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Interaction of Surface Roughness of Polypropylene and Steel under Dry Friction Conditions

Róbert Kohlhéb[1,2], Mihály Réger[1,2], Richárd Horváth[2*]

[1] Doctoral School on Materials Sciences and Technologies, Obuda University, Bécsi út 96/B, H-1034 Budapest, Hungary
[2] Donát Bánki Faculty of Mechanical and Safety Engineering, Obuda University, József körút 6., H-1081 Budapest, Hungary
[*] Corresponding author, e-mail: horvath.richard@uni-obuda.hu

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Abstract

The tribological behavior of metal–polymer friction pairs depends to a large extent on their surface roughness. In this study, we analyze the friction of C45 (1.0503) steel and polypropylene homopolymer (PPH) in terms of the surface roughness characteristics of the material pair subjected to friction. The results of the friction experiments described in the article showed that during the friction process, the investigated roughness parameters of the steel specimen (*Ra* – average surface roughness, *Rz* – roughness height or ten-point height, *Rp* – maximum peak height, *Rv* – maximum valley depth) remained essentially unchanged, while the same roughness parameters of the polymer surface significantly changed and adapted to the roughness characteristics of the steel. Ellipsometric measurements also confirmed the presence of a 20–30 nm thick polymer transition film on the steel surface, and there were parts of steel on the polymer surface as well. The obtained results indicate that in the case of metal–polymer friction pairs, the change in surface roughness is asymmetric (the surface roughness of the harder material shapes the softer surface). In contrast, material transfer is bidirectional. These must be taken into account in friction modeling and wear prediction.

Keywords

metal–polymer tribology, dry sliding friction, surface roughness evolution, material transfer, ellipsometry

1 Introduction

The topography of friction surfaces plays a decisive role in tribological processes, as the contact microgeometry directly influences adhesion, ploughing, wear, heat generation, and energy dissipation [1, 2]. This relationship between surface structure and tribological response has been widely recognized in the literature in polymer tribology and engineering tribology [3–6].

Surface roughness is not a static property during a friction process, but it changes continuously, especially in the case of material pairs with different hardness [7]. If surface characteristics change during the friction process, it not only modifies tribological behavior, but also feeds back to the contact mechanism, thus influencing the friction coefficient, material transfer and intensity of wear [8, 9]. Therefore, understanding the change in surface roughness and the resulting change in tribological processes during friction can be of fundamental importance, for example in friction modeling, coating design and the life prediction of friction systems.

Roughness and friction are important in many areas, such as human perception and the gripping of objects with the fingers [10, 11]. In engineering, Dunkin and Kim [12] demonstrated that even with very smooth surfaces, the contact area during friction is quite small. Several studies have been written on surface roughness and its effect on friction processes. Tangena and Wijnhoven [13] performed finite element simulations to investigate the effect of roughness on the normal and shear forces during the friction process. Hayward et al. [14] demonstrated that the friction coefficient between diamond surfaces ranges from 0.03 to 0.5 depending on their surface roughness, which changes during the wear and friction process. Similarly, Sahin et al. [15] demonstrated with ring compression tests that the friction coefficient depends on surface roughness. Menezes et al. [16], and Menezes et al. [17] looked for a relationship between surface roughness and friction characteristics and emphasize that the average slope of the roughness profile also has a considerable effect on friction. Sedlaček et al. [8] investigated more roughness parameters related to friction and also recommends that the so-called statistical measures of roughness parameters be prioritized in investigations of

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friction. Philippon et al. [18] also observed a very good correlation between the friction coefficient and the decrease in roughness during wear.

The tribological investigation of so-called "hard-soft" material pairs, which have very different hardness, is also an important area of research [19, 20].

In this article, we investigate a C45 (1.0503) steel – polypropylene homopolymer (PPH) pair under dry sliding. Surface roughness parameters are measured before and after sliding using (*Ra*, *Rz*, *Rp* and *Rv*), complemented by SEM–EDS to identify transferred phases on the polymer surface and spectroscopic ellipsometry to characterize the near-surface modified layer formed on the steel, since this technique is highly sensitive to the thickness and effective optical response of ultrathin surface films and roughness-related interlayers [21, 22].

The novelty of the study is the combined demonstration that roughness evolution is strongly asymmetric (hard-soft shaping), while material transfer is bidirectional, evidenced on both mating surfaces.

2 Materials and methods

2.1 Tested materials and equipment

In the friction experiment, we used a C45 steel specimen (18 mm × 18 mm × 150 mm) with a ground surface and a turned polypropylene homopolymer (PPH) (Ø = 15 mm) material pair. The chemical composition of the C45 steel in mass percentage: C = 0.42–0.50%, Si ≤ 0.40%, Mn = 0.50–0.80%, P ≤ 0.045%, S ≤ 0.045%, Cr ≤ 0.40%, Mo ≤ 0.10% and Ni ≤ 0.40%.

The roughness parameters of the surfaces before and after the friction test were determined with a Mitutoyo J310 roughness measuring device, and the surfaces were further examined with a JEOL JSM 5310 electron microscope. The transitional film layer that formed on the steel surface during the friction process was characterized with an M-2000 ellipsometer.

2.2 The tested surface roughness parameters

To evaluate the change in surface roughness, we selected the parameters *Ra*, *Rz*, *Rp* and *Rv* [1, 2], as they together comprehensively characterize contact topography.

The parameter *Ra* describes average roughness and shows the general smoothing or roughening caused by friction. The mathematical definition of *Ra* (Fig. 1) is Eq. (1), and its digital implementation can be calculated with Eq. (2) [23]:

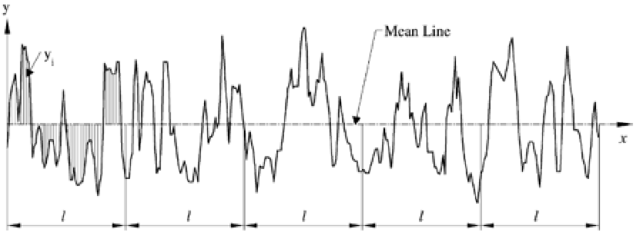


Fig. 1 Characterization of the average roughness parameter (*Ra*) [23]

$$Ra = \frac{1}{l}\int_0^l \left|y(x)\right| dx, \quad (1)$$

$$Ra = \frac{1}{n}\sum_{i=1}^{n} y_i . \quad (2)$$

The parameter *Rz* represents the peak–valley difference (Fig. 2), thus it responds sensitively to a deformation of the microgeometry. It is defined as follows (Eq. (3)):

$$Rz_{\mathrm{ISO}} = \frac{1}{n}\left(\sum_{i=1}^{n} p_i - \sum_{i=1}^{n} v_i\right). \quad (3)$$

The roughness parameter *Rp* shows maximum peak height, therefore this parameter can be used to characterize wear, while the parameter *Rv*, which follows the deepest valley, can characterize the filling of the surface. Therefore, a joint analysis of these parameters allows us to not only follow the general trend of roughness, but also to reveal the mechanism and direction of surface change during the friction process.

3 Results

The tests were carried out on a patented custom-designed and custom-made friction measuring device. (The patent application has been filed.) The tests were performed before the friction tests (on the original pieces) and after the friction tests. The surface pressure between the material pairs was 5 MPa, and friction speed was 50 mm/min. Friction length was 100 mm, and the friction tests were repeated 20 times.

3.1 Changes in the investigated roughness parameters

Surface roughness measurements were performed with the following settings, based on the relevant ISO 21920-2:2021 standard [24] and ISO 16610-21:2025 standard [25]:

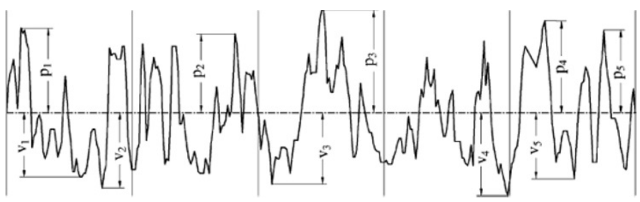


Fig. 2 Characterization of the roughness height (*Rz*) parameter [23]

- cut-off filtering parameter: λc = 0.8 mm;
- base length: lr = 0.8 mm;
- evaluation length: ln = 0.8 mm × 5 = 4 mm;
- measurement length (with overrun): lt = 4.8 mm.

Table 1 shows the mean and standard deviation of the roughness measurements on the polymer–steel material pair in their original state and after drag and friction. Each measurement was performed six times.

The measurement results (Table 1) indicate that the tested roughness parameters of the steel specimen did not change during the friction test, but all four roughness parameters of the polymer sample became very similar to those of the steel sample during the friction tests (Fig. 3).

Fig. 4 shows a more detailed examination of the roughness profiles and shows the state of the steel and the polymer surface before and after the friction test. The roughness profile of the steel specimen remained unchanged

Table 1 The roughness parameters and their standard deviation in the case of the C45–PPH material pair in their original state (raw) before the friction tests, and after the friction tests

	Ra (μm)	*Rz* (μm)	*Rp* (μm)	*Rv* (μm)
PP, raw surface	1.862 ± 0.125	11.153 ± 0.672	4.797 ± 0.593	6.357 ± 0.624
PP, after the friction test	0.303 ± 0.104	2.903 ± 1.031	1.236 ± 0.218	1.667 ± 0.853
C45, raw surface	0.350 ± 0.041	2.531 ± 0.236	1.134 ± 0.097	1.397 ± 0.152
C45, after the friction test	0.371 ± 0.033	2.770± 0.632	1.108 ± 0.051	1.663 ± 0.591

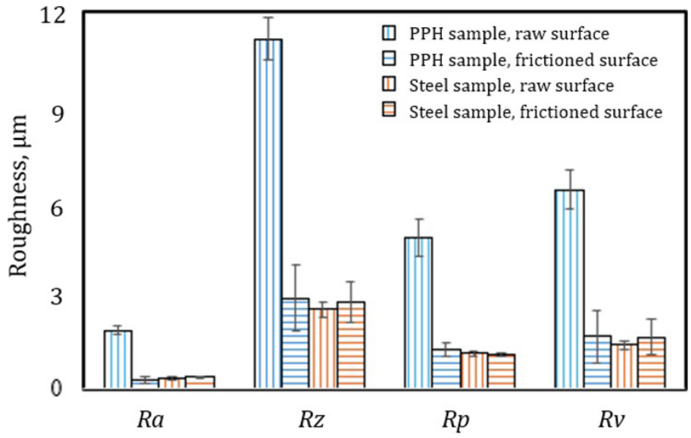


Fig. 3 Measured roughness parameters of the surface of the samples before and after the friction test (based on Table 1)

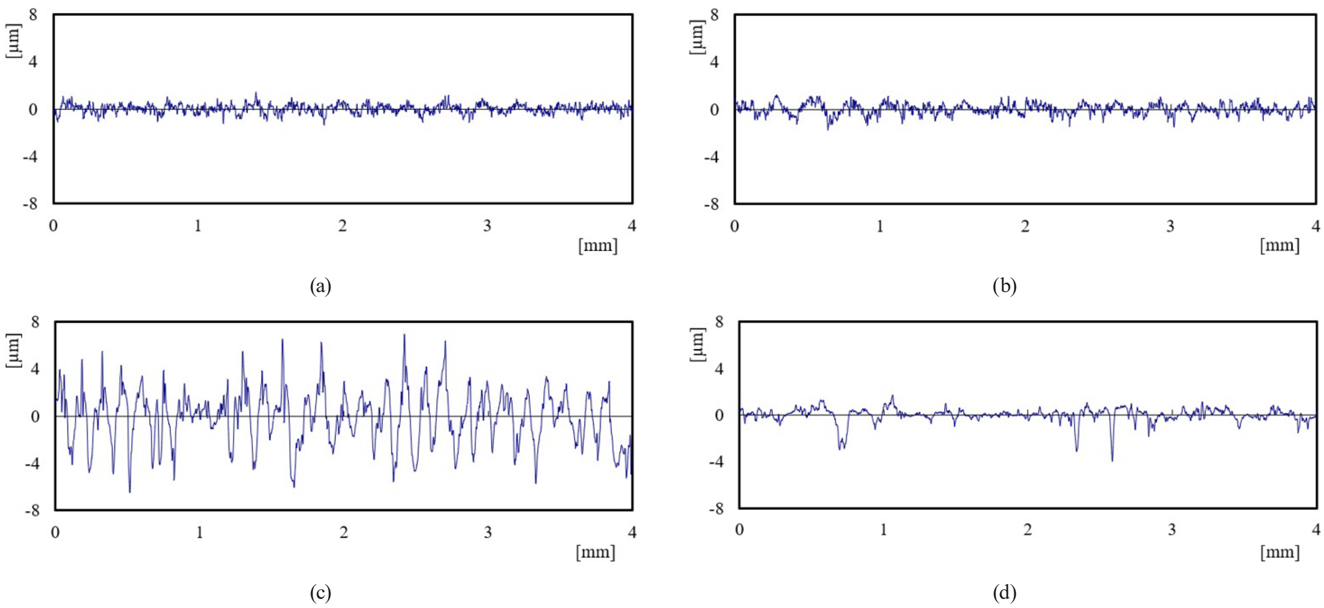


Fig. 4 The measured roughness profiles on the original and friction tested surfaces of the steel and polymer samples: (a) profile of the original ground surface of the steel specimen before the friction tests; (b) the surface profile of the steel specimen after the friction tests; (c) the profile of the original (cross-turned) surface of the polymer sample before the friction tests; (d) the surface profile of the polymer sample after the friction tests

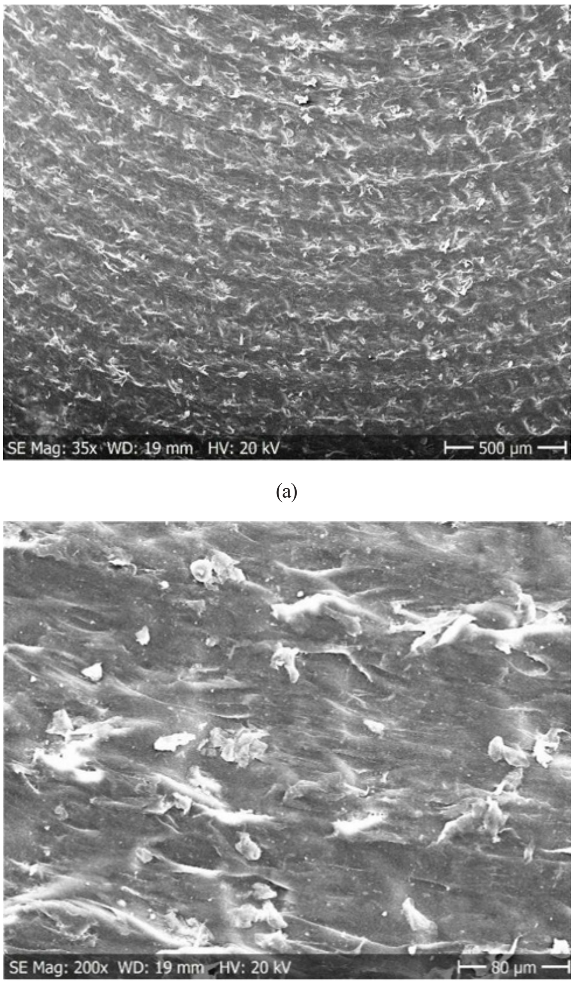
even after the friction effect, while the roughness profile of the polymer sample takes on a similar profile as the roughness profile of the steel, as can be seen from the measured roughness parameters.

3.2 Electron microscopy (SEM) and material composition (EDS) examinations of the tested surfaces

Since the roughness characteristics of the steel specimen did not change during the friction test, we analyzed the surface change of the polymer sample.

SEM–EDS analysis was employed because this combined method is particularly suitable for distinguishing between purely morphological wear features and chemically identifiable transferred phases, and for supporting the interpretation of transfer-layer-related tribological phenomena [26, 27].

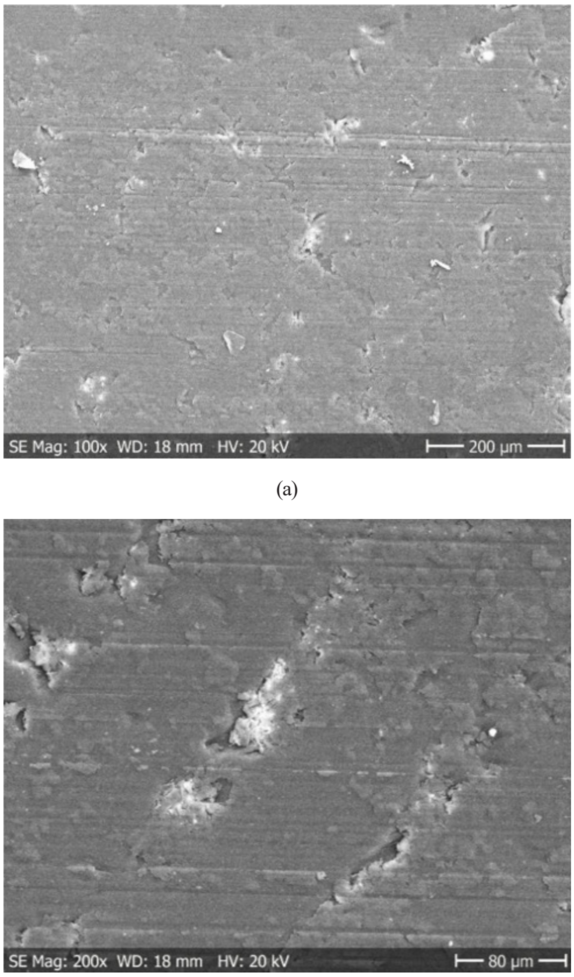
Fig. 5 and Fig. 6 show SEM images of the polymer surface.



(a)

(b)

Fig. 5 SEM image of the turned PPH surface before friction testing: (a) 35× magnification; (b) 200× magnification



(a)

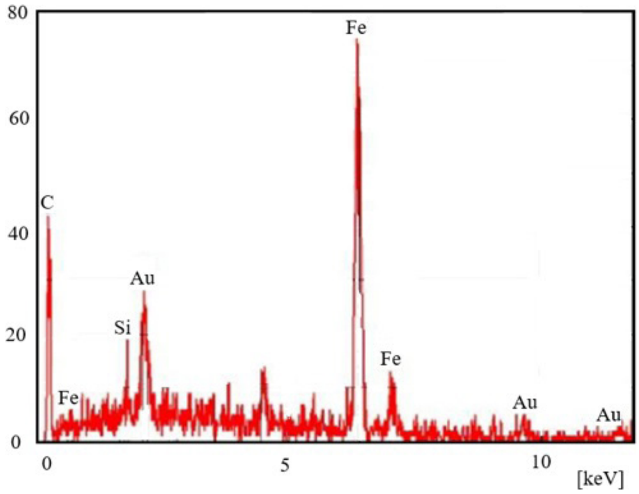
(b)

Fig. 6 SEM image of the PPH surface after friction testing: (a) 100× magnification; (b) 200× magnification

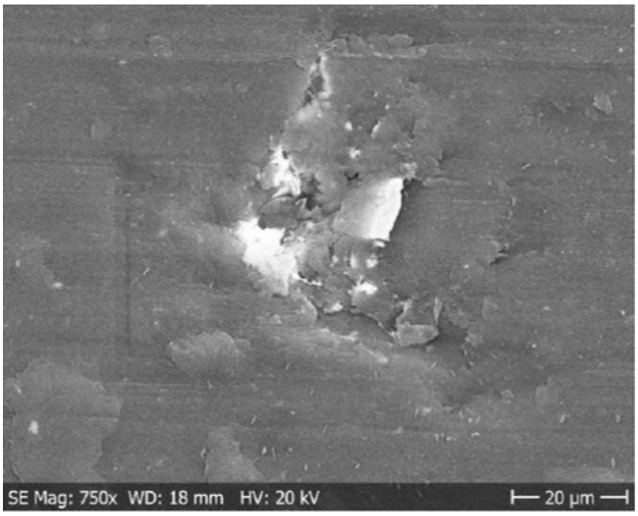
Fig. 5 clearly shows the turning marks on the surface before friction, which shows an oriented texture typical of a surface prepared by machining. After friction, this texture disappears and instead, a parallel grooved pattern appears (Fig. 6), which follows the characteristics of the ground steel in its form and roughness parameters (Fig. 3). Fig. 6 shows the traces of material transfer and surface filling. This can be assumed based on the "filled" microvalleys visible in several places.

3.3 Material transfer results

Fig. 7 shows the SEM image of a typical part of the surface of the polypropylene (PPH) after friction tests. The fragmented areas with bright contrast indicate an embedded foreign phase, which is not typical of the polymer's own structure. The EDS spectrum of the examined surface part on the right side of Fig. 7 confirms this, as it shows a significant Fe peak and, to a lesser extent, silicon, which are



(a)



(b)

Fig. 7 Turned surface of the PPH sample after the friction test, and the EDS spectrum of the surface: (a) the results of EDS spectrum; (b) the SEM image of PPH sample (750× magnification)

typical components of the oxides of the steel surface. This means that the PPH was not only mechanically shaped to the roughness profile of the steel, but also locally enclosed steel particles and their oxidized debris. Thus, the polymer surface is able to trap hard grains of the steel, which can be explained by viscoelastic absorption rather than a classical abrasive phenomenon.

The ellipsometry study of the C45 sample confirmed the presence of a ~24–35 nm thick surface layer on the steel sample exposed to friction. The optical characteristics of the layer show that it is not pure oxide or air (void) but a mixture of a polymer-like coating and empty space (void).

The Effective Medium Approximation (EMA) model of the ellipsometer showed that the layer has a ~50% polymer component, so the polymer partially fills the surface microgeometry, thereby reducing apparent roughness, which is consistent with the change in roughness parameters and the SEM–EDS results described above. The results of these comprehensive studies made it clear that in the C45–PPH system, in addition to the change in the roughness parameters of the softer material, there is also bidirectional material transfer in the wear mechanism.

4 Conclusion

The tribological behavior of metal–polymer friction pairs is highly dependent on their surface roughness during sliding. In this study, we analyzed the friction phenomena of C45 (1.0503) steel – polypropylene homopolymer (PPH) system under dry sliding (p = 5 MPa, v = 50 mm/min, 100 mm stroke, 20 cycles). The results of the friction experiments showed that:

- the steel surface roughness remained essentially unchanged (*Ra* – average surface roughness, *Rz* – roughness height or ten-point height, *Rp* – maximum peak height, *Rv* – maximum valley depth), whereas the PPH surface underwent pronounced smoothing and topographical re-shaping. After sliding, the PPH roughness parameters approached those of the steel. Consequently, the roughness parameters of the polymer sample adapted to those of the steel sample due to friction;
- during the friction test, a bidirectional material transfer can be observed: the oxide and microparticles of the steel are embedded in the polymer surface. Ellipsometric measurements confirmed the presence of a 20–30 nm thick polymer transition film on the steel surface as a result of the friction test;
- the formation of a polymer transition film may indicate that the polymer in the friction zone not only deforms but can also partially fill the surface valleys of the metal;
- in the case of metal–polymer (hard–soft) friction pairs, the effect of the surface roughness of the surfaces on each other is asymmetric – the harder material (C45) shapes the softer (PPH) surface, which can be taken into account in friction modeling and wear prediction.

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