Predictions of Melt-through Times for Laser Heating

Peter J. Torvik*
Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio

Theme

THE principal effect of high intensity continuous laser radiation on a metallic target is a temperature rise leading to melting, and possibly vaporization. Times required for complete melt-through of metal sheets are considered. A numerical method for predicting the thermal response is applied to obtain general conclusions on the influence of radial conduction and melt removal on the melting time. New variables which lead to a means of quickly estimating melt-through times from a given curve and formulas, are introduced.

Contents

Of specific interest is the time required to melt a hole in a disk or thin sheet, the dimensions of which are large compared to those of the region over which an axially symmetric flux is applied. In such cases, the heat flux vector at interior points will have both radial and axial (through the thickness) components. A totally axial flux leads to the minimum melt-through time. This may be computed from a heat balance on a thickness ℓ of material of density ρ and specific heat C absorbing a fraction α of the flux I incident on a unit area.

$$t_l = \frac{\rho\ell}{\alpha I}\,[C(T_m - T_0) + L_m] \tag{1}$$

Here, T_m is the melting temperature, L_m is the heat of fusion, and t_l is the time required for complete melting. All properties are assumed to be independent of temperature, and it is assumed that the melt is removed by some mechanism as soon as it forms. The influence of melt retention will be considered later. The analogous time for complete vaporization is obtained by replacing T_m with T_v and L_m by $L_m + L_v$, where T_v and L_v are the vaporization temperatures and heat of vaporization, respectively.

Normalizing the actual melting times t_m, whether obtained by experiment or by computation, by dividing by t_l yields

$$\theta = t_m / t_l \tag{2}$$

which provides a measure of the one-dimensionality. A large θ corresponds to a radial flux large compared to the axial flux, and will occur if the heated region is small compared to the thickness, or if the heated region is small compared to the depth δ of heating. As one or the other of these conditions must be satisfied if the product of the 2 ratios is small, it follows that the conduction will predominantly be axial if the product is large, or

$$(\sigma/\ell)\ (\sigma/\delta) > M \tag{3}$$

Here σ is a characteristic dimension of the heated region, and M is a dimensionless parameter assumed to be independent of intensity and material properties. The temperature at a depth z into a solid initially at $T = T_0$ and melting at the surface $z = 0$ is

$$T(z) = T_0 + (T_m - T_0)\exp(-Vz/\kappa) \tag{4}$$

where κ is the thermal diffusivity, and speed V of the steady melting front is $V = \ell/t_l$. The depth of heating δ may be defined as the depth where the temperature rise is arbitrarily small, or

$$[T(\delta) - T_0]/[T_m - T_0] = \epsilon = \exp(-\delta\ell/\kappa t_l) \tag{5}$$

Using Eqs. (5) and (1) to eliminate δ and t_l, and noting that the absorbed power is of the form

$$P_a \sim \alpha\sigma^2 I_{\text{peak}} \tag{6}$$

the criterion for one-dimensional melting can be rewritten as

$$P_{\ell a} > P_{\ell a^*} \tag{7}$$

where

$$P_{\ell a} = P_a/\ell\kappa\rho[L_m + C(T_m - T_0)] \tag{8}$$

is a dimensionless absorbed power per unit thickness, and $P_{\ell a^*}$ is a critical value, above which the melting will be predominantly axial. This suggests that the absorbed power per unit thickness governs whether a melting problem is predominantly axial, two-dimensional, or radial.

A numerical method was developed[1] and employed to obtain results[2] which could be used to ascertain if the new variables θ and $P_{\ell a}$ introduced previously have the anticipated significance. The mathematical problem of interest is the transient heat conduction equation for the temperature $T(r, z, t)$ in a disk of radius a, thickness ℓ, and conductivity k,

$$k\nabla^2 T = \rho C \frac{\partial T}{\partial t} \tag{9}$$

in terms of an axial coordinate, z, and radial distance, r. The boundary conditions of general interest are prescribed fluxes on portions of the boundary, with losses due to convection and radiation on the remainder. Particular results given here are for a Gaussian distribution of absorbed intensity over the heated zone with peak value I_{pa}, and no losses elsewhere, or

$$\frac{\partial T}{\partial z} = -\frac{I_{pa}}{k}\, e^{-r^2/2\sigma^2} \text{ on } z = 0,\ r \le 2\sigma \tag{10}$$

and the normal derivative of temperature is zero elsewhere.

A simple finite element approach was chosen. The time rate of change of temperature is computed for each element from the current values of temperature of the element and its neighbors; thus the method is equivalent to an explicit finite difference computation. Phase changes were accounted for by fixing the temperature of a transforming cell during the addition of sufficient net energy to change the phase of the mass in that cell. Two other approaches to the solution of Eq. (9) have been to neglect the influence of phase changes,[3] and to

Received July 22, 1974; presented as Paper 75-114 at the AIAA 13th Aerospace Sciences Meeting, Pasadena, California, January 20-22, 1975; synoptic received August 6, 1975; revision received December 22, 1975. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.**

Index categories: Heat Conduction; Lasers.

*Professor, Department of Mechanics and Engineering Systems.

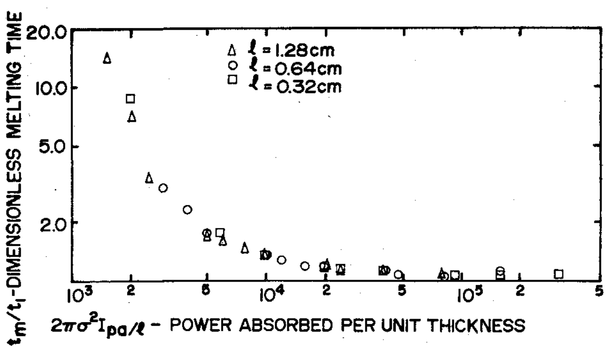

Fig. 1 Computed dimensionless melt-through times for magnesium with melt removal.

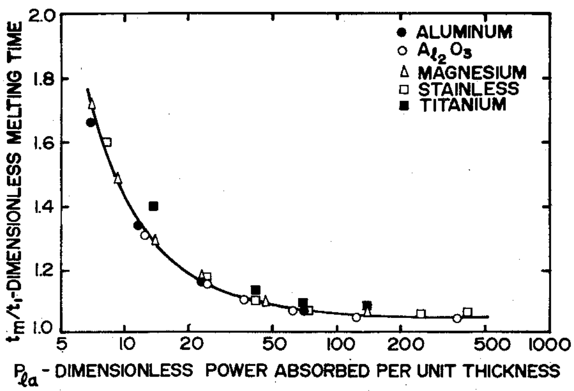

Fig. 2 Computed results for several materials with melt removal and constructed curve for use in predicting melt-through times.

solve analytically an analogous linear problem. This is obtained by using a properly chosen effective specific heat.[4]

Calculations for magnesium were performed using a range of thicknesses, spot sizes, and peak intensities. It is evident from Fig. 1 that all computed results can be adequately described by a single curve, thereby demonstrating the utility of the variables θ and power absorbed per unit thickness. The results suggest a critical value of power absorbed per unit thickness, above which the computed melt-through time is essentially t_l. The usefulness of this pair of variables in consolidating numerical results was recently confirmed by other investigators.[5]

To demonstrate that the dimensionless power absorbed per unit thickness, defined in Eq. (8), properly accounts for material properties, further calculations[2] were undertaken using other materials. The results are given in Fig. 2. It can be seen that for $P_{\ell a} \geq 70$ the melting time for any material considered is within 10% of the value predicted by Eq. (1). This confirms the existence of a single critical value of $P_{\ell a}$ appropriate for any material, and that $P_{\ell a}$ determines the significance of radial conduction.

Using the curve given in Fig. 2, it is possible to estimate the melting time for any thickness of any material, under any given continuous beam, if the assumption of total melt removal is applicable. The dimensionless power per unit thickness is first computed from Eq. (8). Using this, the dimensionless time θ is read from Fig. 2, and the melting time is determined from the product of this ordinate and t_l.

The assumption of complete and instantaneous melt removal may be justified in the presence of a strong air flow. However the alternative of melt retained through vaporization must also be considered. Dimensionless melt-

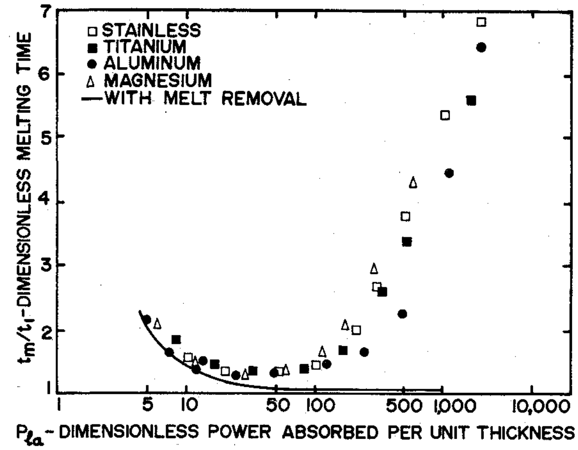

Fig. 3 Computed melt-through times for several materials with retained melt for $\sigma/\ell = 3.25$.

through times (points) for 4 materials with melt retained were computed, and are compared in Fig. 3 with the dimensionless time required for melting with complete melt removal (solid line). It can be seen that the retained melt causes only a slight increase in melt-through time for low values of $P_{\ell a}$. At larger values, the time ratio increases as more and more of the incident energy is "wasted" in heating and evaporating the melt. Retention and vaporization of the melt introduces a dependence of melting time on the ratio σ/ℓ, which is 3.25 for the results in Fig. 3. Little energy is "wasted" through melt heating in an extremely thin sheet as the front surface of the liquid is only a few degrees above melting at the time the rear surface melts, whereas the front surface of a thick sample may vaporize before the rear surface melts.

An estimate of the influence of melt retention on dimensionless melt-through time is

$$t_m/t_l \cong \theta(P_{\ell a}) + \frac{P_{\ell a}}{12\pi}\left(\frac{\ell}{\sigma}\right)^2 \tag{11}$$

where θ is the value of t_m/t_l for no melt retention. This estimate is valid up to the intensity at which front surface vaporization occurs before rear surface melting, or, in terms of the dimensionless absorbed power per unit thickness, for

$$P_{\ell a} \leq 4\pi(\sigma/\ell)^2 \frac{C(T_v - T_m)}{[L_m + C(T_m - T_0)]} \tag{12}$$

As is suggested by Fig. 3 and Eq. (11), a most efficient power for melting any sheet exists, that being a power great enough to minimize two-dimensional effects, but not of such magnitude as to produce "wasted" energy through excessive melt heating or vaporization.

References

[1] Torvik, P. J., "A Numerical Procedure for Two-Dimensional Heating and Melting Calculations with Applications to Laser Effects," AFIT TR-72-2, 1972, AD 757189.

[2] Torvik, P. J., "Some Further Numerical Studies of Laser Induced Melting and Vaporization," AFIT TR 73-1, Jan. 1973, AD 760113.

[3] Ready, J. F., *Effects of High Power Laser Radiation,* Academic Press, 1971, pp. 88-91.

[4] Breaux, H. S., "Simple Formulas for CW Laser Burnthrough Times when Radial Heat Conduction is Significant," BRL-1834, Sept. 1975.

[5] Weckesser, L. B. and Newman, R. W. "Sensitivity of Laser Effects to Material Properties," AIAA Paper 75-717, 1975.