03

Electrocapillary acceleration of molten metal flows during keyhole formation by high-power laser radiation

© R.D. Seidgazov, F.Kh. Mirzade

National Research Center „Kurchatov Institute“, Moscow, Russia
E-mail: seidgazov@mail.ru, fmirzade@rambler.ru

Received November 13, 2024
Revised March 5, 2025
Accepted March 16, 2025

To explain experimentally observed patterns qualitatively during keyhole formation in metals by high-power laser radiation, the mechanism of electrodynamic processes influence on the acceleration of thermocapillary melt flow is proposed, taking into account the coupling of thermoemission of charges, electrocapillary and hydrodynamic processes inside a keyhole.

Keywords: laser radiation, keyhole, electric field, thermal emission, electrocapillarity.

DOI: 10.61011/TPL.2025.06.61293.20184

The deep penetration (DP) mode is used widely in a number of modern laser and electron-beam metal melting techniques to produce welded joints and assemble products by additive molding of metal powders. This mode is characterized by a high aspect ratio (depth of the molten region divided by its width) and necessitates crossing the radiation power threshold that depends on the properties of the medium and the focal spot size. It was demonstrated in [1] that the thermocapillary (TC) mechanism establishes a plausible connection between physical processes in the DP mode and the hydrodynamic flow. This was confirmed experimentally [2] and by numerical calculations [3], comparison of calculated and experimental values of the TC threshold of DP [4], and analysis in [5,6]. At the same time, the TC mechanism does not reveal the nature of the synergistic effect in hybrid laser-arc processing [7] and the reason behind the empirically observed correlations of the penetration depth with the ambient pressure, the characteristics of near-surface plasma, the emission current signal [8], and the direction and strength of the external electric field [9]. In our view, the probable acceleration of flow by electrocapillary (EC) forces, which are induced by dependence $\sigma(\varphi)$ of surface tension on electric potential that is distributed non-uniformly along the surface, may fill this gap. The aim of the present study is to formulate basic concepts regarding the physical mechanism of EC acceleration of melting in the process of DP of metals by high-power laser radiation.

The transition to the DP mode is accompanied by the emergence of laser-induced plasma at the irradiation spot and the melt–plasma contact with the formation of a double electric layer (DEL). Owing to the locality of laser action, this induces non-uniform distributions of electric charge and potential on the melt surface that cause the EC effect (due to dependence $\sigma(\varphi)$ of surface tension on electric potential) and result in the emergence of tangential EC forces. The formation of plasma and a DEL is facilitated by thermionic processes. Thermionic emission is characterized by current density given by the Richardson–Dushman formula

$$j_e = A_R T^2 \exp(-\omega/kT),$$

where ω is the electron work function for the melt surface, k is the Boltzmann constant, and A_R is the thermionic constant. The emission current for iron ($\omega = 4.31\,\mathrm{eV}$) at a boiling temperature characteristic of the DP mode is $j_e = 0.33\,\mathrm{A/mm^2}$. Owing to the loss of electrons, positive charges are induced on the surface from the melt side, which trap electrostatically a certain fraction of electrons above the surface, establishing DEL charge separation. The DEL electric field counteracts the release of electrons from the melt surface and stimulates the emission of positive ions with a current density given by the Richardson–Smith formula

$$j_i = A_P T^2 \exp(-\omega_P/kT),$$

where A_P is a constant and ω_P is the positive ion work function for the emission from a melt. The combined thermionic emission of electrons and positive ions produces a total emission current equal to the sum of oppositely directed emission currents of electrons and ions: $J = Sj = S(j_e - j_i)$, where S is the irradiation spot area. Total current J is zero at $j_e = j_i$ and specific charge $Q = 0$, which corresponds to the EC curve maximum (see the figure).

The application of an external electric field with strength E alters the potential barrier of electron release and the emission current density in accordance with the Richardson–Dushman formula with the Schottky correction

$$j_e = A_R T^2 \exp\left[-(\omega - \Delta\omega)/kT\right],$$

where $\Delta\omega = e(eE/4\pi\varepsilon_0)^{1/2}$ — Schottky correction, e — electron charge, and $\varepsilon_0 = 8.85 \cdot 10^{-12}\,\mathrm{F/m}$ — permittivity of vacuum. If field E is codirectional with the DEL field, a higher potential barrier of electron release translates into a reduction in j_e. This facilitates the emission of positive ions and raises ion current density j_i. External field E enhancing the DEL field should induce the concentration of negative charge on the surface (from the melt side). If the DEL field is weakened by external field E, the concentration of positive charge on the melt surface should be observed. Thus, the external field allows one to control the charge on the molten metal surface, which may be used to control the EC effect and hydrodynamic processes in the DP mode.

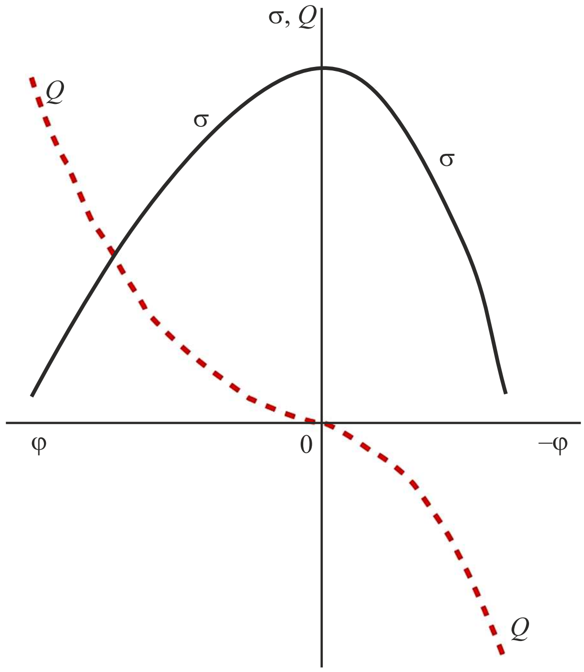
Let us consider the EC effect as flows induced by the surface tension σ gradient. Dependence $\sigma(\varphi)$ is represented by the EC curve with a maximum at $\partial\sigma/\partial\varphi = 0$ with a zero charge potential, which corresponds to zero total current $J = Sj = S(j_e - j_i) = 0$ (see the figure). In the right branch of the EC curve, $\varphi < 0$ and $\partial\sigma/\partial\varphi > 0$ holds. The left branch ($\varphi > 0$) corresponds to $\partial\sigma/\partial\varphi < 0$. Lippmann equation $\partial\sigma/\partial\varphi = -Q$, which is known from the theory of EC phenomena, establishes the relation between the slope of the EC curve and charge Q per unit surface area for a given potential φ taken with the opposite sign. The right and left branches of the EC curve have $Q < 0$ and $Q > 0$, respectively. The dependence of penetration depth on the change in polarity of E (sign of Q) may then reflect the asymmetry of the EC curve relative to axis $\sigma(\varphi = 0)$ with condition $|\partial\sigma/\partial\varphi|_{\varphi,Q>0} < |\partial\sigma/\partial\varphi|_{\varphi,Q<0}$ for its two branches.

Any increase in charge density (positive or negative) will result in a reduction in surface tension. This behavior is attributable to the fact that all charges at the interface act on each other with Coulomb repulsive forces directed tangentially to the free surface. Therefore, a smaller amount of energy is needed to expand the interface, which translates into a reduction in surface tension with an increase in potential.

When metals are exposed to focused laser radiation in the DP mode, the temperature and electric potential at the irradiation spot should vary along the metal surface, decreasing from their maxima in the center of the spot to zero at the periphery ($\partial T/\partial r < 0$, $\partial\varphi/\partial r < 0$). The surface tension will, in contrast, increase in this case, since $\partial\sigma/\partial T < 0$, $\partial\sigma/\partial\varphi < 0$. EC flows arise in addition to TC ones due to the presence of an unbalanced tangential gradient of surface tension induced by the tangential gradient of voltage, which, in turn, is induced by a non-zero tangential electric field component. In the general case, variables T and φ are dependent, although their interrelation has not been established yet. To simplify the problem, we consider the special case of independent variables T and φ. The balance of forces on the surface is then written as

$$\eta\frac{\partial V_r}{\partial z} = -\frac{\partial\sigma(T,\varphi)}{\partial r} = -\frac{\partial\sigma}{\partial T}\frac{\partial T}{\partial r} - \frac{\partial\sigma}{\partial\varphi}\frac{\partial\varphi}{\partial r}, \quad (1)$$

where $-\partial\sigma/\partial T = \gamma > 0$ is the temperature coefficient of surface tension, η is the dynamic viscosity, V_r is the tangential melt flow velocity, and r and z are the coordinates tangential and normal to the surface. Since the thermally and electrically induced terms $(\partial\sigma/\partial T)(\partial T/\partial r)$ and $(\partial\sigma/\partial\varphi)(\partial\varphi/\partial r)$ have the same signs in balance (1), the EC forces are always (regardless of the sign of Q) accelerating the TC flow. Taking $\partial\sigma/\partial\varphi = -Q$ and $\partial\varphi/\partial r = -E_T$ into account, we rewrite (1) in the form



Typical EC curve $\sigma(\varphi)$ and variation of specific charge $Q(\varphi)$.

$$\eta\frac{\partial V_r}{\partial z} = \gamma\frac{\partial T}{\partial r} - QE_T. \quad (2)$$

According to Gauss's law, the surface density of charge Q is related to the normal component of electric field strength E_z in the following way:

$$Q = 2\varepsilon_0 E_z = 2\varepsilon_0(E_N + E_D),$$

where E_N and E_D are the normal components of the external field and the DEL field, respectively (it is assumed that E_N, $E_D = \text{const}$). Tangential field component E_T is determined by the potential difference with maximum $\varphi_{\max}$ in the center of the irradiation spot with diameter d and a zero value ($\varphi = 0$) at the periphery. The estimate for E_T is $E_T \approx -2\varphi_{\max}/d$. Equation (2) then takes the form

$$\eta\frac{\partial V_r}{\partial z} \cong \gamma\frac{\partial T}{\partial r} + 4\varepsilon_0(E_N + E_D)\frac{\varphi_{\max}}{d}. \quad (3)$$

The following estimate of velocity of thermally and electrically induced shear flow (characteristic of the DP mode) with a viscous sublayer of thickness $\delta < d$ is obtained from (3):

$$V_r \cong \frac{\delta}{\eta}\left(\gamma\frac{\partial T}{\partial r} + 4\varepsilon_0(E_N + E_D)\frac{\varphi_{\max}}{d}\right). \quad (4)$$

Formula (4) establishes the relation between thermionic, electrocapillary, and hydrodynamic processes in the DP mode. According to (4), the electrodynamic characteristics at the metal–plasma interface affect the acceleration of TC melt flow at the irradiation spot and, consequently, the penetration depth enhancement. In the DP mode, the estimated TC flow velocity at $d = 0.5$ mm and characteristic values of $\delta \sim 10\,\mu$m is $V_r \sim 10$ m/s [1]. The flow velocity may increase by the same amount due to the EC effect if the TC and EC components in (4) are commensurate. This is confirmed indirectly by an 85 % increase in depth of steel penetration by laser radiation observed in [9] after the application of an external electric field. Relation (4) illustrates the mechanism of correlation of the penetration depth with the characteristics of near-surface plasma and the emission current signal [8]. It should be noted that the total current in the electron-beam irradiation zone includes both total emission current $S(j_e - j_i)$ and system current Sj_b: $J = Sj = S(j_e - j_i - j_b)$. A high electron-beam system current $Sj_b > S(j_e - j_i)$ provides an additional flow of negative charge to the metal surface, facilitating effective EC acceleration of hydrodynamic flows and increasing the penetration depth. An arc discharge in hybrid laser-arc processing has a similar effect on the surface charge density, which may be the cause of the synergistic melting effect [7] (i. e., violation of additivity of thermal effects of irradiation and arc discharge on a metal). In this case, the energy spent on melting may be more than 2 times greater than the sum of the corresponding energies released in the metal processed with each heat source individually (with a corresponding increase in processing efficiency). The presented mechanism allows one to formulate a physical interpretation of the experimentally observed correlations of the DP characteristics with thermionic and electrocapillary phenomena and indicates the direction of further research into the improvement and modeling of laser technological processes.

Funding

This study was carried out under the state assignment of the National Research Center „Kurchatov Institute."

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] R.D. Seidgazov, Math. Models Comput. Simul., **3** (2), 234 (2011). DOI: 10.1134/S2070048211020098.
[2] R.D. Seidgazov, F.Kh. Mirzade, Tech. Phys. Lett., **48** (14), 12 (2022). DOI: 10.21883/TPL.2022.14.52104.18838.
[3] S. Ly, G. Guss, A.M. Rubenchik, W.J. Keller, N. Shen, R.A. Negres, J. Bude, Sci. Rep., **9**, 8152 (2019). DOI: 10.1038/s41598-019-44577-6
[4] R.D. Seydgazov, F.Kh. Mirzade, Welding Int., **35** (7-9), 359 (2021). DOI: 10.1080/09507116.2021.1979829.
[5] R.D. Seidgazov, in *2019 IEEE 8th Int. Conf. on advanced optoelectronics and lasers (CAOL)* (IEEE, 2019), p. 216–219. DOI: 10.1109/CAOL46282.2019.9019431
[6] R.D. Seydgazov, F.Kh. Mirzade, Mat. Models Comput. Simul., **17** (1), 25 (2025). DOI: 10.1134/S2070048224700698
[7] I.V. Krivtsun, V.Yu. Khaskin, V.N. Korzhik, E.V. Illyashenko, Ch. Dong, Z. Luo, Colloquium-journal, № 18 (42), 10 (2019). DOI: 10.24411/2520-6990-2019-10596
[8] P.J. DePond, J.C. Fuller, S.A. Khairallah, J.R. Angus, G. Guss, M.J. Matthews, A.A. Martin, Commun. Mater., **1**, 92 (2020). DOI: 10.1038/s43246-020-00094-y
[9] S.A.H. Fawzi, R.N. Arif, Turk. J. Phys., **23** (6), 959 (1999). https://journals.tubitak.gov.tr/physics/vol23/iss6/2

Translated by D.Safin