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Research paper

Melt surface deformation during stainless steel laser cutting in vacuum and atmospheric pressure

Samia Aggoune

[1]*Centre de Développement des Technologies Avancées, Equipe Traitement des Materiaux par Lasers, P.0. Box 17 Baba- Hassen, 16303 Algiers, Algeria*
**Corresponding author E-mail: saggoune@cdta.dz*

Abstract

The analysis of the recoil pressure generated during stainless steel laser beam irradiation is carried out. The threshold temperature from which the melted surface begins to be deformed is investigated. The corresponding melt expulsion velocity in vacuum and at atmospheric pressure is evaluated. We demonstrate that the recoil pressure contributes weakly to the lateral ejection of the molten material if the surface temperature is equal or is lower than that of the vaporization one at atmospheric pressure. This recoil pressure causes expulsion only only for surface temperatures which are very higher than the boiling point; this conclusion is not valid in vacuum. It is also shown that the initial stage of liquid metal ejection can be predicted by balancing the vapor recoil force with the surface tension force at the periphery of the liquid pool.

Keywords: *Cutting, deformation, laser, recoil pressure, surface tension.*

1. Introduction

For some materials processing, the liquid metal expulsion is desirable, and it is therefore important to recognize the different parameters that affect this expulsion. Recently, a particular interest raised in regard of the recoil pressure determination, since it is relevant for the development of laser processing in industry, and therefore many theoretical and experimental investigations are conducted.

Anisimov and Knight [1,2] proposed in previous works theoretical expressions of the recoil pressure, which have been widely used in numerical studies of laser welding, drilling and cutting processes. In their important assumptions is assumed that the molten surface temperatures are higher than the boiling point, and at the evaporating surface, the ambient surrounding gas is not in contact with that surface so, its partial pressure is not considered in the total pressure. In this case, the total pressure is only the contribution of the recoil pressure due to the metal evaporation. Another work done by Semak and Matsunawa [3], asserted that the average keyhole welding temperature does not need to exceed the boiling point. But, since there is a lack of information on the recoil pressure temperature dependence, this statement cannot be true.

Few experimental studies of recoil pressure were performed [4, 5], since they are focused on the ablation regime which is usually discussed in the context of intense irradiation where the recoil pressure is determined only as a function of the laser intensity, without considering the surface temperature T_s. However, it is well known that when heating rates increased, the corresponding recoil pressures also increased.

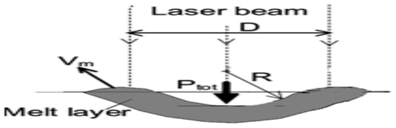
Although it exists in welding and cutting processes, the evaporation is generally neglected both in the theoretical and experimental approaches, when the beam intensity is relatively low. But, in typical welding/cutting conditions the recoil pressure produces a molten flow with high velocities. Such melt flow has an effect on the thermal field [6, 7]. Voisey *et al.* [8] observed that the amount of liquid expulsion depends strongly on the variables involved in the processing such as material properties and laser parameters.

Aden *et al.* [9, 10] analyzed theoretically the dynamics of the metal vapor expansion in three-dimensional configuration. The authors have shown that when the laser intensity is increased, the fraction *ß* of the re-condensed particles to the evaporating ones, approaches 0.2 at the higher laser intensity, so a one-dimensional ejection occurs in a direction perpendicular to the workpiece surface. Bellot *et al.* [11] carried out the influence of *ß* on ambient argon pressure for the evaporation of chromium from the liquid iron surface under vacuum conditions. It was illustrated that we need a higher ambient pressure of argon to restrict the evaporating mass of chromium when the area of the evaporating surface becomes small which leads to keep *ß* at a higher level. In the recent years, a great progress has been made, especially in simulating laser welding and cutting, but there is no theoretical model that can predict the variation of the pressure gradient around T_v specially under atmospheric pressure which can take into account the contribution of the surrounding gas atoms to the total pressure at the surface .

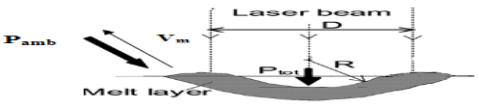
The aim of this paper is to understand the liquid metal expulsion theoretically during laser spot cutting of 304 L stainless steel. We investigate the threshold temperature from which the melted surface begins to be deformed and we try to evaluate the corresponding melt expulsion velocity in vacuum and at atmospheric pressure.

2. Modelling:

We consider a circular laser spot interaction with stainless steel metal surface under vacuum and in atmospheric pressure, and we suppose that the distribution of the absorbed laser intensity of the spot is uniform: $I_{abs}(r) = I_{abs}$. When the laser beam is absorbed by the solid metal, heating and melting take place which increases the melt's surface temperature T_s. The cross section of the melt layer is illustrated in figure 1, (a) and (b), in which the X axis is directed along the twice spot radius, and the Z axis coincides with the normal to the melt surface.



(a)



(b)

Fig. 1: Schematics of melt removal from the interaction zone: (a) under vacuum, (b) at atmospheric pressure**.**

The liquid metal is assumed to be an incompressible and Newtonian fluid. We note that, the pressure and the surface tension forces are both taken into account in this model.

3. Results and discussions:

It is essential to estimate the recoil pressure to compute its contribution. Consider the case of figure 1(a, b), where the central part is depressed and the melt in the center is redistributed to the periphery. We assume that no surrounding gas is present during the laser processing. The analytical expression of Pr can be approximated as [3].

$$\mathrm{Pr} = \frac{1+\beta}{2} P_{sat}(T_s) \tag{1}$$

Where, the coefficient ß representing the fraction of the recondensed particles to the evaporating ones is influenced by the gas flow of evaporating particles above the surface. $P_{sat}(T_s)$ is the saturated pressure at the surface temperature T_s. It can be obtained by the following Clausius-Clapeyron's relation:

$$P_{sat} = p_0 \exp\left[\frac{\Delta H_v}{k_b T_v}\left(1-\frac{T_v}{T_s}\right)\right] \tag{2}$$

Where k_b is the Boltzmann constant, T_v is the vaporization temperature under the pressure p_0, and $\Delta H_v = mL_v$, is the enthalpy of phase transition from liquid to vapour per atom (m: mass per atom, L_v: latent heat of vaporization).

The expression $\frac{\Delta H_v}{k_b T_v}$ is equal to 12.61 in our case.

When the velocity of the metal vapour reaches the sound velocity, the recombination rate ß becomes equal to 0.18, so Pr is equal to 0.6 P_{sat}. We are considering the case of evaporation in a vacuum. But when the evaporation is not strong, so Pr is approximately equal to $0.95P_{sat}$ with $\beta = 0.9$.

The special case where T_s is so small means that the recoil pressure is approximately equal to zero, which also indicates the absence of driving force of the melt and the melt pool surface remains flat. But, when the temperature increases, the melt region size becomes larger and its surface is severely deformed due to the Marangoni force coming from the spatial gradient of surface tension, and from the buoyancy force. We note that buoyancy force results from the variation of density and it can be neglected near the strong convection currents driven by the Marangoni force. On the other hand, the role of the surface tension force is to hold the liquid metal in place, this tends to prevent its expulsion. But, for higher laser beam, the recoil force takes place and the vapour pressure behaves like a piston exerting pressure onto the melt.

When the vapor recoil pressure exceeds the surface tension force of the liquid metal at the periphery, the depression melt at the center occurs and leads to its redistribution to the periphery [12]. Finally, melt is ejected out radially. We can say that under the recoil pressure, the depression in the interaction zone center could be a signal of liquid metal expulsion during the laser cutting process.

It is essential to know that, to drive the melt at atmospheric pressure ($P_{amb}=P_{atm}=1.01\mathrm{x}10^5$Pa), we have to compute the pressure difference at the center and at the periphery. In the following, we assume a steady state velocity and temperature fields and by using the Bernoulli equation: $\mathrm{Pr}-P_{atm}-\sigma/r = 1/2\ \rho_m V_m^2$, we can deduce the ejection velocity V_m at the periphery:

$$V_m = \sqrt{\frac{2(\mathrm{P}_r - P_{atm} - \sigma/r)}{\rho_m}} \tag{3}$$

Where σ is the 304L stainless steel surface tension coefficient (1.9N/m) and r is the variable beam radius.

On figure 2, we calculate the surface tension and the recoil pressure forces and we deduce then the initiation condition of liquid metal expulsion in vacuum and at atmospheric pressure.

Knowing that the ejection of the liquid metal occurs when the vapour recoil force exceeds the surface tension force at the periphery of the cut pool, this means that the recoil force must be greater than 0.322 10^{-2} kg m/s^2 (0.003N). The condition for the beginning of liquid metal expulsion under vacuum can then be obtained by balancing the surface tension force at the boundary of the liquid pool ($F_t=2\pi\sigma r_0$) with the vapour recoil force. This is observed at the critical absorbed intensity I_{abs} of 0.23MW/cm^2 (see figure 2) which corresponds to r_0=0.27mm (see figure 3). We then deduce the corresponding critical saturated pressure P_{sat}=23456.8Pa and the threshold surface temperature T_{scr}= 3023K.

Following the same procedure, at atmospheric pressure, the threshold surface temperature for the melt surface deformation starts at T_{sc}=3451K, which is above the boiling point of 304L stainless steel. This means that the expulsion of liquid metal occurs when the vapour pressure is greater than 1 atm.

We can conclude that in the case of processing under atmospheric pressure, the lateral melt ejection due to recoil pressure is occurring only above the evaporation temperature T_v.

We can also deduce that the vapour pressure is lower than the atmospheric pressure and the temperature is lower than the boiling point when the laser power density is small. But, when the laser power density increases, the surface temperature can become higher than the boiling point, then the free surface deformation occurs.

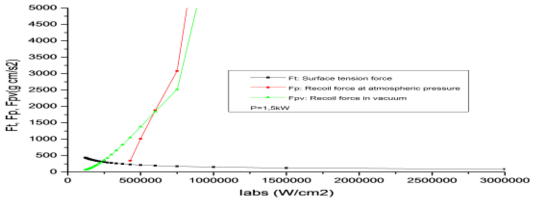


Fig. 2: Variation of recoil and surface tension forces with the absorbed laser intensity for a fixed laser power *Pl*=1.5kW.

In figure 3, it is observed that when the spot diameter is enough large (r > 0.27mm), the expulsion of the metallic liquid is not observed neither in vacuum nor at atmospheric pressure, which corresponds to I_{abs}<0.23MW cm^{-2}.

When decreasing the spot diameter to r=0.2mm, leading to an increasing of the absorbed laser intensity to 0.42MW/cm^2, the expulsion occurs only in vacuum. Further, an increasing in the absorbed laser intensity means a decreasing in the spot diameter, and the metallic liquid expulsion is observed both in vacuum and at atmospheric pressure (r < 0.2mm and I_{abs}> 0.42MW/cm^2).

In figures (2 and 3), we can see that the recoil force increases faster than the surface tension force. Indeed, more heating results in a higher recoil pressure than in surface tension force.

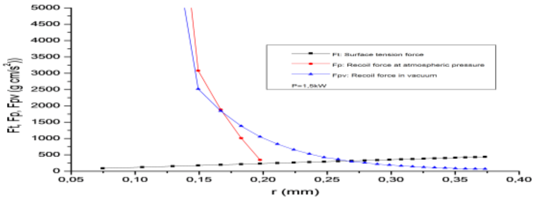


Fig. 3: Recoil and surface tension forces as a function of the beam radius for a fixed laser power Pl=1.5kW.

On figure 4, we show that the ejection melt velocity increased with the increasing in the absorbed laser intensity. So, for low absorbed intensities, the melt velocity is lower than 50m/s but for higher absorbed ones, this velocity increases to reach 550m/s under vacuum, but under normal atmosphere, these velocities remain low and don't exceed 100m/s. It can be concluded that for the same laser conditions, under vacuum the penetration depths of cutting are larger than those obtained under atmospheric pressure. Otherwise, for low absorbed laser beam intensities (less than 0.5MW/cm^2) the ejected velocities are lower than 10m/s in atmospheric pressure. In this special case, the power beam is used to get a melt having surface temperature closer to the melting point.

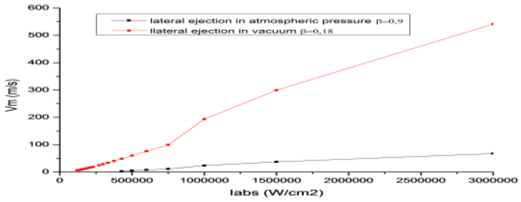


Fig. 4: The effect of lateral melt velocity on the absorbed laser intensity for a laser power of 1.5kW.

4. Conclusions

1. The necessary condition to initiate the metallic liquid expulsion from the laser irradiated area can be determined by balancing the vapour recoil force with the surface tension force at the boundary of the liquid pool.

2. Under vacuum condition, it was revealed that the deformation starts at T_{scr}=3023K for 304L stainless steel material, which is just below the evaporation temperature T_v. Under atmospheric pressure, the melt ejection due to the recoil pressure is observed above T_v.

3. Velocity ejection reaches 550m/s under vacuum, but at atmospheric pressure, it doesn't exceed 100m/s for the same laser conditions.

4. If the absorbed intensity is lower than 0.5MW cm^{-2}, the recoil pressure contributes weakly to the ejection of the molten material at atmospheric pressure. It can play a significant role in ejection only for surface temperatures very greater than the boiling point (T_s>>T_v) (shown experimentally [13]).

5. In laser cutting under atmospheric pressure, when the evaporation rate is low enough to produce a noticeable recoil pressure, no ejection is observed. In this case, the assist gas is the only main mechanism of melt ejection.

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