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Optimization of the repartition of the energy in a laser beam and optimization of the steel hardening treatments

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1- Introduction

If the induction hardening is a very well known process of surface hardening for the case of medium and mass production, it is not the same situation for the thermal surface treatments by CO_2 laser although their laboratory feasibility on ferrous alloys was widely demonstrated since more than twenty years. This situation could be explained by economical criteria but is probably due to a lack of reproducibility and so liability that suffer this technique.

Our purpose will try to give a satisfactory reply to this problem using a keeping of informations concerning the characteristics of the primary beam (shape, power) and an "in line" following of induced effects. We apply our methodology to the treatments of samples having different geometries.

2- Control and regulation of the laser power

The control and the regulation of the emission power of our source are realized according to the figure 1. The central processing unit that permits the keeping of data is constituted by a time-sharing computer. This one can exchange informations with the calculator of the source command, the numerical control and eventually if existing the processor that manages the displacements of the optical elements governing an optical device that transforms the shape of a laser beam into another.

We can right follow and control all our treatments and in a near future, we should servo-control the installation in conjunction with relevant parameters such as surface temperature, treated depth and width.

3- Optical device of beam transformation.

To attenuate the spatial and temporal fluctuations of the primary laser and to uniformly illuminate the irradiated zone too, in regard with the use of lenses or reflecting mirrors, we preferred systems that transform by division and recombination the primary beam and permits the modulation of the energy repartitions in the interaction plane according to wished operating conditions. This device represented on the figure 2 is essentially composed by five optical elements with the following conventions M_1, M_2, M_3, M_4 and L_1. The incident laser beam is divided and reflected by the M_1 mirror. The four sub-beams resulting from this operation are symmetrical in regard with the optical axis of the beam. Then after two reflections on two plane mirrors M_2 and M_3, they are reflected by the M_4 mirror (equivalent to the M_1 mirror). The top angles of M_1 and M_4 mirrors are chosen to form a rectangular spot with a minimal diffraction phenomenon at a distance d_i (called "image" distance) under the lens L_1 (see figure 3). This induced spot in the d_i plane presents a constant energy distribution across the width of the spot l and a central depression along the length of the spot L. The ratio L/l is equalling 1.5. The shape of the energy repartition and the amplitude of the diffraction phenomena depend to the position of the observation plane within
we are (this position is called $Z_j$ in regard with image plane $d_j$).

For a given observation plane it is possible to modify the characteristics of the repartitions:

- changing the lens $L_t$ influence on the dimensions of the spot;
- modifying the length of optical path $M_1-M_4$ influence on the dimensions of the spot;
- throwing the four sub-beams out of balance influence on the shape of the spot.

The losses induced by a such device are measured to $\approx 10\%$ (about $2\%$ loss by optical element). This optical device is very performing because it permits firstly to reduce the influence of the fluctuations into the laser beam and secondly to modulate as we want the energy distribution in the interaction plane to:

- treat samples with some different geometry;
- modify the thermal cycles induced within the material.

Figure 3: Impact on thermal paper of the energy repartition after crossing optical device.

4- Previous model and control of the induced effects

Numerous models exist on this subject and are often based on precise resolution of heat equation by diffusion (finite elements or differences). But our aim is to choose operating conditions and to modify parameters during treatment and so, we prefer to realize a model that tries to be "universal" but also easy to use. So we simplify the problem (in a similar manner as Ashby and al. [11]). We do not research indeed a "perfect description" of induced effects but a "probable description". To do that, we must define a reduced number of relevant and experimentally measurable parameters. Also we can select (see ref. [2]):

- for the beam: the total power $P$, the equivalent radius $r^+$, the central spread factor $g(E)_0$;
- for the interaction: interaction time $\tau$ for stationary beam or equivalent interaction time $\tau^+$ (according to laser velocity $v$ by the relation $\frac{2}{v} \cdot g(E)_0$) for moving beam, if required absorptivity $\rho$;
- for the material that will submitted to a given transformation $M$: equivalent increasing of transformation temperature $\Delta T_M$, mean thermal diffusivity $\alpha$, minimal gradient of power to communicate in order to induce $M$;
- for the induced effects: laser track geometry (depth $e_M$ and width $\Phi_M$), surface temperature $T_{SO}$.

Moreover we could establish analytical relations that permit to correlate $e_M$, $\Phi_M$ and $T_{SO}$ with the other parameters. For usual conditions of treatments of ferrous alloys (i.e., beam diameter of few millimetres, treatment velocity included between 1 and 100 mms$^{-1}$), these relations are:

$$e_M = \frac{\alpha \cdot (\pi \tau^+)^2 \cdot g(E)_0^{11}}{12. v} \cdot \frac{\pi \tau^+^2}{2. P} \cdot M^+$$

$$e_M = \frac{T_{SO}}{\Phi_M - 1} \cdot \frac{\pi \tau^+^2}{2. P} \cdot M^+$$

We validate this model on parallelepipedic samples that are oxidized in melted bath salt in order to increase the efficiency between laser radiation and material. For each treatment, surface temperature measurement with a scanning infrared camera is made. The camera sight line is always perpendicular to displacement direction and continually into beam axis. Emissivity of the coating was estimated to 0.85 on the wave length range from 3 to 5 $\mu$m. The validation has been realized for two powers 960 and 2200 W. Figures 4 and 5 show experimental results and model respectively for $e_M$ versus $v^+$ $1/4$ and $e_M$ versus $T_{SO}$ according to relations 1.

The agreement between experimental data and model is very well good.
5- Examples of treatments

5.1- Notched specimens

We showed in the above mentioned paragraphs our capability to optimize the surface thermal treatments using simple parameters in conjunction with a performing model. This paragraph will deal with notched specimens treatments. These samples will be treated using the optical device presented in the section "Optical device" with the below characteristics (dimensions of the spot 9x6 mm, r+ = 4,25 mm, g(E) = 0,82).

The notches have been treated individually with translation of the specimen below the beam in the transverse direction and with a procedure that permits to correct the edge effects [2]. Three sets of twenty specimens have been treated with operating conditions (issued from our model presented in the section "Previous model") chosen to separate the influence of the surface temperature T§, the interaction time, in this case T+, and the hardened depth eM (see table 1). The surface temperature has been measured for each treatment with our scanning infrared camera. From this measure we can estimate the hardened depth eM.

An example of treated area is given on the figure 6. For all conditions a homogeneous martensitic structure is observed in the hardened zones.

The fatigue limit on notched specimens has been established at 10^7 cycles with the stair case method using 15 specimens in each case. Three points bending with a stress ratio R_a equalling 0,1 has been applied. The results expressed in term of maximal local stress are presented in table 1 with an indication of the standard deviation Δσ.

<table>
<thead>
<tr>
<th>P(W)</th>
<th>v (mm/s)</th>
<th>T+ (s)</th>
<th>T§ (°C)</th>
<th>eM (mm)</th>
<th>øD (MPa)</th>
<th>Δσ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2400</td>
<td>12</td>
<td>0,5</td>
<td>1200</td>
<td>0,75</td>
<td>930</td>
</tr>
<tr>
<td>2</td>
<td>1380</td>
<td>2,3</td>
<td>2,5</td>
<td>1050</td>
<td>0,80</td>
<td>1055</td>
</tr>
<tr>
<td>3</td>
<td>1640</td>
<td>2,3</td>
<td>2,5</td>
<td>1200</td>
<td>1,25</td>
<td>850</td>
</tr>
</tbody>
</table>

Table 1: Operating conditions and measured characteristics for the three conditions.

So, these results (we can compare to [3]) of table 1 clearly show that we increase the limit fatigue of about 50-60 % in regard with the base material (øD = 640 MPa) and that it is more the austenizing temperature than the affected depth that seems to play a major role in regard with fatigue limits. In all the cases the cracks initiate from the surface at the notch tip.

5.2- Treatments of samples having different fillets

We showed above our capability to treat notched specimens and increase their fatigue behaviour in three points bending (R_a = 0,1). In this paragraph we will present the laser treatments of samples with fillets having two different geometries:

- undercut fillet \( r = 1,65 \) mm;
- tangential fillet \( r = 2,8 \) mm.

The fatigue limits of these samples using alternated bending method (R_n = -1) will be presented too.
In order to realize an optimal treatment, we voluntarily threw the optical device out of balance to:

- correctly treat the fillets in a geometrical point of view;
- stay the longest time in an isothermal regime to permit a best homogenization of the microstructure and to reach the lower temperature than we can (see [4]).

The metallurgical results of our treatments are showed in the figure 8. The table 2 presents the operating conditions and the fatigue limits of the specimens with their associated values of maximum bending moment susceptible to be supported by the specimens.

<table>
<thead>
<tr>
<th>Fillet</th>
<th>P (W)</th>
<th>V (mm/s)</th>
<th>eM (mm)</th>
<th>TSo (°C)</th>
<th>σf (MPa)</th>
<th>Mx (%N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>undercut</td>
<td>1700</td>
<td>10</td>
<td>0.6</td>
<td>1100</td>
<td>675</td>
<td>3460</td>
</tr>
<tr>
<td>tangential</td>
<td>1700</td>
<td>10</td>
<td>0.6</td>
<td>1200</td>
<td>600</td>
<td>3810</td>
</tr>
</tbody>
</table>

Table 2: Operating conditions and fatigue results.

The table 2 instils the two following remarks into ourselves:

- the change of the undercut fillet into the tangential leads to an about 10% increasing of the bending moment although the fatigue limits were about 10% below;
- the fatigue limits of our samples seem to be anormaly below to the fatigue limits of notched specimens but can be explained by Crossland criterion [5] [6].

6- Conclusion

During this study we pointed out a certain number of elements that are necessary to the command of the thermal treatments by laser on ferrous alloys:

- capability to modulate and characterize the laser beam repartition;
- priority to "a priori" analyse of the phenomena against an empirical "a posteriori" approach.

But we undergo too much the laser treatments than we get its under control and the approach we presented only constitutes a little link of a "controlled installation".

Our treatment methodology has been successfully applied to the improvement of the fatigue behaviour of specimens having different geometry.