Study of the mechanism of attenuation of thermocapillary convection of the melt during laser powder cladding

O B Kovalev and A M Gurin
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Institutskaya str., 4/1, Novosibirsk, 630090, Russia
kovalev@itam.nsc.ru

Abstract. The results of a numerical solution of the thermocapillary microconvection problem arising under the action of laser radiation in a liquid metal during laser surface treatment are presented. A characteristic feature of the behavior of particles of refractory metals in a multiphase melt pool is revealed. The influence of falling powder particles in the melt on the inhibition of thermocapillary convection is estimated. The mechanisms of slowing the melt flow associated with the addition of powder components for laser alloying or cladding is discussed. The results of three-dimensional calculations are presented, which show how these mechanisms can work.

1. Introduction
The hydrodynamics of the melt pool during laser interaction with metals has always been given great attention in the literature [1-5]. The approaches where the thermoconvection of liquid metal is described using the Marangoni condition have already become classical [2-5]. Additive laser technologies are based on the use of various powdered materials that are usually added to the melt. Powder input modes and materials can be very different: metals, alloys that melt during transport in the laser beam, as well as refractory ceramics that fall into the melt in the solid state. The interaction of powder particles (liquid or solid) with the melt pool, the effect of powder input on the thermal convection of the pool is currently insufficiently investigated. In this paper, a computational and theoretical analysis of the mechanisms of slowing the flow in the melt pool associated with the addition of powdered components used in laser alloying or cladding technologies is carried out.

2. Qualitative analysis of microconvection in a laser melt pool
The process diagram, which includes the powder input, the position of the laser beam with the coaxial nozzle and the melt pool on the substrate, is shown in figure 1. The laser beam heats the metal to the melting point. The temperature gradient that occurs on the surface of the liquid leads to the appearance of thermocapillary forces. Under the influence of these forces in the liquid there is a motion. At the liquid-gas interface, the laws of conservation of mass, momentum and energy should be considered in a strict description. In many works this is done simplistically. For example, only the mass of the powder added to the melt and the energy brought by the particles are taken into account, and the law of conservation of momentum is usually neglected [2-5]. The boundary conditions on the free surface of a liquid $z = h(t, x, y)$ can more generally be written:
\[ \dot{m}_p = \xi \rho_p |\mathbf{V}_p| \cos \varphi , \]  
(1)

\[ \dot{m}_p \cdot (\mathbf{V}_p)_n + \mu \frac{\partial U_n}{\partial n} = \mu_s \frac{\partial (\mathbf{V}_g)_n}{\partial n} + P_g + \sigma \kappa , \]  
(2)

\[ \dot{m}_p \cdot (\mathbf{V}_p)_s + \mu \left( \frac{\partial U_n}{\partial s} + \frac{\partial U_s}{\partial n} \right) = \mu_s \left( \frac{\partial (\mathbf{V}_g)_n}{\partial s} + \frac{\partial (\mathbf{V}_g)_s}{\partial n} \right) + \nabla \sigma , \]  
(3)

\[ \lambda \frac{\partial T}{\partial n} \bigg|_{z=h} = S_{\text{heat}} + S_P - S_{\text{conv}} - S_{\text{rad}} - S_{\text{evap}} . \]  
(4)

Here \( \mu \) is the dynamic viscosity of the liquid; \( U_n, U_s \) are the projections of the velocity vector of the fluid at the normal (\( n \)) and tangential (\( s \)) directions; \( \mathbf{V}_g \) is the velocity vector of the carrier gas; \( \varphi \) is the angle between the surface normal and the velocity vector of the particles \( \mathbf{V}_p \).

![Figure 1. The scheme of the surface laser treatment process (alloying or cladding).](image)

The first equation is the law of conservation of the mass flow of matter. The second is the equality of normal stresses taking into account the viscous stresses in the liquid, as well as the capillary pressure due to the curvature of the free surface, and the gas pressure \( P_g \). The third is describes the balance of stresses tangent to the surface associated with the Marangoni effect, viscous stresses of the gas and the additional momentum brought by the added mass of the powder. The heat inflow (4) on the surface of the melt pool is maintained by absorbing laser radiation \( S_{\text{heat}} = A_{\text{ab}} I(x, y) \cos \gamma \) and energy brought by the flow of incident particles \( S_P = m(P) / \rho_p \cos \varphi \left( H - H^0_p \right) \). Heat losses include convective heat exchange with the surrounding environment \( S_{\text{conv}} = \lambda_s \text{Nu} (T - T^0) / d \), radiation losses \( S_{\text{rad}} = \varepsilon k_s \left( T^0 - T^0_s \right) \), and evaporation of part of the superheated melt \( S_{\text{evap}} = L \dot{m}_{\text{evap}} \) [9]. The power density distribution in the beam is written using the Gauss function: 
\[ I(x, y) = 2W/\pi \alpha^2 \exp \left( -2(x^2 + y^2) / \alpha^2 \right) , \]  
where \( W \) is the power, \( \alpha \) is the radius of the beam, \( x, y \) are the coordinates of the Cartesian system.

In the case where the free surface of the liquid is flat \( z = 0 \), the mechanism of interaction of the particles with the surface is reduced to adhesion \( (\mathbf{V}_p)_n = U_n = 0 \), and \( (\mathbf{V}_p)_s = U_s \). In this case, equation (2) turns into an identity, and equation (3) takes the following form:
\[ \dot{m}_p U_s + \mu \frac{\partial U_s}{\partial x} = \gamma T \frac{\partial T}{\partial s}. \]  \hspace{1cm} (5)

The equation (5) differs from the known Marangoni condition \([1-5]\) by the appearance of an additional term \(\dot{m}_p U_s\) that takes into account the mass flow of the powder on the liquid surface. In the case of a slow fluid flow, the friction stress \(\tau_s = \mu \frac{\partial U_s}{\partial n}\) is approximated by the expression \(\tau_s \approx 4\mu U_{\text{max}} / h\), \([2]\). Then, for flows with a small Reynolds number, the maximum velocity \(U_{\text{max}}\) of the fluid can be estimated by the formula (6) in the case of \(\dot{m}_p \geq 0\).

\[ U_{\text{max}} \approx \left( \frac{\gamma T \Delta T / d}{4 \mu / h + \dot{m}_p} \right), \]  \hspace{1cm} (6)

where \(d\) is the width and \(h\) is the depth of the melt pool; and the width is necessarily greater than the depth \((d > h)\), and the surface temperature gradient \(\partial T / \partial s\) is replaced by the ratio \(\Delta T / d\), where \(\Delta T\) is the temperature difference between the center of the pool surface and its periphery.

In table 1 the calculated estimates of thermal capillary convection deceleration for some low carbon steel, stainless steel SS304 and titanium alloy Ti-6Al-4V substrate materials obtained by formulas (6) with varying \(\dot{m}_p\) are given. Deceleration of the flow can be caused by an increase in the viscosity of the mixture in the presence of solid dispersed components. In this case, the average velocity of the mixture begins to depend on the effective viscosity of the suspension, \(\mu_{\text{eff}}\) which increases exponentially with the increase in the volume content of the solid phase \(f_s\)\([6]\):

\[ \mu_{\text{eff}} = \mu \exp\left[ \alpha f_s / (1 - \beta f_s) \right], \]  \hspace{1cm} (7)

where \(\alpha, \beta\) are empirical constants. With an increase \(f_s\) to 0.7, the effective viscosity increases several times, which can cause a significant slowdown in the flow.

**Table 1.** Effect of powder particle flow \(\dot{m}_p\) on convection in liquid metal.

| Parameter                        | Low carbon steel | Stainless steel SS304 | Ti-6Al-4V |
|----------------------------------|------------------|-----------------------|-----------|
| Surface tension gradient: \(\gamma T\), N/(m K); | \(-4.9 \times 10^{-4}\) | \(-3.5 \times 10^{-4}\) | \(-2.7 \times 10^{-4}\) |
| Dynamic viscosity: \(\mu\), kg/(m s). | \(6.93 \times 10^{-3}\) | \(4.3 \times 10^{-3}\) | \(4.0 \times 10^{-2}\) |
| Liquid temperature: \(T_m\) (\(\Delta T\)), K | \(1785\) (1000) | \(1723\) (1000) | \(1923\) (1000) |
| The melt pool width: \(d\), mm | 4                | 4                     | 4         |
| The melt pool depth: \(h\), mm    | 2                | 2                     | 2         |
| Max velocity: \(U_{\text{max}}\), m/s; \(\dot{m}_p = 0\) | 8.8              | 10                    | 0.84      |
| Max velocity: \(U_{\text{max}}\), m/s; \(\dot{m}_p = 10\) kg/(m² s) | 5.1              | 4.7                   | 0.75      |
| Max velocity: \(U_{\text{max}}\), m/s; \(\dot{m}_p = 30\) kg/(m² s) | 2.8              | 2.3                   | 0.61      |

3. Statement of the problem

It is assumed that the investigated laser heating regimes cause small values of the convective velocities, so that the melt flow is considered to be laminar, and this causes a flat shape of the free surface of the liquid. Mass transfer in a fluid is described by the Navier–Stokes equations in the Boussinesq approximation \((8, 9)\). The heat transfer equation \((10)\), written through the enthalpy \(H\) of the melt, takes into account the processes of metal melting by the laser beam and micro-convection of the liquid phase according to \([5]\):
\[ \nabla \cdot \mathbf{V}_l \]

\[ \rho \frac{\partial \mathbf{V}_l}{\partial t} + \rho (\mathbf{V}_l \cdot \nabla) \mathbf{V}_l = -\nabla p + \mu \nabla^2 \mathbf{V}_l + \rho \mathbf{g} \beta_l (T - T_0) \tag{8} \]

\[ \frac{\partial H}{\partial t} + (\mathbf{V}_l \cdot \nabla) H = \nabla (\lambda \nabla T) \quad , \quad H = \int_{r_0}^{r} \rho c_p(T) dT \tag{9} \]

where \( \mathbf{V}_l = (u, v, w) \) is the velocity of fluid and \( \mathbf{g} = (0, 0, g) \) is the acceleration of gravity; \( p, T \) are the pressure and temperature, \( \rho, \lambda \) are the density and thermal conductivity; \( \mu \) is the viscosity.

The transportation method and the mechanism for adding powder particles to the molten pool are not considered in this study. Particles appear on the surface of the melt pool in locations obtained from a random number generator.

The equations of conservation of energy (in the enthalpy form) and the equation of conservation of momentum during the motion of particles along their trajectories when entrained by an melt moving due to the Marangoni effect should also be added to the equations of fluid flow in the molten pool \([4, 5]\). Theses equations are

\[ \frac{d}{dt} \left( m_p H_p \right) = 4\pi r_p^2 \frac{\lambda}{r_p} \left[ \frac{\lambda}{r_p} \right] N_u \left( T_p - T_l \right) \tag{10} \]

\[ m_p \frac{dV_p}{dt} = \frac{1}{2} \rho C_d \pi r_p^2 \left[ \mathbf{V}_l - \mathbf{V}_p \right] \left[ \mathbf{V}_l - \mathbf{V}_p \right] + m_p \mathbf{g} \left[ 1 - \frac{\rho_l}{\rho_p} \right] \tag{11} \]

\[ \frac{dX_p}{dt} = \mathbf{V}_p, \tag{12} \]

\[ T_p = \begin{cases} H_p / c_s, & H_p < c_s T_{mp} \\ \frac{T_{mp} + (H_p - c_s T_{mp} - H_p) / c_m}{c_m}, & H_p > c_s T_{mp} + H_p \end{cases} \]

\[ \left( \frac{T_r}{T_0} \right) = \int_{T_0}^{T_r} \rho c_p(T) dT \tag{13} \]

\[ C_d(\text{Re}_p) = \frac{24}{\text{Re}_p} \left( 1 + 0.179 \text{Re}_p^{0.5} + 0.013 \text{Re}_p \right), \text{Re}_p \leq 10^1, \text{Re}_p = \frac{2r_p \rho_m |\mathbf{V}_l - \mathbf{V}_p|}{\mu} \tag{14} \]

\[ N_u = 2 + 0.459 \text{Re}_p^{0.55} \text{Pr}^{0.33}, \quad N_u = \left( \frac{2r_p \alpha_r}{k_m} \right) / k_m \tag{15} \]

Here \( \rho, \mathbf{V}_l \) are the density and velocity of the melt; \( m_p = 4/3 \pi r_p^3 \rho_p \) is the particle mass; \( C_d \) is the drag coefficient; \( N_u \) is the Nusselt number; \( H_p \) is the enthalpy; \( r_p \) is the radius; \( \rho_p \) is the density; \( \mathbf{V}_p \) is the velocity of the particle; \( T_{mp} \) is the melting temperature; and \( H_{mp} \) is the latent heat of melting.

4. Calculation results

Figures 2 and 3 show the pattern of steady-state flow in the molten pool of the steel substrate. Absorption coefficient \( A_{ab} = 0.19 \). The current lines and the flow velocity distribution are shown in the space occupied by the fluid. Separately, the position of the melting front, which limits the melt zone, is highlighted. For a laser beam with a power of 5 kW and a spot size of 3 mm (noted in the figure), a liquid pool with a diameter of 5 mm and a depth of about 400 microns was obtained. The behavior of the current lines indicates a multi-vortex pattern of fluid flow. In the radiation area there are two vortices symmetrically located relative to the scanning direction of the beam. The colder melt is carried from the bottom of the pool to the surface by these vortices. Within the beam spot, the melt heats up and, due to the Marangoni effect, rushes to the periphery of the pool, where a toroidal vortex is formed. Here, the heated melt is mixed with the colder liquid metal. At the back of the pool, a
stream is formed, rushing to a depth. Then this flow goes up with the formation of the already
mentioned two vortices transferring the melt from the bottom to the surface. Then everything repeats.

**Figure 2.** Velocity field along streamlines of the liquid metal, the top view in the XY plane.

**Figure 3.** Flow diagram in a toroidal vortex, view in the plane: XY (a); XZ (b).

**Figure 4.** Horizontal sections of the molten pool with particles at a powder flow rate of 5 g/min,
scanning speed 10 mm/s. Depth of sections z, microns: -10 (a), -200 (b), -300 (c), -400 (d).
The analysis of the behavior of powder particles falling on the surface of the pool with already developed thermocapillary convection is of interest. The spatial distribution of particles of refractory ceramics (TiC) in the melt pool of the steel substrate (16NCD13) is illustrated in figure 4.

The unevenness of the spatial distribution of the powder is explained by the dynamic delay of the particles with respect to the motion of the fluid carrying them. Particles accumulate most at the periphery and bottom of the pool, where the flow rate is low. Therefore, the centers of vortex flows and some regions with an increased flow velocity, which the particles overcome quickly, turn out to be free of particles.

Two series of calculations were carried out to illustrate the effect of particles on the weakening of the melt convection. First, a modified Marangoni condition (5) was used. The powder consumption varied from 0 to 50 g/min, and the effective viscosity of the melt remained constant: $\mu_{\text{eff}} = \mu$.

Changes in the mass-average velocity of the melt $U(x)$ along the $OX$ axis with variations in the flow rate of the powder $G$ are shown in figure 5. Note that the maxima of the velocity distribution $U(x)$ decrease when the powder flow rate $G>25$ g/min. At the same time, the temperature of the melt in the beam spot increases, since the melt is less intensively mixed and has time to heat up more, this leads to an increase in the Marangoni force. For this reason, the convection deceleration in figure 5 is not as significant.

![Figure 5](image)

**Figure 5.** The effect of the modified Marangoni condition (5) on the attenuation of fluid convection (a) and temperature change (b) with varying powder flow rate $G$.

Further, calculations were made with variations in the flow rate of powder $G$, but taking into account the exponential dependence of the effective viscosity of the melt $\mu_{\text{eff}}$ on the particle content $f$ according to formula (7). In this case, the classical Marangoni condition was used, which is obtained if $\dot{m}_p = 0$ in (5). Figure 6 shows the changes in the mass-average velocity $U(x)$ and temperature on the surface of the liquid. A noticeable weakening of convection is already observed at $G = 10$ g / min. It can be seen that with an increase in the flow rate of the powder added to the pool, the increase in the effective viscosity of the suspension has a decisive effect on convection.

**Conclusions**

A modified Marangoni condition is proposed to describe the deceleration of microconvection when microparticles of refractory powders are added to the melt. It is shown that one of the determining mechanisms of convection deceleration is to increase the effective viscosity of the mixture by increasing the content of particles fed into the pool as an alloying or depositing material.
The accumulation of particles is observed in stagnant areas of the melt pool, which increases the unevenness of the change in the effective viscosity of the mixture and further slows the flow rate. It is shown that the fluid flow regions having an increased velocity are free of particles.

**Figure 6.** The effect of the effective viscosity of the suspension $\mu_{\text{eff}}$ on the attenuation of fluid convection (a) and temperature change (b) with varying powder flow rate $G$.

**Acknowledgments**
The authors appreciate with gratitude the financial support of the Russian Foundation for Basic Research (project No. 17-20-03197). The research was partially carried out within the Program of Fundamental Scientific Research of the state academies of sciences in 2013–2020 (projects No. AAAA-A17-117030610120-2, AAAA-A18-118021590032-2).

**References**
[1] Rykalin N N, Uglov A A and Kokora A N 1975 *Laser Processing of Materials* (Moscow: Mashinostroenie Press)
[2] Antonova G F, Gladush G G, Kosyrev F K, Krasyukov A G, Likhanskii V V, Loboiko A I and Sayapin V P 1998 *Quant. Electr.* 28(5) 430
[3] Kou S and Wang Y H 1986 *Metallurgical Transactions* A17 2265
[4] Gurin A M and Kovalev O B 2013 *Thermophys. Aeromech.* 20 227
[5] Kovalev O B and Gurin A M 2014 *Int. J. Heat and Mass Trans.* 68 269
[6] Kondratiev A S and Shvydko P P 2014 *Scientific journal "Izvestiya MGTM "MAMI", Series Natural Sciences* 4(2) 40