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Contact surface temperature and coefficient of friction of CNT/epoxy nanocomposites during sliding wear

Contact surface temperature of a tribo-system is one of the main characteristics that affect the tribological properties of materials for slide bearings. In this work, IR monitoring was applied for the evaluation of the contact temperature of CNT-epoxy nanocomposites during sliding wear. In most cases, the contact temperature slightly decreases with increasing the CNT content and with the application of CNT modfication. At sliding speeds ≥1 m/s a cyclic behaviour was observed in both temperature and coefficient of friction. The results of the temperature characterization during sliding are of relevance for the understanding of the wear behaviour and at least the development of CNT nanocomposites with improved tribological performance.

Kontakttemperatur und Reibungskoeffizient von CNT/Epoxidharz-Nanokompositen bei Gleitreibung

Die Temperatur in der Gleitfläche eines Tribosystems ist ein wichtiger Faktor für das tribologische Verhalten von Gleitlagerwerkstoffen. In dieser Arbeit wurde die Kontakttemperatur der Paarung CNT/Epoxidharz gegen Stahl versuchsparallel gemessen. In den meisten Fällen fällt die Kontakttemperatur mit steigendem CNT-Anteil sowie einer chemischen Vorbehandlung der Nanotubes ab. Bei Gleitgeschwindigkeiten von ≥1 m/s wird ein zyklisches Verhalten sowohl in der Temperatur als auch im Reibungskoeffizienten beobachtet. Die Resultate tragen zum Verständnis des Verschleißverhaltens bei und können die Entwicklung von Tribowerkstoffen aus CNT-Nanokompositen fördern.

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1 INTRODUCTION

Contact surface temperature is one of the main characteristics that affect tribological properties of nanocomposites during sliding wear [1-6]. This temperature is attributed with the amount of heat energy generated at the contact surface and due to possible deformation of the specimen, conducted from the surface through the material and partly dissipated due to the energy exchange with the ambient environment. The generated heat can lead to the destruction of materials mainly due to physical and chemical processes starting at the surface. Those frictional processes are caused by molecular or atomic scale interactions at the contacting surfaces of the nanocomposite and the counter-body. The processes take place for at least 95% within the top 5µm [3]. The distribution and dissipation of the heat from the surface due to thermal conductivity of the material reduces contact surface temperature. The competition of those two main factors, namely the generated heat energy due to friction and thermo-conductive ability of nanocomposites reducing the heat energy at the surface determines the contact surface temperature and affects the tribological properties of the material.

Considering that heat produced during friction processes leads to change in the structure of the material, it is important to reduce the heat and, therefore, the temperature at the contact area. This can be achieved by the incorporation of thermo-conductive fillers in polymer matrices. The higher the thermal conductivity of the nanofiller is, the lower the amount of the heat energy is located at the contact area of the sample. By characterizing contact surface temperature it is possible to estimate qualitatively thermal conductivity of nanofillers and nanocomposites and the equilibrium between the generated and dissipated heat energy.

CNT have been successfully used as thermo-conductive filler [7]. Therefore, in addition to the known benefits in mechanical, load bearing properties, electrical conductivity, the application of carbon nanotubes in polymer matrices is expected to improve thermo-conductivity and tribological characteristics of multifunctional nanocomposites. To optimise the chemical composition and the structure of nanocomposites for the tribological performance it is relevant to evaluate the alterations in the contact surface temperature during a wear process.

The goal of this study is to investigate the effect of the type of CNT, the chemical coupling of CNT and the volume fraction of CNT in the composition of epoxy-nanomaterials on contact surface temperature of the nanocomposites using IR radiation monitoring technique. The investigations were performed with different sliding speeds. The changes in the temperature at the contact surface are correlated with the alterations in the coefficient of friction during the sliding wear.

2 MATERIALS AND METHODS

CNT epoxy nanocomposites were used in the study. Multi-wall carbon nanotubes (MWCNT) Baytubes C150P (95% purity) have been provided by Baytubes division of Bayer MaterialsScience AG and were used without any purification. These MWCNT were also modified using melamine in order to attach amino groups to the surface of the filler without previous oxidation or electro-chemical handling of the outer grapheme layers of the MWCNT according to [1].

DER 331 epoxy resin based on diglycidyl ether of bisphenol A (DGEBA) was provided by Dow Chemicals Inc. Amine hardener A2954 obtained from Huntsmann Inc. and melamine from Sigma Aldrich Inc. MWCNT were dispersed in epoxy polymer matrix using three-roll mill type 80H provided by Exact GmbH. The curing cycle is constituted by a curing at 70°C for 8 hours followed by an isothermal post-curing at 120°C for 16 hours.

Prepared nanocomposite plates with the dimensions of 100×100×5 mm^3 were cut in order to obtain pin specimens with the dimensions of 10×4×4 mm^3 and polished to undergo coefficient of friction and contact temperature characterization.

The evaluation of the functional properties was performed using a measurement system mounted on a pin-on-disc machine. The pin-on-disc tests were performed according to ASTM G99-05 “Standard Test Method for Wear Testing with a Pin-on-Disc Apparatus” [8]. Pin specimens were fixed at the pin-holder of the measurement rig and exposed to sliding for 8 hours against a rotating disc made of steel 100 Cr 6, hardness 58 HRC, roughness R≤ 1 mkm, serving as a counter body. Normal force was controlled using a pneumatic system. Friction force and the cumulative coefficient of friction were monitored simultaneously with the test. The measurement of the contact surface temperature and the counterpart surface temperature was performed simultaneously using two IR sensor devices connected to a PC. The measurement system is demonstrated in Figure 1.

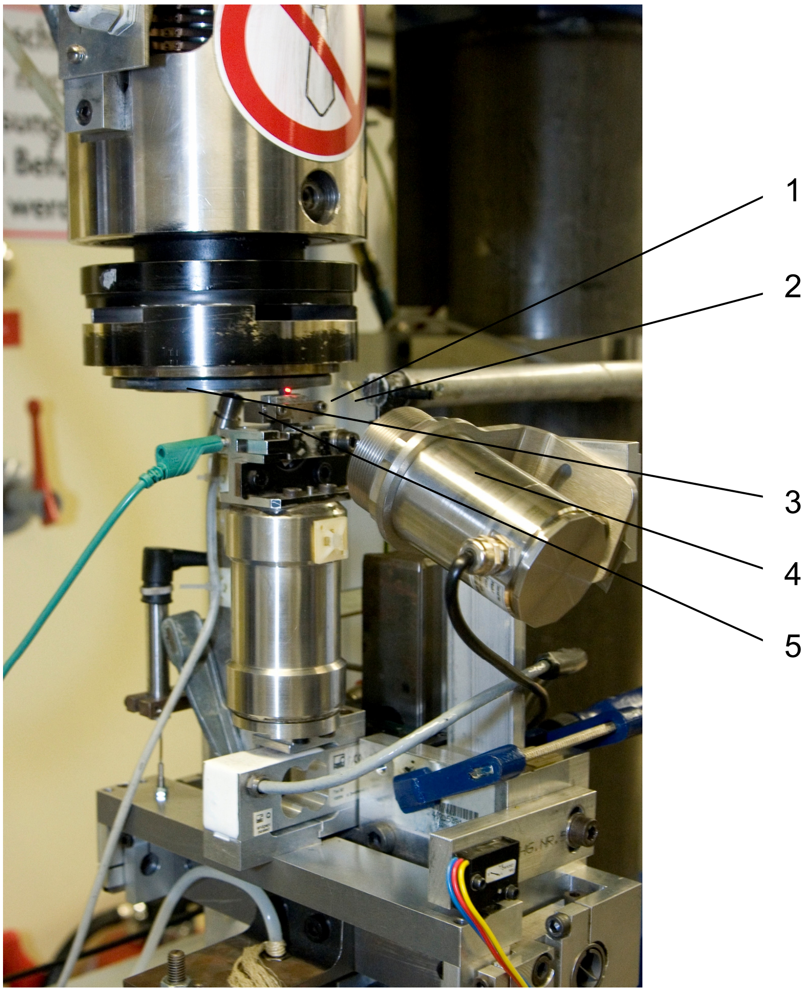

Figure 1: Measurement system for the characterization of multifunctional nanocomposites:

1 - pin specimen; 2 - pin holder; 3 - sliding disc; 4 and 5 - IR sensor devices

3 IR SENSOR FOR THE CONTACT SURFACE TEMPERATURE CHARACTERIZATION DURING THE SLIDING WEAR

For the measurement of contact surface temperature several approaches have been applied [1-3, 9]. However, most of the existing techniques require material destruction and, therefore, cannot be applied for on-line temperature monitoring.

The application of non-contact temperature measurement based on the monitoring of IR radiation incident from a heated surface has several advantages; this method is non-destructive; it is possible to apply the method simultaneously with other testing techniques; it gives the possibility to measure average radiation energy over a spot area that increases the accuracy of the test.

IR radiation is emission of electromagnetic waves that transfer energy from the heated object. The principle of the temperature monitoring based on the IR radiation measurement derives from the relationship between the radiation incident from the surface and the temperature of the object described by the Stefan-Boltzmann equation [10].

There are several techniques for the IR radiation monitoring such as photography, pyrometry, thermal imaging, photon detection and other [1]. One of the most promising approaches is based on the application of an IR sensor. Due to fast response and exposure of the signal of IR sensors this approach gives relatively precise information during the test and, therefore, reproducible results.

To investigate the changes in the contact surface temperature during a wear process, a special device based on the IR radiation sensor was established. The device allows monitoring of the temperature of the pin contact surface when the specimen is exposed to a wear process caused by sliding of a steel disk on the pin surface [11].

The IR radiation sensor was obtained from the CT Laser, OPTRIS, Germany, for recording the temperature at the point close to the contact surface of the sample. A special device that enables adjustment possibilities for the IR sensor was designed and attached to the pin-on-disk testing rig [11]. The device makes it possible to change the position of the sensor directing the light flux to a point close to the surface of the sample, Figure 1. The temperature monitoring was operated using a PC software based on the LabView program package. The measurement was carried out over a spot area of approximately 2 mm in diameter. Therefore, the obtained result is an average data of local flash temperature values.

The data measured by the IR sensor were compared with the data obtained by a thermocouple and a calibration of the sensor was performed.

4 RESULTS AND DISCUSSION

4.1 Sliding speed affects contact surface temperature

During sliding pin-on-disk tests CNT-epoxy nanocomposites exhibit different contact surface temperature when exposed to sliding at different speeds. This is likely to be caused by higher heat generation during sliding at higher speed which is demonstrated by an increase in the contact surface temperature. The difference in the temperature profile during sliding at different speeds is shown in Figure 2 for epoxy nanocomposites containing 0.16 vol% amino-functionalized MWCNT.

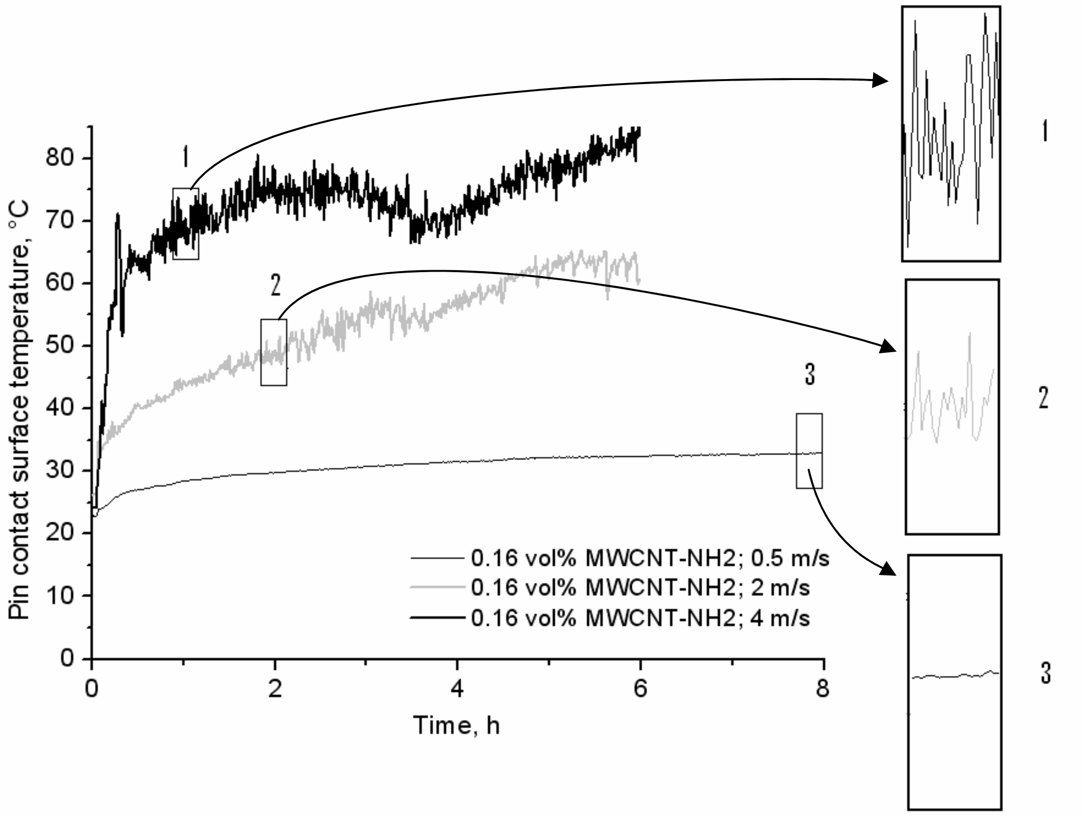

Figure 2: Contact surface temperature versus time of epoxy nanocomposites during sliding at 1MPa

Tests at lower sliding speed of 0.5 m/s, 1 MPa pressure demonstrate a lower increase in the contact surface temperature up to 35-38°C in average compared to the test results at higher sliding speed, Figure 2. The temperature versus time profile is relatively smooth during the whole duration of the sliding process at 0.5 m/s. The fluctuation of the signal at lower sliding speed is less pronounced in contrast to the sliding at more severe speed. With increasing speed the temperature profile shows higher temperature values and rather cyclic behavior, Figure 2. By converting the sliding time into sliding distance it can be seen that the period of the fluctuation is almost identical, Figures 2 and 3.

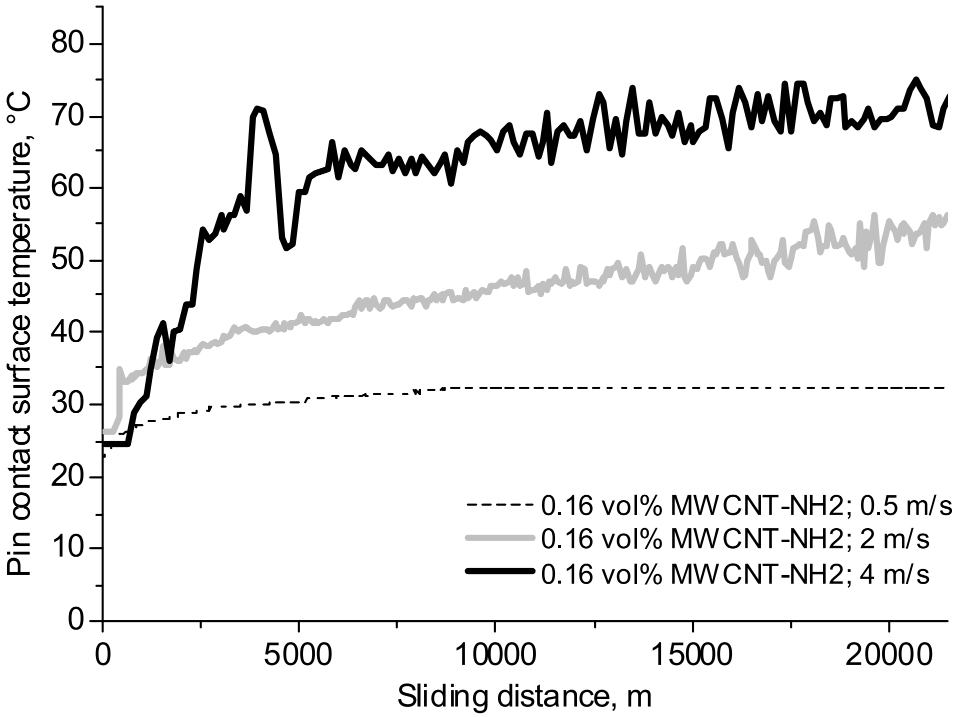

Figure 3: Contact surface temperature of epoxy nanocomposites during sliding at 1MPa as a function of sliding distance

Demonstrated higher heat generation at higher sliding speed agrees with the dependence of the heat energy on the sliding speed [1]:

$$Q=\mu Fv,$$

here μ is the coefficient of friction, F is the applied load and v is the sliding speed, $\mu=Q/(Fv)$.

During pin-on-disk sliding at different speeds, two periods of the contact surface temperature change are distinguished, Figures 2 and 3. The first period is characterized by a relatively fast growth of the temperature and the second period is a steady stage.

The periods of the changes in the contact surface temperature correspond to the stages of the alterations in the coefficient of friction, see Figures 2 and 4.

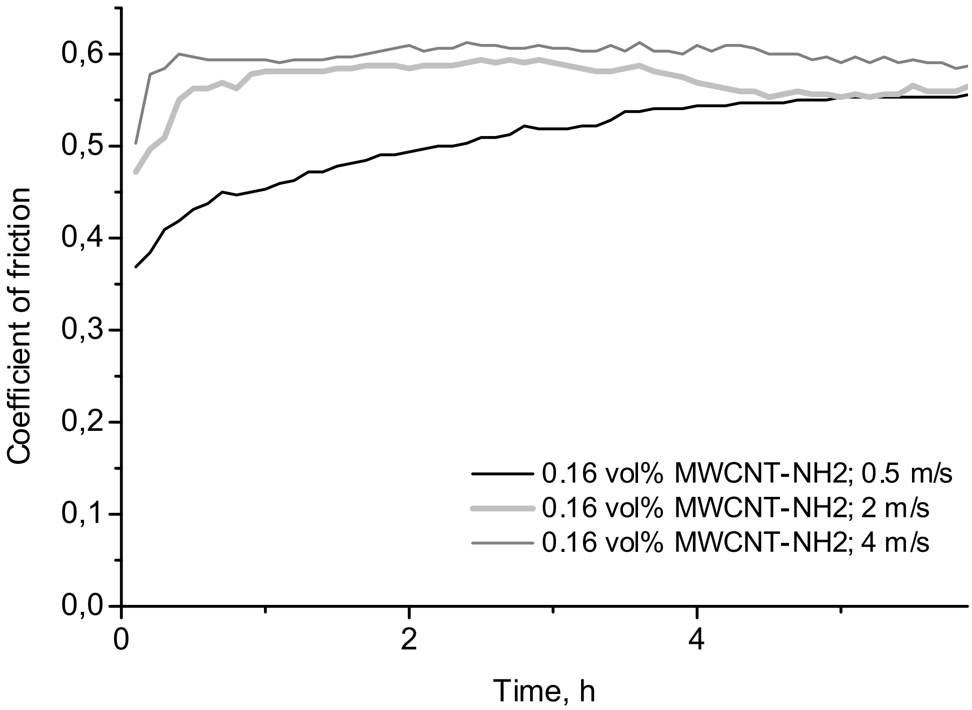

Figure 4: The coefficient of friction of epoxy nanocomposites during sliding at 1MPa

The coefficient of friction is slightly different during sliding at different sliding speeds likely due to the difference in the temperature at the contact surface; it is higher at higher sliding speed.

The cyclic character of the contact temperature appears only at higher sliding speed that can be associated with higher temperature and demonstrates its effect on the contact temperature profiles. The cyclic behavior starts not from the beginning of sliding but after a period of time when the temperature achieves a certain value. The explanation of the cyclic behavior of the temperature and the coefficient of friction profiles is a subject of our further investigation.

4.2 The effect of surface modification of MWCNT on contact surface temperature

Surface modification was made by chemical attachment of polar groups to CNT surface. This provides the possibility to enhance the dispersibilty of nanotubes in epoxy matrix [12-15]. Amino-modification among other types of surface modification applied to CNT is known to lead to advantageous properties of CNT-epoxy nanocomposites [16-22] due to providing sufficient interfacial bonding between CNT and epoxy polymer matrix that enhances load transfer from the polymer matrix to nanotubes at the CNT-polymer interface. The application of surface functionalization to CNT is expected to improve the dispersion state of CNT, distribution of CNT in polymer matrix, thermal conductivity of the nanocomposites and their tribological behaviour.

Due to expected more homogeneous distribution of surface-modified MWCNT in polymer matrix, the rate of heat transfer in the nanocomposites is supposed to increase. Improved interfacial bonding between CNT and polymer matrix can reduce thermal resistance of the CNT-polymer interface [23] and, therefore, would lead to lower contact surface temperature for nanocomposites containing surface-modified MWCNT. In addition, considering that contact surface temperature is affected by generated frictional heat, the temperature can be reduced due to lower coefficient of friction for nanocomposites containing modified CNT.

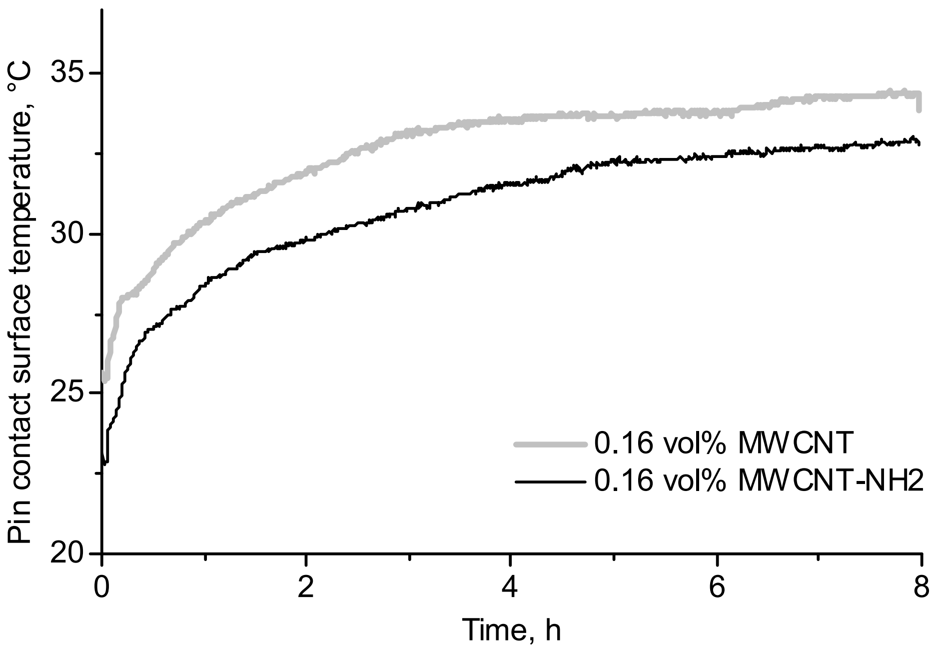

Figure 5: Contact surface temperature of surface modified and non-modified CNT nanocomposites during sliding at 1 MPa pressure, 0.5 m/s speed

As it is demonstrated by the sliding tests results, contact surface temperature of CNT filled nanocomposites slightly decreases with the application of amino-functionalization to CNT, see Figure 6. This can be considered as a benefit in the thermoconductive properties of the nanocomposites due to surface modification and in lower heat generation at the contact surface. This tendency agrees with the results reported at [24] demonstrating that moderate chemical functionalization leads to improved thermal conductivity of CNT nanocomposites.

The changes in the contact surface temperature during sliding wear process agree with a decrease in the coefficient of friction for surface modified CNT nanocomposites, see Figures 5 and 6. Stronger bonding due to surface modification affects lower adhesion to the counter-body surface with the application of amino-modification to CNT, therefore, the coefficient of friction decreases resulting in lower heat generation. This agrees with results obtained by Dong et. al. [25].

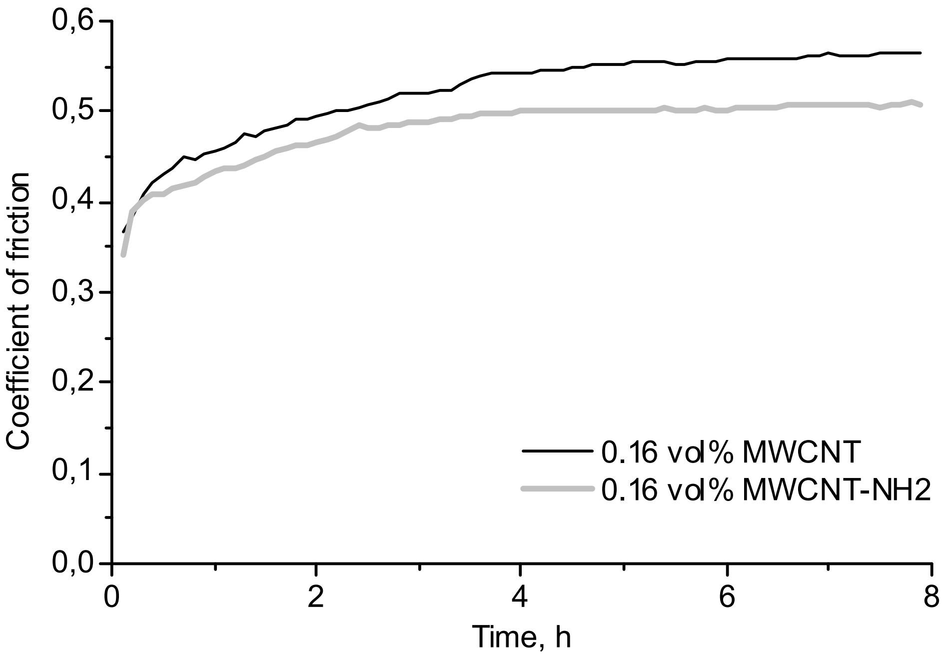

Figure 6: The coefficient of friction for modified and non-modified CNT nanocomposites during sliding at 1 MPa pressure, 0.5 m/s speed

4.3 The effect of surface modification of MWCNT on contact surface temperature

CNT incorporated in polymer matrix provide dissipation of thermal energy in the nanocomposite due to phonon conduction along the nanotube axe [26-29]. The phonon conduction of heat energy in nanocomposites is related to the number of defects and to the overall size of the interface [29]. Therefore, thermo-conductive properties of the nanocomposites are affected by the amount of thermo-conductive filler used in the composition which was also demonstrated by Hohe [28]. The higher the amount of a thermo-conductive nanofiller, the more intensive the energy transfer process is in the nanocomposite. At the same time, with higher volume fraction of CNT in epoxy matrix the coefficient of friction decreases leading, therefore, to lower amount of frictional heat generated at the contact surface. Both factors are expected to decrease contact surface temperature of the nanocomposites with increasing the fraction of CNT.

It is shown by the tests results that, as predicted, with increasing the CNT content in polymer matrix, contact surface temperature decreases. Figure 7 demonstrates contact surface temperature of CNT-epoxy nanocomposites with different CNT content.

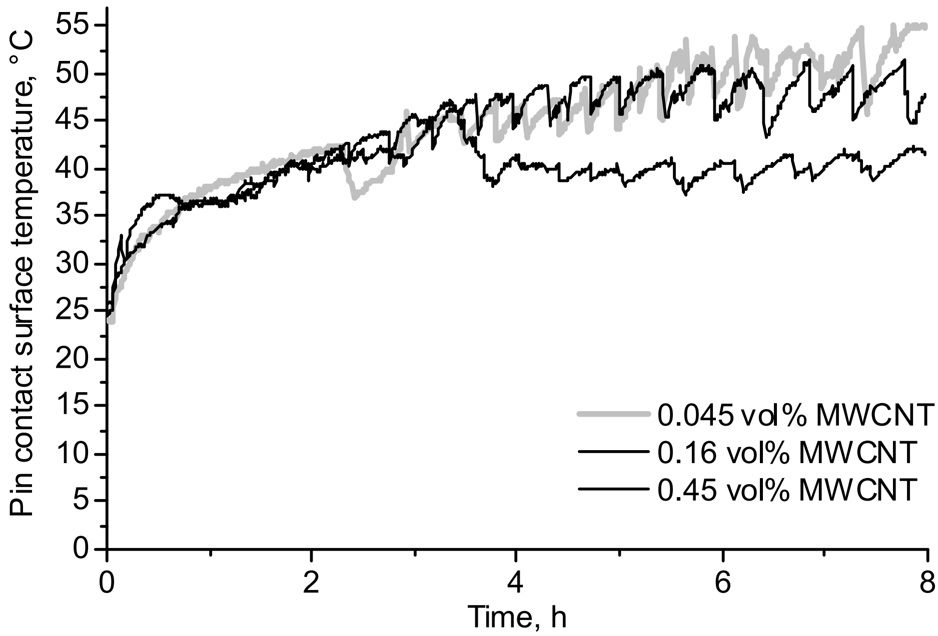

Figure 7: Contact surface temperature of CNT–epoxy nanocomposites during sliding at 1 MPa pressure, 1 m/s speed

The difference in contact surface temperature due to different CNT content takes place not from the beginning of the sliding wear process but after a certain initial period of time, see Figure 7. This period can be associated with initial transfer film formation. The initial period of time likely depends on the composition, structure of nanocomposites and on the sliding conditions. The decrease in temperature is higher with more significant change in the CNT content. Thus, when raising the volume fraction of CNT from 0.045 vol% to 0.16 vol% the temperature decreases slightly whereas with the change in the CNT content from 0.16 vol% to 0.45 vol% the decrease in the temperature is more pronounced. The indicated tendency demonstrates the effect of the thermal conductivity of nanocomposites on the contact surface temperature and the balance between the generated and dissipated heat energy.

The demonstrated tendency shows that it is beneficial to increase the CNT volume fraction above the percolation threshold maintaining relatively uniform distribution of CNT in polymer matrix to obtain nanocomposites with lower contact surface temperature during sliding wear and, therefore, to improve the tribological properties.

5 CONCLUSIONS

Surface temperature monitoring using an IR radiation sensor has been performed for the evaluation of the effect of the surface modification and volume fraction of MWCNT on contact surface temperature of nanocomposites during sliding wear. It is demonstrated that contact surface temperature depends on the sliding conditions. It is lower during sliding at lower speed. Higher sliding speed affects a cyclic behaviour of the profiles of temperature and coefficient of friction versus time. Two periods in the temperature profile can be distinguished. The periods correspond to the stages of the alterations in the coefficient of friction during sliding wear process.

It is shown that the application of the surface amino-modification to CNT leads to a decrease in contact surface temperature of CNT-epoxy nanomaterials. With increasing the volume fraction of CNT contact surface temperature decreases. This is likely to be caused by increasing the thermal conductivity of the nanocomposites and decreasing the generated frictional heat.

The obtained results can be applied in the development of the composition for CNT nanocomposites with advanced functional characteristics.

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