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STUDY ON FRICTION TEMPERATURE OF UHMWPE/MULTILAYER GRAPHENE/PARAFFIN NANOCOMPOSITES

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The friction temperature of UHMWPE nanocomposites with various loadings of multilayer graphene /paraffin was directly measured using thermocouple temperature recorder. It is found that friction temperature of the end of the composite materials is lower to a varying degree compared to the pure UHMWPE. Direct measurement of friction temperature of the composite materials tends to lag, and friction flash temperature is much higher than the measured temperature. Through comparing the friction temperature field of the measured values and the analytical values, it is concluded that analytical values better conform to the change trend of actual temperature. The analytical estimation method for the material of friction temperature has a certain guiding significance to the prediction.

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*Keyword:*Friction temperature field; UHMWPE;multilayer graphene

1. Introduction

The mechanical and tribological properties of most polymer materials are highly dependent on temperature. At higher temperature, the friction and wear of polymer materials often exhibit severe volatility and irregularities, especially when the temperature reaches nearly the glass transition temperature or exceeds the melting point of the materials. UHMWPE, just like typical polymer materials, is readily to cause rapid heat accumulation during friction processes on account of low heat conduction. Therefore, the tribological properties of UHMWPE show sensitivity to temperature. The sharp rapid rise of temperature increases the thermal motion of the molecular chain of UHMWPE, which makes highly entangled molecular chains unwrap. The rapid thermal motion of the molecular chain will greatly accelerate the creep rate of UHMWPE material, which affects the tribological properties of the materials further. The above-mentioned point will have a notable influence on the application fields of UHMWPE.

In order to broaden the scope of polyolefin materials, a lot of methods of reinforcement including blends [1-5], irradiation cross-linking [6, 7], and adding rigid filler to reinforce the material [8-11] are carried out. Among the above-mentioned methods, the reinforcement using rigid filler is widely adopted, which has the advantage over other methods due to the diversity of filler type. As a type of carbon filler, porous multilayer graphene material (MG) has received much attention recently [12-14]. Porous multilayer graphene material has excellent properties such as good thermal conductivity, high temperature resistance etc. Porous multilayer graphene material has great surface area with high adsorption property on account of massive pore structure. To modulate the frictional heat, we expect to find a heat absorption material to enter UHMWPE matrix to prepare a new composite material and study its tribological performance. Multilayer graphene / paraffin material with high phase change latent heat is prepared after dipping

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adsorption and corresponding composites are fabricated. The design concept of the composite not only solved the flow of the leak of the phase change materials after solid-liquid change, but also fulfilled phase change heat of paraffin and the high strength of MG.

Because the temperature field is closely related to a series of friction and wear phenomena displayed by the material itself, it is very important to measure it effectively. Then the temperature value of the equilibrium state can be obtained by proper test method such as thermal couple and thermal imager. During the process of friction, block and the counterpart steel ring have been in a relative sliding state and the positions of the two friction contact points are changing in succession. Thus, it is very difficult to catch the instantaneous high temperature rise (flash temperature) in the friction process. The measurement device can not be spaced to the sliding surface at zero clearance, the thermal conductivity of the polymer materials is poor, and the use of sensors can only be read to the material friction endpoint of the steady temperature; all these factors combined further aggravate the measurement error. At present, one usually solve the instantaneous temperature rise in the friction process by establishing mathematical model and the method of creating empirical formula [15,16]. In view of the actual condition of the sliding friction in the experiment, the depth of wear is so small to be omitted approximately, so the classical model of single heat source and infinite body sliding friction proposed by Jaeger [17]can be used.

In this paper, we test the friction temperature values of the UHMWPE/ multilayer graphene / paraffin nanocomposites by a thermal couple and imager, and then we use established mathematical model and the method of creating empirical formula to verify the results. The conclusions can be a great asset to polymer tribology both scientifically and technically.

2. Experimental

Multilayer graphene were prepared from expandable graphite (Qingdao graphite Co., Ltd) by the method of thermal exfoliation. The obtained multilayer graphene particles were directly added in melt solution of solid paraffin (National reagent group Co., Ltd), and the mixture were mechanically stirred for 0.5 hour and ultrasonically processed for 0.5 hour. The sample of multilayer graphene/paraffin was cooled and collected. The UHMWPE matrices (Beijing Second Chemical Plant) were mixed with multilayer graphene/paraffin of weight fractions of 0wt%-40wt%, respectively; the mixture samples were fabricated by hot pressing.

This experiment of the frictional contact model is block-on-ring, and the friction contact area is small. Therefore, the temperature measurement of the friction surface not only requires the measuring device sufficiently close to the actual area, and the location of the measured point has obvious influence on the accuracy of the results. There is some difficulty to measure the temperature by using conventional non-contact infrared device; therefore, thermocouple meter (TES 1384) is used in this study. This kind of temperature measurement method avoids thermal radiation loss of the non-contact temperature measurement and overcomes the shortcomings of movement of the measured position. It can obtain the real friction surface temperature, but there is still some differences between the actual contact friction surface temperature and the measured temperature.

3. Results

The morphology of the prepared nanoscale particles are typically characterized using transmission electron microscope (TEM) on account of its high magnification. Figure 1 lists the TEM image of the sample of multilayer graphene. Through analyzing the image, it can be seen that most of platelets of multilayer graphene appear with a multilayer structure and a width size of a few hundreds nanometers; the thickness size of one layer is ca. one nanometers. It is concluded that multilayer graphene was successfully fabricated.

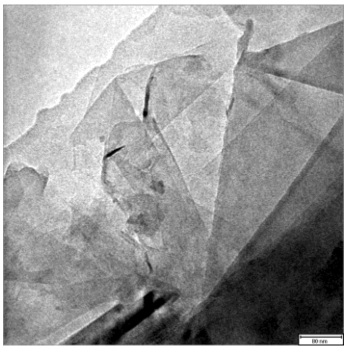

Fig. 1.Transmission electron microscope image of multilayer graphene

Fig. 2 lists the effects of filler contents on the final temperature of UHMWPE composites under the testing condition.

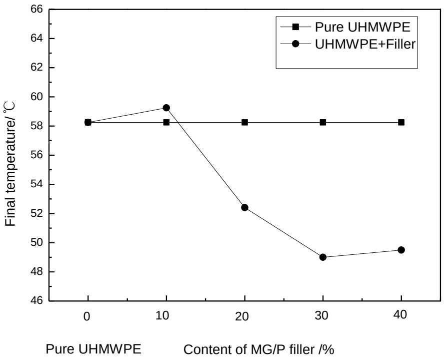

Fig. 2Effects of filler type and contents on the final temperature of UHMWPE composites

As you can see, pure UHMWPE materials has friction end point temperature of 58.8 ℃. Most of UHMWPE composites filled with multilayer graphene / paraffin (except 10% of multilayer graphene / paraffin) present low friction end temperature. Under the condition of low speed test, friction end temperature of composites with 30% and 40% multilayer graphene / paraffin dropped to the lowest, and the values reduced by 6 ~ 10 ℃compared with pure UHMWPE. Factors to produce lower temperature mainly come from the following aspects.On the one hand, the composite material can improve the performance of friction surface and results in lower coefficient of friction, thus friction heating reduce. On the other hand, thermal storage effect of phase change materials can suppress the temperature rising rate; the addition of the filler enhances the thermal conductivity of the polymer and promotes the heat transfer and heat dissipation between the material and air medium. With comprehensive influence of all the factors, the end friction temperature of the composite material has significantly changed compared to that of the pure UHMWPE. The change tendencies of friction temperature and wear track widths of composite materials have similar trends. This result verifies the action of friction temperature field on tribological properties of composite materials, and it is also illustrated that the friction and wear of composite materials is a process with the influence of multiple factors among friction, wear and temperature rise effect.

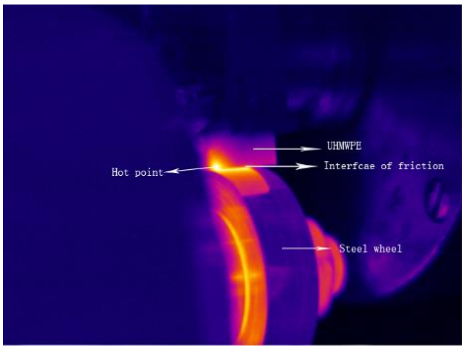

Fig. 3.The infrared thermal image of temperature field in the process of friction test

Flash temperature originates from instantaneous overheating in the process of friction. The UHMWPE sample is fixed although the steel ring keeps rotating during the friction and wear process. This means that the friction area on one side of the UHMWPE material remains unchanged and continues to suffer the shear friction from counterpart steel ring. The real contact area is small and the temperature rises fast as time goes on. It is easy to produce local hot spots with higher temperature (flash temperature) than bulk temperature. The local overheating will change to the state of friction interface and cause rearrangement and fracture phenomenon of UHMWPE chain, thus specimen and steel counterface might weld together. The flash temperature plays a crucial role in the tribological properties of materials [18]. Figure 3 shows the friction temperature field of friction counterpart in test status using Ti400 infrared thermal imager. As the friction testing proceeds, the internal temperature of UHMWPE materials and steel counterface gradually increased and showed a different distribution of temperature field, in which the side of UHMWPE has a strong and hot temperature. This side is also the most prone to transient overheating. Around the hot spot, temperature signal is relatively weak and divergence attenuation trend presents by the hot temperature. The corresponding side of steel ring presents a potential difference along the axial direction, and the temperature varies at different positions.

4. Discussions

In order to calculate conveniently, it is assumed that there is no heat exchange between materials and the environment medium, and thermal physical parameters and the material itself does not change with temperature. The heat transfer model of the friction system can be regarded as heat transfer process of $2a \times 2b$ rectangle heat source sliding in one and a half infinite parallel surface with the speed V. The rectangular surface is equal to worn track of the material. Half the length along the sliding direction of worn track is a, and the half width of the wear surface is b. The relative sliding velocity between UHMWPE materials and steel ring is V. In this experiment, the simulation condition concludes V = 0.43 m/s, a = 6.18 mm and 2b = 7 mm; thermal physical property parameters of UHMWPE materials and steel ring are shown in Table 1.

Table 1. Thermo-physical properties of UHMWPE and the steel wheel

Thermal-physical properties	UHMWPE	steel wheel
Thermal conductivity λ (W/m·°C)	0.5	40.108
Specific heat C (J/kg·°C)	2585	460
Density ρ (kg/m^3)	930	7880
Thermal diffusivity α (m^2/s)	2.08×10^{-7}	1.1×10^{-5}

According to an empirical method proposed by B. Bhushan[19], the moving heat source can be used as rapid moving ones while the Peclet constant L>10, and the following relations exist for the experimental friction system:

$$L = \frac{V*a}{\alpha} \tag{1}$$

$$\alpha = \frac{\lambda}{\rho * C} \tag{2}$$

In these formula, *L* is Peclet constant, *V* is the relative sliding velocity, *a* is half the length of the worn track surface along the sliding direction, *á* is the thermal diffusion coefficient, *ë* is thermal conductivity coefficient, *ñ* is the density value, and *C* is specific heat.
According to these formulas, the following judgments are reached.

$$\text{As for UHMWPE：} \quad L = \frac{0.43 \times 3.09 \times 10^{-3}}{2.08 \times 10^{-7}} = 6388 \tag{3}$$

$$\text{As for steel ring：} \quad L = \frac{0.43 \times 3.09 \times 10^{-3}}{1.1 \times 10^{-5}} = 121 \tag{4}$$

UHMWPE materials can be judged to be fast moving heat source for Peclet constant of UHMWPE is greater than 10. For fast moving heat source, there is almost no difference in temperature along the direction of sliding. Therefore, the three-dimensional temperature field structure can be simplified as 2-D direction of heat transfer structure. Most of the heat generated by the sliding friction entered into a steel ring system for the *á*$_{\text{UHMWPE}}$ is far less than *á*$_{\text{steel ring}}$. Thus, the heat source relative to the entire steel ring can be regarded as stationary and the friction contact surface of the steady-state average temperature and the maximum transient temperature can be calculated through the following equations [20]:

$$\overline{\theta} = 1.13 \times \frac{q}{\lambda_{UHMWPE}} \sqrt{\frac{a * \alpha_{UHMWPE}}{V}} \tag{5}$$

$$\theta_{\max} = 4.2 \times 10^{-4} \times \frac{\mu F \sqrt{V}}{b * \sqrt{a}} \tag{6}$$

$$q = \frac{\mu * F * l}{S * t} = \mu P V \tag{7}$$

$$\overline{\theta}_T = \overline{\theta} + \theta_0 \;\;,\;\; \theta_{Tm} = \theta_{\max} + \theta_0 \tag{8}$$

In these formula, $\overline{\theta}_T$ (°C) represents the average temperature in the process of friction, $\theta_{\max}$ (°C) is the instantaneous maximum temperature rise, *q* (W/m^2) is heat generation rate per unit area, μ is the coefficient of friction, *F (N)* is pressure loaded, *l* (m) is friction distance, S (m^2) is the area of heat source, *t* (s) is the friction time, and *P* (N/m^2) is the load per unit area. $\overline{\theta}_T$ and θ_{Tm} represent the steady average temperature and transient maximum temperature of friction interface, respectively. In our experiment, μ for pure UHMWPE is 0.27, the data calculated are as follows: $\bar{\theta}$=47.00°C， $\theta_{\max}$ =74.78°C. If the initial temperature is set as 20.00 °C, ultimate friction temperature value of pure UHMWPE is equal to the sum of the initial temperature and friction rise temperature: $\bar{\theta}$=67.00°C， $\theta_{\max}$ =64.78°C. For filler modified composite, the additions of filler in UHMWPE matrix change physical parameters of the materials [21], so that the temperature field of the solving process is complicated and the temperature results are shown in Table 2.It can be seen that flash point temperature is much higher than the average temperature, and its influence on friction surface microstructure tend to determine the overall tribological properties of materials.

Table 2.The mathematical analysis value of friction contact temperature of the UHMWPE composites modified by MG/P filler

Content of MG/P	$\bar{\theta}_T$	θ_{Tm}
10%	47.62	72.58
20%	39.41	63.12
30%	30.67	47.72
40%	37.60	73.40

Figure 4shows analytic mathematic values of friction temperature field, actual measured values of the UHMWPE matrix composites. As you can see according to the figure, actual measured values are usually higher than the analytical values. The reasons for this phenomenon are that some of the heat loss and heat resistance of material itself may be ignored in the process of simulation. On the one hand, the effects of abrasive wear and adhesive wear coexist in the process of friction and wear, and the actual contact area is greater than the nominal contact friction area so as to contribute to the rise of temperature. On the other hand, the composite with phase changes filler has the endothermic lubrication and improve the effect of matrix coefficient of thermal conductivity, which in turn helps reduce friction temperature. Combined with these two factors, it caused the deviation between the measured value and simulated values. But overall, the simulated values can better accord with the actual temperature of the material change trend, and the temperature deviation is an acceptable range. The analytical estimation method for the material of friction temperature field has a certain guiding significance to the prediction.

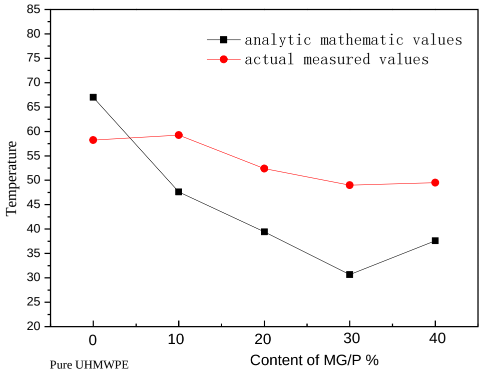

Fig. 4 the calculated and measured results of the UHMWPE composites

5. Conclusions

The temperature profiles of UHMWPE nanocomposites were directly measured. It was found that stable friction temperature of the end of the composite materials was lower to a varying degree compared to the pure UHMWPE.

Direct measurement of friction temperature of the composite materials tends to lag, and friction flash temperature is much higher than the measured temperature; flash point temperature plays a vital role in friction and wear properties of materials.

Through comparing the friction temperature field test of the measured values and the numerical values, it is concluded that analytical value better conforms to the change trend of actual temperature.

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