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Carburization of iron surface induced by laser heating

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The solid state carbon diffusion on an iron surface coated by graphite dag and heated by a continuous wave laser beam has been studied. Experimental values of the diffusion paths have been compared with those calculated by a mathematical model of the thermal cycle induced by laser heating. Case layers have been obtained of about 0.2 mm, with a bainitic structure.

Nomenclature

c is specific heat ($120\,\mathrm{cal\,kg^{-1}\,°C^{-1}}$).
ϱ is mass density ($7900\,\mathrm{kg\,m^{-3}}$).
k is thermal conductivity ($1.28\,\mathrm{cal\,m^{-1}\,sec^{-1}\,°C^{-1}}$).
l is slab thickness (m).
z is abscissa in the direction of slab thickness (m).
t is time (sec).
τ is duration of irradiation (time of interaction between beam/surface) (sec).
F is intensity of impinging radiation ($\mathrm{W\,m^{-2}}$).
F_0 is intensity of absorbed radiation ($\mathrm{W\,m^{-2}}$).
T is temperature (°C).
$\alpha = \dfrac{k}{\varrho c}$ is thermal diffusivity ($\mathrm{m^2\,sec^{-1}}$).
$D = 2(\alpha t)^{1/2}$ is thermal diffusion length (m).

1. Introduction

Often graphite dag is used as a coating material for metallic surfaces to improve the absorption of laser radiation during surface treatments [1].

However, the presence of graphite can induce a carbon enrichment by diffusion into the surface layers. In transformation hardening of a steel surface this can induce damage such as a higher content of retained austenite and a little localized melting [2, 3] as a consequence of the lowering of the melting temperature, increasing the carbon content of the treated surface.

The aim of this research was to study the effective thickness of the carbon enriched layers, during the surface treatments of steels by high power lasers, using graphite dag coatings. A mathematical model was used for the calculation of the diffusion thickness, and the obtained data was compared to that obtained from experimental results of laser surface treatments.

2. Mathematical model

In the present study the diffusion phenomena can be described by Fick's second law, in the z direction normal to the surface (Fig. 1)

$$\frac{\partial c_i}{\partial t} = D\frac{\partial^2 c_i}{\partial z^2} \tag{1}$$

The value of the diffusion coefficient D is temperature dependent, according to an Arrhenius equation of the form

$$D = D_0 \exp(-E/RT) \tag{2}$$

D_0 is not dependent on temperature variations.

The temperature–time variation can be evaluated by the well known Carslaw and Jaeger's equation [4], generally used to describe the thermal transient induced in the surface layers of a slab of semi-infinite thickness, by the laser beam. However in our case, it is sufficient to consider only the one-dimensional heat flow, along the normal to the sample surface. Therefore the heat conduction equation, with a heat flux F_0 entering at $z = 0$ (see nomenclature), can be written with the pertinent boundary conditions, for a slab of semi-infinite thickness ($z \to \infty$)

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{3}$$

if

$$\frac{\partial T}{\partial z} = -\frac{F_0}{k} \quad \text{for } z = 0$$

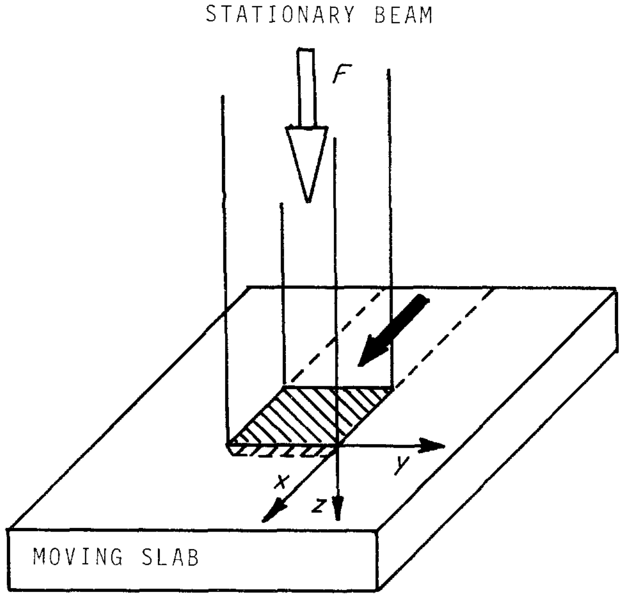

Figure 1 Schematic of laser surface treatment.

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TABLE I

Sample	Intensity of absorbed radiation, F_0(W mm^{-2})	Interaction time (sec)	T_{max} (°C)	Carbon diffusion path (mm)	
				Calculated	Experimental
1	20.00	1	1548	0.037	0.04
2	3.0	20	1051	0.049	0.055
3	3.4	20	1174	0.068	0.07
4	3.8	20	1330	0.08	0.09
5	4.1	20	1422	0.12	0.13
6	4.5	20	1546	0.17	0.17

and

$$T = T_{room} \quad \text{for } z \to \infty$$

If F_0 is a constant Equation 3 gives the solution (Carslaw and Jaeger [4])

$$T(z, t) = \frac{2F_0}{k}\left[\left(\frac{\alpha t}{\pi}\right)^{1/2} \exp\left(\frac{z^2}{4D^2}\right) - \frac{z}{2}\,\text{erfc}\left(\frac{z}{2D}\right)\right] \tag{4}$$

Finally, if as in our case, the treated sample slabs have a finite thickness, the solution must be modified (La Rocca [5]) as

$$T'(z, t) = T(z, t) + \frac{F_0 D}{k}\sum_{n=1}^{\infty}\left[\text{ierfc}\left(\frac{2nl + z}{D}\right) + \text{ierfc}\left(\frac{2nl + z}{D}\right)\right] \tag{5}$$

The last equation was used to calculate thermal cycles in the surface layers of our samples (thickness 6 mm). In Fig. 2 examples are shown of the calculated thermal cycles on the surface. Our calculations were performed using mean values for the physical properties of the base material (ARMCO iron) in the considered temperature range, as indicated in Table I.

In the complete calculation of the carbon diffusion path, it should be necessary to take into account not only the diffusion coefficient dependence on the temperature, but also the temperature profile along the normal to the surface. However, by the mathematical model of the thermal transient, it can be easily verified that, if the interaction time is about 1 sec (or longer) and the surface temperature in the range of 1000 to 1300° C, the difference between surface temperature and values at a depth of 0.1 mm is about 50° C, and never higher than 100° C. It seems therefore justified to calculate D values on the basis of the surface temperature, and neglect, for a simplified assumption the little temperature difference, between the surface and nearest inner layers.

This was confirmed by the calculated values of diffusion paths, lying very near to the surface: 0.04 mm for sample 1 and ~0.15 mm for the other samples.

3. Experimental details

For surface treatments, 6 mm thick ARMCO iron samples were used. These samples were chosen in order to increase both heating and the effect of carbon diffusion.

The laser treatments were carried out using a continuous wave (CW) CO_2 AVCO laser, with 15 kW maximum power. The uniformity of the energy distribution on the spot was optimized using a biaxial scanning system of the beam, with a 12 mm × 12 mm mask to cut off lateral broadening. Argon was used as a shielding gas, and the samples were coated by graphite dag in alcohol.

The parameters used in the surface treatments are shown in Table I. In the first series of tests, together with the highest power density of 10 to 12 W mm^{-2}, the lowest interaction times of 1 sec were assumed. These values are typical of a surface treatment by transformation hardening of steel performed by the laser [3].

In the second series, interaction time was longer, 20 sec, and the power density was lower, 3 to

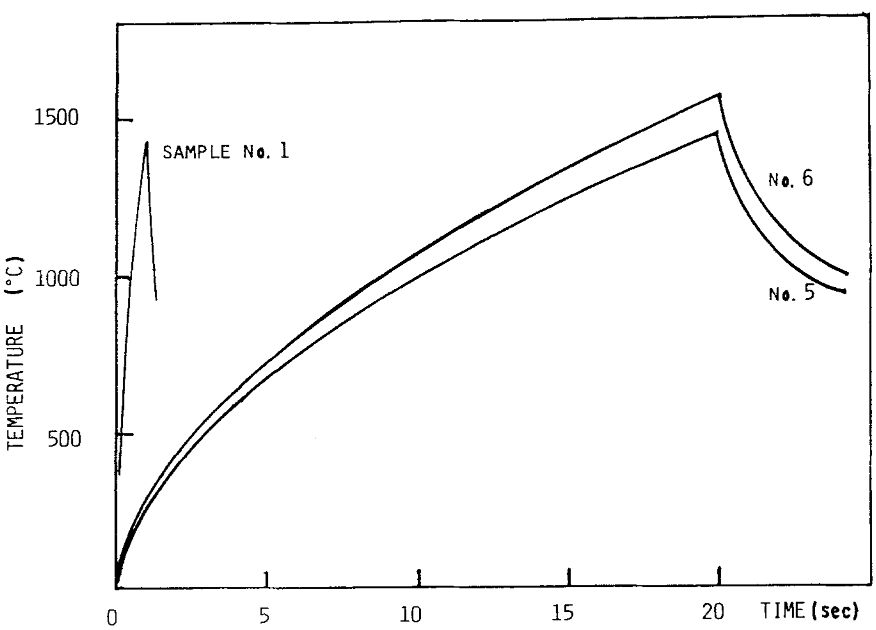

Figure 2 Calculated thermal cycles on samples surfaces.

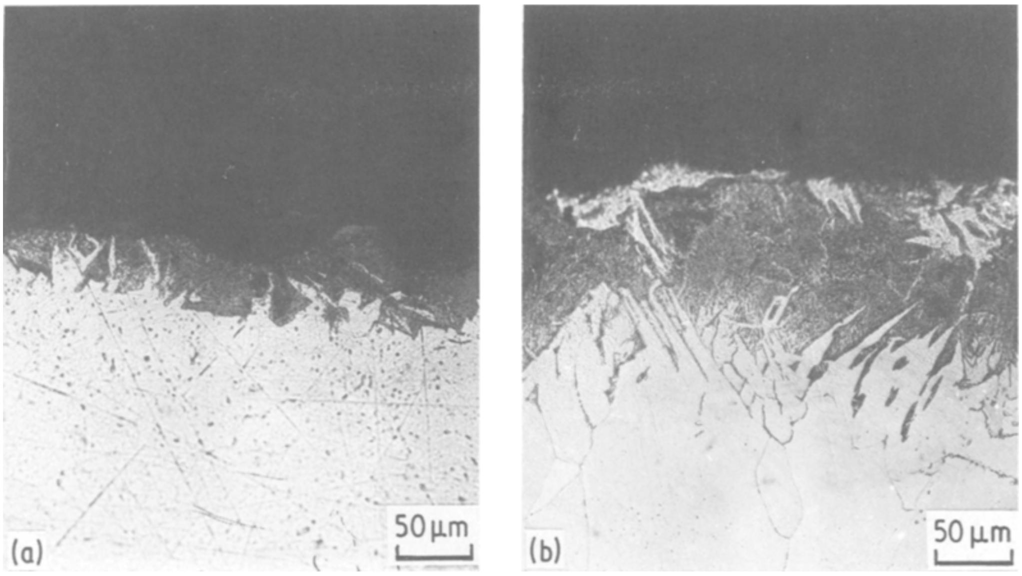

Figure 3 Microstructures of carbon diffusion layers: (a) sample no. 1; (b) sample no. 3.

5 W mm^{-2}. The aim of this second series of tests was to verify the validity of data obtained by the mathematical model, and to study the feasibility of a surface treatment of carbon enrichment by laser, even only by solid state diffusion.

4. Results and discussion

Results obtained from calculations and experimental tests are summarized in Table I. The values of diffusion paths were calculated by the aforementioned mathematical model. The indicated values correspond to the depth where the carbon content is reduced to 10% of the values reached on the surface.

Typical microstructures obtained are shown in Figs 3 and 4, the carbon enriched layer exhibits a bainitic structure. According to the calculations from the mathematical model, interaction times with the laser beam over 2 sec, produce thermal cycles having cooling times of several seconds (by direct heat transmission to the bulk of the sample, and without any external cooling device). Therefore, the corresponding cooling rate is lower than the critical value for martensitic transformation, and the case layer has a final bainitic structure and maximum hardness in the range of 550 to 600 HV.

Comparison of the experimental results and calculated data confirms the validity of the mathematical model used. Indeed the maximum disagreement between calculated and experimental diffusion paths does not exceed 10%. Moreover, the second series of tests shows the possibility of obtaining a noticeable carbon enrichment of iron and steel surfaces, by solid state diffusion and without melting, by heating the surfaces with a laser at high interactions times. Technological implications of this possibility are obvious.

On the other hand, results of the sample no. 1 shows that harmful effects deriving from the graphite dag are almost irrelevant, in steel treatment of transformation hardening by laser. Indeed in this second case the carbon diffusion path is very small, because in this type of surface treatment by laser, the interaction times used must be very short.

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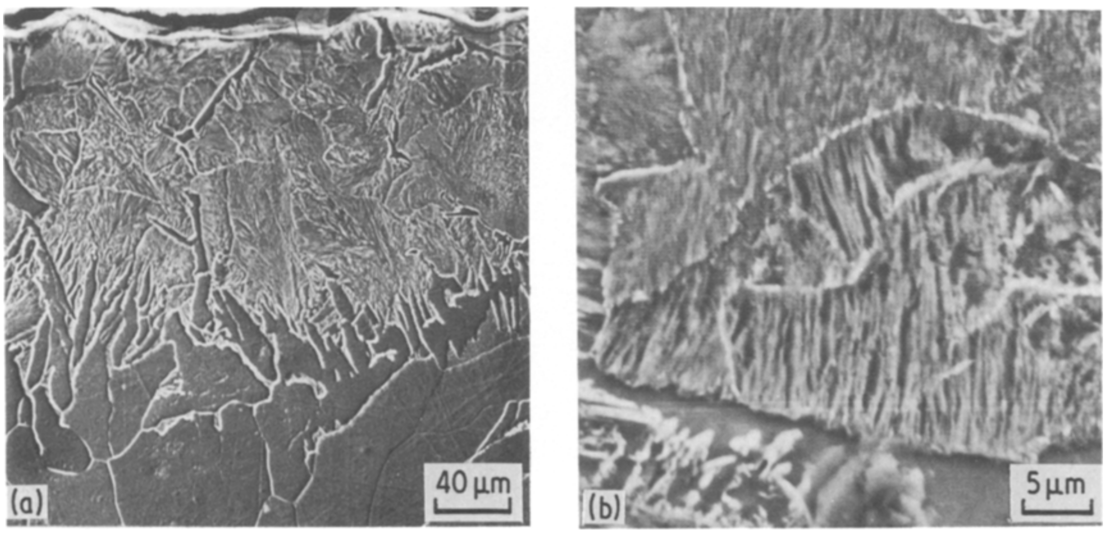

Figure 4 Sample no. 5, microstructure of: (a) carbon diffusion layer; (b) bainite in the treated layer.

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