Threshold conditions for thermocapillary transition to deep penetration mode in selective laser melting of metal powder bed

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Abstract. The keyhole mode of selective laser melting (SLM) of metal powder bed in additive technology is characterized by an intensive hydrodynamic process in a thin molten layer. Such a mode is widely used also in laser and electron beam welding indicating the similarity of hydrodynamic processes in these technologies despite a significant difference of operating parameters. The threshold conditions of thermocapillary keyhole mode transition for various metals (Cu, Fe, Ti) in a wide range of beam parameters used for selective laser melting of metal powder layer and laser welding are investigated. The condition of threshold for thermocapillary transition into keyhole mode by sticking of viscous layer to the solid boundary is formulated. The fulfillment of this condition is confirmed by the convergence of estimated values of the viscous layer thickness and the molten layer depth during the transition to a keyhole mode. Analytical estimates of keyhole threshold and comparisons with experimental values of beam power and spot size corresponding to the transition in keyhole mode for SLM processes and laser welding are presented. The correlation of these values confirms the thermocapillary mechanism of cavity formation and the similarity of hydrodynamic processes in laser welding and SLM processing in keyhole mode at wide range of operating parameters.

1. Introduction
The technology of additive manufacturing with selective laser melting (SLM) of metal powders is used for 3D printing of metal products with CAD-modeling of the process. SLM technology allows creating precise metal parts of components and assemblies by power laser beam successfully replacing in some cases traditional methods of manufacturing.

A 3D part produced by SLM technology is a set of layers (thickness of the order of 20 - 100 µm) fused from particles of a metal powder and deposited sequentially on top of one another. Sintering is carried out under the local heating by a laser beam moving over the selected zone, melts the powder particles. The molten powder material then solidifies in the form of thin strips. After the formation of the first zone is completed, a new layer of powder is applied to the entire surface of the sample and the process is repeated. Its undoubted advantage is the ability to use a fairly wide range of source powders (from plastic to metals and alloys) for the manufacture of products.

The additive production of products by SLM is determined by a number of operating parameters, such as a beam power, rate and strategy of scanning, spot size, physical and dispersion properties of the powder, etc. It should be noted the interconnection of factors affecting the process and the presence of many interacting processes: absorption and scattering of laser radiation energy by the substrate substance and powder particles, heat distribution and convection, evolution of the free surface of the melt strip due to capillary forces, evaporation, shrinkage, crystallization, formation microstructures of the synthesized object. The formation of high-quality layers is associated with the search for the optimal range of technological parameters of the process, which is usually quite narrow.

Layers melting can be carried out in deep penetration mode, when the depth of melt $L$ exceeds the...
width \( D (L > D) \). This mode is widely used in welding by laser or electron beam. The difference lies in a significant difference in the characteristic scales and parameters values of processes in SLM and welding by laser or electron beam. The SLM technology uses a beam spot sizes of \( \sim \) 50 microns in size. And the characteristic diameter of beam spot used in keyhole welding can be \( \sim 200 \div 500 \) microns and even more. The same difference is the depth of penetration. The penetration depth usually varies within \( L \sim 1 \div 100 \) mm in laser/electron beam welding, but is comparable to the powder layer thickness of \( \sim 0.1 \) mm in SLM.

The quality of products produced by SLM technology is largely related to hydrodynamic phenomena in laser melting, which occur particularly intensively in deep penetration (keyhole) mode. This determines the interest in such phenomena in SLM [1-7].

The transition from the low characteristic melting depth \( (L < D) \) conduction mode to the deep penetration mode \( (L > D) \) is accompanied by a sharp increase in the crater depth and the beam penetration deep into the material after reaching a threshold power density values.

It is often assumed that the reason for threshold growth of penetration depth is a sharp increase in vapor pressure under influence of high-power focused radiation, which is supplemented by radiation capture in cavity with an increase of effective absorption due to multiple reflections inside cavity [8,9,10]. This assumption (let's call it the evaporative-hydrodynamic hypothesis) is widely used for about half a century (beginning from first theoretical considerations [11-13]) in the modeling of the deep penetration process in relation to beam technologies of metal melting, although it does not have up to now the necessary experimental evidence. Therefore, the evaporative mechanism of deep penetration phenomenon under the action of high vapor pressure reflects the established tradition rather than a scientifically substantiated fact. As for a wide range of specialists the evaporative-hydrodynamic mechanism of the melt flow which cause a cavity formation is perceived undeniable, reliably established and even obvious fact. But this mechanism of cavity formation allows creating numerical models of deep penetration under the influence of a laser or electron beam, which with acceptable accuracy reproduce only the thermal processes and the shape of the melted zone that is sufficient for some applications.

However, experts note the difficulties in calculation of hydrodynamic processes associated with an adequateness of understanding the real hydrodynamic mechanisms [14,15]. Such a difficulties appear when detailed reproduction in calculations of deep penetration phenomenon, in prediction of defects of hydrodynamic nature (pores, root defects, humping, undercuts, perforation, splashing, etc.). The accuracy of predictions based on the evaporative-hydrodynamic hypothesis is of unacceptably low accuracy, which does not allow solving practical problems. The evaporation rate values obtained by Langmuir equation are by order of magnitude higher then measured results [16]. There are other critical discrepancies between this hypothesis and empirical data [17,18], which indicate negligible evaporation inside a keyhole. It should also be noted that representations of evaporative-hydrodynamic hypothesis did not help to obtain exact values of the threshold radiation parameters for deep penetration mode transition.

The reason for these problems sometimes looks for imperfection of existing knowledge about evaporation process [16]. Attempts are also being made to find a solution by expanding the physical phenomena under consideration. From the other side there are a strong doubts about the validity of the evaporative-hydrodynamic hypothesis application in SLM or keyhole welding, since it has no direct evidence by experimental methods [19,20], including evidence of a causal relationship between the increase in evaporation and the increase in the penetration depth.

Therefore, it is important to pay attention to experimental and theoretical data indicating a deep cavity formation under the action of thermocapillary forces at high surface tension gradients in the melting zone [18,19,21,22]. In this case, the transition into deep penetration mode is associated with the restructuring of the thermocapillary flow when the radiation threshold values are reached.

Knowledge of the threshold parameters for deep penetration mode transition is necessary for confident control of laser melting process in SLM and welding technologies. A detailed analysis of the threshold conditions of deep penetration based on the thermocapillary mechanism is presented in this paper. The calculated and experimental threshold radiation parameters for deep penetration transition are compared. The results are considered for a number of metals (Cu, Fe, Ti) in a wide range of threshold parameters, which covers SLM, LW, EBW technologies.

2. Velocity of thermocapillary flow and the thickness of viscous layer during melting in deep penetration mode

Transition from conduction melting mode \( (L < D) \) to deep penetration mode \( (L > D) \) associates with a molten layer evolution which is differ at prethreshold conditions of laser melting and above the threshold parameters.
Metal surface temperature increases after beam switching on and reaches the melting point $T_m$ during time $t_m$. Thin melted layer appeared in irradiation zone and rapidly increases in size. A surface tension gradient $\partial \sigma / \partial T$ and tangential thermocapillary force $\partial \sigma / \partial T \times \nabla T / \partial r$ that is directed to reducing the surface tension are formed on thin molten layer surface due to the temperature dependence of surface tension $\sigma(T)$. The surface tension is maximal at the melting point $T_m$ and tends to zero under critical conditions ($\partial \sigma / \partial T < 0$). Therefore, thermocapillary force is directed from the center to the beam spot periphery. Some exception to this rule is possible only in a narrow range (within 200–300 degrees) above $T_m$, where the influence of impurities and contaminants can affect. In this small range $\partial \sigma / \partial T$ can have a positive sign ($\partial \sigma / \partial T > 0$), and the direction of thermocapillary force can be directed from spot periphery to center. However, keyhole effect is characterized by melt temperatures close to the boiling point $T_b$, at which there is no influence of contaminants and impurities on the melt hydrodynamics.

The flow appeared is determined by the balance between thermocapillary stress on melt surface and counteracting viscous friction of lower layers

$$\eta \partial V_x / \partial z = |\partial \sigma / \partial T| \partial T / \partial r$$ (1)

$\eta$ - dynamic viscosity, $V_x$ - the tangential velocity of thermocapillary melt flow, $r$ - tangential coordinate $z$ - normal coordinate.

When melting start the liquid layer thickness is always smaller than focus spot diameter and the convective transfer can be neglected. Therefore, the linear Navier-Stokes equations can be used

$$\partial \vec{V} / \partial t = -\lambda / \rho \text{ grad } p + \nu \Delta \vec{V}$$

To exclude pressure, let us apply the $\text{rot}$ operation to both sides of this equation. Taking into account $\text{rot grad } p = 0$, receive

$$\partial \text{rot } \vec{V} / \partial t = \nu \Delta \text{rot } \vec{V}$$

The Navier-Stokes equation in this form is similar to the heat equation. So a characteristic distance of viscous forces propagation can be defined as $2(\nu t)^{1/2}$. If the thickness of the viscous layer $\delta$ is small compared to the irradiation spot diameter $d$, then after a time $t \approx \delta^2/4\nu$ the thermocapillary flow is formed:

$$V_x \approx [\partial \sigma / \partial T] \partial T / \partial r \times \delta / \eta$$

Neglecting convective heat transfer, the temperature gradient on the melt layer surface (at focusing spot radius $d/2$) can be estimated as $\partial T / \partial r \approx 2q / \varrho \lambda d$, where $q$ is the absorbed power density, $\lambda$ is the thermal conductivity. For the thermocapillary flow velocity can be written

$$V_x \approx 2[\partial \sigma / \partial T] q \delta / (\varrho \lambda d)$$ (2)

To estimate the velocity $V_x$ using the expression (2), it is necessary to determine the thickness of the viscous layer $\delta$ from the flow conservation condition. The radial thermocapillary spreading of molten layer at a rate $V_x$ under the fast laser heating leads to a lowering of liquid level at a rate $V_x$ determined by the condition of mass conservation $V_x \approx 4V_x \delta / d$. The growth of velocity $V_x$ causes in response the decreasing of molten layer thickness $h$ and the increasing of temperature gradient $\partial T / \partial z$, which values will have quickly (during the heat propagation time $t \approx h^2/4\nu$) corrected by an increasing of melting boudary rate $V_m$ according to the condition of heat flux conservation $q/\lambda \approx \partial T / \partial z$. As a result, both interfacial boundaries (“solid - liquid" and "liquid - gas") move simultaneously deep into the metal in a steady state mode, forming a deep crater. This steady-state melting process is characterized by the equality of velocities $V_m = V_x$ at a constant thickness of molten layer $h$ and viscous layer thickness $\delta$. Estimating the melting front velocity as $V_m \approx (\varrho h)^{1/2}$, and the time period needed for establishing the melt flow as $t \approx \delta / (4\nu)$, it can be written $V_m \approx (\varrho h)^{1/2} / \delta$.

Let us write the equality of velocities $V_m = V_x$ for cavity formation during deep penetration mode:

$$(\varrho h)^{1/2} \delta = V_x \delta / d$$

Or after application (2):

$$(\varrho h)^{1/2} \delta = 2[\partial \sigma / \partial T] q \delta / (\varrho \lambda d)$$

It turns out for an estimation of thickness of viscous thermocapillary layer during melting in deep penetration mode:

$$\delta = (\varrho h^{1/2} \eta^{1/2} d) / (2\rho^{1/2}[\partial \sigma / \partial T] q)^{1/4}$$ (3)
Having determined the viscous layer thickness $\delta$ from (3), we can then use relation (2) to determine the thermocapillary flow velocity $V_X$ during motionless beam action depending on the irradiation conditions (beam power and the focusing spot diameter) and the cavity growth rate $V_S = 4V_X \delta/d$. Calculations according (3) are confirmed by direct measurements of the melt flow velocities on the front wall inside a keyhole [23] when welding of steel with a scanning beam focused into a spot with a diameter $d = 0.9$ mm. Average melt velocities $V_X = 7.5$ m/s, 10.77 m/s and 16.24 m/s were recorded at beam power of 6, 10 and 14 kW respectively. The calculated values of the thermocapillary flow velocity for these conditions with use the iron properties from Table 1 ($V_X = 10$ m/s, 13 m/s and 15.3 m/s) are very close to these empirical values. Such proximity confirm the thermocapillary mechanism of melt removal on the front wall inside a keyhole in [23].

![Figure 1](image1.png)

**Figure 1.** Change of thermocapillary melt flow velocity $V_X$ and the rate of beam penetration (crater growth) $V_S$ by a fixed beam ($d = 50$ µm) at SLM of iron powder layer in deep penetration mode (a little above the threshold power density $q_{TH} = 1.5$ MW/cm$^2$ for deep penetration).

![Figure 2](image2.png)

**Figure 2.** (a) - pre-threshold melting ($q < q_{TH}$ and $V_S < V_M$) leads to rapid flow formation with circulating structure, (b) - upon reaching the deep penetration threshold ($q > q_{TH}$ and $V_S > V_M$) the preservation of shear structure in flow leads to a keyhole formation.
The obtained relations allow estimating the main hydrodynamic parameters of the thermocapillary flow in SLM technology. For example, during SLM of iron powder in deep penetration mode ($d = 50 \mu m$ and beam power of 20-100 W), the temperature gradient on melt surface reaches values $dT/dr \sim 10^7-10^8$ °K/m, which gives rise to the thermocapillary melt removal from the irradiation zone with speed of $V_\delta \sim 10-20$ m/s and beam penetration into powder layer with speed $V_s \sim 2.5 - 3.5$ m/s (Fig. 1). As will be shown below (Fig. 6), the thickness of viscous layer at the same conditions is only $\delta \sim 1.5 - 3.5 \mu m$. It should also be noted that the velocity values $V_\delta \sim 10-20$ m/s and $V_s \sim 2.5 - 3.5$ m/s are obtained near the threshold power density $q_{TH} = 1.5$ MW/cm² (iron, $d = 50 \mu m$), which is determined by the ratio (5), which will be discussed below.

In order to formulate the threshold condition of a deep penetration mode transition with use the thermocapillary mechanism, it is necessary to analyze the hydrodynamic processes in a thin molten layer at beginning of melting. Thermocapillary flow under the point laser impact starts with the appearance of a thin molten layer of thickness $h$. At the initial stage of melting, it always has the structure of shear flow with sticking of viscous layer $\delta$ to the melting boundary, as shown in the upper images Fig. 2. The further evolution of the hydrodynamic processes depends on the ratios of the velocities of the phase boundaries limiting the molten metal layer ($V_M$ and $V_s$).

Fig. 2 (a) presents the evolution of the molten layer under subthreshold conditions at $q < q_{TH}$ and $V_s < V_M$. When sufficient thickness is reached in a molten layer, the viscous layer is separated from solid melting boundary ($h > \delta$), which creates favorable conditions for ring connection a current lines and the formation of circulating thermocapillary flow. It should be noted that the inequality $V_s < V_M$ become stronger at small values of $q$ and $V_s$ and the transition from shear to circulation structure of thermocapillary flow occurs faster than at high values of $q$ and $V_s$.

The molten layer evolution at threshold power density ($q = q_{TH}$) is shown in Fig. 2 (b). A sufficiently high speed of thermocapillary flow $V_\delta$ provides fast lowering of molten layer in this case. At the same time to fulfill the conditions of mass conservation and heat flux conservation the melting boundary is also going to move deeper into the metal with the same speed $V_M = V_\delta$, ensuring the constancy of molten layer thickness $h$ and preserving the shear structure of flow during deep cavity formation. The longer condition $V_M = V_\delta$ is fulfilled and the shear structure of flow is preserved, the deeper cavity is formed.

The condition of thermocapillary "drying" $V_s > V_M$ corresponding to the exceeding of threshold power density ($q > q_{TH}$) seems to exist only as a short-term fluctuation because it must be quickly compensated by the movement of melting front to meet the heat flux conservation. We should expect an alternation of $V_s > V_M$ and $V_s < V_M$ ratios in this case with the generation of surface structures similar to those previously observed in experiments [24]. Since the existence of this fluctuation is determined by very short thermal ($h^3/4\chi$) and viscous ($\delta^3/4\nu$) response times, which are estimated as $10^{-3} \div 10^{-6}$ sec, we can assume $V_s \approx V_M$ in case of $q > q_{TH}$.

3. Conditions for sticking of viscous layer ($\delta = h$) and maintaining shear structure of thermocapillary flow during transition to deep penetration mode

The necessary condition for transition to deep penetration mode under thermocapillary mechanism of melt removal is preservation of shear structure of thermocapillary flow. Such a structure should be maintained during the time of crater formation until it reaches a maximum depth under static beam exposure. When melting by scanning beam, maintaining shear structure of thermocapillary flow is ensured by running of cold metal into beam impact zone with maintenance of thickness of molten layer within of small values close to viscous layer size ($h \sim \delta$).

The shear structure of the stream is formed simultaneously with the thermocapillary melt flow starts when the molten metal layer is still very thin. This structure is maintained as long as the thickness of the viscous layer $\delta$ remains close to the thickness of the molten layer ($\delta \sim h$) and the condition of sticking the viscous layer to the solid wall (melting boundary) is met. The deep penetration effect occurs if the shear structure of thermocapillary flux is maintained for the time needed to form a crater.

With slow heating of liquid metals, the shear structure is not maintained, as the viscous layer is separated from the solid bottom, converting the shear structure of stream into a recirculated one without forming a crater. This case (Fig. 2 (a) $q < q_{TH}$, $V_s < V_M$) is characterized by the usual Prandtl number $Pr = \nu/\chi$, which shows the ratio of temperature fields and velocity fields. If heating is slow enough the Prandtl number for melted metals is very small ($Pr = \nu/\chi < 1$) and the thickness of viscous layer is significantly smaller than the temperature propagation distance ($\delta < h$). For slow heating the condition of sticking of viscous layer to solid bottom is not fulfilled. So, the shear flow is not formed and deep penetration mode is not realized.
However, at fast heating by laser beam of high power when temperature gradient in metal reaches very high degree $\partial T/\partial z \approx 10^9$ °K/m, and the speed of a thermocapillary flow is about $V_X \approx 10$ m/s, the values of $\delta$ and $h$ can keep commensurable magnitudes ($\delta \sim h$) during time needed for cavity formation.

This condition is disrupted upon reaching the crater to its extreme depth, when the speed of thermocapillary flow slows down and the thickness of the molten layer starts to grow rapidly, causing separation of the viscous layer separation from the solid boundary melting with subsequent closure of streamlines and transformation of shear structure of thermocapillary flow in circulation flow structure.

From this moment, the crater flows, fills with the return flow of circulation stream until it disappears completely. Such a complete and final collapse of the crater has not yet been described in studies, although it has been observed in some experiments [21, 25].

In the case of melting with a scanning beam, the crater is maintained by a stream of solid and cold metal, which rushes into irradiation zone through the front wall of keyhole and thereby provides a commensurability of $\delta$ and $h$.

Taking into account that effective absorption of laser radiation in keyhole close to 100% [8], we write the condition of commensurability $h$ and $\delta$ near threshold conditions as $\delta \sim h \approx \lambda T_B / q$. Given that the melt temperature in keyhole is limited by the boiling temperature $T_B$ [26], we get:

$$\delta \sim h \approx \lambda (T_B - T_M) / q$$

Determining $\delta$ from (3), at given size of focus spot $d$, we obtain an expression for the threshold power density [13]:

$$q_{TH} \approx \lambda (T_B - T_M)^{4/3} (d \sigma / dT)^{1/3} (\rho / \chi)^{1/6} / (4 d^{2/3} \eta^{1/2})$$

or for the threshold beam power

$$P_{TH} \approx \pi \lambda (d (T_B - T_M)^{4/3} (d \sigma / dT)^{1/3} (\rho / \chi)^{1/6} / (4 \eta^{1/2})$$

The resulting threshold values of power and intensity depend on the diameter of focus spot $d$. Let us show that the obtained dependences agree well with the experimental data.

![Figure 3](image-url)

**Figure 3.** Transition to deep penetration (keyhole) mode in welding: (a) - steel A3 (experiment [27]), (b) - copper (experiment [28]). The arrows indicate the threshold values $q_{TH}$ calculated with (4).
Figure 4. Surface depression depth during SLM of Ti–6Al–4V in the steady state scanning (a) and in turn point of laser beam (b) [2] in dependence of beam power and scan speed. Linear extrapolation of data gives an empirical value of threshold power for transition to deep penetration mode in experiments [2] as $P_{TH} \approx 20$ W (at the used beam with spot diameter $d = 50$ µm). The red arrows indicate the power values $P_{TH} = 21$ W calculated for $d = 50$ µm using (5).

Figure 5. Surface depression depth during SLM of Ti–6Al–4V with diameter of beam spot $d = 95$ µm (a) and $d = 140$ µm (b) [3] as function of power and scan speed. The red arrows indicate the threshold power $P_{TH}=79$ W calculated by (5) for $d = 95$ µm (a) and $P_{TH}=143$ W for $d = 140$ µm (b).

The threshold power density $q_{TH}$ for steel A3 at two values of focal spot diameter $d = 0.36$ and $d = 0.55$ mm determined in the experiments [27], the results of which are presented dependencies of the penetration depth $L$ from $q$ for two values of $d$ (Fig 3-a). The $q_{TH}$ calculations (4) for these experiments agree well with the measurements and correctly reflect the influence of beam diameter on the threshold power density. Figure 3 (b) shows a similar comparison and good agreement of calculated value $q_{TH}$ for copper using data from experiments [28].

Figures 4 and 5 represent an experimental data on SLM of Ti-6Al-4V at $d = 50$ µm [2], $d = 95$ µm and $140$ µm [3] as a change of surface depression depth in dependence of beam power and of scanning speed. Applying linear extrapolation to the data presented in Fig. 4 (a) and (b), it is possible to determine the threshold power for the transition to deep penetration mode, which is 20 W. We will receive from (5) the calculated power value $P_{TH} = 21$ W for the conditions of experiment [2] with the properties of titanium taken from Table 1. Similarly, we obtain the corresponding calculated values for the experimental conditions [3]: $P_{TH}=79$ W for $d = 95$ µm (Fig. 5-a) and $P_{TH}=143$ W for $d = 140$ µm (Fig. 5-b) for the conditions of experiment [3].
The high correlation of the calculated and empirical parameters, which is observed in a wide range of changes in the beam parameters for different metals, convincingly confirms the thermocapillary mechanism of deep penetration effect.

**Table 1. Properties of metals.**

| Properties                              | Fe   | Ti   | Cu   |
|-----------------------------------------|------|------|------|
| Density, kg/m³                          | 7800 | 4380 | 9150 |
| Heat conductivity, W/(m×grad)           | 30.8 | 30   | 320  |
| Thermal diffusivity, ×10⁴ m²/s          | 5.36 | 9    | 80   |
| Dynamic viscosity, ×10⁻³ N×s/m²         | 4.95 | 5.2  | 3.1  |
| Temperature coefficient of surface tension, ×10⁻³ N/(m×grad) | 0.49 | 1.075 | 0.21 |
| Melting temperature, ºC                 | 1535 | 1680 | 1083 |
| Boiling temperature, ºC                 | 3050 | 3300 | 2590 |

**Figure 6.** Conditions of threshold transition to deep penetration mode for structural metals (Cu, Fe, Ti) at change of laser power and diameter of focus spot for SLM technology (a) and for laser welding (b). Points are the experimental data for laser welding [27], [28] and SLM of Ti-6Al-4V [2], [3].

**Figure 7.** The fulfillment of hydrodynamic condition of thickness comparability of viscous (δ) and molten (h) layers in molten iron for SLM and beam focused in spot d = 50 μm above the calculated threshold value of beam power density is 1.5 MW/cm². The hatched region corresponds to the condition of sticking of viscous layer to the melting boundary (h = δ).
Conditions of threshold transition to deep penetration mode for different metals (Cu, Fe, Ti) at change of laser power and diameter of focus spot are presented in Fig. 6. The lines show such a calculated (5) conditions at operating parameters of laser beam for SLM (Fig. 4, 5) and for keyhole welding (Fig. 3). Points are the experimental data obtained for different metals.

The fulfillment of hydrodynamic condition of thickness comparability of viscous (δ) and molten (h) layers in molten iron for SLM and beam focused in spot d = 50 μm is shown in Figure 7. The calculated threshold value of beam power density is 1.5 MW/cm². The hatched region corresponds to the condition of sticking of viscous layer to the melting boundary (h = δ).

We emphasize that the threshold condition, understood on basis of the evaporative-hydrodynamic hypothesis, does not imply dependence on spot diameter d (in contrast to the dependencies (4) and (5) obtained for the thermocapillary mechanism of keyhole formation). Therefore, the noticeable influence of the beam diameter d on the threshold value of the power density $q_{th}$ indirectly indicates the thermocapillary mechanism of crater formation during deep penetration.

4. Conclusion

Thus, we have considered hydrodynamic aspects of deep penetration mode based on thermocapillary mechanism of melt removal from irradiation zone. Hydrodynamic characteristics of melt flow were analyzed at characteristic parameters of radiation (d = 50 μm) used for additive manufacturing by SLM method.

The rates of hydrodynamic flow of molten iron ($V_x \sim 10 \div 20$ m/s) expected in SLM of metall powder (at $d = 50$ μm) were estimated using the thermocapillary model of cavity formation. The validity of this forecast is confirmed by a good correlation between the calculated and empirical values of the $V_X$ flow rate of iron during keyhole formation by a laser beam at $d = 900$ μm.

The analysis of the threshold transition to deep penetration mode for thermocapillary hydrodynamic mechanism of melt removal is presented. The threshold conditions for various structural metals (Cu, Fe, Ti) and in a wide range of radiation parameters, which covers the SLM of powder bed and welding is calculated. The obtained dependences are compared to experimental data, including the results taken from analysis of published experiments on SLM of a Ti-6Al-4V. It is noted that the dependence of threshold conditions on diameter of focusing spot corresponds to thermocapillary deep penetration mechanism.

The correlation of the calculated and empirical data gives the basis for conclusion about similarity of thermocapillary hydrodynamic processes in the deep penetration mode occurring during SLM of powder layer and welding.

The condition of thermocapillary threshold transition to deep penetration mode is formulated as a necessity of sticking a viscous layer to the solid melting boundary, which is characteristic of rapid heating. The fulfillment of this condition in deep penetration mode is confirmed by checking the comparability in thickness both of viscous and molten layer near the threshold conditions.

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References

[1] Matialainen V-P, Piili H, Salminen A, Nyrhila O. 2015 Preliminary investigation of keyhole phenomena during single layer fabrication in laser additive manufacturing of stainless steel Physics Procedia 78 pp 377-387
[2] Martin A A, Calia N P , Khairallah S A, et al. 2019 Dynamics of pore formation during laser powder bed fusion additive manufacturing Nature Communications 10 1987
[3] Cunningham R. et al. 2019 Keyhole threshold and morphology in laser melting revealed by ultrahigh-speed x-ray imaging Science 363 pp 849–852
[4] Thanki A, Goossens L, Mertens R et al. 2019 Study of keyhole-porosities in selective laser melting using X-ray computed tomography. 9th Conference on Industrial Computed Tomography (iCT) 13-15 Feb Padova Italy (iCT 2019) (https://doi.org/10.29007/3qvj)
[5] Gunenthiram V, Peyre P, Schneider M, Dal M et al. 2017 Analysis of laser–melt pool–powder bed interaction during the selective laser melting of a stainless steel Journal of Laser Applications 29 (2) 022303 DOI: 10.2351/1.4983259

[6] Bidare P, Bitharas I, Ward R M et al. 2018 Fluid and particle dynamics in laser powder bed fusion Acta Materialia 142 pp 107–120

[7] Guo Q, Zhao C, Escano L I et al. 2018 Transient dynamics of powder spattering in laser powder bed fusion additive manufacturing process revealed by in-situ high-speed high energy x-ray imaging Acta Materialia 151 pp 169–180

[8] Fabbro R, Dal M, Peyre P et al. 2018 Analysis and possible estimation of keyhole depths evolution, using laser operating parameters and material properties Journal of Laser Applications 30 No 3 032410

[9] Gladush, G. G., Smurov I. 2011 Physics of Laser Materials Processing: Theory and Experiment Berlin Springer-Verlag

[10] Khomenko M D, Mirzade F.Kh 2017 Parametric investigation of microstructure after laser melting of metal powder layer Procedia Engineering 201 pp 645–654

[11] Batanov V A, Fedorov V B 1973 Flushing Out the Liquid Phase - a New Mechanism of Producing Crater in Planar Fully Developed Evaporation of a Metallic Target by a Laser Beam. ZhETF Pis. 17 No 7 pp 348-351 (http://www.jetpleters.ac.ru/ps/1541/article_23562.shtml)

[12] Andrews J G, Athgney D R 1976 Hydrodynamic limit to penetration of a material by a high-power beam J. Phys. D: Appl. Phys. 9 No 15 pp 2181-2194

[13] Klemens P G 1976 Heat balance and flow conditions for electron beam and laser welding J. Appl. Phys. 47 p 2165

[14] Fabbro R, Hamadou M, Coste F 2004 Metallic vapor ejection on melt pool dynamics in deep penetration laser welding Journal of Laser Applications 16 No 1 pp. 16-19

[15] Courtois M, Carin M, Le Masson P, Gaied S, Balabane M 2016 Guidelines in the experimental validation of a 3D heat and fluid flow model of keyhole laser welding J. Phys. D: Appl. Phys. 49 155503 (13pp)

[16] DebRoy T, David S A 1995 Physical processes in fusion welding. Rev. Mod. Phys. 67 No 1

[17] Seidgazov R D 2009 Verification of the melt displacement mechanism in deep penetration laser welding Proceedings of the 4th Int. Conf. Laser Technologies in Welding and Material Processing Ed. by B.E. Paton and V.S.Kovalenko p 62.

[18] Seidgazov R D 2019 Analysis of The Main Hydrodynamic Mechanisms in Laser Induced Keyhole Welding The 8th Int. Conf. on Advanced Optoelectronics and Lasers (CAOL) Bulgaria Sozopol IEEE Xplore Digital Library (in press)

[19] Seidgazov R D 2009 Thermocapillary mechanism of melt displacement during keyhole formation by the laser beam J Physics D: Appl Phys 42 No 17 (175501) (7 pp)

[20] Mahrle A, Beyer E. 2019 Theoretical evaluation of radiation pressure magnitudes and effects in laser material processing Physica Scripta 94 075004

[21] Seidgazov R D, Senatorov Yu M 1988 Thermocapillary mechanism of deep melting of materials by laser radiation Sov. J. Quantum Electronics 18 (3) pp 396–398

[22] Seidgazov R D 2011 Thermocapillary Mechanism of Deep Penetration in Laser Beam Welding Mathematical Models and Computer Simulations 3 No 2 pp 234–244

[23] Eriksson I, Powell J, Kaplan A F H 2011 Measurements of fluid flow on keyhole front during laser welding Science and Technology of Welding and Joining 16 (7) pp 636-641

[24] Banishev A F, Golubev V S, Khramova O D 1993 Study of the Key-Hole formation dynamics under high power laser action upon metals Laser Phys. 1 (6) pp 1198-1202

[25] Kayukov S V 2000 Extension of potentialities of millisecond pulsed Nd:YAG lasers in the welding technology Quantum Electronics 30 (11) pp 941–948

[26] Hirano K, Fabbro R, Muller M 2011 Experimental determination of temperature threshold for metal surface deformation during laser interaction on iron at atmospheric pressure Journal of Physics D: Applied Physics 44 (435402)

[27] Zou J L, He Y, Wu S, Xiao R S 2015 Experimental and theoretical characterization of deep penetration welding threshold induced by 1-μm laser Applied Laser Science 351

[28] Garaschuk V P, Velichko O A, Davydova V V 1971 Influence of the average illumination in the spot of focusing on the depth of penetration in the pulse laser welding Avtomaticheskaya Svarka No 5 p 31 (in Russian)