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CALCULATION OF THE DEPOSITED LAYER THICKNESS THROUGH SIDE INJECTION OF POWDER USING CO_2 LASER

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ABSTRACT

The paper presents a simplified theoretical model for estimating the operating parameters of the laser deposition by injecting the powder into the metal bath. The study considered the influence of the powder particles on the transfer of energy from the laser beam to the surface of the substrate to be deposited. The following parameters were determined: the metal bath depth, the diameter of the metal bath, the mass of the powder deposited, the average temperature of the metal bath, the thickness of the deposited layer.

KEYWORDS: laser deposition by powder injection into the molten bath, determination of coat characteristics, influence of injected particles

1. Introduction

Laser deposition is used to improve the mechanical properties and corrosion resistance of layers at the surface of the materials.

As a superficial treatment of hardening, laser radiation processing aims at increasing the level of hardness of the surface layers, with a direct effect in terms of improving wear resistance. The specific characteristics of laser processing, namely ultra-fast heating speeds and variables in a wide range of values (v > $10^3 \div 10^7$ $^oC \cdot s^{-1}$), high energy densities and a characteristic energy distribution into the beam, determine the particularities of the thermal transformations generated in the material being processed.

Laser deposition leads to a multi-zone structure: deposited layer, dilution layer where there is practically a surface alloying, a layer hardened in the solid phase, an annealed layer and finally the base material.

Laser processing, in hardening, alloying or deposition process, induces additional microstructural hardening mechanisms: over-saturation of the solid solution in carbon and alloying elements (martensitic hardening), increasing the degree of finishing of the structure and substructure respectively, a dispersion hardening or precipitation of carbides. The mechanism, the kinetics of these transformations, the morphology as well as the resulting properties are determined by the type of processing, the material under processing and the deposition material used.

Several models have been suggested for calculating the height of the laser deposited layer.

The theoretical model proposed in this paper involves a uniform distribution of the laser power and a one-dimensional heat flux inside the workpiece.

It is a simplified theoretical model used to estimate the dimensions of the molten layer and the deposited one, taking into account the parameters of the laser beam and the thermophysical characteristics of the support and the powder used. The influence of powder particles on the transfer of energy from the laser beam to the surface of the deposited substrate was considered using Mie's theory [1, 4, 5].

2. The theoretical model

For calculating the maximum height of the deposited layer, it was considered that this would be obtained for a maximum amount of thermal energy accumulated in the metal bath. However, the temperature at the bath surface should not exceed the boiling temperature of the support material.

Thus, the time dependence of conductive heat in the space under the irradiated surface is described by equation [1, 4, 5]:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = k \cdot \frac{\partial^2 T}{\partial z^2} \qquad (1)$$

Limit conditions will be:

$$k \cdot \frac{\partial T}{\partial z}(z=0) = (1-R) \cdot P/S$$

$$T(z=\infty) = T_0$$

where: ρ - material density; c – material specific heat; k – thermal conductivity; T – temperature; z – depth; P – laser power; R – reflexivity of the piece surface; D – diameter of the laser beam; v – laser motion speed; S – area of the laser irradiated surface.

The solution of this equation is (4):

$$T(z,t) = \frac{8 \cdot (1-R) \cdot P}{\pi \cdot k \cdot D^2} \cdot \sqrt{(a \cdot t)} \cdot e^{-\frac{z}{2 \cdot \sqrt{(a \cdot t)}}} \quad (2)$$

where: a – thermal diffusivity

The maximum local temperature achieved during the laser-material interaction for $t =$ D/v is:

$$T\left(z, t = \frac{D}{v}\right) = \frac{8 \cdot (1-R) \cdot P}{\pi \cdot k \cdot D^2} \cdot \sqrt{a \cdot D/v} \cdot e^{-\frac{z}{2 \cdot \sqrt{a \cdot D/v}}} \quad (3)$$

From eq. (3), the max. temperature of the irradiated surface may be written as:

$$T(z=0) = \frac{8 \cdot (1-R) \cdot P}{\pi \cdot k \cdot D^2} \cdot \sqrt{a \cdot D/v} \quad (4)$$

In laser deposition, however, where the powder is fed into the melt at the point where the beam strikes the substrate, the current power density that is distributed over the surface of the sample is lower than the apparent laser power by a factor that quantifies the transmission coefficient, φ. Thus:

$$P = \phi \cdot P_0 \quad (5)$$

where: P_0 – apparent power of the laser; φ - factor of attenuation

Thus, the temperature at the surface of the metal bath becomes:

$$T(z=0) = \frac{8 \cdot P_0 \cdot \phi \cdot (1-R) \cdot \sqrt{(a \cdot D/v)}}{\pi \cdot k \cdot D^2} \quad (6)$$

The temperature at the depth z inside the metal bath:

$$T(z) = \frac{8 \cdot (1-R) \cdot P_0 \cdot \varphi}{\pi \cdot k \cdot D^2} \cdot \sqrt{a \cdot D/v} \cdot e^{-\frac{z}{2 \cdot \sqrt{a \cdot D/v}}} \quad (7)$$

The attenuation coefficient of the laser beam intensity:

$$\varphi = \exp\left[-\frac{Q \cdot D}{m_p \cdot V_L \cdot v} \cdot D \cdot K \cdot \pi \cdot r_p^2\right] \quad (8)$$

But: $m_p = \rho_p \cdot V_p = \rho_p \cdot \frac{4}{3} \cdot \pi \cdot r_p^3$

K = 5, constant

$V_L = \frac{\pi \cdot D^2}{4} \cdot 5d$, laser operation volume

$Q = Q_0 \cdot \Gamma$, powder feed velocity

Γ - particle fraction contained in the metal bath

Then:

$$\varphi = \exp\left[-\frac{3 \cdot Q_0 \cdot \Gamma}{\pi \cdot r_p \cdot \rho_p \cdot v \cdot D}\right] \quad (9)$$

2.1. Calculation of the metal bath depth

In the case of laser deposition, it is desired to obtain a low- depth melt layer of approx. 0.3-0.5 mm. The model assumes that the ratio between the laser beam diameter and the maximum depth of the metal bath is $\frac{D}{z_m} \leq 10$.

In eq. (7) make sure that at the depth z = z_m the melting temperature T_m is reached.

$$T_m = \frac{8 \cdot (1-R) \cdot P_0 \cdot \varphi}{\pi \cdot k \cdot D^2} \cdot \sqrt{a \cdot D/v} \cdot e^{-\frac{z_m}{2 \cdot \sqrt{a \cdot D/v}}} \quad (10)$$

And at surface z = 0 temperature shall be acc. to the relation:

$$T(s) = \frac{8 \cdot P_0 \cdot \phi \cdot (1-R) \cdot \sqrt{(a \cdot D/v)}}{\pi \cdot k \cdot D^2} \quad (11)$$

Dividing T_m/T_s we get $T_m / T_s = e^{-\frac{z_m}{2 \cdot \sqrt{a \cdot D/v}}}$

By applying a logarithm to the expression, we reach the maximum depth of the metal bath:

$$z_m = 2 \cdot \sqrt{\frac{a \cdot D}{v}} \cdot \ln \frac{T_s}{T_m} \quad (12)$$

2.2. Calculation of the metal bath diameter

This is the actual diameter of the laser beam, d_e, as shown in Fig. 1. By setting the condition $T_s(z = 0) = T_m$ in equation (11):

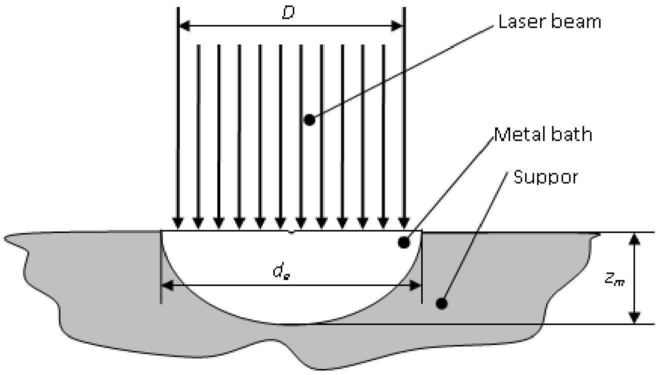

Fig. 1. *Image of the laser beam and the metal bath on the support*

$$T_m = \frac{8P_0\varphi(1-R)}{\pi k d_e^2}\sqrt{\frac{ad_e}{v}} \quad (13)$$

After squaring, we can obtain:

$$d_e = \sqrt[3]{\frac{64P_0^2\varphi^2(1-R)^2 a}{\pi^2 k^2 T_m^2 v}} \quad (14)$$

After squaring eq. (11):

$$T_s^2 = \frac{64P_0^2\varphi^2(1-R)^2 a}{\pi^2 k^2 D^3 v} \quad (15)$$

it is possible to obtain the sweep speed at which at temperature T_s, is obtained the melting temperature T_m and is reached at the bottom of the bath with z_m, depth:

$$v = \frac{64P_0^2\varphi^2(1-R)^2 a}{\pi^2 k^2 T_s^2 D^3} \quad (16)$$

Substituting this speed in eq. (14) the actual diameter of the laser beam can be determined:

$$d_e = D\sqrt[3]{\frac{T_s^2}{T_m^2}} \quad (17)$$

2.3. The approximation of the radius of the spherical calotte by which the shape of the metal bath is created on the support

From the rectangular triangle OAB, as seen in Fig. 2, it can be written: $OB^2 = OA^2 + AB^2$ (18), but,

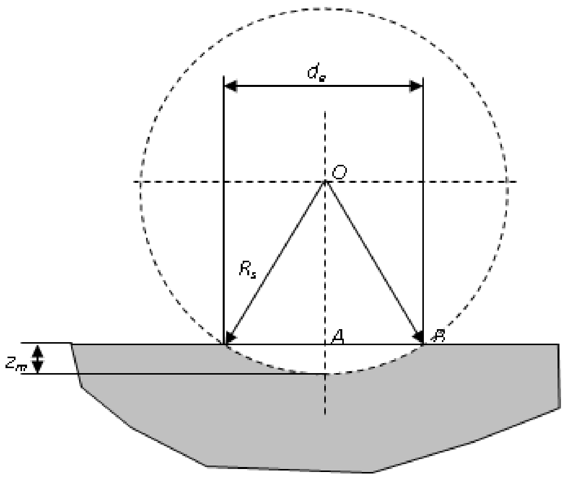

Fig. 2. *The characteristics (the radius Rs and the depth z_m) of the spherical calotte*

$$AB = \frac{d_e}{2}; OA = R_s - z_m; OB = R_s$$

After substituting them in the previous relation, we have:

$$R_s^2 = (R_s - z_m)^2 + \left(\frac{d_e}{2}\right)^2$$

2.4. Thermal balances, during the interaction time, $\left(t = \frac{d}{v}\right)$ in the metal bath injected with powder

Available energy in the metal bath to melt the injected powders:

$$\Delta E^s = m_b^s c_p^s \left[T_{mb}^s - T_{ma}^s\right] \quad (20)$$

- T_{ma}^s - apparent melting temperature of the support:

$$T_{ma}^s = T_m^s + \frac{L^s}{C_p^s}$$

- T_m^s - melting temperature of the support, [°C];
- L^s - latent melting heat of the support, [J/kg];
- C_p^s - specific calorific capacity of the support material, [J/(kg°C)];
- T_{mb}^s -average temperature of the metal bath formed on the support (no powder intake), [°C].

The energy required to melt the powder:

$$E^p = m^p\left[C_p^p\left(T_m^p - T^p\right) + L^p\right] \quad (21)$$

And finally, the radius of the spherical calotte is obtained to further approximate the metal bath:

$$R_s = \frac{1}{2}\left(z_m + \frac{d_e^2}{4z_m}\right) \quad (19)$$

- T_m^p - melting temperature of the powder [°C];
- T^p -powder temperature at the metal bath intake [°C];
- L^p - latent melting heat of the powder material [J/kg];
- m^p -mass of the molten powder [kg].

Equaling expressions (20) and (21):

$$m_b^s c_p^s \left[T_{mb}^s - T_{ma}^s\right] = m^p\left[C_p^p\left(T_m^p - T^p\right) + L^p\right]$$

the mass of the deposited powder can be calculated:

$$m^p = \frac{m_b^s c_p^s \left[T_{mb}^s - T_{ma}^s\right]}{\left[C_p^p\left(T_m^p - T^p\right) + L^p\right]}, \text{[kg]} \quad (22)$$

Since the maximum temperature of the metal bath and its maximum depth lie on the same perpendicular, to the surface of the bath and in its center, it results that there are conditions for melting a maximum amount of powder in this area. It can, therefore, be assumed that the deposited layer will be in the form of a spherical calotte, characterized by the values: h_m - the calotte height (laser deposition layer), z_m - maximum depth of the metal bath (molten layer) and de - the diameter of the base, as shown in Fig. 3.

2.5. Calculation of the average temperature of the metal bath - T_{mb}^s

Since the temperature distribution in the depth of the bath is given by equation (7), the temperature field is considered to consist of isotherms in the form of concentric spherical surfaces.

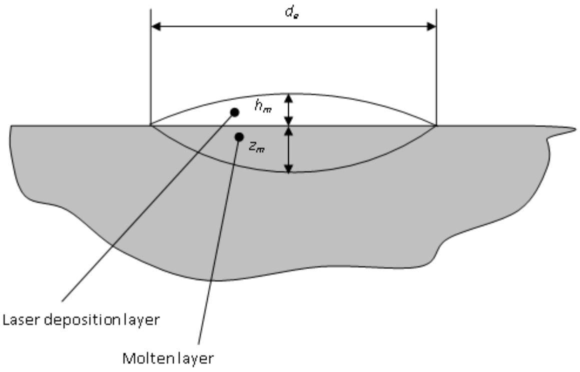

Fig. 3. *The characteristics of the laser deposition layer*

The volume of the metal bath will be divided into an infinite number of volume elements, as very thin sheets, of *dz* thickness and which practically fuse with the isotherms. The mean radius of each spherical sheet will be R (z) as shown in Fig. 4.

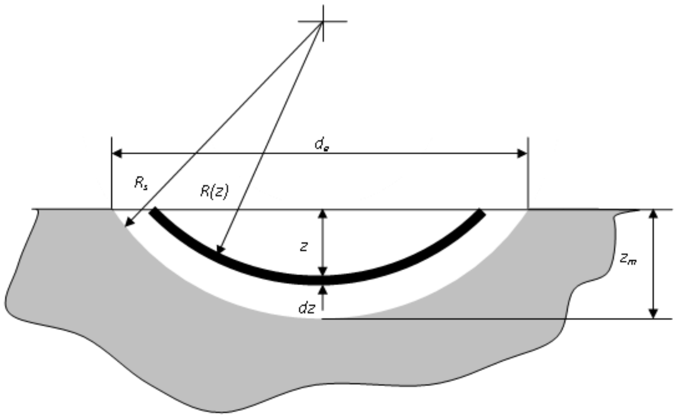

Fig. 4. *The characteristics of the volume of the metal bath*

Temperature of this volume element will be:

$$T(z) = \frac{8P_0\varphi(1-R)}{\pi k D^2}\sqrt{\frac{aD}{v}}\exp\left(-\frac{z}{2\sqrt{\frac{aD}{v}}}\right) \quad (23)$$

and the radius of the sphere considered for the middle of the element thickness:

$$R(z) = R_s - z_m + z$$

The volume of the volume element can be calculated by the expressions:

$$dV = 2\pi R(z) z dz$$

After replacing expression of *R(z)*:

$$dV = 2\pi\left[(R_s - z_m)z + z^2\right]dz$$

the average bath temperature shall be a weighted average of the type:

$$T_{mb}^{s} = \frac{1}{V_b}\int_0^{z_m} T(z)dV \quad (24)$$

where $V_b = \frac{\pi z_m^2}{3}(3R_s - z_m)$ is the volume of the metal bath calculated acc.to the formula of the spherical calotte; after substitution in relation (24) this becomes:

$$T_{mb}^{s} = \frac{3}{\pi z_m^2(3R_s - z_m)}\int_o^{z_m} T(z) 2\pi\left[(R_s - z_m)z + z^2\right]dz$$

After replacing the expression of T (z) and solving the integral, the average temperature of the metal bath is obtained:

$$T_{mb} = \frac{96(R_s - z_m)(1-R)P_0\varphi}{z_m^2(3R_s - z_m)\pi k D^2}\sqrt{\frac{aD}{v}}\left\{2\sqrt{\frac{aD}{v}}\left(1+\sqrt{\frac{aD}{v}}\frac{4}{R_s - z_m}\right) - e^{-\frac{z_m}{2\sqrt{\frac{aD}{v}}}}\left[\left(z_m + 2\sqrt{\frac{aD}{v}}\right)\left(1+\frac{4}{R_s - z_m}\sqrt{\frac{aD}{v}}\right) + \frac{z_m^2}{R_s - z_m}\right]\right\} \quad (25)$$

2.6. The volume of the powder deposited on the support

To be calculated by the simple relation:

$$V^p = \frac{m^p}{\rho^p}$$

This volume will be distributed over the surface of the solidified metal bath of diameter d_e, in the form of a spherical calotte of height h_m.

2.7. Maximum thickness of the deposited layer

Taking into account the calculation of the volume of the spherical calotte, when the height and diameter of the base are known, the volume Vp can also be written as:

$$V^p = \frac{\pi h_m}{6}\left[h_m^2 - 3\left(\frac{d_e}{2}\right)^2\right]$$

which can be transformed into the 3rd degree equation with the unknown h_m:

$$\frac{\pi}{6}h_m^3 + \frac{\pi}{8}d_e^2 h_m - V^p = 0$$

The canonical form of the 3rd degree equation is: $y^3 + p \cdot y + q = 0$ which means:

$$h_m^3 + \frac{3}{4}\cdot d_e^2 \cdot h_m - \frac{6 \cdot V^P}{\pi} = 0$$

$$p = \frac{3}{4}\cdot d_e^2; \qquad q = -\frac{6 \cdot V^P}{\pi}$$

Note that the determinant of the equation:

$$\left(\frac{d_e^2}{4}\right)^3 + \left(\frac{3V^p}{\pi}\right)^2$$

is positive and then the equation shall have only one real solution which is exactly the maximum thickness of the deposited layer:

$$h_m = \sqrt[3]{\frac{3V^p}{\pi} + \sqrt{\left(\frac{d_e^2}{4}\right)^3 + \left(\frac{3V^p}{\pi}\right)^2}} + \sqrt[3]{\frac{3V^p}{\pi} - \sqrt{\left(\frac{d_e^2}{4}\right)^3 + \left(\frac{3V^p}{\pi}\right)^2}} \qquad (26)$$

3. Conclusions

The model proposed in this paper is a simplified theoretical model used to estimate the dimensions of the molten layer and the deposited one, taking into account the parameters of the laser beam and the thermophysical characteristics of the support and the powder used.

The model assumes uniform distribution of the laser power across the laser beam and one – dimensional heat flow into the workpiece.

The influence of the powder particles on the transfer of energy from the laser beam to the surface of the substrate to be deposited was considered.

The following parameters were determined: the metal bath depth, the diameter of the metal bath, the mass of the powder deposited, the average temperature of the metal bath, the thickness of the deposited layer.

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