Study of powder coatings formation modes in Transport Machine-Building Industry

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Abstract. This article describes the use of powder coating materials as an effective corrosion protection system. The correlation between the substrate heating temperature on the optical characteristics of the radiator used and coating material applied was analyzed. The assumption that the process of thermoradiation curing of powder coatings is influenced by two factors (temperature and radiation effect) is confirmed. It was determined that there is a possibility of improving the resource-saving technology based on the conducted studies.

1. Introduction.
An important problem facing Transport Machine-Building Industry is significant losses due to corrosion. According to the research of national scientists, the annual direct corrosion losses in Russia are 2 ... 5% of the national income, which is approximately 10 ... 20% of the overall production of ferrous metals. Taking into account the fact the metal-bearing machinery of the Transport Machine-Building Industry is about 400 million tons, the corrosion losses are enormous [1 - 5].

Implementation of powder coating systems allows not only reducing the emission of volatile organic compounds, but also reducing the volumes of liquid and solid waste produced during the process of painting construction and road machines [6 - 7]. In comparison with conventional coating materials, powder-coated paints provide practically waste-free coatings production technology (losses of coating material are 1 ... 2%). Furthermore, the physical and mechanical properties of coatings made out of powder-coated paints are superior to coatings made out of liquid coating materials by many factors [8-11].

Production of coatings made of powder coating materials is made possible by convective and thermoradiation types of heating. In order to select optimal curing conditions for powder coating materials, it is important to know the temperature patterns inside the substrate as well as inside the paint layer applied to it. The optimal mode of coating curing would be defined when there is such temperature distribution at which the temperature maximum is at the boundary of both layers.

Two kinds of radiation are used for curing by the thermoradiation method. Shortwave radiation with a wavelength of $\lambda = 760 \ldots 2500$ nm is considered as a “light radiation”. This type of radiation is produced by lamp (or "light") radiators. In contrast, radiation with a wavelength of $\lambda = 3500 \ldots 4500$ nm is called a “dark radiation”. [12, 13].

2. Mathematical modeling and results
Coating materials have different degrees of absorption of the radiation energy with different wavelengths. Thus, the effect of radiation energy impact when cured would be different.
Based on the results of the experiments presented in [16], it can be concluded that the process of a paint film curing is not a purely thermal. Its intensity is largely due to the specific effect of infrared radiation, which should be related to the spectral characteristics of the radiation applied to a paint film.

That implies the effect of certain frequency radiation on the polymerization of molecules.

It is natural to assume that the effect of radiation energy with a frequency corresponding to the frequencies of natural vibrations of those groups of atoms that participate in the polymerization process on the coating materials should cause a phenomenon similar to a resonance. As a result, interatomic bonds can collapse and create new high molecular formations.

The process of theromoradiation curing of coatings can be represented as follows (Figure 1). The flux of radiation energy a-b-c-d enters the layer of material 2 applied to substrate 1. A part of that flux (a) is absorbed by the material layer and converted to heat. As a result, only the b-c-d flux reaches the surface of the substrate. A part of that flux (b) is absorbed by the surface layer of the substrate, heating the latter, and radiation energy c-d is reflected off the substrate surface. Reflected radiation is partially absorbed by the coating material layer (c). A certain amount of it (d) comes out of the coating material layer into the environment and is practically not used. The parts of the radiation flux marked in the figure with letters a, b, c are of a particular importance for the process of coating curing.

**Figure 1.** Diagram of IR penetration into coating material layer:

1 – substrate; 2 – coating material; \( l_1 \) – substrate thickness; \( l_2 \) – thickness of coating material applied; \( t_0 \) – ambient temperature; \( x \) – coordinate of temperature maximum; a – part of radiation flux absorbed by the coating material layer; b – part of radiation flux absorbed by the substrate layer; c – part of reflected radiation flux absorbed by the coating material layer; d – part of reflected radiation flux unabsorbed by the coating material layer.

Assuming that the total energy density is \( E_0 \), the origin at the boundary of both layers and the radiant reflectivity of the substrate material \( R \), the amount of radiation energy adsorbed by a section of the layer from the interface to an arbitrary section \( x \) are determined by the expression:

\[
E = E_0 \cdot \left[ e^{-k(l_2-x)} - e^{-l_2} + Re^{-l_2} (1 - e^{-l_2}) \right].
\]  

(1)

where \( k \) — extinction (attenuation) coefficient of monochromatic radiation; \( l_2 \) — thickness of coating material.

The non-steady temperature field in the two-layer medium with an internal heat source, the intensity of which is determined taking into account (1) according to the equation:

\[
\omega = \frac{dE}{dx} = kE_0 \left[ e^{-k(l_2-x)} + Re^{-l_2} \right].
\]  

(2)

The boundary conditions for the task are:

1. At the initial time, the temperatures across the section of substrate

\[ t(x) \mid x = 0 = t_0. \]

2. The external heat source is not involved.
and powder layer are constant and equal $t_H$.

2. At any specific time, $\tau > 0$, the temperatures of both layers at the interface of their contact are the same.

3. The radiation flux adsorbed by the substrate surface layer, determined by expression $E_0(l - R)e^{-t_2}$, is transformed into heat, which is extracted through the coating material layer and the substrate.

4. Heat transfer from the substrate side and the coating material layer with the ambient air, which maintains constant temperature $t_B$ throughout the process, occurs by convection.

Thus, one needs to solve the system of equations:

$$\frac{\partial t'}{\partial \tau} = a_1 \frac{\partial^2 t'}{\partial x^2},$$

$$\frac{\partial t''}{\partial \tau} = a_2 \frac{\partial^2 t''}{\partial x^2} + \frac{kE_0}{c_2 \gamma_2} \left[ e^{-k(l_2 - x)} + Re^{-\lambda x} \right],$$

where prime and double prime refer respectively to the first and second layers;

$c_2$ and $\gamma_2$ - (the) heat capacity and unit weight of coating material;

$a$ - temperature conductivity coefficient;

$h = \frac{\alpha}{\lambda}$, $a$ and $\lambda$ - heat-transfer and thermal conduction coefficients.

After solving equation (3), the heating temperature of the substrate and the coating material layer is determined by equations (4) and (5), respectively

$$t' = t_H e^{-\nu^2 F_{\nu}} + (A_1 + B_1 x)(1 - e^{-\nu^2 F_{\nu}}),$$

$$t'' = t_H e^{-\nu^2 F_{\nu}} + \left[A_2 + B_2 x - \phi(x)\right](1 - e^{-\nu^2 F_{\nu}}).$$

Here $F_{\nu}$ - Fourier criterion;

$\nu$ - root of the transcendental equation.

Based on the performed calculations, the substrate heating temperature as a function of the curing time was obtained (Fig. 2).

When conducting studies on the thermoradiation curing of powder coating materials, a selection in favor of "light" emitters was made. The fact is that the powder coating materials are permeable enough for IR rays, while the permeability decreases with increasing wavelength, but the relative transparency of the powders due to the large scattering power over the whole wavelength range is much less than for liquid coating materials. As the coatings are formed, the permeability of powder film-formers for IR radiation increases sharply.

Optical characteristics of pigmented coatings, especially reflectivity, can vary depending on the type of the pigment. This affects the rate of the coatings formation using the radiant heating. Hence, by changing the spectral characteristics of the infrared radiation, the optical properties of the coating materials and the substrate, it is possible to obtain the desired temperature of the paint film, the substrate or the paint film and the substrate at the same time. In case of powder coating materials, it is necessary to create a maximum temperature at the interface between the substrate and the coating material since under this condition the most qualitative coating is obtained [16].

When curing coatings made of powder coating materials by the thermoradiation heating method, the dependence of the samples adhesion degree on the color of the applied coating was noted. This is clearly shown in Figure 3. The following figure shows the degree of adhesion of samples of different colors under the thermoradiation curing for 40 minutes.

This can be explained by the fact that coating materials have a different degree of absorption of the radiation energy with different wavelengths. Thus, the effect of radiation energy impact when cured is different.
reflectivity correspond to a spectral characteristics of the radiator, thus resulting in a change in the extinction coefficients of the samples. This conclusion is based on the fact that a certain extinction coefficient and implicitly, but it affects the limitation of the radiation spectrum. To obtain a high degree of adhesion in white color have a higher degree of blackness, so the amount of accumulated radiation is lower, compared to the other samples (Figure 5). This is due to the fact that samples that differ from the samples of different colors, i.e. the radiation energy adsorbed by the substrate for white samples is lower, compared to the other samples (Figure 5). This is due to the fact that samples that differ from white color have a higher degree of blackness, so the amount of accumulated radiation is higher. Accumulated radiation depends on the curing temperature. The influence of temperature is expressed implicitly, but it affects the limitation of the radiation spectrum. To obtain a high degree of adhesion in the samples, it is necessary to increase the curing temperature since it leads to a change in the spectral characteristics of the radiator, thus resulting in a change in the extinction coefficients of the samples. This conclusion is based on the fact that a certain extinction coefficient and a monochromatic reflectivity correspond to a spectral region of the radiator bound by certain wavelengths.

The substrate heating temperature is affected by the extinction coefficient (attenuation coefficient of monochromatic radiation). As the coefficient increases, the substrate heating temperature decreases, which leads to coatings with different degrees of adhesion. When determining the degree of adhesion by the cross-cut test of samples colored with different colors, it can be noted that under identical curing conditions (type and power of the radiator, the distance between the radiator and the curable surface), coatings with different degrees of adhesion are obtained, which is explained by different abilities of coatings of different colors to absorb infrared radiation.

Figure 4 shows the substrate heating temperature as a function of the curing time. This figure shows how the substrate heating temperature differs for materials with different colors of coating applied. The difference in substrate heating temperatures can be explained by different optical characteristics (attenuation coefficient of monochromatic radiation) of the coating materials used. Based on the analysis shown in Figure 4, it can be concluded that the attenuation coefficient of the monochromatic radiation (extinction coefficient) of the white coating is greater than the coefficient for the samples of different colors, i.e. the radiation energy adsorbed by the substrate for white samples is higher. Accumulated radiation depends on the curing temperature. The influence of temperature is expressed implicitly, but it affects the limitation of the radiation spectrum. To obtain a high degree of adhesion in the samples, it is necessary to increase the curing temperature since it leads to a change in the spectral characteristics of the radiator, thus resulting in a change in the extinction coefficients of the samples. This conclusion is based on the fact that a certain extinction coefficient and a monochromatic reflectivity correspond to a spectral region of the radiator bound by certain wavelengths.

Figure 2. Theoretical temperature of substrate heating as a function of the curing time

Figure 3. Degree of adhesion of samples of different colors cured under the emitter with an exposure of 40 minutes.
Figure 4. Dependence of the substrate heating temperature of the samples of white, gray and brown colors on the curing time

Figure 5. Dependence of the substrate heating temperature of the samples of green and red colors on the curing time

Figure 6. Dependence of the substrate heating temperature of the samples of blue and "gray metallic" colors on the curing time

Figure 7. Degree of adhesion of samples of white, gray, brown, red, green, blue and "gray metallic" colors, cured for 60 minutes.

As can be seen from Figures 4 ... 6, the lowest substrate heating temperature is observed in the light samples (white), and the largest substrate heating temperature - in the dark samples (the density of the incident radiation flux is $q_{rad} = 0.8 \text{ W/cm}^2$). The base coat heating temperature of the other samples is within the same temperature range. However, the degree of adhesion is different. Thus, for the gray and brown samples, this temperature is sufficient to obtain the degree of adhesion of one point, while the degree of adhesion in the remaining samples is unsatisfactory (Figure 7).

3. Conclusion

The theoretical and experimental studies carried out have shown the relation between the substrate heating temperature and the optical characteristics of the radiator used and coating material applied. The difference in degrees of coatings adhesion obtained in the same temperature range ($80 \ldots 90 \, ^\circ \text{C}$) demonstrates that the thermoradiation curing process is not a purely thermal. Its intensity is largely due to the specific effect of infrared radiation, which should be related to the spectral characteristics of the radiation applied to the paint film (the effect of a certain frequency radiation on the molecules polymerization). Thus, the results support the assumption that the process of thermoradiation curing is influenced by the temperature and the radiation effect.
The obtained results make it possible to develop a resource-saving technology for the painting of construction and road machines, which can be realized in the conditions of Transport Machine-Building Industry.

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