Solar absorptivity of metallic layers subject to a short-flash of concentrated solar energy. Theoretical-experimental calculation

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Abstract. The paper develops a procedure for the theoretical-experimental calculation of the solar absorption coefficient of metallic layers under the action of a short flash of concentrated solar energy. The knowledge of this coefficient is relevant when the solar thermal processing is used to make a quench in a thin superficial layer of metallic slabs. The experimental data of temperature of the sample are obtained using the SURFSOL experimental device at SOLFACE (High Flux Solar Facilities for Europe), France. In particular, the sensors of temperature are located on its back side as the solar radiation impinges the front irradiated one. The theoretical data are obtained solving the nonlinear inverse transient heat conduction problem using the IHCP1D software based on the well-known function specification method (FSM). It gives transient surface heat fluxes as well as temperatures on the irradiated side of the sample using internal temperature histories. Then a transient radial fin model accounts for the heat diffusion in the radial direction and re-calculates the heat fluxes. Once temperatures and heat flows are known, an estimate of the solar absorption coefficient of the metallic layer (during the flash solar heating process) may be obtained as a function of temperature (AISI 316L steel).

1. Introduction

In science and technology literature we can find some result of experimental activities which demonstrate that it is possible to realize the surface hardening of steels by means of a concentrated beam of solar energy [1, 2].

In general, any thermal treatment of a metallic material is effective (from the viewpoint of the improvement of specific mechanical properties) only if a complete control of the heating process can be realized. In particular, for high-energy superficial hardening treatments (e.g. laser or concentrated solar beam treatments) this control is critical because the heating process is extremely rapid (short-
For both laser and solar surface processes, a thin layer of metal absorbs part of the incident radiation according to its own absorptivity depending on the surface temperature as well as surface conditions such as coatings, surface roughness and oxide layers. As a consequence, the above processes may be controlled provided the absorption characteristics of the metals are known in relation to the radiation source used. As regards the solar hardening which is here of interest, the absorption properties are resumed by the so-called solar factor, which is a both global and hemispherical coefficient.

For several metallic and non-metallic materials, various authors have studied the spectral absorptivity dependence on both the incident radiation wavelength and the boundary temperature [3, 4]. On the contrary, in literature there are few data about solar absorptivity of materials of interest for engineering applications [5]. Also, they are limited to thermal levels much lower than those achievable during a hardening treatment which is here of interest. In fact, most information available are relative to coating materials for both thermal and thermodynamic applications of the solar energy.

The aim of this work is to provide a procedure to evaluate the ‘short-flash’ solar absorption coefficient of metals in order to obtain a correct hardening. The idea is to evaluate this temperature-dependent coefficient by means of a theoretical-experimental approach. It requires to set up an appropriate test facility [1, 2] and to solve an inverse transient heat conduction nonlinear problem [6] with unknown heat flux and temperature at the front side of the sample. In particular, the inverse problem is solved using the IHCP1D software based on the well-known function specification method (FSM) [7]. Then a discrete-in the radial direction lumped modeling accounts for the heat diffusion in this direction and re-calculates the heat fluxes and temperatures. Finally, the results of the solar absorptivity and transient surface heat flux are given in a graphical form as a function of the surface temperature and time, respectively, for the AISI 316L stainless steel as a very powerful tool for users.

2. Test facility

The experimental tests have been carried out on the SURFSOL (SURface SOLair) device, a 2 kW solar furnace hosted at the PROMES-CNRS laboratories in Odeillo-Font Romeu. Figure 1 shows a scheme of this apparatus: a flat heliostat on the ground reflects direct sunlight onto a parabolic mirror (2 m of diameter with 85 cm of focal length) which focuses it.

The axisymmetric distribution of the solar flux can be well represented by a Gaussian distribution, that is \( \phi(r) = \phi_0 e^{-r^2/\gamma_0^2} \), as shown in figure 2. In particular, the peak flux is \( \phi_0 = 14 \text{ MW/m}^2 \) and the standard deviation is \( \gamma_0 = 5.1 \text{ mm} \) for a direct irradiation of 1 kW/m\(^2\). However, depending on the current direct irradiation, the solar peak flux can vary in the range 14\(\rightarrow\)18 MW/m\(^2\). A fast mechanical shutter - composed of two sliding horizontal screens placed very close to the focal plane (whose opening and closing times are between 10 and 30 ms) - allows the concentrated flux to be delivered onto the sample.

The sample is a disk-shaped element (50 mm and 2 mm nominal diameter and thickness, respectively) made of AISI 316L stainless steel and fitted into a thermally insulating envelope. Only the top surface is exposed to the solar flux and the ambient air, while the side and bottom ones, being surrounded by the envelope, may be treated as thermally insulated surfaces. The sample with its envelope is then placed on the sample holder. This is made by a 80 mm diameter water-cooled disk placed on a slide for positioning the sample’s centre on the focus of the mirror. The slide is actuated by a drive stepper with a 1\(\rightarrow\)50 mm/s speed range and a 0.1 mm precision. The experimental system is completed by 1) a fast radiometer to measure the reflected energy from the exposed surface, and 2) a pyrheliometer to measure the direct solar radiation. Also, a multi-channel data acquisition system is used to store the signal from the thermocouples, the radiometer and the pyrheliometer, at a 250 kHz frequency.

Six thermocouples measure the sample temperature at different radial locations, starting from the disk centre with a radial step of 2 mm, as shown in figure 3. They are soldered on the bottom surface of the sample, otherwise they would be probably damaged by the concentrated solar flux and their
measurements would be unreliable. The concentrated solar beam and the related high temperatures cause significant local transformations, whose macroscopic effect is the formation of a “target” around the point where the solar beam hits, visible also on the bottom surface (Figure 3). With the aid of this target, the real distance between the axes of the beam and disk can be computed as well as the thermocouples locations from the beam centre.

Figure 1 – Scheme of the CNRS 2 kW solar furnace.

Figure 2 – Measured and computed (Gaussian approximation) normalized flux distribution at the focal plane.

Figure 3 shows that the concentrated beam irradiates the sample slightly far from its centre and it is closer to the second thermocouple (2 mm far from the disk centre) than to the first central one. Using a digital image of the sample, the actual position of the solar beam and thermocouples can easily be determined by inspection. The sample image (figure 3) is inscribed into a square, whose edge size hence coincides with the sample diameter and allows the image calibration to be determined. Also, as the edge size is of 1450 pixels vs. 50 mm of the sample diameter, its calibration is equal to 29 pixels/mm. Then the beam and the thermocouples are handily localized on the image (green X) and their positions recorded. Finally, the distance between the beam and the thermocouples can be computed.

Figure 4 shows the temperature values recorded by the thermocouples during tests with a time interval of 4 ms. As the thin wires (0.2 mm in diameter each) of the thermocouples are welded directly onto the metallic surface of the sample (figure 3), no contact resistance is induced. The measurement is local, the contact area is estimated to be less than 0.5 mm x 0.5 mm. The response time of the thermocouples depends upon the so-called thermal constriction of the heat flux and upon the thermal inertia resulting from the mass of couple which is welded. It is of about 1 ms. As the heating rate is less than 1 °C/ms, a delay of 1 ms does not affect the results of the analysis.

3. Modeling of the solar heating process

The most general heating model for the tested samples should take into account all the variables and phenomena involved during the short-flash of concentrated solar irradiation, that is, 1) heat transfer to the sample (by solar energy absorption) and from itself towards environment (by convection and short- and long-wavelengths radiation); 2) eccentricity between solar flux and sample axes as well as the focal plane of the parabolic mirror and the top surface of the sample; 3) variation of sample solar
absorptivity with the surface temperature; and 4) temperature-dependence of the thermal properties (table 1). Also, as attested by figure 3, the steel plate undergoes strong structural alteration, even including state changes. This can induce heat sinks in the heat conduction equation as well as a change in the thermal properties which could surely modify the temperature field. However, this aspect was not considered here.

![Figure 3 – Localization of solar beam and thermocouples positions.](image)

![Figure 4 - Temperature measured when the solar heating process is ‘on’.](image)

### Table 1. Thermal properties of AISI 316L for $T \in [0\, ^\circ C, 1100\, ^\circ C]$.

| Property          | SI correlation            |
|-------------------|---------------------------|
| Conductivity      | $k(T) = 13 + 0.0137 T$    |
| Density           | $\rho(T) = 7964 - 0.4265 T$ |
| Specific heat     | $c(T) = 461 + 0.2216 T$   |

The result is a highly nonlinear 3D model with a nonhomogeneous boundary condition at the exposed surface dependent on both time and space coordinates. However, the adopted model is simpler because the above convective and radiative contributions to the heat transfer are negligible in comparison with the absorbed solar energy. In addition, as there exists a very small distance between solar flux and sample axes, the relative eccentricity may be neglected with good approximation, so reducing the 3D model to a 2D one with the same boundary conditions. Also, the top surface of the sample is assumed to exactly belong to the focal plane of the mirror and the heat sinks due to structural alteration of the sample are fully neglected in the heat conduction equation.

From what has been said, the most natural choice is to have a 2D cylindrical frame of reference, as shown in figure 5. Thus, the governing equations of the solar heating process are ($0 \leq r \leq R$, $0 \leq z \leq L$ and $t > 0$):

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( k(T) r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right) = \rho(T) c(T) \frac{\partial T}{\partial t} \tag{1} \]

\[
\frac{\partial T}{\partial r} \bigg|_{r=0} = 0 \quad \frac{\partial T}{\partial r} \bigg|_{r=R} = 0 \quad k(T_s) \frac{\partial T}{\partial z} \bigg|_{z=0} + a_s (T_s) \phi e^{-(r^2 + z^2) / \sigma} = 0 \quad \frac{\partial T}{\partial z} \bigg|_{z=L} = 0 \tag{2} \]
where $T_s = T(r, z = 0, t)$ and $T_0$ is the room ambient temperature.

\[ T(r, z, t = 0) = T_a \quad (3) \]

The 2D model defined by Equations (1)-(3) is non-linear because of the 1) nonlinearity due to the heat conduction equation (1) with temperature-dependent properties (table 1), and 2) nonlinearity due to the boundary condition of the $2^{nd}$ kind at the focal plane (non-linear dependence of the solar absorptivity from temperature). However, as this quantity is unknown, the heat flux is also unknown and may be derived in first approximation using the IHCP1D software [7] based on the function specification method (FSM) [6]. It gives transient surface heat fluxes as well as temperatures on the irradiated side of the sample modeled as an 1D flat using the ‘back side’ temperature histories of figure 4. The obtained results are shown in figure 6.

4. Control-volume simplified model

Once the 1D heat flux is calculated, a 2D correction based on a control-volume scheme is proposed to account for the heat diffusion in the radial direction, as shown in figure 8. An energy balance on the $i$-th element ($i = 1, 2, ... n$; each element is considered lumped in both the $r -$ and $z -$directions) of the sample gives

\[
q_{i,in}(t_j)\left[\pi(r_i + s_i^+)\pi(r_i - s_i^-)\right] + q_{i,out}(t_j)\left[2\pi(r_i - s_i)\right] = \frac{\rho c L}{\Delta t} \left[\frac{T_i(t_{j-1}) - T_i(t_j)}{\Delta t_{i,j}}\right] 
\]

(4)

where $t_j = j \Delta t$ and $r_i$ indicates the location of the $i$-th sensor. Also, we have

\[
s_i^+ = \frac{r_i + r_{i+1}}{2}, \quad s_i^- = \frac{r_i - r_{i+1}}{2} \quad T_i(t_j) = \frac{T(r_i,0,t_j) + T(r_i,L,t_j)}{2} 
\]

(5)

\[
q_{i,in}(t_j) = k\frac{T_i(t_{j-1}) - T_i(t_j)}{2s_i^-} \quad q_{i,out}(t_j) = k\frac{T_i(t_j) - T_i(t_{j+1})}{2s_i^+} 
\]
Figure 6 – Heat flux on the front side as a function of time for different locations.

Figure 7 – Temperature on the irradiated side plotted vs. time for different locations.

Figure 8 – Schematic representation of the i-th specimen element.
The number \( n \) of elements is chosen equal to the number of temperature sensors. The \( T(r_i, L, t_j) \) is the measured temperature at the location \( r_i \) where the \( i \)-th thermocouple is located and time \( t_j = j\Delta t \) of interest. The \( T(r_i, 0, t) \) is the temperature at the same time and radial location (but on the sample front side) obtained solving the inverse problem and plotted in figure 7. The time step \( \Delta t \) is calculated applying the concept of penetration time [8], i.e. \( \alpha t_p / L^2 = 0.1 / m \), where \( m \) denotes the accuracy desired (\( 10^{-m} \)). For \( m = 1 \), \( L = 2 \text{ mm} \) and AISI 316L, we have \( t_p = 100 \text{ ms} \) and, hence, \( \Delta t = 100 \text{ ms} \).

Now, the variation of internal energy on the r.h.s. of equation (4) may approximately be taken as (per unit of area)

\[
\rho c L \frac{T_i(t_j) - T_i(t_{j-1})}{\Delta t} \approx q_{s,1D,i}(t_j)
\]

where \( q_{s,1D,i}(t_j) \) is the 1D heat flux calculated using the IHCP1D software [7] (figure 6). Therefore, equation (4) reduces to

\[
q_{s,i}(t_j) = q_{s,1D,i}(t_j) + \left\{ \frac{q_{s,ouf}(t_j) \left[ 2\pi \left( r_i + s_i^+ \right) L \right] - q_{s,in}(t_j) \left[ 2\pi \left( r_i - s_i^- \right) L \right]}{\pi \left( r_i + s_i^+ \right)^2 - \pi \left( r_i - s_i^- \right)^2} \right\}
\]

Applying equation (7) re-calculates the heat fluxes and gives the data plotted in figure 9. Notice that equation (7) has iteratively been applied until its convergence (three steps). Comparing figures 6 and 9 shows that the diffusion of heat in the radial direction is relevant. It in fact increases notably the heat fluxes in correspondence of the first two thermocouples, located at \( r = 0 \) and \( r = 2 \text{ mm} \).

Once the corrected heat fluxes \( q_{s,i}(t_j) \) are calculated, the changes for the front side temperature profiles can be obtained using Eq. (6) where \( q_{s,1D,i}(t_j) \) is replaced by the corrected value. However, because of space limitations, the related results are not given here.

Once the corrected heat fluxes and temperatures are evaluated, an estimate of the ‘short-flash’ solar absorption coefficient may be obtained. In fact, we have

\[
a_s \left[ T(r_i, 0, t_j) \right] = \frac{q_{s,i}(t_j)}{\phi_0 e^{-\alpha T_{\infty}}} \]

The solar absorptivity may be known as a function of temperature. Figure 10 shows the obtained data when the peak flux \( \phi_0 = 16 \text{ MW} / \text{m}^2 \). The solar coefficient trend indicates that it is nearly constant in the range of \( (400, 800^\circ\text{C}) \). This is due to a sudden change of metal properties related to the short-duration of the heat process, as it is clearly proven by figure 3 (different color). The theoretical-experimental correlation is

\[
a_s(T) = (3 \cdot 10^{-9})T^3 - (5 \cdot 10^{-6})T^2 + (2.7 \cdot 10^{-3})T + 0.05
\]

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Figure 9 – Corrected heat flux on the irradiated side plotted vs. time for different locations.

Figure 10 – ‘Short-flash’ solar absorptivity versus temperature for $\phi_0 = 16 \text{ MW/m}^2$.

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