Study of substrate temperature dependence upon nozzle traverse speed at cold spraying

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Abstract. The paper presents the results of investigation of dependence of substrate temperature upon nozzle traverse velocity under cold spray conditions. A model is proposed for prediction of substrate temperature. Experimental and simulated data were obtained in the typical range of change in the nozzle traverse speed (1-400 mm/s) and air stagnation temperatures (200-600°C), encountered in the practice of cold spraying. The simulated data are in good agreement with experimental. An approximate analytical equation is proposed for estimation of substrate temperature during cold spraying in a wide range of gas stagnation temperatures and nozzle traverse velocities.

1. Introduction
Cold gas-dynamic spraying is a rapidly developing method, which originates from the discovery of the phenomenon of coating formation upon impact of non-molten metal particles in Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch of Russian Academy of Sciences, in the early 1980s [1].

The presence of a critical (minimum) particle impact velocity [2], the presence of a deposition delay [3], the necessity for plastic deformation of particles, the ability to produce coatings on non-metallic materials (glass, ceramics, building materials [4-6]) etc. are the main regularities of coating formation. Cold spraying enables to obtain composite coatings [7-14]. Gas dynamics of flows in De Laval nozzles [15-19], as well as in nozzles of other geometries [20-22] are important for successful deposition because for acceleration of powder particles gases like air, nitrogen and helium are often used. At present, worldwide, further researches are being conducted and industrial technologies are being developed using cold spraying.

In practical use, a continuous coating is created by scanning the substrate surface with a two-phase jet at a given nozzle travel speed. Since the surface temperature of the substrate affects the spraying process [1, 23-31], the study of its dependence on the nozzle travel speed is an urgent task. This paper presents preliminary (without taking into account the contribution of particles) experimental and simulated data in the typical range of change in the nozzle travel speed (1-400 mm/s) and air stagnation temperatures (200-600°C), encountered in the practice of spraying.

2. Experimental
The measurements were carried out by using an assembly comprising a base to which a layer of ceramic thermal insulator is attached, on which aluminum substrate is placed sized 50 × 50 × 1 mm. The substrate was pressed by 1 mm thin steel frame, also through a ceramic insulator. The frame had a
rectangular cutout sized 40 × 20 mm, through which the jet impinged on the substrate. The first thermocouple (for measuring the jet temperature) was installed in front of the substrate and frame. The second and third thermocouples were placed flat to the substrate surface symmetrically relative to its middle. The distance between second and third thermocouples was 20 mm. Air flow parameters were the next: stagnation pressure 3 MPa, stagnation temperature 200, 400 and 600°C. An axisymmetric profiled supersonic nozzle with an estimated exit Mach number of 3 (critical nozzle diameter 6.5 mm) was used to produce supersonic jet.

3. Model description

For computation, a grid was used with a cubic cell which side was equal to the substrate thickness. We consider relatively thin substrates, the thickness of which is many times smaller than the characteristic dimensions in plane, i.e., it is assumed that the temperature gradient along the substrate thickness is negligible. In the first step, the heat fluxes are calculated through the faces of each cell (numbered \(i\) along \(x\)-axis that is directed along nozzle traveling speed, and \(j\) along \(y\)-axis that is perpendicular to the nozzle traveling speed):

\[
q_{x,i,j} = -\lambda h dy \frac{T_{i,j} - T_{i-1,j}}{dx}, \quad q_{y,i,j} = -\lambda h dx \frac{T_{i,j} - T_{i,j-1}}{dy}, \quad q_{w,i,j} = -c \rho h dx (T_0 - T_{i,j}).
\]

(1)

Here, \(T_{i,j}\) is a substrate temperature in cell \((i, j)\), \(\lambda\) is a heat conductivity of substrate material, \(h\) is substrate thickness, \(\alpha\) is a coefficient of heat transfer between jet and substrate, \(T_0\) is jet stagnation temperature over cell \((i, j)\), \(dx\) is a cell size in \(x\)-direction, \(dy\) is a cell size in \(y\)-direction.

For an axisymmetric jet, the distribution of the heat transfer coefficient and the stagnation temperature along the substrate surface is taken as:

\[
T_0(r) = \frac{T_{00}}{1 + 15 \left( \frac{r}{r_T} \right)^2 \left( \frac{r}{r_T} \right)^{0.25}}, \quad \alpha(r) = \frac{\alpha_0}{1 + 15 \left( \frac{r}{r_a} \right)^2 \left( \frac{r}{r_a} \right)^{0.25}}.
\]

(2)

Here, \(T_{00}\) is a stagnation temperature in nozzle pre-chamber, \(\alpha_0\) is a heat transfer coefficient at the jet axis, \(r_T\) is characteristic coordinate where stagnation temperature is twice lower than that at the jet axis, \(r_a\) is an analogus coordinate for heat transfer coefficient. In simulation we adopted \(\alpha_0 = 7 \times 10^3\) W/K m², \(r_T = 25\) mm, \(r_a = 4\) mm. The last two values are taken on the basis of previous studies [1]. As for \(\alpha_0\), it should be noted that its value was selected to achieve the best match of the measurement results at the jet stagnation temperature 400°C. Further, in all presented cases of calculation, it was kept constant.

In the second step of the simulation the average temperatures of the substrate cells are calculated:

\[
T_{i,j}^{k+1} = T_{i,j}^k + \left( q_{x,i,j} - q_{x,i+1,j} + q_{y,i,j} - q_{y,i,j+1} + q_{w,i,j} \right) \frac{dt}{c \rho h dx dy}.
\]

(3)

Here, \(c\) is a heat capacity of substrate material, \(\rho\) is a density of substrate material, \(k\) is a number of time steps \(dt\).

In the case of nozzle moving at a constant speed \(u_n\), the radius in the distributions of stagnation temperature and heat transfer coefficient (2) for each cell is calculated by the formula:

\[
r_{i,j} = \sqrt{(x_i - s)^2 + (y_j - L_y / 2)^2}, \quad s = u_n \cdot k \cdot dt.
\]

(4)

Here, \(L_y\) is a width of the substrate.
4. Results and discussion

Figure 1 shows the experimental and calculated data performed for three different air stagnation temperatures. The substrate temperatures shown were taken as the average between the maximum readings of the two thermocouples. Further, the approximation of the calculated and experimental data was carried out. It is seen that in the logarithmic coordinates of the nozzle travel speed there is almost a linear relationship. Deviation from this dependence takes place at the most extreme points.

A generalization of the obtained in simulation and experimental data was also carried out, as shown in figure 2. For this generalization a reference nozzle travel speed of 10 mm/s was selected; the substrate temperature gain at this speed was selected as the base. All substrate temperatures were divided by this base temperature, so that all curves of calculations and experiments intersect at this one point in the plot.

Figure 1. Dependence of the substrate temperature gain (relative to the initial temperature) on the nozzle travel speed. 1-3 simulation results, 4-6 experimental results, 7-9 approximation; 1, 4, 7 – stagnation temperature 200°C; 2, 5, 8 – 400°C; 3, 6, 9 – 600°C.

Figure 2. General dependence of the relative substrate temperature on the nozzle travel speed. 1-3 simulation results, 4-6 experimental results, 7 approximation by formula \(1 – 0.556 \cdot \log \left( \frac{u_n}{u_{nr}} \right) \); 1, 4 – stagnation temperature 200°C; 2, 5 – 400°C; 3, 6 – 600°C.
As it can be seen, the results are described by a single dependence with a good accuracy, at least in the studied range of stagnation temperatures and nozzle traveling speeds. The values of the base temperature are equal to 97.8, 209.5, and 321.25°C for the stagnation temperatures 200, 400, and 600°C, respectively. In the first approximation it is possible to estimate this base temperature as a half of the stagnation temperature.

The results of calculations and experiments in the stagnation temperature range of 400 and 600°C coincide with a good accuracy. At stagnation temperature 200°C there is some difference (not exceeding 30-35°C, see figure 1). Thus, for practical estimates the simple expression (5) can be used, obtained as a result of the present work:

$$\Delta T_s = \Delta T_{nr} \left(1 - 0.556 \cdot \lg \left( \frac{u_n}{u_{nr}} \right) \right), \text{ where } u_{nr} = 10 \text{ mm/s}, \text{ } \Delta T_{nr} \approx 0.5T_{b0}.$$  

These relations, however, are true only for experimental conditions: a thin (1 mm) aluminum heat-insulated substrate fixed by a frame with a slot. When using thicker substrates fixed without thermal insulation, lower substrate temperatures should be expected. Therefore, the values obtained here should be taken as the maximum possible, at least for aluminum substrates.

5. Conclusion
Dependence of substrate temperature upon nozzle traverse speed is investigated under cold spray conditions. For the first time, experimental and simulated data were obtained in a wide range of change in the nozzle traverse speed (1-400 mm/s) and air stagnation temperatures (200-600°C), typically encountered in the practice of cold spraying. The simulated data are in good agreement with experimental. It is shown that there is almost a linear relationship between substrate temperature and logarithm of nozzle traverse velocity. Moreover, the results can be described by a single generalized dependence with a good accuracy, at least in the studied range of stagnation temperatures and nozzle traveling speed. An approximate analytical equation was proposed for estimation of substrate temperature during cold spraying in a wide range of gas stagnation temperatures and nozzle traverse velocities.

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References
[1] Papyrin A, Kosarev V, Klinkov S, Alkhimov A and Fomin V 2007 Cold Spray Technology (Amsterdam: Elsevier Science) p 336
[2] Alkhimov A P, Kosarev V F and Papyrin A N 1990 Soviet Physics Doklady 35 1047–9
[3] Klinkov S V and Kosarev V F 2006, J. Therm. Spray Technol. 15 364–71
[4] Shikalov S V, Klinkov S V and Kosarev V F 2016 Proc. 18th Int. Conf. on the Methods of Aerophysical Research (ICMAR 2016) AIP Conf. Proc. 1770, ed V M Fomin (Mellville NY: American Institute of Physics) p 040015 https://doi.org/10.1063/1.4964084
[5] Shikalov S V, Klinkov S V and Kosarev V F 2017 Proc. XXV Conf. on High-Energy Processes in Condensed Matter (HEPCM 2017) AIP Conf. Proc. 1893, ed V M Fomin (Mellville NY: American Institute of Physics) p 030038 https://doi.org/10.1063/1.5007496
[6] Kosarev V F, Klinkov S V, Melamed B M, Nepochatov Yu K, Ryashin N S and Shikalov V S 2018 Proc. 19th Int. Conf. on the Methods of Aerophysical Research (ICMAR 2018) AIP Conf. Proc. 2027, ed V M Fomin (Mellville NY: American Institute of Physics) p 030047 https://doi.org/10.1063/1.5065141
[7] Lomovsky O I, Dudina D V, Ulianitsky V Yu, Zlobin S B, Kosarev V F, Klinkov S V, Korchagin M A, Know D-H, Kim J-S and Know Y-S 2007 Mater. Sci. Forum 534–536, 1371–6
[8] Kim J S, Kwon Y S, Lomovsky O I, Dudina D V, Kosarev V F, Klinkov S V, Kwon D H and Smurov I 2007 Composites Sci. Technol. 67 2292–6
[9] Kosarev V F, Klinkov S V, Sova A A and I. Smurov I 2008 Surf. Coat. Technol. 202 5858–62
[10] Klinkov S V, Kosarev V F, Sova A A and I. Smurov I 2009 J. Therm. Spray Technol. 18 944–56
[11] Sova A A, Kosarev V F, Papyrin A P and I. Smurov I 2011 J. Therm. Spray Technol. 20, 285–91
[12] Klinkov S V and Kosarev V F 2012 J. Therm. Spray Technol. 21, 1046–53
[13] Kosarev V F, Polukhin A A, Ryashin N S, Fomin V M and Shikalov V S 2017 Mechanics of Solids 52, 457–64
[14] Fomin V M, Golyshhev A A, Kosarev V F, Malikov A G, Orishich A M, Ryashin N S, Filippov A A and Shikalov V S 2017 J. Appl. Mech. Tech. Phys. 58 947–55
[15] Papyrin A N, Alkhimov A P, Kosarev V F and Klinkov S V 2001 Proc. Thermal Spray 2001: New Surfaces for a New Millennium, ed C C Berndt (Singapore: ASM International) p 423–31
[16] Alkhimov A P, Klinkov S V and Kosarev V F 2003 J. Therm. Spray Technol. 10 375–81
[17] Kosarev V F, Klinkov S V, Alkhimov A P and Papyrin A N 2003 J. Therm. Spray Technol. 12 265–81
[18] Kosarev V F, Klinkov S V and Papyrin A N 2007 The Cold Spray Materials Deposition Process: Fundamentals and Applications, ed V K Champagne (Cambridge: Woodhead Publishing) pp 178–216
[19] Klinkov S V, Kosarev V F and Zaikovskii V N 2011 J. Therm. Spray Technol. 20 837–44
[20] Sova A A, Klinkov S V, Kosarev V F, Ryashin N S and Smurov I 2013 Surf. Coat. Technol. 220 98–101
[21] Klinkov S V, Kosarev V F and Zaikovskii V N 2016 Surf. Eng. 32 701–6
[22] Kiselev S P, Kiselev V P, Klinkov S V, Kosarev V F and Zaikovskii V N 2017 Surf. Coat. Technol. 313 24–30
[23] Fukumoto M, Wada H, Tanabe K, Yamada M, Yamaguchi E, Niwa A, Sugimoto M and Izawa M 2007 J. Therm. Spray Technol. 16 643-50
[24] Rech S, Trentin A, Vezzu S, Legoux J G, Irissou E and Guagliano M 2011 J. Therm. Spray Technol. 20 243-51
[25] Suo X K, Yu M, Li W Y, Planche M P and Liao H L 2012 J. Therm. Spray Technol. 21 1091-8
[26] Yin S, Suo X, Guo Z, Liao H and Wang X 2015 Surf. Coat. Technol. 268 252-6
[27] Ernst K-R, Braeutigam J, Gaertner F and Klassen T 2013 J. Therm. Spray Technol. 22 422-32
[28] Watanabe Y, Yoshida C, Atsumi K, Yamada M and Fukumoto M 2015 J. Therm. Spray Technol. 24 86-91
[29] Kulmala M and Vuoristo P 2008 Surf. Coat. Technol. 202 4503-8
[30] Danlos Y, Costil S, Guo X, Liao H and Coddet C 2010 Surf. Coat. Technol. 205 1055-9
[31] Lupoi R, Sparkes M, Cockburn A and O'Neill W 2011 Mater. Lett. 65 3205-7