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Scaling laws for the laser welding process in keyhole mode

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ABSTRACT

This study shows that the keyhole model derived for determining the scaling laws of keyhole depths for laser welding when high power incident laser beams are used (typically in the multi-kW incident power range), can be also applied to determine the melted depths observed during the Selective Laser Melting process, where much lower incident powers of typically few hundred watts are focused on very small focal spots. The solution of the thermal analysis of this keyhole configuration is described by only three independent dimensionless parameters that are also involved for the analysis of a more general problem of heat conduction using similar input parameters. This global approach and the keyhole model describing the process of laser welding have been also validated by analyzing the melted depths generated by the Selective Laser Melting process. The dependence of the melted depths on the operating parameters of this process has been established, as well as the formation thresholds of the keyhole.

1. Introduction

Laser welding, which has been used since the 1970s, has become one of the most important laser processes in the industrial world. It allows the assembly of metal parts for a very wide range of thicknesses, from very thick, greater than ten millimeters, thanks to the use of power lasers delivering powers in the multi-kW range, to much smaller thicknesses, less than a millimeter using lasers of much lower power. Many experimental, analytical or numerical studies have made it possible to understand the main physical processes occurring during this very characteristic and complex welding mode, the keyhole (KH) welding, whose melt pool transverse cross sections are characterized by rather large aspect ratios R, defined as the melt pool depth/laser spot diameter (Katayama, 2013). The prediction or the analysis of these KH depths according to the different operating parameters and materials used is therefore of the utmost importance for this application.

In addition, metal addition manufacturing processes, and more particularly the Selective Laser Melting (SLM) of powders, have also become more recently widely used processes (Yap et al., 2015). They produce molten zones of much smaller dimensions, but which can also present the same characteristics of the keyhole mode observed in welding (so with high aspect ratio), whereas the operating parameters used are very different (typically laser incident powers of a few hundred W, laser spot diameters less than 0.1 mm and processing speeds of the order of m/s). Therefore, the occurrence of the KH mode for SLM conditions has been suggested, but never really proven quantitatively, and the knowledge of these melted depths is also very important because the quality of the resulting densification has been shown to be directly related to the melt pool sizes (Tang et al., 2017).

It is the purpose of this article to show that these two very different processes can both be described quantitatively by the same model describing the evolution of the aspect ratio R according to the operating parameters used and the thermo-physical parameters of the material. In a first step, the use of Buckingham's theorem allows to define the number of independent parameters controlling this thermal problem and justifies its solution thus determined, which is recalled. This model is then applied to the analysis of recently published experimental data obtained in SLM conditions, and it is shown that it is possible to reproduce precisely these experimental data as well as the observed thresholds for KH formation.

2. Scaling law methodology

2.1. Definition of the problem

In order to determine the scaling laws that control the KH depth e as a function of the main operating parameters and thermophysical properties of the welded material, several simplifying hypothesis have been used. The KH is assumed to be a vertical cylinder with a diameter d that is equal to the spot diameter of the incident laser beam; this KH is moving with the welding speed V, inside a material at an initial temperature T_0. The incident laser beam is P and A is the fraction of this power absorbed inside the KH. One knows also that the KH walls must have a temperature at least equal to the vaporization temperature T_v;

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So, one will consider that the wall temperature of the cylindrical KH is constant at T_v. The used material is also characterized by its heat conductivity K(W/m.K) and by one of the two last thermophysical parameters: its heat capacity per unit volume ρC_p (J/m^3.K) or its diffusivity κ (m^2/s).

So, in the frame of these hypothesis, one can consider that this problem is totally defined and closed by these previous p = 7 parameters: the resulting KH depth e(m), function of the 3 operating parameters, which are P(W), V(m/s), d(m), the 3 thermophysical parameters: K(W/m.K), ρCp (T/m^3.K) and the KH wall temperature relative to the initial material temperature ($T_v - T_0$)(K). This means that there is a unique relation involving these p = 7 parameters.

Moreover, these 7 parameters are only depending of u = 4 fundamental units, which are the mass [M], the length [L], the time [T] and the temperature [K]. Therefore, the Vaschy-Buckingham π-theorem (Buckingham, 1914) states that under these conditions, there must exist p - u = 3 dimensionless independent parameters (π_1, π_2 and π_3), derived from these initial p parameters, which must satisfy a relation $f(\pi_1, \pi_2, \pi_3) = 0$.

2.2. Construction of the 3 dimensionless independent parameters

From these 7 initial parameters, 3 dimensionless independent parameters have to be defined (a given dimensionless parameter cannot be derived from another one). There are several possibilities for this construction, by choosing ratios of parameters (or combination of parameters) using for example units of length, velocities, power, power per unit length or volume. A first obvious dimensionless parameter π_1 is the ratio e/d, which is none other than the usually defined aspect ratio R of the KH. A second dimensionless parameter can be defined as $\pi_2 = V\rho C_p\, d/K$, which the ratio of the welding speed V and another velocity such as $K/(\rho C_p\, d)$. In fact one can recognize that this parameter is similar to the well-known Peclet number $Pe = V\rho C_p d/2K$ that will be used below instead. A third dimensionless parameter can be $\pi_3 = P_a/(dK(T_v - T_0)$, which is the ratio of two powers, one is the absorbed laser power P_a = A P (with A and P being the absorptivity and the incident power respectively), and the other one results from the combination: $d.K.(T_v - T_0)$.

So the Vashy-Buckingham π-theorem says that it exists one relation between these 3 dimensionless parameters, which could be written as: $\pi_1 = R = F(\pi_3, \pi_2)$.

Now, if one adds that the experimentally observed KH depths are usually proportional to the laser power P, one could finally write:

$$\pi 1 = R = \frac{e}{d} = \pi 3\,.\, f(Pe) = \frac{P_a}{d.\,K.\,(T_v - T_0)}.\, f(Pe) \tag{1}$$

The relation (1) has been obtained only from dimensional analysis, which is rather efficient because it already gives an interesting scaling law with the parameters of this thermal problem. However, a complete dependence with all the involved parameters is not obtained, because the function f(Pe) is not defined here. We will see in Section 3 how f(Pe) can be only obtained from a complete solution of this thermal problem.

2.3. Other possibilities for defining dimensionless parameters

In the previous analysis, the dimensionless parameter $\pi_1 = e/d = R$ is adapted to the process of laser welding in KH mode, because it involves deep penetrations characterized by large KH depths e compared to KH diameters d (i.e. R > 1). But for laser processes involving heat diffusion, (as surface treatments such as laser hardening or surface melting), where the thickness of the affected material has to be determined, a characteristic normalizing dimension that would be more appropriate to this process of heat diffusion, could be some diffusion length δ obtained during the time τ: $\delta = (\kappa.\tau)^{1/2}$, where $\kappa = K/(\rho C_p)$ is the heat diffusivity and $\tau = d/2V$ is a characteristic dwell time. So another dimensionless parameter can then be defined such as: $\pi_1' = e/\delta$. One can easily see that π_1 and π_1' are related through the relation:

$$\pi_1' = \pi_1.2Pe^{1/2} \text{ or } e/\delta = 2R.Pe^{1/2} \tag{2}$$

One could also consider another dimensionless parameter $\pi_3' = \Delta H/\Delta h(T)$, which is the ratio of two energy densities, being expressed in J/m^3. This approach was initially used by Hann et al. (2011) for describing the melted depths evolution during laser processing. King et al. (2014) showed that the energy density ΔH represents the energy absorbed A.P.τ during the dwell time τ, which is distributed inside a volume defined by the focal spot diameter and the diffusion length δ: $\pi(d/2)^2\delta$.

This energy density is finally written as $\Delta H = (2^{3/2}\pi)^{1/2}.4.AP.\tau/(\pi.d^2.\delta) = 2^{3/4}AP/(\pi\kappa V(d/2)^3)^{1/2}$ (Rubenchick et al., 2018). (The term $(2^{3/2}\pi)^{1/2}$ was introduced so that ΔH is consistent with the initial definition of Hann et al. (2011)

The second energy density Δh(T) can be defined by using the usual enthalpy formulation $\Delta h(T) = \rho C_p.(T - T_0)$. If the laser welding process in the KH mode is analyzed, the enthalpy at vaporization $\Delta h(T_v)$ should be used. But one could also use the enthalpy at the melting $\Delta h(T_m)$, if the melting temperature T_m is the main involved characteristic temperature, as for example in surface treatment.

Similarly to Eq. (2), one has the following relation between π_3' and π_3:

$$\pi_3' = \frac{\Delta H}{\Delta h(T_v)} = \left(\frac{2^{7/2}}{\pi.\,Pe}\right)^{1/2}.\,\pi_3 \tag{3}$$

Finally, it is also possible to define another energy density ΔH_O (in J/m^3) that is only related to the operating parameters P, V, d such as: $\Delta H_O = AP/(V.d^2)$. Similarly to Eq. (3), a dimensionless parameter $\pi_3'' = \Delta H_O/\Delta h(T_v)$ could be defined. These different dimensionless parameters verify the relation:

$$\pi_3'' = \frac{1}{2Pe}.\pi_3 = \left(\frac{\pi}{2^{11/2}.\,Pe}\right)^{1/2}.\,\pi_3' \tag{4}$$

The different dimensionless parameters involved in this paper are summarized in Table 1:

3. Solution of this thermal model

3.1. Analysis of high power laser experiments

With the different hypothesis for the KH thermal model defined in § 2.1, it is possible to determine the KH depth resulting from these conditions and compare it with the previous scaling law of Eq. (1). As this determination has already been detailed in a previous publication (Fabbro et al., 2017), the main results will be shortly recalled here.

One considers that the absorbed laser power P_a is homogenously distributed over the KH wall surface at T_v, along the KH depth e. Therefore, if one knows the absorbed power per unit depth $P_z = dP/dz$ that is conducted through the KH wall necessary for maintaining the KH surface at T_v, the KH depth must simply verify the relation $e = P_a/P_z$.

For determining the absorbed power per unit depth $P_z = dP/dz$, we assume a 2D thermal field induced inside the material, because the KH aspect ratio R ≥ 1. Considering stationary conditions, it can be shown that the solution of the 2D heat equation is then only dependent of the

Table 1
Possible dimensionless parameters involved in this thermal problem that depends of the 7 parameters : e(m), P(W), V(m/s), d(m), K(W/m K), ρCp(J/m^3 K), (T_v-T_0)(K). The relations between them are given by the Eqs. (2)–(4).

π_1 (=R) (aspect ratio)	π_2 (=Pe) (Pe number)	π_3	π'_1	π'_3	π''_3
e/d	$V\rho C_p d/2K$	$AP/(dK(T_v-T_0)$	e/δ	$\Delta H/\Delta h(T_v)$	$(AP/Vd^2)/\Delta h(T_v)$

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