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To cite this article: A V Zotov *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **224** 012038

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Environmentally Friendly Technology for Applying Coatings with Various Functional Purposes

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Abstract. The paper presents an environmentally safe technology of combined surface treatment of mechanical engineering parts. It is a method of cladding with mechanical impact by means of a flexible tool. An integrated approach to the appointment of rational treatment modes was considered. On the one hand, the quality characteristics of the formed coating are taken into account, and on the other hand - the durability of the wire tool. The scheme of impact on the treated surface is presented. The main analytical dependences for determining the degree of coverage and the degree of uniformity of the depth of the hardened layer are given. An analytical relationship is presented for determining the maximum actual stresses formed in the pile of a flexible tool as it slides along the contact area of the treated surface. The dependence is based on the theory of flexible elastic rods. Analytical dependencies are given to determine the surface temperature of the workpiece and the relative strength of adhesion of the coating to the substrate. The algorithm for selecting treatment modes for cladding with a flexible tool is presented. The purpose of the algorithm is to promote the formation of coatings with parameters that best match the functional purpose of the treated surface.

1. Introduction

The competitiveness of machine-building industries directly depends on innovative investments in the development of promising technologies. The structure of engineering technologies is dominated by basic and outdated technologies - the share of advanced technologies is only a fifth part [1]. And at the same time, the introduction of progressive technologies and new equipment does not give such fast and significant results in any industry as in engineering. The most important components of mechanical engineering are technologies, technological support and, to a large extent, the formation of demand for products. All of them are determined by the requirements of environmental safety, which is one of the main criteria by which the assessment of new engineering technologies takes place.

The development of new cost-effective ways of forming coatings for various functional purposes, is always an important area in search studies. Special functional requirements for the surfaces define a set of requirements for the roughness, composition and structure of the surface layer material, residual stresses, microhardness. Coatings are used for various purposes. This may be an increase in durability, wear resistance, corrosion resistance, decrease in the setting of moving parts, increase in bearing capacity, tightness, smoothness of movements, noise reduction, or for decorativeness. For coatings



operating under different conditions, the requirements are different. The basic demands for coatings are thickness, uniformity of coating, and strength of adhesion to the substrate.

The vast majority of methods of forming coatings are environmentally unsafe practices. This is due to both the stage of surface preparation for coating, as well as the methods of applying the coatings themselves. When preparing the surface under the coating, it is degreased, etched using alkaline solutions, organic solvents, emulsions. Some methods require jet-abrasive surface preparation with intensive dusting. Ultrasonic cleaning is also used. Coating is often carried out in gaseous media. Because of this, equipping workplaces with complex ventilation and air purification systems is required. To ensure environmental standards, complex wastewater treatment is involved.

However, the known methods of coating have significant drawbacks. With the hot method of applying metal coatings, brittle intermetallic compounds can be formed and the base metal is softened due to high temperatures. Because of this, changes in the chemical composition also pass, significant deformations and residual tensile stresses are formed. All this has a negative impact on the operational durability of the processed products.

Methods of chemical and electrolytic deposition of coatings require complex surface preparation [2-4]. During operation, powerful exhaust ventilation and multi-level cleaning of drains and air from gas pollution are required.

When spraying coatings, it is also necessary to prepare the surface of the processed product in an environmentally unsafe way. At the same time, the formed coating is porous and adhesion is not always of the required quality [5].

Methods of physico-chemical modification of materials, as a rule, are quite expensive and require all the same surface preparation [6].

In addition, all these methods are power-consuming. In addition to high-energy equipment, preheating and slow cooling of the workpiece itself, drying of the powder for spraying are required. The applied coatings are required to be machined mechanically, and these are mainly finishing methods, including grinding with the use of coolant.

Under these conditions, the introduction of a new high-performance method of combined surface treatment of engineering products of cladding with mechanical impact using a flexible tool is the necessary solution.

This method is relatively simple to implement, economically viable and environmentally friendly, as it does not require preliminary surface preparation, and coating can be performed on conventional metal-cutting equipment with a small upgrade.

2. Relevance

Coatings of various functional purposes are applied by the method of cladding with a flexible tool. In recent years, the study of different aspects of this coating method has reached new levels [7-15]. So in [9] the authors investigate the influence of electric current on the rate of the process and the thickness of the coating. This method of surface modification is used in the processing of gears [10], sliding guides [11], large-size engineering products [12], etc. At the same time, in addition to the main purpose of the coating (wear resistance, corrosion resistance), such side effects as reduction of noise of gears, smoothness of movement of metalworking equipment units, increase in bearing capacity are achieved.

In addition, experimental studies of the structure and properties of composite materials for the formation of coatings, their optimal compositions and methods of production were carried out [13]. In papers [14-17] the issues of adhesion strength of applied coatings are considered. In [14] a comparison of the coatings cladding by flexible tool with a coating applied by electroplating. During the peeling test under bending, it has been found that cladded coatings were not peeled off from the basic material, even in the case when experimental samples were broken, and the peeling of coating in the samples with galvanic coatings has been observed on half of the first bending cycle.

Despite the positive results of the use of flexible cladding tool, an important task at the moment is to create an integrated approach to the appointment of rational treatment modes of processing products

with the formation of the coating, the parameters of which correspond to the functional purpose of the corresponding surface.

3. Factors of the cladding process with a flexible tool

The basis of cladding with a flexible tool is the simultaneous deformation hardening of the surface to be treated and the application of coatings on it.

Figure 1 shows a schematic diagram of the cladding process with a flexible tool.

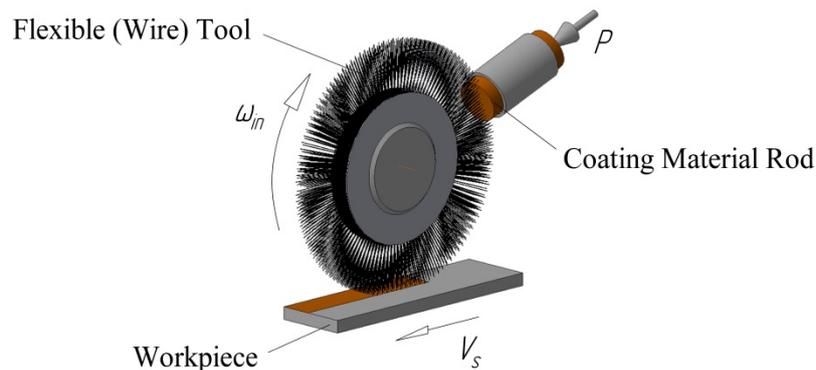


Figure 1. The process of cladding: ω_{in} is tool rotational speed; P is the pressing force of the coating material; V_s is the feed rate of the treated surface relative to the flexible tool

Friction cladding is performed as follows. The coating material should initially exist in the form of a rod or a similar item. The major production tool is a rotating cylindrical metal brush with velocity ω_{in} . The brush rotates at high speed, and it is pressed against the processed surface. In another place, the rod of the coating material is pressed against the brush with the force P . Each one of the wires of which the brush consists removes a material particle from the rod of the coating material, some fraction of a micron in size, and transfers it to the processed surface. The high rotational speed of the brush results in a significant force of impact between a particle and the surface; the particle is fused to the processed surface. The large number of wires in the brush and the high rotational speed provide high efficiency and uniformity of material transfer from the rod to the processed surface [9].

To create an integrated approach, the problems were solved, allowing to correlate the distribution of wire pile prints and the corresponding plastic deformation zones, geometric, energy and thermal characteristics of the pile during sliding, with quality characteristics of the process, such as thickness and uniformity of the coating, as well as adhesion of the coating to the base of the workpiece.

The appearance on the surface of the workpiece prints from the blows of the pile occurs randomly, which determines the probabilistic approach to determining the degrees of coverage of these prints (figure 2).

Imprints from impacts form a Poisson field on the surface of the workpiece, because, firstly, the hitting probability of a given pile in any area of the treated surface does not depend on the number of piles that fell into any areas that do not intersect this and, secondly, the probability getting into the elementary region of two or more piles is negligible compared to the probability of hitting one pile. We obtain the surface density of the distribution increasing in time, based on the analysis of the kinematics of processing wire tool based on the actual filling factor of the peripheral surface of the pile tool:

$$\lambda_s = \frac{4 \cdot V_{cs} \cdot \eta}{\pi \cdot d_v^2 \cdot V_s} \quad (1)$$

where V_{cs} is circumferential speed of tool rotation, m/s; η – the actual fill factor of the working surface of the tool; d_v – diameter of the pile, m.

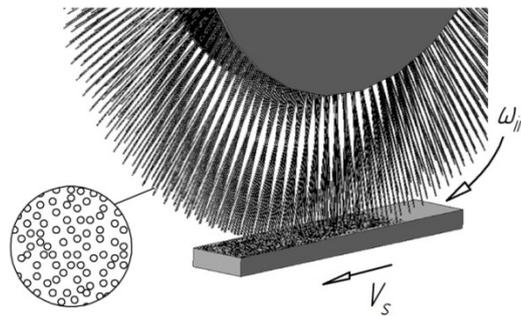


Figure 2. Diagram of the prints formation under impact on the treated surface

This allows us to proceed to finding of the average probable number of impacts in an area equal to the area equivalent to their own imprint, with a radius of r_{imp} , which depends on the plasticity of the material, the tension of the brush wires, and the pile diameter:

$$a_{imp} = \pi(r_{imp})^2 \lambda_s. \quad (2)$$

According to the basic provisions of the theory of probability, we can determine the degree of coverage of the treated surface. It is considered as the share of the processed area covered by prints at least once, twice, etc. $P(a)$ and covered by prints a certain number of times $P(a)^*$:

$$P(a) = 1 - \sum_{k=0}^{n^*-1} \frac{a_{imp}^k}{k!} e^{-a_{imp}}. \quad P(a)^* = \frac{a_{imp}^n}{n^*!} \cdot e^{-a_{imp}} \quad (3)$$

where n^* is the multiplicity of the coverage.

For practical purposes, it is of greater interest to ensure uniform distribution of plastic deformation zones.

The degree of uniformity of the hardened layer depth is defined as the ratio of the plastic deformation depth in the overlap zone of the deformed volumes h_μ to the maximum depth of the hardened layer h_s , assuming that the shape of the deformed zone is a spherical segment.

From the geometric connection of the overlap of deformed volumes and the degree of overlap of the treated surface, we obtain the degree of uniformity of the depth of the hardened layer as a function of the surface density distribution λ_s and the maximum depth of hardening h_s .

$$\psi_s = \sqrt{1 - \frac{1}{8 \cdot \pi \cdot h_s^2 \cdot \lambda_s}} \quad (4)$$

Thus, by changing the designing parameters of the wire tool and the treatment modes, we can obtain the required degree of coverage and the degree of uniformity of the hardened layer depth.

Next, it is necessary to evaluate the geometric and power characteristics of the contact zone. For this purpose, the theory of flexible elastic rods is used, since displacements during bending of the pile are comparable to the length of the pile itself. The proposed model allows in the contact zone throughout its length at any point directly determine the magnitude of the contact force, the maximum stresses in flexible elements, the maximum deflection of the pile, the length of the contact zone.

In particular, the stresses arising in flexible elements directly affect the durability of the wire tool and their analysis is necessary to eliminate fatigue wear of the pile.

The calculation of the maximum stresses in the flexible elements during deformation is produced according to the algorithm, which is based on a mathematical model for calculating geometrical and power parameters of the contact area of the flexible tool with the treated surface, built on the basis of nonlinear large displacement theory in the plane bending of thin elastic rods [8]:

$$\sigma_{\max i} = \frac{\omega_i}{\beta_i} \cdot P_i \cdot l \cdot \frac{d_{v.eqv}}{2J_{eqv}}. \quad (5)$$

where ω_i is torque scaling factor; β_i is power scaling factor; P_i is the contact force corresponding to the maximum stresses during pile sliding, H; l is the length of the wire bent region, mm; $d_{v.eqv}$ is pile equivalent diameter, mm; J_{eqv} is axial cross-sectional area moment of inertia with a diameter of $d_{v.eqv}$, mm⁴.

Taking into account the parameters of the treatment zone, the temperature of the workpiece base surface is calculated, which is one of the determining factors of the cladding process [15].

$$\theta_o = \frac{Q \cdot (3 + \varphi_s)}{8 \cdot \varphi_s \cdot \pi \cdot \lambda \cdot S \cdot \psi} \cdot \exp\left(-\frac{\zeta^2 \cdot \varepsilon_\eta \cdot Pe_s}{4 \cdot \psi}\right) + \theta_\Sigma. \quad (6)$$

$$\theta_\Sigma = \frac{Q}{2 \cdot \pi \cdot \lambda \cdot S} \cdot \sum_{\psi=1}^{n_\psi} \left(\frac{1}{\psi}\right) + 2 \cdot \frac{Q}{2 \cdot \pi \cdot \lambda \cdot S} \cdot \sum_{\psi=1}^{n_\psi} \left(\frac{1}{\psi} \cdot \exp\left(-\frac{\zeta^2 \cdot \varepsilon_\eta \cdot Pe_s}{4 \cdot \psi}\right)\right). \quad (7)$$

where Q is the power of the source, W; φ_s is the dimensionless coordinate; λ is coefficient of thermal conductivity of the processed material, W·(m·°C)⁻¹; S is step in the longitudinal direction, m; $\psi = x \cdot S^{-1}$, $\zeta = y \cdot S_p^{-1}$ are dimensionless coordinates; x, y are coordinates of the contact spot on the machined surface, m; S_p is step in the transverse direction, m; ε_η is the multiplicity factor of the step; Pe_s – Peclet criterion; θ_Σ is total influence of all wires in the contact zone on the local temperature of the point source under consideration, °C; n_ψ is the number of tool wires passing past the point source currently being considered.

In contrast to the previously used models, the factor of mutual influence of temperatures of unevenly distributed areas of pile contact during its sliding is taken into account.

Here the step, both in the longitudinal and transverse direction between the spots of contact of flexible elements with the surface, significantly exceeds their area in each case. Therefore, the heat sources were defined as point-like, and taking into account the processing speeds – as quickly moving on the surface of the half-space.

All the considered factors to some extent affect the adhesion of the applied coatings to the base of the product, the numerical characteristic of which is expressed in terms of the coefficient of relative adhesion strength [15]:

$$K_{cm} = 1 - \exp\left[vt_o \cdot \left(K_{em} \cdot \exp\left(\frac{E_a}{k_b \theta_k}\right)\right)^{-1}\right]. \quad (8)$$

where ν is the frequency of natural vibrations of atoms, s⁻¹; t_o is the time of physic-chemical interaction of the particle with the base material, s; $K_{em} = 1 - E_p \cdot E_a^{-1}$ is the coefficient of mechanical activation; E_a is the energy of thermal activation, J; E_p is the energy of mechanical activation, J; k_b is the constant Boltzmann; θ_k is the contact temperature, °C.

The relationship of the instrument design parameters and cladding modes with the energy of mechanical and thermal activation is described in detail in [15].

4. Algorithm of choice of rational treatment modes for cladding

In order to select rational treatment cladding modes, an algorithm was developed, the block diagram of which is presented in Figure 3.

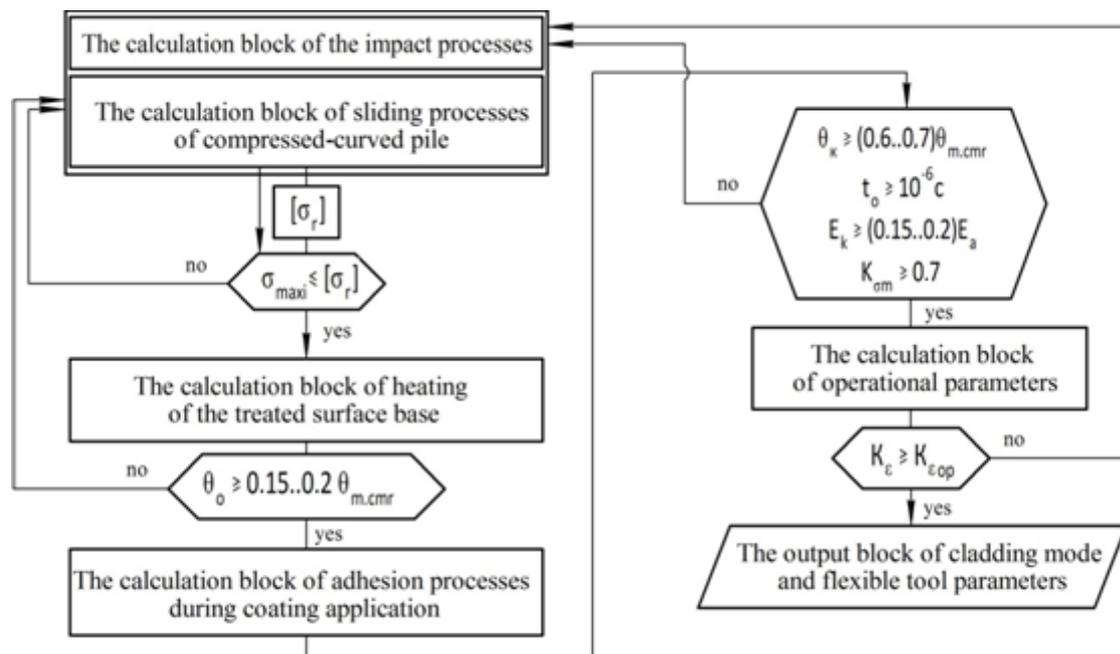


Figure 3. Block diagram of the algorithm for selecting the rational cladding modes

At the first stage, taking into account the experimental and analytical studies carried out, the choice of the design parameters of the wire tool (pile size, material, filling density of the working part) is made.

Next, the selection of valid intervals of cladding modes, based on the properties of the coating material and the product, which must be given the required performance properties.

At the second stage, the calculation of the deformation, geometric and energy-power parameters of the cladding process is carried out. At the same time, the durability of a flexible cladding tool is evaluated and, with unsatisfactory values, a change in the initial data and a recalculation of the process parameters.

Fatigue strength assessment [8] is performed using a known endurance condition:

$$\sigma_{\max} \leq [\sigma_r]. \quad (9)$$

where σ_r is endurance limit at asymmetric cycle, MPa.

$$[\sigma_r] = \frac{2 \cdot [\sigma_{+1}] \cdot [\sigma_{-1}]}{(1-r) \cdot [\sigma_{+1}] + (1+r) \cdot [\sigma_{-1}]}$$

where $[\sigma_{+1}] = \sigma_t / k_0$ is allowable stresses under static load, MPa; σ_t is tensile strength of the pile material, MPa; k_0 is basic safety factor; $[\sigma_{-1}]$ is allowable stresses for a symmetric cycle, MPa; $r = \sigma_{\min} / \sigma_{\max}$ is asymmetry cycle factor; σ_{\min} is minimum cycle stresses when the pile output from contact with the workpiece, MPa.

At the third stage, the temperature of the base surface of the processed product is calculated. In order to ensure high-quality adhesion of the coating, it should not be less than 0.15-0.2 of the melting temperature of the coating material.

At the fourth stage, a set of parameters is calculated that affect the formation of strong adhesive bonds. Failure to comply with any of the conditions (Figure 3) (temperature in contact, interaction time, mechanical activation energy, relative coefficient of adhesion of particles) will lead to insufficient adhesion strength and therefore it is necessary to select other values of the source data from the initially established intervals.

At the fifth stage, the calculation of operating parameters and the assessment of predicted values is made. If the assessment is unsatisfactory, then recalculation is carried out in order to improve operational performance.

Using this algorithm, effective technological modes of the cladding process are quickly selected for the formation of the coating, the parameters of which provide a given level of performance of the processed product.

5. Conclusions

An integrated approach has been developed for the calculation and selection of the cladding mode and the design parameters of a flexible tool. The peculiarity of this approach is taking into account the relationship of the parameters of cladding as a two-stage process with thermal parameters in the treatment area and with adhesion, expressed through the coefficient of relative adhesion strength. The first impact cladding stage is the area at the entrance of the pile into contact with the workpiece, the second stage is the sliding area of the compressed-bent pile along the contact zone. The algorithm takes into account the parameters of natural wear of the pile of the wire tool.

Thus, the considered algorithm provides conditions for applying high-quality coatings in an environmentally friendly way. At present, the described approach is used in the repair production of PJSC AvtoVAZ.

Acknowledgments

This work was financially supported by the Ministry of Education and Science of the Russian Federation for the project № 11.2054.2017/Project task within the framework of the state task for 2017-2019. (project number 11.2054.2017/4.6)

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