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Melted matter temperature and machining length in power laser CO_2 process

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Abstract— **Power laser in machining process is equivalent to two sources of heat. The first source, results from the interaction between the laser and melted matter, its energy depends on the absorbed laser power and on interaction time. Its role is to increase the quantity and the temperature of melted matter. The second source, results from the interaction between the melted matter and material core, its energy depends on the surface and the interaction time of the melt matter. Part of this energy will be diffused by conduction and give rise to thermally affected zone. Another part will be lost by convection with the inert evacuation gas. The mechanical action of gas, allows the melted matter to travel a machining length before its solidification. The proposed model calculates the melted matter temperature, the time of melted matter solidification and machining length.**

Keywords— *Laser processing; Thermal diffusion; Convection energy; Cutting laser*

I. INTRODUCTION

The CO_2 laser is a tool for wide range of applications: for high power (exceeding 500 Watt), the laser is a machining tool. All materials having a thermal conductivity of about or less than 100 W m-1 K-1 are easily machined by the laser. The laser tool compared to conventional techniques has several advantages. In fact, the laser is a non-contact machining tool, which eliminates tool wear. The laser can be easily automated and adapted to a flexible manufacturing.

The aim of the work is to highlight the physics phenomena involved in the laser machining process, which aims to mastering CO_2 laser tool. Used sample in this work is the XC42 steel.

The goal is to supplement previous work and to propose a model able to determine the temperature of the melted material, the time of melted matter solidification, the evacuated length and other characteristic parameters of the groove in function of the laser parameters.

II. MATERIALS AND METHODS

The high-power continuous CO2 laser beam is the machining tool that illuminates the material surface to be machined. The wavelength of the laser used (λ=10.6 mm) drives the Drude interaction laser-matter, where the absorbed energy is converted into heat by photonic effects. According to the thermal properties of the material, this heat quantity will diffuse toward the core material. The energy, brought by the laser beam in that way, is enough to melt steel. A gas jet with the optimal pressure is then used to eliminate melted part by the laser beam.

According to several authors [1, 2, 3], the velocity of the melt front is greater than laser speed at the beginning of the process, so the melting front will move faster than laser. When the steady state is established, the velocity of the melting front is equal to the laser speed. This speed is then called machining speed.

In the case of laser machining, the interaction time is very short (of the order of milliseconds), so the heat would not have the time to be dissipated in the air.

If used gas is inert, the work [1] and [5], proved that the melting energy E_m as well as the energy dissipated by conduction (i.e. heating energy Ec) are proportional to the laser absorbed energy (Ea). To verify this result, in the figure1 is reported the experimental evolution of melted energy with absorbed laser energy, for impact diameter range [0.096, 0,712 mm], speed range [0,5; 6 m/min] and power range [500; 3000 Watts]. This evolution is compared with the relation:

$$E_m = 0{,}14\, E_a \quad \text{Joules} \tag{1}$$

The value of the melting energy E_m is:

$$E_m = \rho\, L_m\, V_m \tag{2}$$

$$V_m = 0{,}25\, p_r\, \pi\, (0{,}18\, D + 0{,}16\, 10^{-3})^2 \tag{3}$$

Were, ***D***: laser impact width, ***ρ***: masse density, L_m: latent heat of fusion, V_m: melted volume during laser matter interaction time and ***pr***: groove depth. Absorbed laser energy ***Ea*** depends on impact diameter, speed and power laser according the relation:

$$Ea = A\, P\, t_i \tag{4}$$

Where, ***A***: absorption coefficient, ***P***: laser power and t_i: time of interaction laser matter.

$$t_i = D/V \tag{5}$$

V: laser speed.

During the grooving process, for absorbed laser energy E_a in the range of [0,63; 13,10 Joules], the experimental results

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show that melting energy $\mathbf{E_m}$ evolves linearly as a function of absorbed laser energy $\boldsymbol{E_a}$ and the relation ***(1)*** fit very well this evolution. This result confirms published results in precedent work [1].

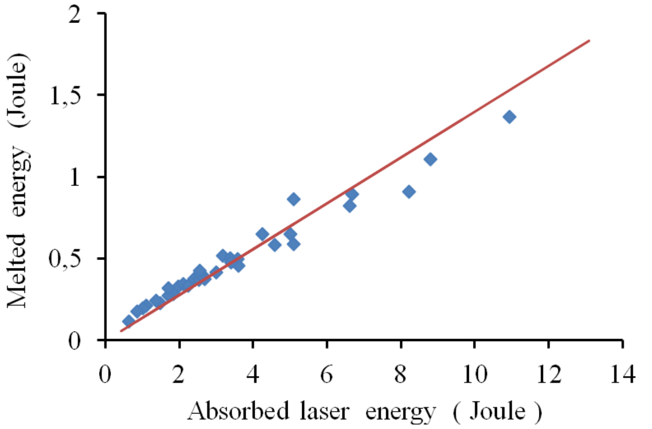

Fig. 1 Evolution of melted energy with laser energy during laser interaction time.

Absorbed laser energy Ea is transformed in to melting energy E_m and conduction energy Ec.

The dissipated conduction energy Ec is distributed in three quantities Ec_1, Ec_2, and ΔEl:

$$Ec = Ec_1 + Ec_2 + \Delta El \qquad (6)$$

All this energy is well defined and calculated in [5]:

$\boldsymbol{Ec_1}$ is the energy that serves to heat, the volume V_m from the ambient temperature to the fusion temperature.

for XC42

$$Ec_1 = 9{,}08\ 10^9\ V_m \qquad (7),$$

$\boldsymbol{Ec_2}$ is the energy dissipated in the metal, helping to create the TAZ. The energy Ec_2 can be considered to be the quantity Q of heat diffused by conduction from the melted surface to the core:

$$E_{c_2} = Q(z=0,t) = \frac{4\,\rho C\,(T_f - T_0)}{\sqrt{\pi}} D^2 Z_{TAZ} \qquad (8),$$

Where, ***C***: calorific capacity, $\boldsymbol{Z_{TAZ}}$: width thermal affected zone.

The energy ***ΔEl*** is deduced from relations (1) to (7). This quantity of energy is supposed to be a part of the laser energy stored in the molten volume before being removed by a jet of inert gas. It will allow the volume Vm to have a temperature T greater than the melting temperature $\boldsymbol{T_f}$ [5].

$$\Delta El = Ea - Em - Ec = (\kappa V + \mu)\, Ea \qquad (9),$$

Where, κ and μ depend on the laser power P.

For $\boldsymbol{D = 0.2\ mm}$ ***gives [4]:*** $\boldsymbol{\kappa = 4.8\ P^{-1}\ (s\ m\text{-}1)}$

$\boldsymbol{\mu = 5.5\ 10^{-3}\ P^{0.5} - 4\ 10^{-5}\ P - 0.081}$

III. RESULTS AND DISCUSSION

A. Temperature of melted volume

Assuming that, ρ V_m C were constant in the range of those temperatures. Writing that during the interaction time the melted volume is heated by conduction from T_f = 1500 °C to T, The following equation gives access to the molten volume temperature T.

$$\Delta E_l = \int_{T_f}^{T} \rho V_f C\, dT = (T - T_f)\rho V_m C \qquad (10),$$

$$T = \frac{\Delta E_l}{\rho V_f C} + T_f = \frac{(\kappa V + \mu) L_f}{0{,}14 C} + T_f \qquad (11),$$

Expression (11) is obtained using (3), (7) and (8) expressions. Temperature T increases linearly with the laser speed. In figure 2 temperature is plotted for powers and impact diameter equal respectively to 1500 watts and 0,2 mm, with varying laser speed.

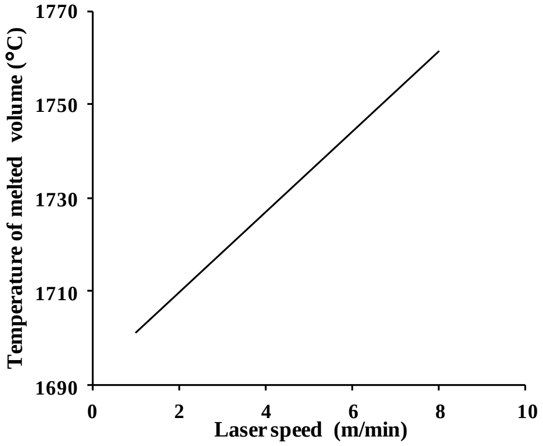

Fig. 2 Melted matter temperature evolution with laser speed during interaction time

During interaction time, beam laser increase temperature of melted matter to reach 1700 °C at 1 m min^{-1} and 1770°C at 8 m min^{-1} laser speed.

From (12), the slope of the curve decreases with the increase of the laser power P and is equal to:

$$\frac{\Delta T}{\Delta V} = \frac{4.8\, L_f}{0.14\, P\ C} = \frac{34.27\, L_f}{P\ C} \qquad (12),$$

At constant power P, Relations (11) and (12) proved that temperature T increase and melted volume V_f decrease with machining speed V, corresponding to lower volume with higher temperature.

B. Duration of melted volume evacuation

Moreover, ΔEl is exchanged by convection with gas. Let us assume that all this energy ΔEl is equal to heat flux exchanged by convection Φ between the fluid (melted matter) at temperature T and the jet inert gas at ambient temperature T_0:

$$\Phi = h\,(T - T_0) = \frac{\Delta E_l}{S\, t_e} \quad \Rightarrow \quad t_e = \frac{\Delta E_l}{h\, S\,(T - T_0)} \qquad (13),$$

Where, ***h*** is the convection coefficient (15 IS in this case), ***S*** is the interaction gas and molten area, then ***S*** is the heat exchange surface, t_e the duration of the heat exchange to achieve the balance.

The action of gas being permanent, it is capable of packed the small amount of melted metal from its inception. This explains the fact that melted matter is evacuated in the form of small balls of the same size. Their weights are in the range of [3; 25 mg]. Assume that the heat is exchange from the melted small ball to the gas, the molten area ***S*** is then deduced from melted volume:

$$S= (4\pi)^{1/3} (3 V_m)^{2/3} \qquad (14)$$

From the relationship (1) and (2), the melted volume is:

$$V_m = 0,14\, E_a /(\rho L_m) \qquad (15)$$

The evolution of this surface with interaction time is then reported in fig.3.

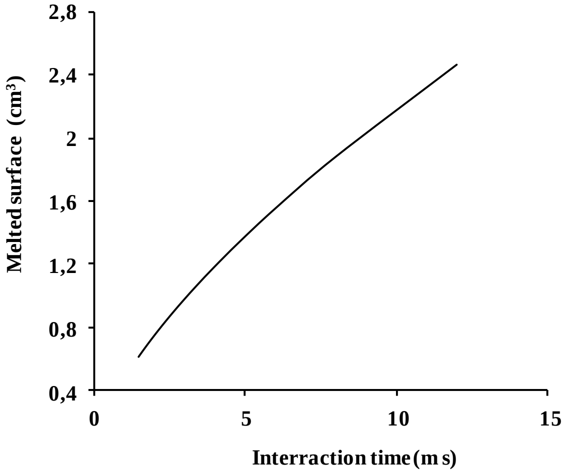

Fig. 3: Heat exchange surface evolution with interaction time.

It is clear that melted surface increase with interaction time.

The duration t_e of melted volume evacuation is then deduced from relation (13) and (15). The evolution of t_e with interaction time is then reported in fig.4

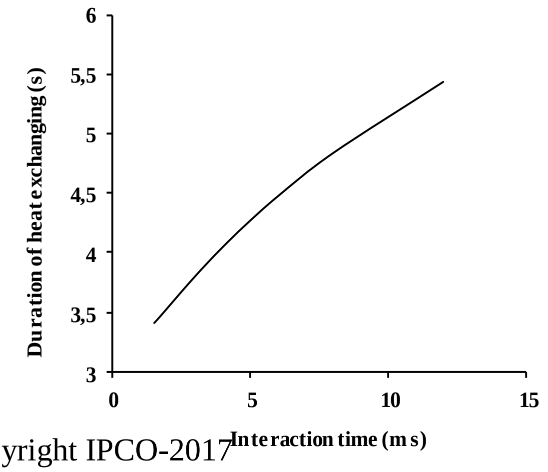

Fig. 4: Evolution of the duration of the heat exchange with interaction time.

Evacuation time is 10^3 greater than the interaction time.

Distance traveled by the molten material before solidifying is called machined length L_u. Evolution of **experimental** machined length with the duration of the heat exchange is reported in figure 5.

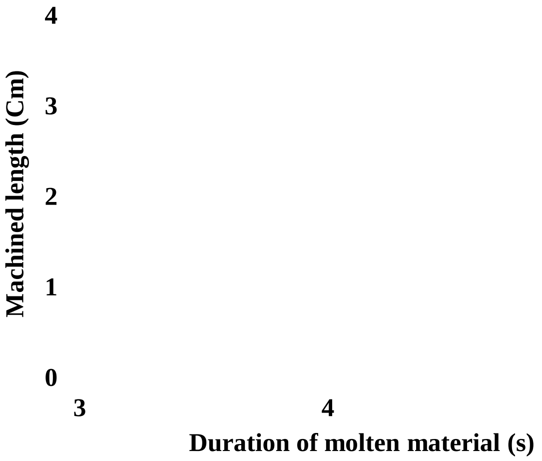

Fig. 5: Evolution of the machining length with duration of melted matter time.

This evolution is linear and fitted as

$$L_u = V_a\, te + C \qquad (16)$$

$$L_u=0,026\, te - 0,087\ (m)$$

V_a is the **average value** of evacuated speed. This speed has the same order of laser speed. It appears that this speed has same value for different laser speed.
To be evacuated melted matter need kinetic energy equal to:

$$E_k= 0.5\, \rho\, V_m\, V_a^2 \qquad (17)$$

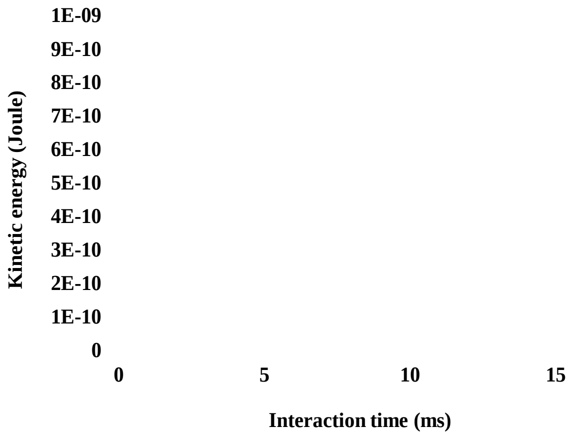

Fig. 6: Evolution of the kinetic energy with interaction time.

Kinetic energy is in order of 10^{-10} joule, lower than the error value used in this work.

The dimensions of the melted volume, supposed spherical, is 10^{-2} times lower than the distance traveled before solidification. This movement can be modeled by the laws of the dynamics of the material point.

Figure 7 represents a mapping of the movement of the molten body.

It is necessary that the pressure forces (Pg S) cancel the frictional forces (F), so that the melted volume of mass m is set in motion.

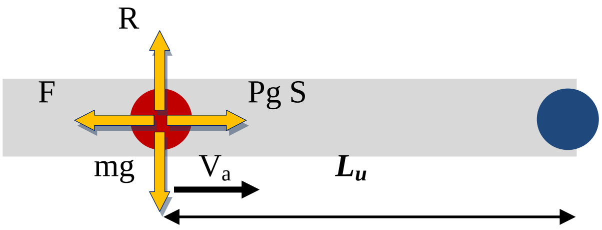

Fig. 7: Schematic movement of the molten body.

III. CONCLUSION

This study proved that during the interaction time of laser - XC42 steel, beam laser increase temperature T of melted matter to reach 1700 °C at 1 m min^{-1} laser speed and 1770°C at 8 m min^{-1} laser speed. T increase when melted V_f volume decrease with machining speed V, corresponding to lower volume with higher temperature.

The duration of the heat exchange increase with interaction time and is 10^3 greater than the interaction time.

The evolution of distance traveled by the molten material before solidifying is linear with the duration of the heat exchange.

The speed of evacuated body has the same order of laser speed. It appears that this speed has same value for different laser speed. This movement can be modeled by the laws of the dynamics of the material point.

Microscopic study is necessary to explain this result.

REFERENCES

[1] Jebbari N, Jebari M, Ahdad F, Tarrats-Saugnac A, Longuemard J.P. Appl Phys B, 70 (2000) 99–103.

[2] Jebbari N, Tarrats-Saugnac A, Melhaoui A. Mécanique Industrielle et Matériaux, 48 (1995) 232.

[3] Vannes AB. Laser et industrie de transformation; Technique et documentation, 1986, Paris, Lavoisier, p. 225.

[4] Yuan S. Ph D thesis, Institut National des Sciences appliquées de Lyon, 1989.

[5] Jebbari N. Jebari M. M., Saadallah F. Tarrats-Saugnac A. Bennaceur R. Longuemard J. P. Optics & Laser Technology 40 (2008) 864–873

[6] Pantelis D. Technique de l'ingénieur, traite généralités A1095. p. 1–18.