Investigation of temperature conditions during friction of metal and polymer materials

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In many engineering designs, knowledge of friction properties of materials is necessary. The coefficient of friction (static or dynamic) depends on many parameters - surface roughness parameters, temperature, surface pressure, velocity, humidity - in addition to the materials used. In this paper, the friction properties of aluminum (Al 6082-T6) and polypropylene homopolymer surface pairs are investigated at different surface loads (5-15 MPa) and different velocities (4-8-48-96 mm/min). The different loads and speeds of motion result in different degrees of heating on the friction surfaces. The magnitude and distribution of the resulting temperature change were modelled to determine how the heat generated during the measurement affects the measured values. Our results show that, over the range of parameters used in the measurement (surface roughness parameters, temperature, surface pressure, velocity, humidity), the temperature change that develops on the friction surfaces during the measurement does not significantly affect the measurement results. The static and dynamic friction coefficients decrease with increasing surface load. The dynamic coefficient of friction increases with increasing velocity, while the variation of static coefficient of friction is negligible.

KEYWORDS: FRICTION – TEMPERATURE CHANGE – MODELING – METAL/POLYMER

INTRODUCTION

Friction is a complex phenomenon that depends on many physical and operational parameters. There are engineering tasks where it is necessary to know the friction conditions exactly, since it determines the operating range of the machine or working parts (force-locking or friction-locking joints, brakes, clutches). Nowadays, the number of material pairs used is increasing intensively, but at the same time, the relevant literature does not always provide adequate or sufficiently accurate friction data for the chosen material pairs.

Several approaches and theories related to friction have been created, which described comprehensively in Pennestrì et al. [1] and Al-Bender [2].

Materials included in our investigation (aluminum – AL and polypropylene – PP) materials are widely used in household and engineering applications. During use of them, sliding surfaces are worn out and the interfacial properties change affecting friction. This phenomenon was researched for polypropylene by Cho et al. 3. Sedlak et al. 4 in their study determined the changes in the sliding friction coefficient and wear mechanism of PP impregnated by oils with respect to the unmodified PP under dry sliding conditions. Al-Samarai et al. 5 investigated the effect of load and speed on sliding friction coefficient of aluminum–silicon casting alloy using a pin-on-disc with three different loads at three speeds. In their results they showed that the load and the speed affect the coefficient of friction.

The product p⋅v, where p means surface pressure and v means relative movement speed, is widely used in practice to characterize the permanent load capacity and relative movement speed of pairs of materials moving on each other. Typically, the p⋅v value is used in two main areas. On the one hand, in the field of bearing materials — here this only refers to materials of slide bearings — and on the other hand, in the field of friction materials. In addition to the product p⋅v, it is customary to indicate the limit values p and v as well. In case of bearing materials, the two members of material pair constantly move on each other during operation, so the value of p is usually small and the value of v is large. In case of friction materials—such as friction clutch and brake material pairings—the two members of the material pair do not always move relative to each other, or they only have to bear the relative movement temporarily. In this case, the value of p is typically large, and the value of v is typically small.

In the present study, as part of a development task, the static and dynamic friction conditions of a pair of frictional materials had to be determined at different relative speeds and surface loads. We chose the values of p and v according to the planned range of use of the material pair. In the next chapter, we analyze the friction conditions of aluminum and polypropylene using four relative traction speeds as 4–8–48–96 mm/min and two different surface loads as 5–15 MPa. The surface load 5 MPa is the planed load for a PP part together with 4-8 mm/min speed and the 15 MPa is about the half of the yield strength of the PP homopolymer material (32 MPa) used for the test which is considered as the safe maximum of the engineering surface load in case of limited speed of traction (4-96 mm/min).

Basically, this research results show how different surface pressures affect the values of static and dynamic friction coefficient. Given the real conditions of the task, it is important to know the extent of the temperature change caused by friction and its effect on the friction conditions. Using the force and displacement data obtained during the measurement, magnitude and distribution of temperature change were modeled during friction with the geometry corresponding to the measurement arrangement. During the modeling, we regularly checked the temperature change according to the load and traction speed settings used during the measurement and the measured data.

Results are displayed with the help of following diagrams and pictures.

According to our results, the temperature increment occurred in a range that does not affect the friction characteristics.

MATERIALS AND METHODS

Materials

The tests were performed on aluminum (Al 6082-T6) and extruded polypropylene (PP) homopolymer pairs, after the so-called run-in was performed. The aluminum samples were produced by milling (machining parameters: cutting speed, vc = 160 m/min, feed, fz = 0.08 mm) and the PP samples by turning (machining parameters: cutting speed, vc = 80 m/min, feed, f = 0.05 mm). Run-in means initial wear, in this case 6–10 preliminary tests at the same load and the same relative speed. As a result, the transition layer resulting from the interaction of the two layers was definitely formed, and the measurement results probably characterize actual operating conditions. Table 1 contains the average values of the main roughness parameters 6 of the samples before and after run-in.

Tab. 1 – main roughness parameters of the aluminum test specimen and the PP sample (before and after run-in)

	Average surface roughness Ra, µm	Ten-point height, Rz, µm	Maximum height of profile, Rp µm	Maximum profile valley depth, Rv, µm
Aluminum specimen	1.094/0.812	4.681/3.465	2.458/1.173	2.223/1.639
PP sample	0.812/0.487	3.465/2.454	1.773/0.981	1.693/1.473

Methods

The tests were carried out on the ~ 26–288 mm section of the aluminum specimen by dragging the Ø15 mm PP samples, using a given relative speed and a given surface pressure. During the test, $F_{friction}$ force and relative displacement data were registered respectively with the frequency of 30 Hz. The test parameters were selected according to the intended use of the materials and surface pressure was applied in the order of magnitude of the surface limit load of PP (p=5 and 15 MPa), Maximum surface load value can be determined as the half of the yield strength of PP homopolymer used.

The static (µ0) and dynamic (µ) coefficients of friction were calculated with the following equations:

$$\mu_0 = \frac{F_{friction\_max}}{F_{load}} \qquad (1)$$

where $F_{friction\_max}$ is the maximum of the friction force.

$$\mu = \frac{F_{friction}}{F_{load}} \tag{2}$$

where $F_{friction}$ is almost steady state of the registered value and traction speed is constant.
Patent application has been filed concerning measurement device.

Using the traction speed, v_f and friction force, $F_{friction}$ values measured, temperature change on the surface of the sample and specimen was investigating in case of specific load of samples of 15 MPa. The real size of the samples and specimen were used for modeling; however, the length of the specimen (Aluminum bar) was considered infinite. The modeling was done with a surface load of 15 MPa and all traction speeds. The worst case, i.e. the maximum temperature increment is shown with 15 MPa, and 96 mm/min input parameters. In this case the friction force was $F_f = 408$ N and traction speed was $v_f = 0{,}0016$ m/s (96 mm/min) for the calculation. The complete input parameter set can be seen below:

Ff	408	Friction force, N
vf	0.0016	Traction speed, m/s
Ps	Ff*vf	Friction power, W
dm	0.015	Sample diameter, m
Am	dm*dm*pi/4	Sample surface, m2
Pm	Ps/Am	Specific power, W/m2
roAl	2700	Aluminum density, kg/m3
cpAl	900	Aluminum specific heat, J/(kg K)
kAl	201	Aluminum thermal conductivity W/(mK)
roPolim	900	Polymer density, kg/m3
cpPolim	1680	Polymer specific heat, J/(kg K)
kPolim	0.23	Polymer thermal conductivity, W/(mK)
Tkulso	300	Environment temperature, K
h_Al_lev	25	Al-Air heat transfer coefficient, W/(m2 K)
h_Polim_lev	10	Polymer-Air heat transfer coefficient, W/(m2 K)

RESULTS

The effect of surface load on friction

The tests were performed at a surface load of 5 MPa and 15 MPa using four speeds (4–8–48–96 mm/min). The characteristics of friction were the same in all cases. Figure 1 shows the results for the speed of 8 mm/min in detail. The shape of pre-sliding and gross sliding regions are almost identical even though the surface load is different, but μ_0 and μ depend on surface load. As surface load increases, both the static and dynamic coefficients of friction decrease.

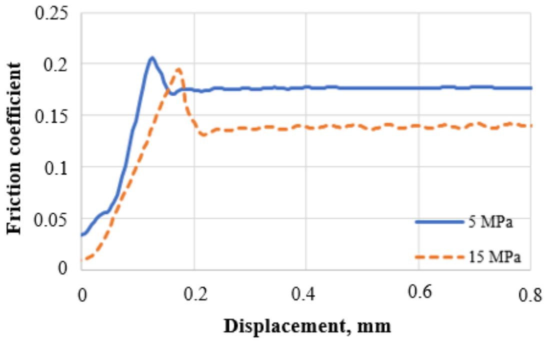

Fig. 1 Registered friction ranges for different surface loads (p = 5 MPa – 15 MPa; v = 8 mm/min; frictional surface pairs: Al 6082-T6 – polypropylene homopolymer)

The effect of the relative speed difference on friction

The series was also aimed at assessing the effect of the relative speed difference between the surfaces on friction. The test results are listed in Table 2. The dependence of the static and dynamic coefficients of friction on load and speed difference is shown in Figures 2 and 3.

Tab. 2 - static (μ_0) and dynamic (μ) coefficient of friction of the aluminum test specimen and PP sample under different surface loads and speeds

	Surface load = 5 MPa		Surface load = 15 MPa	
Traction speed	μ_0	μ	μ_0	μ
4 mm/min	0.211	0.176	0.188	0.138
8 mm/min	0.206	0.18	0.196	0.142
48 mm/min	0.214	0.21	0.173	0.151
96 mm/min	0.24	0.23	0.18	0.163

Figures 2 and 3 show that—in the case of the studied material pair and within the applied test parameter range—increasing the surface load reduces both the static and dynamic coefficients of friction, regardless of relative displacement speed difference. Changing the relative displacement speed difference does not have a significant effect on the static coefficient of friction, it can be considered approximately constant in the test range ($\mu_0 = 0.214 \pm 0.1$, p = 5 MPa; $\mu_0 = 0.184 \pm 0.1$ p = 15 MPa). In contrast to the static coefficient of friction, the dynamic coefficient of friction depends on relative speed difference; an increase in speed difference increases the dynamic coefficient of friction in the parameter range examined.

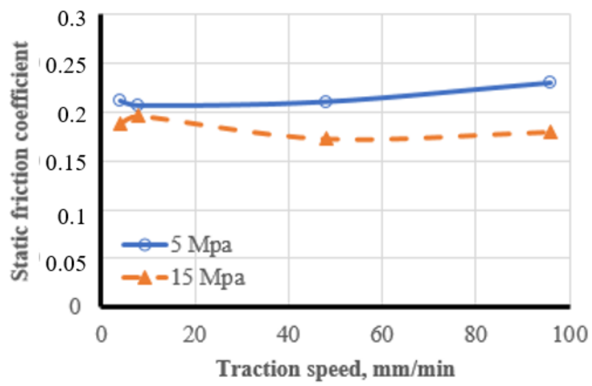

Fig. 2 Static friction coefficients (surface load is 5 MPa and 15 MPa; traction speed is 4–8–48–96 mm/min; frictional material pairs: Al 6082-T6 – polypropylene homopolymer)

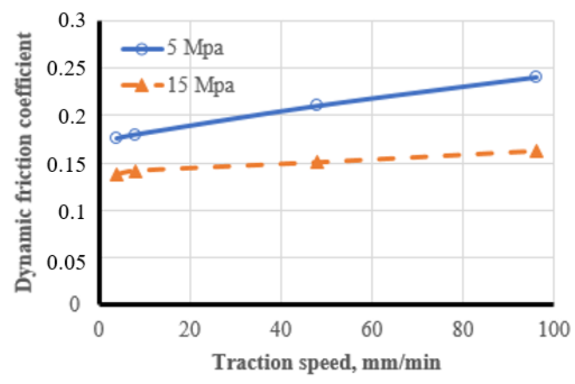

Fig. 3 Dynamic friction coefficients (surface load is 5 MPa and 15 MPa; traction speed is 4–8–48–96 mm/min; frictional material pairs: Al 6082-T6 – polypropylene homopolymer)

In Figure 4 temperature trajectories on the surface of Al specimen are shown at every 10 seconds (surface load = 15 MPa; traction speed = 0,0016 m/s; friction force = 408 N) in a moving window coordinate system with the center of PP sample Ø15 mm and overall length of 200 mm on the Al bar.
It was shown by the modeling, the heat developed by friction caused less than 2 K temperature increment which does not significantly affect the measurement results.

In Figure 5 temperature fields by colors in the sample and in the specimen can be seen after 180 s run-in which means the displacement was 288 mm upwards (surface load = 15 MPa; traction speed = 0,0016 m/s; friction force = 408 N).

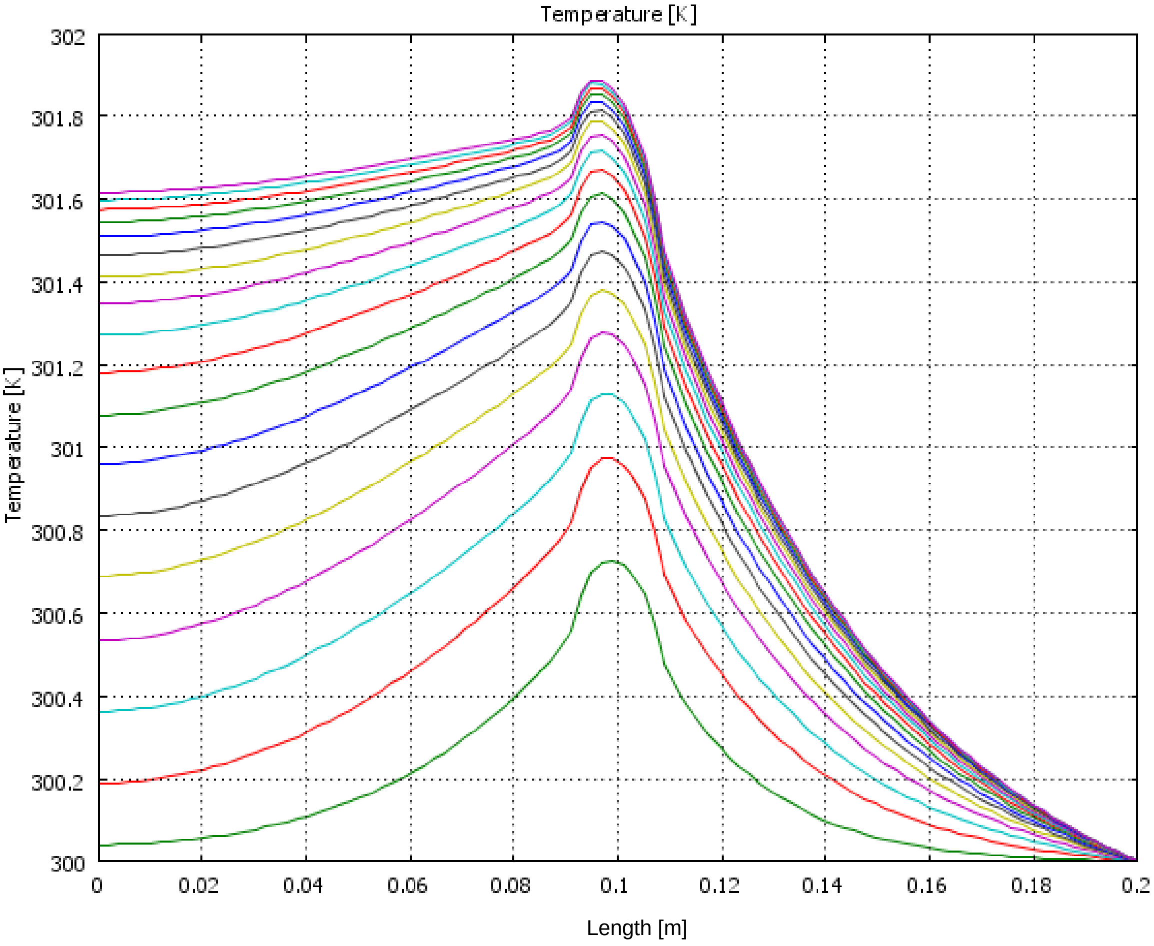

Fig. 4 Temperature trajectories on the surface of Al specimen in every 10 seconds; 0,0016 m/s; 408 N

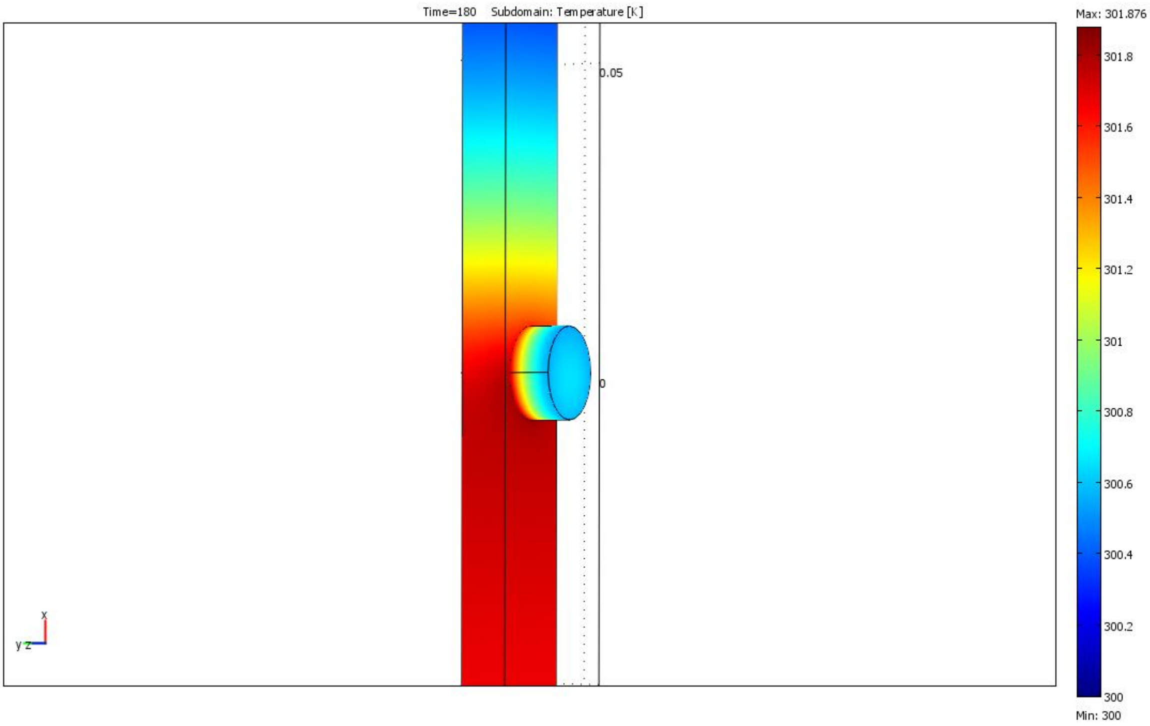

Fig. 5 Temperature fields in the sample and specimen after 180 s; 0,0016 m/s; 408 N

CONCLUSION

In this study, we investigated the friction conditions of a pair of materials often used in engineering practice (aluminum, Al 6082-T6 – polypropylene homopolymer). The static and dynamic coefficients of friction depend on many parameters. We analyzed the friction conditions with two surface loads (5 MPa and 15 MPa) in the range of 4–96 mm/min relative displacement speed difference. The different loads and speeds of motion result in different degrees of heating on the friction surfaces. The magnitude and distribution of the resulting temperature change were modeled to determine how the heat generated during the measurement affects the measured values.

The following conclusions can be drawn from the tests:

- Friction heat modeling showed that over the range of parameter set used in the measurement (surface roughness parameters, environment temperature, surface pressure, velocity, humidity), the temperature change – less than 2 K - develops on the friction surfaces during the measurement does not significantly affect the measurement results;
- Both the static and dynamic coefficients of friction decrease with increasing surface load;
- Dynamic coefficient of friction increases with increasing relative speed;
- Static coefficient of friction can be considered constant in the examined speed range (4 – 96 mm/min; $\mu_0 = 0.214 \pm 0.1$, p = 5 MPa; $\mu_0 = 0.184 \pm 0.1$ p = 15 MPa).

ACKNOWLEDGMENTS

Supported by the ÚNKP-23-3 New National Excellence Program of the Ministry for Culture and Innovation from the source of the national research, Development and Innovation Fund.

This research was funded by the 2020-1.1.2-PIACI-KFI-2020-00129 project. The authors acknowledge the financial support of this work by Hungarian-Japanese bilateral project (2019-2.1.11-TÉT-2020-00204.)

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