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FOREIGN TECHNOLOGY DIVISION

CALCULATION OF THE SURFACE TEMPERATURE OF METAL TARGET, HEATED BY LASER RADIATION, OPERATING IN FREE-RUNNING MODE

by

V. B. Lugovskoy

EDITED TRANSLATION

FTD-ID(RS)I-1554-76 11 November 1976

FTD-76-C-001131

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English pages: 7

Source: Izvestiya Akademii Nauk UZSSR Seriya, Fiziko-Matematicheskikh Nauk, 1970, Vol 14, Nr 5, PP. 51-54.

Country of origin: USSR
Translated by: Robert Potts
Requester: FTD/PDRR
Approved for public release; distribution unlimited.

PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

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Г г	*Г г*	G, g	У у	*У у*	U, u
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Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α ∝		Nu	Ν	ν
Beta	Β	β		Xi	Ξ	ξ
Gamma	Γ	γ		Omicron	Ο	ο
Delta	Δ	δ		Pi	Π	π
Epsilon	Ε	ε ∈		Rho	Ρ	ρ ϱ
Zeta	Ζ	ζ		Sigma	Σ	σ ς
Eta	Η	η		Tau	Τ	τ
Theta	Θ	θ ϑ		Upsilon	Τ	υ
Iota	Ι	ι		Phi	Φ	φ ϕ
Kappa	Κ	ϰ κ		Chi	Χ	χ
Lambda	Λ	λ		Psi	Ψ	ψ
Mu	Μ	μ		Omega	Ω	ω

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

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rot	curl
lg	log

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CALCULATION OF THE SURFACE TEMPERATURE OF A METAL TARGET, HEATED BY LASER RADIATION, OPERATING IN FREE-RUNNING MODE

V. B. Lugovskoy

With the fulfillment of certain conditions [1] the heating of metal by laser radiation pulse can be calculated within the theory of thermal conductivity. In this case the solution of the thermal problem can be obtained in general form by standard methods. However, during the practical computation of the temperature of the metal target surface, heated by laser radiation, operating in free-running mode, considerable difficulties appear, which are connected with the complex character of change of the power and density of radiation power in time.

The methods of solving thermal problems, based on the summation of temperature increments, caused by the action of radiation peaks, standardized with respect to power, form and pulse repetition [2, 3], although they permit revealing some peculiarities of the thermal action of laser radiation on metals, are little suitable for practical use during the study of the kinetics of heating of a substance by laser pulses.

It is expedient to obtain the approximate solution by examining separately the action of a single peak and the combined action of a large number of radiation peaks. If the solution of the boundary value problem of thermal conductivity can be represented in the form of Duhamel integral

$$T(x, y, z, t) = \int_0^t h(x, y, z, t-\vartheta) f(x, y, 0, \vartheta)\, d\vartheta = h(x, y, z, t) * f(x, y, 0, t), \quad (1)$$

where

$T(x, y, z, t)$ - change of temperature at point $\{x, y, z\}$ at moment of time t;

$f(x, y, o, t)$ - absorbed part of the density of light flux at point $\{x, y, o, t\}$ on the metal surface;

$h(x, y, z, t)$ - function, the form of which is determined by the equation of thermal conductivity, initial and boundary conditions, then by using one-sided Laplace transform with respect to time it is easy to show that the action of linear differential operator L (with respect to variable t) on T(t) is equivalent to its action on any of the functions of convolution $h(t)$ or $f(t)$.

If as such an operator we use the averaging operator on interval $(t - \Delta t, t)$ or close to it (with sufficiently large values $t > \frac{\Delta t}{2} = \tau$), the operator of smoothing of the signal of RC-chain with time constant τ, then the change of temperature, caused by laser pulse, can be found by the successive application of two operations.

First let us calculate the average (smoothed) value

$$\bar{T}(t) = h(t) * \bar{f}(t), \quad (2)$$

and then, acting on $\bar{T}$ with operator L^{-1}, inverse to L, we obtain

$$T(t) = L^{-1} \bar{T}(t). \quad (3)$$

The precise determination of temperature from relationships (2) and (3) is connected with the same difficulties as with the use of equation (1). However, from these relationships we can find the approximate value of T*(t), the difference of which from T(t) is connected with the loss of high-frequency components of the signal during recording of the smoothed laser pulse $f(t)$ and during numerical integration (2). The values of T*(t) and T(t) can be represented in the form

$$T^*(t) = T_i(t) + T_n, \quad (4)$$

$$T(t) \approx T^*(t) - \bar{T}_n + T_n, \quad (5)$$

where $T_i(t)$ - lower envelope of temperature pulse, subsequently called the integral temperature;

T_n - change of temperature, caused by a separate peak;

$\bar{T}_n$ - its average value on the interval between two adjacent peaks.

With smoothing of the laser signal by RC-chain T* can be found from relationship

$$T^*(t) = T(t) + \tau \frac{dT(t)}{dt}. \quad (6)$$

Thus, for the characteristic of target heating at assigned moment of time t it is necessary to find integral heating $T_i(t)$ and change of temperature $T_n(t)$ under action of a separate radiation peak at the considered moment of time. Calculation of the integral temperature is substantially simplified with the use of smoothed functions of laser power $f(t)$, which are not difficult to obtain experimentally.

As practice has shown, sufficiently "smooth" functions are obtained with $\tau \approx 10^{-5}-10^{-4}$ sec. Because of the comparative simplicity, smoothed functions in some cases can be approximated by linear or other known functions of time and a final solution for integral heating can be obtained in analytical form.

By the described method of calculation we established the main distinctive features of the thermal action of laser radiation, operating in free-running mode, on metal targets if the average and statistical parameters of the laser pulse and the peaks entering its composition are known. In particular, we can determine the relationship between peak and integral heating, find the threshold density of energy or density of power, at which failure of the target material is started, we can establish their connection with space-time parameters of real laser pulses.

If we consider that all the thermophysical characteristics of the material do not depend on the temperature, and the dimensions of the illuminated part of the target surface and its thickness are much smaller than the length of diffusion of heat $\sqrt{at}$ (a -coefficient of thermal conductivity), and we assume that radiation is distributed uniformly within the irradiated zone for each peak, then the relationship of maximums of peak and integral heating γ_i and the threshold value of the energy density of laser pulse w_{exper} are determined by relationships

[illegible] (7)

[illegible] (8)

here

$$\gamma_0 = \frac{T_{n\max}}{T^*_{\max}} = \frac{1}{N}\frac{\gamma_n}{\gamma_i}\sqrt{\frac{\tau_i}{\tau_n}}$$

$$\gamma_{11} = \frac{\bar{T}_n}{T_{n\max}}$$

(for rectangular peak $\gamma_{11} \approx \frac{1-\frac{1}{Q}}{\sqrt{Q}}$, Q -smoothness of peaks);

τ - pulse duration; γ - magnitude depending on its form (for π -pulse $\gamma=1$, for triangular pulses γ can take values from 0.94 to 1.09 depending on the relationship of durations of the forward and rear fronts);

indices n and i pertain respectively to the peak and total pulse;

K and R - coefficients of thermal conductivity and reflectivity of the metal;

c and ρ - its specific heat and density; N - total number of peaks in the laser pulse.

Comparison of experimental and calculated data during the study of electron emission from nickel [4], and also the computed and observed values of $w_{n.pad}$ has shown that during the determination of the temperature of the target surface it is necessary to consider the nonidentity of the spatial distribution of the radiation intensity in the separate peaks and in the total laser pulse.

If we assume that the area, irradiated by the separate peak, on the average is n times smaller that area S, irradiated by the total laser pulse, but during time t'=nt the average value of density of radiation power remains the same as with identical distribution of radiation in the peaks and pulse, then it is easy to show that

$$T^{*\prime} = T^*, \quad T_n^{\prime} = nT_n,$$

$$\eta^{\prime} \approx \frac{n\tau_0}{1 - \tau_1\tau_0\sqrt{n}} \quad \text{and} \quad w_{\text{порог}}^{\prime} \approx \frac{1 + \tau_i(1 - \tau_1)}{1 + \tau_i^{\prime}\left(1 - \frac{\tau_1}{\sqrt{n}}\right)} w_{\text{порог}}$$

(the primes correspond to the nonidentical distribution of intensity).

With large spacings of peaks $(Q \geqslant 30)$ or considerable space-time nonuniformity of radiation the peak heating can be equal in value or even exceed the maximum integral temperature. Under these conditions exceeding the threshold density of energy will lead to decrease of the rates of growth of integral heating due to losses of of energy on evaporation of the surface layer of substance.

Examination of the simplified model of target heating with the vaporization of metal by separate peaks of radiation has shown that along with the limitation of maximum attainable integral temperature there should occur a shift of the center of gravity of the temperature pulse toward the start of the reading of time with increase of the density of the power of radiation hitting the target.

If $w < w_{\text{порог}}$, the dependence of the maximum of integral heating on the radiation power density is linear. For $w > w_{\text{порог}}$ a discontinuity of this dependence should be observed at temperature

$$T_{\text{разр}} \approx \frac{T_{\text{исп}}}{1 + \frac{n}{N}\sqrt{\frac{\tau_1}{\tau_u}}}.$$

It should be noted that a decrease of the reflection of light by the target surface with rise of its temperature will lead to the opposite phenomena. In particular, increase of the radiation power density is accompanied by a shift of the center of gravity of the integral heating pulse to the right along the time axis. As was shown in [3], for peak heating high rates of change of temperature during heating and the cooling down of metal are characteristic. Intergal heating describes a slower process with considerably smaller temperature gradients and deeper pene-ration of heat into the metal.

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Submitted 18 Oct. 1968

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4. TITLE (and Subtitle) CALCULATION OF THE SURFACE TEMPERATURE OF A METAL TARGET, HEATED BY LASER RADIATION, OPERATING IN FREE-RUNNING MODE		5. TYPE OF REPORT & PERIOD COVERED Translation 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) V. B. Lugovskoy		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Foreign Technology Division Air Force Systems Command U. S. Air Force		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE 1970 13. NUMBER OF PAGES 7
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