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ABSORPTION OF THE INFRARED RADIATION IN LASER SURFACE TREATMENTS OF FERROUS ALLOYS

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Abstract - In this paper we have shown the importance of taking into account some parameters like the incident angle, the beam polarization and the refractive index of the materials when we deal with absorption problems of the infrared radiation in laser surface heat treatments of materials. We have carried out some experiments with spheroidal graphite cast iron samples, directly from polishing, superficially oxidized or spray coated with a graphite powder. The obtained results were explained applying the Fresnel equations for reflection and transmission coefficients generalized to absorbing media [1].

1. - Introduction

The absorption of the infrared radiation in laser surface treatments of metallic workpieces is often studied by an empirical way. A painting or a coating may be reputed to have good capacities for absorption of the infrared radiation at 10,6 µm (corresponding to the current CO_2 laser sources) with a more or less resistence to the temperature (see for example [2]) but there are only few works with a scientific character about this subject [2, 3, 4], nevertheless very important for industry.

We must also remark that the published results are related to interactions at normal incidence. However this situation is not always present in practice particularly when the geometry of the piece to be treated or the conception of the optical device determines to work at a more or less great deviation from normal incidence. So it is very important to envisage these situations especially as it is well known in cutting [5] and in a less extent in welding [6] that the laser material interaction changes notably with the incident conditions specially when the beam is linearly polarized. This is systematically ignored in laser surface treatments although the first article showing this influence was published 15 years ago [7].

So we have carried out experimental studies about the evolution of the absorption in function of the incident conditions for ferrous alloying samples. We have tried to explaine the obtained results by the application of the elementary Fresnel equations for the interaction of an electromagnetic wave with a material medium [1].

2. - Experimental study

We have carried out experiments with pearlitic spheroidal cast iron samples of dimensions 10 x 30 x 100 mm^3 previously polished in order to have a surface roughness of about one micron. The samples were studied in three conditions: i) directly from polishing; ii) superficially oxidized in a melted salt bath during two hours so that a coating of 5 µm of thickness and essentially composed of Fe_3O_4 was developped; iii) spray coated with a graphite layer of thickness greater than 5 µm.

We used a cw.CO_2 laser beam from a CILAS CI 4000 source presenting a linear polarization and the following characteristics: $P \approx 150$ W, radius of the equivalent beam [8] $r^+ \approx 4,4$ mm (giving a maximal irradiance $I_M \approx 260$ W/cm^2) and an energy repartition with a central maximum (nearly gaussian).

Measurements of the incident power on the surface of the sample (P_i) and of that reflected by it (Pr) were made using a power meter "Cohérent LM 3000". The reflected power P_r was measured for incident angles θ_i varying from 15° to 85° for samples in the three conditions referred above with a polarized wave parallel ("p") and perpendicularly ("s") to the plane of incidence (see figure 1). The absorption coefficient or absorptivity in these two situations, A_p and A_s respectively, were evaluated from the ratio $(P_i - P_r)/P_i$. The increasing of temperature ΔT of the sample was follwed simultaneously by a thermocouple placed inside the sample below the interaction zone.

We note from the results shown in figure 2 that for a beam polarization parallel to the plane of incidence the absorption increases with the incident angle and it reaches a maximum value at an incident angle θ_B called "Brewster angle" [1], whereas for a polarization perpendicular to the plane of incidence the absorption decreases with the incident angle. So the effects related to the absorption of a polarized light by a metallic piece are showed up in an indisputable manner.

However, in an industrial point of view, if on the one hand we can increase the absorption by increasing the incident angle for a polarization "p", on the other hand the energy on the surface piece is spreaded and so the incident power density decreases (function of $\cos\theta_i$). Consequently the rate of temperature increasing which is proportional to power density also decreases. To compensate this undesirable effect we can for example transform the beam energy repartition with a cylindrical lens (figure 3). By this way we can show up a faster heating of the piece (see figure 4 in the case at $\theta_i \approx 75°$).

The simultaneously registration of P_r and ΔT allowed us to evaluate the evolution of the absorption in function of the temperature from the room one to 200 °C and for an oxidized cast iron sample. We note from the figure 5 that the absorptivity increases with the temperature for small angles of incidence and we note equally that the angle of maximal absorptivity decreases with the temperature.

3. - Discussion of results

The obtained results show in an indisputable way that the absorption coefficient of the laser material interaction depends on the incident conditions of the polarized laser beam, the state of the material surface (presence or not of a coating and its nature) and on the temperature. They are in agreement with the few studies about this subject that we could find in the literature [6, 9,, 10, 11].

Moreover these results can be explained by the classical theory governing the interaction of an electromagnetic wave with the media in which it propagates (Fresnel equations for reflection and transmission). To do this we must evaluate the values of the refractive index (n + ik) of the materials. The realized measures concerning reflectivity give for the polished cast iron $A(\theta_i \approx 0°) \approx 0{,}08$ and $A(\theta_i \approx \theta_B \approx 85°) > 0{,}5$ which lead to an estimation of $n_f \approx 10 \pm 3$ and $k_f \approx 20 \pm 4$; for oxidized cast iron $A(\theta_i \approx 0°) \approx 0{,}84$ and $A(\theta_i \approx \theta_B \approx 60°) \approx 0{,}95$ is compatible with the oxide index values $n_o \approx 1{,}7 \pm 0{,}1$ and $k_o \approx 0{,}9 \pm 0{,}1$; for cast iron samples coated with a graphite layer $A(\theta_i \approx 0°) \approx 0{,}08$ and $A(\theta_i \approx \theta_B \approx 70°) \approx 0{,}95$ lead to $n_g \approx 2{,}0 \pm 0{,}1$ and $k_g \approx 1{,}2 \pm 0{,}1$ for the graphite.

Table 1 shows some mean values found in the literature corresponding to the optical constants of various metallic elements at $\lambda \approx 10\ \mu m$ [12, 13, 14] and the corresponding range of values found for silicon oxides [15] and graphites [16]. The coefficient "d" is the penetration depth of the radiation which can be expressed by $d = \lambda/4\pi k$ [1, 17].

Table 1. Optical constants for several materials.

λ=10 μm	Fe	Cu	Al	Mo	Ni	Ti	Glasses SiO_2,...	Graphite
n	7	10	28	12	9	4	1,0 - 2,5	2,0 - 3,0
k	29	57	97	56	37	20	0,2 - 1,2	1,0 - 2,0
d(nm)	27	14	8	14	21	40	700 - 4000	400 - 800

We note that d remains always of about ten nanometers for metals and it is two orders higher for non metallic materials.

Comparing the values evaluated by us with those of table 1 we note that the index n of the cast iron is a little higher than that of the pure iron. Its imaginary part k is lower than the pure iron one corresponding to a greater penetration of the radiation which can be understood by the presence of graphite in the cast iron composition. Unfortunately we couldn't find in the literature the optical constants for Fe_3O_4 oxides type, neverthless if we compare the evaluated values with the glasses ones (SiO_2) we note that they are of the same order. The evaluated values for the graphite powder are included in the corresponding range of table 1.

The absorptivity depends on the thickness "h" of the layer applied to the substrate surface. However we can show [17] that after a particular thickness value "h_c" (of about 4d) the absorptivity is independent of the thickness. This means that all the radiation is absorbed by the layer and transformed into heat that is conducted to the substrate by thermal conduction. Our samples satisfied this condition.

The increasing of the absorption with the temperature corresponds to a decreasing of the index k.

4. - Conclusion

We have shown up the influence of the incident angle, the refractive index of the materials and the temperature on the absorption of the infrared radiation in laser surface heat treatements of materials.

In particular we can conclude that as far as the geometry of piece to be treated or the conception of the "focalisation device" of the energy repartition at the interaction zone permits to work with a polarized "p" wave nearly "brewsterien" incident condition ($\theta_i > 60°$) it may be possible to treat a metallic piece without any coating. However it must be necessary to transform previously the energy repartition in order to correct the spread effect on the irradiance.

On the other hand if we are obliged to work nearly normal incidence and so without making use of the polarization properties of the radiation only the presence of a coating with appropriate optical, geometrical and thermal characteristics will permit to increase the absorption (see [17]).

Finally a minimum of reflections based on the classical theory of propagation of light waves in material media would permit to deal less empirically with the absorption problems of the IR radiation which is not commonly done.

References:

[1] M. Born, E. Wolf, Principles of Optics, Pergamon Press, New York (1980).
[2] E. Ramous, Laser Surface Treatment of Metals, Ed. C. W. Draper and P. Mazzoldi (Matinus Nijhoff Publish) 475 (1986).
[3] W. W. Duley et al., Optics and Laser Technolgy, Business Press 313 (1979).
[4] A. D. McLachlan, L. B. Whitbourn, J. Appl. Phys. 53, 4038 (1982).
[5] F. O. Olsen, DVS Berichte 63, S.197, (1980).
[6] E. Beyer et al., Ind. Laser Annual Handbook, Ed. D. Belforte and M. Levitt, Laser Focus USA,157 (1990).
[7] B. A. Sanders, V. G. Gregson Jr., Proceedings of Electro-Optical Systems Design Conference, 24 (1973).
[8] J. Dietz, J. Merlin, Rev. Phys. Appl. 23, 1787 (1988).
[9] A. Giesen, R.W. Serchinger, Rapport interne, Kugler-Seroptic.
[10] W. T. Walter et al.,Lasers in Metallurgy, Ed. H. Mukherjer and J. Mazumder, The Metallurgical Society of AIME, New York 179 (1981).
[11] C. T. Walters et al., Lasers in Metallurgy, Ed. H. Mukherjer and J. Mazumder, The Metallurgical Society of AIME, New York 195 (1981).
[12] M. A. Ordal et al., Appl. Opt. 22, 1099 (1983).
[13] M. A. Ordal et al., Appl. Opt. 24, 4493 (1985).
[14] M. A. Ordal et al., Appl. Opt. 27, 1209 (1988).
[15] G. W. Cleek, Appl. Opt. 5, 771 (1966).
[16] V. P. Tomaselli et al., Appl. Opt. 20, 3961 (1981).
[17] C. Oliveira et al., Journal de Physique III, submitted to publication.

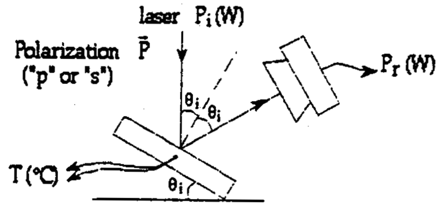

Fig. 1. - Schematic diagram of the experimental setup used for reflection measurements of a polarized laser beam.

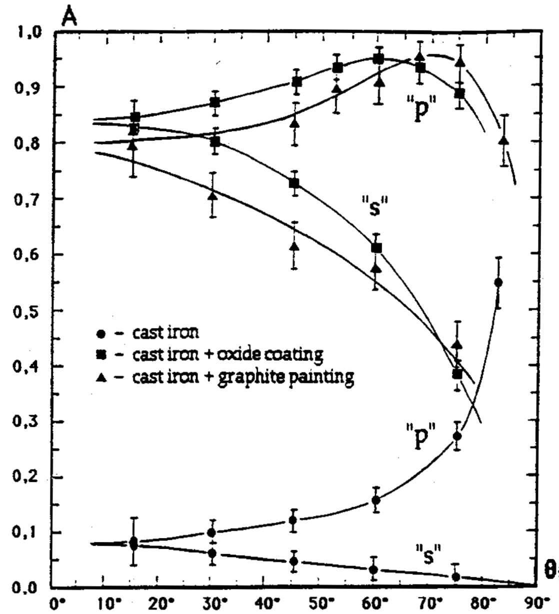

Fig. 2. - Experimental data for the absorptivity as a function of the incident angle at $\lambda = 10{,}6\ \mu m$.

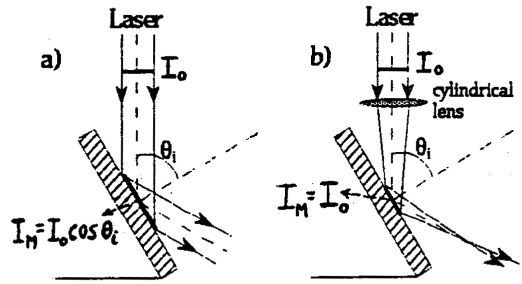

Fig. 3. - Scheme of the energy spread on a surface workpiece (a) and its correction (b)

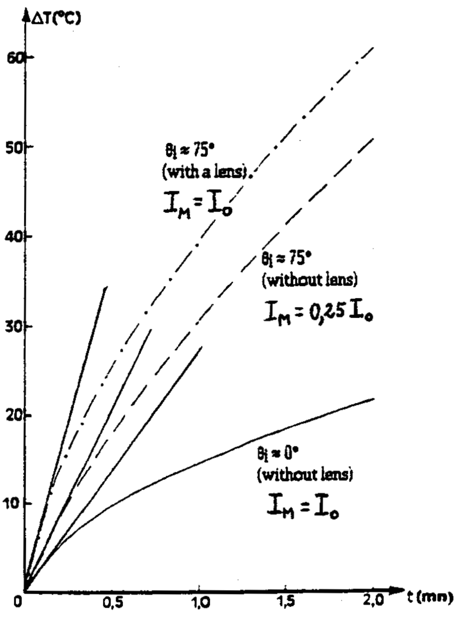

Fig. 4. - Temperature increasing as a function of time for a polished cast iron sample with no coating or painting; polarization "p" for $\theta i \approx 75°$.

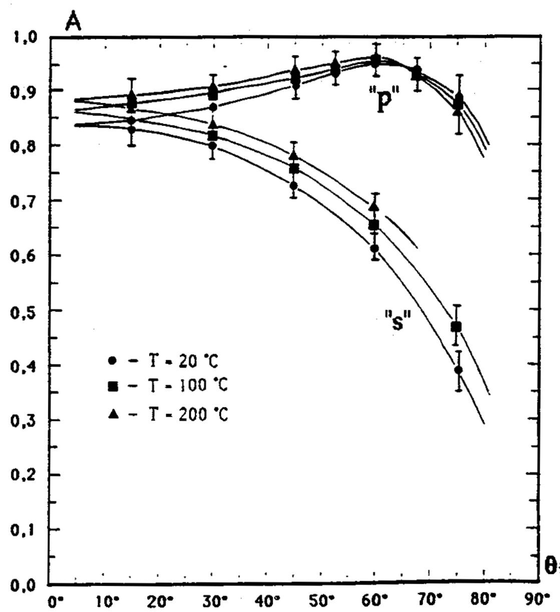

Fig. 5. - Experimental data for the temperature dependence of the absorptivity as a function of the incident angle for an oxidized cast iron sample at $\lambda = 10{,}6\ \mu m$.