INCREASING THE SUSTAINABILITY OF BEARINGS RENOVATED WITH POLYMER COMPOSITE MATERIALS

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INTRODUCTION

Estimates made by many home and abroad scholars show that one of the major causes influencing on the cost of the agricultural machinery repair is bearing wear, especially those in the housing, and of bearings parts. The reason for seeking of some effective ways to increase the sustainability of mounting locations of bearings as well as of contact surfaces of bearings was and is always a current concern of scientists and of agricultural equipment manufacturers.

The overall goal of this study is to increase the joints sustainability of bearing type refurbished with polymer composite materials (PCM). As the research object served the joints of bearing type components of agricultural equipment and of related branches refurbished with PCM. The study of the research subject, in terms of reliability and especially of durability and maintainability in particular, presents the topic of discussion and great interest for specialists concerned with the operation and maintenance of agricultural equipment and related industries.

The paper presents the results of testing a polyamidepoxy material intensively reinforced with hollow glass microspheres proposed to renovate worn bearings surfaces and places of bearings.

1. MATERIAL AND METHODS

Experiments were conducted to study two groups of PCM the constitution of which was established based on the analysis of data from the literature and as the result of some preventive experiments [1-3].

In the first group of PCM, as a matrix was used polyamide ПА12 (OCT 6-05-425), which is an assortment of polyamide with improved resistance to UV radiation and weather and has an increased resistance to wear and shocks showing physics-mechanical properties in a wide temperature range, with the lowest density of all known polyamides today. It is also resistant to most chemicals, the fats, oils, fuels, hydraulic fluids, various organic solvents (aliphatic and aromatic hydrocarbons, ketones, esters, ethers, oils, etc.). For comparison, the grip of the composite material was confronted with that of the base material.

In the second group of PCM, as a matrix was used the hybrid material on the basis of a mixture of the epoxy oligomer of the type П-ЭП354 and polyamide ПА12, 30% volume proportion of the epoxy oligomer the remaining part polyamide.

CM reinforcement was performed with the following agents: molybdenum disulphide MD-1 (ТУ 48-19-133-90), used to improve the behavior of CM load and wear without affecting shock and fatigue resistance, hollow glass microspheres (glass microballoons) СМ-ВП gr.5 with the following chemical composition: SiO_2: 76-78%; Na_2O; 10-12%; CaO: 6%; ZnO: 1-1,5%; B_2O_3; 4%, properties: 0,37 to 0,42 g/cm^3 density, compression strength 150 kg/cm^2 (attrition 10%) moisture, not more than 0,3% basalt microfibers (ТУ У В.2.7-26.8-32673353-001/2007), used to increase tensile strength, stiffness, shrinkage during training, improving lubrication.

Composite was obtained by mixing the components in the ball mill ZE-101 for 30 min. the speed of drum 80…120m^{-1}.Crushing of the basalt microfibers and their sorting was done in the shredding device Ц-10 with subsequent sorting through oscillating sieves. The coatings were applied by hot pressing of carbon steel substrates of usual quality in delivery state by hydraulic press DV 2428. The dimensions and shape of the samples were determined according to the investigated properties. Processing parameters were maintained under semi-automatic system.

The research was carried out in four distinct phases according to the matrix - 3 Factors Box program - Benkin presented in table 1 [1, p.51], and the data were processed by applying the following schedule STATGRAPHICS: Special ► Experimental design ► Create design► Response surface.

Physics-mechanical properties were determined by standard methods or approved in respective areas. Thus, adhesion was estimated by the method of pins, hardness SHORE method, SR ISO868-95 scale D, the degree of hydrophilicity / hydrophobicity of the studied CM was estimated according to ISO (ASTM D570).

2. EXPERIMENTAL RESULTS AND DISCUSSION

2.1. Ensuring reliability level by choosing and optimizing the material constitution of wear compensator layer

Experiments made in order to optimize the PCM by studying the adhesion of filler material on steel substrates have shown different behavior of the materials of the reinforcement of the relative adhesion of PCM on carbon steel substrates Rz80 roughness μm. This behavior is observed both in family PCM polyamide matrix and the matrix of polyamidepoxy and is described by regression equations which in the coded coordinates have the following form:

$$A_r = 0,91 - 0,002x_1 - 0,07x_2 - 0,04x_3 + 0,008x_1^2 + \\ +0,01x_1x_2 - 0,008x_2^2 - 0,03x_2x_3 - 0,008x_3^2, \quad (1)$$

$$A_{r\cdot \text{PPECM1}} = 1,6 - 0,02x_1 - 0,025x_2 - 0,035x_3 + 0,005x_1^2 - \\ -0,035x_2^2 - 0,03x_2x_3 - 0,055x_3^2, \quad (2)$$

$$A_{r\cdot \text{PPECM2}} = 1 - 0,012x_1 - 0,016x_2 - 0,022x_3 + \\ +0,003x_1^2 - 0,022x_2^2 - 0,019x_2x_3 - 0,034x_3^2, \quad (3)$$

where A_r is the relative adhesion of PCM family of polyamide matrix determined by reference to polyamide adhesion; $Ar._{\text{PPECM1}}$ - relative adhesion of PCM family of polyamidepoxy matrix determined by reference to polyamide adhesion; $Ar._{\text{PPECM2}}$ - relative adhesiveness of PCM family of polyamidepoxy matrix determined by reference to matrix adhesion (mixture of hybrid polyamidepoxy) x_1, x_2 and x_3 represents the percentage of components of coded coordinates, respectively MoS_2, and hollow glass microspheres and basalt microfibers.

Based on the analysis equations 1-3 show that, for both groups of composite materials, all reinforcing agents adversely affect adhesion of PCM on carbon steel substrates (b_1, b_2 and b_3 in all regression equations differs from 0 with negative values). Relative adhesion of PCM of polyamide matrix is most significantly influenced by the hollow glass microspheres, followed by basalt microfibers ($|b_2|>|b_3|>|b_1|$).

In the PCM family of polyamidepoxy matrix the relative adhesion is most influenced by basalt microfibers, followed by hollow glass microspheres ($|b_3|>|b_2|>|b_1|$).

With regard to the percentage of the basalt microfibers much lower than that of the glass microspheres and molybdenum disulfide can be concluded more significant negative influence of these reinforces on the adherence in relation to the hollow glass microspheres.

At the same time it is found that the influence of the content of MoS_2 on adhesion to both sets of experiments, it is insignificant ($b_1<0$). Moreover, the PCM family of polyamide matrix, under certain conditions, disulfide Mo has a beneficial effect that is increasing along with the increasing of the glass microspheres *($b_{11}>0$ and $b_{12}>0$)*, this influence being diminished for polyamidepoxy PCM family *($b_{12} = 0$ in equations 2 and 3)*.

As a result of optimization of relationships 1-3 in order to maximize and minimize the relative adhesion were obtained the results shown in table 1. The data presented clearly demonstrate the possibility of increasing adhesion by changing the PCM matrix by mixing the addition of epoxy oligomer. As a result of this change an increase of relative adhesion of 1,63 times was obtained.

Evolution of relative adherence of PCM families for optimal concentration can be seen in figures 1 and 2. From these figures it appears that for the PCM family of polyamide matrix, in the case of CM reinforcement with an insignificant quantity of molybdenum disulfide (1%) microspheres of glass and basalt microfibers decrease the relative adhesion to a relatively small range (from 0,98 to 0,8), and for the PCM family of polyamidepoxy matrix this range is extremely small (1,6 -1,5). These findings are sufficient to conclude that PCM of polyamidepoxy matrix the glass microspheres practically do not affect the adhesion of these materials on steel substrates.

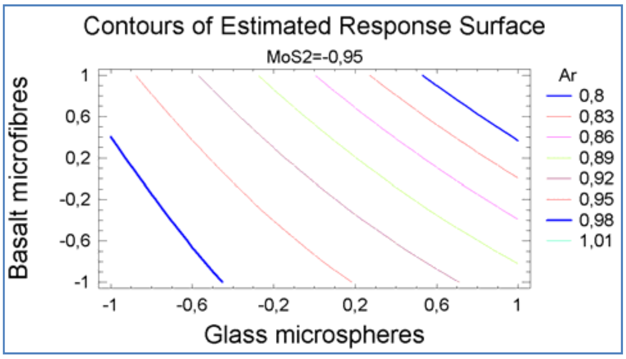

Figure 1. Estimating the PCM relative adherence of poliamide matrix to the concentration of polyamide matrix constituents (for the case of disulphide Mo concentration -0,95 (code) 1,1% (real).

The results of the foregoing experiment on adherence PCM polyamide demonstrated that the addition of epoxy oligomer has lead to obtain such

Table 1. Optimum values on the relative adhesion strength according to constitution for PCM polyamide matrix and polyamidepoxy matrix.

Factor	Optimum values											
	Minimize						Maximize					
	PPCM		PPECM1		PPECM2		PPCM		PPECM1		PPECM2	
	code	real	code	real,	code	real	code	real	code	real	code	real
MoS_2	1	5	1	5	1	5	-1	1	-1	1	-1	1
Glass microspheres	1	30	-0,99	10,1	-0,99	10,1	-0,97	10,3	-0,56	14,3	-0,56	14,3
Basalt microfibres	1	6	1	6	1	6	-1	2	-0,47	3,06	-0,47	3,06
A_r	**0,742**		**1,446**		**0,903**		**1**		**1,63**		**1,01**	

Legend: PPECM1 - relative adhesion of PCM family of polyamidepoxy matrix determined by reference to polyamide adhesion; PPECM2 - relative adhesion of PCM family of polyamidepoxy matrix determined by reference of polyamidepoxy matrix adhesion.

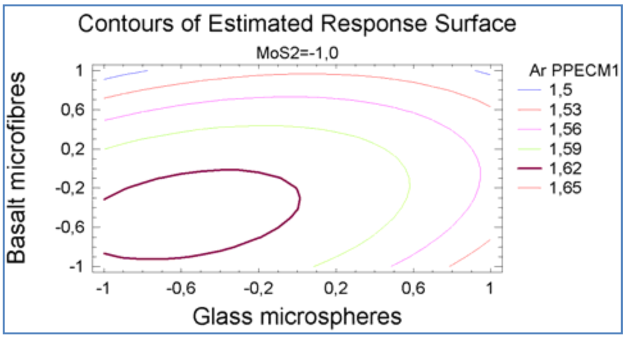

Figure 2. Estimating the relative adhesion of the PCM of polyamidepoxy matrix by reference of the concentration of the constituents (for the case of Mo concentration of disulfide 1 (code) 1% (real).

an adhesion of applied material to the carbon steel substrate which equals, virtually the tensile strength of the CM, but attempts to PCM with the polymer matrix of this type shows that the adhesion strength tends to decrease to the operation of the water coating and high humidity environments.

The experimental results performed on samples maintained under hydrostatic conditions shows specific behavior of the PCM polyamide in terms of change in adherence. Thus the samples kept in higrostat at a temperature of 60°C and relative humidity 95-100% were detached from the substrate after 520 hours exhibition and those kept in increased humid weather conditions (outside in the months of October to May) for 8 months have not presented changes to the initial adhesion which remains equal to 40MPa.

2.2. Research on the hardness of PCM reinforced with glass microspheres

PCM hardness in many cases is determined to relate a number of properties that are difficult to determine. Thus hardness can be used to estimate the moisture content gradient and its penetration depth [11, p.102-103].

Processing of data obtained in the result of experiments conducted in accordance with the schedule in table 1, yielded the following regression equation which in coded coordinates highlights the dependence of hardness estimated by Shore D depending on the content of constituents of PCM of polyamidepoxy matrix (30% oligomer epoxy the remaining Polyamide 12 percentage volume):

$$H.ShoreD/15 = 82,0 + 0,125x_1 + 1,375x_2 + 0,25x_3 - \\ -0,25x_1x_2 + 1,0x_2^2 + 0,25x_2x_3 - 0,25x_3^2, \quad (4)$$

where H Shore D15 is the hardness after Shore estimated with durometer type D (15-time, in seconds, after which the reading was done), x_1, x_2 and x_3 is the volume percentage of components in coded coordinates, respectively MoS_2, glass microspheres and basalt microfibers.

Using STATGRAPHICS program features and the outcome of optimizing the response factor corresponding to the H Shore D/15 = 84,72, we find the following percentages of constituents: MoS_2 = -0,9 (9); glass microspheres =+ 0,996; basalt microfibers = +1,0.

In the synthesis of research of designed PCM hardness was found that in the case of PCM polyamidepoxy heavy reinforced with glass microspheres, introduction of particles hardness of the composites produced, while adding the glass microspheres increased the hardness reaching the maximum value at the level of 0,99 in the coded coordinates that in natural coordinates corresponds to the quantity of 29,9% of the total volume.The reinforcement with basalt microfibers also resulted in increased hardness, achieving the maximum hardness for the high level (+1 – in the coded of molybdenum disulphide decreased the coordinates and 6% - natural coordinates. It should be noted that the increase of the percentage of glass microspheres of more than 30% does not contribute to increase of hardness, while the zone of the maximum for glass microfibers is outside of the carried out experiment.

2.3. Study the degree of hydrophilicity / hydrophobicity of PCM intensive reinforced with glass microspheres

Researchers' interest opposite the CM interaction problems with different liquids is motivated by the practical importance of the behavior of those materials in real operating conditions. The sorption capacity for water of the PCM, which includes the ability to both the absorption and adsorption, has a mixed significance for refurbished parts with such materials. The undesirable aspect, in the first place, is related to the degree of liquid sorption influence on the dimensional stability of the covered surfaces with PCM [4, pp. 108-110], and the desired aspect is that higher sorption capacity contributes to the incorporation by outside diffusion of some substances favorable to tribological process in a contact area of conjunctive surfaces.

Some authors have proposed special procedures to enhance porosity of superficial coating of PCM used to offset the surfaces wear of tribologic couplings [2]. Also liquids sorption rate by PCM is an important parameter that talks about the level of improvement of the application process and formation of polymeric coatings [3, p.89-93].

It is obvious that knowledge of the kinetics of sorption processes of liquids in PCM provides valuable information on the behavior of refurbished parts in inclemencies of weather conditions, poor lubrication etc. Thus, in the following, are presented Kinetic sorption processes of water and oil to the series of materials prepared by enhanced adding of hollow glass microspheres.

The result of processing experimental data on the evolution of the rate of sorption of water by coatings of PCM of polyamidepoxy matrix studied were obtained the results described by the following regression equation:

$$W_{water} = 1,6333 + 0,0025x_1 + 0,1312x_2 + 0,0412x_3 + 0,0058x_1^2 - \\ -0,0775x_1x_2 - 0,0025x_1x_3 + 0,0533x_2^2 + 0,005x_2x_3 - 0,0317x_3^2, \quad (5)$$

where W_{water} is the water sorption capacity expressed in per cents; x_1, x_2 and x_3 are percentages of the components in the coded coordinates, respectively MoS_2, glass microspheres and basalt microfibers.

Similar research conducted on the second group of samples that have been immersed in SAE oil 15W-40 at the temperature (20 ± 2)°C showed similar behavior to the oil-immersed with those submerged in water. After statistical processing of the experimental data the following regression equation was obtained:

$$W_{oil20} = 1,597 - 0,002x_1 + 0,129x_2 + 0,049x_3 - 0,01x_1^2 - \\ -0,075x_1x_2 - 0,01x_1x_3 + 0,089x_2^2 + 0,02x_2x_3 - 0,047x_3^2, \quad (6)$$

where W_{oil} is the oil sorption capacity at 20°C expressed as a percentage, x_1, x_2 and x_3 represents the percentage of components coded coordinates, respectively MoS_2, glass microspheres and microfibers basalt.

Analysis of equation 6 shows that the glass microspheres have a dominant influence on the absorption capacity of the oil. Basalt microfibrils also increase absorption of oil but only to a halve of it and MO_2, practically does not influence the oil sorption.

Optimization of response factor, which corresponds to the value of W_{oil20}. = 1,901, ascertains the following percentage of constituents for maximum oil sorption SAE15W40 maintained at 20°C: MoS_2 = -0,99988; glass microspheres = +1; basalt microfibers = + 0,6494.

The test results of the two groups of samples, namely samples immersed in water and those oil-immersed, it was found that the optimum composition that ensures the maximum rate of sorption of water (1,92%) and oil (1,9%), are within the boundaries: +1 glass microspheres, basalt microfibers +0,65 ...+ 0,77, and molybdenum disulfide -1 (in coded coordinates) corresponding to the natural coordinates: glass microspheres - 30%, basal microfibers - 5,3 ... 5,54% and molybdenum disulfide - 2%. (seetable 2).

Tests carried out on samples made of the constitution PPCM: glass microspheres - 30%, basalt microfibers – 5,3 ... 5,54%, molybdenum disulfide - 2%, the remainder PA12 immersed in water at 20°C and the oil SAE15W40 temperatures 20, 40, 60 and 80°C showed that the temperature of the medium in which the samples are immersed, practically does not influence the rate of sorption of oil to the samples made of the polyamide in the state of delivery, while samples with heavy reinforced glass microspheres have a slow growth of oil sorption with increasing of medium temperature. Probably this is due to the presence of glass microspheres which are some of the oil storage cavities.

Table 2. Rates of sorption of various lubricants to the PCM according to the temperature of the immersion medium.

Immersion time, hours	Immersion medium																			
	water		SAE 15W40								water		SAE 15W40							
	heat treated us										annealed									
	20°C		20°C		40°C		60°C		80°C		20°C		20°C		40°C		60°C		80°C	
	PA12	PPMP	PA12	PPMP	PA12	PPMP	PA12	PPMP	PA12	PPMP	PA12	PPMP	PA12	PPMP	PA12	PPMP	PA12	PPMP	PA12	PPMP
12	*1,34*	*1,48*	*1,30*	*1,62*	*1,34*	*1,66*	*1,38*	*1,68*	*1,38*	*1,70*	*0,80*	*0,80*	*0,00*	*0,20*	*0,00*	*0,32*	*0,08*	*0,38*	*0,32*	*0,38*
24	*1,48*	*1,88*	*1,37*	*1,88*	*1,42*	*1,90*	*1,42*	*1,92*	*1,42*	*1,92*	*0,90*	*0,88*	*0,00*	*0,20*	*0,00*	*0,32*	*0,08*	*0,39*	*0,32*	*0,40*
36	*1,52*	*1,92*	*1,42*	*1,90*	*1,46*	*1,91*	*1,46*	*1,92*	*1,46*	*1,92*	*1,00*	*1,18*	*0,00*	*0,20*	*0,00*	*0,32*	*0,08*	*0,39*	*0,32*	*0,40*
48	*1,52*	*1,92*	*1,42*	*1,90*	*1,46*	*1,91*	*1,46*	*1,92*	*1,48*	*1,92*	*1,00*	*1,18*	*0,00*	*0,20*	*0,00*	*0,32*	*0,08*	*0,39*	*0,32*	*0,40*
60	*1,52*	*1,92*	*1,42*	*1,90*	*1,46*	*1,91*	*1,46*	*1,92*	*1,48*	*1,92*	*1,00*	*1,18*	*0,00*	*0,20*	*0,00*	*0,32*	*0,08*	*0,39*	*0,32*	*0,40*
72	*1,52*	*1,92*	*1,42*	*1,90*	*1,46*	*1,91*	*1,46*	*1,92*	*1,48*	*1,92*	*1,00*	*1,18*	*0,00*	*0,20*	*0,00*	*0,32*	*0,08*	*0,39*	*0,32*	*0,40*

Legend: PA12 - polyamide 12; PPCM – polymer composite material of PA 12 matrix reinforced with: MoS_2 *-2%; ВП - CM -30%; MF Basalt -5,5%.*

The assumption made is supported by the second set of experiments and namely tests carried out on samples that are made of the same material and the same technological schemes but which have undergone extra heat treatment by heating in an oil bath at a temperature of 180°C, kept at this temperature for 30 ± 5 min and cooled with oil bath. Finally, it should be noted that the effects described in this section can serve prerequisites for choosing constitution of CM used to renovate worn areas of tribological joints of bearing type. It has been shown that intensive alloying CM with hollow glass microspheres creates favorable conditions for storing lubricants in microcavities formed by respective materials.

2.4. Tribological behavior PCM reinforced with hollow glass microspheres

2.4.1. Studies on tribological properties of PCM-reinforced with hollow glass microspheres tested in terms of friction without lubrication

It is obvious that at the choice of materials for tribological couples renovation it is insisted on a coefficient of friction of the materials, which make the couple, as small as possible. For this reason, the purpose of carried out tests on the family of PCM in this subchapter is to establish PCM constitution that would ensure the lowest coefficient of friction, and that would guarantee and other physical and mechanical important properties for maintaining a sustainable refurbished joints technical requirements imposed by the regulations in force.

Tests carried out on tribometer UMT2, revealed different tribological behavior of the family CM of polyamide matrix and polyamidepoxy depending on the percentage of reinforcement with molybdenum disulfide, hollow glass microspheres and basalt microfibers (Fig. 3).

Regression equations (7) and (8), in the coded coordinates, express PCM development of the coefficient of friction of the polyamide matrix P12 and the matrix of polyamidepoxy hybrid mixture.

$$K_{PPMC_{dry.}} = 0{,}187 - 0{,}012x_1 - 0{,}009x_2 - 0{,}004x_3 - 0{,}006x_1^2 + 0{,}001x_1x_2 - 0{,}011x_1x_3 + 0{,}001x_2^2 - 0{,}003x_2x_3 - 0{,}006x_3^2, \quad (7)$$

$$K_{PPECM_{dry.}} = 0{,}188 - 0{,}018x_1 - 0{,}009x_2 - 0{,}001x_3 + 0{,}001x_1^2 + 0{,}001x_1x_2 - 0{,}006x_2^2 - 0{,}004x_2x_3, \quad (8)$$

From the analysis of equations (7) and (8) results that, for both PCM families, all reinforcing agents contribute to the reduction of the coefficient

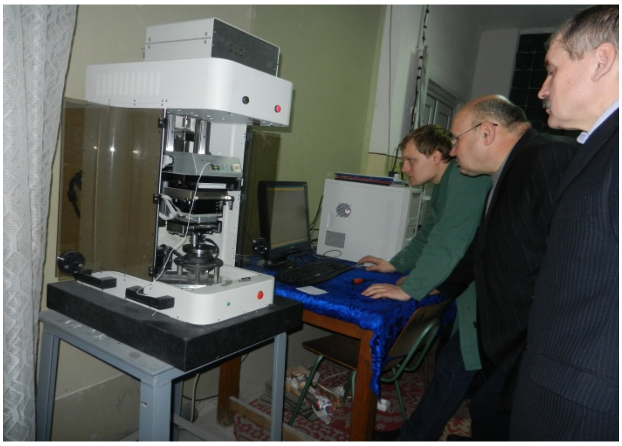

Figure 3. Aspects from the measurement of the coefficient of friction with the universal tribotester UMT2 (CETR ®, USA) with pin-on-disk configuration: *1 - dual sensor for friction and load, 2 -suspension, 3 - pin support, 4 - pin, 5-disc, 6 – table- support for disc.*

of friction of the composite polyamidepoxy (b_1, b_2 and b_3 vary from 0 having negative values). Both in the case of PCM of the polyamide matrix and in that of poliamidepoxy matrix mostly influences the coefficient of friction the desulphurised Mo followed by the glass microspheres and, finally, the basalt microfibers ($|b_1| > |b_2| > |b_3|$).Experiments carried out found that the optimal values of both PCM families are quite close (see table 3). These values, when optimizing the purposes of determining the minimum values of the coefficient of friction, is: for the PCM family of polyamide matrix – 0,14, and for PCM of polyamidepoxy matrix - 0,146. For the case of optimizing with the purpose of maximizing the coefficient of friction for PCM of polyamide matrix is equal to 0,209 and for family PCM of polyamidepoxy matrix is 0,22. These values are obtained by processing the regression equations (7) and (8).

Table 3. Optimal values of the friction coefficient depending on the constitution for PPCM and PPECM tested under dry friction.

Factor	Optimum values							
	Minimize				Maximize			
	PPCM		PPECM		PPCM		PPECM	
	code	real, %	code	real %	code	real, %	code	real, %
MoS_2	*+1*	*5*	*+0,92*	*4,84*	*-1*	*1*	*-1*	*1*
Glass Microspheres	*+1*	*30*	*+1*	*30*	*-1*	*10*	*-0,5*	*15*
Basalt Microfibres	*+0,98*	*5,96*	*+1*	*6*	*+0,72*	*5,44*	*-1*	*2*
$K_{optimum}$	0,14		0,146		0,209		0,22	

Based on the results of tribology tests, performed in this chapter, it can be concluded that the friction resistance of the PCM of hybrid mixture of polyamidepoxy matrix is essentially on the same domain as the PCM of polyamide matrix (K_{ppecm} = 0,146 and Kppcm = 0,14). It is possible to decrease the coefficient of friction with increasing percentage of glass microspheres and basalt microfibers as the minimum values for the coefficient of friction are at the boundary of the experiment. At the same time the increase of the percentage of hollow glass microspheres is not recommended because according to the results obtained in section 2.1 the increased percentage of glass microspheres impairs the adhesion capacity of the PCM.

2.4.2. Studies on tribological prop erties of PCM-reinforced with glass microspheres tested in various lubrication conditions

Wear, being defined as a process of destruction of the surface layer of a solid body at mechanical interaction with another solid body, is greatly influenced by the medium in which the friction occurs and tribological coupling superficial layers ability to store and maintain, in the area of the contact for a certain period of time, the specific agent for the operating medium.

The research conducted on aspects of tribology of couples operated in conditions of lubrication under low-capacity led to the use of some materials with enhanced properties of storage and retention of lubricant in the contact area [2 p 68-75, 6, 7].

Experimental studies conducted at the Department of Machine and graphics at the University of the Lower Danube Galati on lubrication with low-capacity fluid lubrications have indicated specific processes in superficial layers of tribological semicouples ,optimal intervals being established for speeds, loads, concentrations of filler materials, etc. in the case of PCM. [8-10].

In the following the experimental results are presented carried out in order to determine the friction coefficient of PCM in conditions of contamination of the contact area with water, oil of type SAE15W40 and greases of type LITOL 24, STAS 21150-87 all for the cases PIN with the end covered with PCM - ordinary quality carbon steel disc non heat treated (in state of delivery).

A comparative analysis of the obtained results shows that the variation of the friction coefficient values with respect to the friction coefficient for the dry lubrication is different (see table 4).

Thus it is noted that the coefficient of friction of PCM-intensively reinforced with hollow glass microfibers of both polyamide matrix and the matrix of polyamidepoxy mixture, is reduced in comparison with the reference material.

Table 4. Comparative data on the values of the coefficient of friction for various lubrication conditions.

Lubricant type and lubrication character	Coefficient of friction			Reported coefficient of friction				
	PA12	PPCM	PPECM	KPPCM/up	KPPECM/up	KPPECM/up	KPPCM/PPECM	KPPECM/PA12
water (a)	0,11	0,107	0,091	0,764	0,650	0,623	0,850	0,827
water (l)	0,12	0,123	0,112	0,879	0,800	0,767	0,911	0,933
oil (a)	0,02	0,016	0,010	0,114	0,071	0,068	0,625	0,500
oil (l)	0,04	0,035	0,025	0,250	0,179	0,171	0,714	0,625
LITOL (a)	0,03	0,025	0,024	0,179	0,171	0,164	0,960	0,800
LITOL (l)	0,1	0,063	0,042	0,450	0,300	0,288	0,667	0,420
drying	0,18	0,14	0,146				1,043	0,811

Legend: Kppcm/up - the ratio of the coefficient of friction of PPCM tested under lubrication and friction coefficient of PPCM tested under dry friction; Kppecm/up - the ratio of the coefficient of friction of PPECM tested under lubrication and coefficient of friction of PPCM tested under dry friction; Kppecm/up - the ratio of the coefficient of friction of PECM tested under lubrication and friction coefficient of PPECM tested under dry friction; Kppecm / ppcm - the ratio of the coefficient of friction of PPCM and the PPECM tested under lubrication; Kppecm/PA12 - the ratio of the coefficient of friction of the PPECM and that of polyamide matrix (PA12).

In the case of dry friction, samples of PPCM have a coefficient of friction of 1,28 times less than the control samples (PA12 in state of delivery condition) and PPECM samples of 1,23 times lower (Kppecm/PA12 = 0,811) . This can be explained by the fact that during the friction under dry regime thermochemical processes take place specific to each material separately.

The strongest reduction of the coefficient of friction for PPECM tested under various conditions of lubrication, relative to the control material (PA 12) refers to samples tested in limit lubrication conditions with LITOL24 – 2,38 times smaller (Kppecm/PA12 = 0,420) and those tested under conditions of abundant lubrication with oil - 2 times lower (Kppecm/PA12 = 0,5), followed by samples tested under boundary lubrication with oil – 1,6 times lower (Kppecm/PA12 = 0,625) and abundant lubrication conditions with LITOL24 – 1,25 times lower (Kppecm/PA12 = 0,8).

For sliding bearings refurbished with PCM a special importance has, namely the behavior at wear of the aging joints of tribological couples behavior under dry friction and lubricating with greases under boundary limit. This is explained by the fact that the mentioned conditions are specific to joints of bearing type of agricultural machinery and related industries. Thus, the good behavior at wear of the PPECM in conditions of lubrication with LITOL24 type lubricating greases, particularly under limit regim, as well as a rather good behavior in conditions of dry friction, argues fully the perspective use of PPECM as compensation material of wear to renovate the joints of bearing type operated under poor lubrication conditions.

Using the conditions of compromise, based on the weight of the influence of various factors on the coefficient of friction, for restoring worn parts constituting the bearing type joints PPECM is recommended with the following constitution: MoS_2 - 5% + hollow glass microspheres - 30% + basalt chopped microfibers - 5% the rest of the mixture of epoxy oligomer PA12 in the volume ratio of 7/3.

2.5. Research on durability of bearing type joints renovated with PCM intensively reinforced with hollow glass microspheres

Sliding bearings composed of bush made of carbon steel brand 35 in state of delivery and spindle of carbon steel coated with PPECM (MoS_2 -5% +hollow glass microsphers -30% + basalt chopped microfibers – 5%, the rest a mixture of PA 12 and epoxy oligomer in volume ratio of 7/3 were subjected to tests.

Evolution of adjusting change of these tribological couplings tested under conditions of dry friction and lubrication under limit regim with LITOL 24 limit, is convenient to follow in figure 4.

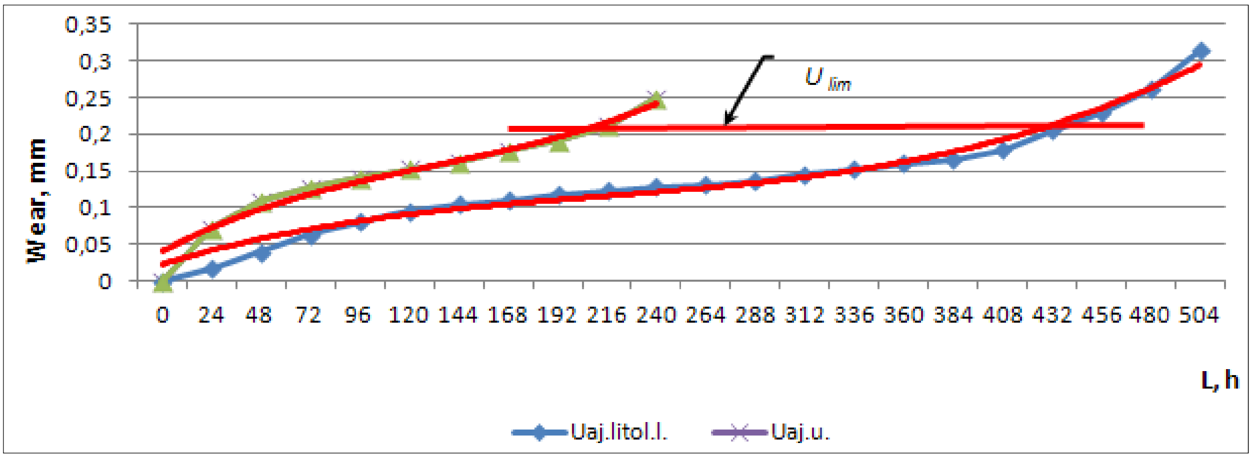

Figure 4. Evolution of wear of tribological co couplings adjustment Ø40H8/e7 tested under dry friction and boundary lubrication with LITOL24 STAS 21150-87: *Test conditions: accelerated tests under cyclic oscillating regim, p = 3,5 MPa, n = 1800 min^{-1} (v = 3,8 m / s, the measurements were carried out at parts temperature of 20 ± 2°C and air relative humidity 60 ... 70%.*

Slower wear of joints tested under boundary lubrication with LITOL can be explained by a few aspects of major importance. On the one hand, can result the obtained tribological characteristics can be the result of increased resistance to wear due to the addition of Mo disulfide, and increased resistance to deformation due to the addition of micro basalt microfibers and glass microspheres, embedded reliably in a polyamidepoxy matrix due to the presence of epoxy oligomer.

On the other hand, the microcavities caused by glass microspheres, provides a more pronounced penetration layer of grease in the superficial layer of semicoupling with PPECM, penetration which increases concomitant with the warming of the contact area. This situation amplifies the storage capacity of the surface layer with heated grease molecules and the ability to maintain for a longer period the grease from the microcavities of the contact area.

The results of the durability tests, carried out by accelerated tests on an exhausted sample consisting of 25 sliding bearing renovated with PPECM with Ø40H8/e7 are shown in figures 5 and 6. The objective of these tests is to simulate the operation of sliding bearings tested in its operating medium. To do this, on the bearings included in the study were applied stress quasi - identical to those appearing in the agricultural machinery during operation. In these tests, the tests were performed up to exhaustion of exploitation resource (appearance of catastrophic play). Sustainability was estimated by resource percentage range of 80 to 90% - values accepted by the technical regulations on farm equipment.

Figure 5 shows that the variation of the resource percentage range of γ = 0,8 to γ = 0,9, for bearings tested without lubrication, is 5 hours being within the range 245,5 and 249,5 hours. It is noteworthy that with a probability of 99,9% all of the pieces studied, will operate up to 240 working hours of guaranteed resource continuously.

Plain bearings tested under boundary lubrication with lubricating LITOL24 presents a durability net superior to bearings tested under dry friction. Thus the data presented in figure 6 permit to conclud that for γ = 0,8 resource percentage range is 434,6 hours and 430,4 hours respectively for γ = 0,9 hours. In addition, it is found that, with a probability of 99,9%, all parts included in the study have a durability of at least 420 hours.

These results correlate with the data presented in the previous sections and can be explained by the effect of anti-friction of the layer of PPECM.

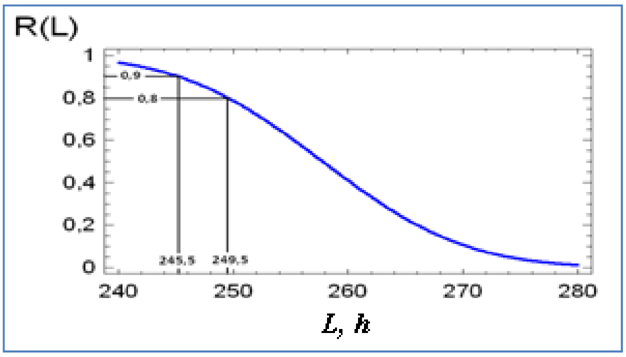

Figure 5. Sustainability percentage range of 80 to 90% of metallpolimers Ø40H8/e7 joints tested under dry friction: *Conditions: accelerated tests under cyclic oscillating, p = 3,5 MPa, n = 1800 min*$^{-1}$ *(v = 3.8 m/s), measurements were carried out at parts temperature of 20 ± 2°C and air relative humidity of 60 ... 70%.*

After polymerization of the CM, on the surface of the coated part a layer of microdisperse particles of glass microspheres, basalt microfibers and Mo disulfide is formed. In the initial phase of lubricating with greases the later enter in the microcavities on the surfaces of junction parts. In the process of friction, some of the lubricant particles are transferred to microirregularities onto the surface of junction part and the other part into the microcavities on the surface of the covered part storing into them.

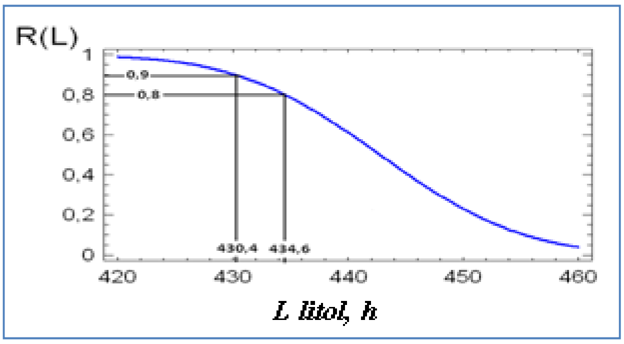

Figure 6. Sustainability percentage range of 80 to 90% of metallpolimers couplings Ø40H8/e7 tested under boundary lubrication with LITOL24: *Conditions: accelerated tests under cyclic oscillating regim, p = 3.5 MPa, n = 1800 min*$^{-1}$ *(v = 3,8 m/s); measurements were made at parts temperature of 20 ± 2°C and air relative humidity 60 --- 70%.*

In the wear process, the particles of lubricant penetrated into surface microcavities are oriented in parallel to the direction of movement, forming a smooth sliding microfilm. This microfilm is maintained a rather long period due to the amount of lubricant in the cavities formed continuously as a result of appearance of new micropores caused by damage of the glass microspheres.

Here it should be noted that the dispersed particles of the Mo disulphate, with a capacity of solid lubricants also continuously appear in the contact area and they have an influence on the tribological processes of the area.

Since the test bench is designed in such a way that each engine speed to provide an oscillating cycle (on the shaft is installed a cam which, at each rotation, unbalances the shaft on which the bearing is installed). Thus, the shaft speed of 1800min^{-1}, is established that the limit state of bearings operated in the regime of dry friction with a probability of 90% occurs after 26528730 cycles, and of those tested under boundary lubrication regime with LITOL24 - after 46509024 cycles.

Since the law of wear mechanism, followed in previous researches on the evolution of changing parts size ranging and comprehensive of metalpolimer tribocoupplings tested and of that followed in the accelerated reliability test has the same shape (NLD) the obtained results can be validated and compared with operational tests performed on natural components.

3. CONCLUSIONS

1. Experiments carried out on the adhesion of PCM intensively reinforced with hollow glass microspheres confirm that the adhesion of PCM to the matrix of a mixture of polyamide and epoxy oligomers contribute to the increase of adhesion as compared with PCM analogue but with the polyamide matrix in the delivery condition. It has been shown that the addition of epoxy oligomer in a proportion of 30% of the matrix material increases the adhesion of 1,63 times.

2. It was argued the optimal constitution of PPECM on the basis of adhesion tests, hardness, degree of hydrophilicity / hydrophobicity and resistance to wear. It has been shown experimentally that the reinforcement of polyamidepoxy PCM with hollow glass microspheres in an amount up to 30%, practically does not influence the adherence and its stability on carbon steel substrates and toughness, on the contrary - increases, requiring the maximum values in the case of reinforcement with the glass microspheres at the level of 29,9%.

3. On the basis of synthesis of hardness research of designed PPCM it was found that in the case of reinforcement with the glass microspheres, the introduction of the molybdenum disulfide particles decreased the hardness of the composites produced, while the addition of glass microspheres, on the contrary, increased the hardness, reaching a maximum value at the level of 29,9% of the total volume. The reinforcing with basalt microfibers also resulted in increased hardness, achieving the maximum toughness for the level of 6% of the total volume.

4. It has been shown that intensive alloying of CM with hollow glass microspheres creates favorable conditions for storing lubricants in microcavities formed by respective materials. It was found that the optimum composition that ensures the maximum rate of sorption of water (1,92%) and oil (1,9%) is within the: glass microspheres - 30%, basalt microfibers – 5,3... 5,54% and molybdenum disulfide - 2%.

5. Comparative tests carried out at different temperatures showed that the temperature of the medium in which samples are immersed practically does not influence the rate of oil sorption by the samples made of polyamide in a state of delivery, while samples with heavy reinforced glass microspheres have a slow increase of the oil sorption with increasing of medium temperature.

6. Tribological characterization of laboratory samples of PPECM intensively reinforced with glass microspheres tested under different conditions of friction confirms the assumption that hollow glass microspheres causes less friction in the polymer-metal contact under all conditions of lubrication thanks to storage capacity and maintaining it a longer period of time in the contact area.

7. Based on the monitoring of the friction coefficient and wear it was revealed that:

- in the case of dry friction, samples of PPCM have a coefficient of friction of 1,28 or lower and PPECM samples of 1,23 times less than the control samples (PA 12 in the state of delivery) with a coefficient of reported friction K_{ppecm}/PA12 = 0,811;
- in the case of friction under boundary lubrication, the friction coefficient of the PPECM in relation to the material sample (PA 12 in the state of delivery) is 1.6 times lower for the conditions of oil lubrication and 2,38 times lower for lubrication conditions with LITOL 24;
- in the case of friction in conditions of abundant lubrication, the friction coefficient of the PPECM in relation to the material sample (PA 12 in the state of delivery) is 2 times lower for the conditions of lubrication with oil and 1,25 times lower for the conditions of lubricating with LITOL 24.

8. Durability test results, achieved by accelerated tests under boundary lubrication conditions with lubricating LITOL 24, demonstrated a net superior durability of PPECM samples in relation to those tested under dry friction. Thus it was established, with a probability of 99,9% that all parts under study have a durability of at least 420 hours, while those tested under dry friction only 240 continuously working hours.

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