FORMATION OF LIQUID METAL FILM AT THE TIP OF WIRE-ANODE IN PLASMA-ARC SPRAYING

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A mathematical model is proposed, describing formation of a molten metal film at the tip of sprayed anode-wire under the conditions of plasma-arc spraying of coatings. Numerical analysis of the influence of spraying mode parameters on the position of molten wire tip relative to plasma jet axis, thickness of liquid interlayer contained on the wire tip, temperature and velocity of metal flow in it was performed.

Keywords: *plasma-arc spraying, coatings, wire-anode, spraying modes, thermal condition, molten metal film, mathematical model*

Stability of the process of plasma-arc wire spraying, as well as formation of specified quality characteristics of coatings, are largely determined by the conditions, under which the concentrated flow of spraying material particles is formed. Parameters of the formed dispersed particles depend chiefly on the intensity of the processes of thermal and gas-dynamic interaction of melting wire-anode with arc plasma flow moving around it. Therefore, detailed study of the above processes, including development of the appropriate mathematical models, is highly important for further progress of plasma-arc spraying technology.

Spraying of wire consumables is not given enough attention in scientific-technical publications, the available work being devoted, mainly to the process of electric-arc metallizing [1–3]. Results obtained in the above studies are not applicable to the process of plasma-arc spraying, as it differs by the location of sprayed wire relative to the arc (the latter form an angle of 70–90°), as well as high values of temperature (up to 30,000 K) and velocity (up to 4000 m/s) of plasma, flowing around the wire [4].

For the conditions of plasma-arc spraying a model was earlier proposed for thermal processes in solid metal wire-anode, fed into the plasma arc behind the plasmatron nozzle tip [5]. This model allows forecasting the temperature field and calculating the molten metal volume depending on the parameters of plasmatron operation mode, wire feed rate and diameter, as well as its position in space relative to the tip of plasma-shaping nozzle and distance from molten wire tip to plasma jet axis. However, the melt zone thickness obtained within this model can differ considerably from that observed in the experiments. The reason for that is the molten metal at the wire tip being under a considerable dynamic impact of the plasma flow that results in just part of the melt being contained at the wire tip, forming a liquid interlayer, and part being carried off into a thin jet — so-called tongue [1]. Here, the molten wire tip takes up such a position relative to plasma jet axis that corresponds to the thickness of liquid interlayer, ensuring a balance of thermal and dynamic impact of plasma on the molten metal. In other words, for a correct determination of the parameters of liquid metal interlayer contained on the sprayed wire tip, as well as distance from the molten wire tip to the plasma jet axis, it is necessary to coordinate the calculations within the thermal model [5] with calculations of gas-dynamic impact of the transverse plasma flow on the molten metal. Development of such a self-consistent model is exactly the objective of this study.

When plotting a mathematical model of formation of molten metal film at the tip of sprayed wire-anode under the conditions of plasma-arc spraying, let us assume that solid metal wire of round cross-section of radius R_w is fed into the plasma arc at constant rate v_w normal to the axis of symmetry of the plasma flow (Figure 1). The arc closes on the wire right end which is the anode. Let us also assume that the melting front is flat (plane $z_b = 0$) and is located normal to the plasma flow axis at distance L_p from it, and the rate of wire melting is equal to its feed rate. Under the impact of the arc anode spot and high-temperature plasma flow moving around the arc, it is heated, and molten metal volume of thickness L_{liq} forms at its tip, that is carried off into a thin jet by plasma flow moving around the arc. Let us assume that the upper part of liquid interlayer contained at the wire tip takes the form of a spherical segment under the impact of the arriving plasma flow, the spherical segment having height L_b and radius R_b of a sphere forming the segment with the center in a point located at distance L_0 from the melting front ($R_b = L_0 + L_b$; $R_b^2 = L_0^2 + R_w^2$) (see Figure 1).

As a result of removal of part of the melt from the wire tip, the conditions of heat balance in it are violated. Tending to an equilibrium condition, the wire will take up such a position relative to plasma jet axis, defined, for instance, by distance $L_p - L_b$, at which the volume of liquid interlayer contained at the wire tip V_b will correspond to the volume of wire molten metal $V_{liq} = \pi R_w^2 L_{liq}$, i.e. condition $V_b = V_{liq}$ will be fulfilled. A problem is posed to determine wire position, at which the above condition is satisfied at specified parameters of the spraying mode, and the volume of liquid interlayer contained at the wire tip, temperature, as well as molten metal flow, are calculated.

Let us move over to construction of the model of liquid interlayer formation at the wire tip. Thickness L_{liq} and volume V_{liq} of molten metal layer, respectively, depending on the distance from molten wire tip to plasma jet axis $L_p - L_{liq}$ at other assigned spraying mode parameters being equal can be determined from the model of wire thermal condition [5].

To assess the thickness of liquid interlayer contained on the wire tip, let us consider the interaction of two flows — viscous outflow of incompressible liquid (molten metal) along the boundary of wire melting and turbulent flow of arc plasma along the surface of liquid metal boundary with the medium intephase at $z_0 = L_b$ (see Figure 1). Let us assume that the main force, acting on the melt from the side of the plasma flow, is the viscous force. Considering that the melt flow occurs in the following plasma flow, viscous forces on the medium interphase prevail, so that such an approximation can be regarded as quite justified.

A boundary layer [6] forms in the plasma flow in the immediate vicinity of the liquid metal boundary, which is characterized by an abrupt change of the main parameters of the flow in the transverse direction. In particular, plasma velocity changes from its value in the outer flow to the value of the velocity of flowing of liquid wire material on the medium interphase (satisfying the «sticking» condition is assumed).

In view of the turbulent nature of plasma flow [4], several subregions can be singled out in the considered boundary layer [7]. The outer layer is a region of fully developed turbulent flow, its properties being dependent on the flow prehistory. The inner region of the turbulent boundary layer in the general case consists of a viscous underlayer, transition region and region of logarithmic profile of velocity. Universal nature of velocity distribution corresponds to flowing in the inner region, that is the basis for plotting special near-wall functions, connecting the flow parameters with the distance from medium interphase [6, 7].

Considering the smallness of liquid interlayer thickness, flowing of liquid metal in it can be considered to be practically laminar, and a linear dependence of tangential component of velocity can be assumed here [6, 7]:

$$v_{liq}(z_b) = \frac{z_b}{L_b} v_m, \quad (1)$$

where v_m is the melt flow velocity on the medium interphase (at $z_b = L_b$). Value v_m can be connected

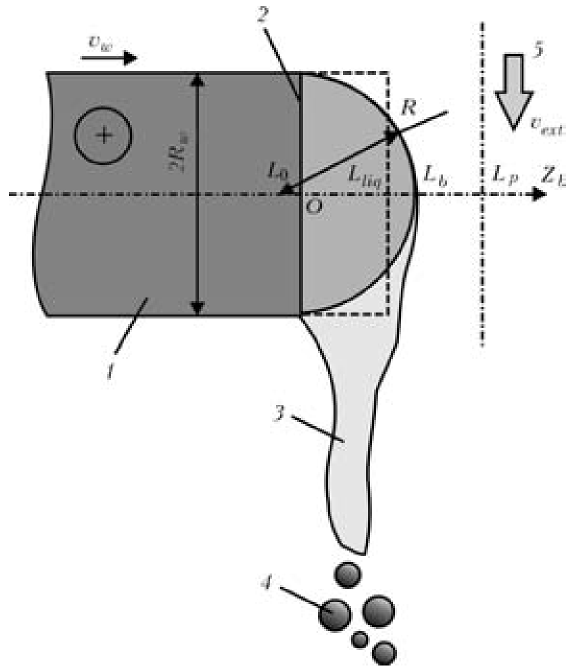

Figure 1. Schematic of liquid interlayer formation at the tip of current-carrying wire in plasma-arc spraying: *1* — current-carrying wire; *2* — fusion boundary; *3* — molten metal jet («tongue»); *4* — sprayed particles; *5* — plasma flow

with parameters of plasma flow moving around the arc, proceeding from the assumption that tangential stresses in the plasma and melt on the medium interphase are equal:

$$\eta_{liq} \left.\frac{\partial v_{liq}}{\partial z_b}\right|_{L_b} = \eta_p \left.\frac{\partial v_p}{\partial z_b}\right|_{L_b}, \quad (2)$$

where η_p, η_{liq} are the coefficients of dynamic viscosity of plasma and molten metal of the wire, respectively; $v_p(z_p)$ is the distribution of tangential (relative to melt surface) plasma velocity along axis z_b. To find $v_p(z_p)$ we will apply the logarithmic near-wall function, which is often used at description of flow parameters in near-wall regions [7, 8]. For the flowing around conditions considered by us, this function can be written as follows:

$$v^+ = \frac{1}{\mathrm{Kar}} \ln (Ey^+). \quad (3)$$

Here $v^+ = \overline{v}_p / v^*$ is the dimensionless tangential velocity of plasma; $\overline{v}_p(z_b) = v_p(z_b) - v_m$ is the velocity of plasma flow relative to the melt flow velocity; v^* is the dynamic velocity determined as

$$v^* = \sqrt{\tau_p / \rho_p}, \quad (4)$$

where $\tau_p = \left(\eta_p \frac{\partial u}{\partial r}\right)_{L_b}$ is the friction stress in the plasma on the flowing surface; ρ_p is the plasma density; Kar ≈ ≈ 0.41 is Karman constant; E is the constant determining the degree of wall roughness (for smooth wall E = 8.8 [7]); y^+ is the dimensionless distance from the interface, determined as $y^+ = \frac{\rho_p (z_b - L_b)}{\eta_p} v^*$.

We will assume that the transition from the melt flowing velocity («sticking» condition) to the velocity of undisturbed plasma flow, which can be determined, for instance, by model [4], occurs in region $0 \le y^+ < 400$ [8]. Then, based on expression (3) tangential stress in the plasma can be presented as follows:

$$\tau_p(v_m) = \frac{\bar{v}^2_{ext}(v_m)}{\left(\frac{1}{\mathrm{Kar}} \ln (Ey^+)\right)^2} \rho_p = \frac{\bar{v}^2_{ext}(v_m)\rho_p}{396.71}, \tag{5}$$

where $\bar{v}_{ext}(v_m) = v_{ext} - v_m$ is the flowing velocity of undisturbed plasma flow near the wire tip v_{ext} relative to the melt flowing velocity v_m.

As a result, in order to determine the thickness of liquid interlayer L_b, it is necessary to consider the balance of the weight of molten wire material. Considering the made assumption that the molten metal in the upper part of the wire tip takes the shape of a segment of a sphere, consumption of liquid wire material passing through axis z_b normal to the axis of the plasma jet can be determined as

$$G_2 = 2\rho_w \int_0^{L_b} v_{liq}(z_b) \int_0^{y(z_b)} dydz_b, \tag{6}$$

where $y(z_b) = \sqrt{R_w^2 - 2((R_w^2 - L_b^2)/(2L_b))z_b - z_b^2}$ is the curve of crossing of the segment of a sphere with the above plane; ρ_w is the density of the metal wire. In its turn, proceeding from the conditions of the constancy of the velocities of wire feed and melting, quantity of wire material, melting in a unit of time, and, therefore, crossing section $z_b = 0$, is given by the expression

$$G_1 = \rho_w v_w S_w, \tag{7}$$

where $S_w = \pi R_w^2$ is the wire cross-sectional area.

Then considering that half of the molten wire material comes to the considered half of the segment of a sphere, we will come to the following relationship:

$$G_1/2 = G_2. \tag{8}$$

Substituting expressions (6) and (7) into (8), and considering assumption (1), we obtain the dependence of maximum melt flowing velocity on its interlayer thickness at the wire tip:

$$v_m(L_b) = \frac{S_w}{4} \frac{v_w L_b}{\int_0^{L_b} z_b \int_0^{y(z_b)} dydz_b}. \tag{9}$$

Now condition (8) can be rewritten as follows:

$$\frac{v_w S_w}{2} = 2 \frac{\tau_p(v_m(L_b))}{\eta_{liq}} \int_0^{L_b} z_b \int_0^{y(z_b)} dydz_b, \tag{10}$$

whence thickness L_b of liquid interlayer on the wire tip can now be determined. Equation (10) closed by relationships (5) and (9) can be solved by one of the numerical methods of solution of nonlinear equations [9]. This can be done using the simplest method of dichotomy or, considering that the antiderivative of the integrand in (5) and (9) is expressed analytically, Newton iteration method can be applied.

Using the model of thermal processes in the wire [5] for determination of the volume of its molten part V_{liq}, as well as expression (10), on the basis of which the volume of liquid interlayer contained at the wire tip is found:

$$V_b = \pi \int_0^{L_b} [y(z_b)]^2 dz_b, \tag{11}$$

it is possible to determine what position of the molten wire tip relative to plasma jet axis is set at the specified spraying mode. For this purpose, fixing the mode parameters and varying just value L_b, based on model [5] we obtain dependence $V_{liq} = V_{liq}(L_p - L_{liq})$, and based on expressions (10), (11) — dependence $V_b = V_b(L_b)$, and find such a position of the wire at which their equality is achieved. This condition, essentially, is the connecting link between the models of thermal [5] and gas-dynamic interaction of wire with plasma flow moving laterally around it, and it allows determination of the distance, to which the molten wire tip is removed from the plasma flow axis, depending on the values of spraying mode parameters. In its turn, this value is the basis, which can be used to determine using expressions (1), (9), (11) and model [5], the characteristics of the liquid metal contained at the wire tip, including its flowing velocity and temperature. The above characteristics will have a direct influence on the dimensions and temperature of drops separating from the wire tip, and will determine the point of their entering the plasma flow.

Let us conduct numerical analysis of the influence of spraying mode parameters on the characteristics of liquid interlayer, contained at the tip of sprayed wire-anode, as well as spatial position of the latter. Calculations were performed for the conditions of plasma-arc spraying of steel wire, the thermo-physical characteristics of which are taken from [10]. The following parameters of the spraying mode were selected [4]: arc current $I = 160$–240 A, plasma gas (argon) flow rate $G_{Ar} = 1.0$–1.5 m^3/h, wire feed rate 6–15 m/min, wire diameter 1.2–1.6 mm. It was assumed that the anode-wire is located at 6.3 mm distance from the plasmatron nozzle tip, normal to the axis of the plasma flow. Distributions of velocity and temperature of undisturbed plasma flow along the wire-anode for various modes of plasmatron operation were calculated in advance based on model [4] and are given in Figure 2.

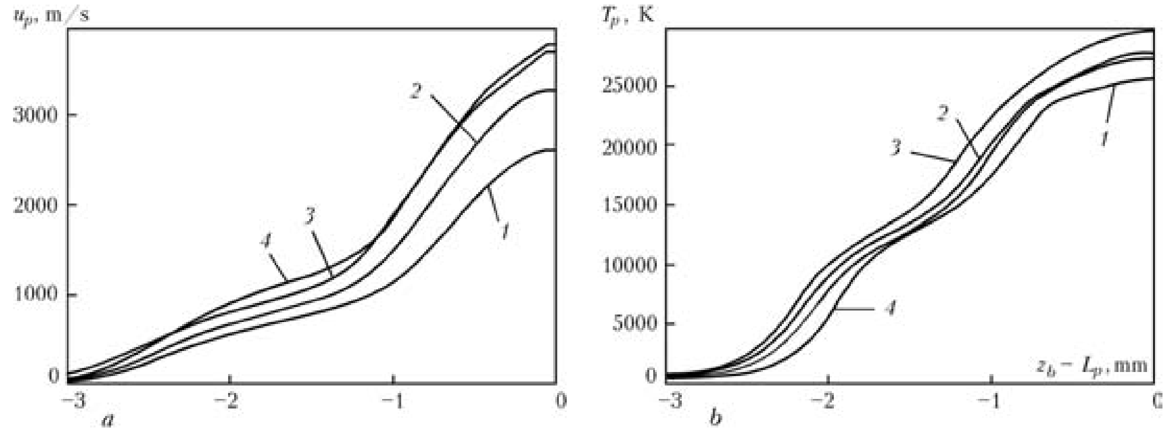

Figure 2. Distribution of axial component of velocity (*a*) and temperature (*b*) of arc plasma along anode-wire: *1* — I = 160; *2* — 200; *3* — 240 A at G_{Ar} = 1.0 m^3/h; *4* — G_{Ar} = 1.5 m^3/h at I = 200 A

As is seen from Figure 2, values of plasma velocity and temperature change quite abruptly in the transverse direction relative to plasma jet axis. Therefore, the conditions of viscous and thermal interaction of the plasma flow with wire essentially depend on the position of the molten wire tip relative to the plasma flow axis. The closer to the jet axis, the larger is the thermal flow into the wire, and the more increased are the viscous forces acting on the melt surface, carrying the liquid metal off the wire tip. Therefore, it should be noted that in spraying modes, at which heat propagation in the wire is difficult, its molten tip is located closer to the plasma jet axis. For instance, at increase of the feed rate the region of wire heating and melting become smaller, and the wire comes to the plasma jet axis until the molten metal volume can be contained at its tip. The same situation should be observed also when larger diameter wire is used.

Influence of plasmatron operation mode on the position of the molten wire tip relative to plasma jet axis, as well as thickness of the liquid interlayer contained at the wire tip, can be illustrated in Figure 3. For all the considered modes, the molten wire tip is located at distance 0.1–1.4 mm from the jet axis at interlayer thickness of 0.10–0.15 mm. Increase of arc current leads to increase of plasma velocity and temperature (see Figure 2), convective-conductive and radiation-thermal flows into the wire increasing, as well as the intensity of viscous force acting on liquid metal at the wire tip. As a result, the increased melt volume cannot be contained at the wire tip, and part of it is carried off by the plasma flow, and the wire tip will take a new equilibrium position, farther from the plasma flow axis. At increase of the plasma gas flow rate, the flow velocity rises, temperature profile, however, being more compressed towards the jet axis (see Figure 2, curves *2* and *4*). Here, wire melting occurs at wire tip location in near-axis regions of the plasma jet, and increase of the intensity of dynamic interaction of the plasma flow will lead to reduction of the volume of liquid interlayer, contained at the wire tip, and, therefore, also its thickness (see Figure 3).

Molten material of the wire is entrained by the plasma flow, forming a liquid metal jet, which at further flowing separates into individual drops — dispersed particles of the spraying material — under the impact of external and inner disturbing factors. Here, transverse dimensions of the liquid interlayer and melt flowing velocity determine the characteristics of the above jet flowing, and, therefore, also the conditions of drop formation. In its turn, the melt flowing velocity is connected to the quantity of wire material molten in a unit of time, as well as the set thickness

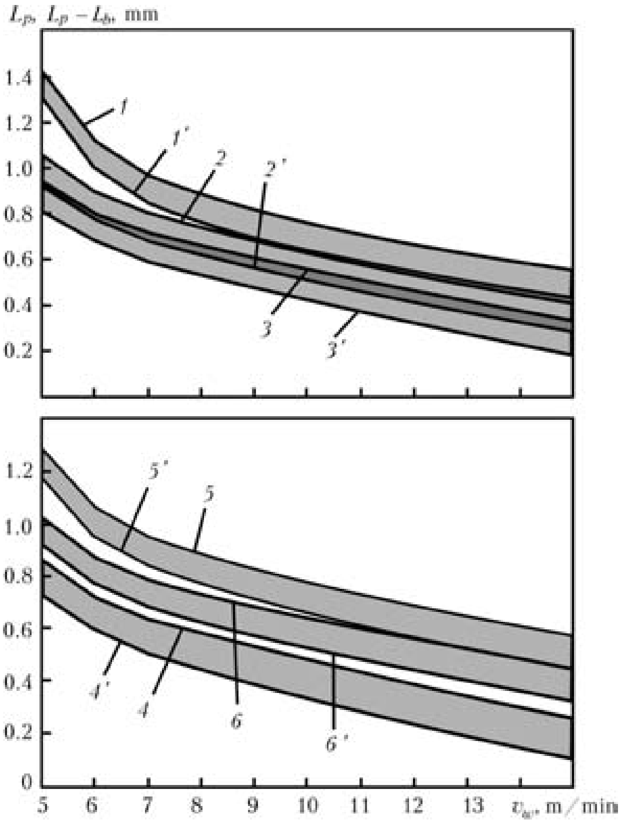

Figure 3. Influence of wire feed rate on distance from wire melting plane L_p (*1–6*) and distance from molten wire tip $L_p - L_b$ (*1′–6′*) to plasma jet axis at different parameters of the spraying mode: $2R_w$ = 1.2 (*1*; *1′*), 1.4 (*2*; *2′*), 1.6 (*3*; *3′*) mm at I = 200 A, G_{Ar} = = 1.0 m^3/h; I = 160 (*4*; *4′*), 240 (*5*; *5′*) A at $2R_w$ = 1.4 mm, G_{Ar} = = 1.0 m^3/h; G_{Ar} = 1.5 m^3/h (*6*; *6′*) at $2R_w$ = 1.4 mm, I = 200 A

Parameters of liquid interlayer contained at the tip of sprayed wire-anode at plasma-arc spraying of coatings

I, A	G_{Ar}, m^3/h	$2R_w$, mm	v_w, m/min	$L_p - L_b$, mm	L_b, mm	v_m, m/s	T, K
200	1.0	1.4	5	1.054	0.113	1.81	2070
			6	0.893	0.117	2.05	1931
			7	0.798	0.127	2.42	1774
			9	0.686	0.129	2.64	1773
			12	0.550	0.133	3.07	1774
			15	0.428	0.141	3.61	1774
		1.2	9	0.811	0.125	2.10	1775
		1.6	9	0.604	0.131	2.68	1774
160	1.0	1.4	9	0.526	0.140	2.18	1776
240	1.0	1.4	9	0.829	0.118	2.61	1773
200	1.5	1.4	9	0.684	0.109	2.83	1774

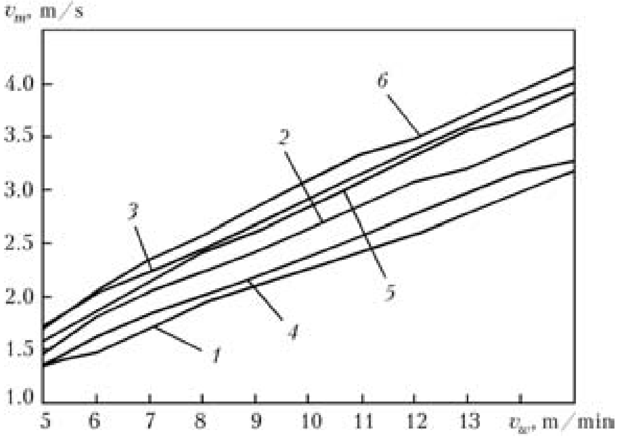

Figure 4. Dependence of melt flow rate in liquid interlayer at the wire tip on its feed rate at different diameters of wire-anode and plasmatron operation modes: $2R_w$ = 1.2 (*1*), 1.4 (*2*), 1.6 (*3*) mm at I = 200 A, G_{Ar} = 1.0 m^3/h; I = 160 (*4*), 240 (*5*) A at $2R_w$ = = 1.4 mm, G_{Ar} = 1.0 m^3/h; G_{Ar} = 1.5 m^3/h (*6*) at $2R_w$ = 1.4 mm, I = 200 A

of the liquid interlayer, that is illustrated, for instance, by dependencies in Figure 4.

Liquid interlayer parameters at plasma-arc spraying are given in the Table. As is seen, for most of the modes, overheating of liquid metal above the melting temperature does not exceed 20 K, as the molten material does not have enough time for any significant overheating and is immediately carried off by the flow from the wire tip. Metal overheating in the liquid interlayer by 200–250 K above the melting point is, as a rule, characteristic for melting modes with low wire feed rates, at which the heat conductivity mechanism has a significant role in heat propagation in the wire.

CONCLUSIONS

1. Mathematical model of thermal condition of wire-anode at plasma-arc spraying of coatings was improved by allowing for gas-dynamic impact on the wire of plasma flow moving around it. Such a self-consistent model allows determination of wire position relative to plasmatron axis, as well as characteristics of liquid interlayer contained at the wire tip, including its thickness and melt flowing velocity, depending on the spraying mode parameters.

2. Distance, to which the molten wire tip is removed from the plasma flow axis, is determined by the condition of equality of the wire molten part to the volume of liquid metal interlayer that can be contained at the wire tip at plasma flow moving laterally around it, and is equal to 0.1–1.4 mm under the considered conditions at interlayer thickness of 0.10–0.15 mm, depending on the spraying mode parameters.

3. At plasma-arc spraying of coatings metal temperature at the molten wire tip reaches 1780–2100 K, here for most of the spraying modes liquid metal overheating above melting temperature (1773 K) is insignificant, and is not higher than 20 K, as the forming melt is carried by the plasma flow out of the interaction zone, and the total heat content of the wire is not decreased.

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