

Effect of prior elevated-temperature exposure on static friction of polymer-polymer sliding pairs

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ABSTRACT

This study investigated the retained effect of prior elevated-temperature exposure on the coefficient of static friction of self-mated polymer–polymer sliding pairs. This is one of the first studies analysing how short-term thermal history affects the static friction of self-mated engineering polymers after cooling to room temperature. Three engineering thermoplastics, PA6, PET, and POM, were tested under technically dry contact conditions. Before friction measurements, the specimens were heated at 50–100 °C for 30 min and then stabilised at room temperature for 30 min. Static friction was measured using an inclined pin-on-plate test setup under nominal contact pressures of 0.67, 1.16, and 1.65 MPa. The results were supported by SEM observations, areal surface roughness measurements, Vickers microhardness analysis, and statistical evaluation. Prior thermal exposure caused a strongly material-dependent and non-linear response. PA6–PA6 showed an increase in static friction from approximately 0.23–0.24 at room temperature to 0.32–0.45 after heating, with the highest values after exposure to 50–60 °C. In contrast, PET–PET and POM–POM generally showed lower static friction after thermal exposure. The results indicate that even short-term prior heating may produce retained surface-layer changes affecting motion initiation after cooling. Therefore, thermal history, polymer type, contact pressure, surface topography, and near-surface mechanical response should be considered when designing polymer sliding pairs operating under start-up and stop conditions.

Keywords: polymer tribology, elevated-temperature exposure, static friction, polymer–polymer contact, surface roughness, microhardness, SEM analysis, dry friction.

INTRODUCTION

Polymers are increasingly used as engineering materials in sliding systems due to their favourable combination of low weight, corrosion resistance, processability, and tribological performance under dry or lubricated contact conditions [1, 2]. In many technical applications, polymer-based sliding pairs are used in components operating under start-up, intermittent-motion, or highly loaded conditions, where the resistance to motion initiation is of particular importance [3, 4]. In such systems, the coefficient of static friction determines the force required to initiate motion after a period of rest and is directly related to the start-up behaviour and the tendency to stick–slip

phenomena [3, 5, 6]. In contrast to metallic contacts, polymer friction is strongly affected by viscoelastic deformation, adhesion, surface forces, molecular mobility, local temperature rise, and transfer-film formation [1, 2]. Therefore, analysing temperature effects on the static friction coefficient of polymer–polymer pairs is highly important, yet experimental studies combining these specific contact configurations with thermal history remain limited.

In study [3], the effect of standstill time and unit pressure on the coefficient of static friction in self-mated polymer pairs, including POM–POM, PET–PET, and PA6–PA6, was investigated. It was demonstrated that the coefficient of static friction depends on the duration of loading at rest, applied

unit pressure, and polymer type, confirming the importance of time-dependent viscoelastic deformation and changes in the real contact area before motion initiation. In another study [4], static friction tests were conducted for highly loaded polymer–polymer systems under dry and lubricated conditions. It was shown that, under dry friction conditions, PA6–PA6 and POM–POM exhibited lower static friction coefficients than PET–PET, while the introduction of lubricant increased the coefficient of static friction in comparison with dry contact. These observations are particularly relevant in the context of elevated-temperature exposure, because thermally induced softening of polymer surfaces may intensify creep, stress relaxation, and real-contact-area growth before the onset of sliding.

The distinction between static and dynamic friction has also been emphasised in recent studies on polymeric materials and composites. In study [5], the frictional response of reinforced polymer composites sliding against a Ti6Al4V counterelement was investigated under quasi-static and fast-transient dry contact conditions. The results showed that the measured frictional response depends on the contact regime, indicating that friction values obtained under one type of contact loading should not be directly transferred to another. In study [6], static and kinetic friction of 3D-printed polymers and composites sliding against a steel counter-body was analysed, and differences between static and kinetic coefficients of friction, including the COF jump associated with stick-slip, were reported. These findings are relevant to the analysis of static friction because the mechanisms controlling motion initiation differ from those governing steady sliding. During the static stage, the contacting surfaces remain at rest before macroscopic motion begins, which allows time-dependent viscoelastic deformation, adhesion, and changes in the real contact area to develop [3, 5, 6].

The effect of interfacial history has also been addressed in recent research on lubricant exposure in polymer–polymer pairs. In study [7], self-mated construction polymer pairs made of PET, PA6, and POM were analysed after different durations of contact with a lubricating medium. The study showed that the duration of contact with lubricant affects the values of the static coefficient of friction. Although this work was not focused on elevated-temperature testing, it indicates that the static friction response of polymer–polymer

contacts may depend on the prior state of the interface and the history of surface exposure. This observation is relevant for thermally loaded systems, where temperature, dwell time, and contact conditions may jointly influence the state of the near-surface layer and, consequently, the resistance to motion initiation [3, 8, 9].

The relationship between polymer–polymer friction and material properties has also been described using the concept of cohesive energy density. In study [10], polymer–polymer sliding combinations including PPS, PC, PA66, HDPE, and PTFE were investigated in self-mated and dissimilar configurations. It was demonstrated that, for self-mated polymer pairs, an increase in cohesive energy density was associated with an increase in the coefficient of friction and a reduction in specific wear rate. For dissimilar polymer pairs, the coefficient of friction was related to the absolute difference in cohesive energy density between the two materials, with larger CED differences corresponding to higher friction values. The study also indicated that the adhesion between the mating polymers is an important factor controlling friction, while polymer wear is closely related to shear strength. Under elevated-temperature conditions, this relationship may be modified by changes in molecular mobility, surface softening, real contact area, and near-surface mechanical properties [8, 9].

A complementary explanation of polymer–polymer friction mechanisms was provided in study [11], where material transfer in polymer pairs was analysed using X-ray photoelectron spectroscopy. The study confirmed the occurrence of polymer transfer onto the mated polymer surface and showed that the degree of surface coverage by the transferred material depends strongly on the polymer combination. This observation is relevant to elevated-temperature studies because temperature may affect the formation, stability, and adhesion of transfer films in polymeric contacts [11–13]. In the case of static friction, the state of the interface formed before the onset of sliding may additionally be influenced by contact time, adhesion, viscoelastic deformation, and local temperature rise [1, 3, 8].

Recent investigations of polymer transfer films over wide temperature ranges confirmed that temperature effects in polymer tribology may be strongly non-linear. In study [12], transfer-film formation was analysed for ATSP/PTFE- and PEEK/PTFE-based polymer composite coatings

tested from cryogenic to elevated temperatures. It was demonstrated that both the coefficient of friction and the characteristics of the transfer film were temperature-dependent, confirming that thermal conditions can substantially modify interfacial film formation. Although the tested systems were polymer-based coatings sliding against a metallic counterelement rather than bulk self-mated polymer pairs, the results are mechanistically relevant to polymer-dominated contacts because they show that temperature can affect the formation, composition, and morphology of the transfer layer. These findings suggest that elevated temperature may modify friction by changing the stability and continuity of the interfacial film.

High-temperature behaviour of self-lubricating high-performance polymer composites has also been examined in the studies focused on operation up to 300 °C. In study [14], ATSP-, PI-, and PEEK-based polymer composites were tested under dry sliding conditions at different environmental temperatures from room temperature to 300 °C. It was shown that tribological performance at elevated temperature is strongly related to the development of transfer films and their subsequent effect on friction and wear. In a related extreme-environment study [15], advanced bearing polymer coatings were evaluated over a wide temperature range from cryogenic conditions to 300 °C. It was demonstrated that ATSP-based coatings exhibited low friction and negligible wear over a broad temperature range, whereas PEEK-based coatings showed less stable performance at the highest investigated temperatures. These findings indicate that elevated temperature does not have a universal effect on friction; depending on the polymer system, it may either support the formation of a favourable transfer layer or lead to less stable interfacial behaviour.

The importance of thermal effects in polymer contacts was further emphasised in study [8], where contact temperatures and their influence on the tribological performance of PEEK and PTFE were modelled in a dual-pin-on-disk tribometer. The study showed that the temperature field in the shared wear track is governed by the combined effect of heat generated by the interacting sliding components, while the local flash temperature depends on the characteristics and working conditions of each pin. It was also demonstrated that an increase in applied load may lead to a peak contact temperature exceeding the glass transition temperature of the polymer pins, resulting

in blocked tribofilm formation and failure of the hybrid wear system. Although this study was not focused on static friction in self-mated polymer–polymer pairs, it provides important support for considering local contact temperature and frictional heat accumulation in polymeric tribological systems. In the case of static friction, the influence of temperature should be considered together with dwell time, viscoelastic deformation, adhesion, and real-contact-area development before the onset of sliding [3, 8].

A similar conclusion can be drawn from study [16], in which unfilled polymer–polymer sliding contacts involving POM, PP, PA6.6, and PC were investigated. The effects of load, sliding velocity, temperature, and the PV factor were analysed. It was demonstrated that the PV limit is not a sufficient criterion for predicting the behaviour of polymer–polymer contacts, because each material combination may be controlled by a different critical parameter, such as contact pressure, sliding velocity, or temperature. This is particularly important for the design of polymer–polymer sliding systems, since the operating temperature may have either a beneficial or negative effect on contact durability, depending on the material combination. In relation to static friction, these findings support the need to analyse motion initiation not only in terms of nominal load or apparent contact pressure, but also with regard to temperature-dependent deformation and heat-related changes in the contact zone [16].

The influence of roughness and operating conditions in actual polymer–polymer contacts was recently analysed in study [17], which concerned cast polyamide 6 deflection pulleys working against thermoplastic polyurethane-coated ropes. It was shown that the coefficient of friction between the polymeric pulley and the TPU-coated rope strongly affects rope lifetime. The study also demonstrated that surface roughness influences the coefficient of friction, particularly under low-load conditions. This study is important because it deals with a real polymer-on-polymer engineering contact, rather than a simplified polymer–metal configuration. Although it does not focus on static friction or elevated-temperature exposure, it confirms that surface topography and operating conditions should be considered when analysing the frictional response of polymer–polymer contacts.

The role of elevated temperature has also been studied for PTFE-based composites. In

study [18], the high-temperature friction and wear behaviour of PTFE matrix composites containing carbon fibre, PEEK, and TiC particles was analysed in the temperature range from 25 °C to 250 °C. It was shown that the synergistic effect of these fillers significantly improved the wear resistance of the PTFE matrix, although the coefficient of friction did not show a clear temperature-dependent trend. In study [19], PTFE/MoS₂ composites were investigated at testing temperatures from 25 °C to 250 °C. The results showed relatively low friction coefficients and wear rates in this temperature range, while the addition of MoS₂ contributed to improved lubrication and wear resistance at elevated temperature. Although these studies mainly concern sliding friction of PTFE-based composites rather than static friction of bulk polymer–polymer pairs, they are useful for showing that elevated temperature can modify wear mechanisms, lubrication behaviour, and the tribological stability of polymer composites containing solid-lubricant or reinforcing phases.

Temperature-dependent tribological behaviour has also been reported for polyoxymethylene materials. In study [9], the influence of temperature on the tribological properties of POM was analysed in the range from 25 °C to 110 °C. The results showed that both friction and wear coefficients tended to increase with increasing temperature, and adhesive wear was identified as the primary wear mechanism influenced by temperature. Material transfer was also observed under all tested velocity and load conditions. Although this study does not concern static friction in self-mated POM–POM contacts, its results provide useful indirect evidence for interpreting the temperature-dependent tribological response of POM. In the context of polymer–polymer static friction, such literature data should be considered together with the specific contact configuration, surface condition, contact pressure, and thermal history of the tested specimens.

Biomedical polymer–polymer contacts provide additional evidence that even moderate changes in lubricant temperature and medium composition can affect polymer friction and wear. In study [20], UHMWPE-on-PEEK OPTIMA™ contacts were investigated using different lubricant protein concentrations and two lubricant temperature conditions. The study showed that the wear response of this polymer–polymer pair depended on both lubricant temperature and

protein concentration, while friction decreased with increasing protein concentration once protein was present in the lubricant. Although the temperature range was much lower than that typically considered in industrial high-temperature applications, the work confirms that thermal and medium-related effects can modify the tribological response of polymer–polymer contacts. In the context of static friction, these observations should be treated as indirect evidence and considered together with the studies focused specifically on standstill time, lubricant exposure, and motion initiation in polymeric contacts [20].

The importance of adhesion in polymer friction has been widely discussed in the literature. In study [21], polymer–polymer friction was related to adhesion energy, indicating that the coefficient of friction is governed not only by surface energy components but also by the overall adhesive response of the contacting materials. This approach is consistent with the broader view presented in review [1], where adhesion and surface forces were indicated as key factors in polymer tribology. These concepts are particularly relevant to static friction, since the state of the interface before motion initiation may be affected by standstill time, adhesion, and time-dependent deformation of the contacting polymer surfaces [21]. Under elevated-temperature conditions, these effects may be further modified by increased molecular mobility, viscoelastic compliance, and temperature-dependent transfer-film formation [12, 13].

The influence of surface-layer formation and transfer-film stability at elevated temperatures was also shown in study [13] for PEI- and PI-based composites. The tests were conducted at room and elevated temperatures, and it was demonstrated that the tribological properties were strongly controlled by the formation and adherence of transfer films on the sliding surfaces. Although the study is not strictly related to static friction in bulk polymer–polymer pairs, it is mechanistically relevant because it demonstrates that temperature-dependent transfer-film behaviour can strongly influence the tribological response of polymer-based materials.

In summary, the literature indicates that temperature effects in polymer tribology are complex, non-linear, and strongly dependent on polymer type, contact conditions, adhesion, viscoelastic deformation, surface topography, and transfer-film stability [16, 17]. Previous

studies have provided important information on static friction of self-mated polymer pairs, the effects of standstill time, contact pressure, lubrication history, temperature-dependent sliding behaviour, and transfer-film formation [13, 16]. However, most available studies focus either on dynamic sliding friction, polymer–metal contacts, lubricated contacts, or testing performed directly at elevated temperature. In contrast, the retained effect of prior thermal exposure on the static friction of fully polymeric self-mated contacts after cooling to room temperature has not been sufficiently clarified.

This constitutes the main research gap bridged in the present study. The novelty of this work lies in analysing whether short-term prior exposure to elevated temperature can cause persistent changes in the surface layer of engineering thermoplastics and, consequently, alter the coefficient of static friction after the specimens have been cooled and stabilised at room temperature. Unlike studies focused on real-time elevated-temperature sliding, the present work investigates thermal history as a separate factor affecting motion initiation under technically dry polymer–polymer contact conditions.

Therefore, the aim of this study was to determine the influence of prior elevated-temperature exposure on the coefficient of static friction of self-mated PA6–PA6, PET–PET, and POM–POM sliding pairs under different nominal contact pressures. The friction results were supported by SEM observations, areal surface roughness measurements, Vickers microhardness analysis, and statistical evaluation. This combined approach makes it possible to relate changes in static friction to retained modifications of the near-surface layer, including surface topography, local deformation, wear-product distribution, and near-surface mechanical response.

METHODOLOGY

Polymeric materials

The experimental programme included 21 self-mated polymer–polymer sliding pairs manufactured from three engineering thermoplastics: polyoxymethylene (POM), polyamide 6 (PA6), and polyethylene terephthalate (PET). These materials were selected due to their common use in mechanical and tribological applications, commercial availability, and ability to operate under dry sliding conditions with relatively low friction resistance. In addition, the selected polymers differ in molecular structure, crystallinity, mechanical response, and thermal sensitivity, which makes them suitable for comparative assessment under varying temperature conditions. Their use therefore provides both practical relevance and the possibility of analysing the relationship between polymer structure and tribological behaviour during thermal exposure. The selected properties of the investigated materials are summarised in Table 1.

Each tribological pair consisted of two elements made of the same polymer: a cylindrical pin measuring 8 mm in diameter and 15 mm in height, and a rectangular plate measuring 10 mm in width, 100 mm in length, and 5 mm in thickness. The geometry of the specimens and counter-elements is presented in Figure 1.

Before testing, all mating elements were properly prepared and then subjected to cyclic thermal conditioning in a climatic chamber. The specimens were exposed for 30 min to selected elevated temperatures. After completion of the heating stage, the specimens were removed from the chamber and conditioned at room temperature for 30 min before the friction measurements were carried out. The adopted thermal exposure conditions are listed in Table 2.

Table 1. Comparative overview of selected properties of the investigated polymers [22–29]

Parameter category	Parameter	PA6	PET	POM
General	Composition	Unmodified	Unmodified	Unmodified
Physical	Density [g/cm ³]	1.12–1.14	1.30–1.40	1.41–1.42
	Moisture absorption [%]	1.60–1.90	0.10–0.20	0.15–0.50
Thermal	Coefficient of linear thermal expansion [1/°C]	$(5 - 12) \times 10^{-5}$	$(6 - 8) \times 10^{-5}$	$(10 - 15) \times 10^{-5}$
	Temperature of glass transition [°C]	40–70	67–81	–60–(–50)
Mechanical	Vickers hardness [HV]	~15	10–20	15–18
	Young's modulus [GPa]	2.62–3.20	2.76–4.14	2.80–3.70

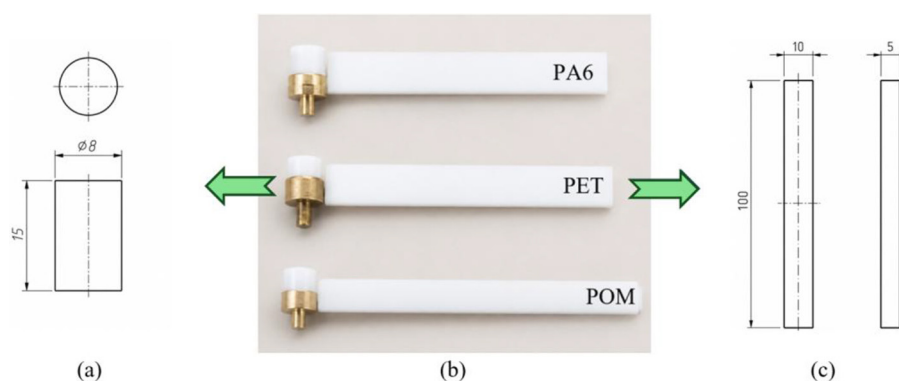


Figure 1. Geometry and representative view of the investigated polymers: (a) cylindrical pin specimen, (b) tested PA6, POM, and PET elements, and (c) rectangular plate counterelement

The temperature range of 50–100 °C was selected as the first stage of thermal-history investigations of polymer–polymer sliding pairs. It represents possible prior thermal exposure of polymer materials or finished sliding components during storage, pre-heating, operation in enclosed machine spaces, or local heating before start-up. Such conditions are relevant for polymer sliding elements, because the temperature of a sliding component may exceed ambient temperature due to frictional heating and limited heat dissipation [30]. Previous studies on unfilled polymer–polymer contacts have also shown that application temperature may significantly affect friction and wear, depending on the material combination [16]. From the material perspective, the selected range includes temperatures close to the T_g ranges of PA6 and PET, while for POM it enables evaluation of exposure far above T_g . Since all specimens were stabilised at room temperature before friction measurements, the results should be interpreted as the effect of prior thermal history rather than direct elevated-temperature sliding.

Measurement method of the coefficient of static friction

The coefficient of static friction was evaluated for polymer–polymer surface contact under technically dry sliding conditions. The measurements

were carried out using a specially designed pin-on-plate apparatus operating according to the inclined plane principle. The test rig consisted of a tilting arm driven by an electric actuator, a laser pointer fixed parallel to the friction surface, a measuring scale, and a rotating loading system enabling controlled normal loading of the specimen.

During the test, the rectangular plate was fixed to the movable arm in a horizontal position, whereas the cylindrical pin was placed directly on its surface. The normal load was applied by means of a rotating loading pan with a mass of 0.94 kg, supplemented with additional weights of 2.5 kg, 5 kg, and 7.5 kg. This loading arrangement made it possible to perform measurements at three nominal contact pressures: 0.67 MPa, 1.16 MPa, and 1.65 MPa. The main testing conditions and measurement parameters are listed in Table 3.

Before each measurement, the contacting surfaces were cleaned with white spirit in order to remove possible contaminants and ensure repeatable contact conditions. During the experiment, the movable arm was gradually inclined until the onset of relative motion between the pin and the plate was observed. The displacement of the arm at the moment of motion initiation was recorded using the measuring scale and laser indicator. On this basis, the inclination angle corresponding to the friction angle was determined, which was then used to calculate the coefficient of static friction.

Table 2. Pre-test thermal exposure conditions for specimens

Stage	Temperature [°C]	Duration [min]
Elevated-temperature exposure	50, 60, 70, 80, 90, 100	30
Room-temperature cooling and stabilisation	21	30

Table 3. Experimental parameters for static friction measurements

Parameter category	Parameter	Value
Tribological system	Test configuration	Pin-on-plate
	Material configuration	Polymer–polymer
	Tested pairs	PA6–PA6, PET–PET, POM–POM
Contact conditions	Friction conditions	Technically dry
	Contact pressure [MPa]	0.67
		1.16 1.65
Measuring system	Distance from pivot point of the arm to the measuring scale [mm]	1920
Measurement protocol	Number of repetitions for each material configuration	10

For each material configuration and set of testing conditions, ten repeated measurements were performed. The schematic representation of the measuring system and the view of the mounted polymer–polymer sliding pair are shown in Figure 2.

Microhardness measurements

Tribological contact may lead to changes in the near-surface region of the interacting materials. This is particularly important for polymeric materials, the surface layers of which are sensitive to mechanical loading, frictional heating, and thermally induced structural changes. Depending on the applied load, temperature level, and exposure time, these effects may modify the local mechanical response of the material, even when the duration of testing is relatively short. Therefore, microhardness measurements were used as an indirect method

for assessing possible changes in the surface layer caused by thermal conditioning and frictional interaction.

The microhardness of the co-working surfaces was measured using a SHIMADZU HMV-2T microhardness tester (SHIMADZU, Germany). The tests were performed according to the Vickers method, using a diamond indenter pressed into the material surface under a load of 980.7 mN for 5 s. These parameters were selected to obtain clear and reproducible indentation marks suitable for further analysis.

For each specimen, four indentations were made at different locations on the tested surface: three points were distributed along the circumference, while one point was located in the central region, as illustrated in Figure 3. The indentation dimensions were measured and processed using the software integrated with the microhardness tester.

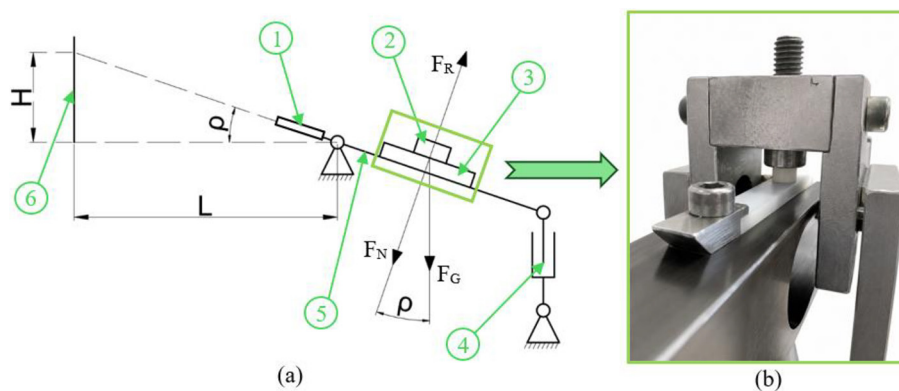


Figure 2. Schematic representation of the static friction measurement setup (a): 1 – laser indicator, 2 – specimen, 3 – counterelement, 4 – electric actuator, 5 – pivoting arm, 6 – measuring scale, H – height corresponding to the onset of sliding, L – distance between the measuring scale and the arm pivot point, ρ – friction angle, F_R – reaction force, F_G – gravitational force, F_N – normal force;
b) view of the mounted polymer–polymer sliding pair

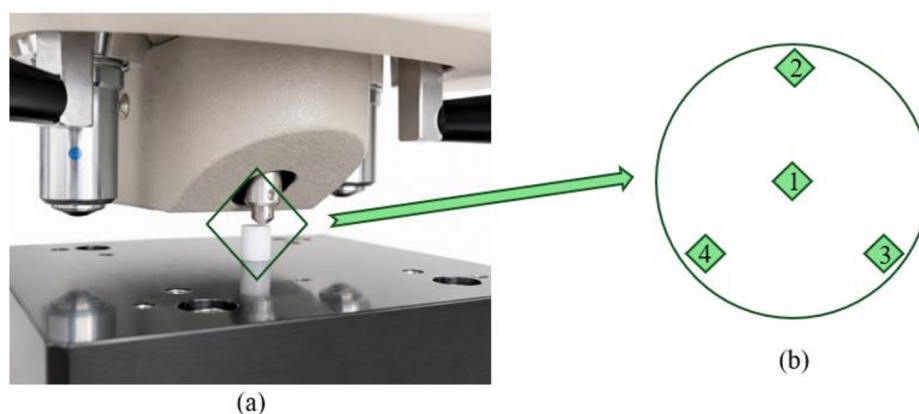


Figure 3. View of (a) the specimen subjected to microhardness measurement, (b) the schematic of the distribution of measurement points on its surface

Microscopic investigations

The interaction of two contacting surfaces involves a complex combination of mechanical and thermal phenomena occurring within the contact zone. These processes develop at both macroscopic and microscopic levels and may lead to local changes in the surface layer of the tested materials. In polymer–polymer sliding pairs, such effects are particularly important because polymers are sensitive to friction-induced deformation, heat generation, and structural changes near the surface.

Microscopic examination was therefore carried out to support the qualitative evaluation of wear and to identify the characteristic features formed on the specimen surfaces after tribological testing. The analysis made it possible to assess the changes in surface morphology, including traces of deformation, cracking, material removal, wear debris, and other forms of surface damage associated with the friction process.

The observations were performed using a Phenom-World ProX scanning electron microscope (ThermoFisher Scientific, Waltham, MA, USA). The specimen surfaces were examined in topographical mode with a backscattered electron detector. SEM images were recorded at an accelerating voltage of 15 kV, which enabled detailed visualisation of the surface condition and identification of wear-related features formed during testing.

Surface roughness measurements

Surface topography plays an important role in the formation and evolution of tribological

contact, as it influences the real contact area, frictional response, and wear behaviour of interacting materials. In polymer–polymer sliding pairs, the changes in surface roughness may result from both mechanical interaction and thermal effects occurring during testing. Therefore, the analysis of surface texture provides useful information on the condition of the surface layer and may help identify the prevailing wear mechanisms.

In this study, the surface condition of the tested specimens was evaluated using three-dimensional optical profilometry. Compared with conventional two-dimensional roughness profiles, 3D surface parameters provide a more complete description of the working surface, especially when wear traces, local deformation, or material transfer are present.

Surface topography measurements were performed using a KEYENCE VR-6000 optical 3D profilometer (KEYENCE, Japan). The surface topography was evaluated using the areal roughness parameters S_a , S_z , S_{pc} , and S_{dr} , which together characterise the surface height, peak curvature, and surface area development in accordance with ISO 25178. For each specimen, measurements were performed over at least 90% of the entire nominal contact surface (specimen diameter: 8 mm) after tribological testing. Surface reconstruction, data processing, and determination of the areal roughness parameters were carried out using the dedicated software supplied with the measuring system. The obtained results were used to evaluate changes in the surface topography of the investigated polymers resulting from prior thermal exposure followed by tribological testing.

Statistical analysis

Statistical analysis was performed for the coefficient of static friction, Vickers microhardness, and surface roughness parameters. The level of statistical significance was set at $p < 0.05$. The statistical analysis was based on individual repeated measurements available for each analysed parameter.

For the coefficient of static friction, separate two-way analysis of variance (ANOVA) was performed for PA6–PA6, PET–PET, and POM–POM pairs. For each combination of polymer pair, prior exposure temperature, and nominal contact pressure, ten repeated measurements were available. In each ANOVA model, prior exposure temperature and nominal contact pressure were treated as independent factors, while the coefficient of static friction was used as the dependent variable. The interaction between prior exposure temperature and nominal contact pressure was also included in the analysis.

For Vickers microhardness, two-way ANOVA was performed using material type and prior exposure temperature as independent factors. The analysis was based on four individual indentation measurements for each material–temperature condition. The material type $\times$ prior exposure temperature interaction was also included in the model.

For surface roughness, separate two-way ANOVA analyses were performed for each areal surface parameter: S_a , S_z , S_{pe} , and S_{dr} . In these models, material type and prior exposure temperature were treated as independent factors, while the respective roughness parameter was used as the dependent variable. The interaction between material type and prior exposure temperature was also included. The analysis was based on ten individual roughness measurements for each material–temperature condition.

The ANOVA results were reported as F-values with corresponding p-values or summarised in terms of statistical significance. Since the coefficient of static friction was the main response variable of the study, Tukey's honestly significant difference (HSD) post-hoc test was applied to compare individual exposure temperature levels for the friction results. The post-hoc results were interpreted using adjusted p-values.

RESULTS

Tribology investigations

The results of the coefficient of static friction measurements are presented in Figures 4 and 5 for three self-mated polymer pairs: PA6–PA6, PET–PET, and POM–POM. The tests were performed after exposure to elevated temperatures in the range from 21 °C to 100 °C and under three nominal contact pressures: 0.67 MPa, 1.16 MPa, and 1.65 MPa. For each combination of material, temperature, and contact pressure, the mean value of the coefficient of static friction was determined together with the confidence interval at a significance level of $\alpha=95\%$.

For all investigated polymer pairs, changes in the coefficient of static friction were observed as a function of temperature. However, the character of these changes depended strongly on the polymer type. The PA6–PA6 pair exhibited the highest increase in friction after exposure to elevated temperature. At 21 °C, the coefficient of static friction was approximately 0.23–0.24, whereas after heating it increased to values ranging mainly from about 0.32 to 0.45. The highest values were recorded at 50–60 °C, where it reached approximately 0.42–0.45, depending on the applied contact pressure. In the temperature range of 70–80 °C, a temporary decrease in the

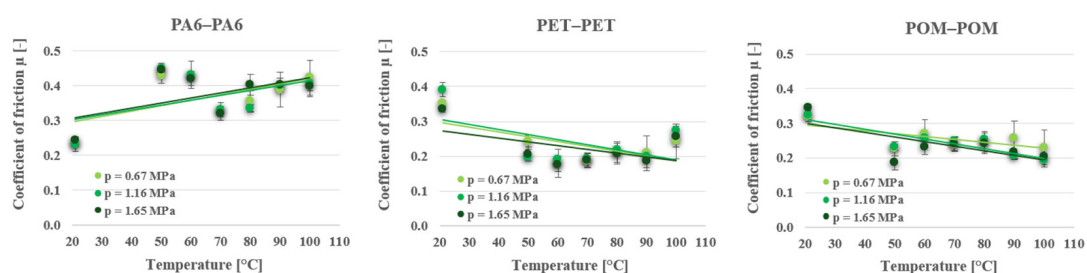


Figure 4. Coefficient of static friction of PA6–PA6, PET–PET, and POM–POM as a function of elevated temperature at different contact pressures, with corresponding trend lines

coefficient of friction was observed, followed by another increase at 90–100 °C.

A different behaviour was observed for the PET–PET pair. At 21 °C, the coefficient of static friction reached approximately 0.35–0.39, while after the exposure to elevated temperatures it decreased considerably. In the temperature range from 50 °C to 90 °C, the values were generally within approximately 0.18–0.24. At 100 °C, a slight increase was observed for all contact pressures, with values reaching approximately 0.24–0.27. Despite this increase, the coefficient of friction for PET–PET remained lower than the initial values recorded at 21 °C.

For the POM–POM pair, heating also resulted in a general reduction in the coefficient of static friction compared with the room-temperature conditions. At 21 °C, it was in the range of approximately 0.32–0.35, whereas after elevated-temperature exposure the values decreased mainly to approximately 0.19–0.27. The temperature dependence was not strictly monotonic, as local increases and decreases were observed depending on the applied contact pressure. Nevertheless, the friction values recorded for POM–POM at elevated temperatures were generally lower than those obtained at 21 °C.

The influence of contact pressure was visible, although its effect varied depending on the material. For PA6–PA6, the differences between the values obtained at individual pressures were relatively small compared with the temperature-induced changes. For PET–PET, the pressure effect was also not fully uniform, although the lowest friction values were usually observed in the intermediate temperature range. In the case of POM–POM, an increase in contact pressure generally led to lower or comparable values of the coefficient of static friction, particularly after the exposure to elevated temperatures.

The confidence intervals were mostly narrow, typically within the range of approximately

0.01–0.05, which indicates satisfactory repeatability of the measurements. Larger scatter was observed only for selected measurement points, mainly for PA6–PA6 at elevated temperatures. Overall, the results show that the coefficient of static friction of the investigated polymer–polymer pairs depends on both the exposure temperature and the applied contact pressure, with the strongest temperature-related changes observed for PA6–PA6.

SEM micrographs

Scanning electron microscopy is an important technique used for the qualitative assessment of the friction surfaces of interacting materials. It allows the identification and characterisation of wear mechanisms and enables direct observation of changes occurring in the surface layer of the material, including surface damage on the tested specimens.

Figure 6 presents an example of the specimen surface after the preparatory stage prior to testing. The changes observed on the material surfaces after the heating process and tribological testing are shown in Figures 7–9. Figures 7a–f present the surfaces of the PA6 specimens, Figures 8a–f show the PET specimens, and Figures 9a–f correspond to the POM specimens. Before microscopic observation, each specimen was cleaned with a stream of compressed air for 3–5 seconds in order to remove loose particles from the friction surface.

Analysis of the microscopic images of the surfaces of the investigated materials heated at temperatures of 50–100 °C (Figure 7a–f) and subjected to tribological testing revealed distinct changes in the polymer structure caused by elevated temperatures.

With respect to the structure of the reference PA6 (Figure 6a) specimen, the surfaces of the material after testing showed changes in the

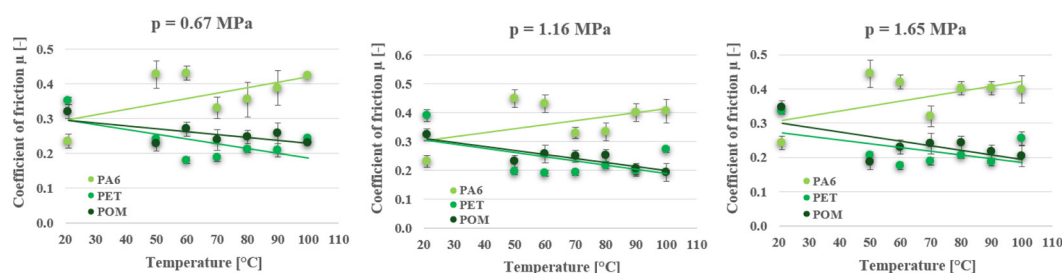


Figure 5. Coefficient of static friction of PA6–PA6, PET–PET, and POM–POM as a function of elevated temperature for different contact pressure levels, with corresponding trend lines

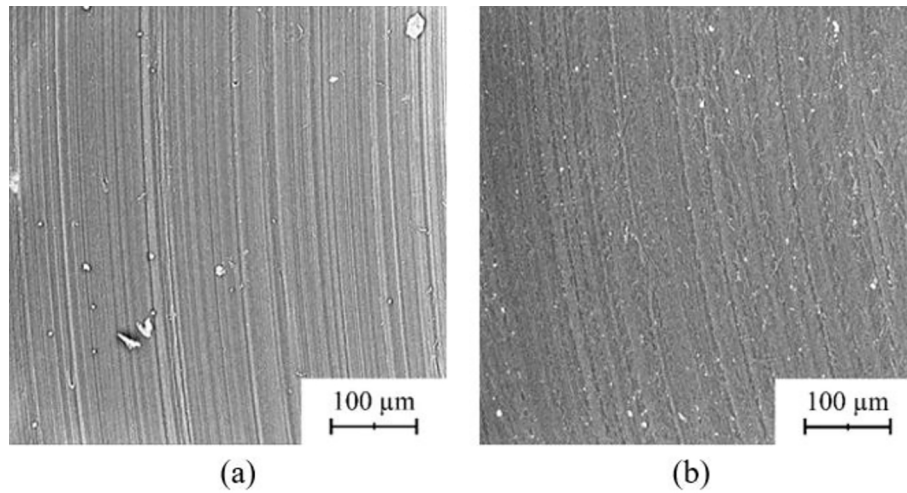


Figure 6. Representative SEM micrographs of the surfaces of non-heated PA6 (a) and PET (b) reference specimens after preparatory machining process and prior to thermal treatment

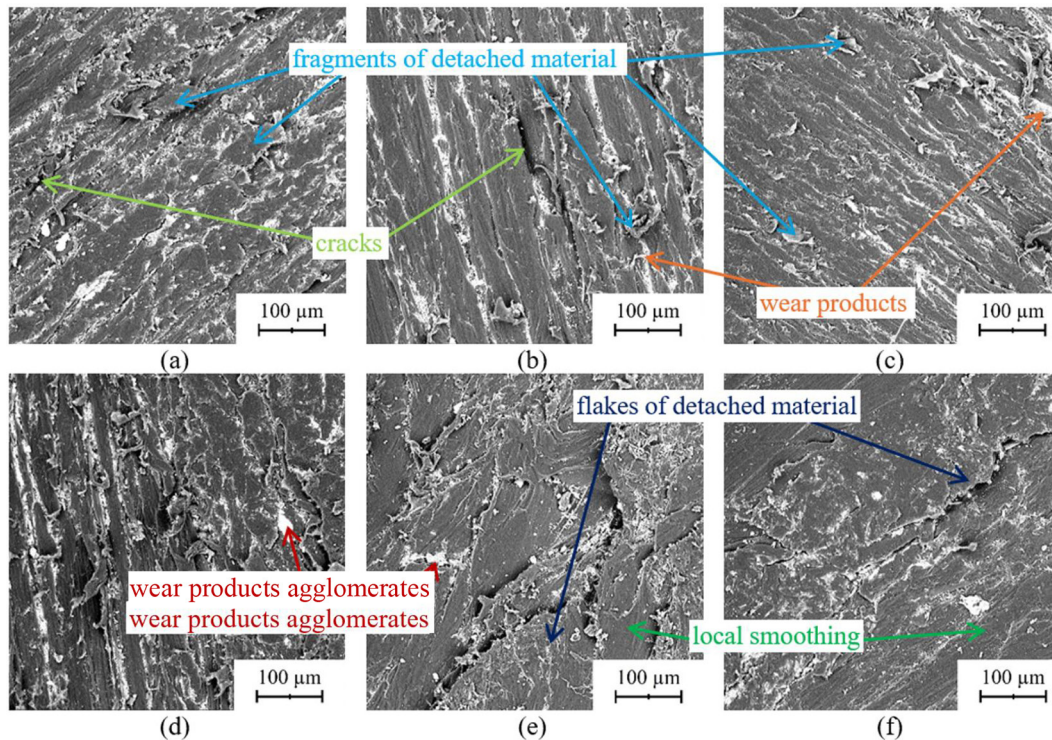


Figure 7. Representative SEM micrographs of the surfaces of the PA6 specimens heated at selected temperatures: (a) 50 °C, (b) 60 °C, (c) 70 °C, (d) 80 °C, (e) 90 °C, and (f) 100 °C, after the tribological testing

initial topography and the presence of a large amount of wear products.

At temperatures of 50–70 °C (Figure 7a–c), the surface topography was the most similar to the initial condition, indicating local deformation. Bright regions corresponding to wear products were observed along these deformed areas. These products were partly accumulated in larger

clusters and smeared in the direction of friction, forming elongated streaks. Fragments of material partially or completely detached from the surface layer were also visible; these fragments were subsequently pressed back into the surface as a result of the friction process. Small, individual cracks were formed in the areas where material detachment occurred.

For the specimens heated at temperatures of 80–100 °C (Figure 7d–f), the highest intensity of completely detached material fragments in the form of flakes was observed. As a result of the friction process, these fragments were re-embedded into the surface. The wear products formed larger, irregularly distributed agglomerates. The original technological surface became no longer visible, while at the highest heating temperatures the material surface showed local smoothing.

Analysis of the microscopic images of the PET specimen surfaces also revealed structural changes in the heated specimens compared with the reference surface (Figure 6b). At 50 °C (Figure 8a), the original surface structure of the material was still clearly preserved. However, local smoothing of the surface was observed, together with detached material fragments that were subsequently pressed back into the surface in the direction of friction. Wear products occurred mainly as fine particles dispersed over the surface, and their amount was relatively small.

With increasing heating temperature up to 90 °C (Figures 8b–e), the extent of the smoothed surface area increased, while both the number of detached material fragments and the amount of

wear products decreased. For the specimen heated at 100 °C (Figure 8f), a reduction in the degree of surface smoothing was observed, accompanied by an increase in the amount of wear products. These products formed elongated bands, which were chaotically distributed over the material surface.

Considering the microscopic images of the surfaces of POM specimens, it can be observed that at 50 °C (Figure 9a), the original surface structure remained partially preserved. Local smoothing of the surface was visible, as well as completely detached material fragments that were subsequently pressed back into the surface as a result of the friction process.

From 60 °C onwards (Figure 9b–f), the surface developed a characteristic wrinkled structure, in which the increase of the temperature caused waviness at the edges of the scratches formed during friction. The observed wrinkles appeared to follow the locations of the technological grooves produced during the preparatory machining process. With increasing temperature, these structures gradually disappeared, while the proportion of smoothed surface areas increased. At the same time, the number of detached material fragments decreased.

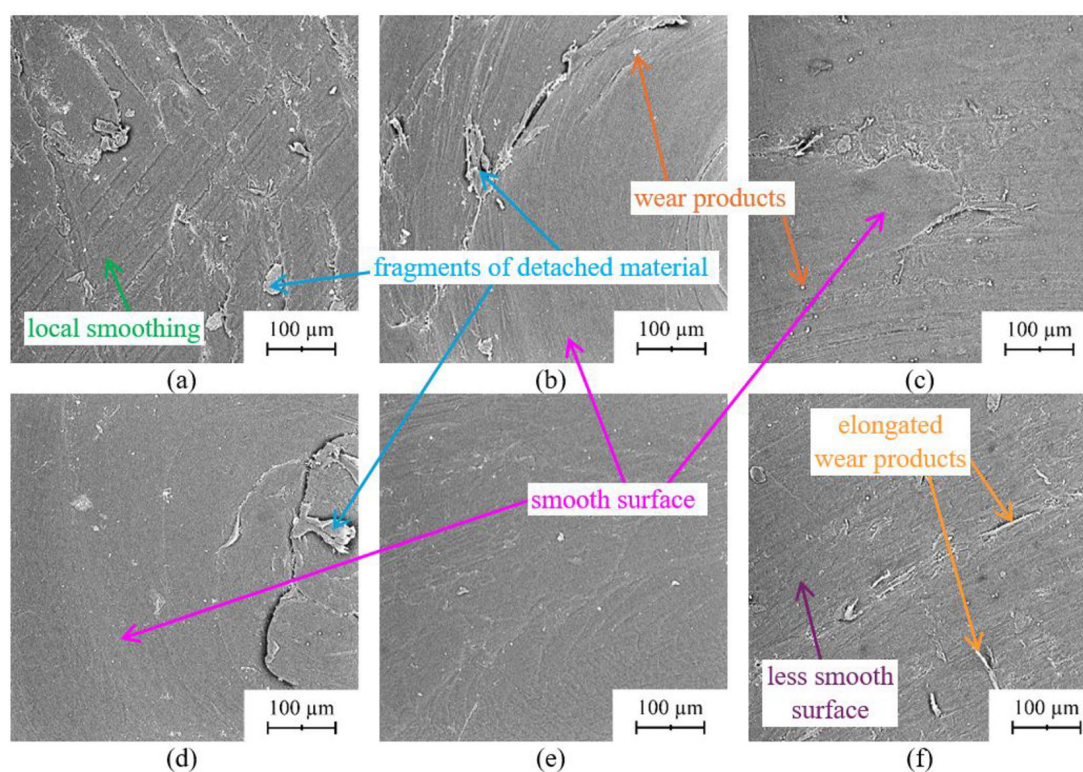


Figure 8. Representative SEM micrographs of the surfaces of the PET specimens heated at selected temperatures: (a) 50 °C, (b) 60 °C, (c) 70 °C, (d) 80 °C, (e) 90 °C, and (f) 100 °C, after the tribological testing

At 50 °C (Figure 9a), only a small number of randomly distributed wear products were present. As the temperature increased (Figures 9b–f), their amount decreased, and at the highest temperatures the wear products almost completely disappeared.

Microhardness

The microhardness results for POM, PET, and PA6 after exposure to elevated temperatures are presented in Figure 10. The measurements were carried out in the temperature range from 21 °C to 100 °C. For each material and temperature condition, the average Vickers microhardness value was determined together with the confidence interval at a significance level of $\alpha=95\%$.

At room temperature (21 °C), PET and POM showed similar microhardness values of approximately 17.8 HV, whereas PA6 reached about 10.0 HV. After exposure to elevated temperatures, PA6 exhibited slightly lower microhardness, with values ranging from approximately 8.2 to 9.1 HV. The lowest value was recorded at 70 °C, while a small increase was observed at the highest temperatures.

PET showed the most stable behaviour among the tested materials. Its microhardness remained

within a narrow range of approximately 16.8–17.6 HV over the entire temperature range, with only minor fluctuations relative to the room-temperature value.

The greatest changes were observed for POM. After heating to 50–90 °C, the microhardness increased markedly, reaching values from approximately 34 HV to 46 HV. The highest values were recorded at 50 °C and 70 °C. At 100 °C, however, the microhardness decreased distinctly to approximately 15.7 HV, reaching a value lower than that measured at room temperature.

The results show clear material-dependent differences in microhardness variation with temperature. PA6 maintained the lowest microhardness values, PET remained nearly unchanged, whereas POM exhibited the most pronounced temperature-related changes. The confidence intervals were generally narrow, although increased scatter was observed for selected measurement points, particularly for POM and PET at higher temperatures.

Surface roughness

The results of surface roughness measurements obtained after the friction process are

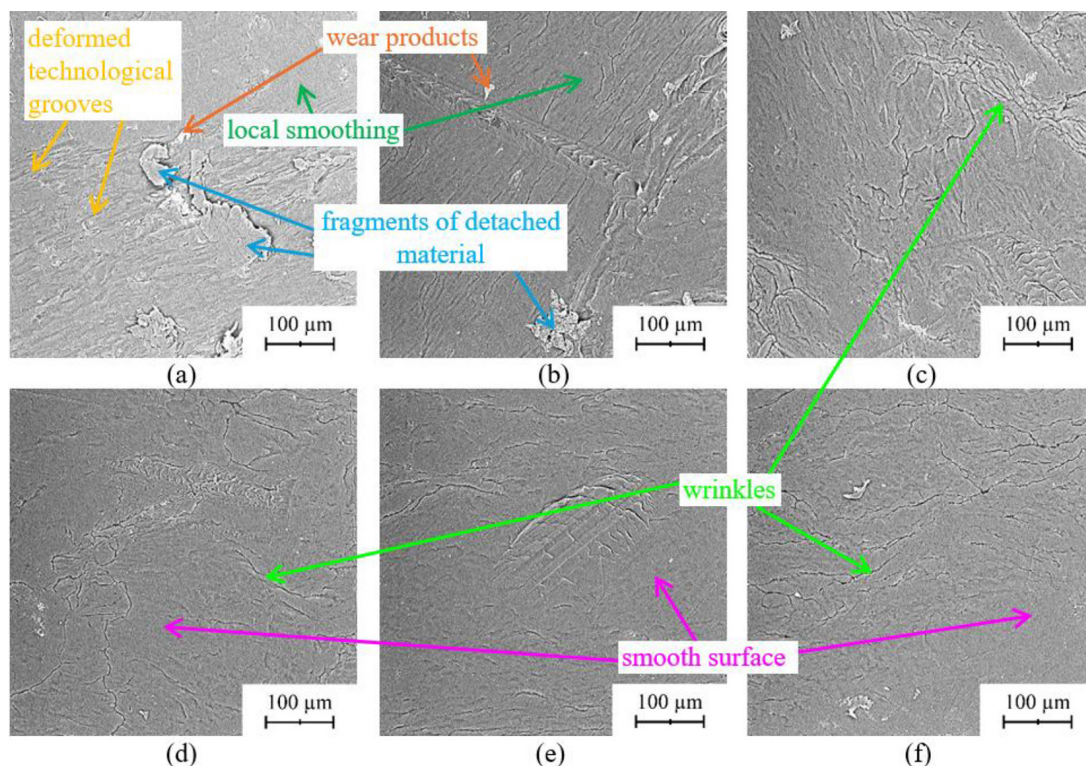


Figure 9. Representative SEM micrographs of the surfaces of the POM specimens heated at selected temperatures: (a) 50 °C, (b) 60 °C, (c) 70 °C, (d) 80 °C, (e) 90 °C, and (f) 100 °C, after the tribological testing

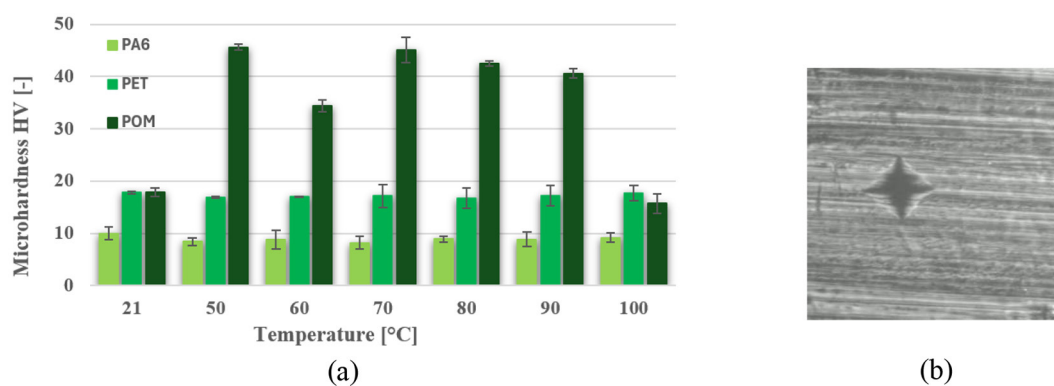


Figure 10. Results of microhardness measurements: (a) average Vickers microhardness of PA6, PET, and POM for individual elevated temperatures; (b) representative SEM image of a Vickers indentation on the surface of a PET specimen

presented in Table 4. The analysis included selected areal surface parameters: S_a , S_z , S_{pc} , and S_{dr} . The S_a parameter represents the arithmetical mean height of the surface, S_z describes the maximum height of the surface, S_{pc} refers to the arithmetic mean peak curvature, while S_{dr} defines the developed interfacial area ratio. These parameters enabled a quantitative comparison of changes in the surface topography of PA6, PET, and POM after the exposure to elevated temperatures ranging from 50 °C to 100 °C, with the room-temperature condition used as a reference. Figure 11 presents an example of the analysis, showing the height distribution on the PET specimen surface together with the area selected for the determination of roughness parameters.

For PA6, a clear increase in the S_a parameter was observed with increasing temperature. At 21 °C, S_a was equal to approximately 28.4 μm , whereas after heating to 80–100 °C it increased to values above 160 μm , reaching the highest value of approximately 194.5 μm at 80 °C. A similar tendency was observed for S_z , which increased from about 183 μm at 21 °C to more than 1000 μm at 80 °C. The S_{pc} parameter also increased with temperature up to 80 °C, while at 90 °C and 100 °C slightly lower values were recorded. The S_{dr} parameter remained low over the entire temperature range and did not show a monotonic trend.

In the case of PET, the surface roughness parameters changed in a non-linear manner. The lowest S_a value was recorded at 50 °C and was equal to approximately 4.5 μm . At higher temperatures, S_a increased considerably, reaching approximately 80.4 μm at 80 °C, followed by a decrease at 90 °C and 100 °C. The S_z parameter

showed a similar variation, with the lowest value at 50 °C and higher values in the range of 60–100 °C. The highest S_{pc} value was observed at 70 °C, whereas the S_{dr} parameter reached its maximum at 90 °C.

For POM, the S_a parameter remained relatively stable compared with PA6 and PET. The measured values ranged from approximately 20.0 μm to 25.6 μm over the entire investigated temperature range. In contrast, the S_z parameter showed pronounced local increases at 70 °C and 80 °C, reaching approximately 814.9 μm and 726.5 μm , respectively. The S_{pc} parameter varied between approximately 10.7 and 28.6 1/mm, with the highest value recorded at 80 °C. The S_{dr} parameter also showed local maxima at 70 °C and 80 °C, while at the remaining temperatures it remained lower.

A comparison of the investigated polymers shows that PA6 exhibited the highest increase in height-related roughness parameters at elevated temperatures, especially in the range of 80–100 °C. PET showed the greatest variation between individual temperatures, whereas POM was characterised by the most stable S_a values, despite local changes in S_z , S_{pc} , and S_{dr} .

Statistical analysis

To verify whether the observed differences in the coefficient of static friction were statistically significant, two-way ANOVA was performed separately for each self-mated polymer pair. Prior exposure temperature and nominal contact pressure were treated as independent factors, and the coefficient of static friction was treated as the dependent variable. The interaction between prior

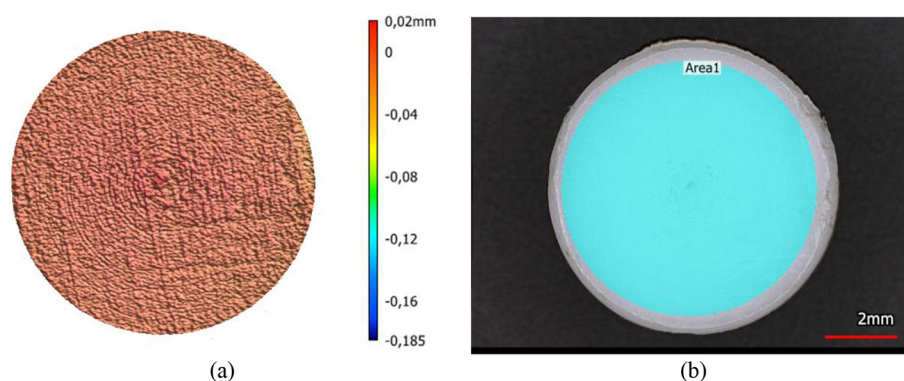


Figure 11. Representative surface topography of a PET specimen after exposure to 50 °C: (a) corresponding colour height map and (b) marked area selected for roughness measurement

Table 4. Results of surface roughness parameter measurements of the tested specimens after the friction process

Material	Parameter	Temperature [°C]						
		21	50	60	70	80	90	100
PA6	S_a [μm]	28.372	31.154	47.508	67.418	194.454	164.854	183.765
	S_z [μm]	183.200	387.200	375.300	423.800	1047.200	773.800	850.600
	S_{pc} [1/mm]	5.946	6.773	9.149	10.059	11.251	9.780	9.854
	S_{dr} [-]	0.017	0.011	0.017	0.011	0.002	0.016	0.018
PET	S_a [μm]	15.833	4.456	58.287	66.259	80.350	59.023	46.471
	S_z [μm]	107.720	56.770	390.030	487.000	414.800	409.980	311.700
	S_{pc} [1/mm]	4.992	8.592	10.046	18.488	13.651	17.109	8.208
	S_{dr} [-]	0.005	0.010	0.026	0.053	0.028	0.096	0.014
POM	S_a [μm]	25.478	25.599	21.940	25.555	23.653	21.643	20.047
	S_z [μm]	162.000	177.800	128.800	814.900	726.500	121.600	129.400
	S_{pc} [1/mm]	25.583	22.933	14.512	15.958	28.581	13.199	10.737
	S_{dr} [-]	0.056	0.051	0.021	0.116	0.080	0.021	0.018

exposure temperature and nominal contact pressure was also included in the analysis. The results are summarised in Table 5.

The two-way ANOVA confirmed that prior exposure temperature had a statistically significant effect on the coefficient of static friction for all investigated polymer pairs. For PA6–PA6, the effect of prior exposure temperature was significant ($F = 61.12$, $p < 0.001$), whereas the effect of nominal contact pressure was not statistically significant ($F = 0.19$, $p = 0.829$). The temperature–pressure interaction was also not significant for PA6–PA6 ($F = 1.06$, $p = 0.395$).

For PET–PET, both prior exposure temperature and nominal contact pressure significantly affected the coefficient of static friction. The temperature effect was particularly strong ($F = 302.31$, $p < 0.001$), while the pressure effect was weaker but still statistically significant ($F = 4.37$,

$p = 0.014$). A significant temperature–pressure interaction was also found for PET–PET ($F = 4.67$, $p < 0.001$).

For POM–POM, prior exposure temperature was also statistically significant ($F = 38.67$, $p < 0.001$). The effect of nominal contact pressure was significant but weaker than the temperature effect ($F = 4.17$, $p = 0.017$). The temperature–pressure interaction was statistically significant as well ($F = 2.32$, $p = 0.009$). These results confirm that prior thermal exposure was the dominant factor affecting static friction, while the influence of contact pressure was weaker and material-dependent.

Tukey's HSD post-hoc test was used to identify the differences between individual exposure temperature levels. For all three investigated polymer pairs, the room-temperature condition differed significantly from each thermally

Table 5. Results of two-way ANOVA for the coefficient of static friction

Material pair	Factor	F-value	p-value
PA6–PA6	Prior elevated-temperature exposure	61.12	< 0.001
	Contact pressure	0.19	0.829
	Elevated temperature × contact pressure	1.06	0.395
PET–PET	Prior elevated-temperature exposure	302.31	< 0.001
	Contact pressure	4.37	0.014
	Elevated temperature × contact pressure	4.67	< 0.001
POM–POM	Prior elevated-temperature exposure	38.67	< 0.001
	Contact pressure	4.17	0.017
	Elevated temperature × contact pressure	2.32	0.009

exposed condition (adjusted $p < 0.001$). For PA6–PA6, all thermally exposed conditions showed significantly higher static friction than the room-temperature condition, confirming that prior heating caused a statistically significant increase in friction. In contrast, for PET–PET and POM–POM, all thermally exposed conditions showed significantly lower static friction than the room-temperature condition. At the same time, not all differences between individual heated conditions were statistically significant, which supports the interpretation that the effect of prior thermal exposure was non-linear rather than monotonic.

The statistical analysis was also extended to Vickers microhardness and surface roughness parameters. Since these measurements were not performed under different nominal contact pressures, the statistical models included material type, prior exposure temperature, and the material type × prior exposure temperature interaction. For Vickers microhardness, statistically significant effects were found for material type, prior exposure temperature, and their interaction ($p < 0.001$). Similarly, for all analysed areal surface roughness parameters, namely S_a , S_z , S_{pc} , and S_{dr} , the effects of material type, prior exposure temperature, and their interaction were statistically significant ($p < 0.001$).

These results confirm that the microhardness and surface topography responses after prior thermal exposure were material-dependent. The significant interaction effects indicate that PA6, PET, and POM did not respond to prior heating in the same way. Therefore, the observed changes in microhardness and roughness parameters should be interpreted not only as a function of exposure temperature, but also in relation to the specific near-surface response of each polymer.

DISCUSSION

This study analysed the influence of elevated temperatures and contact pressure on the tribological properties of self-mated polymer–polymer pairs made of PA6, PET, and POM. The experimental programme included measurements of the coefficient of static friction under technically dry conditions, qualitative assessment of changes occurring in the surface layer of the materials using scanning electron microscopy, measurements of surface roughness parameters, and Vickers microhardness measurements. It should be emphasised that, prior to the measurements, the specimens were heated at temperatures ranging from 50 °C to 100 °C and then stabilised at room temperature. Therefore, the obtained results should be interpreted as the effect of prior thermal exposure and of changes retained in the surface layer of the material. A particular aspect of the present study is the analysis of the persistent influence of prior thermal exposure on the tribological properties of polymer–polymer pairs after the materials had been cooled to room temperature. The obtained results indicate that heating may lead to retained changes in the surface layer, which affect the value of the coefficient of static friction even after the thermal exposure has ceased.

The results of the coefficient of static friction measurements showed that the influence of prior thermal exposure was not uniform for all investigated materials. For the PA6–PA6 pair, a clear increase in the coefficient of static friction was observed after heating. At room temperature, the coefficient of friction was approximately 0.23–0.24, whereas after the thermal exposure it increased to the range of 0.32–0.45. The highest values were recorded after heating at 50–60 °C.

This temperature range corresponds to the glass transition temperature range of PA6, which is approximately 40–70 °C [22–29]. Therefore, the observed increase in static friction may be related to enhanced segmental mobility in the amorphous phase of PA6 near T_g [31].

Near the glass transition temperature, polymer-chain segments become more mobile and the amorphous phase becomes more susceptible to time-dependent deformation, stress relaxation, and local viscoelastic flow [30]. Under static contact conditions, these effects may increase the real contact area, improve local conformity between surface asperities, and intensify adhesive interactions before the onset of macroscopic sliding [1, 3]. After cooling to room temperature, part of the deformation and rearrangement occurring in the near-surface layer may be retained, especially when the surface has been locally damaged or plastically/viscoelastically deformed during prior thermal exposure [7, 31]. This interpretation is consistent with the observed increase in static friction, the decrease in PA6 microhardness after heating, and the SEM evidence of intensive surface-layer modification, detached material fragments, local cracks, and embedded wear products.

The possible influence of moisture absorption should also be considered when interpreting the PA6–PA6 results. PA6 is more hygroscopic than PET and POM, as indicated by the higher moisture absorption values listed in Table 1. The absorbed moisture may modify the near-surface mechanical response of PA6 by affecting its deformability, microhardness, and adhesive interactions under static contact conditions. Therefore, the pronounced increase in static friction observed for PA6 after prior thermal exposure may result not only from molecular mobility near T_g and retained surface-layer deformation, but also from the specific sensitivity of PA6 to moisture-related changes. Since humidity was not independently controlled in the present study, this factor should be treated as a possible additional contribution, rather than as a separately quantified effect.

A different trend was observed for the PET–PET and POM–POM pairs. In the case of PET, the coefficient of static friction after the exposure to elevated temperatures was lower than that measured at room temperature. Under the reference condition, it reached approximately 0.35–0.39, whereas after heating in the range of 50–90 °C it decreased to approximately 0.18–0.24. At 100 °C, a slight increase in the coefficient of static friction

was recorded; however, the values still remained lower than those obtained for the non-heated specimen. The glass transition temperature of PET is approximately 67–81 °C; therefore, some of the applied exposure temperatures were close to or above T_g [22–29]. In this case, increased molecular mobility near T_g probably did not lead to stronger interlocking or adhesion, as observed for PA6, but rather promoted local smoothing and partial rearrangement of the near-surface layer [31]. This may have reduced mechanical interlocking between asperities and decreased the resistance to motion initiation, which is consistent with the literature showing that surface roughness can affect polymer–polymer friction [17]. The slight increase in static friction at 100 °C may be associated with more pronounced surface disturbance and the larger amount of wear products observed on the PET surface.

For the POM–POM pair, a general decrease in the coefficient of static friction was also found after prior thermal exposure. This behaviour should be interpreted differently from PA6 and PET, because the glass transition temperature of POM is far below room temperature, approximately -60 to -50 °C [22–29]. Thus, all measurements and thermal exposure conditions were performed far above T_g , where the amorphous phase of POM is already above the glass-transition region. Consequently, exceeding T_g cannot explain the observed changes. The frictional response of POM is more likely related to structural and morphological changes in the semicrystalline near-surface layer, local smoothing, deformation of technological grooves, and changes in the distribution of wear products. This interpretation is consistent with previous studies showing that the tribological behaviour of POM is temperature-dependent, but it also highlights that the present work concerns static friction after prior heating and cooling, not sliding friction measured directly at elevated temperature [9]. SEM observations showed that the initially visible wrinkled surface structures gradually disappeared with increasing exposure temperature, while the proportion of smoothed areas increased and the amount of wear products decreased. These retained surface modifications after cooling may have contributed to the lower static friction of POM–POM after prior thermal exposure.

The comparison of PA6, PET, and POM shows that T_g should not be treated as the only factor controlling the static friction response after

prior thermal exposure. The glass transition temperature is important because it defines the temperature range in which the amorphous phase becomes more mobile and more susceptible to viscoelastic deformation and stress relaxation [31]. However, the retained frictional response after cooling also depends on residual stresses, the degree of viscoelastic recovery, local surface deformation, surface smoothing or roughening, and possible structural rearrangement in the near-surface layer [7, 8, 31]. During heating, residual stresses introduced during manufacturing or machining may be partially relaxed, while asperities and surface irregularities may undergo local deformation. During subsequent cooling, these changes may not be fully reversible, which means that the room-temperature static friction test reflects not only the intrinsic polymer properties, but also the modified surface state produced by the previous thermal cycle.

The influence of contact pressure on the coefficient of static friction was noticeable; however, it was less unequivocal than the effect of temperature. For the PA6–PA6 pair, the differences between the values obtained at individual contact pressures were smaller than the changes induced by thermal exposure. For the PET–PET pair, the dependence on contact pressure was irregular, and the lowest values of the coefficient of friction were usually observed in the intermediate temperature range. In the case of the POM–POM pair, an increase in contact pressure most often led to lower or comparable values, particularly after heating. This may result from local smoothing of surface asperities and stabilisation of the contact; however, this effect was strongly dependent on the polymer type and the condition of its surface.

The statistical analysis confirmed that the prior exposure temperature had a statistically significant effect on the coefficient of static friction for all investigated polymer–polymer pairs ($p < 0.001$). Tukey's HSD post-hoc test showed that the room-temperature condition differed significantly from each thermally exposed condition. However, the direction of this effect depended on polymer type: PA6–PA6 exhibited significantly higher static friction after prior heating, whereas PET–PET and POM–POM showed significantly lower friction after thermal exposure.

The influence of nominal contact pressure was less universal and material-dependent. For PA6–PA6, contact pressure did not significantly

affect the coefficient of static friction within the investigated range, while for PET–PET and POM–POM its effect was statistically significant. Significant temperature–pressure interactions were also found for PET–PET and POM–POM, indicating that the influence of pressure depended on prior thermal history. These findings confirm that the static friction behaviour of polymer–polymer sliding pairs after prior heating cannot be interpreted only in terms of nominal contact pressure, but should also account for polymer type and retained temperature-induced changes in the near-surface layer.

The analysis of surface roughness revealed a clear differentiation in the response of the investigated materials to thermal exposure. The greatest changes in the surface parameters were observed for PA6, particularly after heating at temperatures of 80–100 °C. The S_a parameter increased from approximately 28.4 μm at room temperature to values exceeding 160 μm , reaching a maximum of approximately 194.5 μm after exposure to 80 °C. At the same time, the S_z parameter increased to values exceeding 1000 μm . These changes indicate intensive modification of the surface layer, including deformation, detachment of material fragments, formation of wear products, and their secondary embedding into the surface, which is confirmed by the changes observed in the SEM micrographs. For PET, the changes in roughness were non-monotonic. The lowest S_a value was recorded after heating at 50 °C, whereas in the range of 60–90 °C a clear increase in this parameter was observed. For POM, the S_a parameter remained the most stable over the entire temperature range, despite local increases in the values of the other parameters. This may indicate a smaller change in the average level of surface irregularities, accompanied by the occurrence of local defects or topographical changes.

The changes in microhardness were consistent with the observed differences in the surface behaviour of the investigated materials. PA6 exhibited the lowest microhardness values over the entire temperature range. After heating, these values were slightly lower than those measured at room temperature and were mainly within the range of approximately 8.2–9.1 HV. This may be related to the increased susceptibility of the amorphous phase to deformation near and above the glass transition temperature, which affects the mechanical response of the surface layer. PET showed the greatest stability of microhardness

values, maintaining them within a narrow range of approximately 16.8–17.6 HV. The largest and most non-monotonic changes were recorded for POM. After heating at temperatures of 50–90 °C, the microhardness increased to approximately 34–46 HV, whereas after exposure to 100 °C it decreased to approximately 15.7 HV. This pronounced increase in POM microhardness may be associated with thermally induced rearrangement or densification of the near-surface layer, relaxation of machining-related residual stresses, and changes in the local semicrystalline morphology. Since POM has a glass transition temperature far below room temperature, the observed increase cannot be explained by crossing T_g during heating. Instead, it may reflect the structural changes occurring within the semicrystalline surface layer below the melting range. The decrease in microhardness after exposure to 100 °C suggests that this effect was not monotonic and may have been accompanied by local surface softening, recovery, or disturbance of the modified surface layer. However, this interpretation remains indirect, because no additional structural analyses such as DSC or XRD were performed in the present study.

Additional ANOVA performed for Vickers microhardness and surface roughness parameters confirmed that material type, prior exposure temperature, and their interaction significantly affected microhardness and all analysed roughness parameters, including S_a , S_z , S_{pc} , and S_{dr} ($p < 0.001$). The significant material type $\times$ prior exposure temperature interactions indicate that the retained surface-layer response after heating and cooling was not uniform for all polymers. This supports the conclusion that PA6, PET, and POM underwent different near-surface modifications after prior thermal exposure, which should be considered when interpreting their static friction behaviour.

SEM observations provide qualitative support for the interpretation of surface-layer changes after prior thermal exposure. For PA6, a large amount of wear products, fragments of material detached from the surface layer, local cracks, and areas of secondary embedding of material into the surface were observed after heating. These changes were most intense after exposure to temperatures of 80–100 °C. For PET, local surface smoothing was dominant, particularly up to 90 °C, accompanied by a simultaneous decrease in the number of detached material fragments

and wear products. After heating at 100 °C, an increase in the amount of wear products was observed, forming elongated and irregularly distributed bands. In the case of POM, from 60 °C onwards, a characteristic wrinkled surface structure was visible, probably associated with deformation of the edges of scratches and technological grooves. With increasing temperature, these structures gradually disappeared, the proportion of smoothed areas increased, and the amount of wear products clearly decreased.

The combined analysis of the coefficient of static friction, surface roughness, microhardness, and SEM observations indicates that the frictional response after prior thermal exposure cannot be explained by a single surface parameter. For PA6–PA6, the increase in static friction after heating was accompanied by low microhardness, a pronounced increase in height-related roughness parameters, and SEM evidence of intensive surface-layer modification, including detached material fragments, local cracks, and embedded wear products. This suggests that the PA6 surface became more susceptible to deformation and adhesive contact formation, which may have increased the real contact area and resistance to motion initiation [1, 3].

For PET–PET, the decrease in static friction after prior thermal exposure was not accompanied by a simple monotonic decrease in roughness parameters. Instead, PET showed non-monotonic changes in S_a , S_z , S_{pc} , and S_{dr} , while its microhardness remained relatively stable over the investigated temperature range. SEM observations indicated local surface smoothing and a reduced amount of detached wear products up to 90 °C. Therefore, the lower static friction of PET–PET after heating was probably related not to a general reduction of all roughness parameters, but to local smoothing of the contact surface, reduced mechanical interlocking of asperities, and a more stable near-surface layer. The slight increase in static friction at 100 °C is consistent with the increased amount of wear products observed on the PET surface.

For POM–POM, the coefficient of static friction generally decreased after prior thermal exposure despite pronounced and non-monotonic changes in microhardness. At the same time, S_a remained relatively stable compared with PA6 and PET, although local changes in S_z , S_{pc} , and S_{dr} were observed. SEM images showed gradual smoothing of the surface and a reduction in

the amount of wear products at higher exposure temperatures. This indicates that, for POM, the frictional response was more strongly related to local surface restructuring and the reduction of loose wear products than to the average height parameter S_a alone. These results show that surface roughness and microhardness should be interpreted together with SEM morphology, because static friction depends on the combined effect of surface topography, near-surface mechanical response, adhesion, and wear-product distribution [1, 17].

The results are consistent with the previous studies showing that polymer–polymer friction is governed by a combined influence of material type, contact conditions, adhesion, viscoelastic deformation, surface topography, and interfacial history [1–4, 7, 17]. The present work confirmed this material-dependent character, but extended previous static-friction studies by demonstrating that short-term prior thermal exposure may leave retained changes in the surface layer and affect motion initiation after cooling to room temperature. This is important because most temperature-related tribological studies focus on friction measured directly at elevated temperature or during continuous sliding, whereas the present study concerned the persistent effect of thermal history.

For PA6–PA6, the increase in static friction after prior heating was accompanied by low microhardness, increased surface roughness, and SEM evidence of intensive surface-layer modification. This agrees with the general concept that softer and more deformable polymer surfaces may develop a larger real contact area and stronger adhesive interactions before the onset of sliding [1, 3]. In contrast, PET–PET and POM–POM showed a general decrease in static friction after thermal exposure. For PET, this was accompanied by relatively stable microhardness, local surface smoothing, and non-monotonic changes in surface topography, while for POM relatively stable S_a values and gradual reduction of wear products were observed. These results indicate that thermal exposure may either increase or decrease static friction depending on the polymer type and the retained condition of the near-surface layer.

Some differences between the present results and earlier temperature-dependent studies can be attributed to the different experimental approach. For example, studies on the POM tested directly at elevated temperatures reported increasing friction and wear with temperature [9], whereas in

the present work POM–POM generally showed lower static friction after prior heating and cooling. This apparent discrepancy is most likely related to the fact that the present study concerned static friction after thermal exposure and room-temperature stabilisation, not real-time sliding friction at elevated temperature. Therefore, the measured coefficient of static friction reflects retained surface-layer changes rather than the direct effect of elevated contact temperature during sliding. This distinction is important when comparing the present results with studies focused on dynamic sliding or testing performed directly at elevated temperature.

CONCLUSIONS

The results confirm that the influence of prior elevated-temperature exposure on self-mated polymer–polymer sliding pairs is complex, non-linear, and strongly material-dependent. The response cannot be explained solely by the nominal contact pressure or by the glass transition temperature. Although T_g is important for interpreting changes in molecular mobility and viscoelastic deformability of the amorphous phase, the retained frictional response after cooling also depends on residual-stress relaxation, incomplete viscoelastic recovery, local surface deformation, roughness evolution, microhardness response, local smoothing, possible near-surface structural rearrangement, and the presence or reduction of wear products. Therefore, the assessment of polymer sliding pairs operating under start-up conditions should include not only the polymer type and contact pressure, but also thermal history and the resulting surface-layer condition.

The study was intentionally focused on the retained effect of prior thermal exposure after cooling and stabilisation at room temperature. Therefore, the results should be interpreted as the influence of thermal history on static friction, rather than as direct friction behaviour during real-time elevated-temperature sliding. Future research may extend the present findings by including direct contact-temperature monitoring, real-time elevated-temperature friction tests, repeated heating–cooling cycles, and longer exposure or stabilisation times. Additional structural and thermal characterisation, such as DSC, DMA, FTIR, or XRD, as well as quantitative SEM/image analysis of wear debris and damaged

or deformed surface areas, could further support the interpretation of near-surface changes after heating. In the case of PA6, controlled humidity conditions should also be considered, because moisture absorption may affect both mechanical and tribological behaviour.

The presented results are relevant for the design and operation of polymer sliding pairs working under periodic temperature changes and start-up/stop conditions. They indicate that even short-term prior thermal exposure should be considered during material selection, because it may change the static friction response after cooling.

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