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Examination of Dynamics of Polymeric Coatings Erosive Wear Process

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An assessment of erosive wear process dynamics of epoxy coatings is presented in the paper. From the examination results it was stated that kinetics of erosive wear depends on erosive particles velocity, their concentration, micro- and macrostructure of coating and impact angle of particles. Microcutting of coatings is a dominant process of examined coatings wear and its greatest share is observed for impact angles $\alpha < 30°$. However, the participation of fatigue spalling of coating material, processed by its plastic deformation, increased with increase of erosive particles impact angle. The proposed mathematical model of erosive wear process of construction element surface effectively describes dynamics of this process in dependence on: erosive particles impact angle, their concentration and velocity in the moment of impact. Finite elements method enabled effective prediction of surface profile shape of polymer coatings subjected to the erosive particles action.

Keywords: polymer coating, erosion, erosive wear rate, prediction of wear.

1. INTRODUCTION

Erosive wear process of polymeric coating depends on such mechanical properties of erosive particle and coating material as hardness of contacting elements, tensile and fatigue strength as well as impact energy absorbing capacity of coating material and coefficient of friction between the hard particle and the coating [1 – 11]. Dynamics of coating erosive wear depends also on other aspects of the process like kinetic, geometric (erosive particles shape, coated element shape) [5, 12 – 14], energetic (friction heat), impact energy of erosive particles and also climatic factors: ultraviolet and infrared radiation, humidity, wind speed, thermal shocks [15 – 18].

An angle of hard particles impacting on coating surface influences significantly the wear rate of polymer coatings [18]. The depth of particles inclusions into coating surface layers depends on impact angle (α). A position of extreme on characteristic of coating wear rate versus impact angle of hard particle is subjected to coating hardness [19, 20 – 22].

In the case of coatings made of plastic polymers, characterized by low modulus of elasticity, the highest wear speed is observed for acute impact angles.

An increase of friction coefficient shifts the characteristic extreme in the direction of lower angles [11 – 14, 23 – 26].

Appearance of erosive wear products results from formation of relief on coating surface in the moment of elementary events of interaction between the hard erosive particles and polymeric material [27].

Therefore, in order to predict wear of polymer coatings, it is necessary to create a model of their erosive wear that includes dynamics of coating relief changes, and this problem is considered in the paper.

2. EXPERIMENTAL

2.1. Examination method

The erosive wear examination method employing the testing device (Fig. 1), recommended by the Polish Standard PN-76/C-81516, was used.

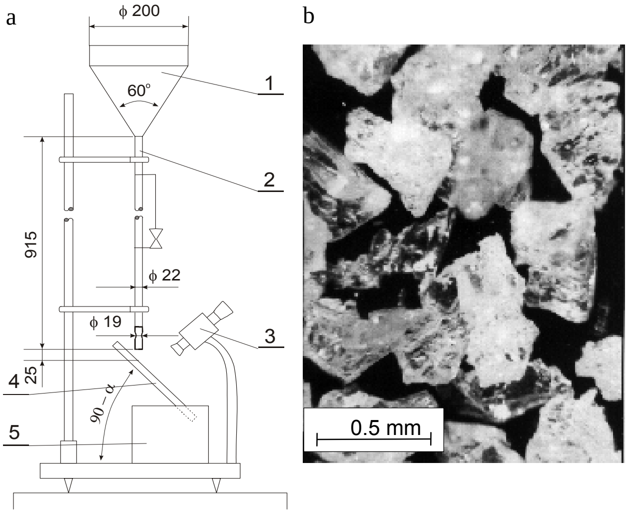

Fig. 1. Apparatus for testing erosive wear of organic coatings (a): 1 – container for erosive material; 2 – pipe transporting of erosive material; 3 – optical microscope; 4 – rotational holder for fixing metallic test specimen with an organic coating; 5 – container collecting erosive material after the test; b – particles of granulated alundum (magnification ×30)

In order to study the influence of an impact angle of the erosive particles on the wear of an organic coating, the test specimen was mounted in a specially designed specimen holder which allowed precise setting of the angle of the specimen surface, which was subsequently subjected to testing. The tilt range was from 0° to 90°. Particles of granulated alundum of grain size (0.60 – 0.71) mm (according to the Polish Standard PN-76/M-59111) have been used as the abrasive material. Aluminium trioxide (Al_2O_3) is the

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main constituent (99 % by weight) of the abrasive while SiO_2, Fe_2O_3, CaO and Na_2O make up its residual part. The mass of one charge of alundum delivered to the container 1 (Fig. 1) was 3.5 kg, while at the end of the test, i.e. when the substrate material was exposed, the charge of alundum was reduced to 0.5 kg. In order to assess the resistance of the coating to erosive wear the *I*-criterion, calculated from equation (1), was used.

$$I = \frac{G}{M}, \tag{1}$$

where I is the intensity of erosive wear of organic coating (μm/kg), G is the coating thickness (μm) and M is the mass of erosive particles (kg). The above mentioned formula displays the ratio of the coating thickness to the total mass of erosive particles producing the total wear of the coating within the tested area, i.e. generating the exposure of the substrate material in the elliptic shape of the minor diameter of d = 3.6 mm ±0.1 mm.

2.2. Preparation of the epoxy coating

The first type of coating examined consisted of three epoxy layers. The second type of coating consisted of three epoxy layers with the composite interlayer containing 10 wt % of glass microspheres (Fig. 2) of diameter of $\phi < 30$ μm [21]. The third type of coating consisted of three composite layers. All types of coating were produced on steel test plates.

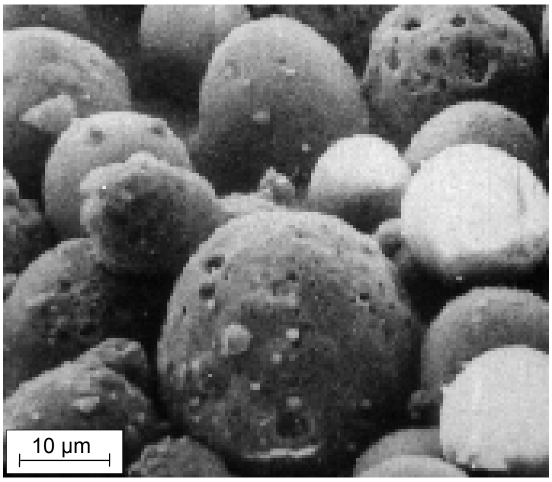

Fig. 2. Morphology of glass microspheres

The epoxy coatings subjected to the wear resistance tests were prepared from red oxide epoxy paint, which is resistant to chemicals. This paint was blended with a polyamide curing agent at the mass ratio 77 : 23, respectively. In the case of the modified coating, filler in the form of glass microspheres was added into the mixture. Then, 30 min. mixing was performed and after a period of 2 h the application of coatings began. Three layers were deposited consequently by means of air-operated spraying. Each layer was subjected to a two-stage hardening for 24 h at the temperature of 20 °C ±2 °C and then for 30 min. at the temperature of 120 °C. Before the testing procedure was performed all the specimens were subjected to 10 days acclimatisation at the temperature of 20 °C ±2 °C and at the relative humidity of 65 % ±5 %.

The thickness measurements of the coating were performed by means of an electromagnetic thickness gauge (A-52) and the average thickness of the three-layer coating was 120 μm. Examinations of coatings of different thickness (90 μm to 199 μm) showed that maximum erosive resistance were obtained for thickness from the range of (120 – 40) μm [22].

Glass microspheres used as filler were spherical particles of alumino-silicate filled with carbon dioxide CO_2 and nitrogen N_2. The main constituents of their walls are silicon dioxide SiO_2 (49 % – 61 %) and aluminium trioxide Al_2O_3 (26 % – 30 %). Production of glass microspheres is based on fly-ashes which are by-products of burning hard coal in power plants. Well developed surfaces of glass microspheres as well as coating their surfaces with a specially invented polymer finish, composed of methyl methacrylate and methacrylic acid [21], ensure strong and tight binding of the filler and the epoxy resin. Differentiated diameters of the glass microspheres as well as their irregular shape enable effective filling of internal voids in the structure of the epoxy resin, which yields lower porosity of the coating. This improves both the mechanical properties and thermal resistance of the coating. It also reduces the ability of the plastic to absorb water and aggressive agents [15 – 19, 26].

3. RESULTS AND DISCUSSION

3.1. Influence of epoxy coating structure and impact angle of hard particles on erosive wear intensity

The organic coating consisting of three composite layers revealed the lowest resistance to erosive wear (see Fig. 3).

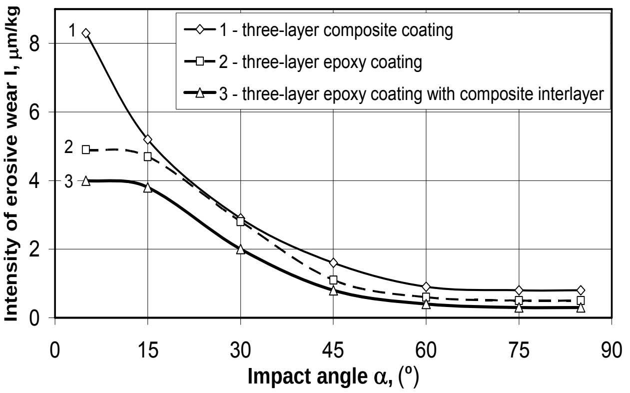

Fig. 3. Influence of epoxy coating composition on intensity of wear resulting from alundum particles impacts: 1 – three-layer epoxy coating modified with glass microspheres (composite coating), 2 – three-layer epoxy coating, 3 – three-layer epoxy coating with composite interlayer

It is worth noting that low resistance of the walls of the glass microspheres to shear stresses is responsible for this effect. The epoxy coating with the composite interlayer was the most resistant to erosive wear. The reason of this effect is dissipation of energy, released during the collision of alundum particles with the coating by the composite interlayer. The reduction in intensity of mass loss of the organic coating with the composite interlayer may be due to erosive wear products accumulation inside spherical caps of the glass microspheres.

The process of erosive wear of an organic coating was investigated for the values of alundum particles impact angle α ranging from 5° to 85°. Detailed examination of these figures shows that the lower α – angle, the higher the intensity of the erosive wear of a coating. The most intensive erosive wear resulting from impact of alundum particles was recorded for the impact angles $\alpha < 45°$, while the lowest was for the impact angle $\alpha > 60°$. Morphology of the surfaces of the epoxy coatings modified with glass microspheres which were subjected to erosive wear tests at an impact angle $\alpha = 45°$ is presented in Fig. 4 and Fig. 5.

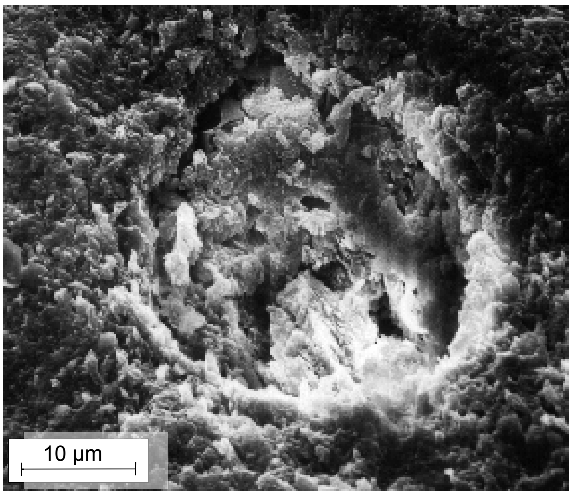

Fig. 4. Erosive wear of the surface of the epoxy coating modified with glass microspheres

At the initial stage of the erosive wear of the composite coating, the walls of glass microspheres situated at the surface of the coating are subjected to shearing, while the surface layer of the coating around the filler particles undergoes strong plastic deformation (Fig. 6). During the subsequent stages, microcutting of epoxy material and shearing of the walls of glass microspheres proceeds, until the steel base material appears.

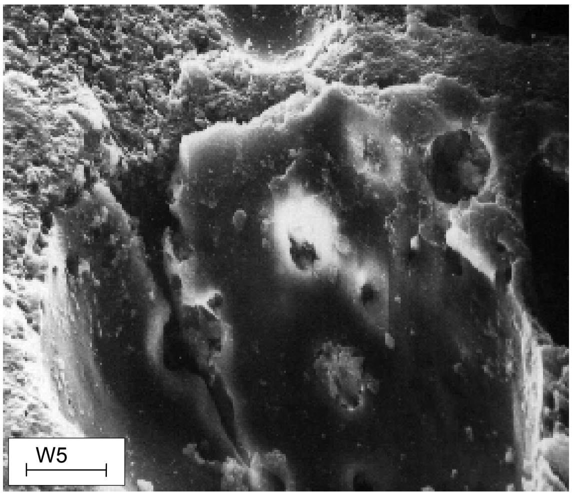

Fig. 5. Erosive wear of the glass microsphere included in the epoxy material

On the basis of the carried out examination it can be stated that resistance of epoxy coating to erosive wear increases as coating thickness increases too. It means, of course, that intensity of the coating wear decreases. It should be explained by more effective dissipation of thermal energy (released during impacts of hard particles) by the coating of higher thickness (volume). However, increase of the coating thickness over critical value leads to increase of internal stresses in the coating. It can be a reason of microcracks generation in the coating resulting in intensity of coating erosive wear increase [3, 21, 26, 27].

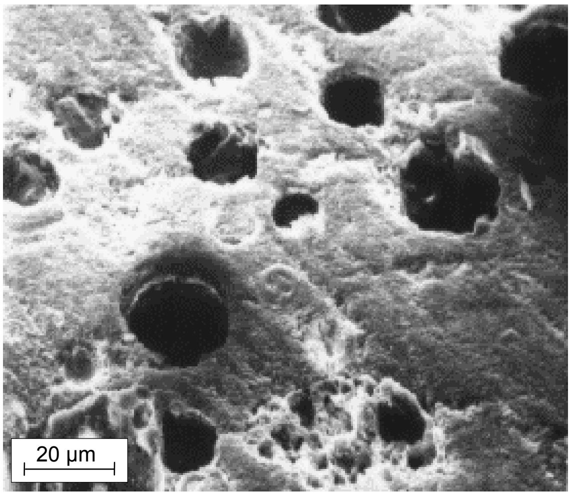

Fig. 6. Morphology of epoxy coating surface subjected to erosive action of alundum particles for $\alpha = 45°$

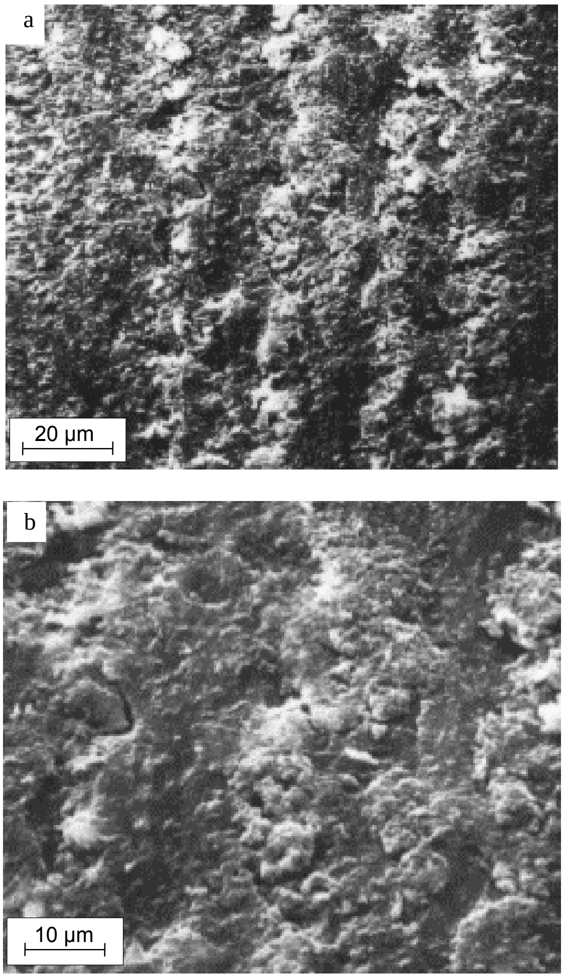

Fig. 7. Morphology of epoxy coating surface subjected to erosive action of alundum particles (for $\alpha = 45°$)

Under the influence of alundum particles the relief of epoxy coating surface layer changes (Fig. 7).

The morphology of epoxy coating surface layer presented in Fig. 7, a, testifies to microcutting while the morphology of coating in Fig. 7, b, documents fatigue breaking away of coating pieces. These processes occur simultaneously. However, for acute impact angles of erosive particles microcutting of coatings dominates that results in cutting of relief protuberances what has an effect on speed increase of erosive wear process.

3.2. Model of polymeric coatings erosive wear

Basic assumptions for the erosive wear modelling of elements covered with polymeric coatings are as follows:

- speed of erosive wear of any construction element is defined as a relation of its thickness loss value (in direction perpendicular to the element surface) to the value of given period of time;
- speed of erosive wear depends on impact angle of the erosive particles.

In the proposed model it is assumed that rate of changes in element surface layer is proportional to the amount of material loss occurring during hard particles erosive action.

The rate of erosive wear of machine element surface can be described by dependence:

$$D_n = -\frac{F'_t\,(x,y,t)}{\sqrt{(F_x')^2 + (F_y')^2}}\ , \qquad (2)$$

where $F(x, y, t) = 0$ is the general equation of structural element surface at moment of time t.

As a result of the carried out examination of polymeric coatings of erosive wear, the dependence was obtained between the wear rate of protective coatings and incidence (impact) angle of erosive particles:

$$D_n = \left(\frac{V}{V_0}\right)^2 \frac{c}{c_0}\Phi(\alpha)\ , \qquad (3)$$

where: α is the impact (incidence) angle of abrasive particles; V is the abrasive particles rate (standard – $V = 4.29$ m/s); V_0 is the abrasive particles rate in experimental tests in carried out tests $V = V_0$); c is the concentration (standard) of erosive particles; c_0 is the concentration of erosive particles in experimental tests (in carried out tests $c = c_0$).

Rate of erosive wear of machine element surface can be described by dependence:

$$\frac{\partial F}{\partial t} = \sqrt{1+(F_x')^2}\cdot\Phi\left(arc\cos\frac{|F_x'|}{\sqrt{1+(F_x')^2}}\right)\ , \qquad (4)$$

where: $F(x, y, t) = 0$ is the general equation of construction element surface at moment of time t,

$$\cos\alpha = \frac{|F_x'|}{\sqrt{1+(F_x')^2}}\ , \qquad (5)$$

$$\alpha = arc\cos\frac{|F_x'|}{\sqrt{1+(F_x')^2}}\ . \qquad (6)$$

In order to solve the equation (4), describing rate of erosive wear of machine elements surface, the finite elements method was used. In case of erosive wear, the element of shape shown in Fig. 8 was assumed (R = 10 mm, h = 4 mm). Polymeric coating applied on steel element surface had thickness h_p = 120 µm.

Alundum particles beam impacted with speed V = 4.29 m/s along Y-axis (Fig. 8) on the steel element surface causing change of the element thickness h (7):

$$h(x,t) = \frac{f(x,t)}{\sqrt{1+(f_x')^2}}\ , \qquad (7)$$

where: $f(x,t)$ is the surface equation.

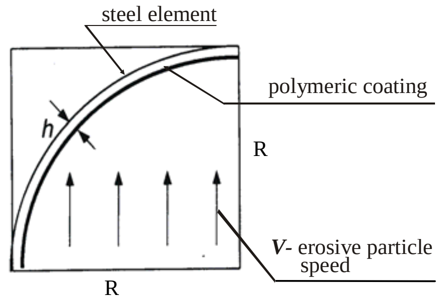

Fig. 8. Shape of discussed constructional element covered with polymer coating of thickness h_p

The above discussed model has been applied to predict erosive wear of steel element surface layers. In the first case this element used without any coating and other two cases two kinds of epoxy coating were used. The experiments were run in the conditions of hard particles erosive action.

Initial thickness of steel element $h(x, 0)$ = 4000 µm. Curves shown in Fig. 9 represent predicted thickness loss characteristics for different moments of time as a function of distance from the left edge of the element. Profile of the steel element surface assumes change of the shape of a crater that becomes deeper and deeper in time as a result of wear. It is clearly seen that the deepest point of the crater shifts from the centre of the element to its left side.

The results of the carried out calculations of the surface profile shape of polymeric coating subjected to alundum erosive action are presented in Figs. 10 and 11 for different ranges of impact angles. They show that process of erosive wear of elements with polymeric coatings runs in another way than process of erosive wear of steel elements without coating [27]. The highest intensity of erosive wear is observed in these places of parts with polymeric coating where their surfaces are inclined under acute angles (α < 40°) with respective to the erosive particles beam.

The characteristics, describing thickness of epoxy coating changes in time, indicate that dimensions of erosive crater originating in polymeric coating increase during alundum particles erosive action. The original thickness of the coating was 120 μm. Curves presented in Fig. 10 correspond to 10-second periods of time. The deepest recess occurs at 0.04 mm distance from the left side of the element as it can be seen from Fig. 8.

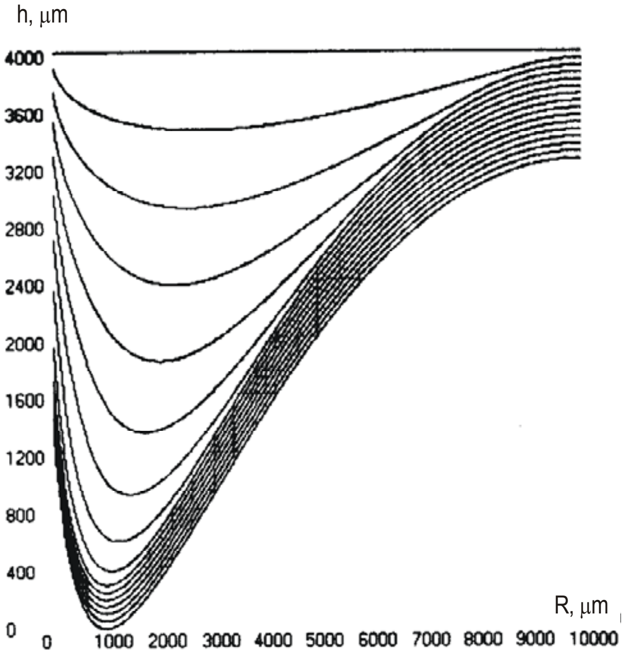

Fig. 9. Dynamics of the surface profile change of steel element (without polymer coating) as a result of erosive action of alundum particles

Such shape of the crater can be explained by the fact that microcutting of epoxy coating prevailes during alundum particles erosive action.

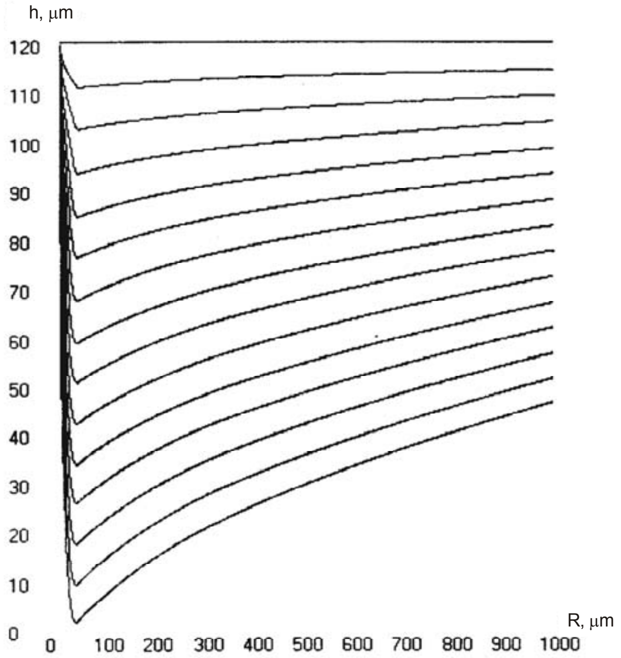

Fig. 10. Prediction of the surface profile of epoxy coating subjected to the erosive influence of alundum particles, for the impact angles $0 < \alpha < 40^o$

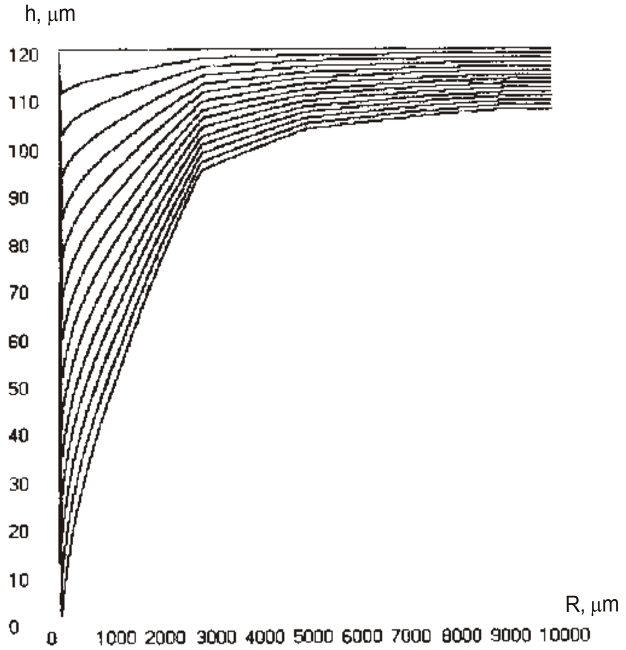

Fig. 11. Prediction of the surface profile of epoxy coating subjected to the erosive influence of alundum particles, for the impact angles $0 < \alpha < 90°$

4. CONCLUSIONS

1. Erosive wear of machine elements is the complex process where crucial role is played by mechanical properties of contacting materials. For this reason the process of erosive wear of metallic machine elements is different than one for elements with polymeric coatings.
2. Presented mathematical model of erosive wear process of machine structural elements effectively describes dynamics of the process in dependence of erosive particles impact angle, erosive particles concentration and their speed in the moment of impact on surface. Application of finite elements method enabled effective prediction of surface profile shape changes for polymeric coatings subjected to erosive particles action.
3. Action of erosive particles promotes the process of fatigue spalling of coating material from the surface layer. However, dynamics of polymeric coatings erosive wear process depends essentially on the impact angle of erosive particles. For angles lower than 40° the process of coating cutting dominates. For angles higher than 40° plastic deformation of coating surface layers, as a result of alundum hard particles intrusion into elastic epoxy material, is dominating process of wear.
4. Epoxy coating composition shows essential influence on erosive wear kinetics. The lowest intensity of wear is observed for three-layer epoxy coating with interlayer modified with the glass microspheres. The glass microspheres suspended in elastic epoxy material dump mechanical energy released during the impacts of hard particles on coating surface. The highest intensity of erosive wear is demonstrated by the epoxy coating consisting of three layers modified with the glass microspheres. It results from higher roughness of

composite coating as well as low coating resistance to action of shearing forces causing cutting of coating.

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