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The application of statistical models in wear resistance simulations of Al-Al_2O_3 composites

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ABSTRACT

Purpose: The purpose of this paper is application of statistical models in tribological properties simulation of composite materials based on porous ceramic preforms infiltrated by liquid aluminium alloy.

Design/methodology/approach: The material for studies was produced by a method of pressure infiltration of the porous ceramic framework. In order to investigate the influence of reinforcing phase's shape the comparison was made between the properties of the composite material based on preforms obtained by Al_2O_3 Alcoa CL 2500 powder sintered with addition of pore forming agent in form of carbon fibres Sigrafil C 10 M250 UNS from Carbon Group company and composite materials based on much more expensive commercial fibrous preforms. The wear resistance was measured by the use of device designed in the Institute of Engineering Materials and Biomaterials. The device realize dry friction wear mechanism of reciprocating movement condition. The simulation of load and number of cycles influence on tribological properties was made by the use of statistical models.

Findings: The received results show the possibility of obtaining the new composite materials with required tribological properties moreover those properties can by simulated by the use of statistical models.

Practical implications: The composite materials made by the developed method can find application as the elements of devices where beside the benefits from utilizable properties the small weight is required (mainly in aircraft and motorization industries).

Originality/value: Worked out statistical models can be used as helpful tool to predicate the wear of aluminium matrix composite materials in condition of dry friction.

Keywords: Materials; Composites; Infiltration; Simulation; Statistical models

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ENGINEERING MATERIALS PROPERTIES

1. Introduction

Currently, the most widespread use have found the composite materials with the light metals matrix, and especially from the aluminium alloys, reinforced with the ceramic particles or fibres that can be employed in many industry branches, first of all in the aircraft industry, automotive, and armaments ones, as well as in electrical engineering and electronics, etc. Aluminium and its alloys are characteristic of good mechanical properties, and the reinforcing particles are introduced to improve them further, e.g., ceramic particles, and the composite materials obtained in this way have much better mechanical properties than alloys [1-3].

In last years, much interest was focused on the use of Al_2O_3 fibres or particles reinforced aluminium matrix composite materials. The process of manufacturing these composites includes solid-state processes such as powder metallurgy (PM) [4-8], where metal and ceramic powders are blended than hot-pressed, and liquid-state processes such as melt infiltration, blending ceramic powder with molten aluminium than casting, melt stirring, pressurized infiltration and squeeze casting [8-14].

Pressure infiltration method is used more and more often in manufacturing of the composite materials with metal matrix and has also become the subject of many research projects [8-14]. The usage of infiltration process as the high-profitable technology is a base of getting the wide range of composite materials and allows to obtain the following technological-organizational profits [8,15]: the possibility of obtaining the composite products of precise shape mapping and the high-quality surface (near net shape), adaptation of the process to the mass scale production, free variability of reinforcing phase and matrix material, high-productivity process with relatively low-cost of production, the possibility of local reinforcement of the product.

The ceramic preforms, being a framework, are the base of the composite materials manufactured by infiltration method. These preforms mainly determine the structure and the properties of the final product. The properly manufactured semi-finished product should be characterized by open porosity allowing the liquid metal to flow as easily as possible. The occurrence of the closed pores or blind canals causes the formation of micro voids. Several fundamental development ways of porous ceramic material manufacturing are observed but sintering of ceramic powders with the addition of pores forming agent is the most flexible method and allows obtaining the diverse structure materials and ceramic phase content. The level of porosity and its character can be adjusted with different pore forming agents (PFA) addition, that are degradated in high temperature in the areas where the pores are originated [8,15].

The relatively poor wear resistance of aluminium alloys has limited their uses in certain tribological environments. Seizure and wear resistance in aluminium alloys could be substantially improved by incorporating of hard ceramic particulates or fibres (e.g., Al_2O_3, SiC, BN, Ti(C,N) and ZrO_2) [8,16]. Designing of composite materials with advantageous tribological properties is not easy and is connected with analysis of many factors [8,16]:

- chemical composition of reinforcement,
- portion of reinforcement,
- changes of the shape and size of reinforcement.

The goal of this work is examination and simulation of tribological properties of the EN AC - AlSi12 alloy matrix composite material manufactured by the pressure infiltration process. As a reinforcement were used the Al_2O_3 preforms fabricated by sintering of Alcoa CL 2500 powder with addition of pore forming agent, and much more expensive commercial fibrous preforms.

2. Experimental procedure

The material for investigation was produced by the method of pressure infiltration of porous ceramic frameworks with liquid aluminium alloy. The composites matrix consisted of eutectic alloy EN AC – AlSi12 and as the reinforcement the porous ceramic frameworks were used consisting of Al_2O_3 particles or fibres, respectively.

Ceramic preforms from Al_2O_3 particles were produced by Alcoa CL 2500 powder sintering method with addition of pore forming agent in form of carbon fibres Sigrafil C 10 M250 UNS from SGL Carbon Group company. The properties and chemical composition of the used carbon fibres and ceramic powder are shown in Tables 1 and 2 respectively.

Table 1.
Properties of Sigrafil C10 M250 UNS carbon fibers

Property	Value
Fiber diameter [µm]	8
Mean fiber length [µm]	135
Fiber density [g/cm^3]	1.75
Tensile strength [GPa]	2.5
Young's modulus [GPa]	26
Carbon content [%]	>95

Table 2.
Chemical composition of Alcoa CL 2500 powder

Mean mass concentration of components, wt.%						
Al_2O_3	Na_2O	Fe_2O_3	SiO_2	CaO	B_2O_3	The others
99.80	0.05	0.02	0.01	0.01	0.01	0.10

Producing the ceramic preforms included preparation of powder and carbon fibres mixture, their pressing and sintering. The Al_2O_3 powder was wet grinded in ball mill to destroy particles agglomerations. Into the suspension the 30, 40 or 50% addition of mass carbon fibres were added and polyvinyl alcohol Moviol 18-8 soluted in water (binding agent). Mixture of powder prepared in such a way was dried by freezing and water sublimation in low pressure. Dry powder was sieved through a sieve No 250, and then placed onto the flat surface and sprayed with destilated water to activate the polyvinyl alcohol. After 24 h the powder was submitted to uniaxial pressing with laboratory Fontune TP 400 hydraulic press fitted with 45x65 mm. steel form. The pressure was 100 MPa and pressing time was 15 s. Mouldings were sintered in "Gero" pipe furnace in air atmosphere (20 l/min). The temperature during the sintering process was ensuring the carbon fibres degradation (heating for 10 h at temp. 800 ºC) and Al_2O_3 powder sintering at temperature of 1500 ºC for 2 h. The porosity of the ceramic preforms was established on the basis of geometric measurement of their weight with the known Al_2O_3 particles density. The porosity depends on the carbon fibres content 69% at 30% of carbon fibres addition, 75% at 40% of carbon fibres addition and 80% at 50% of carbon fibres addition, respectively. For the comparison of properties of the composite materials on the grounds of the produced frameworks with materials reinforced by fibrous preforms for further studies the commercial semi-finished products were used with 25% portion of Al_2O_3 fibres.

The internal surfaces of ceramic preforms were coated with nickel in order to improve the Al_2O_3 wettability by the liquid aluminium alloy. Solutions containing metallic Pd were used for activation of the ceramics surface. Reagents were pumped through preforms to cover their internal surfaces on especially designed device.

All types of uncoated and coated by Ni ceramic preforms were heated in furnace up to temperature 800 ºC. Covered by graphite form was warmed up to 450 ºC (maximal temperature of the press plates) and then fulfilled with preform and liquid alloy EN AC – AlSi12 with temperature of 800 ºC which chemical composition is presented in Table 3. The whole was covered by the stamp and placed in hydraulic plate press Fontune TP 400. The maximum infiltration pressure was 100 MPa and its influence was 120 s. After solidification obtained materials were removed from the form and cool down under pressured air stream.

Table 3.
Chemical composition of EN AC-AlSi12 aluminium alloy

Mean mass concentration of elements, wt.%							
Si	Fe	Cu	Mn	Zn	Ti	Others	Al
12	≤0.55	≤0.05	≤0.35	≤0.15	≤0.2	≤0.15	The others

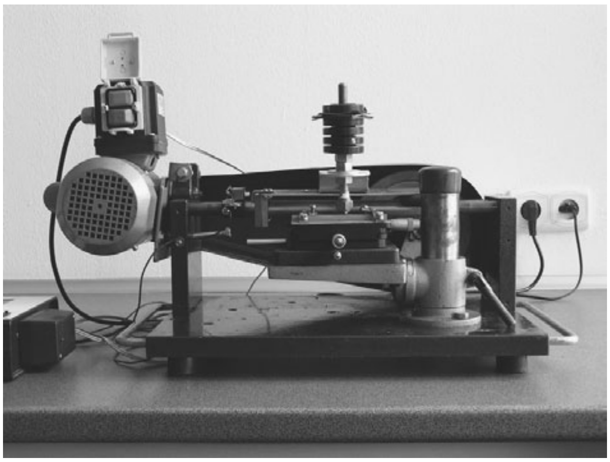

Fig. 1. Device for wear resistance measurements

The wear resistance was measured by the use of device designed in the Institute of Engineering Materials and Biomaterials (Fig. 1). The device realize dry friction wear mechanism of reciprocating movement condition. The samples preparation for examinations consisted of grinding by the use of abrasive paper with grit # 1200 to obtain flat and smooth surface. On samples prepared in this way there were made investigations with the steel ball 8.7 mm diameter as counter-sample. Investigations were made with different number of cycles 1000, 2000, 3000, 4000, 5000, respectively 24, 48, 72, 96 and 120 m, and under various load 2.5, 5, 7.5, 10 N.

Samples after examinations were rinsed in ultrasonic washer to clean its surface, and then the degree of wear was established on the base of geometrical measurements of wear track and calculation of its volume. The volume loss as the indicator of absolute wear is used when the mass lost is too small and difficult to estimate. There were also made observations on the light microscope LEICA MEF4A of the wear track character.

To evaluate the correlation between the amount of reinforcement phase, load, number of cycles (friction distance) and the abrasive wear expressed by the volume of wear track statistical models were used.

The multiple regression method was used for development of the statistical models, which makes investigation possible of relationships among many independent variables (exogenous variables, predictors) and the dependent variable (criterion variable, endogenous variable).The base of the analysis is multiple regression equation in the general form (for linear regression):

$$\hat{y} = b_0 + \sum_{i=1}^{m} b_i x_i \qquad (1)$$

where:
$\hat{y}$ - dependent variable
bi - coefficient of regression equation,
xi - independent variables of regression equation,
m - number of independent variables of regression equation.

There was evaluated a mathematical model which allow to determine the abrasive wear for matrix material, composite materials reinforced by commercial fibres preforms and reinforced by manufactured ceramic preforms. There were also made separate models for the case when additional Ni coating was used or not. This solution was used because in this statistical method it is impossible to use simultaneously the quantitative (load and friction distance) and qualitative (application or not the Ni coating).

In consequence five regression models were made to evaluate the wear resistance for each group of investigated materials.

Application of multiple linear regression needs assumption that the dependence between variables is linear as was found in [17], procedure of multiple regression are sufficiently resistant to small departure from the assumption of linearity of investigated dependence. There were made as pre-analysis (not shown in this paper) linearity analyses of two-dimensional diagrams of assumptions. Correctness of assumption was confirmed by investigation results.

The estimation of equation (1) coefficient was made by least squares method. To check the assumptions correctness of models linearity, the evaluation of multiple correlation coefficient and its significance and significance of equation coefficient was made. The calculations of regression equation coefficients and the other analyses were made using StatSoft Statistica 6.0 software.

3. Experimental results and their discussion

As a result of tribological measurements there was estimated the wear resistance in the condition of dry friction of composite materials and its matrix (aluminium casting alloy EN AC – AlSi12). There were made investigations of the ceramic content, presence of Ni layer on Al_2O_3, load and number of cycles (friction distance) and reinforcement shape influence on the wear of investigated materials.

The size of damage caused by the removal of reinforcement from matrix during friction process in large degree depends on its shape. Least of all benefits are hard and sharp Al_2O_3 particles, which staying even for short time between acting element destroy their surface. Surface's damages are much smaller when during the friction process the spalling of ceramic fibres took place, because it plays a role as rolling element. Sometimes even smoothing of cavities by rolling fibres took place. The results of friction measurements show that worked out composite materials are characterized by much lower friction in comparison with aluminium casting alloy EN AC – AlSi12 which were used as the matrix. The abrasive wear resistance of composite materials is inversely proportional to the content of ceramic phase apart from the load and number of cycles. The higher content of reinforcement the lower local stresses in the friction zone is caused by bigger number of particles for the surface unit what increases the area of real contact. Wear of all manufactured materials is proportional to the number of cycles under the constant load and to the load by constant number of cycles (Figs. 2-4).

Coating deposited onto the reinforcement to improve its wettability by liquid aluminium alloy, decreases tribological properties of manufactured composite materials. Taking into consideration fact that composite materials with reinforcement covered by nickel are characterized by a little bit smaller content of ceramic phase than materials without Ni coating and its influence on the level of few percent can be neglected.

For modelling abrasive wear of composite materials reinforced by ceramic preforms statistical models were used to calculate the volume of wear loss. As input there were used three variables: content of reinforcement, load and number of cycles.

By the use of multiple regression statistical method five models were evaluated allowing to calculate the abrasive resistance of matrix material (equation 2), composite material reinforced by porous fibres framework without Ni coating (equation 3), composite material reinforced by porous fibres framework with Ni coating (equation 4), composite material reinforced by manufactured porous framework without Ni coating (equation 5) and composite material reinforced by manufactured porous framework with Ni coating (equation 6). According to the assumption the linear model were used in general form (equation 1) where equations 2-6 shows equations with coefficients for all of examined cases.

a)

b)

c)

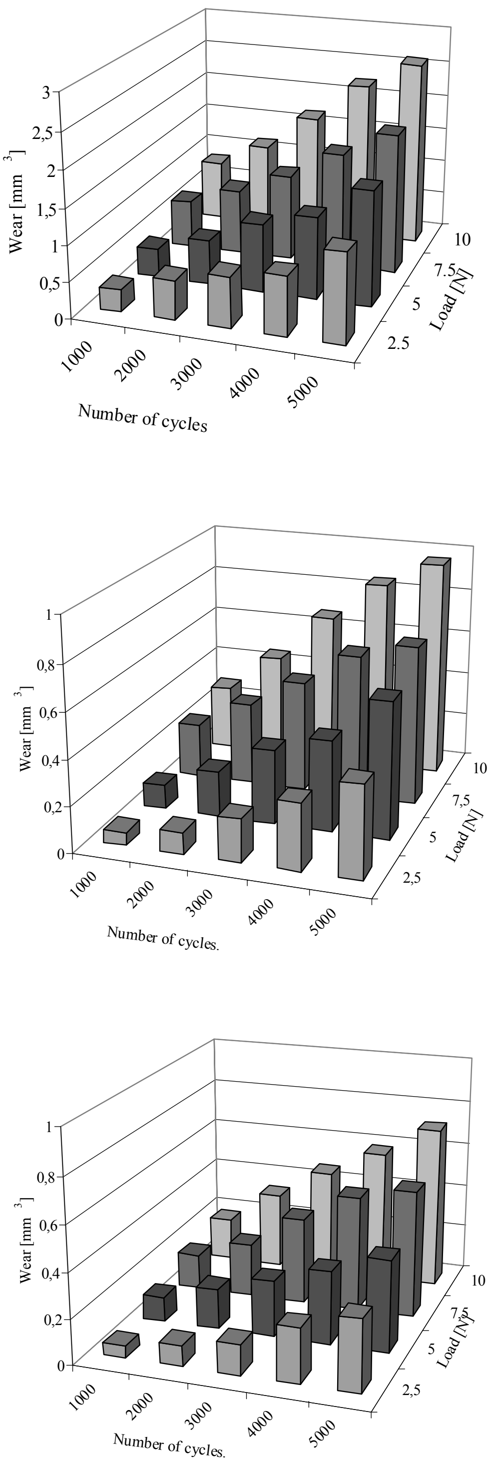

Fig. 2. The influence of load and friction distance on the wear of a) matrix and obtained composite materials base on fibres preforms b) uncoated and c) coated by Ni

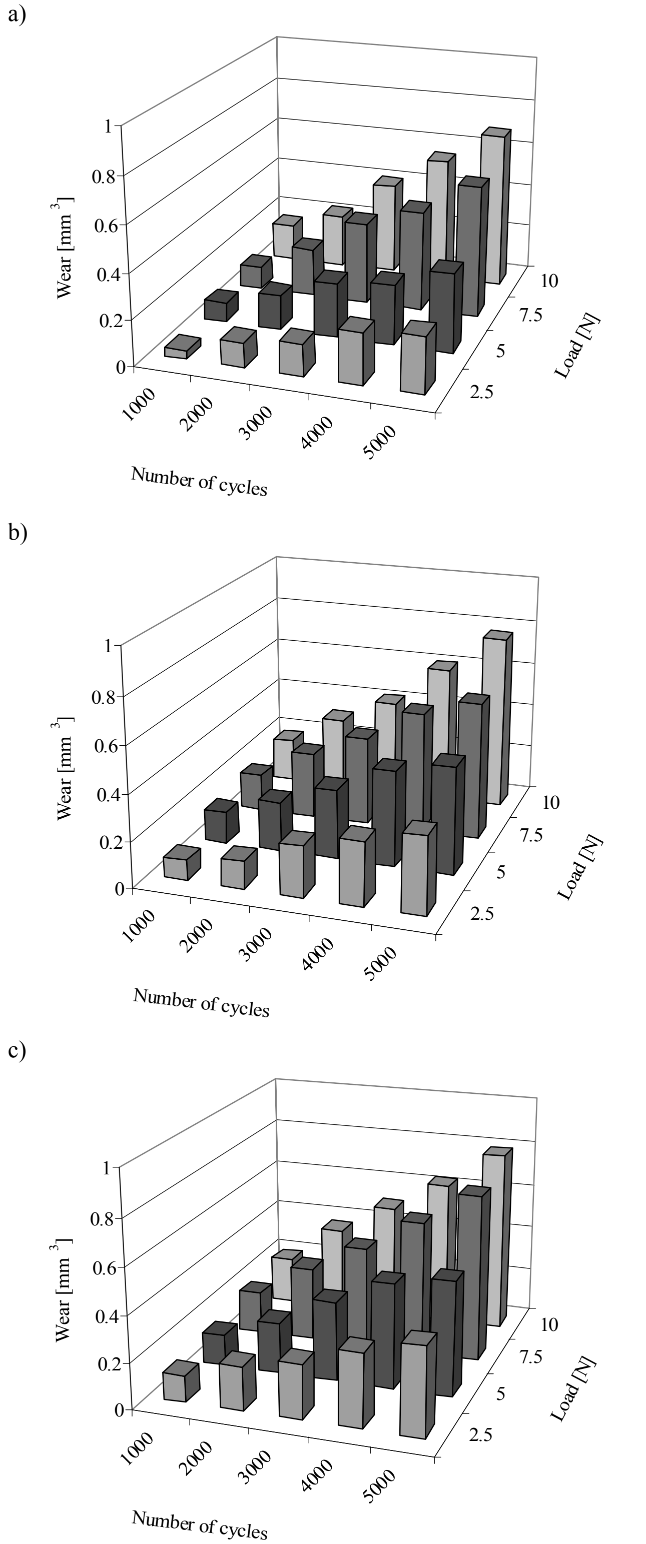

Fig. 3. The influence of load and friction distance on the wear of obtained composite materials with different ceramic content (uncoated reinforcement): a) 31%, b) 25% and c) 20%

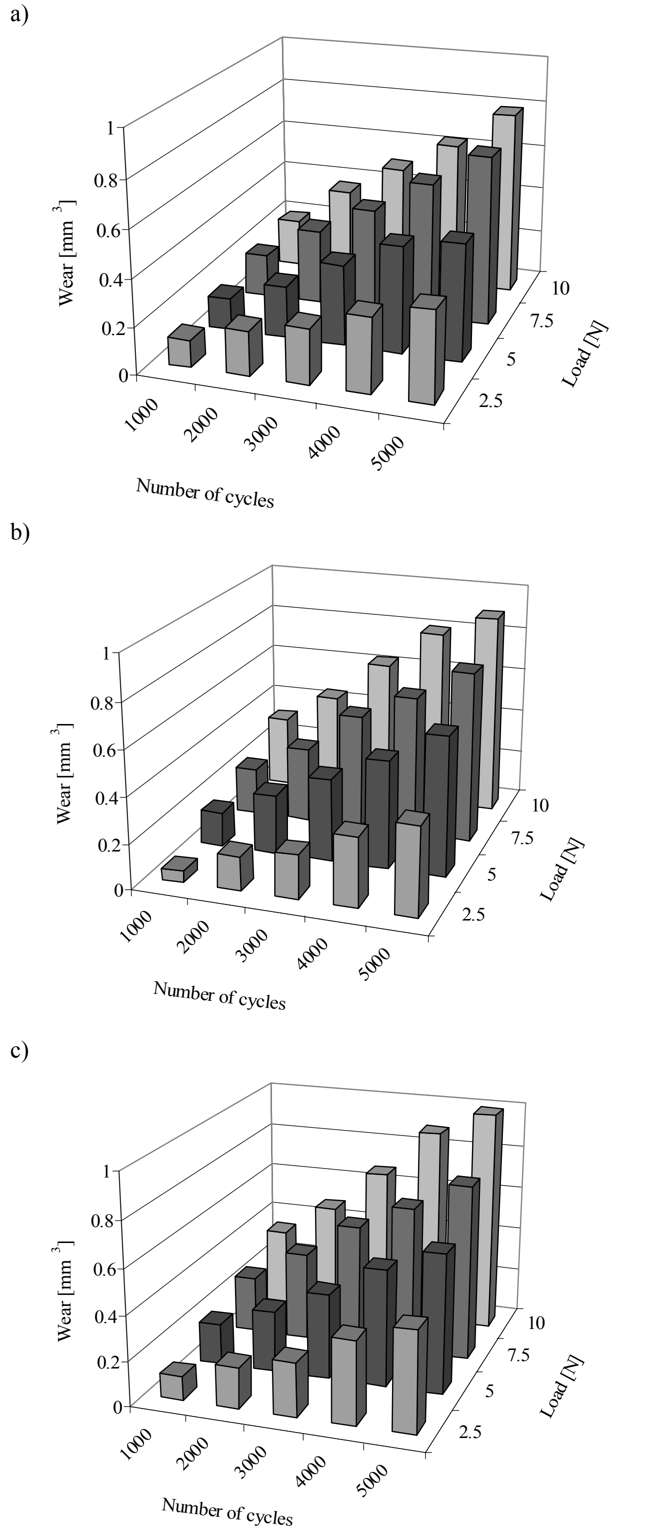

Fig. 4. The influence of load and friction distance on the wear of obtained composite materials with different ceramic content (reinforcement coated by Ni): a) 31%, b) 25% and c) 20%

There was used the same nomanclature of variables: W – Wear, NC – number of cycles ($\cdot 10^{-3}$), L – Load [N], C – Ceramic content.

$$W = -0.637796 + 0.324572 \cdot \mathrm{NC} + 0.132411 \cdot \mathrm{L} \quad (2)$$

$$W = -0.22604 + 0.095684 \cdot \mathrm{NC} + 0.04041 \cdot \mathrm{L} \quad (3)$$

$$W = -0.331249 + 0.126319 \cdot \mathrm{NC} + 0.059315 \cdot \mathrm{L} \quad (4)$$

$$W = 0.043357 + 0.102233 \cdot \mathrm{NC} + 0.035265 \cdot \mathrm{L} + 0.008675 \cdot \mathrm{CC} \quad (5)$$

$$W = -0.004255 + 0.116223 \cdot \mathrm{NC} + 0.051401 \cdot \mathrm{L} + 0.010106 \cdot \mathrm{CC} \quad (6)$$

Simulation of the load and cycles number influence on the wear of composite materials and their matrix is presented in Figs. 5 and 6.

Evaluating the usability of worked out models it can be concluded that artificial neural networks will be a better tool than statistical methods because they allow to take into account simultaneous different factors (quantitative for example load and friction distance and qualitative the presence or not the Ni coating). In consequence by their use it is possible to create a small number of more universal models than in statistical methods [8].

4. Conclusions

Tribological investigations reveal considerable increase of wear resistance of all worked out composite materials in comparison with their matrix.

It was found that the wear level of composite material manufactured by infiltration method of porous ceramic performs with liquid aluminium EN AC – AlSi12 is directly proportional to the ceramic content, load of counter sample and friction distance (number of cycles).

The size of damage caused by the removal of reinforcement from matrix during friction process in large measure depends on its shape. Least of all benefits are hard and sharp Al_2O_3 particles, which staying even for short time between acting elements destroy their surface.

Worked out statistical models allow to determine the abrasive wear of examined materials depending on the content of ceramic phase, friction distance, load and are fully adequate to obtained results of experimental data. Application of worked out calculation model allows the simulation of the influence of reinforcement, load, friction distance on abrasive wear of manufactured composite materials.

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a) b) c)

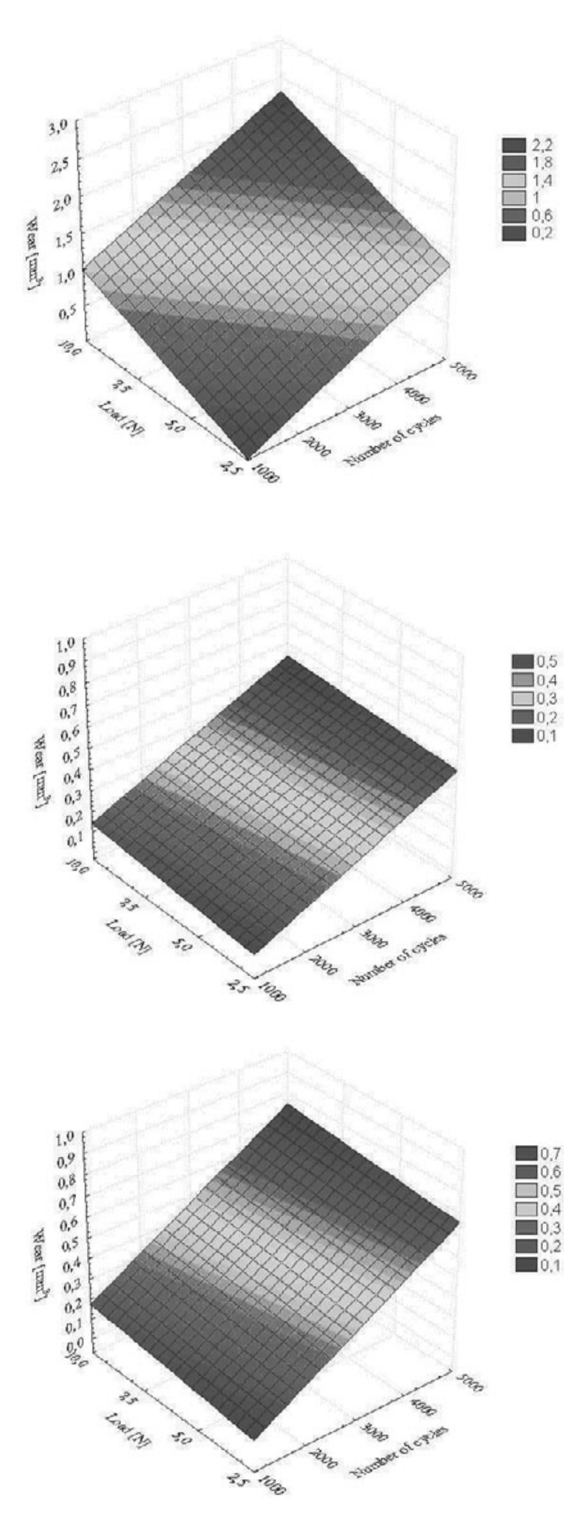

Fig. 5. The influence of load and friction distance on the wear of a) matrix, and obtained composite materials base on fibres preforms b) uncoated and c) coated by Ni

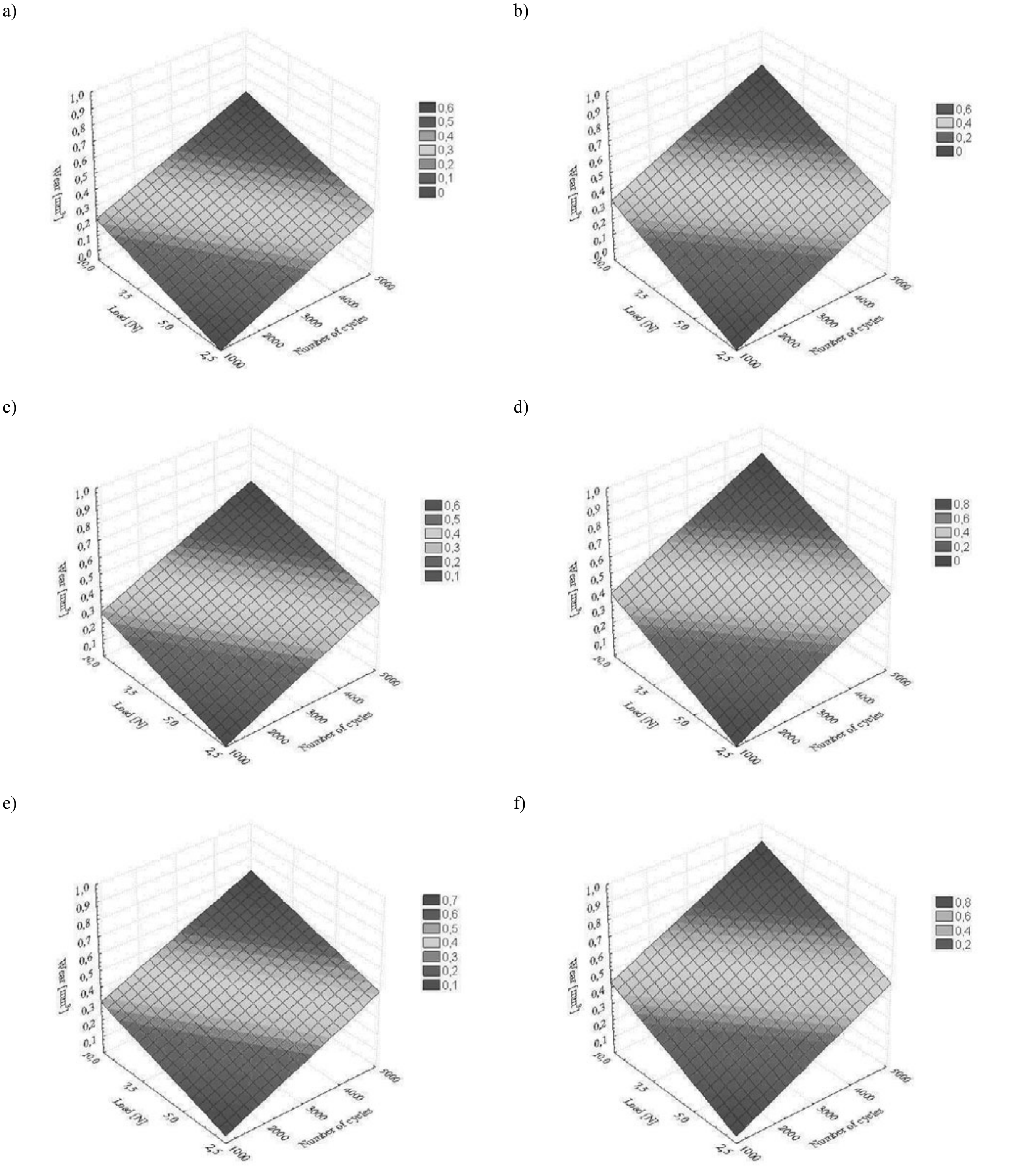

Fig. 6. Simulation of the load and number of cycles influence on the abrasive wear of composite materials with volumetric portion of ceramic phase: a,b) 31%, c,d) 25% and e,f) 20%, (a, c, e - uncoated reinforcement, b, d, f - reinforcement coated by Ni)

Additional information

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The paper is published also in the Archives of Materials Science and Engineering.

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