

# Change of the nature of skin absorption during CO<sub>2</sub>-laser beam irradiation of a metallic target

M. TUTUNARU, D. TĂȚAR

University of Craiova, Romania.

I. N. MIHĂILESCU

Central Institute of Physics, Bucharest, Romania.

The change of the absorption mechanism from the normal skin effect to the anomalous skin effect is predicted theoretically and confirmed experimentally in the case of high power cw laser irradiation of metallic samples.

## 1. Introduction

The absorption of the laser radiation by a metal can occur under either normal or anomalous skin-effect conditions [1].

In the case of laser absorption occurring under normal skin-effect conditions, the role of the metal surface with the current induced in the metal by the electromagnetic wave is considered. The length  $l$  of the electron free path is much smaller than the depth  $\delta$  of the skin-layer, and therefore the electron collision frequency  $\nu(0)$  is much higher than the laser radiation frequency  $\omega$ .

In case of laser absorption under anomalous skin-effect conditions the length of conductivity electron free path is much larger than the skin layer depth, thus resulting in an important influence of the metal surface on the process of electromagnetic radiation absorption. In this case, the conductivity electron collision frequency  $\nu(0)$  is much lower than that of the laser radiation  $\omega$ .

## 2. Theoretical approach

The theoretical description of the process of laser radiation absorption by the contaminated metal in air must include both the diffusion of impurities from the surface towards the inner part of metallic target and the process of target oxidation. The dynamics of metallic surface temperature change is usually described by a set of equations comprising: i) the metal thermal conductivity equation in which the capacity of absorption of the laser radiation, sometimes called absorpti-

vity  $A(x)$ , is included, this quantity being calculated by means of the metal surface impedance  $Z_3(\nu)$ ; ii) the diffusion equation for impurities with boundary and initial conditions specific to the considered problem, wherefrom by calculating the impurity concentration  $N(z, t)$  we can find the frequency of electron-impurity collision  $\nu^n$ ; and iii) Maxwell equations which give the metal surface impedance  $Z_3$ .

The dynamics of change of the temperature  $T$  of the in-air irradiated, contaminated metal targets is described by the set of equations [2]:

$$mc_0 \frac{dT}{dt} = PA(x) - P_p(t), \quad (1a)$$

$$P_p(T) = S[\eta(T - T_0) + \bar{\sigma}\bar{\sigma}_0(T^4 - T_0^4)], \quad (1b)$$

$$A(x) = 1 - |R(x)|^2, \quad (1c)$$

$$R(x) = \frac{r_{12}e^{2i\psi} + r_{23}}{e^{2i\psi} + r_{12}r_{23}}, \quad (1d)$$

$$r_{23} = \frac{r_{12} - r_{13}}{r_{12}r_{13} - 1}, \quad (1e)$$

$$r_{12} = \frac{1 - \sqrt{\epsilon_2}}{1 + \sqrt{\epsilon_2}}, \quad (1f)$$

$$\sqrt{\epsilon_2} = n_2 - i\kappa_2, \quad (1g)$$

$$\psi = \frac{2\pi}{\lambda} x \sqrt{\epsilon_2}, \quad (1h)$$

$$r_{13} = -1 + \frac{c}{2\pi} Z_3, \quad (1i)$$

$$\frac{dx}{dt} = \frac{d_0}{x} \exp(-T_D/T), \quad (1j)$$

$$Z_3 = \frac{2\pi}{c} \frac{\omega}{\omega_p} \left[ \sqrt{\sqrt{1 + \frac{\nu^2(0)}{\omega^2}} + \frac{\nu(0)}{\omega}} - \sqrt{\sqrt{1 + \frac{\nu^2(0)}{\omega} - \frac{\nu(0)}{\omega}}} \right] \\ + i \frac{2\pi}{c} \frac{\omega}{\omega_p} \left[ \sqrt{\sqrt{1 + \frac{\nu^2(0)}{\omega^2}} + \frac{\nu(0)}{\omega}} + \sqrt{\sqrt{1 + \frac{\nu^2(0)}{\omega} - \frac{\nu(0)}{\omega}}} \right], \quad (1k)$$

$$\nu(0) = \nu^{ef} + \nu^n, \quad (1l)$$

$$\nu^n = \langle N(z) \rangle a\nu_F \quad (1m)$$

where  $m$ ,  $c_0$  and  $S$  are the metallic target mass, specific heat and area, respectively;  $P$  and  $P_p$  are the power of the incident laser radiation and the power lost by the metallic target through convection and radiation, respectively;  $x$ ,  $\epsilon_2$ ,  $n_2$  and  $\kappa_2$  are respectively the thickness of the oxide deposited on the metal surface, the permittivity, the refraction index and the metal absorption index;  $\eta$ ,  $\bar{\sigma}$  and  $\bar{\sigma}_0$  are the convective heat exchange constant, the emissivity of the sample surface and the Stefan-Boltzmann constants,  $d_0$  and  $T_D$  are the constants characterizing the natures of the oxide and the metal related to the oxidation law;  $\nu^{ef}$  is the electron-phonon collision frequency, while  $a$  and  $v_F$  are the impurity electron scattering area and Fermi surface electron velocity, respectively.

During the laser irradiation the oxide layer thickness  $x$  is increasing and surface impurities diffuse towards the inner part of target, therefore "cleaning" its surface [2-5]. Consequently, the length of the electron free path, which at the beginning is shorter than  $\delta$ , will become larger than  $\delta$  at the end of the laser irradiation. Initially, the laser beam absorption occurs under normal skin-effect conditions which after a certain cleaning time  $t_c$  are changed into the anomalous ones.

In the case of anomalous skin absorption, the condition  $\nu(0) \ll \omega$  is met and therefore the surface impedance  $Z_3$  will have the following simplified form:

$$Z_3^a = \frac{\pi}{c} A_0(t) \left[ 1 + i \frac{2\omega}{\nu(0)} \right]. \quad (2)$$

In the case of laser absorption under normal skin conditions the condition  $\nu(0) \gg \omega$  is satisfied, and the simplified form of the surface impedance is

$$Z_3^n = \frac{\pi}{c} A_0(t) (1 + i). \quad (3)$$

The amplitude coefficient of the wave reflected on the metal-air boundary will accordingly have the following simplified forms:

$$r_{13}^n = -1 + \frac{A_0(t)}{2} (1 + i), \quad (4a)$$

$$r_{13}^a = -1 + \frac{A_0(t)}{2} \left[ 1 + i \frac{2\omega}{\nu(0)} \right] \quad (4b)$$

where  $r_{13}^n$  and  $r_{13}^a$  denote the coefficients of the wave reflected on the metal-air boundary in case of normal and the anomalous skin absorption, respectively. The collision frequency  $\nu(0)$  will be calculated using the average value of  $\langle N(z) \rangle$  of the solution of the equation of impurities diffusion towards the target inner part, and will be equal to

$$\nu(0) = \nu^{ef} + \frac{N_0}{\sqrt{1 + \varphi}} a v_F \quad (5)$$

where

$$\varphi = \frac{4D_0}{z_0^2} \int_0^T \exp[-T_{00}/T(\tau)] d\tau, \quad (6)$$

here  $D_0$ ,  $z_0$  and  $T_{00}$  are the coefficient characterizing the diffusion, the depth of the layer homogeneities and the temperature of activation of the diffusion process, respectively.

The metal absorption coefficient  $A_0(t)$ , in which the impurity diffusion phenomenon is taken into account, is

$$A_0(t) = A_{01} + (A_{02} - A_{01})(1 + \varphi)^{-1/2} \quad (7)$$

where  $A_{01}$  is the pure metal absorption capacity,  $A_{02}$  is the contaminated metal absorptivity.

The time of metallic surface cleaning will be calculated considering that the impurities are diffused along a depth equal to that of the skin layer

$$\delta^2 = 2d_0 \int_0^{t_c} \exp(-T_D/T) dt. \quad (8)$$

Assuming that within this range the temperature is a linear function of time, we can write

$$\delta^2 = \frac{d_0 mc_0 T_D}{PA_0} (T/T_D)^2 \exp(-T_D/T). \quad (9)$$

The linear dependence of the temperature in the first heating state is justified by small heat losses when the temperature  $T$  is low. We shall therefore assume

$$T - T_0 = \frac{PA_0}{mc_0} t. \quad (10)$$

The time for cleaning the metallic target will be equal to

$$t_c \simeq \frac{mc_0}{PA_0} \frac{T_D}{\ln \left( \frac{32\pi^2 d_0 mc_0 T_D}{P\lambda^2 A_0^3} \right)}. \quad (11)$$

### 3. Results and discussion

We have solved numerically the set of equations (1) in case of cw  $\text{CO}_2$  laser irradiation ( $P \simeq 30$  W) of a non-polished copper sample having a rather high laser absorptivity  $A_0 \sim 0.1$ , according to the field where both the impurities diffusion and surface oxidation phenomena are present during in-air irradiation. We have assumed that the laser irradiation occurs under normal skin conditions, and used therefore the expression (4) of the reflection coefficient  $r_{13}$ . The theoretical diagram

of the absorption coefficient  $A = A(t)$  departs at a certain moment from the experimentally established diagram. Supposingly, this temporal moment corresponds to the experimental cleaning time (Fig. 1).

The cleaning time  $t_c^{\text{theor}}$  determined theoretically from the formula (11) fits well to the experimental one.  $t_c^{\text{exp}} \sim 10.7$  s. Our experimental arrangement will not be

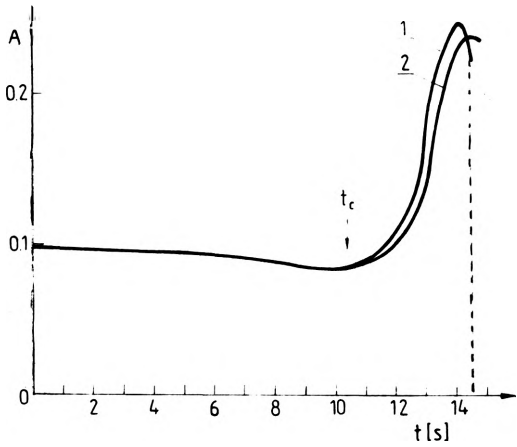


Fig. 1. Theoretical (1) and experimental (2) time-variations of a copper sample surface absorptivity during cw CO<sub>2</sub>-laser irradiation in-air

described in details, since such a description can be found in literature [6–8]. We shall only mention that we have used  $5 \times 5 \times 0.5$  mm<sup>3</sup> copper samples, which after mechanical polishing were kept in vacuum, their surfaces being cleaned with alcohol before laser irradiation. The heating curves under the action of the power-stabilized cw CO<sub>2</sub> laser source ( $P \approx 30$  W) were obtained with the aid of chromel-alumel thermocouples, and then the absorptivity variation was derived according

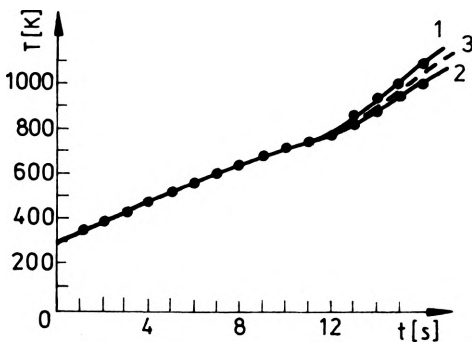


Fig. 2. Time-variation of the temperature reached on the copper sample surface during cw CO<sub>2</sub> laser irradiation in-air. Calculations performed respectively within anomalous (1), normal (2), and normal (3) skin effect approximations, for  $t < t_c$ , and anomalous skin effect for  $t \geq t_c$  (here  $t_c$  stands for the starting moment of the laser cleaning process)

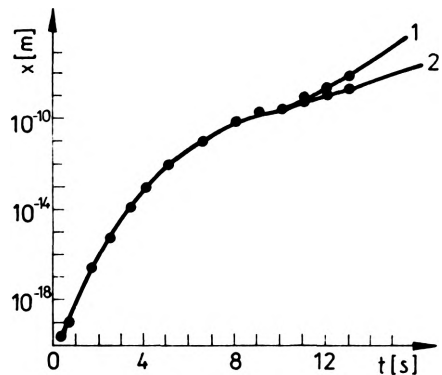


Fig. 3. Time-variation of the computed thickness of the oxide layer;  $x$  corresponds to the anomalous (1) and normal (2) skin approximations

to the procedure described in paper [9]. Postirradiation investigations were performed by optical and/or electron microscopy, X-ray diffraction, etc.

We have developed a computational program which was meant to integrate numerically the set of first order differential equations, consisting of the equations (1a) and (1j) and of the derivative equation (6).

The coefficient  $r_{13}$ , up to the time  $t \leq 11$  s, was determined from the expression (4a), and for  $t \geq 11$  s the expression (4b) was used (Fig. 2).

A better agreement of the absorption coefficient  $A$  with experiments was found.

We have also obtained the dependence  $x = x(t)$ , Fig. 3.

It can be seen that the growth rate of the oxide layer deposition on the metal surface, as well as that of the temperature in the case of anomalous skin absorption are higher than under conditions of normal skin absorption.

## References

- [1] SOKOLOV A. V., *Optical Properties of Metals*, Ed. Fizmatizd, Moscow 1961.
- [2] BOIKO V. I., BUNKIN F. V., KIRICHENKO N. A., LUKYANCHUK B. S., DAN, Ser. Fiz. **250** (1980), 78.
- [3] ARZUOV M. I., BUNKIN F. V., KIRICHENKO N. A., KONOV V. I., LUKYANCHUK B. S., Preprint FIAN No. 39 (1978).
- [4] BUNKIN F. V., KIRICHENKO N. A., LUKYANCHUK B. S., Izv. AN SSSR, Ser. Fiz. **45** (1981), 1018.
- [5] URSU I., APOSTOL I., CRACIUN D., DINESCU M., MIHĂILESCU I. N., NISTOR L. C., POPA A., TEODORESCU V. S., PROKHOROV A. M., CHAPLIEV N. I., KONOV V. I., J. Phys. D: Appl. Phys. **17** (1984), 709.
- [6] URSU I., APOSTOL I., MIHĂILESCU I. N., NISTOR L. C., TEODORESCU V. S., TURCU E., PROKHOROV A. M., CHAPLIEV N. I., KONOV V. I., RALCHENKO V. G., TOKAREV V. N., Appl. Phys. **A29** (1982), 209.
- [7] URSU I., NISTOR L. C., TEODORESCU V. S., MIHĂILESCU I. N., NANU L., PROKHOROV A. M., CHAPLIEV N. I., KONOV V. I., Appl. Phys. Lett. **44** (1984), 188.
- [8] URSU I., NISTOR L. C., TEODORESCU V. S., MIHĂILESCU I. N., APOSTOL I., NANU L., PROKHOROV A. M., CHAPLIEV N. I., KONOV V. I., TOKAREV V. N., RALCHENKO V. G., [in] *Industrial Applications of Laser Technology*. Proc. SPIE **298** (1983), 398.
- [9] ARZUOV M. I., KARASEV M. E., KONOV V. I., KOSTIN V. V., METEV S. M., SILENOK A. S., CHAPLIEV N. I., Sov. J. Quant. Electron **8** (1978), 892.

*Received November 28, 1985,  
in revised form February 18, 1986*

## Изменение механизма поверхностной абсорбции во время облучения металлических образцов пучком лучей CO<sub>2</sub> лазера

Теоретически предусмотрено изменение механизма абсорбции с нормального поверхностного эффекта на аномальный поверхностный эффект, а также оно подтверждено экспериментально в случае облучения металлических образцов лазером высокой мощности и непрерывной работы.