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THE SELECTION AND DEVELOPMENT OF TRIBOLOGICAL COATINGS

IZBIRA IN RAZVOJ TRIBOLOŠKIH PREVLEK

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The main objectives of this study are the strategy and methodology for selecting the optimal surface treatment for a given tribological application. The classification of the main methods of the coating processes and the surface modification is given and the scheme of the development of the operation technology of the surface treatment and coating deposition is proposed. The main initial data are: the structure of tribological system (TrS); the individual properties of the TrS parts; the lubricant properties; the method of lubrication of the TrS parts; the properties of the surrounding environment; the external influences on the TrS; the technological limitations on the TrS parts treatment; and the managerial and economic limitations. The selection of the surface technology method includes the following steps: the preliminary analysis of the TrS part interaction; the development of models of friction and the wear process of the TrS parts; the choice of rational values of the parameters of the surface layers of the TrS parts; the choice of the rational composition and the structure parameters of the surface layers of the TrS parts; the choice of a rational technological route and the methods of the surface treatment of the TrS parts; the experimental examination of surface-strengthened materials and the TrS and the correction of the surface-treatment technology.

Key words: coatings, friction pair solid surfaces contact, surface engineering, tribological system

Glavni cilj tega članka sta strategija in metodologija optimalne izbire metode za utrditev površine za neko tribološko uporabo. Dana je razvrstitev glavnih metod in procesov obdelave površine in nanosa prevlek ter predložena je shema razvoja tehnologije obdelave površine in nanosa prevlek. Najbolj pomembni začetni podatki: struktura tribološkega sistema (TrS); lastnosti posamičnih delov TrS; lastnosti maziv za TrS; lastnosti okolja; zunanji vplivi na TrS; tehnološke omejitve obdelave TrS-delov; poslovne in ekonomske omejitve. Metoda izbire površinske tehnologije ima naslednje korake: izbira racionalnih parametrov za površinske plasti TrS-delov; izbira racionalnih parametrov sestave in strukture površinskih plasti TrS-delov, izbira racionalne tehnologije za površinsko obdelavo TrS-delov; eksperimentalna preiskava površinsko utrjenih plasti TrS-delov in popravki tehnologije za površinsko utrditev.

Ključne besede: prevleke, torni par kontakta trdih površin, utrditev površine, tribološki sistem

1 INTRODUCTION

The use of surface engineering methods in tribological applications is growing and will continue to grow, as evidenced by a literature survey [1–9]. A surface treatment in the form of coatings and films and the modification of surface layers can offer certain economic and technical advantages over the use of materials without the surface-strengthening treatment. Their main advantage is that the strengthened surface layers allow the base material of tribological system (TrS) parts to be optimized for strength purposes, while the surface layer is optimized for reducing the wear and increasing the corrosion resistance, promoting film lubrication, enhancing lubricant effectiveness, the modification of surface function, etc. Furthermore, replacing the surface layer by coating deposition during repair may be more cost effective than the manufacture of a new TrS part. But the principal disadvantage in using coatings concerns the possibility of the separation from the base material of TrS part during use. While the discussions that follow emphasize the considerations important in the selection of tribological surface treatment, it should be noted that other alternatives might exist for any particular problem. This could involve, for example, use of a more effective lubricant, or a redesign of the tribological system's elements, the use of more effective methods of lubrication, the development of new or the use of improved materials, etc.

2 CLASSIFICATION OF SURFACE-ENGINEERING METHODS

Many technological methods and processes of surface engineering are available for the modification of surface characteristics. Tribological surface-treatment methods are used for different purposes: 1. Replacing surfaces with coatings and the deposition of films; 2. Surface modification (surface alloying and/or microstructure is altered); and 3. Combination of methods for coating deposition and surface modification. A wide variety of surface-modification methods are available for tribological purposes. The main categories are: 1. Modification of surface layers in the process of shape processing; 2. Heat (volume) treatment; 3. Surface heat treatment; 4. Treatment by surface plastic deformation; 5. Surface thermomechanical treatment; 6. Surface alloying; 7. Chemical and thermochemical treatment, including microarc oxidization; 8. Ion implantation; 9. Formation of a surface-layer composite structure by the introduction of hardening phase particles; 10. Others and hybrid methods.

Resurfacing essentially replaces the surface layer of a base material (or previously deposited coating) with another having more desirable friction and wear properties. Usually, the new surface is harder than the surface replaced, but not always. A wide variety of coating compositions is available. Each of these compositions can be applied by a variety of processes. The main categories of the coating-deposition processes are: Electroplating; Electrophorus; Electroless plating; Welding; Thermal spraying; Physical Vapour Deposition; Chemical Vapor Deposition (CVD); Immersion on melt; Electro-spark alloying; Electro-magnetic alloying; Bonding of powder layers; Solid phase plating (bonding of plates); Painting; and Continuous deposition of films in process of friction (rotaprint, from environment, etc.).

Some of these application processes are very simple and inexpensive, such as painting. Others are very complex, either requiring vacuum processing or requiring a series of treatments and pre-treatment. Some of them can be applied in the field, while others can only be applied at particular facilities. There is no shortage of tribological coatings and surface layers to try for almost any need. The primary problem that exists is knowing which surface treatment to select for any given application. A related problem is that surface treatment developers often do not know where their coatings should be used or what coating or kind of surface modification to develop to meet a particular need. There is a need for a strategy or methodology for selecting a surface-layer composition and structure, and the methods for obtaining a given tribological application. In this paper such a strategy is proposed and elements of that strategy are discussed.

3 SOLID SURFACE CHARACTERISTICS

The difficulties of the selection of surface-treatment methods are connected with a very large number of parametric variables of solid surface quality, which could be described by the following ensemble of characteristics

$$K \supseteq G_{ex} \cup G_{in} \cup S_c \cup S_s \cup Ph_c \cup Ph_s \cup Ch_c \cup Ch_s \cup Df_c \cup Df_s \cup St_c \cup St_s \cup Pmp_c \cup Pmp_s \cup Ptp_c \cup Ptp_s \cup ...$$

where G_{ex} is an ensemble of characteristics that are characterized by the geometry parameters of the external surface of the strengthened layer and in its turn could be characterized by the ensemble $G_{ex} \supseteq G_{exw} \cup G_{exm}$, where G_{exw} and G_{exm} are ensembles of the parameters of waviness and roughness of the surface, respectively; G_{in} is the ensemble of parameters that are characterized by the geometry parameters of the internal surface of the strengthened layer (or coating) and in its turn could be characterized by the ensemble $G_{ix} \supseteq G_{ixw} \cup G_{ixm}$; S_c and S_s are the ensembles of the parameters that are characterized by the geometry configuration inaccuracy of the surface of the strengthened layer (or coating) and its interface with main material, respectively; Ph_c and Ph_s are the ensembles of parameters that can be characterized; Ch_c and Ch_s are the chemical compositions; St_c and St_s are the ensembles of parameters that are characterized by the structure; Df_c and Df_s are the ensembles of parameters that are characterized by the deformation; Pmp_c and Pmp_s are the ensembles of the parameters that are characterized by the physico-mechanical properties; Ptp_c and Ptp_s are the ensembles of the parameters that are characterized by the thermophysical properties; the indices *c* and *s* are for the strengthened layer (or coating) and the structure of near-surface layer of the main material and/or the transition zone, respectively.

In searching for the optimal solution of a particular tribological problem it is necessary to consider the ensemble of parameters that is characterized by the assembly and friction surface working conditions

$$TrS \supseteq E \cup C_e \cup L_e \cup F \cup M_e \cup W_e$$

where E is the ensemble of the characteristics of the TrS workpieces; L_e is the ensemble of the characteristics of the linking between workpieces; F is the ensemble of the kind of friction and its main characteristics; M_e is the ensemble of the mutual shifting of the TrS workpieces; W_e is the ensemble of the wear characteristics of the TrS.

For dataware of the choice of the surface-treatment method it is necessary to elaborate the ensemble of the parametric variables of the solid surface quality that influences on the wear-resistance at different kinds of wear and control may affect the wear resistance

$$QPSS_i \supseteq G_{exi} \cup G_{ini} \cup S_{ci} \cup S_{si} \cup Ph_{ci} \cup Ph_{si} \cup Ch_{ci} \cup Ch_{si} \cup Df_{ci} \cup Df_{si} \cup St_{ci} \cup St_{si} \cup Pmp_{ci} \cup Pmp_{si} \cup Ptp_{ci} \cup Ptp_{si} \cup ...$$

where the index mark "i" is given for a certain kind of wear. Furthermore, it is necessary to elaborate the ensemble of parametric variables of the solid surface quality that is possible to control for each method of surface treatment and to determine the limits of this control.

$$QPSS_j \supseteq G_{exj} \cup G_{inj} \cup S_{cj} \cup S_{sj} \cup Ph_{cj} \cup Ph_{sj} \cup Ch_{cj} \cup Ch_{sj} \cup Df_{cj} \cup Df_{sj} \cup St_{cj} \cup St_{sj} \cup Pmp_{cj} \cup Pmp_{sj} \cup Ptp_{cj} \cup Ptp_{sj} \cup ...$$

where the index mark "j" is given for a certain kind of surface treatment.

4 METHODOLOGY FOR THE SELECTION OF THE SURFACE-ENGINEERING METHODS

Coating deposition and surface modification have rapidly evolved in recent decades from simple and traditional methods to extremely sophisticated technologies. These developments are part of an effort to eliminate the limitations imposed by oil-based lubrication and are changing the general perception of the limits of wearing contacts [6]. Knowledge of the mechanisms behind these improvements in lubrication and wear resistance is, in most cases, very limited. The methods employed in most studies on surface coatings and modification are empirical and there is relatively little information available on which surface technology is the most suitable for a particular application. Prior to selecting the coating material and the technological method it is necessary to determine the prime objective that could be used to reduce the friction or suppress the wear – or both. During the selection of the most effective surface material and process to suppress wear in a particular situation, the prevailing wear mechanism must first be recognized and assessed.

In the last years, much research is being carried out in the field of tribological coatings and surface treatment, and although they are being increasingly used in practice, little is still known about their properties and their tribological behaviour, especially for new, advanced surface technology. Different types of coatings of the same composition have different mechanical and tribological properties, depending mainly on the type of deposition process and the substrate material. Furthermore, due to the specific test methods and conditions for given applications or research facilities of an organization, it is seldom possible to compare the results obtained by different researches. The selection of a coating-material and coating-process combination for a specific substrate can be complex. There are a great number of possible combinations, not all of which lead to satisfactory solutions [1,6–9]. To overcome these problems, the strategy and the methodology for the selection of the optimal tribological coatings and the surface treatment for a given application are proposed.

The selection of the types of surface-strengthening treatment include the following stages, shown in **Figure 1**:

1. study of the initial data, including: composition and internal relations of the TrS (parts; relations between them; lubricant; surrounding environment); individual properties of the TrS parts, including the geometry parameters of the parts and the friction surfaces (macro- and micro-geometry) and the properties of the main material; the lubricant properties (volume and surface properties, chemical and physical, etc.); the aggregate properties of the lubricant and the TrS parts (the adsorption properties, moistness, etc.); the lubrication manner influencing, at first, on techniques and the lubrication type; the properties of the surrounding environment (the chemical composition, the corroding influence, the humidity, the temperature, the pressure, etc.); external influences on the TrS (kinetic – sliding (rolling) the velocity *V*, the hydrodynamic velocity; the dynamic – mechanical force, the pressure *P*, the electric field parameters; the thermal – temperature ϑ_0, the thermal flow, the thermal gradient); the technological limitations on the TrS parts treatment (the shape and the sizes of the parts and surfaces, the materials, the variability of the properties, the technological heredity, etc.); the managerial and economic limitations (the required productivity, the presence of equipment, the materials, the energy sources and others, the sanitary, hygienic and ecological demands, the permissible expenses, etc.).
2. the determination of the TrS parts' interaction during the static and dynamic conditions (adhesion, adsorption, chemosorption, oxidation, corrosion, diffusion, elastic strain, plastic deformation, micro-cutting, scratching, structure and phase transformation, etc.).
3. the development of the scheme of the TrS action, including the preliminary determination of the TrS characteristics for describing the input values *X* transformation in the output values *Y*

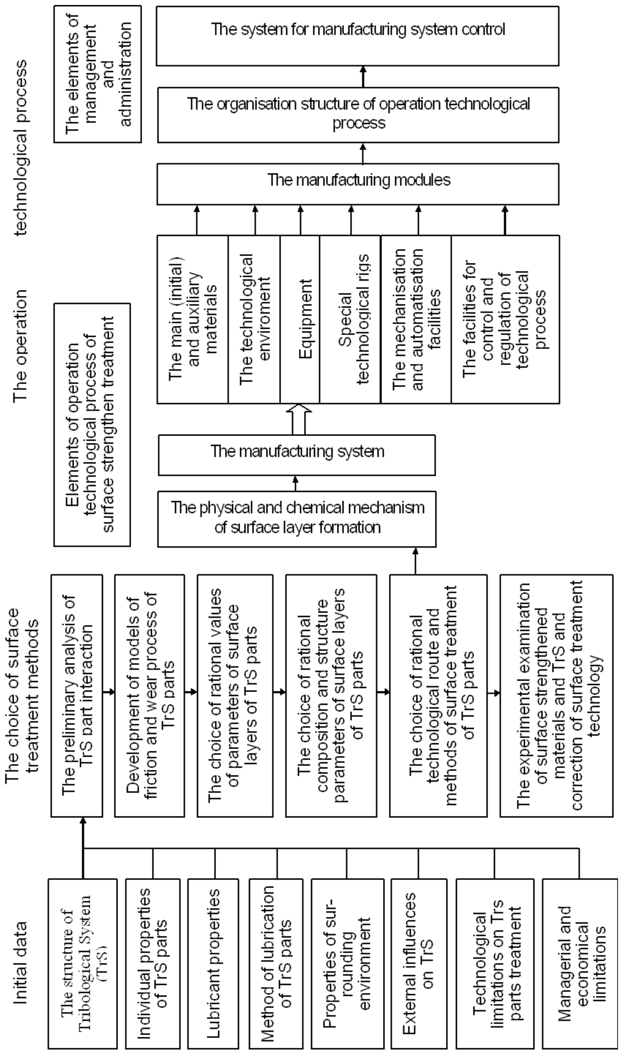

Figure 1: Scheme of the development of the operation technology of the surface-strengthening treatment
Slika 1: Shema razvoja operacij tehnologije za utrditev površine

$$\{X\} = \{P,V,\vartheta_0\} \Rightarrow \{Y\} = \{F_t,Z,P_t\}$$

where F_t is the friction resistance, Z is the wear and seizure, P_t is the accompanying processes.

4. the development of the models of friction and the wear process of the TrS parts (physical, mathematical, imitative, analogue);
5. the determination of the rational values of the parameters of the surface layers' properties by using the models of friction and wear (by obtaining the permissible values of Y);
6. the selection of the rational composition and the structure of the surface layer of the TrS parts (we must take into account the existing analogues and also the structure–properties correlations);
7. the determination of the direction of the surface-strengthening treatment of the friction surface of the TrS parts: or the surface layers' modification, or the coating deposition or their combination;
8. the determination of the list of possible physico-chemical methods of surface-strengthening treatment;
9. the preliminary selection of the optimal methods of surface-strengthening treatment by using elected criterions of optimisation and the maintenance of the required technique-economic limitations;
10. the experimental test of the surface-strengthening treatment in the laboratory or the empirical-industrial conditions;
11. the preliminary projection of the operating methods of the surface treatment – equipment, the special technological rigs, the technological variables, the technological environment, the facilities of the mechanisation, the robotisation and the automation, the methods of management and control, the techno-economic comparison of the operating variants;
12. the clarification of the relationships between the operation technology of the surface-strengthening treatment and the manufacturing procedure of the TrS parts' production; the correction of the structure for both processes for the purpose of their optimisation;
13. the final selection of the surface-strengthening treatment methods, the development of measures for the reliability of the maintenance of the demanded characteristics of the technological process; the development of a project for the processing system of the surface treatment.

The selection of the optimal methods of the surface-strengthening treatment usually realized by employing technical criteria to secure the required TrS tribotechnical characteristics according to scheme, shown in **Figure 2**. In the case of the presence of some equivalent surface-treatment variants on the tribotechnical characteristics for the final selection economic criteria are used. The system of the selection of the optimal surface-strengthening treatment includes the scheme of the TrS action and the database of the multitude of surface-strengthening treatment classes and the methods' characteristics. Preliminarily, by using the technological limitations, other initial data and the database, one could select a recommended group of parameters of the surface layers' quality, which promoted the increasing wear resistance. The next would be the selection of respective methods of surface-strengthening treatment, which allowed a control of the desirable parameters of the surface-layer quality. Then, with use of the earlier developed model of friction and wear for the TrS we can make a more detailed valuation of the selected decision, including the calculation and the experimental determination of the tribotechnical characteristics and the following test of the TrS. The use of different methods of surface-strengthening treatment opens up vast possibilities for the control of friction surfaces' contact interaction, independent of the composition and the structure of the main materials of the TrS parts.

Depending on the kind of aggregate of the contacting surface layers of the friction pairs it is possible to divide

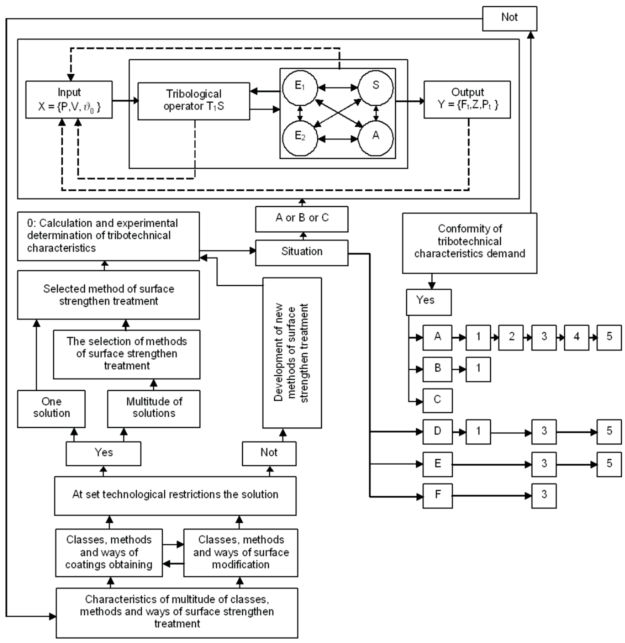

Figure 2: Scheme of the selection of the optimum methods of surface-strengthening treatment. Situation: A – the development of a tribological system not having analogues; B – the selection of a new friction pair instead of an out-of-date one; C – the selection of a friction pair for a weak-loaded typical tribological system; D – the improvement of a typical tribological system; E – the replacement of friction pair by a new serial one; F – the determination of an inter-repair cycle. The stages of selection: 0 – the calculation and the experimental determination of the tribotechnical characteristics; 1 – the research test at the determined parameter; 2 – the boundary research test (under extreme conditions); 3 – the model research test; 4 – the defined nature test; and 5 – the exploitation test

Slika 2: Shema za izbiro optimalne metode za utrditev površine. Situacija: A – razvoj tribološkega sistema brez analogov; B – izbira novega tornega para namesto opuščenega; C – izbira tornega para za malo obremenjen tribološki sistem; D – izboljšanje tipičnega tribološkega sistema; E – zamenjava tribološkega sistema z novim standardnim; F – določitev vmesnih popravil. Izbira stopnje: 0 – izračun in eksperimentalna določitev triboloških značilnosti; 1 – preizkus pri določenih parametrih; 2 – mejni preizkus (v ekstremnih razmerah); 3 – preizkus modela; 4 – določitev naravnega preizkusa; 5 – preizkus uporabe them into three classes: 1) the contact of two one-phase surface layers; 2) the contact of a one-phase layer and a composite-structure surface layer; and 3) the contact of two composite-structure surface layers.

Only in the case of the contact of one-phase surface layers is the common number of possible variants of the contacts very high and can be evaluated with the next equation

$$K_{\text{sum}} = 2(n^2 + m^2 + q^2) - 3(n + m + q) + 6 + \\ + 2(nm + nq + mq)$$

where n is the number of simple substances, m is the number of two- and many-component solid solutions, and q is the number of two- and many-component chemical compounds.

These multiplicity of possible variants of the contact in the case of only one-phase surface layers is allowed by the choice of the composition of the surface-layers materials and their structure to control the quality of the physical contact of the friction pairs, in particular the size of real contact area, of the tendency to form desirable secondary structures in the process of friction, the properties of a third (intermediate) substance, and the fatigue-wear resistance, etc.

In reality, the factual variety of the possible contacts of one-phase layers is considerably more, inasmuch as the friction processes depend not only on the chemical composition of the contacted surface layers, but also on their structure and energetic parameters, including the size, shape and character of the mutual orientation of the grains; the structure and strength of the intercrystalline boundaries; the level of the strain hardening; the type of the crystal lattice; the mechanical properties; the surface properties, etc.

The creation on one or both friction surfaces for the layers with a composite structure leads to an essential increasing of the possible variants of the friction surfaces' contacts and to the appearance of some new physico-chemical phenomena in the process of friction. The peculiarities of the contact interaction of such friction pairs are at first connected with the simultaneous presence of the contact aggregate between the friction surfaces. But the description of the friction zone in the contact of such surface layers demands the use of complex or special parameters.

5 CONCLUSION

The approach to the development and selection of a surface-strengthening treatment for tribological purposes has to involve methods of system analyses. The tribological system's workpieces' and friction surfaces' functions must be accurately defined in functional, technological, economic, ecological and other respects. The proposed strategy has the potential for simplifying the selection and design of coatings and/or surface layers and the reduction of the development time for new tribological systems and/or the improvement of existing ones. But the subsequent laboratory tests at several levels must also be completed. The development of computer-modelling methods for the selection of surface-engineering processes and expert systems for developing the surface-engineering technology for a particular application is necessary. The system approach could also be useful for the development of new tribological coatings and surface-modification methods. However, a lot has still to be done for the development of a methodology for the selection of optimum methods for surface engineering and their improvement.

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