

THERMAL MODEL FOR PHASE TRANSFORMATIONS IN KEYHOLE LASER WELDING

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ABSTRACT

In laser welding, a melted area called welding bath appears in the material. This welding bath contains a vapor area. Melting and vaporization are induced by a certain thermal flux density absorbed by the material and by the necessary time for these processes to take place. The thermal flux density has different expressions for the heating process and for the phase transformation process. Phase transformation propagation is isotropic, fact that leads to an equality of the lengths of the melting fronts in various sections. The model applies this equality to two sections placed in perpendicular planes. The melting and the vaporization are treated in similar ways. The surface diameter and the penetration depth, measures that the model estimates, characterize the welding bath and the keyhole respectively.

KEYWORDS Laser keyhole welding, metal melting, metal vaporization, thermal conduction

NOTATIONS

a - thermal diffusivity [m^2/s]
 k - thermal conductivity [$W/cm\ ^\circ C$]
 ρ - density [kg/m^3]
 V - volume [m^3]
 S - surface [m^2]
 z - coordinate in workpiece depth [m]
 Q - heat [J]
 q - thermal flux density [W/m^2]
 v - velocity (of melting /vaporization) [m/s]
 L_m - melting latent heat [J/kg]
 L_v - vaporization latent heat [J/kg]
 t - times [s]
 T - temperature [$^\circ C$]
 w - width melting /vaporized zone [m]
 h - depth melting /vaporized zone [m]

1. INTRODUCTION

The keyhole phenomenon is a distortion of the welding bath, a flute in it. This is characteristic to laser, electron and plasma arc welding [1].

Laser and electron welding are based on evaporation[1]. Quick evaporation through recoil pressure that presses down the surface of the liquid (piston effect) and the vapors that appear in the material, determines the keyhole formation [2]. The main consequence of the keyhole is the increased penetration of

the welding belt. This is a way to recognize the deep welding or keyhole welding working conditions[3].

The time interval in which melting and vaporization are the main phenomena that occur in the material (approximately at the same time) in the detriment of melt or vapor movement is called keyhole initiation period.

It is characterized by a compact area of melt (the welding bath) in which there is a compact area of vapors called keyhole. The following model aims to estimate the dimensions of these areas (the welding bath and the keyhole) based on the flux density coupled in the material.

2. FLUX DENSITY IN PHASE CHANGE

We consider that the melting happens starting from the surface of the material with a semi-spherical symmetry. A thermal source of flux density q develops the melting. We shall arbitrarily choose the development direction of the model as being the direction of z -axis (oriented towards the interior of the material). We can write the melt volume and its differential respectively as follows:

$$V = \frac{2}{3} \pi z^3 \quad (\text{volume of a semi-sphere}) \quad (1)$$

$$dV = 2\pi z^2 dz \quad (2)$$

For the surface occupied by the melted material, we shall have the following relations:

$$S = 2\pi z^2 \text{ (surface of a semi-sphere)} \quad (3)$$

$$dS = 4\pi z dz \quad (4)$$

The following relation gives the heat variation during the melting process:

$$dQ = L_m \rho dV \quad (5)$$

From the given relations we shall obtain:

$$\frac{dQ}{dS} = \frac{1}{2} L_m \rho z \quad (6)$$

The following relation gives the thermal flux density:

$$q_{melt} = \frac{1}{t} \left(\frac{dQ}{dS} \right) = \frac{1}{2} \rho L_m \frac{z}{t} \left[\frac{W}{m^2} \right] \quad (7)$$

We shall have:

[4] [5] present analogous relations that differ from the above relation by the fact that they add to the latent heat, the heat necessary to warm up the material to the phase transformation temperature.

3. FLUX DENSITY REPARTITION IN MELTING AND VAPORIZATION PROCESSES

After [4], the following formulas give the expressions for the heating and for the heat accumulation (for vaporization) flux densities

$$q = \frac{0,885T k}{(at_i)^{\frac{1}{2}}} \left[\frac{W}{m^2} \right] \quad (10)$$

$$q \approx \rho L_v v_v \left[\frac{W}{m^2} \right] \quad (11)$$

We shall that the vaporization velocity is equal to the heating velocity.

$$v_v = \frac{q}{\rho L_v} = \frac{\sqrt{at_i}}{t_i} = \sqrt{\frac{a}{t_i}} \left[\frac{m}{s} \right] \quad (12)$$

In addition, we shall consider that the same flux density is coupled for both the material

Table 1. Data for calcul

met al	$\rho \left[\frac{g}{cm^3} \right]$	$L_v \left[\frac{j}{g} \right]$	$k \left[\frac{W}{cm \text{ } ^\circ C} \right]$	$a \left[\frac{cm^2}{s} \right]$	$T_M [^\circ C]$	$T_V [^\circ C]$	$\frac{T_{ech_v}}{T_v}$	$\frac{T_{ech_m}}{T_m}$
Ag	10,491	2324	4,07	0,65	961	2212	0,98	0,1
Al	2,7	1052	2,09	0,87	660	2467	0,26	0,37
Cu	8,96	4790	3,89	1,12	1083	2595	2,66	0,28
Fe	7,87	7106	0,73	0,2	1533	2750	3,12	0,21
Ni	8,88	6441	0,67	0,18	1453	2730	3,15	0,28
Sn	5,765	2383	0,64	0,387	232	2270	0,82	0,48
Ti	4,5	3650	0,15	0,06	1700	3250	1,13	0,25
Zi	7,13	1779	1,12	0,4	420	906	2,79	0,34

$$q_{melt} = \frac{1}{2} \rho L_m v_m \left[\frac{W}{m^2} \right] \quad (8)$$

Analogously, for the vaporization of the material we shall have:

$$q_{vap} = \frac{1}{2} \rho L_v v_{vap} \left[\frac{W}{m^2} \right] \quad (9)$$

heating and for the phase transformation.

$$q_{heating} = q_{faze\ change} \left[\frac{W}{m^2} \right] \quad (13)$$

Using the above relations, the equilibrium temperature for vaporization is:

$$T_{ech_v} = 0,56 \frac{\rho L_v a}{k} \quad [^{\circ}C] \quad (14)$$

This is a hypothetical measure that shows the temperature for which the thermal flux density used to heat the material is coupled completely in the heating phenomenon and in the phase transformation.

For melting, the equilibrium temperature is smaller than the melting temperature and for vaporization is greater, (there are some exceptions among the studied materials). This way of thinking is closer to reality for vaporization.

Analogously with the vaporization, for melting we shall have the following relation:

We shall consider that a fraction of this flux density is active in melting and in vaporization respectively.

This fraction is calculated as the ratio between the equilibrium temperature and the phase transformation temperature. Hence, for melting and for vaporization we shall have the following relation respectively:

$$f_m = \frac{T_{ech_m}}{T_m} \quad [-] \quad (16)$$

$$f_v = \frac{T_{ech_v}}{T_v} \quad [-] \quad (17)$$

The reason for choosing such a distribution criteria is the fact that the equilibrium

metal	Thermal flux density in faze change [W/cm ²]		Melting and vaporization times [ms]		melting zone dimension [mm]		Vaporized zone dimension [mm]	
	q_m	q_v	t_m	t_v	w_m	h_m	w_v	h_v
Ag	$0,3 \cdot 10^5$	$2,94 \cdot 10^5$	20,6	26,8	3,5	5,21	2	2,97
Al	$1,11 \cdot 10^5$	$0,78 \cdot 10^5$	1,9	12,8	1,2	1,78	2,2	3,27
Cu	$0,84 \cdot 10^5$	$7,98 \cdot 10^5$	13,9	20,5	3,8	5,65	2,4	3,57
Fe	$0,63 \cdot 10^5$	$9,36 \cdot 10^5$	5,4	24,2	1	1,48	2,57	3,82
Ni	$0,84 \cdot 10^5$	$9,45 \cdot 10^5$	4,6	24,3	0,89	1,32	2,55	3,79
Sn	$1,44 \cdot 10^5$	$2,46 \cdot 10^5$	0,05	7,4	0,13	0,19	0,84	1,25
Ti	$0,75 \cdot 10^5$	$3,39 \cdot 10^5$	9,5	23,1	2,3	3,42	3	4,46
Zi	$1,02 \cdot 10^5$	$8,37 \cdot 10^5$	0,485	2	0,4	0,59	0,84	1,25

$$T_{ech_m} = 0,56 \frac{\rho L_m a}{k} \quad [^{\circ}C] \quad (15)$$

We consider as reference point the flux density coupling in liquid phase. The flux density distribution in the melting and vaporization processes is given by the ratio that would be obtained by coupling in the material the same flux density in a heating process and in a phase transformation respectively.

We consider these flux densities as being coupled into the material. If we make an approximation, these flux densities may be identified with the laser's intensity.

temperature models the situation where the flux density is completely coupled in the phase transformation, the ideal case, and the phase transformation temperature represents the real case. The calculation for this fractions and valor for physical constants are shown in table 1.

5. MELTING AND VAPORIZATION TIME

For an interaction time of ms, the time needed to reach melting or vaporization temperature is a lot less, so this time may be considered negligible when we try to estimate how long the melting/vaporization process will take.

Energetic coupling in melt phase influences the melting / vaporization time. This coupling has a density value close to that of the solid,

and so, the thermal constants may be approximated with those of the solid.

We shall consider that these time intervals have the same expression as the time necessary to reach melting or vaporization but with a flux density ten times smaller. This arbitrary threshold separates the initialization of the keyhole from its evolution process where the main phenomenon is heat transfer through convection.

$$t_T = \frac{0,79T^2 k^2}{q^2 a} \quad [\text{s}] \quad (18)$$

6. THE MODEL

We take into consideration the following hypothesis:

1. Melting and vaporization take place during the pulse and remain totally in the material.
 2. The two processes, melting and vaporization, are independent from one another and may be treated in similar ways.
- We shall obtain a welding bath with a keyhole in it.

3. The geometrical hypothesis

metal	Thermal flux density in faze change [W/cm ²]		Melting and vaporization times [ms]		melting zone dimension [mm]		Vaporized zone dimension [mm]	
	q_m	q_v	t_m	t_v	w_m	h_m	w_v	h_v
Ag	$0,8 \cdot 10^5$	$7,84 \cdot 10^5$	2,9	3,7	1,3	1,93	0,75	1,11
Al	$2,96 \cdot 10^5$	$2,08 \cdot 10^5$	0,26	1,8	0,4	0,59	0,83	1,23
Cu	$2,44 \cdot 10^5$	$21,28 \cdot 10^5$	1,9	2,8	1,5	2,23	0,88	1,31
Fe	$1,68 \cdot 10^5$	$24,96 \cdot 10^5$	0,77	3,4	0,38	0,56	0,96	1,42
Ni	$2,24 \cdot 10^5$	$25,2 \cdot 10^5$	0,64	3,42	0,33	0,49	0,95	1,41
Sn	$3,84 \cdot 10^5$	$6,56 \cdot 10^5$	0,007	1	0,04	0,05	0,3	0,44
Ti	$2 \cdot 10^5$	$9,04 \cdot 10^5$	0,13	3,2	0,08	0,11	0,11	0,16
Zi	$2,72 \cdot 10^5$	$2,72 \cdot 10^5$	0,068	0,28	0,16	0,23	0,03	0,04

One may note that if the flux density decreases ten times, the time will increase a hundred times. We shall particularize the above relation for the melting temperature and for the vaporization temperature respectively:

$$t_{TMelt} = \frac{0,79T_m^2 k^2}{q^2 a} \quad [\text{s}] \quad (19)$$

$$t_{TVap} = \frac{0,79T_v^2 k^2}{q^2 a} \quad [\text{s}] \quad (20)$$

Therefore, finally we have:

$$t_m = 100t_{TMelt} \quad [\text{s}] \quad (21)$$

and

$$t_v = 100t_{TVap} \quad [\text{s}] \quad (22)$$

A single dimensional measure will characterize the form of the welding bath and of the keyhole. We note by Δ_m this measure for the welding bath and by Δ_v for the keyhole by Δ_v . It is directly linked with the two flux densities mentioned above, q_m and q_v , respectively. The welding bath and the keyhole are both symmetrical in the section that contains the axis of the laser pencil of rays perpendicular on the direction of the welding velocity, and asymmetrical in the plane that contains the laser pencil of rays axis and the welding velocity. We shall consider that in the case of phase transformation, the thermal source is homogeneously distributed in the melt. This will lead to an equality of the phase transformation fronts for different sections. From these sections, we shall choose two

that are perpendicular to one another, and we shall assume that the welding bath and the keyhole are symmetric to the laser pen of rays' axis.

We shall formulate the following form hypothesis:

The melting (vaporization) front length, in a plane perpendicular to the laser propagation direction, is equal to the melting (vaporization) front length in the plane perpendicular to the welding direction.

We shall note by w the surface width of the welding bath and of the keyhole and by h its depth.

4. In the mentioned context, we can calculate

Based on the melting and vaporization thermal flux density expressions we calculate the melting and vaporization velocities.

We consider that this velocity may be written as the ratio between the melting (vaporization) front length and the time needed by these processes to take place.

We calculate the width and the depth of the welding bath (and of the keyhole) as follows:

We obtain the following final formulas:

$$w_m = \frac{2q_m t_m}{\pi \rho L_m} \quad [\text{m}] \quad (24)$$

Table 4 Calculation results for thermal flux density $q_{\text{ref}} = 2 \cdot 10^6$

metal	Thermal flux density in faze change [W/cm ²]		Melting and vaporization times [ms]		melting zone dimension [mm]		Vaporized zone dimension [mm]	
	q_m	q_v	t_m	t_v	w_m	h_m	w_v	h_v
Ag	$2 \cdot 10^5$	$19,6 \cdot 10^5$	0,46	0,6	0,53	0,78	0,3	0,44
Al	$7,4 \cdot 10^5$	$5,2 \cdot 10^5$	0,04	0,28	0,17	0,25	0,32	0,47
Cu	$5,6 \cdot 10^5$	$53,2 \cdot 10^5$	0,31	0,46	0,57	0,84	0,36	0,53
Fe	$4,2 \cdot 10^5$	$62,4 \cdot 10^5$	0,12	0,545	0,14	0,2	0,38	0,56
Ni	$5,6 \cdot 10^5$	$63 \cdot 10^5$	0,1	0,547	0,13	0,19	0,38	0,56
Sn	$9,6 \cdot 10^5$	$16,4 \cdot 10^5$	0,001	0,168	0,01	0,01	0,12	0,17
Ti	$5 \cdot 10^5$	$22,6 \cdot 10^5$	0,21	0,52	0,34	0,5	0,45	0,67
Zi	$6,8 \cdot 10^5$	$55,8 \cdot 10^5$	0,01	0,04	0,06	0,08	0,11	0,16

the phase transformation velocity as the ratio between the front's length and time.

$$h_m = \frac{q_m t_m}{\rho L_m} \sqrt{1 - \frac{1}{\pi^2}} \quad [\text{m}] \quad (25)$$

7. CALCULATIONS

Applying the equality of the fronts' lengths in the two sections, we shall obtain the relationship between the two measures.

We assume that in the section along the laser ray axis the melt area and the vaporized area have convergent shape. Under these conditions, we obtain the maximum depth, h , for a cone shape of the welding bath (and of the keyhole respectively).

$$\pi w = 2 \sqrt{h^2 + \left(\frac{w}{2}\right)^2} = \Delta \quad (23)$$

We take into consideration the flux density involved in the phase transformation.

$$w_v = \frac{2q_v t_v}{\pi \rho L_v} \quad [\text{m}] \quad (26)$$

$$h_v = \frac{q_v t_v}{\rho L_v} \sqrt{1 - \frac{1}{\pi^2}} \quad [\text{m}] \quad (27)$$

The shapes of the welding bath and of the keyhole are considered standard. They are characterized by the ratio between the surface width w and the depth h . The calculation will be done for a few reference flux densities:

$3 \cdot 10^5 \text{ W/cm}^2$; $8 \cdot 10^5 \text{ W/cm}^2$ and

$2 \cdot 10^6 \text{ W/cm}^2$

Results are shown in table 2, 3,4.

8. DISCUSSIONS

The model shows that the increase of the reference flux density that we consider coupled in the material, leads to a decrease of the melted/vaporized area.

This shows that the model is valid only for the considered interaction times.

It can describe only the initial aspects of the welding bath and keyhole formation. After that, heat transport through convection has the main role in increasing the penetration of the welding bath in the material.

We obtain dimensions for the vaporized area that are greater than those of the melted area are.

Obviously, this case is not a real one, but this shows that the vapors are compressed in the welding bath. For Ag and Cu we obtain parameters that place the keyhole in the welding bath. For these metals, the model is directly applicable.

9. CONCLUSIONS

We obtained a relation that shows the flux density in a phase change.

We established a method to split the coupled flux density between melting and vaporization.

We established a way to describe the form created in the material by the phase transformation.

We drawn up a model that predicts the dimensions of the melted and vaporized area based on the duration of the two processes and on the flux densities coupled in them.

This model is applicable to the initial part of the laser welding process where in can predict the geometry of the welding bath and of the keyhole, or the degree of vapor compression (measure that has not been calculated).

REFERENCES

- [1] J.F LANCASTER (editor) *The physics of welding* Pergamon Press 1986
- [2] Vladimir V SEMAK, William David BRAGG, Brian DAMKROGE Steven KEMPKA, *Transient model for the keyhole during laser welding* J. Phys. D: Appl. Phys. 32 (1999)
- [3] Alexander F. H. KAPLAN Masami MIZUTANI, Seiji KATAYAMA, and Akira MATSUNAWA *Keyhole Laser Spot Welding* ICALEO 2002
- [4] N. RYKALIN, A UGLOV, A KOKORA *Laser Machining and Welding* Mir Publishers 1978.
- [5] V. DRAGANESCU V.G. VELCULESCU *Prelucrari termice cu laser* Editura Academiei R.S.R 1986.

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