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Modeling of surface tempering by a pulsed laser beam: Study of the material type's influence

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Abstract

In recent years, laser technology has became one of the bases of modern technology thanks to its importance and its effectiveness to achieve what other classical energy sources are unable to do, especially in the process of surface tempering of materials. During the current industrial competitiveness, it is too hard to realize products that would stay intact, resistant to corrosion, and preserve by time their mechanical, electrical, optical or thermal properties. Laser surface tempering of materials can be introduced more quickly, in the sense of reaching high accuracy, requires a control of processes. The latter has not provided experimentally a proper solution, which encouraged researchers to develop several mathematical models. Moreover, mathematical modeling reduces the experimental cost and predicts the best parametric data and their influence on the optimization of the processing operation.

In this work, we suggest a semi-analytic solution for the equation of heat conduction resulting from laser surface tempering of semi-infinite material, in 1D, with a convective boundary condition and receiving a pulsed laser beam on its lateral face. A Semi-analytical approach, based on GAVER-STEHFEST algorithm for the inversion of the solution in real domain is adopted. And the effect of the material's types on the temperature is obtained and discussed.

Keywords*: Surface tempering, pulsed laser beam, modeling:*

1. Introduction

With the ever more precise answers they provide to increasingly diverse and demanding industrial situations, the laser surface tempering has become essential due to its extreme power and energetic localization. It allows obtaining more preferment structures that are difficult or impossible to obtain by classical energetic sources, and helps most of the time solving problems related to the optimization of surface properties**[1-2]**. Surface Tempering by laser can be more quickly introduced in a sense to reach an enhanced precision using a command control of the process .However, the control of the spatial and temporal evolution of temperature in the material is essential during the operation. **[3]**

In the field of metallurgy, particularly in surface tempering of metals by the laser technique, the problem of the process control has not yet found an adequate solution through experimental measures

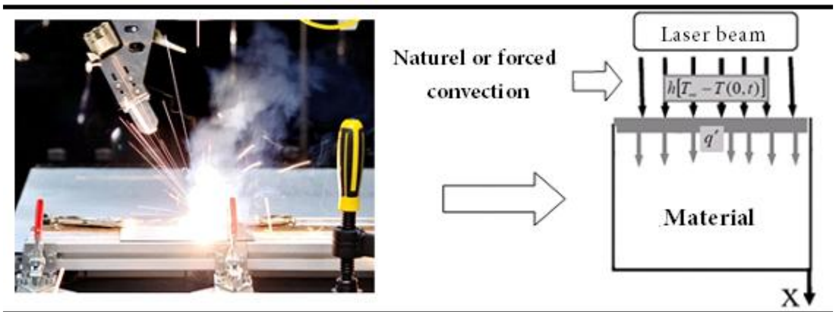
which encouraged researchers to develop several analytical, numerical and mathematical models**[3-9]**, based on simplified and realistic hypothesis in accordance with a description of the probable induced effects and phenomena which govern heat treatment .Mathematical modeling reduces the experimental cost and enhances the understanding of the implied physical processes. **[4]**

The main problem mentioned by several authors, concerns the adoption of the boundary conditions while using the time-dependent laser source which explains the limited works in this sense. The experience shows that the use of periodic laser pulses allows getting several forms resulting from the evolution of the transitory temperature's profile that develops inside the material during the treatment. This makes it possible to modify the action's period of the thermal process, this is on one hand. On the other hand, the reached temperature is higher than the temperature of structural transformation related to the processed material's type, without reaching very high surface temperatures and with a better use of energy. **[10]**

The temperature profile of surface hardening for material considered as semi-infinite medium, with a convective boundary condition and receiving a laser source of periodic pulses on its lateral face cannot be simulated directly by the analytical formulations. Among the mathematical models which have received particular attention are those of **Zubair** and **Chaudhry [6]**, are reported and discussed in this paper. It is on the basis of this development that a semi-analytical model is developed .And the effect of material type's on the temperature profile is also obtained and discussed.

2. Mathematical analysis

Surface tempering consists of heating locally and rapidly the material to a temperature superior to the critical temperature of the structural change, and slightly lower than its melting point. The Cooling of the treated zone is done by quenching towards the core of the piece.



Laser Surface Modification and *Tempering Process*

The phenomena of this process for a semi-infinite, homogeneous and isotopic body receiving on its lateral facing a laser beam depending on time is given by the following differential equation:

$$\begin{cases} \rho C_\rho \dfrac{\partial T}{\partial t} = k\dfrac{\partial^2 T}{\partial x^2} + \dot{I}_0(t)(1-R)\mu\exp(-\mu x) f(t) \\ \\ f(t) = \begin{cases} 1 & t \le \tau \cdots heating\_phase \\ 0 & t \rangle \tau \ldots cooling\_phase \end{cases} \end{cases} \quad (1)$$

The initial and boundary conditions are modeled as follows:

$$\begin{cases} T(x,0) = T_0 \\ -k\dfrac{\partial T(x,t)}{\partial x}\Big|_{x=0} = h[T_\infty - T(0,t)] \\ \dfrac{\partial T(\infty,t)}{\partial x} = 0 \end{cases} \quad (2)$$

- ***The analytical solution proposed by Zubair–Chaudhry***

The solution for equation (1) of the heating phase in the Laplace domain is obtained by the Laplace transform then by analytical inverse transform, the solution in the real field is given by the following compact solution:

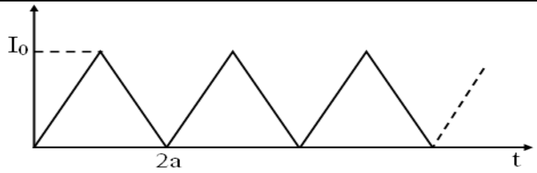
$$\theta(x,t) = (T_\infty - T_0)\left[erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) - E\left(\frac{hx}{k}, \frac{\alpha t}{x^2}\right)\right] - \frac{\mu(1-R)}{\rho Cp}\left[\frac{\left(\mu + \frac{h}{k}\right)}{\frac{h}{k}} \times \left\{erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) - E\left(\frac{hx}{k}, \frac{\alpha t}{x^2}\right) - \right\} * \left\{\frac{\partial}{\partial t}\left[\exp(\alpha\mu^2 t) * \dot{I}_0(t)\right]\right\} - \left\{\exp(-\mu x + \alpha\mu^2 t)\right\} * \dot{I}_0(t)\right] \quad (3)$$

3. Critic:

The analytical solutions obtained by **Zubair** and-**Chaudhry** are limited to simple variable laser sources, "details are shown in **[6]**", because of the inability to perform a simplification of the compact solution due to the convolution product(*).

Concerning periodic pulses of laser signals, which are recognized in the field of material processing, having a complicated mathematical formulation in the real field, such as laser beam of triangular pulses, **Table1**, this complexity is due to the summation term that represents the repetition of pulses. Discontinuity makes it impossible to record real-time determination of the reached temperature during the treatment operation.

Table 1 : Representation of the laser periodic signal, type triangular

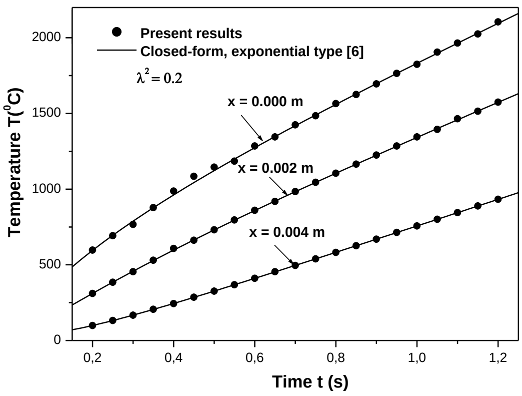
Graphics representation	**Governance equation**
	$\dot{I}_0(t)=\sum_{n=0}^{\infty} I_0 \frac{t}{a}(-1)^n\left[u(t-na)-u(t-(n+1)a)\right]$

4. Validation of the model

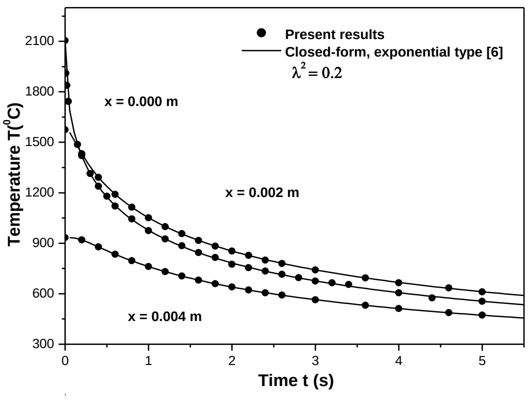
Extension of the procedure:

In this work, we solve the problem with a semi-analytical approach. The basis of our approach is based on the Laplace transform; the compact solution in this field is given by **Zubair-Chaudhry**.

To avoid the problem discussed due to the analytical inversion, we can use numerical methods; the most practical one for the inversion is that of **GAVER-STEHFEST [11]** it is used to solve equation (3) for a triangular laser signal type in real time, following a FORTRAN program. The results are collected for four types of materials **Table 2**, aiming at studying their influence on the temperature's profile.



Heating phase



Cooling Phase

Validation of the proposed semi-analytical solution with the analytical solution of **Zubair - Chaudhry [6]** for the laser source type exponential $\dot{I}_0(t)=I_0\exp(\lambda^2 t)$

Table 2 : Thermo-physical properties of materials used in the simulation

Material	Cp $[J/KgK]$	$k\ [W/mK]$	$\rho\ [Kg/m^3]$	$\alpha\ [m^2/s]$ $\times 10^{-6}$	$\mu\ [1/m]$ $\times 10^{7}$	Melting point $[^0K]$
Steel	460	80.3	7880	22.15	6.16	1800
Nickel	447	90.3	8900	22.696	6.75	1726
Copper	383	386	8954	112.5576	6.7	1356.6
Chrome	450	94	7190	29.0527	6.7	2130

5. Results and discussion :

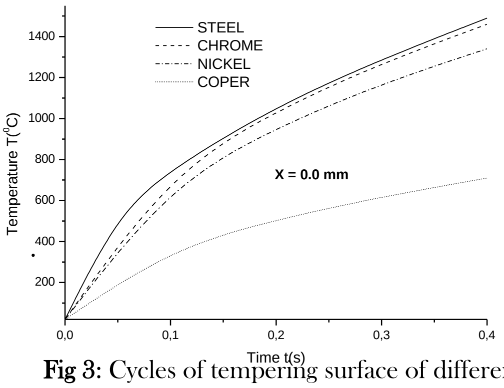


Fig 3: Cycles of tempering surface of different materials

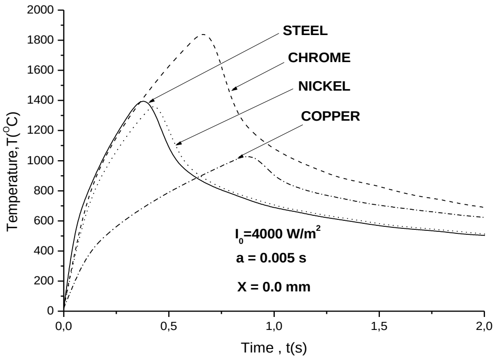


Fig 4: Temperature profile evolution in the Heating phase for different materials

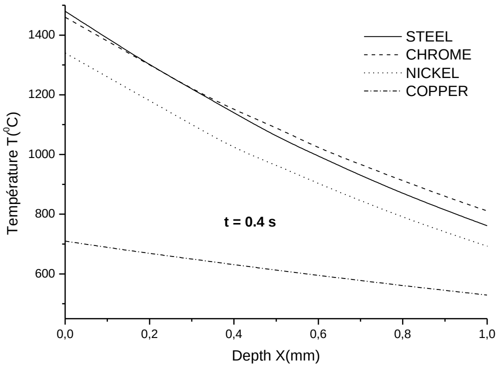


Fig 5: Evolution of temperature in depths for different materials in heating phase at t=0.4s

fig3 shows that the evolution of temperature profiles differ from one material to another, however, all these materials are kept in the same processing conditions, a simple comparison (Fig.4) reveals that the material with the lowest coefficient of absorption and thermal diffusivity (Table 2) shows the most advanced profile of surface temperature in the following order, Steel, Chrome, Nickel and finally Copper. On the other side, **fig5** shows that temperature gradient for the different materials becomes increasingly important in the sense of the decrease in thermal conductivity (**Table2**),while the effect of temperature penetration into the different materials becomes also important in the following order, copper, Chrome, Nickel and finally steel, in the sense of the increase in thermal conductivity. So for these reasons, it is preferable to use the powerful lasers in the surface tempering of materials which have an important thermal conductivity in order to avoid material hardening in volume.

6. Conclusion:

The surface tempering process of a semi-infinite body in1D, with a convective boundary condition, receiving a periodical laser source pulses on its lateral surface cannot be simulated directly by nalytical formulations.

A semi-analytical approach based on GAVER-STEHFEST algorithm for the inversion of the solution in the real field is adopted. The effect of the material's types on the temperature profile during the heating phase is also noted and discussed for four different kinds of materials.

Nomenclature

τ :Time interaction laser-material in the heating phase $[s]$; λ^2: Parameter of the laser pulse $[1/s]$, R : coefficient of Reflectivity, T_0: initial temperature of material, T_∞: environment temperature $[^0K]$, $i_0(t)$: Power of the laser source $[W/m^2]$. $\theta = T - T_0$

$E\left(\frac{hx}{k}, \frac{\alpha t}{x^2}\right)$, a known complex function **[6]**

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