Research of Thermomechanical Processes When Processing Cylindrical Surfaces with Wear-Resistant Coatings

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Abstract. The possibilities of technical support of the quality of finishing processing of the cylinder working surfaces using coatings of wear-resistant materials are considered. For this, a design scheme is proposed for determining the stress-strain state of the cylinder-coating system. The influence of the processing regimes of a cylindrical group with a wear-resistant coating on its physical and mechanical characteristics is determined. The dependence of SIF on the delamination angle α and the roughness of the working area of the cylindrical surface Ra is presented. A design scheme is proposed for studying the mutual influence of exfoliation sections on stress intensity in a wear-resistant coating. The effect of particles on the wear resistance of the coating deposited by the electrochemical method is determined. A study of composite materials based on Ni/Ni-TiO_2 in a scanning electron microscope. The calculated and experimental values of the ultimate dimensions of crack-like defects during grinding of wear-resistant coatings are considered. The dependence of crack formation on the surface of the surface processed by grinding under the cutting depth and tool characteristics is determined.

Keywords: Durability · Reliability · Wear resistance · Delamination · Thermomechanical processes · Diamond abrasive processing · Tribocorrosion

1 Introduction

Analyzing the literature on tribology revealed that the operating costs of all technological cycles of machines exceed the costs of producing new equipment. In developed countries, the losses caused by friction and wear, account for 4…5% of national income [1–3].

The wear resistance of parts that work in conditions of sliding friction and have cylindrical surfaces, determines the durability of many machines [4]. Solving the problem of wear resistance of machine parts will lead to an increase in machine durability [5, 6]. Thus, the current area of research today is to increase the wear resistance of machine parts [7].

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2 Literature Review

Often, qualitative modification of the structural composition in all the main elements of the material is not taken into account when protecting related parts from production and improving the quality of products, therefore this problem is solved taking into account the modification of the surface layer of the composite material because in this case only the surface layer is strengthened [1, 2]. The hardening of the surface layer is understood as increasing the mechanical characteristics such as hardness [8, 9].

Various methods of hardening have been proposed in a large number of works, which were devoted to improving the mechanical characteristics of rubbing surfaces [1, 2]. The use of modern methods for producing wear-resistant coatings using composite materials based on compounds such as oxides, nitrides, and carbides is today a promising direction for the development of surface-strengthening technologies [6, 7]. The creation of hardening coatings from dissimilar materials leads to the formation of a fundamentally new composite material of the surface layer, which has not only high strength, but also sufficient ductility, as well as increased wear resistance, and not only to the modification of the surface layer [10, 11].

3 Research Methodology

The paper describes the study of thermomechanical processes in products with reinforcing composite coatings during processing and operation to determine the conditions for the formation of various defects such as cracks, chips, and delaminations of coatings from the base material, as well as their elimination taking into account the technological parameters of finishing, hereditary defects arising during coating operations taking into account the physicomechanical state of the surface layer.

The research helped to define the parameters of delamination at which the destruction of the composite coating occurs, taking into account the roughness of the working surface of the cylinder, its geometrical error, as well as the physicomechanical properties of the material of the cylinder and reinforcing wear-resistant composite coating.

The stress-strain state of the cylinder-coating system is depicted in the analytical model (Fig. 1).

Let's consider the heat equation for a two-layer cylinder with symmetric heating, with free heat transfer from the inner and outer surfaces of the cylinder. The temperature and heat flux of the vicinity of the interface varies continuously. The obtained problem is to find a continuous temperature function $t_i(r, \tau)$ in the domain $\mathrm{D}[\mathrm{R}_1 \leq \mathrm{r} \leq \mathrm{R}_3, 0 \leq \tau < \infty]$. satisfying the equation [12–15]:

$$\frac{\partial t_i}{\partial \tau} = a_i \left(\frac{\partial^2 t_i}{\partial r^2} + \frac{1}{r} \frac{\partial t_i}{\partial r} \right), \tag{1}$$

where $i = 1$ for the first area $D[R_1 \leq r \leq R_3, 0 \leq \tau < \infty]$

$i = 2$ for the second area $D[R_1 \leq r \leq R_3, 0 \leq \tau < \infty]$

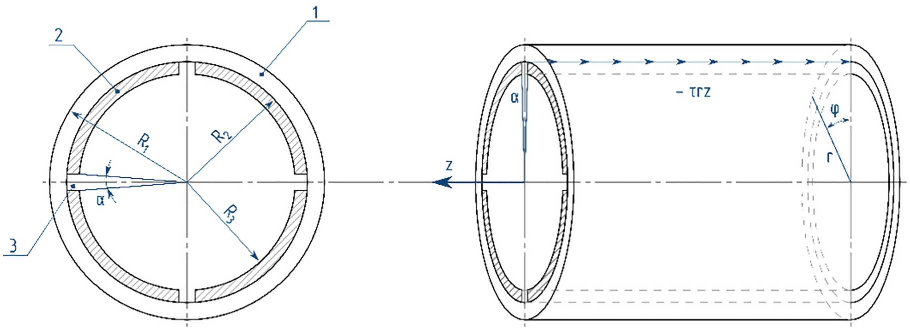

Fig. 1. The calculation scheme for determining the stress-strain state: 1 – the cylinder body; 2 – the body of the coating; 3 – areas of absence (exfoliation) of the coating.

Boundary conditions:

$$\begin{array}{l} \frac{\partial t_1}{\partial r} - h_1[t_1 - T_1(\tau)] = 0, at\, r = R_1, \\ \frac{\partial t_2}{\partial r} - h_2[t_2 - T_2(\tau)] = 0, at\, r = R_3, \end{array} \tag{2}$$

pairing conditions:

$$t_1 = t_2, \lambda_1 \frac{\partial t_1}{\partial r} = \lambda_2 \frac{\partial t_2}{\partial r}, \; at\, r = R_2; \tag{3}$$

initial condition:

$$t_i(r, 0) = \Phi_i. \tag{4}$$

Here a_i, h_i, λ_i are the coefficients of thermal diffusivity, relative heat transfer, and thermal conductivity, respectively, of the coating ($i = 2$) and the base material ($i = 1$).

The final solution to the problem is written as:

$$t_i(r,\tau) = \psi_i(r,\tau) + \sum\nolimits_{n=1}^{\infty} \exp\left(-\gamma_n^2 \tau\right) \left[\overline{\Theta_n}(0) + \int\limits_0^{\tau} \frac{d\bar{\psi}_n(\bar{\tau})}{d\bar{\tau}} \exp\left(-\gamma_n^2 \bar{\tau}\right) d\bar{\tau} \right] u_{in}(r).$$

Here $\psi_i(r,\tau) = [T_2(\tau) - T_1(\tau)](A_i \ln r + B_i) + T_i(\tau)$.

To determine the stress-strain state of a coated cylinder exposed to a temperature field, the following problem is considered. A two-layer unlimited hollow cylinder is subject to the action of the temperature field $t_i = t_i(r, \tau)$. The material of the cylinder and the coating are in contact over the entire interface and, therefore, movements on the interface will be continuous. Another condition at the interface is obtained from the condition of continuity of normal stresses σ_r. On the outer surfaces, σ_r is assumed to be zero. Thus, the following problem is to find the continuous deformation function $u_i(r, \tau)$ in the domain $D[R_1 \le r \le R_3, 0 \le \tau \le \tau_0]$ satisfying the equation:

$$\frac{1}{c_i^2}\frac{\partial^2 u_i}{\partial \tau^2} = \frac{\partial^2 u_i}{\partial r^2} + \frac{1}{r}\frac{\partial u_i}{\partial r} - \frac{u_i}{r^2} - m_i\frac{\partial t_i}{\partial r}, \tag{5}$$

where $i = 1$ for the first area when r changes from R_1 to R_2 and $i = 2$ for the second area, when r changes from R_2 to R_3; $u_i(r, \tau)$ – the displacement; c_i – the propagation velocity of expansion waves in an elastic medium.
Boundary conditions:

$$\begin{array}{l} \frac{\partial u_1}{\partial r} + p_1 u_1 = m_1 t_1, at\, r = R_1, \\ \frac{\partial u_2}{\partial r} + p_2 u_2 = m_2 t_2, at\, r = R_3; \end{array} \tag{6}$$

pairing conditions:

$$u_1 = u_2, p_{12}\frac{\partial u_1}{\partial r} + q_{12}u_1 = \frac{\partial u_2}{\partial r} + p_{12}m_1 t_1 - m_2 t_2 \, at\, r = R_2; \tag{7}$$

initial condition:

$$u_i(r, 0) = \Phi_i(r), \frac{\partial u_i(r, 0)}{\partial \tau} = \Psi_i(r). \tag{8}$$

Having analyzed the calculated dependencies, the area of the peeling of the coating from the base material increases with increasing roughness of the inner surface of the cylinder because of the friction process in this area.

This means that the destruction of the coating will occur when the process stresses exceed the adhesion strength σ_{adh} in magnitude.

Figure 2(a) shows the processing mode of the working surfaces of the cylinder which provides the roughness to maintain the functional properties of the coated piston-cylinder group [1, 2, 6, 7, 14–16].

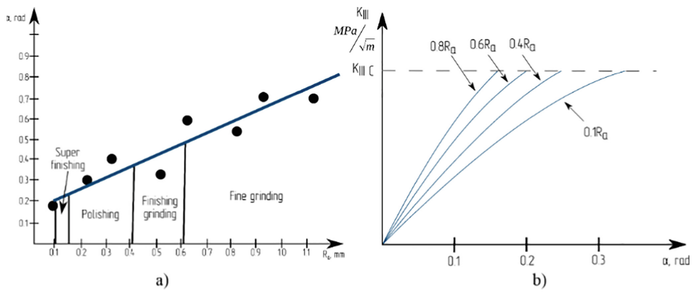

Fig. 2 a) The influence of the processing regimes of the coated cylindrical group on its characteristics; b) SIF dependency onto detachment angle α and cylinder surface's working area roughness Ra.

The quality of the machined surfaces of the cylindrical group will be ensured if, using the control technological parameters, we select such processing modes, cutting fluids and tool characteristics that the current grinding temperature $T_i(r,\tau)$ and heat flux $q(r,\tau)$, stresses $\sigma(r,\tau)$ will not exceed their limiting values [14, 15].

The processing of materials and alloys without grinding cracks can be achieved if the stresses formed in the intensive cooling zone are limited by the limiting values:

$$\sigma_{max}(r,\tau)|_{r=R_1} = 2G\frac{1+v}{1-v}\alpha_t T_k \mathrm{erf}\left(\frac{r}{2\sqrt{\alpha\tau}}\right) \le [\sigma_{adh}] \tag{9}$$

Let $U_z^{(i)}, U_r^{(i)}, U_\phi^{(i)}$ denote the displacement of the points of the cylinder-coating system in the direction of the corresponding coordinates of the cylindrical system (z, r, φ). Since under the influence of technological coupling stresses τ_{rz} in system 1-2 (Fig. 1), the displacements $U_z(r,\varphi)$ will be nonzero, the Lame equations can be written in the form:

$$\mu^{(i)}\Delta^2 U_z^{(i)} = \mu^{(i)}\left(\frac{\partial^2 U_z^{(i)}}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial U_z^{(i)}}{\partial r} + \frac{1}{r^2}\cdot\frac{\partial^2 U_z^{(i)}}{\partial \phi^2}\right) = 0. \tag{10}$$

Or $U_z(r,\phi) = W(r,\phi), 0 \le r \le R_z, -\pi \le \phi \le \pi$ the equation (26) takes the form:

$$\Delta W(r,\phi) = \frac{\partial^2 W}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial W}{\partial r} + \frac{1}{r^2}\cdot\frac{\partial^2 W}{\partial \phi^2} = 0. \tag{11}$$

Boundary conditions:

$$\tau_{rz}|_{z=R_2} = 0, \tag{12}$$

$$\tau_{rz}(R_1 - 0, \phi, T) = \tau_{rz}(R_1 + 0, \phi, T) = -\tau_{adh}, |\phi| \le \alpha. \tag{13}$$

Defect conditions:

$$W(R_1 - 0, \phi, T) - W(R_1 + 0, \phi, T) = \begin{cases} \chi(\phi), -\alpha \le \phi \le \alpha \\ 0, |\phi| > \alpha \end{cases}. \tag{14}$$

The conditions of continuity of tangential stresses at the cylinder-coating interface:

$$\tau_{rz}(R_1 - 0, \phi, T) = G_1 \frac{\partial W}{\partial r}\bigg|_{r=R_1-0},$$

$$\tau_{rz}(R_1 + 0, \phi, T) = G_2 \frac{\partial W}{\partial r}\bigg|_{r=R_1+0},$$

$$\tau_{rz}(R_1-0,\phi,T)-\tau_{rz}(R_1+0,\phi,T)=G_1\frac{\partial W}{\partial r}\Big|_{r=R_1-0}-G_2\frac{\partial W}{\partial r}\Big|_{r=R_1+0}$$
$$=G_1<W'(R_1,\phi)>-(G_2-G_1)\frac{\partial W}{\partial r}\Big|_{R_1}=0.$$

Equations (11)–(14) constitute an anti-plane problem for the cylinder-coating system taking into account a defect of the delamination, which arises because of the roughness of the working surface of the cylinder or its non-circularity.

The solution to the discontinuous problem can be obtained in the form [12–15]:

$$W_n(r)=\int_0^{R_2}G(r,\rho)f(\rho)d\rho+\sum_{j=0}^{1}r_jW_{n,j}(r)+grad\,T \tag{15}$$

In this problem, of practical interest is the stress intensity factor (SIF) at the delamination edges at $\phi=-\alpha-0$ and at $\phi=\alpha+0$, i.e.:

$$K_{III}^{-}=\lim_{\phi\to-\alpha-0}\sqrt{2\pi(-\alpha-\phi)}\tau_{rz}(R_{1,}\phi,T), \tag{16}$$

$$K_{III}^{+}=\lim_{\phi\to\alpha+0}\sqrt{2\pi(\phi-\alpha)}\tau_{rz}(R_{1,}\phi,T) \tag{17}$$

Taking into account the substitution $\phi=\alpha\phi'$ and symmetry, these relations will take the form [12, 13]:

$$K_{III}^{\mp}=\lim_{\phi'\to\mp1\mp0}\sqrt{2\pi\alpha(\mp1\mp\phi)}\tau_{rz}\left(R_{1,}\alpha\phi',T\right)$$

and at the same time [12–15]:

$$\tau_{rz}\left(R_1,\alpha\phi',T\right)=\frac{-(h+1)G_1}{2\pi^2(2+h)\alpha}$$
$$\times\frac{d^2}{d\phi'^2}\int_{-1}^{1}\mathrm{X}(\alpha\phi')\left[\ln\frac{1}{|\phi'-\psi'|}+R^*(\alpha\phi',\alpha\psi')\right]d\psi'. \tag{18}$$

Using the correlation between the roughness of the working zone of the cylinder and the value $(-\alpha,\alpha)$ of the coating peeling section during various finishing operations: fine grinding, finishing grinding and polishing, we find the SIF dependence $K_{III}=f(\alpha)$ (Fig. 2 (b)).

We find the calculated values of K_{III} depending on the magnitude of the defect $(-\alpha,\alpha)$ delamination by the given values of τ_{adh} of the adhesion of the coating to the cylindrical surface, at different values of the tool surface roughness (Fig. 2 (b)) (Fig. 3).

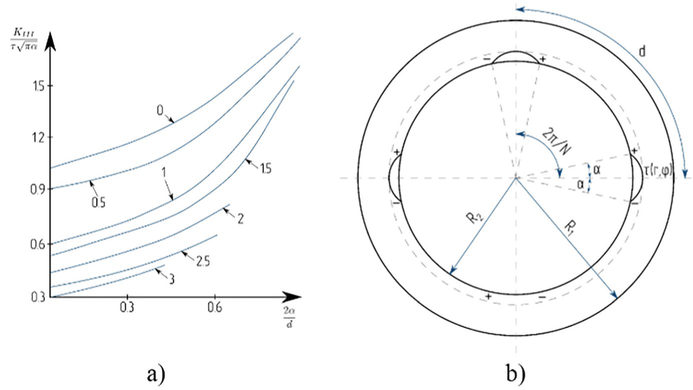

Fig. 3 a) Dependency of SIF $\frac{K_{III}}{\tau\sqrt{\pi\alpha}}$ at longitudinal displacement; b) Calculation scheme for researching the reciprocal influence between detachment areas and stress intensity K_{III}.

4 Results

To ensure the required reliability and durability of the coated cylindrical group, it is necessary to provide a roughness of $0.8 \leq Ra \leq 1,2$ when applying coatings on their working surfaces. Such roughness can be achieved through finishing grinding and subsequent finishing polishing.

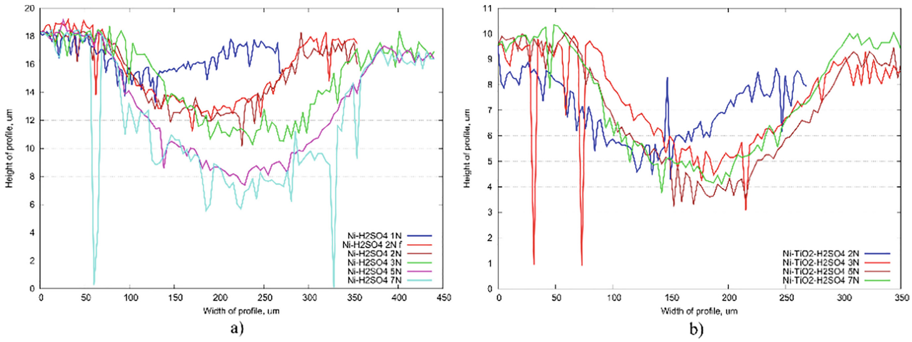

Fig. 4. The effect of particles on the wear resistance of an electrochemical deposited coating: a) nickel coating, b) Ni-TiO_2 coating.

To confirm the above analytical model, tribocorrosion studies of Ni/Ni-TiO_2-based composite materials obtained by electrochemical deposition were carried out [18].

Electrochemical deposition of coatings was carried out using Autolab and the Nova program with the following parameters [18]:

- Mode – Galvanostatic;
- Current range – 100 mA;
- Bandwidth – High stability;

- Apply current – 0.035 A/dm2;
- Duration – 1800 s;
- Interval time – 0.1;

After tribocorrosion studies of Ni/Ni-TiO_2 materials, it was determined that for Ni coating, an increase in the depth and width of cracks is noticeable, depending on the increase in load with constant exposure time. Here, the crack profile for the Ni-TiO_2 coating does not change with increasing load and constant time. One can single out the positive effect of TiO_2 particles in the coating, which increases the protective functions of the coating against mechanical abrasion, and the load for Ni-TiO_2 ceases to play such a significant role (Fig. 4) [18].

The adequacy of the constructed model was tested experimentally on duplex steel samples (Table 1), on the surface of which a wear-resistant Ni-TiO_2-based coating with a thickness of 0.4–0.6 mm was deposited by electrochemical deposition. To calculate the parameters of defect-free processing, the following physical and mechanical characteristics were used: *KS = 2 MPa m1/2; α = 8.58 K-1; G = 168 GPa*.

To check the criterion for the absence of grinding cracks on the surface to be treated, the contact temperature in the grinding zone was determined. Taking into account the fact that the dominant factor of the grinding modes affecting the thermal stress of the grinding process is h – the depth of grinding, the dependence $T = f(h)$ was found. The remaining modes were selected from the conditions of maximum performance while maintaining the required quality. So, when grinding the coating with circles made of polycrystalline-crushed diamonds (Fig. 5: curve 1), circles made of synthetic diamonds (Fig. 5: curve 2), circles made of white electrocorundum (Fig. 5: curve 3), the remaining grinding modes were selected as follows: $V_g = 0.17$ m/s; $V_{cr} = 30$ m/s; $S_{non} = 5$ mm.

Table 1. The chemical composition of duplex steels

Type / %	Cr	Ni	Mo	N	Sec. phases
Depleted	20–24	1–5	0.1–0.3	0.1–0.22	24–25
Standard	21–23	4.5–6	2.5–3.5	0.1–0.22	33–35
Saturated	24–29	4.5–8	2.7–4.5	0.1–0.35	>40
Enriched	27	6.5	5	0.4	49

Experimental studies have shown that circles from natural and synthetic diamonds have a stable cutting ability, high dimensional stability, have relatively low temperature in the grinding zone, which also affects the absence of cracks at large grinding depths (compared to circles made of white electrocorundum) [11].

It was found that grinding the coating with circles made of polycrystalline-crushed diamonds (Fig. 5: curve 1) was the most productive while maintaining the required quality.

The results of the study of the microhardness of the treated surface and the microstructure of the surface layer indicate that in the range of the studied modes there are no structural changes after grinding the wear-resistant Ni-TiO_2 coating. The diagram (Fig. 6) shows that while maintaining the quality characteristics of wear-resistant coatings the most productive tool for processing wear-resistant coatings are No. 6 and No. 7, which allow processing this surface at great depths of cut.

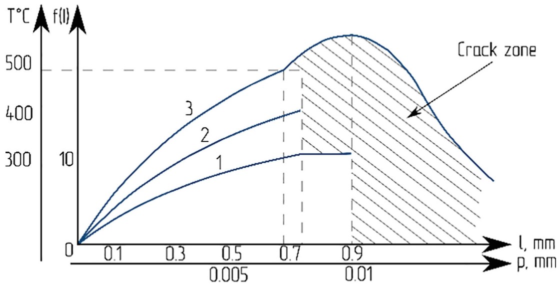

Fig. 5. Calculated and experimental values of the limiting sizes of crack-like defects when grinding wear-resistant coatings based on Ni-TiO_2 coatings in circles: 1 - circles made of polycrystalline-crushed diamonds; 2 - circles made of synthetic diamonds; 3 - circles made of white electrocorundum).

The nature of the crack formation of coatings depending on the characteristics of the wheels, cutting conditions can be followed using the criterion of the limiting heat flux $q*$. The heat flux entering the part during grinding is not only a function of cutting modes — V_g, V_{cr}, t_{shl}, P_Z, but also the characteristics of wheels — the hardness of the bond, the graininess of the properties of cutting grains, their hardness, etc. its value of the limiting heat flux at which coatings containing defects of *2l* in size will not be subject to cracking [8, 10, 11].

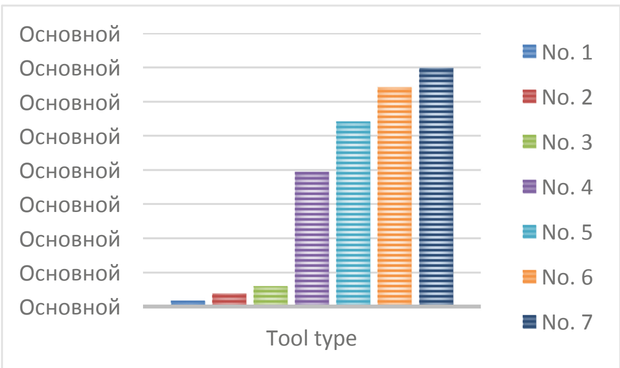

Fig. 6. Cracking on the surface of a wear-resistant coating processed by grinding, depending on the depth of cut and the characteristics of the tool.

5 Conclusions

An analytical model has been developed to determine the thermomechanical state of the working surface of a cylinder with a wear-resistant coating having partial detachment areas during application. The possibilities of technological support for the quality of finishing processing of the cylinder working surfaces using coatings of wear-resistant materials are considered. For this, a design scheme is proposed for determining the stress-strain state of the cylinder-coating system. The influence of the processing regimes of a cylindrical group with a wear-resistant coating on its physical and mechanical characteristics is determined. The dependence of SIF on the delamination angle α and the roughness of the working area of the cylindrical surface Ra is presented. A design scheme is proposed for studying the mutual influence of exfoliation sections on stress intensity in a wear-resistant coating. The effect of particles on the wear resistance of the coating deposited by the electrochemical method is determined. Tribocorrosion studies of composite materials based on Ni/Ni-TiO_2 obtained by electrochemical deposition were carried out. A study of composite materials based on Ni/Ni-TiO_2 in a scanning electron microscope. The calculated and experimental values of the ultimate dimensions of crack-like defects during grinding of wear-resistant coatings are considered. The dependence of crack formation on the surface of the surface processed by grinding under the cutting depth and tool characteristics is determined. The technological quality assurance of the finish treatment of cylindrical surfaces with wear-resistant coatings based on Ni-TiO_2 by a rational choice of processing modes, and the characteristics of the tool taking into account hereditary defects during coating, is presented.

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