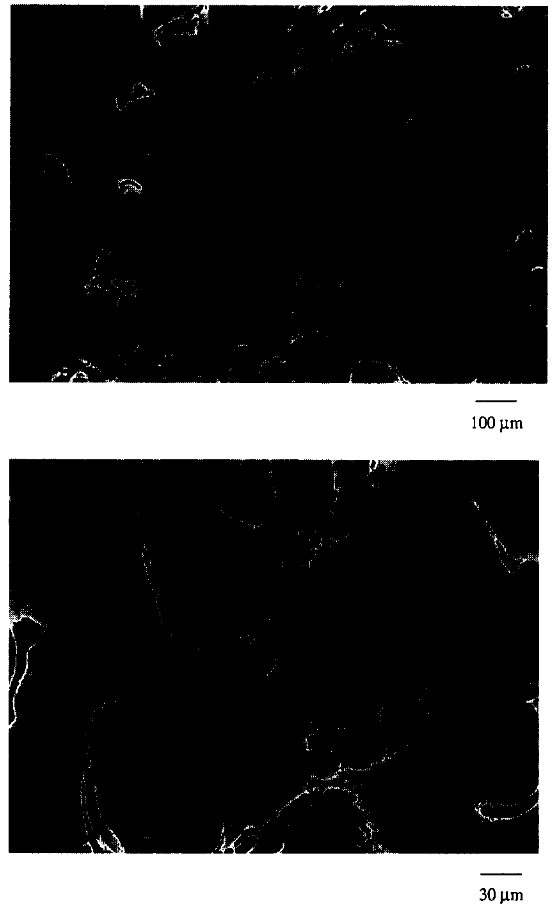

Fig. 2. Bubble formation on an aluminum surface exposed to plasma with 15 MJ/m^2 energy density deposited in 40 μs at the MK-200UG facility.

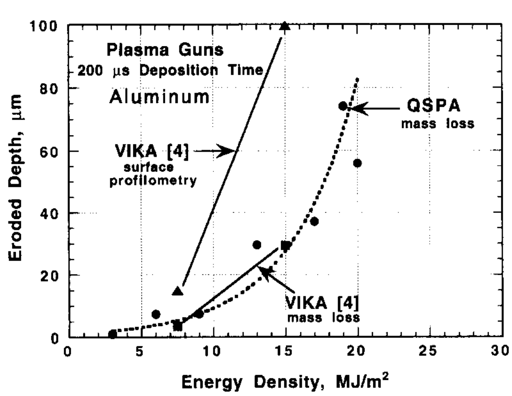

Fig. 1. Eroded thickness of an aluminum target in two different plasma gun experiments (dashed line is a fitting of QSPA data).

4. Theoretical predictions

Numerical models have been implemented in detail in the SPLASH code to study dynamic erosion of the evolving melt layer due to various mechanisms and different existing forces. This code is currently being coupled with the A* THERMAL-S code, which calculates the details of plasma/vapor interaction, in order to accurately predict melt-layer evolution, time-dependent melt erosion and its interaction with the developing vapor cloud above the liquid surface during intense energy deposition [12]. The analysis presented in this work is devoted to further study melt-layer erosion from bubble vaporization and K–H hydrodynamic instability to help explain the obtained experimental data.

In reality, a four-moving-boundaries problem must be solved consistently, as schematically shown in Fig. 3. The front of the vapor cloud, generated from the initial plasma energy deposition, is one moving boundary determined from the solution of vapor hydrodynamic equations [12]. The second moving boundary due to surface vaporization of the target is calculated from target thermodynamics. Immediately following the surface vaporization front is a third moving boundary due to the melt layer splashing front. Finally, the fourth moving boundary is at the liquid/solid interface, which further determines the new thickness of the melt layer. These moving boundaries are interdependent and a self-consistent solution should link them dynamically and simultaneously. It is, however, the third moving boundary (the liquid splashing front) that determines the extent of metallic PFC erosion and lifetime due to plasma instabilities.

Models for studying liquid splashing erosion from volume bubble vaporization have been further developed and enhanced for this work. Bubble vaporization erosion is assumed to occur only if the liquid layer surface temperature, T_s, exceeds the surface vaporization temperature, T_v, at the corresponding pressure above the surface [1]. This extent of overheating is required for bubble expansion and explosion upon reaching the liquid surface. In addition, for bubble vaporization to occur, the bubble energy, E_b, must exceed the bubble vaporization energy, E_v, where

$$E_v = \int c_p \, dT + E_m + E_s,$$

where c_p is the specific heat, E_m is the melting energy, and E_s is the splashing energy required to remove the bubble from the liquid. The splashing energy consists of the kinetic energy of the liquid metal surrounding the bubble surface, the kinetic energy of the formed liquid droplets and the vapor energy inside the bubble. The model solves time-dependent kinetic equations for bubble growth inside the liquid and for vaporization of bubbles when they reach the surface. Because of the very high estimated bubble density (which was also demonstrated experimentally, see Fig. 2), it is assumed that the surface of the liquid metal consists of a continuous bubble layer. It is further assumed that melt-splatter erosion has a form of a splashing wave with a time-dependent velocity determined from the energy balance. Details of the model are published elsewhere [13]. The liquid droplets, once ejected from the surface, are assumed to be carried away and therefore lost by the incident plasma stream, as schematically illustrated in Fig. 4.

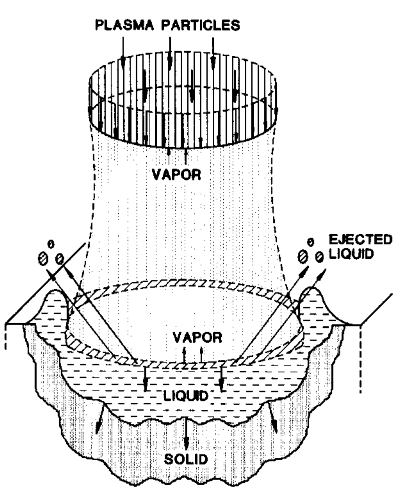

Fig. 3. Schematic illustration of different interaction zones and boundaries during a disruption.

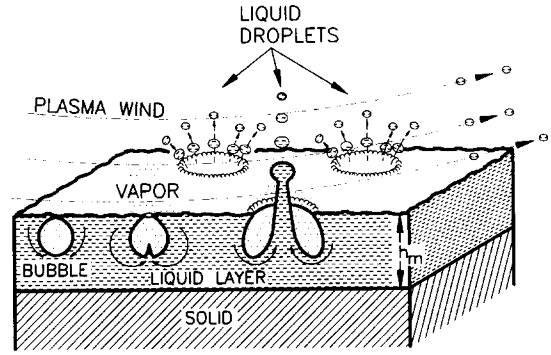

Fig. 4. Bubble growth, vaporization and loss by incident plasma wind.

Splashing liquid velocity from K-H instability is calculated using the following approach. The momentum of the disrupting plasma particles, M, is given by

$$M = \int P \sin \alpha \cos \alpha \, dt$$

where P is the incident plasma pressure and α is the angle between the incident particles and the liquid surface. Most of the incident plasma momentum is transmitted through the vapor cloud to the liquid surface. This momentum is absorbed within a thin surface layer of the melt-layer. The thickness of this layer is calculated from the momentum diffusion thickness which is governed by the liquid metal kinematic viscosity. As a result, this thin surface layer ($h < 5$ μm) of liquid will move with a very high velocity. The liquid flow then becomes unstable and is subject to K-H hydrodynamic instability. Surface waves on the liquid metal surface will arise and grow to a strong nonlinear stage with sharp spikes of the liquid. When the surface tension of these spikes exceeds the liquid pressure, these spikes break into droplets that are carried by the plasma flow above the surface. The time required for the strong non linear waves to grow has been calculated to be much shorter than the plasma disruption time. It is assumed that the times for the plasma to deposit its momentum in the liquid, liquid metal motion, formation and growth of the high non linear wave to form droplets and the loss of these droplets by plasma wind are very short and continue in a quasi-stationary state until the end of the plasma instability. A surface splashing velocity is also derived for the K-H instability, which depends on the incident plasma wind parameters and the plasma-facing material. Details of this model are provided in Ref. [13].

Fig. 5 shows mass-loss data of aluminum erosion from the QSPA and VIkA facilities and the theoretical predictions from the models implemented in the A* THERMAL-S and SPLASH computer codes. The models of both mechanisms slightly underestimate the average eroded depth at the higher energy densities of the QSPA facility. This may suggest additional melt-layer erosion mechanisms such as that due to non-uniform incident plasma dynamic pressure. Another possible erosion mechanism, not included in this study, is Rayleigh–Taylor hydrodynamic instability due to inertial forces resulting from the acceleration of the melt-front at the solid/liquid interface [2]. The erosion from volume bubble vaporization is roughly equal to that from the K-H instability in this case. The relative contribution of both mechanisms is found to depend on the magnitude of plasma momentum, amount of overheating, liquid metal properties, geometrical effects etc. Melt-layer erosion of heavier materials such as copper, for example, is found to be lower by a factor of 3 than aluminum erosion under similar irradiation conditions of the QSPA facility. This is explained by the modeling simulation to have two main causes. The first is the required higher energy to remove the volume bubbles and the associated heavier liquid droplets. The second is the lower splashing velocity from K-H instability, again, because of the higher density effect that requires more energy to liberate the liquid droplets.

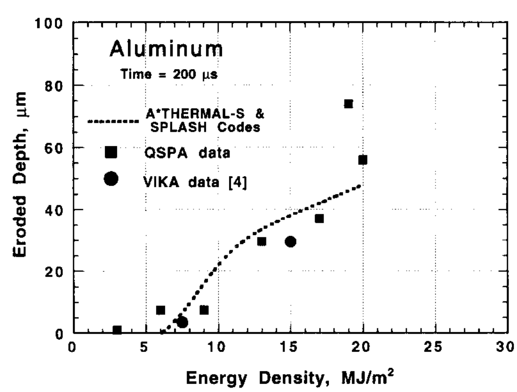

Fig. 5. Comparison of experimental data and current model predictions.

The interaction of various forces during a reactor disruption above the liquid metal surface may further affect the stability and splatter behavior of the melt layer. Surface rippling and roughening can also be caused by vapor pressure above the surface and from melt-layer acceleration inside the material. A strong plasma wind in the reactor environment can enhance material erosion and plasma contamination [14]. Magnetic forces generated by current decay during the current-quench phase of a disruption can also cause hydrodynamic instabilities, melt-layer movement and loss of melt layer [2]. Longer plasma instabilities expected in reactor conditions will significantly increase the thickness of the melt layer [15]. This overall result in increased melt-layer erosion due to various mechanisms. In addition, mechanical vibration associated with reactor disruption can pull off parts of the melt layer, causing additional erosion.

5. Conclusions

Experimental results and preliminary models and calculations have been presented to study melt-layer erosion of metallic PFCs. Hydrodynamic instabilities and volume bubble vaporizations are among the mechanisms that lead to melt-layer erosion during interaction of plasma instabilities with PFMs. Melt-layer erosion of PFMs will significantly shorten the lifetime of these components. Erosion in the reactor environment may be more severe than shown in laboratory simulation experiments. More-detailed modeling and more reactor-relevant simulation experiments are required to assess the damage from various types of plasma instabilities and correctly evaluate PFC lifetime, plasma contamination and other safety issues. Future studies are planned to investigate these concerns.

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