Study of metallic powder flow in discrete coaxial nozzles

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Abstract. Additive technologies are gradually introducing into modern manufacturing, complementing or dislodging conventional material processing technologies. This is because of they have a unique advantage in the manufacture of products. Currently, among the popular additive laser technologies the most promising and productive technology is the direct laser deposition (DLD). The distribution of powder particles in a gas-powder flow is an important parameter that determines the powder capture coefficient (PCC) and, as a consequence, the efficiency of the DLD process. The powder flow distribution depends on the shape of the particles, the stability and the parameters of supply of the carrier gas and powder. When above conditions are fulfilled, gas-powder flow becomes stationary, which allows to determine PCC. The measurements of the PCC for different amounts and cases of nozzle positions were conducted. Having analysed the experimental and calculated results we can conclude that the model of the powder stream satisfactory describes one tube nozzle.

1. Introduction
Additive technologies are gradually introducing into modern manufacturing, complementing or dislodging conventional material processing technologies [1, 2]. This is because of they have a unique advantage in the manufacture of products [3]. Currently, among the popular additive laser technologies the most promising and productive technology is the direct laser deposition (DLD).

The distribution of powder particles in a gas-powder flow is an important parameter that determines the powder capture coefficient (PCC) and, as a consequence, the efficiency of the DLD process. The powder flow distribution depends on the shape of the particles, the stability and the parameters of supply of the carrier gas and powder. When above conditions are fulfilled, gas-powder flow becomes stationary, which allows to determine PCC.

2. Mathematical model
Many different forces affect the metallic powder in the gas-powder flow. Effects of all these forces can’t be predicted. Distribution of powder particles in gas flow determines an amount of powder, which falls to the molten pool. The volume of the molten metal includes this powder. It has an influence on geometry of clad or layer. The process diagram is shown in Figure1.
Figure 1. Schematic of laser cladding and the reference frame

According to [4-11] assume that particle concentration in gas-powder flow has Gaussian distribution. The Gaussian distribution for the spherical shaped powder particles can be written as:

$$F(x, y) = \frac{1}{2\pi \cdot \sigma_x^2 \cdot \sigma_y^2} \exp \left( -\frac{(x-\mu_x)^2 + (y-\mu_y)^2}{2 \cdot \sigma_x^2 \cdot \sigma_y^2} \right),$$  \hspace{1cm} (1)

where $\sigma_x, \sigma_y$ are the standard deviation at axis $x$ and $y$; $\mu_x, \mu_y$ are the mathematical expectations.

The mathematical expectations in our case are equal to zero, because the origin of the reference frame is on the axis of the gas-powder flow. The standard deviation is an effective radius of the gas-powder stream $R_{ef}$:

$$R_{ef} = \sigma_x \cdot \sigma_y = \frac{d_n}{2} + f \cdot tg \theta$$  \hspace{1cm} (2)

where $\theta$ is a half of flow divergence angle; $f$ is the distance between nozzle and substrate; $d_n$ is the nozzle diameter.

The gas-powder flow distribution is shown in Figure 2.
A combination of equations (1) and (2) gives the powder mass distribution of the stream:

\[
F(x, y) = \frac{m}{2\pi \left( \frac{d_n}{2} + f \cdot \tan \theta \right)^2} \exp \left\{ -\frac{x^2 + y^2}{2 \left( \frac{d_n}{2} + f \cdot \tan \theta \right)^2} \right\}, \tag{3}
\]

where \(m\) is the mass flow rate.

The equation (3) can be used only for the flow that is normal to the substrate. To take into account the inclination \(\alpha\) of the flow to x-axis in X0Z plane we substitute:

\[
\begin{align*}
x' &= \frac{x}{\cos(\alpha)} \\
y' &= y \\
f' &= f - x \cdot \tan(\alpha)
\end{align*} \tag{4}
\]

The PCC can be obtained by integration of equation (3) over the molten pool area. In our case, the area of interests is a circle (\(\alpha = 0\)) or ellipse (\(\alpha > 0\)) like a transverse section of capture tubes, which is used in experiments. In the simplest case of the PCC calculation for a circle-area with radius \(R\) the equation (4) should integrated as follows:

\[
G_{calc} = \int_{0}^{R} \int_{0}^{2\pi} \frac{m}{2\pi \left( \frac{d_n}{2} + f \cdot \tan \theta \right)^2} \exp \left\{ -\frac{(r \sin \varphi)^2 + (r \cos \varphi)^2}{2 \left( \frac{d_n}{2} + f \cdot \tan \theta \right)^2} \right\} r \, d\varphi \, dr \tag{5}
\]

3. Experimental procedure
The nozzle with three feeding tubes was used for experimental measurements of PCC. The following experimental trials were carried out: (1) gas-powder flow was fed through a single tube normally...
oriented to the capture tube; (2) gas-powder flow was fed through single tube oriented at 70˚ angle to the capture tube; (3) gas-powder flow was fed through three tubes simultaneously.

The diagram of experiments is presented at Figure 3.

Figure 3. The diagram of experiments

Three capture tubes of 1.5, 2 and 3 mm diameter were used for the measurement of the powder capture coefficient. These capture tubes were imitating a molten pool. PCC is calculated as a ratio between the weight of the powder caught by the capture tube and the total weight of the feed powder. The PCC was measured for different distances $f$ and for every capture tube diameter $D$.

4. Adjustment of the gas-powder flow divergence angle

In order to adjust the divergence angle of the flow the following optimization problem should be solved taking into account experimentally determined PCC values for capture tubes of different diameters. For the additional condition we used an abstract capture tube with diameter $D_a$, $D_a > R_{ef}$. This abstract capture tube grabbed all powder particles of stream. Thus, for the constant distance between exit of nozzle and substrate we have target function, which depends on divergence angle of the stream:

$$F_{opt} (\theta) = \sum_{i=1}^{4} \int_{0}^{\frac{D_i}{2}} \int_{0}^{2\pi} \frac{m}{2\pi} \left( \frac{d + f \cdot \tan \theta}{2} \right)^2 \exp \left\{ -\frac{(r \sin \varphi)^2 + (r \cos \varphi)^2}{2 \cdot \left( \frac{d + f \cdot \tan \theta}{2} \right)^2} \right\} d\varphi r - G_i \right\}^2,$$

where $i$ is the number of capture tubes; $G_i$ is the experimental powder capture coefficient for those tubes.

5. Results and discussion

After the rectification of $\theta$ the experimental and calculated results of PCC were compared. Powder mass distribution within gas-powder stream in effective radius at different distance $f$ is shown in Figure 4. Figure 5 is shows the dependence of the effective radius on the distance between borders of the nozzle and substrate.
Figure 4. Powder mass distribution of the gas-powder stream within the effective radius at different distances.

Figure 5. Plot of dependence of the effective radius on the distance between borders of the nozzle and substrate.

In the figures 6 and 7 we can see the results and the difference of calculated and experimental PCC. The numbers over the plots in the figure 7 represent the distances $f$ between the border of the nozzle and the border of the capture tube. The difference does not exceed 4%.
Figure 6. The plot of experimental PCC (blue line) and the calculated PCC (red line) for normal falling stream case.

Figure 7. The plot of the difference between calculated and experimental values of PCC for normal falling stream.

The comparison of experimental and calculated data for second case, which the stream falling on substrate with angle $\alpha$ presented on Figure 8 and Figure 9. In Figure 8 the blue line are referred to experimental data and the red line are referred to the calculated data. In fig.9 presented the difference between experimental and calculated data.
Figure 8. The plot of experimental PCC (blue line) and the calculated PCC (red line) for case which stream have the angle $\alpha$ equal to 70°

Figure 9. The plot of the difference between calculated and experimental values of PCC for falling stream with the angle $\alpha$ equal to 70°

The difference between experimental and calculated data in case of falling stream with the angle $\alpha$ equal to 70° is less than 6%. But this difference is more than in normal falling stream case. This can be explained by the gravity effect.

Having analyzed the experimental and calculated data of the experiment with the three tubes nozzle, we can conclude that the gas flow interaction in the focus point has a strong influence on PCC. For the cladding head of the chosen geometrical configuration the focal point, that is a position of the gas-powder flows collision, is 10 mm away from the nozzle. In the figure 10 the plot of experimental and calculated values of PCC is presented. In the figure 11 we can see the difference between experimental and calculated data for different distances $f$. 
Figure 10. The plot of experimental PCC (blue line) and the calculated PCC (red line) for the case of the three tubes nozzle.

Figure 11. The difference between experimental and calculated values for the case of the three tubes nozzle.

It is obvious, that because the error is over the 30% the model of powder stream can’t be used to predict the PCC for the three tubes nozzle. It’s necessary to take into account the gas stream interaction.

6. Conclusion

The measurements of the PCC for different amounts and cases of nozzle positions were conducted. Having analysed the experimental and calculated results we can conclude that the model of the powder stream satisfactorily describes one tube nozzle. It can predict the PCC with a good accuracy, nearby 6%. For the complex cladding heads with two or more tubes this model can predict the PCC with the error of 30%. This error occurs because the model does not take into account the interaction between gas-powder streams.

Acknowledgements
The work was carried out with financial support from the Ministry of Education and Science of the Russian Federation in the framework of realization complex project, Contract No 14.574.21.0175, 26.09.2017.

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