TIME DEPENDENT ELECTRON DEPOSITION WITH THERMAL TRANSPORT AS APPLIED TO SURVIVABLE ANODES IN FLASH X-RAY MACHINES*

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Abstract

The in-depth instantaneous temperature distribution in the anode was calculated for a flash x-ray (FXR) machine. This analysis was compared with measurements made on the Arnold Engineering Development Corporation, AEDC, MBS (Modular Bremsstrahlung Source) FXR and applied to predicting the maximum electron beam loading acceptable for the Defense Threat Reduction Agency (DTRA) Compact X-ray Simulator (CXS). The time dependent calculation of the anode temperature was done in three steps. First, the dose deposition profile from a small time increment of the electrical pulse was obtained by interpolation using range scaling from a table of ITS [1] generated deposition profiles. Next, this additional change in energy (enthalpy) was converted to an increase in temperature. Finally, the thermal transport during the time increment was calculated by using a finite difference procedure for solving the partial differential equation for thermal transport. The thermal transport solution was applicable to the solid-to-liquid phase transition so that the depth of vaporization could be estimated. The vaporized material was thermally decoupled from the rest of the anode. Experimental measurements were made on the AEDC MBS FXR using a smaller area anode and cathode than normally used on the MBS to purposely increase the electron energy density on the anode. The analytical modeling of the heating of the anode showed that the anode material remained on the anode surface until the anode reached its boiling point. The material ejected from the anode not only eroded the anode surface but caused unacceptable damage to the cathode.

I. INTRODUCTION

The maximum available fluence from a FXR survivable reflection anode is a function of the beam potential, beam energy, and the beam area. Although a small amount of anode debris is acceptable, large amounts of debris can damage the cathode or coat the vacuum insulator which would make the diode "non-survivable." The generation of debris from the anode is caused by vapor formation due to electron beam heating in the anode. This paper describes a procedure for estimating the amount of anode erosion by calculating the depth to which vapor is formed.

II. COMPUTATIONAL PROCEDURE

The electron beam current and potential waveforms were divided into a finite number of time steps. The incremental energy deposition profile for each time step was calculated and converted into an increase in temperature from the previous time step. The re-distribution of temperature was then calculated for the time step except that vaporized material was de-coupled from the thermal transport calculation.

Thermal diffusion was calculated as a simple 1D problem with insulated boundaries and no heat input. In this case the thermal diffusion equation is given by

$$\frac{\partial u}{\partial t} = \kappa \frac{\partial^2 u}{\partial^2 x}$$

and

$$\kappa = \frac{K(t)}{C_p(t)\,\rho(t)} \quad ,$$

where κ is the temperature dependent thermal diffusivity. K is the thermal conductivity, C_p is the heat capacity, and ρ is the density.

The finite difference solution for insulated boundaries is given by [2]:

$$u(i,n+1) = u(i,n) + \lambda(u(i-1,n) - 2u(i,n) + u(i+1,n)) \quad ,$$

where

$$\lambda = (\kappa \Delta t)/(\Delta x)^2 \ .$$

The i index is for depth and the n index is for time. This solution is convergent provided $0 < \lambda < 0.5$.

C_p was used instead of C_v since the spatial dimensions were small (~1 µm) and the shock speeds are relatively large (~1E6 cm/s). A comparison of C_p with C_v up to the

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melting point of tantalum is shown in Fig. 1. The data shown for the C_p measurements were from several sources as collected by AMPTIAC [3]. The solid lines were calculated from a theoretical model [4]. Unfortunately, data were not found on the specific heat of liquid tantalum. The value used was based on typical changes observed in the specific heats of other metals when changing from the solid to liquid state. Both the melt and vaporization phase changes were allowed to take place over a finite temperature change. The heat of fusion and the heat of vaporization were incorporated into C_p.

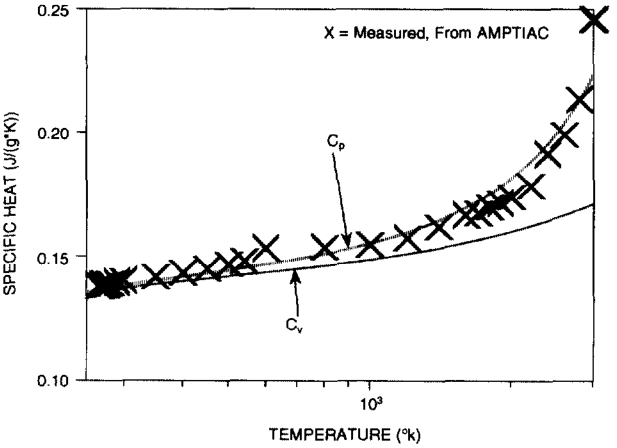

Figure 1. Specific heat of tantalum.

III. MEASUREMENTS MADE ON AN MBS STYLE REFLECTION DIODE

A small MBS anode and cathode were made to decrease the beam area from about 160 to 100 cm^2. A series of shots were taken on the AEDC MBS FXR in which the energy loading was gradually increased to study the damage on the anode. Anode erosion was not observable from depth measurements until peak currents of 370 kA were reached for the peak potentials of 230 kV used in the test. The before and after erosion depth measurements were made with a Boice Coordinate Measuring Machine at AEDC for 10 shot sequences. Erosion of ~0.1-mil/shot agreed with calculated depth of vapor formation.

The calculated temperature distribution in the tantalum anode at the end of the electron beam deposition period is shown in Fig. 2 for both a typical standard MBS shot at 200 kV and 340 kA and a typical shot from the smaller CXS anode at 230 kV and 370 kA. The depth of vaporization increased from less than 0.5 to over 2 μm. This increase in mass removal from the anode caused noticeable increase in the damage to the cathode wires as compared with the standard MBS diode. Using the constraint of less than 0.5 μm of anode removal per shot, the maximum fluence over 1000 cm^2 with ±20% uniformity was calculated for the smaller CXS diode as a function end point potential as shown in Fig. 3. By increasing the end point potential to 300 kV a fluence of 1.0 mcal/cm^2 can be obtained.

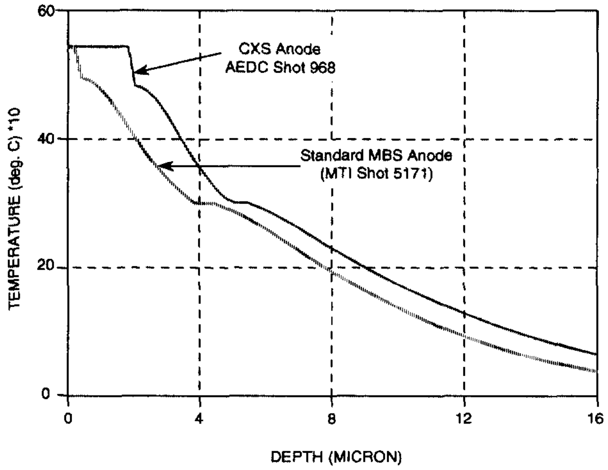

Figure 2. Comparison between the in-depth heating of a standard MBS anode versus the CXS anode tested at AEDC (shot 968).

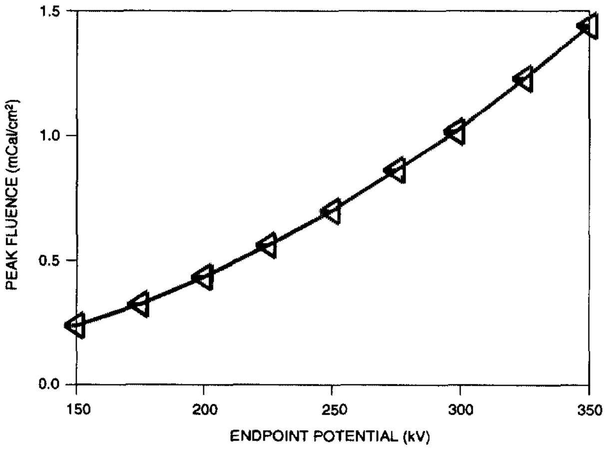

Figure 3. X-ray fluence obtainable from a survivable CXS reflection anode.

IV. CONCLUDING REMARKS

The anode erosion measurements and the model for depth of vapor formation were consistent. This implied that the liquid tantalum metal was too viscous to leave the anode surface until increased pressure from vapor expelled the anode material. Increasing the electron beam potential increased the electron penetration depth which lowered the anode surface temperature per unit electron beam energy. Increasing the electron beam potential not only increases the x-ray fluence production but allows the use of higher e-beam energies before excessive anode damage. Vapor formation on the anode surface is a natural constraint in the design of a survivable anode. The computation of the temperature rise in the anode allows one to design a survivable anode and predict the fluence obtainable under this constraint.

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