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Melting Induced In a Finite Silver Selenide(Ag_2Se) Slab by a Time-Dependent Laser Source

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The problem of melting a finite silver selenide (Ag_2Se) slab induced by pulsed laser source is studied .The integral form of the heat diffusion equation and boundary condition of fourth kind are considered to obtain the rate of melting and the thickness of the molten layer. It is found from the obtained expressions for both functions that they depend linearly on the maximum power irradiance of the considered laser pulse , while the dependence on the other operating conditions is not linear .Computations for an illustrative example are given .

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I. Introduction

Laser interaction with matter has aroused the interest of many authors[1-15]The absorption of such high power density radiation may be associated with change of phase of the absorbing material .This phenomenon has vital applications including welding , cutting of metals, scribing of holes , laser shock hardening, laser glazing,local diffusion and alloying to form p-n junction and information recording .

The considered material (Ag_2Se) is of great technological importance as a promising thermoelectric power generator material[9].It has also applications in the switching devices [10,11].

This material has two phases : a low temperature phase below 400K and is identified as (β- Ag_2Se) with a structure of orthorhombic and shows metallic nature and another phase at a higher temperature T > (403±2)K and is denoted as (α-Ag_2Se)phase with body-centered-cubic (bcc) form which shows metallic nature[10].The aim of the introduced trial is to study theoretically

the melting of a homogeneous slab of silver silenide Ag_2Se material induced by pulse laser to obtains the functions expressing the

the thickness of the molten layer and the rate of melting and explore their functional dependence on the laser parameters and other operating conditions.

II.THEORY

The problem of heating the considered solid target is studied by El-Adawi et al[14].A pulsed laser source that induced the heating effects was of the following Gaussian form[4,14] :

$$q_\circ(t) = q_{\max} \exp[-(\frac{t-t_\circ}{\Gamma})^2] \qquad (1)$$

Where $q_{\max}$ W/m^2 is the maximum value (the peak) of the pulse attained at $t = t_\circ$, Γ is the full width at half maximum (FWHM) ofthe suggested laser pulse.

In sitting up the problem it is assumed that the laser radiation is partly reflected and partly absorbed at the front surface. The heat flow is considered one dimensional when the diameter of the laser spot is large compared to the penetration depth of heat within the considered target[2,6].The authors obtained the temperature field within the irradiated target in the form[14] :

$$\theta(x,t)=\frac{1}{2\rho C_p L}(1-R)\,q_{\max}\,\Gamma\,\sqrt{\pi}\;\; erf[\frac{t-t_\circ}{\Gamma}]+\frac{q_{\max}\exp[-(\frac{t-t_\circ}{\Gamma})^2]\,(1-R)}{\lambda}[\frac{L}{3}-x+\frac{x^2}{2L}]+$$

$$\sum_{n=1}^{\infty}\;\frac{-2}{n\pi}q_{\max}\exp(-(\frac{t-t_\circ}{\Gamma})^2)$$

$$+\frac{2\alpha}{L^2}\{q_{\max}(\frac{\Gamma^2-t_\circ{}^2}{\Gamma^2})(\frac{L^2}{\alpha n^2\pi^2})(1-\exp(-\alpha(\frac{n\pi}{L})^2 t))-$$

$$\frac{q_{\max}}{\Gamma^2}(\frac{L^2(-2L^4\exp(-\alpha(\frac{n\pi}{L})^2 t)+2L^4-2L^2n^2\pi^2 t\alpha+\alpha^2n^4\pi^4t^2)}{\alpha^3n^6\pi^6})+$$

$$(\frac{2q_{\max}t_\circ L^4\exp(-\alpha(\frac{n\pi}{L})^2 t)-2q_{\max}L^2t_0(L^2-\alpha n^2\pi^2 t)}{n^4\pi^4\alpha^2\Gamma})\}]\frac{L}{\lambda}Cos\frac{n\pi}{L}x \quad (2)$$

Equation (2) can be rewritten in the form :

$$\theta(x,t)=f(t)+A(t)[\frac{L}{3}-x+\frac{x^2}{2L}]+B(t)\frac{L}{\lambda}\cos\frac{n\pi}{L}x \quad (3)$$ where,

$$f(t)=\frac{1}{2\rho C_p L}(1-R)\;q_{\max}\,\Gamma\sqrt{\pi}\;erf\;[\frac{t-t_\circ}{\Gamma}]\;\;(I)$$

$$A(t)=\frac{q_{\max}(1-R)\exp(-(\frac{t-t_\circ}{\Gamma})^2)}{\lambda_s}\quad (II)$$

$$B(t)=\sum_{n=1}^{\infty}[\;\;\frac{-2}{n\pi}q_{\max}\exp(-(\frac{t-t_\circ}{\Gamma})^2)$$

$$+\frac{2\alpha}{L^2}\{q_{\max}(\frac{\Gamma^2-t_\circ{}^2}{\Gamma^2})(\frac{L^2}{\alpha n^2\pi^2})(1-\exp(-\alpha(\frac{n\pi}{L})^2 t))-$$

$$\frac{q_{\max}}{\Gamma^2}(\frac{L^2(-2L^4\exp(-\alpha(\frac{n\pi}{L})^2 t)+2L^4-2L^2n^2\pi^2 t\alpha+\alpha^2n^4\pi^4t^2)}{\alpha^3n^6\pi^6})+$$

$$(\frac{2q_{\max}t_\circ L^4\exp(-\alpha(\frac{n\pi}{L})^2 t)-2q_{\max}L^2t_0(L^2-\alpha n^2\pi^2 t)}{n^4\pi^4\alpha^2\Gamma})\}]\quad (III)$$

Where ,
L,m is the thickness of the slab
α (= $\frac{\lambda}{\rho c_p}$, m^2/sec) is the thermal diffusivity of the slab material in terms of the thermal conductivity λ , W/mk and the heat capacity per unit volume ρc_p , J/m^3K , θ (= $T-T_0$) is the excess temperature relative to the ambient T_0, K .

The melting process starts when the temperature of the front surface reaches the melting temperature θ_m . In addition it is assumed that the temperature in the molten layer is kept constant at the phase-changetemperature θ_m[6] . By the passage of time the thickness of the molten layer X(t) increases and the temperature distribution in the solid phase increases gradually .The temperature at the interfacial boundary X(t) is kept constant at θ_m at $t \geq t_m$. The rate of melting is expressed as $\frac{dX(t)}{dt}$.

The heat balance equation at the interfacial boundary X(t) is written in the form[6,15] :

$$q_0(t)\,(1-R) = \rho_s\, Q_{L,x}\, \frac{dX}{dt} - \lambda_s \left.\frac{\partial\theta}{\partial x}\right|_{x=X(t)} \qquad (4)$$

Where , $Q_{L,x}$ (J/kg)is the latent heat of fusion
ρ_s (kg/m^3) is the density of the solid phase,
λ_s is the thermal conductivity of the solid phase .
At the interface x = X(t) the condition is :

$$\theta_\ell = \theta_s = \theta_m \qquad (5)$$

Moreover, at the rear surface x=L :

$$\left.\frac{\partial\theta}{\partial x}\right|_{x=L} = 0 \qquad (6)$$

Equation (6) indicates that the slab is thermally insulated at the rear surface .The heat conduction equation in the solid phase is given in the form :

$$\frac{\partial\theta}{\partial t} = \alpha_s \frac{\partial^2\theta}{\partial x^2} \qquad , t \geq t_m , X \leq x \leq L \qquad (7)$$

Let us consider the integral form of the heat conduction equation (7) as follows :

$$\int_{X=X(t)}^{L} \frac{\partial\theta}{\partial t}\, dx = \alpha_s \int_{X=X(t)}^{L} \frac{\partial^2\theta}{\partial x^2}\, dx \qquad (8)$$

Using the following relation[15,16]:

$$\frac{d}{d\beta}\int_a^b f(x,\beta)\,dx = f(b,\beta)\frac{db}{d\beta} - f(a,\beta)\frac{da}{d\beta} + \int_a^b \frac{\partial f}{\partial\beta}\,dx \qquad (9)$$

Thus one can write equation(8) in the form :

$$\frac{d}{dt}\left(\int_X^L \theta(x,t)\,dx\right) - \theta(L,t)\frac{dL}{dt} + \theta(X,t)\,\frac{dX}{dt} = \alpha_s \int_{X=X}^{L} \frac{\partial^2\theta}{\partial x^2}\,dx \qquad (10)$$

Applying the boundary conditions(equations (5),(6))to equation (10) one gets :

$$\frac{d}{dt}\left(\int_X^L \theta(x,t)\,dx\right) + \theta_m \frac{dX}{dt} = -\alpha_s \left.\frac{\partial\theta}{\partial x}\right|_{x=X(t)} \qquad (11)$$

Substituting for $\left.\frac{\partial\theta}{\partial x}\right|_{x=X(t)}$ from the heat balance equation (4) intoequation (11) one gets :

$$\frac{d}{dt}\left(\int_X^L \theta(x,t)\,dx + \theta_m X(t)\right) = \alpha_s\left(\frac{-\rho_s Q_L}{\lambda_s}\frac{dX}{dt} + \frac{q_\circ(t)\,(1-R)}{\lambda_s}\right) \qquad (12)$$

Equation (12) can be rewritten in the form :

$$\frac{d}{dt}\left(\int_X^L \theta(x,t)\,dx + \left(\theta_m + \frac{Q_L}{c_p}\right) X(t)\right) = \frac{q_\circ(t)\,(1-R)}{\rho_s\, C_p} \qquad (13)$$

On the otherhand one can evaluate $\left.\frac{\partial\theta}{\partial x}\right|_{x=X(t)}$ considering the temperature profile equation (3) to get :

$$\left.\frac{\partial\theta}{\partial x}\right|_{x=X(t)} = A(t)\,(\frac{X}{L}-1) - B(t)\,\frac{n\pi}{\lambda}\,\sin\frac{n\pi}{L}X \qquad (14)$$

Evaluating the integral in equation (13) using the expression (3) one gets :

$$\int_X^L \theta(x,t)\,dx = f(t)\,(L-X) + A(t)\,[\frac{L}{3}(L-X) - \frac{1}{2}(L^2-X^2)$$

$$+\frac{1}{6L}(L^3-X^3)] - \frac{B(t)\,L^2}{\lambda n\pi}\sin\frac{n\pi}{L}X \qquad (15) \qquad\qquad (5-16)$$

Thus equation (13) can be rewritten as follows :

$$\frac{d}{dt}[[\ f(t)\,(L-X) + A(t)\,\{\frac{L}{3}(L-X) - \frac{1}{2}(L^2-X^2) + \frac{1}{6L}(L^3-X^3)\} - \frac{B(t)L^2}{\lambda n\pi}\sin\frac{n\pi}{L}X\ ]+$$

$$(\theta_m + \frac{Q_L}{C_p}\,X(t)] = \frac{q_\circ(t)\,(1-R)}{\rho\,C_p} \qquad (16)$$

On the otherhand , substituting for $\left.\frac{\partial\theta}{\partial x}\right|_{x=X(t)}$ from equation (14) into equation (4) one gets:

$$q_0(t)\,(1-R) + \lambda_s[A(t)\,(\frac{X}{L}-1) - \frac{B(t)\,n\,\pi}{\lambda}\sin\frac{n\pi}{L}\,X] = \rho_s\,Q_L\,\frac{dX}{dt} \qquad (17)$$

Let us consider the following expansions :

$$\sin\frac{n\pi}{L}X = \frac{n\pi}{L}X - \frac{1}{6}(\frac{n\pi}{L})^3\,X^3 + \ldots\ldots.. \qquad (18)$$

$$\cos\frac{n\pi}{L}X = 1 - (\frac{n\pi}{L})^2\,\frac{X^2}{2!} + \ldots.. \qquad (19)$$

This makes it possible to express $\dot{X}(t)$ in terms of $X(t)$ as follows :

$$\dot{X}(t) = \frac{1}{\rho_s\,Q_L}[q_\circ(t)(1-R) + \lambda_s\{A(t)(\frac{X}{L}-1) - B(t)\frac{n\pi}{\lambda_s}(\frac{n\pi}{L}X - \frac{1}{6}(\frac{n\pi}{L})^3X^3)\}] \qquad (20)$$

Moreover,considering the operator $\frac{d}{dt}$ in equation (16) together with the expression of $\dot{X}(t)$ in equation (20) makes it possible to get the following equation :

$$[\dot{f}\ \ (t)(L-X) - f(t)\,\dot{X}(t) + \dot{A}(t)\{\frac{L}{3}(L-X) - \frac{1}{2}(L^2-X^2) + \frac{1}{6L}(L^3-X^3)\}+$$

$$\dot{X}(t)\{A(t)\,(-\frac{L}{3} + X - \frac{1}{2L}X^2) + (\theta_m + \frac{Q_L}{C_p})\} - \dot{X}(t)\ \{\frac{B(t)\,L}{\lambda}\ (1-\frac{1}{2}(\frac{n\pi}{L})^2\ X^2)\}-$$

$$\{\frac{\dot{B}(t)\,L^2}{\lambda\,n\,\pi}(\frac{n\pi}{L}\ X - \frac{1}{6}(\frac{n\pi}{L})^3\,X^3)\ \}] = \frac{q_\circ(t)\,(1-R)}{\rho C_p} \qquad (21)$$

Substituting for $\dot{X}(t)$ from equation (20) into equation (21) and rearranging the different terms of increasing power of $X(t)$ one getsthe following equation for the thickness of the molten layer :

$$C_1 X + C_2 X^2 + C_3 X^3 + C_4 X^4 + C_5 X^5 + C = 0 \qquad (22)$$

Where :

$$C = [L\,\dot{f}(t) - \frac{f(t)}{\rho_s\,Q_L}\,q_\circ(t)\,(1-R) + \frac{f(t)\,\lambda_s}{\rho_s\,Q_L}\,A(t) - \frac{L\,q_\circ(t)\,(1-R)\,A(t)}{3\rho_s\,Q_L} + \frac{q_\circ(t)\,(1-R)}{\rho_s\,Q_L}(\theta_m + \frac{Q_L}{C_p}) - \frac{q_\circ(t)\,B(t)\,L\,(1-R)}{\rho_s\,Q_L\,\lambda_s} + \frac{\lambda_s\,A^2(t)\,L}{3\rho_s\,Q_L} - \frac{\lambda_s\,A(t)}{\rho_s\,Q_L}(\theta_m + \frac{Q_L}{C_p}) + \frac{L\,A(t)\,B(t)}{\rho_s\,Q_L} - \frac{q_\circ(t)\,(1-R)}{\rho\,C_p}\;] \qquad (23)$$

$$C_1 = [-\dot{f}(t) - \frac{f(t)\,\lambda_s}{\rho_s\,Q_L\,L}\,A(t) + \frac{(n\,\pi)^2\,f(t)}{\rho_s\,Q_L\,L}\,B(t) - \frac{L}{3}\dot{A}(t) + \frac{q_\circ(t)\,(1-R)\,A(t)}{\rho_s\,Q_L} - \frac{\lambda_s\,A^2(t)}{3\rho_s\,Q_L} - \frac{\lambda_s\,A^2(t)}{\rho_s\,Q_L} + \frac{\lambda_s\,A(t)}{\rho_s\,Q_L\,L}(\theta_m + \frac{Q_L}{C_p}) - \frac{A(t)\,B(t)}{\rho_s\,Q_L} + \frac{(n\,\pi)^2\,A(t)\,B(t)}{3\rho_s\,Q_L} - \frac{(n\,\pi)^2\,B(t)}{\rho_s\,Q_L\,L}(\theta_m + \frac{Q_L}{C_p}) + \frac{(n\,\pi)^2\,B^2(t)}{\rho_s\,Q_L\,\lambda_s} - \frac{\dot{B}(t)\,L}{\lambda_s}] \qquad (24)$$

$$C_2 = [\,\frac{1}{2}\dot{A}(t) - \frac{q_\circ(t)\,(1-R)\,A(t)}{2\rho_s\,Q_L\,L} + \frac{(n\pi)^2\,q_\circ(t)\,B(t)\,(1-R)}{2\,\rho_s\,Q_L\,\lambda_s\,L} + \frac{\lambda_s\,A^2(t)}{\rho_s\,Q_L\,L} + \frac{\lambda_s\,A^2(t)}{2\,\rho_s\,Q_L\,L} - \frac{(n\,\pi)^2\,A(t)\,B(t)}{2\rho_s\,Q_L\,L} - \frac{(n\,\pi)^2\,A(t)\,B(t)}{\rho_s\,Q_L\,L}] \qquad (25)$$

$$C_3 = [-\frac{(n\,\pi)^4\,f(t)\,B(t)}{6\rho_s\,Q_L\,L^3} - \frac{1}{6L}\dot{A}(t) - \frac{\lambda_s\,A^2(t)}{2\rho_s\,Q_L\,L^2} + \frac{(n\,\pi)^2\,A(t)\,B(t)}{2\rho_s\,Q_L\,L} + \frac{(n\,\pi)^2\,A(t)\,B(t)}{2\rho_s\,Q_L\,L^2} - \frac{(n\,\pi)^4\,B^2(t)}{2\rho_s\,Q_L\,\lambda_s\,L^2} - \frac{(n\,\pi)^4\,B(t)\,A(t)}{18\rho_s\,Q_L\,L^2} + \frac{(n\,\pi)^4\,B(t)}{6\rho_s\,Q_L\,L^3}(\theta_m + \frac{Q_L}{C_p}) - \frac{(n\,\pi)^4\,B^2(t)}{6\lambda_s\rho_s\,Q_L\,L^2} + \frac{(n\pi)^2\,\dot{B}(t)}{6\,\lambda_s\,L}] \qquad (26)$$

$$C_4 = [\,\frac{(n\,\pi)^4\,B(t)\,A(t)}{6\rho_s\,Q_L\,L^3}\,] \qquad (27)$$

$$C_5 = [-\frac{(n\,\pi)^4\,B(t)\,A(t)}{12\,\rho_s\,Q_L\,L^4} + \frac{(n\,\pi)^6\,B^2(t)}{12\,\lambda_s\,\rho_s\,Q_L\,L^4}] \qquad (28)$$

Estimating the order of magnitude of different factors C_i ,together with the fact that the thickness L is of order O(-6) and considering that $X(t) \leq L$ makes it possible to simplify equation (22) to be a quadratic equation of the form :

$$C_2 X^2 + C_1 X + C = 0 \qquad (28)$$

With roots :

$$X(t) = \frac{-C_1 \pm \sqrt{C^2{}_1 - 4\,C_2\,C}}{2\,C_2} \qquad (29)$$

II. Computations

As an illustrative example the thickness of the molten layer $X(t)$ is computed for a slab of silver selenide of thickness L = 10^{-5} m , subjected to a laser pulse of the Gaussian shape of parameters : $q_{\max}$ = 0.7 x 10^8 W/m^2 , Γ = 3.5μs , t_0 = 4μs . The physical and thermal properties of silver selenide slab material[17,18]are given in table I

T**ABLEI**.The physical,thermal,optical properties[17,18]of the chosen material of silver selenide

material	ρ, kg/m^3	λ, W/mK	α, m^2/s	θ_m,K	θ_{ph},K	C,J/kgK	(1-R)
silver selenide	8200	1.08	29x10-7	855	403	277	0.322

The critical time required to initiate melting for such a case is t_m=1.29μs[14], the latent heat of fusion Q_L= 10^5 J/kg . The obtained resultsare given in table IIand are illustrated graphically in figure I.

The TABLE II. Thickness of the molten layer of silver selenide slab $X(t)$ as a function of the exposure time, for time intervals greater than the melting time t_m=1.29μs[14], $q_{\max}$= 0.7 x 10^8 W/m^2

t,μs	$X(t)$,m
1.3	0
1.4	2.67 x10^{-21}
1.5	4.34 x10^{-21}
1.6	5.15 x10^{-21}
1.7	6.01 x10^{-21}

Sometimes, one gets decreasing values of $X(t)$ and these are excluded.

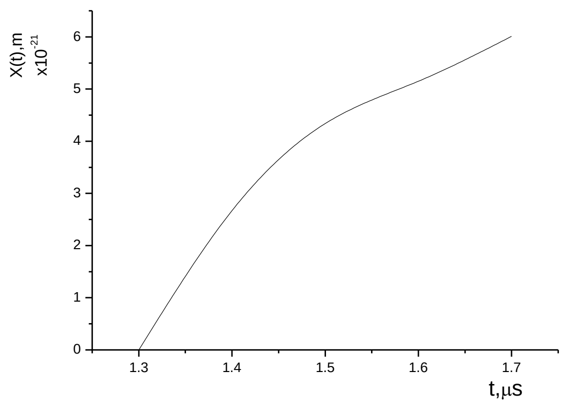

figure. The thickness of the molten layer of silver selenide slab $X(t)$ as a function of exposure time,for time intervals greater than the melting time t_m=1.29μs),q_{max}=0.7x10^8 W/m^2.

III. Conclusions

The analysis of the obtained results reveal that :

1- The thickness of the molten layer $X(t)$ and the rate of melting $\dot{X}(t)$ both depend linearly on $q_{\max}$ of the considered laser pulse . This fact was also supported before[6].

2- The dependence of the functions $f(t)$, $A(t)$, $B(t)$,defined in the text on $q_{\max}$is also linear.

3- The dependence of $X(t)$ and $\dot{X}(t)$ on the physical, geometrical, optical, and thermal properties of the considered target is not linear.

4- Further theoretical trials are required to render ,the complicated expressions of $X(t)$ and $\dot{X}(t)$ to be more simplerone.This will be useful for practical purposes .

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