Features of formation of gas-thermal coatings with equal thickness on flat surfaces

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Abstract. The article deals with the formation of uniform gas thermal coatings on flat surfaces. It is substantiated that gas-thermal coatings are formed due to the superposition of single wavy stripes. The technique of obtaining uniform thermal coatings depends on spraying modes. The dependences of the speed of movement and supply of a gas-flame burner on the spraying distance are theoretically substantiated and experimentally confirmed. The dependence of coating thickness on the speed of a spraying device was determined.

1. Introduction
One of the most effective ways to increase the durability of cutting working bodies of forestry machines interacting with the soil and tree-shrub vegetation is to use bimetallic working parts allowing for the effect of self-sharpening. The service life of these parts increases 2-3-fold [1, 2, 3, 4, 7, 9, 12].

The uneven coating thickness of the soil-cutting parts during the hardening of working bodies of forestry machines has an extremely negative effect on the stabilization and shaping of the blade profile which causes wear unevenness. When hardening soil-cutting parts by gas-flame spraying, it is necessary to evaluate the effect of changes in the technological modes of spraying on the equal thickness of coatings and determine their allowable tolerance field.

During the movement of a gas-flame burner on the part surface, the coating becomes wavy. The uneven thickness is due to the fact that the distribution of powder particles in the torch obeys the normal law, and the cross section of the deposited spot is described by the Gauss equation [5, 6, 11, 13]. As a result, the coating undulation is formed. When spraying flame on a flat surface, the coating is formed when the gun is moved along this surface with a speed \( v \). At the end of movement, the pistol moves to the supply \( S \) and moves in the opposite direction. The coating is formed by the superposition of one pass over another (Figure 1). The uniform thickness depends on the speed of movement of the gun and supply. [8, 14, 15]. Therefore, it is necessary to determine technological regimes of the spraying process in which the coating will be uniform in thickness, and the required thickness will be obtained for a minimum number of passes.

These modes are provided by setting appropriate values for flat surfaces: movement speed \( v \) and spraying supply \( S \).

The purpose is to identify and justify the algorithm for determining technological modes of flame spraying to form coatings of uniform thickness.
2. **Research method**

With a straight movement of the sprayer relative to the substrate, a single coating band is formed on the surface. Its cross section thickness obeys the normal distribution law:

\[ y_x = y_0 \exp\left( -\frac{x^2}{2\sigma^2} \right) \]  

where \( y_0 \) and \( y_x \) – thickness of a single strip in the center of the spraying spot and at a distance \( X \) from the center; \( \sigma^2 \) – dispersion. It was recommended to use the term “dispersion radius” \( \rho = \sigma \) – standard deviation.

The shape of a jet and the nature of distribution of sprayed particles over the spot cross section can be represented as Figure 2 with a dispersion field of random value \( y_x \) equal to 6 \( \rho \).

![Figure 2](image2.png)

**Figure 2.** The shape of a jet and distribution of sprayed particles: \( \beta \) – jet opening angle, \( \alpha \) – spraying angle, \( L \) – spraying distance, \( \rho \) – radius of dispersion.

According to Figure 1 the coating stripe width \( S \) (spraying supply) can be identified according to the Gauss law as a dispersion field of a random variable:

\[ S = 3 \rho \]  

where: \( \rho \) – dispersion radius.

The dispersion radius is determined by formula:

\[ \rho = 1/3 \ L \tan(\beta/2) \]  

Then, from (2):

\[ S = L \tan(\beta/2) \]  

To prove expression (1), single strips of gas-flame coating were obtained at different spraying distances (Figure 3). A single strip was formed using an GN-2 gas burner. The material for spraying was a nickel-based PR-H70X17C4R4 self-fluxed alloy with a fraction of 100 \( \mu \)m.

Analysis of the spraying spot cross section (Figure 3), and measurements of the curve coordinates (Figure 4), (Table 1) confirm that the cross section of the spray spot is described by the Gauss equation:

\[ y = y_0 e^{-Kx^2} \]  

where \( y_0 \) – coating thickness at \( x = 0 \), \( K \) – coefficient depending on the spraying distance.
Figure 3. Spray spot cross-section by the coating thickness: 1) \( L = 170 \) mm; 2) \( L = 200 \) mm.

Figure 4. Spray spot cross section curves: Spraying duration \( t = 90 \) s; spraying distance \( L \): 1) 140 mm, 2) 170 mm, 3) 200 mm.

Table 1. The results of measurement of the coordinates \( X \) and \( Y \) and the spraying spot cross section.

| The distance from the axis of the spraying spot, \( X, \text{ mm} \) | Spraying distance – \( L, \text{ mm} \) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 140 | 170 | 200 | 140 | 170 | 200 | 140 | 170 | 200 | 140 | 170 | 200 | |
| \(-12\) | 0.41 | 0.43 | 0.42 | 0.48 | 0.51 | 0.46 | 0.62 | 0.57 | 0.60 | 0.41 | 0.43 | 0.42 | 0.48 | 0.51 | 0.46 | 0.62 | 0.57 | 0.60 |
| \(-10\) | 0.69 | 0.68 | 0.73 | 0.82 | 0.84 | 0.77 | 0.87 | 0.93 | 0.91 | 0.69 | 0.68 | 0.73 | 0.82 | 0.84 | 0.77 | 0.87 | 0.93 | 0.91 |
| \(-8\) | 1.17 | 1.15 | 1.19 | 1.1 | 1.13 | 1.16 | 1.17 | 1.15 | 1.14 | 1.17 | 1.15 | 1.14 | 1.17 | 1.16 | 1.17 | 1.15 | 1.14 | 1.17 |
| \(-6\) | 1.69 | 1.62 | 1.65 | 1.58 | 1.55 | 1.53 | 1.48 | 1.46 | 1.5 | 1.69 | 1.62 | 1.65 | 1.58 | 1.55 | 1.53 | 1.48 | 1.46 | 1.5 |
| \(-4\) | 2.2 | 2.23 | 2.19 | 2.06 | 2.04 | 2.03 | 1.89 | 1.94 | 1.92 | 2.2 | 2.23 | 2.19 | 2.06 | 2.04 | 2.03 | 1.89 | 1.94 | 1.92 |
| \(-2\) | 2.99 | 2.97 | 3.01 | 2.73 | 2.72 | 2.73 | 2.51 | 2.49 | 2.53 | 2.99 | 2.97 | 3.01 | 2.73 | 2.72 | 2.73 | 2.51 | 2.49 | 2.53 |
| 0 | 3.43 | 3.37 | 3.39 | 3.13 | 3.18 | 3.15 | 2.93 | 2.87 | 2.89 | 3.43 | 3.37 | 3.39 | 3.13 | 3.18 | 3.15 | 2.93 | 2.87 | 2.89 |
| 2 | 3.02 | 3.05 | 2.97 | 2.74 | 2.79 | 2.75 | 2.5 | 2.52 | 2.48 | 3.02 | 3.05 | 2.97 | 2.74 | 2.79 | 2.75 | 2.5 | 2.52 | 2.48 |
| 4 | 2.24 | 2.21 | 2.17 | 2.06 | 2.02 | 2.05 | 1.93 | 1.90 | 1.88 | 2.24 | 2.21 | 2.17 | 2.06 | 2.02 | 2.05 | 1.93 | 1.90 | 1.88 |
| 6 | 1.63 | 1.68 | 1.65 | 1.56 | 1.58 | 1.61 | 1.47 | 1.49 | 1.51 | 1.63 | 1.68 | 1.65 | 1.56 | 1.58 | 1.61 | 1.47 | 1.49 | 1.51 |
| 8 | 1.18 | 1.16 | 1.20 | 1.19 | 1.16 | 1.18 | 1.14 | 1.11 | 1.16 | 1.18 | 1.16 | 1.20 | 1.19 | 1.16 | 1.18 | 1.14 | 1.11 | 1.16 |
| 10 | 0.67 | 0.7 | 0.71 | 0.81 | 0.85 | 0.78 | 0.92 | 0.94 | 0.86 | 0.67 | 0.7 | 0.71 | 0.81 | 0.85 | 0.78 | 0.92 | 0.94 | 0.86 |
| 12 | 0.45 | 0.39 | 0.4 | 0.48 | 0.53 | 0.51 | 0.59 | 0.61 | 0.63 | 0.45 | 0.39 | 0.4 | 0.48 | 0.53 | 0.51 | 0.59 | 0.61 | 0.63 |
Table 2. The measurement results for the radius of the spraying spot and calculation data for the coefficient K depending on the spraying distance.

| Spraying distance, \( L \), mm | \( R_1 \) | \( R_2 \) | \( R_3 \) | \( R_4 \) | \( R_5 \) | \( \bar{R} \) | Coefficient \( K, \frac{1}{mm^2} \) |
|-----------------------------|--------|--------|--------|--------|--------|--------|------------------|
| 140                         | 16     | 17     | 16     | 15     | 16     | 16,0   | 0,028           |
| 170                         | 18     | 18     | 18     | 19     | 19     | 18,6   | 0,024           |
| 200                         | 21     | 20     | 20     | 21     | 21     | 20,6   | 0,02            |
| 230                         | 22     | 23     | 22     | 24     | 22     | 22,6   | 0,016           |

The \( y \) and \( x \) coordinates were measured using an MIM-7 instrumental microscope.

3. Research results

The study of the dependence of the spot radius (Table 2) on the spraying distance shows that with its increase, the radius increases, and the coating thickness at \( x = 0 \) decreases (Figure 4). Therefore, coefficient \( K \) which takes into account this dependence should be entered into equation (5). This coefficient characterizes the angle of jet opening \( \beta \), and determines design features of spraying devices.

In general, the coating thickness at any point is determined by formula:

\[
\hat{h} = y_0 e^{-Kx^2} + y_0 e^{-K(x-S)^2} + \cdots + y_0 e^{-K(x-(n-1)S)^2}
\]  

(6)

where \( S \) – spraying supply, \( K \) – coefficient of layering of single bands depending on the spraying distance.

The coating thickness at points with coordinates that are multiples of the spraying supply will be considered as a superposition of two passes (Figure 1).

Then between the passes, the thickness is a sum of two members at \( x=S/2 \):

\[
\hat{h} = 2y_0 e^{-\frac{KS^2}{4}}
\]  

(7)

On the other hand, the total thickness of the coating should be equal to \( y_0 \):

\[
y_0 = 2y_0 e^{-\frac{KS^2}{4}}
\]  

(8)

Transforming equation (8), we have an expression to determine supply \( S \):

\[
S = 2 \sqrt{\frac{\ln 2}{K}} = \frac{1.665}{\sqrt{K}}
\]  

(9)

Thus, calculation if supply \( S \) of the spraying gun is reduced to calculating coefficient \( K \). Let us transform expression (5):

\[
K = \frac{\ln y_0 - \ln y_0}{x^2}
\]  

(10)

where \( y, x \) current coordinates of the spraying spot, mm.

Using Table 1 and Table 2, the dependences of \( K \) (Figure 5) and \( S \) (Figure 6) on the spraying distance were constructed.
To determine the speed of movement of the spray device, it is necessary to determine its relationship with the thickness of a single coating strip.

Knowing the performance of the spray device and the spraying time, let us determine the mass of the sprayed layer:

$$m = G_p \cdot K_{mu} \cdot t$$

(11)

where $G_p$ – spraying performance, $K_{mu}$ – material use coefficient, $t$ – spraying time.

The mass of the sprayed layer can be expressed in terms of density of the layer material $\gamma_l$ and its volume $V_l$:

$$m = \gamma_l \cdot V_l$$

(12)

The volume of a single strip of coverage is equal to:

$$V_l = F \cdot \upsilon \cdot t$$

(13)

where $F$ – area under the curve of normal distribution, $\upsilon$ - speed of movement of the spray spot, $t$ – spraying time:

$$F = y_0 \int_{-\infty}^{+\infty} \exp\left(-\frac{x}{S}\right) dx = y_0 \cdot S \cdot \sqrt{\pi}$$

(14)

From (11-14), the thickness of the single band $y_0$ can be determined

$$y_0 = \frac{G_p \cdot K_{mu}}{\upsilon \cdot \gamma_l \cdot S \cdot \sqrt{\pi}}$$

(15)

From (13), the speed of movement of the spraying device can be determined

$$\upsilon = \frac{G_p \cdot K_{mu}}{y_0 \cdot \gamma_l \cdot S \cdot \sqrt{\pi}}$$

(16)

If the capacity of the device is known, by setting the spraying distance and the coating thickness, it is possible to determine the speed of movement. The gas-flame spraying capacity is 0.00055 kg/s.

4. Conclusion

As can be seen from Figure 7, an increase in the spraying distance causes a decrease in the speed of movement of the gun due to a change in the maximum thickness of the spraying spot.
The modes of application of wear-resistant coatings from self-fluxing alloys depend on the design of the apparatus used, the type and granulation of the powder, and other factors. This creates serious obstacles for the current control of dimensions of sprayed coatings. The required thickness can be obtained by stabilizing or regulating technological parameters. Thus, the dependences help calculate nominal values and the control range for technological parameters of the shape control according to specified requirements for the average thickness, the coating waviness and the spraying mode.

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