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Testing the Friction Between a Hydrogenated DLC Coating and Polypropylene Homopolymer

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Abstract

This study examines dry sliding friction between a hydrogenated amorphous carbon (a-C:H) diamond-like carbon (DLC) coating and a polypropylene homopolymer (PPH). The coating was deposited on a quenched and tempered 42CrMo4 steel specimen (39 ± 1 HRC). Friction tests were performed at three sliding speeds (v = 5, 50, and 500 mm/min) and three surface pressures (p = 2, 4, and 6 MPa). From the recorded friction-force curves, the static friction coefficient (μ_0) was taken as the peak value at the onset of motion, while the dynamic friction coefficient (μ_{dyn}) was evaluated in the near steady-state (gross sliding) region. Both μ_0 and μ_{dyn} increased with sliding speed: μ_0 rose from about 0.24 to 0.33 and μ_{dyn} from about 0.22 to 0.32 in the investigated range. Surface pressure had a smaller effect: μ_0 showed no clear pressure trend, whereas μ_{dyn} increased with pressure at a given speed. A two-factor analysis confirms that sliding speed is the dominant factor for both μ_0 and μ_{dyn}, and it also indicates a weak non-linear speed dependence in this parameter range. Overall, the friction coefficient of the PPH–DLC pair remained approximately within 0.20–0.35 for v = 5–500 mm/min and p = 2–6 MPa.

Keywords

diamond-like carbon (DLC), polypropylene homopolymer, dry sliding friction, friction coefficient, sliding speed

1 Introduction

Diamond-like carbon (DLC) coatings have been widely used in industrial and materials science applications since the beginning of the 21st century [1–5]. The reason is that DLC coatings have several properties close to those of diamond, such as high hardness, high elastic modulus, and chemical inertness. At the same time, they are produced as disordered, grain-boundary-free thin films, with much lower production cost than diamond. In addition, their properties can be adjusted over a wide range by changing the ratio of sp^3/sp^2 carbon bonds in the structure and by doping with chemical elements [6, 7].

One of the most important advantages of DLC coatings is their favorable tribological behavior, which is related to their excellent surface quality. The literature widely covers the friction behavior of DLC coatings in DLC–DLC and DLC–metal material pairs. These studies often focus on surface changes in the contacting materials, the comparison and behavior of lubricants, the effect of different sliding speeds, and the influence of environmental conditions [8–12]. Based on these, it can be stated that the tribological performance of DLC coatings is important in most engineering applications. However, relevant studies on DLC–polymer material pairs are still relatively limited. DLC–polymer contact may occur, for example, in biomedical applications such as prostheses, where wear resistance, corrosion resistance, and low friction are especially important. In addition, DLC–polymer material pairs may also appear in injection molding tools. Escudeiro et al. [13] compared the tribological behavior of DLC and Zr-DLC coatings with that of Ti6Al4V and CoCr surfaces using two different polymer materials, ultra-high molecular weight polyethylene (UHMWPE) and polyether ether ketone (PEEK). The main focus of the study was on friction, wear, coating failure (delamination), and adhesion-related problems caused by a body-fluid-like environment. Their pin-on-disc tests showed that the DLC–UHMWPE pair had a moderately low and relatively stable friction coefficient, whereas the DLC–PEEK pair showed nearly twice as high and much more fluctuating friction values.

Tillmann et al. [14] investigated the tribological behavior of PVD coatings against different polymers (PA, PS, and PP) in injection molding tools. The main aim of their

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study was to determine how the surface roughness and surface free energy of the coatings, especially the ratio of the polar and dispersive components, influence adhesion and, through this, the friction coefficient in polymer–metal contact at temperatures close to injection molding conditions. In the case of polypropylene, higher adhesion resulted in a higher friction coefficient, which means that friction against PP clearly correlated with the adhesive component. For most Cr-based coatings, the friction coefficient remained below 0.4, which was more favorable than in the case of uncoated steel.

In the present study, the investigated material pair was a hydrogenated amorphous carbon (a-C:H) DLC coating and polypropylene homopolymer (PPH). Polypropylene (PP) is one of the most widely used engineering polymers due to its favorable mechanical properties, low density, chemical resistance, and good processability [15, 16]. Due to its higher crystallinity and stiffness, homopolymer (PPH) may exhibit a different tribological response than more amorphous or modified polymers. The industrial and biomedical applications of PP-based systems are continuously expanding, especially in combination with composite reinforcement [17].

In hydrogenated DLC (a-C:H) coatings, the hydrogen content can be a key factor in tribological behavior. The presence of hydrogen may reduce the surface energy and modify the tribochemical reactions [18–20]. In addition, the tribological properties of DLC systems also depend on the presence of different added chemical elements, such as silicon, oxygen, and various metallic elements [21], as well as on the relative humidity of the environment [22] and the surrounding environment, such as H_2O, O_2, and N_2 [23, 24]. However, when a polymer is used as the counter material, the contact mechanism is complex: adhesion, local plastic deformation, and possible transfer layer formation together determine the friction coefficient.

The aim of this study was to investigate the dry sliding friction behavior of a material pair consisting of polypropylene homopolymer and hydrogenated amorphous carbon (a-C:H) DLC coating at different sliding speeds and surface pressures. The static (μ_0) and dynamic (μ_{dyn}) friction coefficients were evaluated separately to determine the effect of sliding speed and surface pressure on the tribological behavior of the system.

2 Materials and methods

2.1 Friction coefficient determination

Friction can be defined as the ratio of two forces acting at the contact surface of two bodies: the normal force, acting perpendicular to the surface, and the friction force, acting parallel to it, when the bodies are in relative motion or at the threshold of motion. Accordingly, based on Fig. 1, two friction coefficients can be determined [25].

The static (μ_0) and dynamic (μ_{dyn}) friction coefficients shown in Fig. 1 can be defined as follows (Eq. (1)):

$$\mu_0 = \frac{F_{\text{friction}_{\text{max}}}}{F_{\text{load}}}, \tag{1}$$

where $F_{\text{friction}_{\text{max}}}$ is the maximum of the registered force (here the local value of sliding velocity is close to zero). The dynamic friction coefficient is defined for the region of constant sliding velocity:

$$\mu_{dyn} = \frac{F_{\text{friction}}}{F_{\text{load}}}, \tag{2}$$

where F_{friction} is the near-steady state of the registered force (gross sliding – see Fig. 1).

2.2 Materials and experimental conditions

A quenched and tempered 42CrMo4 steel specimen (39 ± 1 HRC, 18 × 18 × 150 mm) with a ground surface and a hydrogenated amorphous carbon (a-C:H) DLC coating was used as one member of the friction pair. The counter specimen was made of turned polypropylene homopolymer with a diameter of 15 mm.

The main properties of the applied coating were as follows: layer thickness 2 µm, hardness 1300 HV0.025, and hydrogen content of approximately 40%.

The friction tests were performed using a custom-developed friction measuring device (patent pending). Three sliding speeds and three surface pressures were used in the tests: v = 5, 50, and 500 mm/min, and p = 2, 4, and 6 MPa.

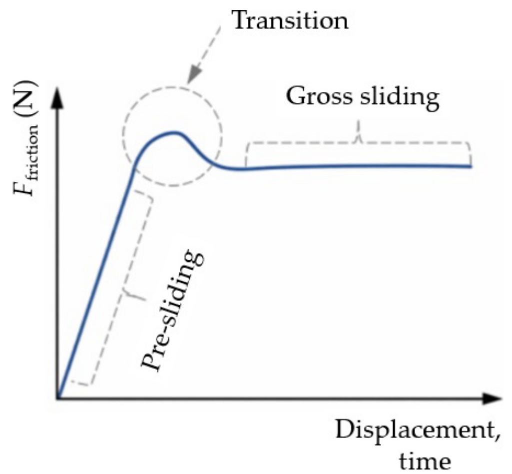

Fig. 1 Schematic friction-force curve as a function of time or displacement

3 Results and discussion

3.1 Measured friction coefficients

Fig. 2 presents the results of a series of tests and clearly shows the friction force requirements during the friction process, with the same speed but with different surface loads.

Based on the explanation in Fig. 1, from the registered force in each measurement point (e.g., Fig. 2), we determined the static (μ_0) and the dynamic (μ_{dyn}) friction coefficient based on Eqs. (1) and (2) (see Tables 1 and 2).

3.2 Empirical regression models

Figs. 3 and 4 present the results of the significance analysis for the factors affecting the static and dynamic friction coefficients.

Based on the significance tests shown in Figs. 3 and 4, it can be stated that, within the investigated parameter range, μ_0 was basically determined by sliding speed (v), and the square of sliding speed also had a smaller but still significant effect, indicating a weak non-linear relationship between sliding speed and the static friction coefficient.

In contrast, the dynamic friction coefficient (μ_{dyn}) was affected not only by sliding speed but also by surface pressure (p), although to a lesser extent. Figs. 5 and 6 graphically present the results in Tables 1 and 2.

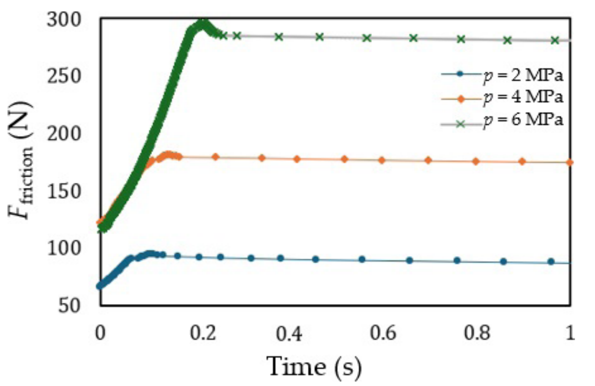

Fig. 2 Friction-force curves as a function of time at different surface pressures for the PPH–DLC material pair (v = 50 mm/min)

Table 1 Static friction coefficients (μ_0) at different friction velocities and different surface pressures

	5 mm/min	50 mm/min	500 mm/min
2 MPa	0.242	0.273	0.319
4 MPa	0.245	0.262	0.328
6 MPa	0.244	0.284	0.334

Table 2 Dynamic friction coefficients (μ_{dyn}) at different friction velocities and surface pressures

	5 mm/min	50 mm/min	500 mm/min
2 MPa	0.216	0.243	0.285
4 MPa	0.227	0.242	0.305
6 MPa	0.231	0.253	0.317

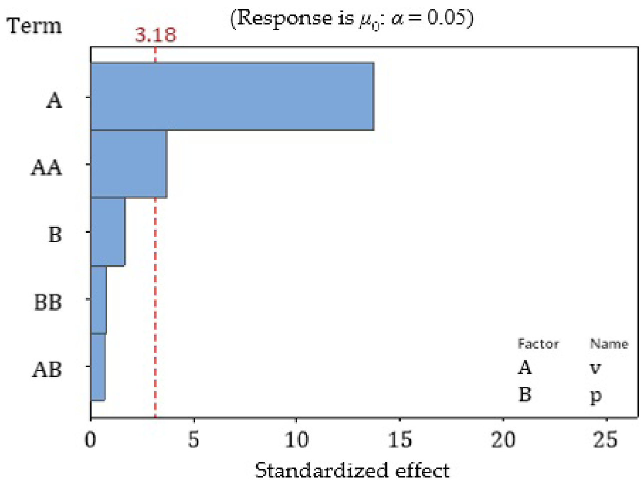

Fig. 3 Results of the significance test of the factors affecting the static friction coefficient (μ_0)

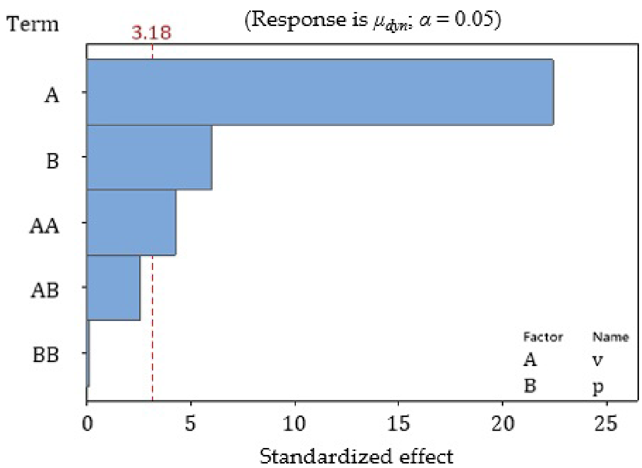

Fig. 4 Results of the significance test of the factors affecting the dynamic friction coefficient (μ_{dyn})

In addition to the significance analysis, second-order empirical regression models were fitted for both friction coefficients based on the principles of response surface methodology (RSM), which is widely used for modelling and optimization of multivariable engineering processes [26, 27]. After evaluating the statistical significance of the model terms, reduced empirical regression models were established by retaining only the statistically relevant effects.

For the static friction coefficient (μ_0), the reduced model showed that sliding speed was the only statistically significant input factor in the investigated range, and its quadratic term was also significant, indicating a weak non-linear relationship between sliding speed and μ_0. Surface pressure and the interaction term were not statistically significant.

For the dynamic friction coefficient (μ_{dyn}), the reduced model confirmed that sliding speed was the dominant factor, while surface pressure also had a statistically significant effect. In addition, the quadratic term of sliding speed remained significant for μ_{dyn}, indicating a non-linear

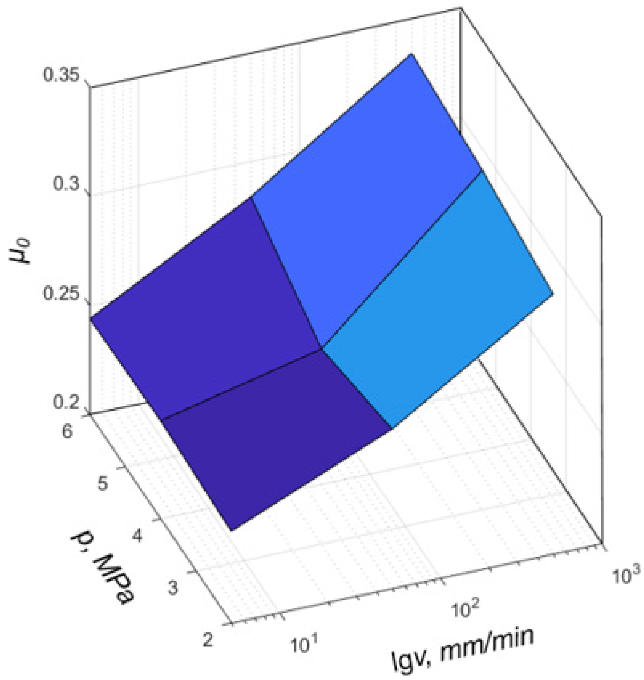

Fig. 5 The static friction coefficient (μ_0) as a function of friction velocity and surface pressure

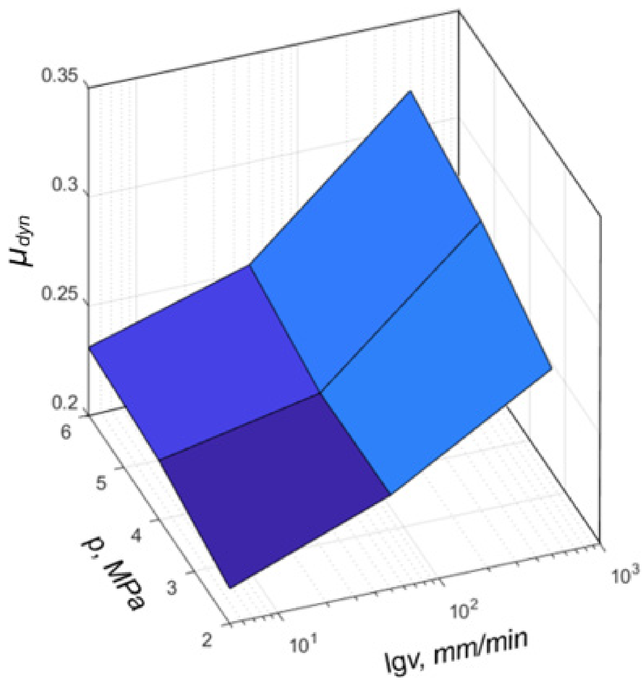

Fig. 6 The dynamic friction coefficient (μ_{dyn}) as a function of friction velocity and surface pressure

dependence on sliding speed. These results show that μ_0 was governed primarily by sliding speed, whereas μ_{dyn} was influenced by both sliding speed and surface pressure.

The reduced regression equations were as follows (Eqs. (3) and (4)):

$$\mu_0 = 0.2401 + 7.110 \cdot 10^{-4} v - 1.000 \cdot 10^{-6} v^2, \quad (3)$$

$$\mu_{dyn} = 0.2031 + 5.130 \cdot 10^{-4} v + 4.750 \cdot 10^{-3} p - 1.000 \cdot 10^{-6} v^2, \quad (4)$$

where v is the sliding speed in mm/min and p is the surface pressure in MPa.

The reduced models showed high goodness of fit, with coefficients of determination of R^2 = 96.7% for μ_0 and R^2 = 98.31% for μ_{dyn}, confirming that the simplified equations preserved the essential relationships between the investigated factors and the friction coefficients. These equations should therefore be interpreted as compact empirical descriptions valid within the investigated parameter range.

The observed increase in both μ_0 and μ_{dyn} with sliding speed suggests that, within the investigated range, the friction response of the PPH–DLC pair was governed not only by the onset of sliding but also by the conditions of gross sliding. The stronger pressure dependence of μ_{dyn} compared with μ_0 may indicate that the dynamic friction response was more sensitive to changes in the real contact conditions during continued sliding. In polymer–coating contacts, this behavior may be related to the combined effects of adhesion, local deformation of the polymer counterbody, and possible transfer layer formation.

Further investigations may therefore focus on clarifying the respective roles of these effects in the friction behavior of the PPH–DLC pair.

4 Conclusion

In this study, the dry sliding friction behavior of a hydrogenated amorphous carbon (a-C:H) DLC coating against polypropylene homopolymer (PPH) was investigated at different sliding speeds (v = 5, 50, and 500 mm/min) and surface pressures (p = 2, 4, and 6 MPa). Based on the experimental results and the reduced empirical regression models, the following conclusions can be drawn:

- sliding speed had a significant effect on both the static (μ_0) and dynamic (μ_{dyn}) friction coefficients in the investigated parameter range;
- the static friction coefficient (μ_0) was governed primarily by sliding speed, and its relationship with sliding speed showed a weak non-linear character. Surface pressure did not have a statistically significant effect on μ_0;
- the dynamic friction coefficient (μ_{dyn}) was also mainly determined by sliding speed, but surface pressure showed an additional statistically significant secondary effect;

- the reduced empirical regression models provided a transparent description of the governing relationships and confirmed that μ_0 depended mainly on sliding speed, whereas μ_{dyn} depended on both sliding speed and surface pressure;
- within the investigated parameter range, the friction coefficient of the PPH–DLC material pair remained approximately between 0.20 and 0.35, indicating a predictable friction response under dry sliding conditions.

These results support the potential application of hydrogenated DLC coatings in polymer–coating tribological systems where predictable friction behavior is required. Future work may focus on the detailed analysis of wear mechanisms, transfer layer formation, and the effects of temperature and environmental conditions.

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