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HIGH HEAT FLUX MATERIALS DUE TO INTENSE HEAT LOADS

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Abstract

The first wall surfaces of a fusion device will be subjected to intense energy deposition under standard and off normal operating conditions. To model this phenomena, the thermal response of copper, niobium, 304 SS and other materials was studied using a well calibrated electron beam. The tests were from 100 to 600 ms in duration with the surface energy density ranging from 0.2 to 6.2 kJ/cm². For each material, the net vaporization and average melt layer thickness was measured as a function of absorbed energy density. These experimental results were compared to predictions from an analytical model developed for this thermal problem. General agreement was found for the threshold energy density required for vaporization and melting, as well as the functional dependence of vaporization on energy density. There is some indication from the results that the heat transfer models for the vaporized layer should be refined. Also, some discrepancies between the predicted and measured melt layer at high energy densities suggest improvements are needed in handling the convective mixing within the molten material.

Introduction

The inner components of a magnetic confinement fusion reactor will be subjected to an intense thermal load during steady state and transient situations. In particular, transient heat loads of several kJ/cm² can persist for hundreds of milliseconds on localized vessel regions. This energy deposition will occur under normal operating conditions in locations such as neutral beam dumps and limiter blade tips. Unplanned events, such as plasma disruptions, could deposit a sizeable fraction of the entire plasma energy on any of the high heat flux components in only a few milliseconds. If this happens, large temperature excursions will occur along with material vaporization (10's of microns), melting (100's of microns), or sublimation. The vapor and melt layers, subject to a strong magnetic field, may be removed from their original location and redeposited elsewhere in the device. The performance of the plasma will be affected and the damaged components will have a reduced lifetime and diminished usefulness. To facilitate high heat flux material and component design, many theoretical studies [1-6] have been conducted to quantify the material response to such intense energy deposition. However, depending upon the heat transfer models and the assumed disruption conditions, the predicted melt layer and vaporization thicknesses can vary by over an order of magnitude [6]. This implies that the theoretical predictions must be correlated with experimental data.

Experiments to model the reaction of high heat flux materials to intense heat loads normally use electron beams as the pulsed heat source [7-10]. The strategy is to collect a body of experimental data concerning thermal processes such as vaporization,

melting, sublimation, and the vapor/incident particle interaction. This data can then be used to verify and enhance the existing theoretical models and suggest further areas of study. The augmented models can in turn aid in the material selection and high heat flux component designs. Throughout this process, a consistent set of boundary conditions and assumptions must be maintained. It is also necessary to transcend dilemmas such as the use of high energy electron beams to simulate lower energy plasma particle fluxes and the use of one or two dimensional theoretical solutions to model three dimensional problems.

The following sections summarize an effort to correlate theoretical predictions and experimental results for intense energy deposition in materials. The analytical thermal models, developed at the University of Wisconsin [1,4,5,10], are briefly outlined. The experimental procedure that utilizes an electron beam to model the material response to heat loads is given. The experimental measurements of vaporization and melt layer thickness are compared to the analytical prediction and conclusions are drawn.

Thermal Model for Material Response
to Energy Deposition

The predicted vaporization and melt layer thicknesses of a high heat flux material subjected to intense energy deposition were obtained with SOAST, a finite difference computer code. This model was based upon the time and space dependent heat conduction equations and solution suggested by Hassanein [4,5]. The vapor-liquid and liquid-solid interfaces cause this to be a double moving-boundary solution. To properly model the steep temperature gradients, temperature dependent vapor pressure and thermo-physical properties were used, but this also causes the equation set to be nonlinear. The deposited energy was distributed into conduction, phase changes, and radiation. Also, the interaction of the incoming particle flux with the vapor rising off of the condensed phases was included. Complete details of the equations, boundary conditions, vaporization model, and solution methods are discussed elsewhere [4,5,10].

For comparison with the experimental data, two models were used to calculate the net vaporization and average melt layer thicknesses as functions of deposited energy density. The first considered vaporization which would result if the entire vapor layer was removed as it was produced. This unshielded case allowed the electron energy flux to deposit into the condensed material, causing the maximum possible vaporization. The second case distributed the incident electron energy uniformly over the particle penetration depth in the vapor. While the electron energy deposition was not treated in an exact manner, this model was useful in determining the role of the vapor in the energy deposition process. Thus, the two cases represent the worst case and more experimentally realistic scenarios.

The Energy Deposition Experiment

The Electron Beam Test System (EBTS) at Sandia National Laboratories, Albuquerque [11] was used for energy deposition testing for eleven different materials. The electron gun is a 30 kW, 30 kV device with a beam that is roughly 1/2 cm at FWHM. For these experiments, the beam was rastered at a rate of 400 Hz over a 1 cm² area. Diagnostics of the facility used for these tests included: a TV monitoring system with video recorder, an optical pyrometer to record sample surface temperature, and residual gas analysis of the species evolved.

Calibration of the EBTS included beam spatial analysis and measurements of the time dependent power density. By scanning a small aperture Faraday cup through the beam, it was determined that the two dimensional current profile was basically constant in the region intersected by the sample. Also the current profile was constant from one pulse to the next. The temperature response of a calorimeter was coupled with a solution of the inverse heat conduction equation, to calculate the power density deposited by the beam as a function of time. This showed that the power density was a square function in time and, by integration, gave the total deposited energy to within 5%. The calorimetry tests were repeated over a range of gun power and pulse duration, thus giving values for the total deposited energy for all thermal test parameters.

The samples were solid cylinders, 1.27 cm in height and 1.0 cm in diameter. A total of 350 samples, distributed evenly between the materials and the associated test conditions shown in Table 1, were tested. The samples were placed upon a water-cooled plate and held with loose thermal contact by a graphite holder. The exposed end of each sample was subjected to only one pulse from the electron gun which was vertically positioned 30 cm over the sample.

Weight loss measurements were used to determine the net vaporized thickness for each sample. Selected specimens were cross sectioned and etched using standard metallographic techniques to expose the melted region. The melt zone shape was digitized and used for a calculation of total melt volume and average melt layer thickness. The results were plotted as

Table 1
Summary of Materials and Thermal Test Conditions

Material	Test Duration (ms)	Energy Density (kJ/cm ²)
Aluminum	100	0.2 - 1.1
Vanadium	100	0.5 - 1.2
Iron	200	0.5 - 2.1
SS 304	100	0.5 - 1.3
	200	0.5 - 1.9
	300	0.4 - 2.3
Nickel	200	0.7 - 2.1
	300	0.8 - 2.7
Copper	200	1.1 - 2.4
	300	0.4 - 3.8
Niobium	300	1.4 - 3.8
Graphite (Poco AXF5Q)	100	0.4 - 1.3
	200	0.6 - 2.7
	300	0.8 - 2.9
Tantalum	400	1.0 - 4.3
	400	2.0 - 4.4
Molybdenum	400	1.7 - 4.6
Tungsten	600	3.6 - 6.2

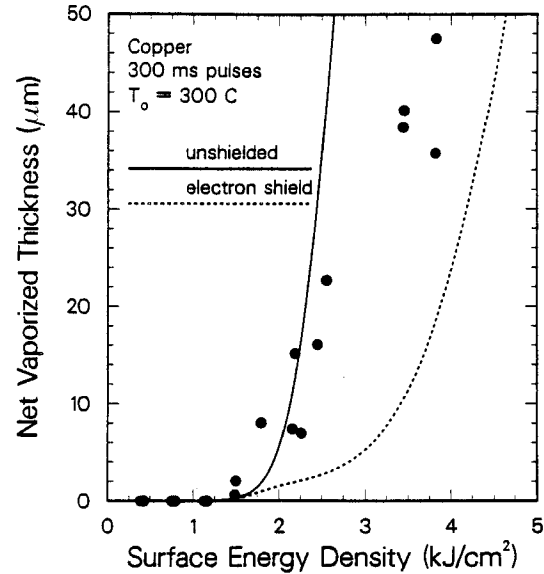


Fig. 1. Theoretical and experimental results for copper vaporization due to 300 ms pulses.

deposited energy, as determined by the calibration process, vs. net vaporization and melt layer thicknesses.

Correlation of Theoretical and Experimental Results

The volume of data is such that only a portion will be presented. The four data sets shown are copper, niobium, and SS 304 tested for 300 ms pulses and SS 304 tested for 100 ms pulses. This allows comparison of different materials under similar energy deposition conditions and analysis of one material subjected to different thermal flux conditions.

Figure 1 shows the net vaporized thickness of copper as a function of surface energy density for 300 ms pulses. Also shown are two theoretical curves as previously described. Figure 2 shows the corresponding data for the melt layer thickness. The theoretical curves and the experimental data agree for the threshold for vaporization and melting. The theory also bands the vaporization data quite well, and the increase in measured vaporized thickness with surface energy density agrees with the electron shield model. The predictions for the melt thickness in copper agree with the data until a value of 3000 μm is reached. At this point the experimental data continues on a linear increase while the unshielded theory curve predicts a maximum melt layer at ~ 4500 μm and 3 kJ/cm². The electron shield theory curve predicts a much slower rate of increase beyond 3 kJ/cm². The theoretical predictions for melting show this behavior because the thermal diffusion is quite slow in comparison to the rate of energy deposition, i.e. the energy is deposited at such a rapid rate that it cannot be conducted into the material to advance the solid-liquid interface. Consequently, the liquid is superheated and vaporization increases. This effectively couples the vaporization to the conduction within the liquid.

Figures 3 and 4 show the vaporization and melt layer results for niobium subjected to 300 ms pulses respectively. The predictions and data also agree for the threshold of vaporization and melting. The vapor-

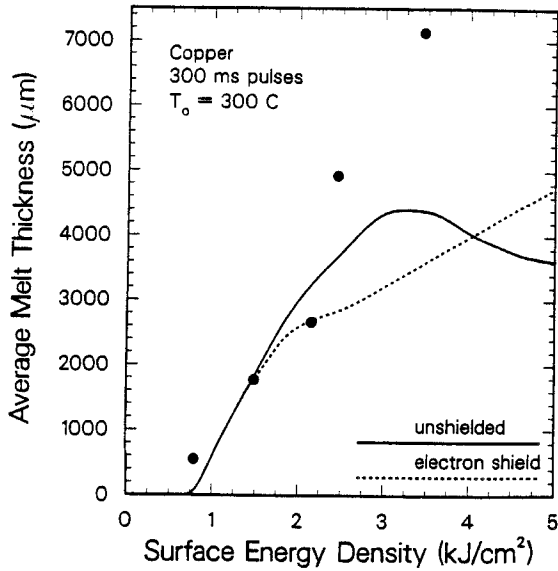


Fig. 2. Theoretical and experimental results for copper melt due to 300 ms pulses.

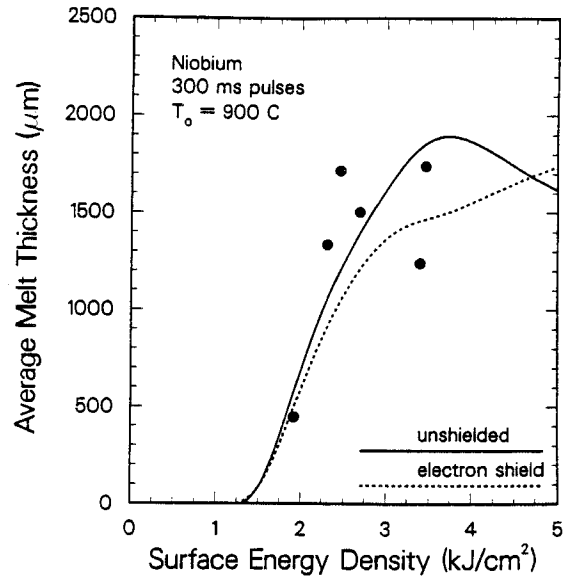


Fig. 4. Theoretical and experimental results for niobium melt due to 300 ms pulses.

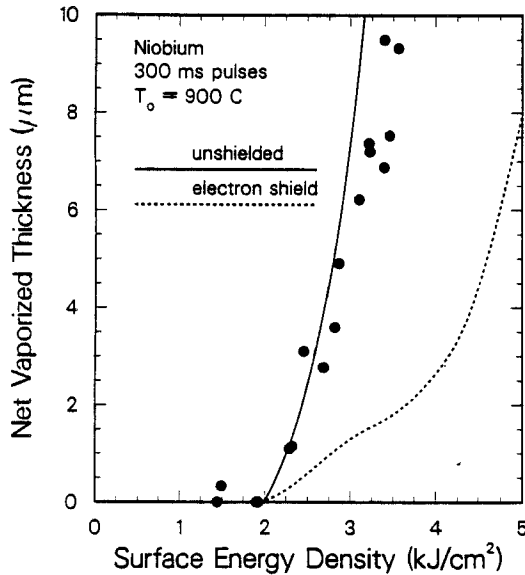


Fig. 3. Theoretical and experimental results for niobium vaporization due to 300 ms pulses.

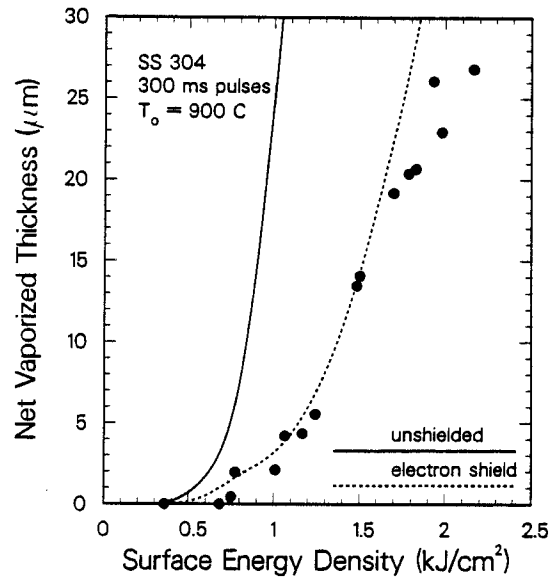


Fig. 5. Theoretical and experimental results for SS 304 vaporization due to 300 ms pulses.

ization data agrees with the unshielded theory curve, although the two seem to diverge at the higher values of vaporized thickness. For melting, the theoretical and experimental results are consistent for values below 1800 μm and $\sim 3 \text{ kJ/cm}^2$. The scatter in the existing data does not indicate if agreement would occur for all surface energy densities.

As seen in Fig. 5, the electron shield theory model fits the data for SS 304 subjected to 300 ms pulses. The threshold for vaporization is predicted and there is slight divergence between the experiments

and models at higher values of energy density. Figure 6 shows the melt data for this set of energy deposition tests. There is some disagreement for the melt threshold although this is exaggerated by the expanded scale. Once again the experimental melt data increases linearly beyond 900 μm and $\sim 1.5 \text{ kJ/cm}^2$ while the theory curves reach a plateau value.

The results for vaporization and melting of SS 304 after 100 ms pulses are shown in Fig. 7 and 8 respectively. The electron shield curve presents a good fit to the vaporization data. This is especially

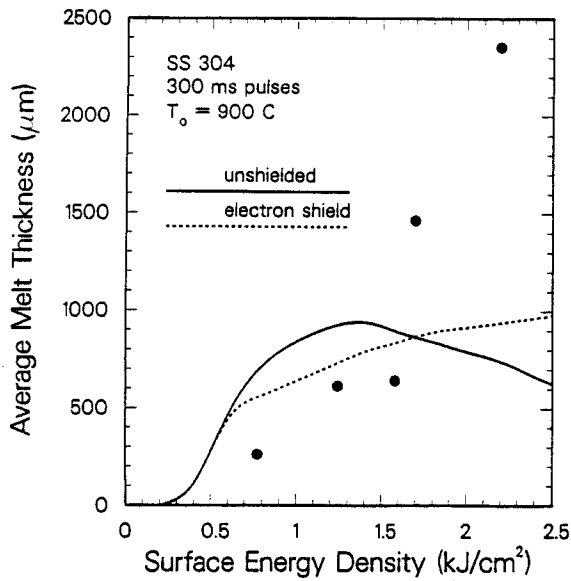


Fig. 6. Theoretical and experimental results for SS 304 melt due to 300 ms pulses.

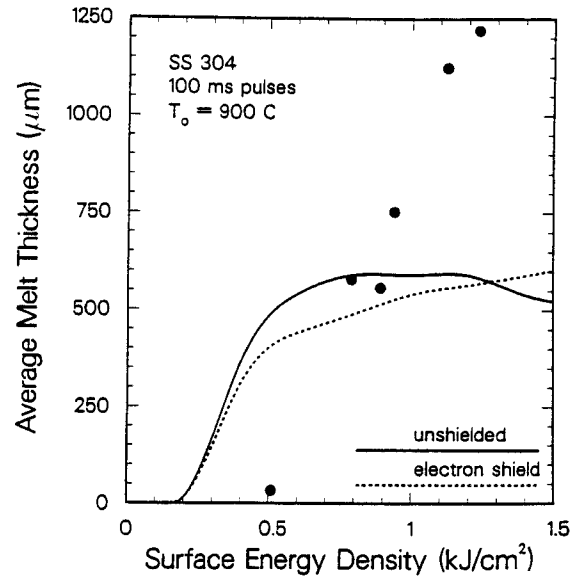


Fig. 8. Theoretical and experimental results for SS 304 melt due to 100 ms pulses.

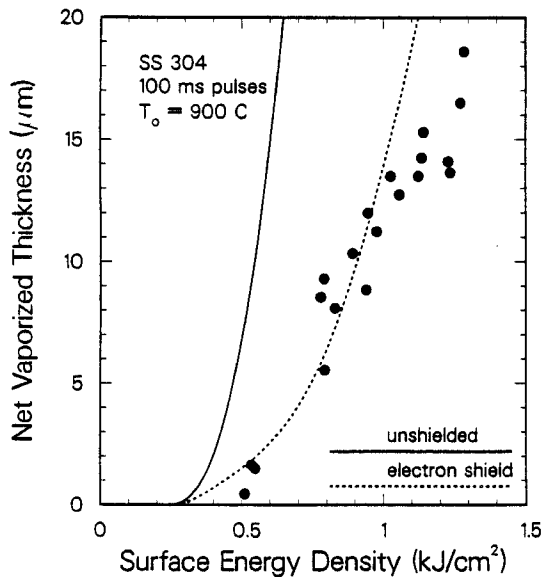


Fig. 7. Theoretical and experimental results for SS 304 vaporization due to 100 ms pulses.

true in the mid-region but the lack of data exactly at the threshold makes the comparison there tentative. The experimental measurements of melting show the typical linear increase beyond 600 μm and $\sim 900 \text{ J}/\text{cm}^2$. As in the previous cases, the theory and the experimental values diverge drastically at the higher values of surface energy density.

Discussion

There is nominally a 10% error associated with the energy density and the vaporization and melt layer

experimental data. First, some error is associated with the beam-sample alignment prior to a pulse. Each sample had to be placed under the electron beam gun such that it would be in the exact center of the beam spot. After alignment each sample was preheated before the beam pulse, but there was variation in the initial temperature of the samples by $\pm 5\%$. The initial temperature obviously affects the amount of sensible heat required to reach melting and thus the time for melting and vaporization. The calibration techniques to determine the surface energy density have to consider the experimental temperature measurements and the numerical methods of the inverse conduction equation solution as sources of error. As would be expected, there is also some error in the weight measurements for vaporization and in the cross sectioning, identification, and digitization of the melt layers.

Since the SOAST code is one-dimensional, it is necessary to minimize lateral heat conduction in the experiment. The samples were cooled at the base and encased in a slow thermal response material to direct the heat transfer through the long axis of the cylinder on the time scale of the pulse. It has been shown that lateral heat transfer due to the spatial variation of the energy density will strongly affect the vaporization and melting caused by energy deposition of this type [12]. To avoid this problem, the electrons were purposely focused into a broad beam and rastered over an area larger than the sample to produce a uniform surface heat flux. Input to the theoretical solution included the temperature dependent thermophysical properties of the materials. The predictions of vaporization and melt layer thicknesses are extremely sensitive to these properties, especially the material vapor pressure and thermal diffusivity. The documented properties are fitted values for materials in controlled laboratory conditions. The properties of the material used for the energy deposition tests would, in all probability, vary from the ideal and that could affect the comparison substantially.

With an understanding of the error inherent to the experimental and theoretical result, it is possible to compare the two. In the four cases presented, reasonable agreement was obtained for the vaporization threshold. In all cases the functional increase of vaporization with increasing energy density is predicted by the theoretical curves. For the range of vaporization measured, the unshielded theory curve has the better agreement for the niobium and copper data, but there is divergence at large values of energy density. The electron shield curve has a close fit to the SS 304 vaporization data, however, the surface energy density of the theoretical curves and the experimental data for SS 304 lie in a narrow band when considered on the scale of the copper or niobium data. When large amounts of vapor are produced as in the case of the copper and niobium, the unshielded model overpredicts the vaporization. This is also true for SS 304 where preferential vaporization of manganese has already been observed [7]. The shielding provided by the manganese rich vapor and the lower vapor pressure of the depleted liquid could combine to lower the measured vaporization in SS 304. The overall indication is that the vapor shields the condensed material in some way, but the theoretical model needs to more rigorously account for the heat transfer in the vapor.

In the melt layer results, the threshold for melting is reasonably well predicted in copper and niobium but the theory predicts too low of a threshold for SS 304. In all of the melt layer results, general agreement between the theory and experimental data is seen for the lower values of energy density, but there is a distinct point at which experiments and theory diverge. It is believed that this is due to convective mixing which is not taken into account in the theoretical models. It is possible that at some melt layer thickness, characteristic to the material, convective cells are formed in the molten pool. This would transfer the hot liquid to the solid-liquid interface and take the cool liquid to the sample surface, thus increasing the melt layer drastically and decreasing the vaporization. This effect would continue with the vapor shield phenomena to reduce vaporization. The experimentally measured melt layer thickness would continue to increase with energy density since the convective mixing decouples the vaporization and conduction, removing the barrier of slow thermal diffusion to increased melting.

Conclusions

The following conclusions can be drawn:

1. The theoretical and experimental results agree for the energy threshold required for vaporization and melting, particularly for single element materials.
2. The same functional increase of the vaporization thickness with increasing energy density is seen in both the analytical model and the experimental data, but improvements in the vapor heat transfer model and the vapor shielding concept are needed to give a more exact solution.
3. The discrepancy between the measured melt layer thicknesses and the model predictions at large magnitudes indicates that a mechanism not previously considered, such as convective mixing, may have an important role in the material response to intense energy deposition.

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