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FRICITION OF ULTRA-HIGH-MOLECULAR-WEIGHT POLYETHYLENE, MODIFIED WITH CARBON NANOTUBES

Kiril NIKOLOV¹, Mara KANDEVA^{2,3} Lubomir DIMITROV¹

¹Faculty of Mechanical Engineering, Technical University – Sofia, 8 Kl. Ohridski Blvd, 1000 Sofia, Bulgaria

²Faculty of Industrial Technology, Tribology Center, Technical University – Sofia, 8 Kl. Ohridski Blvd, 1000 Sofia, Bulgaria

³ South Ural State University, 76 Prospekt Lenina, Chelyabinsk, Russia

*Corresponding author: knikolov90@gmail.com

Abstract: *The present study investigates the coefficient of friction of new composites based on UHMWPE with the addition of different percentages of carbon nanotubes (CNTs) - 0.5%, 0.75%, 1.0% and 1.5%. UHMWPE samples with carbon nanotubes, samples of 0.5%, 0.75%, 1.0% and 1.5% carbon nanotubes (UHMWPE-CNTs) and samples with the same carbon nanotube content were made, but with carbon nanotubes subjected to Electroless Nickel Composite Coating with nanoparticles of SiC (UHMWPE-NiCNTs). The coefficient of friction is investigated with a tribometer in a kinematic scheme "Thumb-Disc" without lubricant in a high-alloy steel frame with hardness HRC=56.9 and roughness Ra=2.35 µm. All samples were tested under the same friction conditions - friction path, sliding speed, roughness of the counterpart and samples, ambient temperature. Results and regularities of the effect of carbon nanotubes UHMWPE-CNTs and UHMWPE-NiCNTs on the coefficient of friction at different normal loads are obtained. The micro-hardness of the materials under investigation was measured and its relationship to the percentage of CNTs and NiCNTs and to the coefficient of friction was analyzed. It was found that the highest micro-hardness belongs to the materials with 1.5% carbon nanotubes having a composite nickel plating (UHMWPE-1.5NiCNT).*

This study and the results are related to the implementation on contract: ДН 07/28-15.12.2016 "Research and creation of new wear-resistant coatings using composites and nanomaterials", funded by the National Science Fund at the Ministry of Education and Science, Bulgaria.

Keywords: tribology, friction, UHMWPE, carbon nanotubes, composite materials

1. INTRODUCTION

The main priority of tribology as interdisciplinary science and technology is to increase the energy efficiency and reliability of the machines. It is known that 30% of energy losses in the world are due to friction and 80%

of failures in machines belong to friction compounds [1-5].

One of the methods for reducing friction and wear is the development of new composites and coatings with physico-mechanical characteristics and properties, providing low tangential stresses and high

wear resistance of friction contacts. A specific feature of the tribological processes is that they occur in the thin surface layers of the contacts, they depend significantly on the operating modes and they change over time [6-10].

The development of modern industry is characterized by a wide variety and intensification of machine operating modes - increasing power, which means high speeds, loads and temperatures, vibration, abrasion, erosion and other extreme conditions. In many of the operating conditions, liquid lubricants are inapplicable and the tribo systems work in "dry" mode. In such cases, dry lubricants are used which are characterized by the anisotropy of their mechanical properties in tangential and normal directions. One such interesting material is ultra-high molecular weight polyethylene (UHMWPE), which has a number of advantages as a tribological material. Its specific molecular structure defines its antifriction properties and belonging to the group of self-lubricating materials with high abrasion resistance under conditions of abrasion and chemically aggressive environments. As a tribological material, UHMWPE has a wide range of applications - in low-revving and periodically operating nodes, guides and gears, in the presence of vibrations and vibration loads, in the presence of abrasive particles and others. Its low thermal conductivity is a flaw that limits some of its applications. One of the methods to improve the mechanical and tribological characteristics of UHMWPE is to introduce into its volume nano-sized particles having different shapes, sizes, concentration and nature [11-15].

The purpose of this paper is to study the effect of carbon nanotubes concentration in UHMWPE on the coefficient of friction without lubricant at different normal loads.

2. Materials

The composite samples under investigation are based on ultra-high molecular weight polyethylene (UHMWPE) with two types of non-oriented carbon nanotubes with different

percentages (by mass). Nine (9) types of samples were prepared in two pieces of each type: samples (UHMWPE) without carbon nanotubes; samples (UHMWPE-CNTs) containing 0.5%, 0.75%, 1%, and 1.5% carbon nanotubes; samples (UHMWPE-NiCNTs) containing 0.5%, 1% and 1.5% carbon nanotubes with Nickel-Phosphorus Coating (Ni-P) applied by the method of electroless plating. The carbon nanotubes (CNTs) are multi-walled (MWCNTs) with a mean diameter of 10÷40 nm, length 1÷25 µm, specific surface area 150÷250 m²/g and 99% purity. In order to increase the cohesive forces of interaction between the carbon nanotubes and the UHMWPE matrix and, accordingly, to improve the functional properties of the composite material, nickel-phosphorus coating (Ni-P).

The new composite material obtained by sintering in a cylindrical press "*piston-cylinder*" (Fig. 1) after pre-homogenization in the following mode: pressure - 200 bar, sintering temperature - 185°C, sintering time - 30 min.



a)



b)

Figure 1. a) Piston and cylinder of cylindrical press; b) Cylindrical press for obtaining UHMWPE composites by sintering

The resulting blanks have the following dimensions - diameter 124 mm and thickness 15 mm – Fig. 2.



Figure 2. Picture of a disk blank with a diameter of 124 mm from composite UHMWPE-0.75CNTs: a) face, b) side

From the disk blanks samples are produced having a cubic shape with dimensions 15x15x15 mm. All specimens are prepared with the same roughness $Ra=0.71\div0.98\ \mu\text{m}$. The roughness of the surface is measured by taking profilegram using a profilometer „TESA Rugosurf 10 - 10G”.

Table 1. Hardness of the test samples

No	Sample	Average Hardness, MPa
1	UHMWPE-0CNTs	54.24
2	UHMWPE-0.5CNTs	53.38
3	UHMWPE-0.75CNTs	49.74
4	UHMWPE-1.0CNTs	48.84
5	UHMWPE-1.5CNTs	44.11
6	UHMWPE-0.5NiCNTs	55.12
7	UHMWPE-1.0NiCNTs	68.16
8	UHMWPE-1.5NiCNTs	77.10

Microhardness of the samples was measured by the Vickers method using a microhardness tester FISCHERSCOPE® H100. Table 1 shows the average hardness of the test pieces.

Designations of the samples include an Arabic number that indicates the percentage of carbon nanotubes without nickel-phosphorous coating (CNTs) and nickel-plated carbon nanotubes (NiCNTs).

3. Device and methodology

The kinetic coefficient of friction is investigated using “UHMWPE-Steel” tribosystem under conditions of sliding without lubricant (“dry” friction). The study was performed with the device on kinematic scheme “thumb-disk” with the functional diagram shown in Fig. 3.

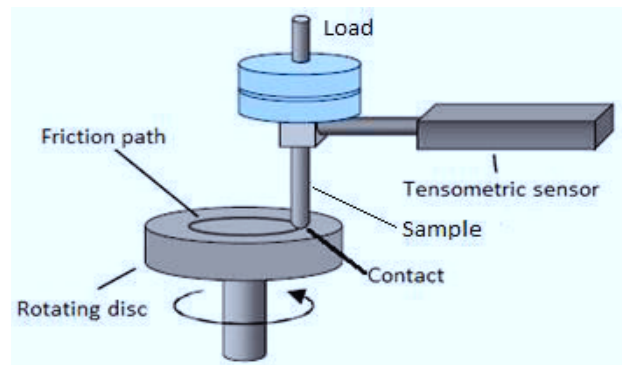


Figure 3. Scheme of the „Thumb-Disk” device

The fixed thumb represents the test specimen and the rotating disc is a high-alloy steel plate with hardness HRC56,9 and roughness $Ra=2.35\ \mu\text{m}$. The friction force T is measured with an accuracy of 0.1 N with a dynamometer attached to the sample holder. The normal load P is set in the center of the specimen by means of weights or with a lever system mounted on the fixed sample holder. The coefficient of friction μ is calculated according to the law of Leonardo-Amonton as the ratio of the measured friction force T and the normal load P :

$$\mu = \frac{T}{P} \quad (1)$$

The methodology consists in measuring the friction force for each sample under the same friction - load modes $P_1=60\ \text{N}$; $P_2=80\ \text{N}$; $P_3=100\ \text{N}$; $P_4=120\ \text{N}$, rotation speed $n=94\ \text{min}^{-1}$ (sliding speed $v=0.83\ \text{m/s}$), ambient temperature 24°C and calculating the coefficient of friction using formula (1).

4. Results and analysis

According to the described method, results were obtained for the friction force and the coefficient of friction at different loads. Figures 4-7 show graphically the friction coefficient dependence on the percentage of uncoated carbon nanotubes and nickel-coated carbon nanotubes, respectively, for the four load types.

The figures show that the presence of carbon nanotubes in UHMWPE influences the coefficient of friction (COF). This influence is not unambiguous, it depends on three factors: the percentage of nanoparticles, their modification with nickel-phosphorus coating and the value of the normal load.

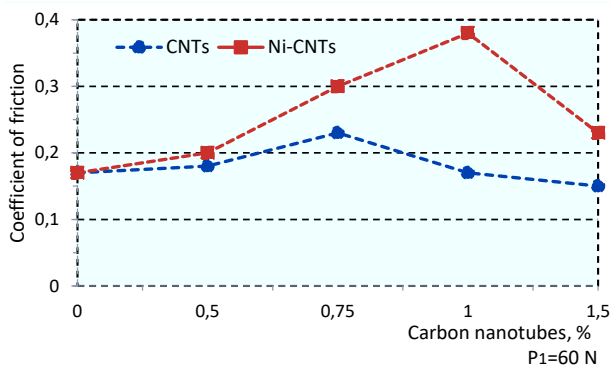


Figure 4. Friction coefficient change from the percentage of CNTs and NiCNTs at load $P_1 = 60$ N

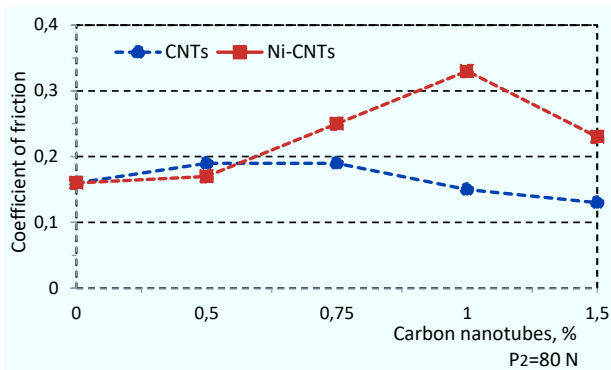


Figure 5. Friction coefficient change from the percentage of CNTs and NiCNTs at load $P_2 = 80$ N

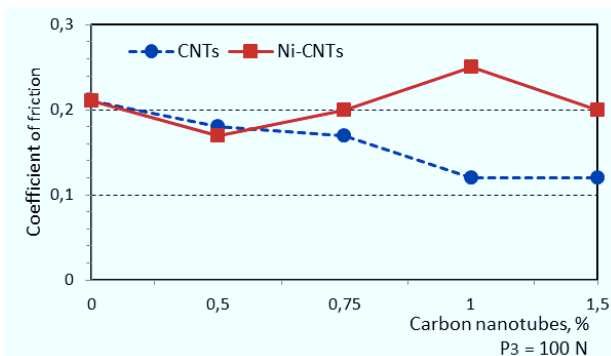


Figure 6. Friction coefficient change from the percentage of CNTs and NiCNTs at load $P_3 = 100$ N

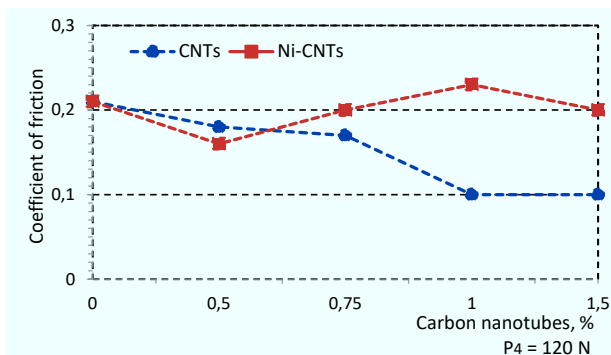


Figure 7. Friction coefficient change from the percentage of CNTs and NiCNTs at load $P_4 = 120$ N

For materials modified with carbon nanotubes without nickel-plated (CNTs), for the same load, COF dependence on the

percentage of nanoparticles is non-linear. At low loads $P_1=60$ N and $P_2=80$ N COF increases to 0.75% CNTs and reaches values higher than COF of non-nanoparticulate materials. When increasing the percentage of CNTs (1.0-1.5%) COF decreases smoothly and reaches values less than those of non-nanoparticulate material (Fig.4, Fig.5). At a higher load in the range $P_3 = 100$ N and $P_4 = 120$ N COF has a one-way change with an increase in the CNTs content - it decreases nonlinearly and there are always lower values than those of UHMWPE without nanoparticles (Fig.6, Fig.7). At these load values for CNTs content = 1% and 1.5%, the coefficient of friction takes the same minimum values, i.e. the coefficient of friction is of a sustained nature.

In the presence of nickel-coated carbon nanotubes (NiCNTs), COF has a higher value than COF for NiCNTs for all their percentages and for all normal loads. In this case, the COF dependence on the percentage of nanoparticles also has a nonlinear character - with an increase in the nanoparticle content, COF increases, reaches a maximum in NiCNTs - 1%, then decreases and reaches a higher COF value as with the non-nanoparticulate material. It is noteworthy that the maximum COF has different values for the different loads but always this maximum is observed for the same percentage of nanoparticles - 1% NiCNTs. At high loads - $P_3=100$ N and $P_4=120$ N, the curve has a wavy character with pronounced minimum and maximum. The minimum coefficient of friction is at 0.5% Ni-CNTs.

From the obtained results it was found that a maximum value of the friction coefficient $\mu=0.38$ was observed in the friction of UHMWPE-1.0NiCNTs materials, i.e. materials doped with 1% nickel-plated carbon nanoparticles at least load $P_1 = 60$ N.

The smallest friction coefficient $\mu=0.1$ is observed at the highest load $P_4=120$ N for nanotubes doped without nickel-phosphorous coating - UHMWPE-1.0CNTs and UHMWPE-1.5CNTs, i.e. the materials containing 1% and 1.5% carbon nanoparticles.

Figures 8 and 9 show COF diagrams for the same load P at different percentages of carbon nanotubes, respectively, with and without nickel coating.

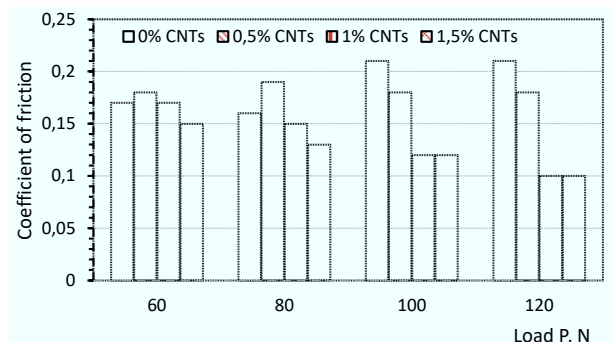


Figure 8. Diagram of COF for the same load P at different percentages of carbon nanotubes CNTs

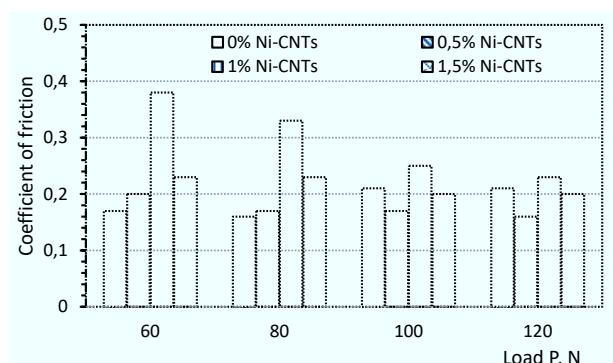


Figure 9. Diagram of COF for the same load P at different percentages of carbon nanotubes NiCNTs

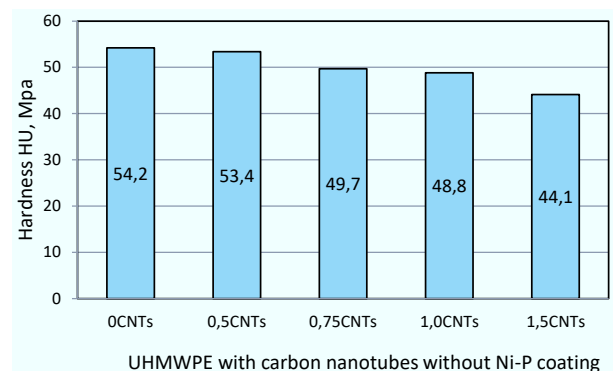


Figure 9. Hardness of UHMWPE with carbon nanotubes without nickel-phosphorous coating

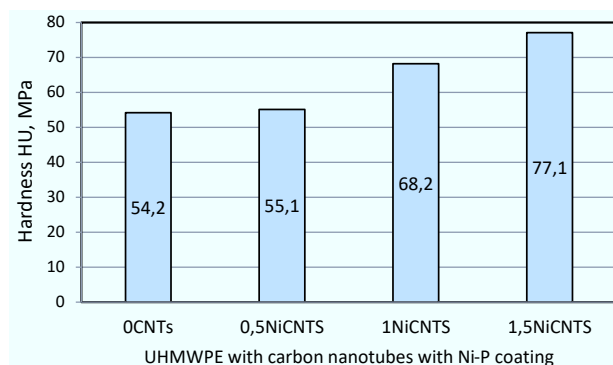


Figure 10. Hardness of UHMWPE with carbon nanotubes with nickel-phosphorous coating

Figures 10 and 11 show UHMWPE hardness graphs with different carbon nanotube contents, respectively, with and without a nickel-phosphorous coating.

The analysis of the results on diagrams in Figures 8 and 9 shows that with increasing the load on materials without nanotubes COF increases with the increasing load.

It is clear from Figures 10 and 11 that when alloying with carbon nanotubes with a nickel-phosphorous coating, the UHMWPE hardness rises by 1.42 times in comparison to its non-nanoparticle hardness. The alloying of UHMWPE with uncoated carbon nanotubes does not increase hardness, on the contrary, a slight decrease is observed with an increase in the percentage content.

The obtained results can be interpreted on the basis of generally accepted in tribology molecular-deformation theory of friction [3]. According to this theory, friction is the result of two interdependent processes: a molecular interaction in the microcontacts that determines the adhesion component of the friction and the contact deformations defining the friction deformation component. The forces of molecular interaction depend mainly on the physico-chemical properties of the surface layers in the contact, the temperature, the transfer of material into the contact from one surface to the other, the presence of reinforcement, new structures and vary within certain limits. These forces resist the mutual movement of the bodies and influence contact deformations. The deformation component of the friction is composed of normal and tangential deformations of the contact spots. It mainly depends on the load, physico-mechanical characteristics of the surface layers and can increase or decrease with the increasing of the normal load. The division of the coefficient of friction in two components - adhesion and deformation has a contingent character. Under different modes of friction - load, speed, temperature, one or the other component can dominate, both influencing each other. The increase in COF with the increasing of the load on the material without nanotubes can be explained by the increase of

the deformation component by friction as a result of sinking of the microroughnesses in the surface layers, increasing the number of contact areas and the actual contact area with a high contact pressure as a result of plastic deformation. For small content of nanoparticles - 0.5% with and without nickel coating the friction coefficient has a stable character, i.e. it has almost the same values for different loads, but its value is greater for nickel-plated nanoparticle materials. With a nanoparticle content of 1% and 1.5%, the friction coefficient decreases with increasing the normal load. This is probably due to the reduction of plastic deformation and the flow of elastic and elasto-plastic contact deformations as well as the reduction of the adhesive component. The high COF value for nickel-phosphorus-coated nanotubes is due to an increase in the friction deformation component, in particular an increase in tangential contact deformities due to the increased rigidity of the composite material, containing such particles (Fig. 11).

5. CONCLUSION

In the current work a comparative study was carried out of the coefficient of friction without lubrication of new composite materials based on UHMWPE, containing two types of carbon nanotubes - uncoated CNTs and carbon nanotubes having a coating of nickel-phosphorus coating by the electroless method NiCNTs.

The main work results are limited to:

It has been found the influence on the coefficient of friction of three factors: carbon nanotube percentage, loading and presence of Ni-P coating on nanotubes.

The effect of the carbon nanotube percentage with and without nickel-phosphorus coating on the UHMWPE hardness was determined.

The dependence of COF on carbon nanotubes percentage CNTs and NiCNTs is non-linear and unambiguous and depends on the normal load. In nanoparticle composites CNTs at low loads COF increased to 0.75% CNTs and

reached values higher than COF of non-nanoparticulate materials UHMWPE-0CNTs. With an increase in the percentage of CNTs (1.0-1.5%) COF decreases smoothly and reaches values less than those of non-nanoparticulate material. At a higher load COF decreases nonlinearly and always has values smaller than those of UHMWPE without nanoparticles.

In the presence of nickel-coated carbon nanotubes (NiCNTs), COF has a higher value than COF for non-coated CNTs for all their percentages and all normal load values. With an increase in the nanoparticle content, COF increases reaching a maximum for Ni-CNTs - 1%, then decreases and reaches a higher COF value of non-nanoparticulate materials.

The smallest friction coefficient $\mu = 0,1$ is observed at the highest load $P_4 = 120$ N for nanotubes doped without nickel-phosphorus coating: UHMWPE-1.0CNTs and UHMWPE-1.5CNTs, i.e. materials containing 1% and 1.5% carbon nanoparticles.

The highest coefficient of friction - $\mu = 0.38$ is observed in the friction of UHMWPE-1.0NiCNTs, i.e. materials doped with 1% nickel-plated carbon nanoparticles at least $P_1 = 60$ N.

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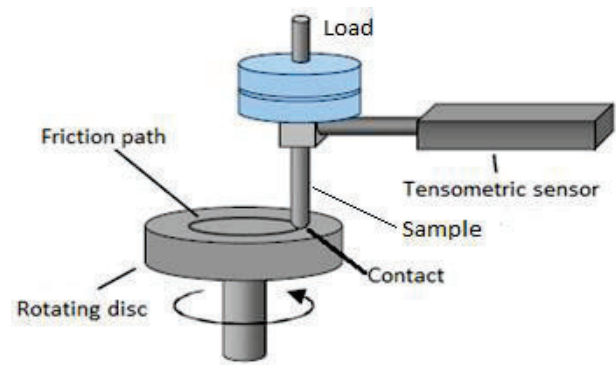


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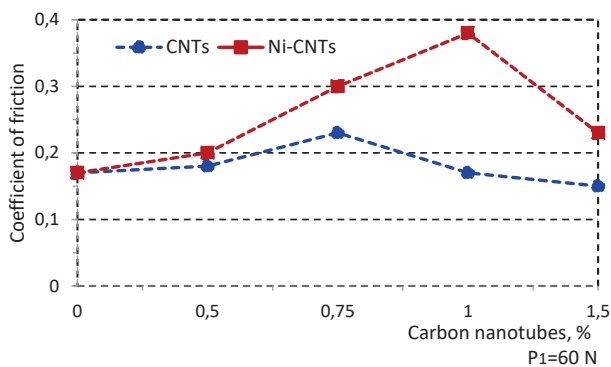


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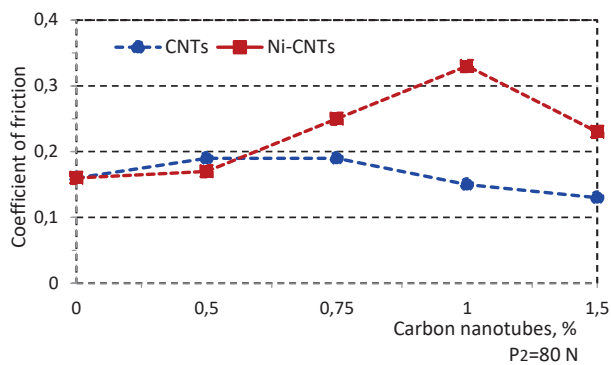


Figure 5. Friction coefficient change from the percentage of CNTs and NiCNTs at load $P_2 = 80$ N

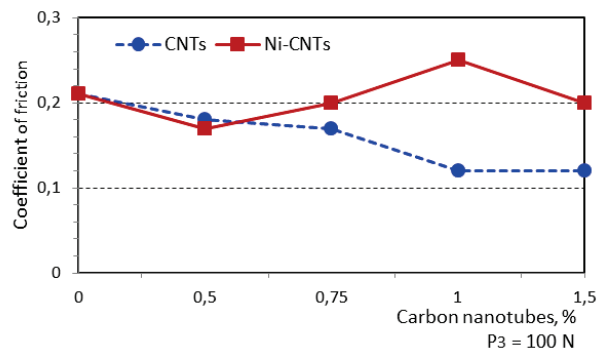


Figure 6. Friction coefficient change from the percentage of CNTs and NiCNTs at load $P_3 = 100$ N

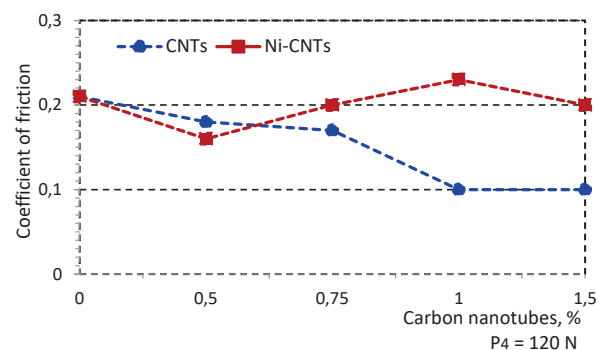


Figure 7. Friction coefficient change from the percentage of CNTs and NiCNTs at load $P_4 = 120$ N

For materials modified with carbon nanotubes without nickel-plated (CNTs), for the same load, COF dependence on the

percentage of nanoparticles is non-linear. At low loads $P_1=60$ N and $P_2=80$ N COF increases to 0.75% CNTs and reaches values higher than COF of non-nanoparticulate materials. When increasing the percentage of CNTs (1.0-1.5%) COF decreases smoothly and reaches values less than those of non-nanoparticulate material (Fig.4, Fig.5). At a higher load in the range $P_3 = 100$ N and $P_4 = 120$ N COF has a one-way change with an increase in the CNTs content - it decreases nonlinearly and there are always lower values than those of UHMWPE without nanoparticles (Fig.6, Fig.7). At these load values for CNTs content = 1% and 1.5%, the coefficient of friction takes the same minimum values, i.e. the coefficient of friction is of a sustained nature.

In the presence of nickel-coated carbon nanotubes (NiCNTs), COF has a higher value than COF for NiCNTs for all their percentages and for all normal loads. In this case, the COF dependence on the percentage of nanoparticles also has a nonlinear character - with an increase in the nanoparticle content, COF increases, reaches a maximum in NiCNTs - 1%, then decreases and reaches a higher COF value as with the non-nanoparticulate material. It is noteworthy that the maximum COF has different values for the different loads but always this maximum is observed for the same percentage of nanoparticles - 1% NiCNTs. At high loads - $P_3=100$ N and $P_4=120$ N, the curve has a wavy character with pronounced minimum and maximum. The minimum coefficient of friction is at 0.5% Ni-CNTs.

From the obtained results it was found that a maximum value of the friction coefficient $\mu=0.38$ was observed in the friction of UHMWPE-1.0NiCNTs materials, i.e. materials doped with 1% nickel-plated carbon nanoparticles at least load $P_1 = 60$ N.

The smallest friction coefficient $\mu=0.1$ is observed at the highest load $P_4=120$ N for nanotubes doped without nickel-phosphorous coating - UHMWPE-1.0CNTs and UHMWPE-1.5CNTs, i.e. the materials containing 1% and 1.5% carbon nanoparticles.

Figures 8 and 9 show COF diagrams for the same load P at different percentages of carbon nanotubes, respectively, with and without nickel coating.

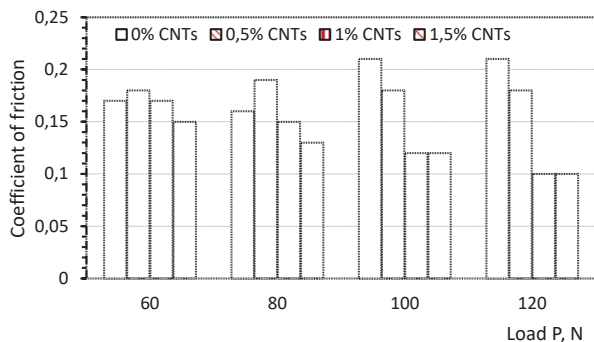


Figure 8. Diagram of COF for the same load P at different percentages of carbon nanotubes CNTs

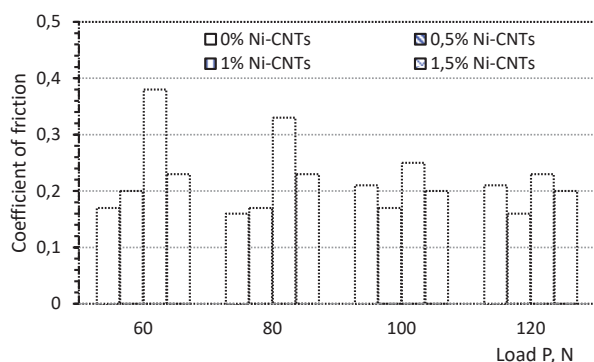


Figure 9. Diagram of COF for the same load P at different percentages of carbon nanotubes NiCNTs

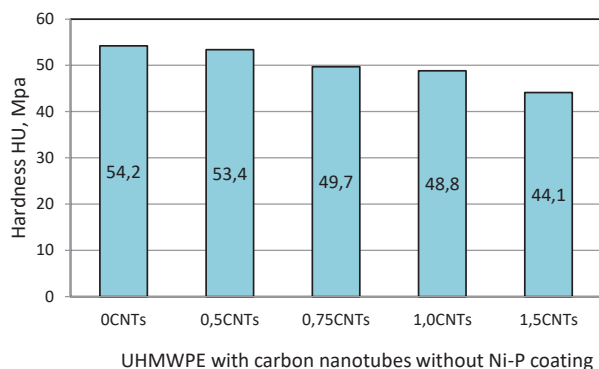


Figure 9. Hardness of UHMWPE with carbon nanotubes without nickel-phosphorous coating

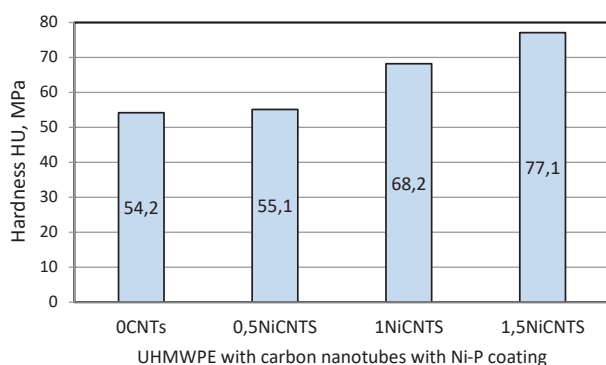


Figure 10. Hardness of UHMWPE with carbon nanotubes with nickel-phosphorous coating

Figures 10 and 11 show UHMWPE hardness graphs with different carbon nanotube contents, respectively, with and without a nickel-phosphor coating.

The analysis of the results on diagrams in Figures 8 and 9 shows that with increasing the load on materials without nanotubes COF increases with the increasing load.

It is clear from Figures 10 and 11 that when alloying with carbon nanotubes with a nickel-phosphorus coating, the UHMWPE hardness rises by 1.42 times in comparison to its non-nanoparticle hardness. The alloying of UHMWPE with uncoated carbon nanotubes does not increase hardness, on the contrary, a slight decrease is observed with an increase in the percentage content.

The obtained results can be interpreted on the basis of generally accepted in tribology molecular-deformation theory of friction [3]. According to this theory, friction is the result of two interdependent processes: a molecular interaction in the microcontacts that determines the adhesion component of the friction and the contact deformations defining the friction deformation component. The forces of molecular interaction depend mainly on the physico-chemical properties of the surface layers in the contact, the temperature, the transfer of material into the contact from one surface to the other, the presence of reinforcement, new structures and vary within certain limits. These forces resist the mutual movement of the bodies and influence contact deformations. The deformation component of the friction is composed of normal and tangential deformations of the contact spots. It mainly depends on the load, physico-mechanical characteristics of the surface layers and can increase or decrease with the increasing of the normal load. The division of the coefficient of friction in two components - adhesion and deformation has a contingent character. Under different modes of friction - load, speed, temperature, one or the other component can dominate, both influencing each other. The increase in COF with the increasing of the load on the material without nanotubes can be explained by the increase of

the deformation component by friction as a result of sinking of the microroughnesses in the surface layers, increasing the number of contact areas and the actual contact area with a high contact pressure as a result of plastic deformation. For small content of nanoparticles - 0.5% with and without nickel coating the friction coefficient has a stable character, i.e. it has almost the same values for different loads, but its value is greater for nickel-plated nanoparticle materials. With a nanoparticle content of 1% and 1.5%, the friction coefficient decreases with increasing the normal load. This is probably due to the reduction of plastic deformation and the flow of elastic and elasto-plastic contact deformations as well as the reduction of the adhesive component. The high COF value for nickel-phosphorus-coated nanotubes is due to an increase in the friction deformation component, in particular an increase in tangential contact deformities due to the increased rigidity of the composite material, containing such particles (Fig. 11).

5. CONCLUSION

In the current work a comparative study was carried out of the coefficient of friction without lubrication of new composite materials based on UHMWPE, containing two types of carbon nanotubes - uncoated CNTs and carbon nanotubes having a coating of nickel-phosphorus coating by the electroless method NiCNTs.

The main work results are limited to:

It has been found the influence on the coefficient of friction of three factors: carbon nanotube percentage, loading and presence of Ni-P coating on nanotubes.

The effect of the carbon nanotube percentage with and without nickel-phosphorus coating on the UHMWPE hardness was determined.

The dependence of COF on carbon nanotubes percentage CNTs and NiCNTs is non-linear and unambiguous and depends on the normal load. In nanoparticle composites CNTs at low loads COF increased to 0.75% CNTs and

reached values higher than COF of non-nanoparticulate materials UHMWPE-0CNTs. With an increase in the percentage of CNTs (1.0-1.5%) COF decreases smoothly and reaches values less than those of non-nanoparticulate material. At a higher load COF decreases nonlinearly and always has values smaller than those of UHMWPE without nanoparticles.

In the presence of nickel-coated carbon nanotubes (NiCNTs), COF has a higher value than COF for non-coated CNTs for all their percentages and all normal load values. With an increase in the nanoparticle content, COF increases reaching a maximum for Ni-CNTs - 1%, then decreases and reaches a higher COF value of non-nanoparticulate materials.

The smallest friction coefficient $\mu = 0,1$ is observed at the highest load $P_4 = 120$ N for nanotubes doped without nickel-phosphorus coating: UHMWPE-1.0CNTs and UHMWPE-1.5CNTs, i.e. materials containing 1% and 1.5% carbon nanoparticles.

The highest coefficient of friction - $\mu = 0.38$ is observed in the friction of UHMWPE-1.0NiCNTs, i.e. materials doped with 1% nickel-plated carbon nanoparticles at least $P_1 = 60$ N.

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