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THE FRICTIONAL PROPERTIES OF NYLON

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SUMMARY

The coefficient of friction of nylon is measured with increasing load over a wide range of sliding speeds. It is found that, at a comparatively high speed, the coefficient of friction reaches a maximum of 1.0–2.0. The value of the maximum and the load at which it is reached vary with the sliding speed, the roughness of the surfaces, the ambient temperature and the contacting materials. The variation of the coefficient of friction with temperature is examined at low sliding speeds when little frictional heat is generated and a maximum friction is observed. It is suggested that the dependence of the friction of nylon on the load can be ascribed to temperature effects caused by frictional heating and that the mechanism of this temperature effect of friction above the glass transition temperature is similar to that of rubber.

INTRODUCTION

At lower sliding speeds, it is known that the coefficient of friction of nylon decreases gradually with increasing load[1,2]. At higher sliding speeds the frictional behavior is not so simple and varies with the testing apparatus and conditions. The systematic study of this subject is generally limited. In this paper, the coefficient of friction of nylon was measured at a comparatively high speed range with changing load under conditions such that the temperature of the sliding surface was increased by the consequent frictional heating. It was found that there was a maximum of the coefficient of friction at a certain load. An almost identical behavior has been found in the case of polypropylene[3] and polyacetal[4]. In this paper, the factors which affect this frictional behavior are examined and its mechanism is discussed.

EXPERIMENTAL

The friction was measured between end surfaces of two cylindrical rings, of 20 mm internal diameter, 25.6 mm external diameter and 15 mm height (shown in Fig. 1). The lower specimen could be rotated against the upper specimen and the torque on the upper specimen due to friction was measured by a load cell. The load was applied by a screw through a load cell. The friction between the upper specimen and other parts of the apparatus was minimized by using ball and needle bearings which had been found to have little effect on the measurement. The speed of rotation of the shaft was changed continuously with a stepless revolution regulator over the speed range

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from 0.01 to 200 cm/sec. The temperature near the sliding surfaces was measured with a copper–constantan thermocouple which was inserted into a small hole (0.3 mm diam.) drilled in the upper steel specimen about 0.4 mm beneath the sliding surface. The roughnesses of the sliding surfaces, which were abraded with 60, 150 and 600 mesh emery papers under running water, were $H_{max}=10$, 2 and 0.1 μ on steel and 22.5, 3 and 0.5 μ on nylon respectively.

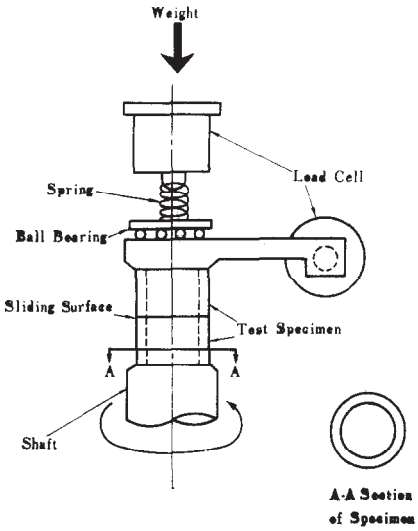


Fig. 1. Schematic arrangement of the friction apparatus.

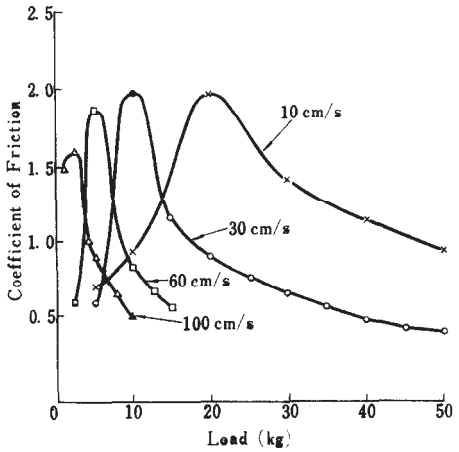


Fig. 2. Load dependence of the coefficient of friction at various sliding speeds (nylon 6–steel).

RESULTS

At a comparatively high sliding speed, it was found that the coefficient of friction of nylon was almost constant for small loads but increased abruptly with increasing load. In order to clarify this behavior, the effect of several factors, *e.g.* sliding speed, ambient temperature, the kind of contacting materials and surface roughness were examined.

Effect of sliding speed on the load dependence of the coefficient of friction of nylon

Friction was measured between nylon and steel specimens which had been abraded with 600 mesh emery paper. The curves in Fig. 2. were obtained at various sliding speeds with a load which was increased by 1–5 kg at intervals of 10 min. This ensured that the frictional temperature of the surfaces reached equilibrium. The coefficient of friction increases to a maximum of 1.6–2.0 at a certain load and then falls as the load increases. The curve is displaced towards the lower load range with increasing speed. Typical data of the frictional force and the surface temperature at a speed of 10 cm/sec are shown in Fig. 3. They both increase sharply at a certain load range and then gradually approach a nearly constant value. Thus S-shaped curves are obtained. The maximum of the coefficient of friction appears at the point A on the S-shaped curve where a straight line passing through the origin contacts the curve. Almost similar

results are also obtained with decreasing load (Fig. 4) or when new samples are used for each load increase, although the location of the maximum is somewhat different. The product of contact pressure and sliding speed at which the maximum occurred is nearly constant suggesting that the cause of this behavior is the rise of temperature due to frictional heating.

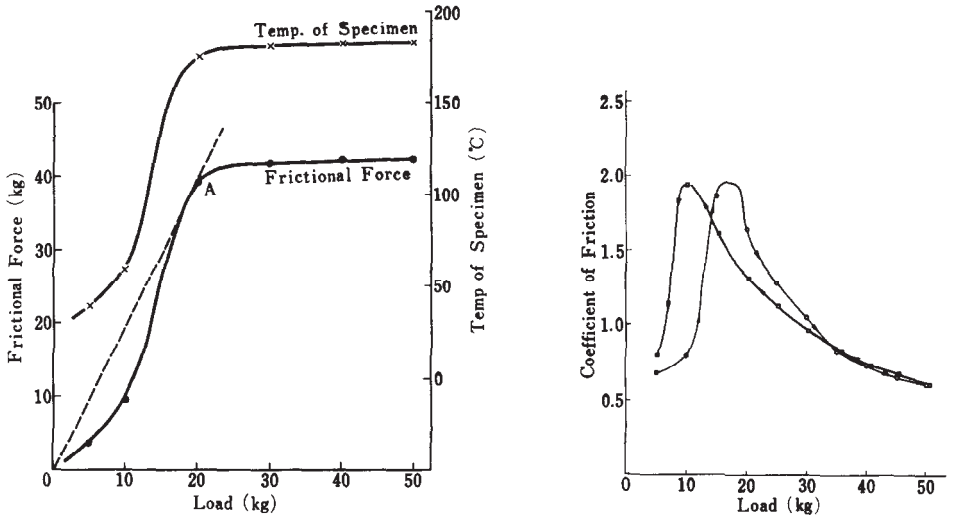


Fig. 3. Frictional force and temperature of specimens as a function of load at a sliding speed of 10 cm/sec.

Fig. 4. The effect of load change process. (Arrows indicate direction of load change.)

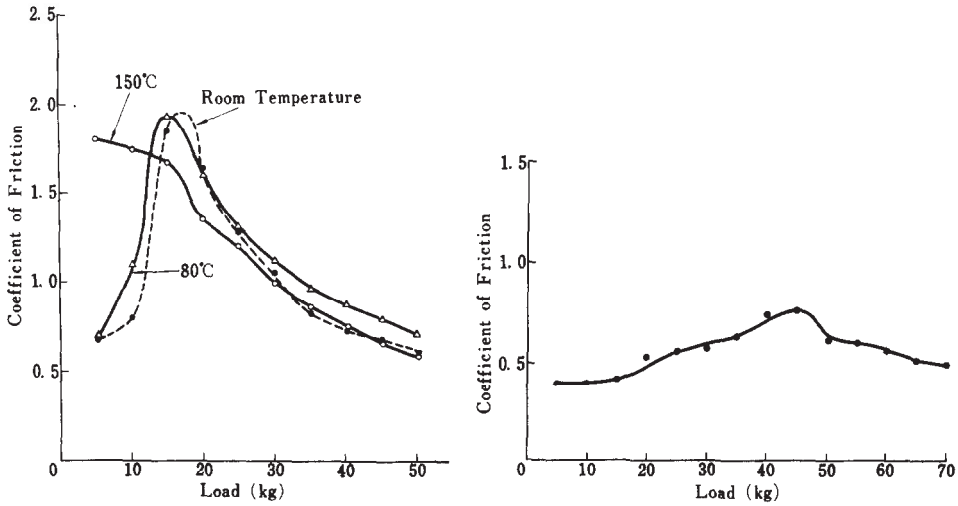


Fig. 5. The effect of ambient temperature on the load dependence of the coefficient of friction. $V =$ 10 cm/sec.

Fig. 6. Friction of nylon 6 on brass. $V =$ 10 cm/sec.

Effect of ambient temperature

Figure 5 shows the effect of ambient temperature on the coefficient of friction *vs.* load curve. Specimens were abraded with 600 mesh emery paper and temperatures around the specimens were kept constant during each experiment. The sliding speed was 10 cm/sec. The curve is displaced towards a lower load range at the higher ambient temperature and, at 150°C, only the simple, decreasing curve is obtained. These facts show that the temperature of the specimen is also a main factor of this behavior.

Effect of the kind of sliding materials

The frictional experiments with nylon 6 were carried out on brass, Teflon and nylon 6 itself (Figs. 6 and 7), all the specimen surfaces being abraded with 600 mesh emery paper. The maximum is displaced towards a higher load on brass and a lower load on nylon 6 itself than on steel. This shift may be due to the difference in heat conductivity of the materials.

No maximum occurs on Teflon because the frictional behavior of the Teflon may, perhaps, predominate over that of nylon.

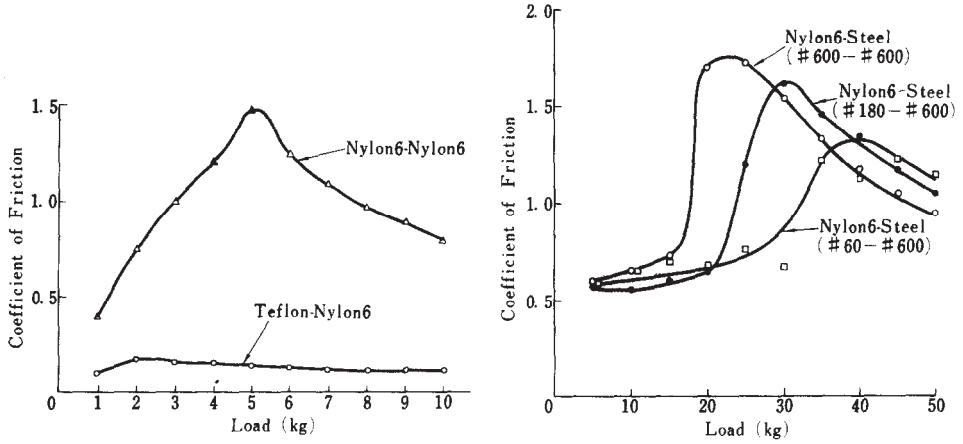


Fig. 7 Friction of nylon 6 on Teflon and nylon 6 itself. $V = 5$ cm/sec.

Fig. 8. The effect of the surface roughness of nylon 6 on the load dependence of the coefficient of friction. $V = 10$ cm/sec.

Effect of surface roughness

Friction was measured at a speed of 10 cm/sec between a smooth steel surface and nylon 6 surfaces which had been abraded with emery papers of various grades. Figure 8 shows the effect of surface roughness on the behavior mentioned above the numbers indicating the mesh sizes of the emery papers used. Similar curves were obtained with varying roughness of steel surfaces on smooth nylon surfaces (Fig. 9). In both cases, the maximum becomes lower and shifts to the higher load range with increasing surface roughness.

The relation between the coefficient of friction and temperature

The experimental results described above suggest that this behavior is due to frictional heating. In order to examine the relation between the coefficient of friction

and temperature of the specimen, the experiment was carried out with increasing specimen temperature in an electric furnace under a constant load of 20 kg and at such a low sliding speed (1 cm/sec) that frictional heating was small. Results are shown in Fig. 10. The maximum obviously occurred at 130–150°C and became lower with increasing surface roughness though its location did not change. Similar results have been obtained by ARAI[5].

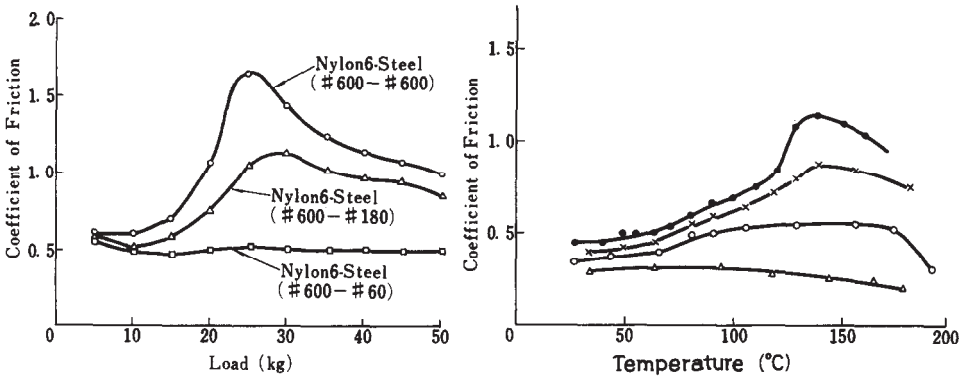


Fig. 9. The effect of the surface roughness of steel on the load dependence of the coefficient of friction. V = 10/cm.

Fig. 10. The variation of the coefficient of friction with the temperature of the specimens. Load = 20 kg, V = 1 cm/sec. ● Nylon 6 (#600): steel (#600); × Nylon 6 (#600): steel (#400); ○ Nylon 6 (#600): (#150); △ Nylon 6 (#600): steel (#60).

DISCUSSION

In the case of rubber GROSCH[6] and BARTENEV[7] have shown that the coefficient of friction reaches a maximum at a certain temperature. It is known that the maximum shifts towards a higher temperature range with increasing sliding speed as does the visco-elastic function as for the dynamic loss characteristics of polymers. The reason for the maximum has been discussed by BARTENEV[7], SCHALLAMACH[8], LUDEMA AND TABOR[9] and SAVKOOR[10]. In the case of nylon, MACLAREN AND TABOR[11] have also shown that the coefficient of friction changes with speed and temperature in a visco-elastic manner even below the glass transition temperature of nylon (approximately 45°C[12]). Though nylon is a crystalline polymer, the amorphous part is larger than the crystalline part (crystallinities of most moldings of nylon are 25–40%[13]). Therefore, the rubber-like behavior of the amorphous areas may play a more important role on friction above the glass transition temperature of nylon. The maximum of the temperature-dependence curve in Fig. 10 was also shown to shift with speed in almost the same way as rubber, and the magnitude of the maximum is of a similar order to that of rubber. Therefore, the cause of this frictional behavior of nylon may be the same as that of rubber.

Figure 11 shows the load dependence of the frictional force at a low sliding speed of 1 cm/sec. The temperatures of the specimens indicated in Fig. 11 were kept constant in the electric furnace during the experiment. Similar data have been obtained with polyvinylchloride[14]. The slope of the curves increases with increasing temperature and then decreases. If this behavior is almost the same at higher speeds, it is very

likely that the frictional force will go through an S-shaped process shown in Fig. 11 due to frictional heating with increasing load. The estimated curve in Fig. 11 is similar to the curve in Fig. 3.

The values of the frictional force in Fig. 3, as described above, were gained after a time interval of 10 min under a constant load. The variations of frictional force with this time interval are shown in Fig. 12. Friction increases with time in the load range where the coefficient of friction increases with increasing load (Fig. 12(a)), but it

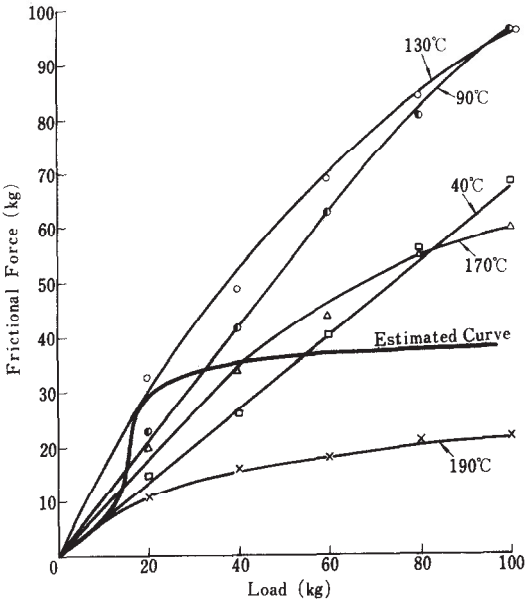


Fig. 11. The effect of the temperature of the specimens on the load dependence of frictional force. $V = 1$ cm/sec.

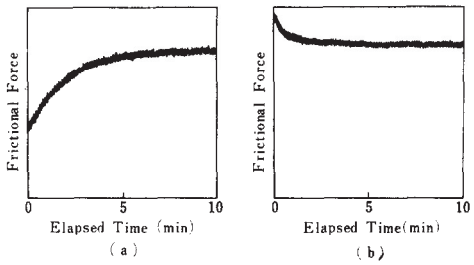


Fig. 12. Frictional force as a function of elapsed time.

decreases in the load range where the coefficient of friction decreases with increasing load (Fig. 12(b)). If the temperature of the specimens increases with time due to frictional heating, the frictional force may increase with time in the former range, as seen in Fig. 11, and it may decrease with time in the latter range. This behavior may be one result of the S-shaped process in Fig. 11.

If the load is increased at a higher sliding speed, it is well known that the surfaces of polymers like nylon melt at a certain load because of frictional heating[15–18].

It is very likely, therefore, that the sliding surfaces of polymers melt locally before complete melting and the friction decreases[3]. But, as considered previously, the rubber-like behavior of the amorphous areas may override other factors.

Another reason for the frictional force approaching a constant value may be that the area of real contact approaches a limiting area of contact which is determined by the geometry of surfaces with increasing load[14,19]. This behavior may be included in the range of comparatively low speeds and high loads. But at a high speed, of the order of 100 cm/sec, the load at which frictional force approaches a constant value is only a few kilograms. It is difficult, therefore, to consider that the area of real contact approaches a limiting area at such a low load as a few kilograms as seen in Fig. 11.

LINCOLN[20] AND SCHALLAMACH[21] have shown that, in the case of elastic materials like rubber, the area of real contact becomes smaller on rough surfaces than on smooth surfaces even under the same load. Therefore, if the friction is mainly due to adhesion under unlubricated conditions, the coefficient of friction is higher on the smooth surface. But, in the case of lubricated rubber, as DENNY[22] has shown, the coefficient of friction is higher on the rough surface because a deformation term is predominant to the adhesion term on the lubricated rubber. In this experiment, since measurements were carried out under unlubricated conditions, it is considered that the friction is mainly due to adhesion and is higher on the smooth surface. On the rough surface, therefore, higher loads may be necessary to obtain the same frictional force as on the smooth surfaces. This may be one of the reasons why the maximum shifts to the higher the load and becomes smaller on rough surfaces.

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