Modeling and numerical study of light-propulsion phenomena of particles acceleration in coaxial laser powder cladding

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Abstract

This work presents the results of investigation of heating and laser acceleration of powder particles in the laser cladding conditions. The model of reactive particles motion developed by the authors made a base for the numerical analysis of the laser particles acceleration. At the laser cladding, the light-propulsion force may be quite high, and powder particles may be accelerated up to several tens of meters per second and more. Numerical studies were carried out for two types of coaxial laser-powder nozzles. Powder feeding ways (symmetrical and asymmetrical), particles size and flow rate were varied. CO\textsubscript{2}-laser radiation had the wavelength of 10.6\,\mu m, power up to 4.5 kW. Stainless-steel and aluminum-oxide powders were studied. Comparability of the model calculation and experimental data is discussed.

Keywords: laser cladding; gas powder stream; evaporation; recoil pressure of vapors; light-propulsion force; acceleration; mathematical modeling; numerical simulation

1. Introduction

The Direct Materials Deposition (DMD) is a promising technology which permits powder material depositing and worn parts recovering, it also permits producing 3D complex-shaped objects Gladush and Smurov (2011). A gas jet transports a metal powder into a melt pool created on a working surface by a laser beam. Recently the coaxial
powder input is mainly used because this technique provides the process symmetry. Fig. 1 illustrates the process of the laser cladding, and the geometry of the channels in the triple coaxial nozzle and schematic of working gases flow.

![Fig. 1. Schematic of the laser head structure (made by TRUMPF) with a triple coaxial nozzle for powder supply, radiation, working and shield gases: (a) the photo of the head and focused powder stream; (b) schematic of the inner structure of the laser-powder head.](image)

In the system where powder supply and laser beam axes are aligned, the phenomenon of the particles accelerated by light field is typical. Light-propulsion force is caused by the recoil pressure of the material vapors from the particle surface Waniek and Jarmuz (1968).

**Nomenclature**

- $t, x, y, z$: time and coordinates of the Cartesian system;
- $m_i, r_i$: particle mass and radius;
- $X_i = (x_i, y_i, z_i)$: mass center coordinate of the $i$-particle;
- $V_i = (u_i, v_i, w_i)$: velocity vector components of the $i$-particle;
- $V_g = (u_g, v_g, w_g)$: gas velocity vector components;
- $F_p = (0,0,f_R)$, $F_R = (0,0,f_R)$: mass and light-propulsion forces;
- $E_i$: specific inner energy of the particle;
- $T_i, T_g$: temperature of the particle and gas, respectively;
- $T_{sl}$, $T_{bo}$: melting and boiling points;
- $L_f, L_e$: specific heats of melting and evaporation of the particles material, respectively;
- $C_s, C_m$: specific heat capacities of the particle material in solid and liquid states;
- $C_{Di}$: drag coefficient for the $i$-particle;
- $H_g$: heat-transfer coefficient;
- $P_{Ri}$: pressure of vapors recoil;
- $W$: laser beam power;
- $K_{ab}$: radiation absorption factor;
- $I(x, y, z)$: laser beam intensity;
2. Motivation

The problem of light-propulsion acceleration of particles under the laser action during the laser-cladding process is discussed by Kovaleva and Kovalev (2011 and 2012), the authors propose the physical and mathematical model and present model calculations imitating the laser cladding conditions. Under study were the stainless-steel particles of 45 μm in the carrier gas flow with speed 15 m/s under the laser-radiation power ranged from 1,000 to 3,000 W. The test calculations showed significant particles acceleration (up to 100 – 250 m/s) and considerable deviation of the particles’ trajectory.

The effect of the laser-induced particles acceleration in the full-scale conditions of the laser cladding has not been fixed yet. The problems of diagnostics of the gas-powder jets in the laser-cladding process were discussed in a number of papers Gladush and Smurov (2011), Meriaudeau et al. (1998), Kebbel et al. (2005), Tan Hua et al. (2012), Liu Weihong et al. (2013), Meriaudeau et al. (1997). The diagnostics of particles parameters was mainly performed by non-contact optical methods such as high-speed shooting, PIV, three-color pyrometry, etc. The particle velocity however was registered with no laser radiation thus the measured velocities slightly differed from the carrier-gas velocity; the laser effect was beyond the study.

The results of experiments of Sergachev et al. (2014) were presented in LANE 2014; the authors utilized the laser-optical measurement equipment developed to register the particles parameters in high-enthalpy gas (plasma) flows. It is demonstrated that in the laser-radiation field the particles of such powders as Al₂O₃, Mo, Ni, Al gain extra acceleration due to the laser evaporation. The observed effect of particles acceleration depends on the radiation power and particles concentration in the flow.

This work presents the results of investigation of heating and laser acceleration of powder particles transported by a carrier gas flow in the conditions of the laser cladding, with a coaxial laser-powder nozzle and radiation of the CO₂ laser with the power up to 4.5 kW.

3. Physical and mathematical models

The methods of gas-disperse flows diagnostics presented by Meriaudeau et al. (1998), Kebbel et al. (2005) Tan Hua et al. (2012), Liu Weihong et al. (2013), Meriaudeau et al. (1997) enable to observe solely external flows between the nozzle and substrate where the shape of the disperse jet and powder particle parameters are fixed. However, the nature of these external flows is generated inside the channels of the coaxial nozzle where the observation is impossible. Kovalev et al. (2011) showed that it was important to compute gas dynamics and particles transportation both for the external and inner flows. In addition, the meaningful fact is that the gas-dynamic processes must be calculated in the model of the compressible gas. Kovalev et al. (2011) and Kovaleva et al. (2013) developed the physical and mathematical models of 3D flows of a viscous compressible gas with powder particles transportation with heating in the laser light field. The software implementation of the models was partially verified by the experimental results for the particle dynamics visualization. The trajectory model was used to describe movements of the powder particles carried by the gas flow. According to this approach, all equations describing the disperse phase motion, are written in Lagrange variables and integrated along the trajectories of individual particles. The gas flow field (temperature and velocity distribution) is calculated in Euler variables with no regard to the particles effect on the gas. This technique is effective for the description of the gas-disperse mixture motion at low powder flow rate up to 1 – 5 g/min. In this case, particles collisions can be neglected; the scattering and attenuation of radiation with the powder jet can be treated as insignificant at such flow rates. The study performed by Kovalev et al. (2011) also showed that the mechanism of particle reflection from the nozzle wall (absolute elastic or inelastic interaction) was used in the model influence significantly the shape and focusing of the powder jet.
3.1. Shield and carrier gas flows

For the numerical modeling of jet gas flows, the system of Navier-Stokes equations for viscous and compressible ideal gas in axisymmetric statement was used; the initial and boundary conditions completely coincided with the ones in the paper of Kovalev et al. (2011). The calculation domain included the internal geometry of the coaxial nozzle channels and the external space for the calculation of free flow of the gas-disperse flow in the laser light field. The internal geometry of the triple or double coaxial nozzle, distance to the substrate gas flow rates in the inlet sections of three or two annular channel, are the data needed for the calculation of the gas-dynamics parameters: the velocity vector \( \mathbf{V}(r,z,t) \), pressure \( p_{g}(r,z,t) \), density \( \rho_{g}(r,z,t) \), and temperature \( T_{g}(r,z,t) \). The conditions \( p_{0}=0.1 \) MPa, \( T_{0}=300 \) K, \( V_{0}=0 \) are taken as the initial ones at the time instant \( t=0 \) in the area occupied by the gas, and as boundary conditions for the computational domain. No-slip and thermal isolation conditions were preset for nozzle walls and for the substrate.

3.2. Heating, melting, evaporation, and acceleration of powder particles in the carrier gas

The obtained distribution of the gas flow parameters was used for the calculation of powder particle thermodynamics and transportation. The values are recalculated from the cylindrical coordinate system \( O_{rZ} \) to the Cartesian system \( O_{xyz} \). The powder particles are expected to be spherical, with the known size distribution and the thermophysical properties of material. The equations of the particle dynamics with due regard to the laser acceleration can be written as (Kovaleva and Kovalev (2012) :

\[
\frac{d\mathbf{X}}{dt} = \mathbf{V},
\]

\[
m_{i} \frac{d\mathbf{V}_{i}}{dt} = \frac{1}{2} \rho_{g} A_{i} |\mathbf{V}_{g} - \mathbf{V}_{i}|(\mathbf{V}_{g} - \mathbf{V}_{i})C_{Di} + \mathbf{F}_{g} + \mathbf{F}_{Ri},
\]

\[
\mathbf{F}_{g} = (0,0,m_{i}g), \quad \mathbf{F}_{Ri} = (0,0,f_{Ri}), \quad m_{i} = \frac{4}{3} \pi r_{i}^{3} \rho,
\]

where \( r_{i} \) is particle radius, \( \mathbf{V}_{i} \) is velocity vector, \( \mathbf{X}_{i} = \{x_{i},y_{i},z_{i}\} \) are coordinates of the mass center, and \( T_{i} \) is temperature averaged over the volume of the particle.

The resultant force \( f_{Ri} \) averaged by the individual \( i \)-particle surface \( A_{i} = 2\pi r_{i}^{2} \) and applied to the particle mass center \( \mathbf{X}_{i} \), is calculated as follows: \( f_{Ri} = A_{i}P_{Ri} \), where the pressure of vapors recoil \( P_{Ri} \)

\[
P_{Ri} = \begin{cases} 
0, & T_{i} < T_{m}, I(x_{i},y_{i},z_{i}) < I_{th}, \\
0.54P_{a} \exp(A_{i} - B_{i}/T_{i}), & T_{i} \geq T_{m}, I(x_{i},y_{i},z_{i}) < I_{th}, \\
I(x_{i},y_{i},z_{i})K_{ab}u_{e}/L_{e}, & I(x_{i},y_{i},z_{i}) \geq I_{th}.
\end{cases}
\]

Let us write the variation of the full energy of a single particle along its motion trajectory as:

\[
\frac{dm_{i}E_{i}}{dt} = A_{i}I_{a}K_{ab} - H_{g}^{\circ}(T_{i} - T_{g})S_{i} - \varepsilon \sigma T_{i}^{4}S_{i},
\]

here \( E_{i} = \int_{T_{i}}^{\infty} C(T) dT \) is the specific inner energy of the \( i \)-particle at the temperature \( T_{i} \).

The right side of the equation (4) regards the heat supply owing to the absorbed laser energy and heat loss for the heat emission and heat exchange with the cold gas flow. The particles temperature is determined with respect to the heat loss for the melting and evaporation:
The drag coefficient $C_{DiC}$ was calculated by the approximation for the sphere:

$$C_{DiC} = (24/Re)(1 + 0.179 Re^{0.5} + 0.013 Re), \quad Re < 1000. \quad (6)$$

The intensity of the laser beam $I(x, y, z)$ is described by the Gaussian distribution:

$$I(x, y, z) = \frac{2W}{\pi \omega_0^2} \exp\left(\frac{2(x^2 + y^2)}{\omega_0^2}\right), \quad \omega_0^2 = \omega_0^2 + K_a^2(z - z_f)^2, \quad K_a = \frac{\lambda}{\pi \omega_0},$$

### 3.3. Initial and boundary conditions for the particles.

The powder particles were supplied into the carrier nozzle channel with the uniform distribution over the annular inlet cross section with the coordinate $z_i = z_0$ at the time instant $t = t_0$, which was assumed to be the start. General quantity of supplied particles $N_p$ is assigned with a certain size-distribution function. The components of the particle velocity vector in the inlet cross section are presented as two summands: $V = V_0 \pm \delta V$. $V_0$ corresponds to the gas velocity components $V_g$ or the known average velocity of the particles in the input point, the other describes the deviation from the gas velocity $\delta V$. The value and operator of this deviation are found in random manner. The particle temperature in the input point is assigned to be constant and equal to the ambient temperature $T_i = T_0$. Particles collisions with the nozzle walls results in their reflection which is treated as absolutely elastic.

### 4. Numerical simulation results

The numerical analysis was performed for two types of coaxial laser-powder nozzles: the Trumpf nozzle DMD 505 machine, and the nozzle of ITAM SB RAS. The powder particle launching ways (symmetrical and nonsymmetrical), particles size and flow rate were varied. CO$_2$-laser radiation with the wavelength of 10.6 $\mu$m and power up to 3 kW was applied; the beam radius in the focus point was 150 $\mu$m, the powders were from stainless steel and aluminum oxide. Table 1 presents the thermophysical properties of the particles materials used in the calculations.

<table>
<thead>
<tr>
<th>Physical quantity and dimension</th>
<th>Stainless-steel</th>
<th>Aluminum oxide, (Al$_2$O$_3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, K: melting $T_m$ / boiling $T_{bol}$</td>
<td>1809/3137.6</td>
<td>2323/3253</td>
</tr>
<tr>
<td>Specific heat, kJ/kg: melting $L_f$ / evaporation $L_e$</td>
<td>272/6100</td>
<td>1070/19390</td>
</tr>
<tr>
<td>Material density, kg/m$^3$: solid $\rho_s$ / liquid $\rho_m$</td>
<td>6900/6610</td>
<td>3970/2540</td>
</tr>
<tr>
<td>Specific heat capacity, J/(kg K): solid $C_s$ / liquid $C_m$</td>
<td>477/810</td>
<td>770/1600</td>
</tr>
<tr>
<td>Radiation absorption coefficient: $K_{ab}$</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>Threshold intensity, W/m$^2$: $I_{th}$</td>
<td>$3\times10^8$</td>
<td>$3\times10^8$</td>
</tr>
</tbody>
</table>

### 4.1. Nozzle of the Trumpf DMD 505 machine
Fig. 2 presents the pattern of gas flows in the calculation domain as the substrate is at the distance of 20 mm. Velocity, density distributions and gas streamlines in the internal and external flows are shown.

In the inlet sections of the annular channels, the following values of the gas flow rates were assigned: the nozzle gas in the axial nozzle – 18 l/min, the carrier gas flow rate – 20 l/min, the shaping gas flow rate – 20 l/min. In the central area between the nozzle and substrate, a cylindrical jet forms, Fig. 2(a). The vortex flows in the space around the jet are non-stationary, but the oscillations initiated by them do not impose any significant effect on the main flow. According to Fig. 2(b), the external gas flow could be reasonably treated as uncompressible one, as the gas density here is comparable to the ambient density; but this is not true for the internal flows in the nozzle channel.

Fig. 3 and 4 show the calculation data for the laser acceleration of stainless-steel particles in the coaxial nozzle Trumpf DMD 505. The data were obtained as per the model described above. Two modes of powder supply were studied. The first one consisted of the utilization of 30 same-size particles (60 μm) launched strictly symmetrically in the annular inlet cross section. It is seen that the particles trajectories in the carrier nozzle channel moved symmetrically. The particles were reflected from the walls and focused in a certain point on the beam axis, Fig. 3, and, passing through the laser light field, were heated. The melting starts and finishes in the point near the focusing point on the beam axis where the intensity density is maximal. When the induced propulsion force \( F_{ri} = 0 \) is missing in the motion equations (2), the particles do not undergo high acceleration. The variations in the particle velocity agree with the variations in the carrier gas velocity. Occurrence of a certain nonzero propulsion force \( F_{ri} \neq 0 \) stimulates the considerable acceleration of all particles; their velocity reaches 150 m/s.

The second mode involved 100 particles with diameter of 60 μm; they were supplied into the flow randomly, with a certain velocity distribution \( V_i = V_s \pm \Delta V \) specified by the random deviation \( \Delta V \). It is evident that, because of the particle reflection from the nozzle walls, many particles do not get into the laser light field and are not even heated. Significant acceleration due to the recoil pressure of vapors is observed only for those particles which flight through the beam axis and manage to melt (12% of all particles in the Figure).

4.2. Nozzle of the ITAM SB RAS

The double coaxial nozzle utilized in the calculations was manufactured in the Physics of Plasma-Arc & Laser Processes Lab of ITAM SB RAS and is a component of the technological plant for plasma spraying Kuz’mín et al. (2012). The internal configuration of the nozzle differs somehow from standard coaxial nozzles for the laser cladding. The coaxial channel of the transport nozzle is inclined to 45 degrees in respect to the central nozzle axis, Fig. 5(a) which is coordinated with the laser beam. The powder is injected into the main flow in such a way that it immediately gets in the beam action zone. At the same time, the flow from the transport nozzle provides protection
of the particles in the jet from the ambient medium. The flow in the central nozzle is needed to protect the optical system. Nitrogen with the following flow rates is used: in the central nozzle (shielding gas) – 1.5 g/s; in the transport nozzle (carrier gas) – 3 g/s. The laser radiation intensity distribution is specified on the base of the experimental data of Sergachev et al. (2014). The laser beam is focused about 5 mm above the nozzle exit plane. The power of the CO₂-laser radiation is 2 kW.

Fig. 3. Symmetrical supply of 30 similar particles of 60 μm in diameter, nozzle Trumpf DMD 505: particles trajectories, their temperature and velocity variation during the flight with no laser acceleration: (a,c) - \( \mathbf{F}_L = 0 \); and at the intensive evaporation and acceleration (b,d) - \( \mathbf{F}_L \neq 0 \).

Fig. 5(a) shows the axisymmetric gas flow created by such a nozzle; it enables to have the stable jet with the uniform distribution of the parameters. When two jet flows interact to each other, a couple of symmetric micro-vortices occur at the nozzle outlet. The interaction with the ambient medium is limited by the involvement of the ambient gas into the carrier-gas flow, which results in two big vortices located symmetrically; the velocity in them is low, about 2 m/s. The flow from the carrier nozzle contracts the flow from the central channel and simultaneously protects it from the mixing with the ambient gas. The maximal gas velocity of 38 m/s is reached at the transport nozzle outlet. In the central nozzle, the average gas velocity is 2.5 m/s.

Powdered aluminum oxide particles (the average diameter 40 μm) were injected in the annular section of the transport nozzle at \( z = -6 \) mm. The particle size was chosen arbitrary in accordance with the size distribution function assigned by Sergachev et al. (2014). The particles, totally 400 pieces, were injected asymmetrically into the flow, the size distribution was specified by the arbitrary deviation \( \delta V \) from the average value of 1 m/s; they were carried away by the carrier gas and collided with nozzle walls. According to Kovalev et al. (2011), the loss
coefficient specified at the inelastic collision was equal to 0.9.

Fig. 4. Asymmetrical supply of 100 particles with the normal size distribution, average diameter 60 μm, nozzle Trumpf DMD 505: particles trajectories, their temperature and velocity variation during the flight with no laser acceleration (a,c) $\text{F}_n = 0$; and at the intensive evaporation and acceleration (b,d) $\text{F}_n \neq 0$.

Fig. 5(b, d) shows the trajectories of each particle and variation of its temperature along this trajectory; the data were obtained without (Fig. 5(b)), and with (Fig. 5(d)) light-propulsion force in the equations (2). During the motion in the transport nozzle channel, the particles temperature is constant and equals to the ambient temperature, 300 K. Upon getting out from the nozzle, the particles pass into the laser light field and start to heat up. The heating rate and particle temperature depend on the time within which it undergoes the radiation action, and on the place where its trajectory is located in the laser light field. The intensity of the field is described by a Gaussian distribution. The particles passing over the beam periphery are heated weakly whereas the ones crossing the beam axis may be heated to the utmost, may melt and even boil. Thus the color array of the particles trajectories, which features their temperature upon passing the powder jet focusing area, Fig. 5(b, d), is very wide.

Most particles do not change the motion direction upon passing the powder jet focusing area. As the light propulsion force is present, however, the trajectory bundle divides to two parts. Quite a lot of the particles (just under one half) change the motion direction and form an internal bundle of trajectories, Fig. 5(d), where the particles temperature is above the melting point. All the rest of unheated particles do not change the motion direction. The
particles velocity in the internal bundle of trajectories reaches 250 m/s, Fig. 5(c).

It is known that the radiation intensity decreases in the divergent laser beam. That is why some particles have time to cool down to crystallization temperature due to the thermal exchange with the gas; at this temperature, the light-propulsion force disappears, and the particles continue to move carried by the gas alone. The aforesaid pattern is presented in Fig. 5(ɫ) which also presents the varying module of the particles velocity.

Fig. 6(ɚ) shows the variation of the average particles velocity calculated by the whole ensemble of the used particles versus the distance by the axis $Oz$ in two nodes: without (blue) and with (red) laser radiation. The stable rise of the average velocity observed right after the particles pass into the beam area at $z = 4.8$ mm continues up to $z = 11$ mm; then the intensity in the beam weakens so much that the light-propulsion force disappears, and the particles are decelerated by the gas flow.

For comparison, Fig. 6(b) shows the histogram of particles velocity distribution from Sergachev et al. (2014), wherein it was founded that the average particle velocity at $z = 10$ mm without radiation equaled to 13 m/s, with the radiation of 1,700 W it was 24 m/s. The average values of the particle velocity in Fig. 6(b) fixed in paper of Sergachev et al. (2014) agree with the calculations in Fig. 6(a).
5. Conclusions

The results of numerical modeling for the powder particles’ motion in the gas flow, under the conditions of the coaxial laser cladding are presented. The model of reactive particles movement developed previously by the authors was used as a base to perform the computation of the particle acceleration phenomenon in the laser light field. The calculations were carried out for two types of the coaxial laser-powder nozzles. The radiation of the CO₂ laser with the wavelength of 10.6 μm and power up to 4.5 kW was used; the powders were from stainless steel and aluminum oxide. It is demonstrated that the light propulsion acceleration of steel particles during the laser cladding takes place when the particles get into the near-axis region with the maximal radiation intensity. In the theoretically possible ideal case for the nozzle of Trumpf DMD when all trajectories pass through the beam axis, the particles heat up quickly and are accelerated up to 150 m/s.

When the start position and initial particle velocity are chosen arbitrary at the startup, i.e. when the powder injection is performed almost similarly to the real process, most particles pass without getting into the region of high-dense radiation; they are not accelerated by the laser. Just 12% of the particles cross the near-axis region and reach the velocity from 50 to 180 m/s.

In the nozzle of ITAM SB RAS, the angle of powder feeding is 45°, and most of injected particles get into the near-axis region. Moreover, the particles trajectories are located closer to the beam focusing point where the radiation intensity density is high. About 40% of aluminum oxide particles are accelerated essentially, the velocity of some ones reaches 250 m/s. As the distance from the nozzle rises, the radiation intensity weakens, some particles during the flight cool down to the temperature below the melting point, and the light-propulsion acceleration disappears.

Comparison of the experimental data of particles parameters in the laser-cladding conditions Sergachev et al. (2014) and the computational data of this work shows that the average particle velocities coincide quite well, accurate within 2 m/s, Fig. 6(a, b). However, the velocity distribution of the particles differs essentially. For example, no particles with the velocity of 250 m/s were registered in the tests.

The reasons may be different. First, the model (1-7) does not include particles collision. When colliding, accelerated particles may give some impulse to unaccelerated ones and hence the velocity distribution is more even. The second reason is that the model (1-7) uses the trigger system of light-propulsion acceleration startup. In reality, this process is apparently continuous and smoother. The values of all constants utilized in the calculations were taken from different independent sources which permits believing that the particles acceleration observed at the laser
cladding is likely to be of the light-propulsion nature.

References


