Determining the temperature values on the surface of complex curvilinearly bent agricultural machine parts during the formation of powder coatings by thermal methods

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Abstract. The development of modern technologies for the restoration and hardening of agricultural machine parts require the development of a mathematical apparatus that simulates the involved processes. For this purpose, the models should take into account the technological features of the process of hardening and restoration of machine parts, including: cleaning; determination of geometric indicators; surface preparation; choice of technology; subsequent machining of the resulting surface; surface quality control. One of the priority directions in the development of technologies for the restoration and hardening of parts is the formation of coatings on machine parts using powder materials applied by the gas-thermal method. One of the most important conditions for obtaining high-quality coatings is temperature control on the surface of the part. In this regard, it is of scientific interest to study the effect of the distance from the surface of the part to the flame nozzle when applying self-fluxing powder on the time-average temperature at the point of coating, the maximum temperature on the back side of the part, and the total power transferred to the part by the gas burner. This paper presents a mathematical model for determining the above-mentioned influence, and also presents the results obtained using a computer program. The novelty of the model is the ability to use it to study temperature values for complex curved-bent machine parts (crankshafts and camshafts of agricultural machines). To check the reliability of the dependences obtained, experiments were carried out and the convergence with theoretical developments was confirmed.

1. Introduction
The efficiency of the use of transport and technological machines is affected by many factors (operating conditions, personnel qualifications, manufacturer's resource, etc.). In this regard, in agriculture, the deadlines for performing agro-technical works are violated and crop losses are increasing. One of the ways to increase the efficiency of the use of machines is the development of technological solutions for the restoration and hardening of machine parts [3, 8, 9].

At present, this problem can be solved in various ways. For example, material scientists of National research engineering university MISIS are conducting research on the development of advanced high-strength AHSS steels of the third generation. They are characterized by an excellent combination of strength and ductility, which makes it possible to use it as a material for the manufacture of parts for cars, tractors, and agricultural machinery. Possessing good plasticity, they take forming well, after which they retain high resistance to fracture. Due to the improved characteristics of these steels, it is possible to manufacture parts of smaller dimensions and weight, but withstanding the same loads as the existing
"heavy" counterparts. In the RSAU-Moscow Agricultural Academy named after K.A. Timiryazev, high-strength steels with high ductility and toughness are being developed [1]. They also propose an additive technology for manufacturing products of complex shapes.

The improvement of additive technologies stimulates the development of powder metallurgy. The production of machinery parts by layer-by-layer sintering of powder materials is becoming more and more common. This takes place due to the continuous improvement of materials, equipment, and software. The technologies that were used only in aviation and space exploration are now entering the automotive and agricultural engineering industries.

We see the solution to the problem of improving technologies for the restoration and hardening of parts (using the example of important and expensive parts of agricultural machinery) based on modeling the processes occurring during the formation of coatings [4]. Thus, the modeling of the process of heat distribution in parts, which affects the quality of the formation of the surface layer of coatings, is of scientific interest. In this regard, the issues of controlling temperature values, for example, during gas-thermal cladding (powder spraying) on the parts surface, remain insufficiently studied. In this case, the formation of a uniform coating layer(s) of a given thickness (i.e., the use of self-fluxing powders based on metals (nickel, cobalt, etc.) is rendered by the elimination of overheating of the part and reduction of the heat-affected zone [2, 5-7]. Therefore, the study of these issues is an urgent task.

2. Materials and methods

One of the main factors affecting the distribution of heat in the product is the distance $d$ from the surface of the part 1 to the burner flame nozzle 2 (Fig. 1). To describe the process of heat distribution, points a (the place of coating) and b (the opposite point) are of interest. In order to reproduce a complex curvilinear curved shape, the method of sampling with a rectangular grid, which consists of nodes, is used. Each grid node has six adjacent nodes from which heat can be received, or to which heat is transferred. To simulate the process of heat distribution in detail, it is necessary to draw up mathematical dependencies of the main technological process parameters. These include the time average temperature at the point of application, the maximum temperature on the back of the part, and the total power delivered to the part by the gas burner.

The time average temperature $T_p$ at the point of coating application is calculated from formula (1):

$$ T_p = \frac{\Delta t}{t_2-t_1} \sum_{k=1}^{[\frac{t_2}{\Delta t}]} \left( T_{jk} \right) \sqrt{(l\Delta x-x_b)^2+(l\Delta y-y_b)^2+(l\Delta z-z_b)^2} \rightarrow \min' \tag{1} $$

where $t_1$ and $t_2$ – time moments of the beginning and the end of coating application process; square brackets indicate the even part of the value; $\tau$ – the counting number of the step of time integration; $\Delta x$ – grid step; $x_b, y_b, z_b$ – burner nozzle position coordinates.

**Figure 1.** Gas thermal cladding process diagram: 1 – cylindrical part being coated, 2 – burner nozzle GN-2; a – coating application point, b – the part’s opposite side
The maximum temperature of the opposite side of the part $T_{ob}$ is calculated from formula (2):

$$T_{ob} = \max_{[x_1, x_2]} \left( T_{ijk} \right)_{x_1 \leq x \leq x_2; \ \ |y_c - y| < \Delta y; \ \ |z_c - z| < \Delta z}$$

where $x_1$ and $x_2$ – coordinates of the beginning and the end of the cylindrical part being restored; $y_c$ and $z_c$ – coordinates of the cylindrical part axis position.

The model assumes that the burner transfers heat (3) power to the grid nodes located on the surface of the part being repaired and in the direct sight from the burner (that is, not covered by other grid nodes):

$$w_{ijk} = \begin{cases} 
    w_c \exp\left(-\frac{a_{ijk}^2}{2\sigma^2}\right); & \{a_{ijk} < 3\sigma; \ n_{ijk} < 26\}, \\
    a_{ijk} \geq 3\sigma; & \{n_{ijk} = 26\}, \\
    0; & \{n_{ijk} = 26\}, 
\end{cases}$$

where $w_{ijk}$ – heat power transferred to the grid node $(i, j, k)$; $w_c$ – model’s gauge coefficient; $a_{ijk}$ – angle between the direction from the burner nozzle position point to the node $(i, j, k)$ and the burner’s axis; $\sigma$ – burner flame dispersion parameter in Gaussian approximation (same meaning as mean-square deviation), $n_{ijk}$ – number of adjoined nodes to the node $(i, j, k)$, where the material is located ($n_{ijk} = 26$ for the node inside of the part, $n_{ijk} < 26$ for the node on the surface of the part).

The total power $W$ transferred to the part by the gas burner is calculated as the sum of heat powers of all nodes $w_{ijk}$ and time averaging (4):

$$W = \frac{\Delta t}{t_2 - t_1} \sum_{t_2}^{t_1} \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} w_{ijk},$$

where $n$ – size of the cube for which the simulation was performed (in our case $n = 100$).

To obtain the graphs of the dependences of $T_p$, $T_{ob}$, $W$ on the distance $d$, four computer experiments were carried out to apply a coating with different values of $d$. In the course of the computer experiment, a 1 mm thick coating layer was simulated on the main crankshaft journal in six revolutions, which corresponded to 3.5 minutes on the model time scale. Each computer experiment lasted about 15 minutes of real (machine) time on a typical modern personal computer.

For basic calculations, the model reproduced the preheating of the crankshaft: the initial temperature of the crankshaft assemblies was 500°C. We also checked the coating mode without preheating the crankshaft, with the temperature at key points of the crankshaft increasing according to a law close to decreasing exponential. The surface temperature at the place where the coating is applied changes slightly over time (by 20 ... 50°C) as the crankshaft rotates due to the lack of axial symmetry in the location of the crankshaft cheeks. Therefore, to obtain the unified numerical characteristic of the temperature at the place of coating formation, we used the time-averaged (over the time of the computer experiment) temperature $T_{ob}$.

To check the results obtained using mathematical simulation, a number of experimental experiments were carried out. In this case, a 1K62 thread-cutting lathe was used, which ensures the rotation of the parts and the movement of the GN-2 gas burner in the longitudinal and transverse directions. The burner uses acetylene-oxygen mixture. A steel cylinder made of Steel 40X was used as a prototype. Temperature measurements were made with a Kraftool Trm-380 pyrometer. The thickness of the recovered layer was determined using an RDS 205 laser rangefinder. The distance between the burner and the recovered part was regulated.
The distance $d$ from the gas burner to the surface to be restored was chosen as the initial parameter. The calculation was carried out using four values of this parameter: 10, 15, 20, and 25 mm. In order to verify the reliability of the dependences obtained, the processing parameters of the experimental part (steel 40X) were calculated, including practical experiments.

3. Results
As a result of the experiments, empirical data were collected, which are presented in the form of some graphs (Fig. 2). The dashed line indicates the data obtained during the experiments, the solid line – the data calculated using the above dependences.

![Figure 2](image)

**Figure 2.** The effect of the distance $d$ from the gas burner to the surface to be restored on the time-average temperature $T_p$ at the point of coating application (a), maximum temperature on the opposite side of the part $T_{ob}$ (b), and the total power $W$, transferred to the part by the gas burner (c); – ■ – empirical results; – ▲ – calculated results

The analysis of the obtained results showed that with the growth of the distance $d$, the time-average temperature $T_p$ at the place of coating application and the temperature of the back surface of the test sample $T_{ob}$ decreases (Figure 2, a, b). This is due to the fact that as the distance $d$ increases, the burner is farther and farther from the surface of the sample and the surface of the part is enveloped in the flame with lower temperature. Due to the increase in the distance $d$ between the gas burner and the surface of the part, the losses of the total power $W$ transferred to the part by the gas burner increase, which leads to the decrease in the amount of energy absorbed by the prototype (Figure 2, c). The range of the distance $d$ from 15 to 25 mm provides an optimal temperature regime, which eliminates the risk of the part overheating. The comparison showed that the calculated values are similar to those obtained in the course of the experiments. The deviations did not exceed 5%.

4. Discussion
The experimental results made it possible to determine the rational distance from the burner nozzle to the part surface. These values are within the range of 15 .. 25 mm. In this case, continuous formation of a coating on the part with no visible defects is observed. The range of values of the time-average temperature $T_p$ at the place of coating deposition is from 850 to 900°C and corresponds to the values of the temperature of the technological process of thermal gas cladding. The temperature values on the
opposite side of the part $T_{ob}$ (500 ... 550°C) exclude the formation of scale, which is confirmed by the results of calculating the total power $W$ transferred to the part by the gas burner.

5. Conclusion
The results of determining the temperature values on the surface of complex curvilinearly bent agricultural machine parts made it possible to determine the optimal parameter ranges for the formation of powder coatings. The developed mathematical apparatus can be used with appropriate corrections for other thermal recovery methods. The results obtained make it possible to be the basis for automatic systems for controlling the coating process and eliminating overheating of the part from the front side and the formation of scale from the back side. The use of the proposed results helps to improve the quality of restored and hardened machine parts.

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