TRIBOLOGICAL PROPERTIES OF POLYURETHANES IN ABRASIVE SOIL MASS

WŁAŚCIWOŚCI TRIBOLOGICZNE TWORZYW POLIURETANOWYCH W GLEBOWEJ MASIE ŚCIERNEJ

Key words: abrasive wear, polyurethanes, abrasive soil mass, friction surface.

Abstract
This paper presents a comparative study of polyurethane wear in abrasive soil mass. Two types of polyurethanes of various chemical compositions and untreated 38GSA steel were tested, the latter being used as a reference standard. The study was conducted in a natural soil mass at a “rotating bowl” stand. Relative wear resistance was determined from measurements of mass wear for the materials under study. The conditions of the surface of the materials under wear tests were analysed.

Słowa kluczowe: zużycie ścierne, poliuretany, glebowa masa ścierna, powierzchnia tarcia.

Streszczenie
W pracy przedstawiono badania porównawcze zużywania poliuretanów w glebowej masie ścierniej. Badaniom poddano dwa rodzaje poliuretanów o różnym składzie chemicznym oraz stal 38GSA w stanie nieobrobionym, która była materiałem wzorcowym. Badania prowadzono w naturalnej masie glebowej na stanowisku typu „wirująca misa”. Na podstawie pomiarów zużycia wagowego dla badanych materiałów wyznaczono względną odporność na zużycie. Przeprowadzono analizę stanu powierzchni zużywanych materiałów.

INTRODUCTION

The development of chemical engineering in regard to the production and processing of plastics has resulted in an increase in the use of such materials in machine parts and working elements as well as in tribological nodes of machines where they have been replacing traditional materials. An increase in the use of polymers necessitates studies of tribological properties of such materials in various conditions. According to numerous authors, some plastics can be more resistant to abrasion than steel under certain conditions [L. 1]. Abrasive wear of plastics is an issue that has been well-examined in dry conditions [L. 2–6] and in water [L. 7]. A methodology mimicking “three-body abrasion” type abrasive wear was applied in these studies. Experiments in which the wear of selected polymers with loose abrasive grains (two-body abrasion) were examined and are presented in [L. 8]. Studies of the abrasive wear of plastics have been supplemented by experiments conducted in an abrasive suspension [L. 9].

Material wear by an abrasive soil mass is closely related to its granulometric composition and compactness of the mass. The use of elements which cut through soil mass is accompanied by intensive abrasive wear. It is caused by loose abrasive particles hitting against a material surface, which results in its fatigue and de-cohesion, whereas material defects typical of abrasive wear occur when compact abrasive mass is used [L. 10–12].

Polyurethane is a plastic material exhibiting high resistance to abrasive wear. Its wear resistance was the greatest of all the plastics under study both in an abrasive suspension [L. 9] and when the wear resulted from use of loose abrasive grains [L. 8]. According to the study results published in [L. 6], the wear resistance of polyurethane is six times higher than steel 45, and its wear resistance increases with its hardness. For this reason, polyurethanes are currently widely used in working parts used in an abrasive environment, e.g., plough blades, scrapers, linings of chutes, mixers, and concrete mixers.

The aim of this study was to assess the tribological properties of polyurethanes in natural abrasive soil masses.
EXPERIMENTAL MATERIAL

Polyurethanes consist of two basic components: polyol and isocyanate. When these components are combined, auxiliary materials are added, such as catalysts, stabilisers, and pore-forming agents. By changing the ingredients and proportions of the mixture, one can obtain materials of various properties, which can be adapted to special requirements [L. 13, 14].

Comparative studies of wear resistance in abrasive soil masses were conducted with two types of polyurethane. The materials under study differed by the polyol used in the production process and the percentage of other various ingredients (Table 1).

### Table 1. Chemical composition of the polyurethanes under study

<table>
<thead>
<tr>
<th>No.</th>
<th>Polyol type A [%]</th>
<th>Polyol type B [%]</th>
<th>Diphenylmethane 4,4-disocyanate (MDI) [%]</th>
<th>1,4-butandiol [%]</th>
<th>Triethylenediamine [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUR 1</td>
<td>61.3</td>
<td>0</td>
<td>30.5</td>
<td>8.1</td>
<td>0.1</td>
</tr>
<tr>
<td>PUR 2</td>
<td>30.7</td>
<td>30.6</td>
<td>30.5</td>
<td>8.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

A polyester polyol type A is obtained from adipic acid, monoethylene glycol and 1,4-butandiol, while a polyester polyol type B is obtained from adipic acid and monoethylene glycol. 38GSA steel used in parts working in soil was taken as a reference material.

The chemical composition of the steel was as follows: C – 0.38%, Mn – 0.97%, Si – 0.90%, P – 0.011%, Cr – 0.05%, Cu – 0.25%, Al – 0.02%, and Mo – 0.02%. 38GSA steel has the microstructure of fine dispersed perlite with grains of ferrite (Fig. 1).

![Fig. 1. Microstructure of 38GSA steel. Etched with 3% HNO3 (Mi1Fe), optical microscopy](image)

Rys. 1. Mikrostruktura stali 38GSA. Trawiono 3% HNO3 (Mi1Fe), mikroskopia świetlna

EXPERIMENT METHODOLOGY

The wear intensity was examined in a laboratory by the “rotating bowl” method [L. 2] (Fig. 2). Cuboidal 30 x 25 x 10 mm samples were tested. The machine bowl was filled with a natural abrasive soil mass equivalent to dry soil with the granulometric composition as per PN-EN ISO 14668-2(2004):

- Light soil: silt: 1.69%; clay: 20.83%; sand: 77.48%,
- Heavy soil: silt: 16.5%; clay: 49.92%; sand: 33.62%.

The following friction parameters were taken for the experiment: velocity 1.66 m/s, friction distance 20,000 m, unit pressure 67 kPa. The test stand was equipped with elements to mix and compact the abrasive mass. Mass wear was measured after 20,000 m with a Radwag AS160.R2 laboratory balance.

Test runs were repeated six times for each tested material.

The wear resistance of the test materials were compared by comparing the wear resistance index $K_b$ calculated along the entire friction distance from the following formula [L. 5, 6]:

$$K_b = \frac{Z_{Vb}}{Z_{Vw}} = \frac{Z_{Vb} \cdot \rho_w \cdot S_{Tw}}{Z_{Vw} \cdot \rho_w \cdot S_{Tw}},$$  \hspace{1cm} (1)

where

- $Z_{Vw}$ – volume wear of the standard material;
- $Z_{Vb}$ – volume wear of the tested material;
- $S_{Tw}$ – friction distance of the standard material;
Due to the wide range of polyurethane densities reported in the literature [L. 14] (1.1 – 1.28 g/cm³), the density of the tested materials was determined in the laboratory from the weight and volume of the samples. The hardness of polyurethanes was determined with a durometer as per the DIN53505 standard. The hardness of 38GSA steel was measured with a Vickers hardness tester, type HV 10D, as per PN-EN ISO 6507-1:1999. The indenting tool was loaded with a weight of 98 N, loading time = 10 s. The wear surface was assessed after the friction distance was completed with a JEOL JSM 5310LV scanning electron microscope in a digital arrangement.

**ANALYSIS OF THE RESULTS**

The results of abrasive wear tests and the results of hardness tests are shown in Table 2.

Table 2. Selected properties of 38GSA and polyurethane plastics  

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [g/cm³]</th>
<th>Hardness</th>
<th>Average mass wear after 20 km in abrasive soil mass [g]</th>
<th>Light</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUR1</td>
<td>1.16</td>
<td>93 'ShA</td>
<td>0.101 1.831</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PUR2</td>
<td>1.2</td>
<td>91 'ShA</td>
<td>0.042 2.865</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38GSA</td>
<td>7.87</td>
<td>414 HV₁₀₀</td>
<td>2.36 3.709</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Despite diverse chemical compositions, small differences were observed in the hardness and density of the polyurethanes under study. An analysis of mass wear has shown that the intensity of wear in a heavy soil mass is 18 times greater for the PUR1 polymer than in a light soil mass. The intensity of wear in a heavy soil mass is 68 times greater for the PUR2 polymer.

Table 3 presents the mean abrasive wear resistance indexes for the materials under study in the abrasive masses under study. The limits of the confidence intervals were determined from Student’s t-distribution at the confidence interval of α = 0.05. A graphic illustration of wear resistance indexes is shown in Fig. 3.

The abrasive wear resistance index has shown that the wear intensity for the polyurethane plastics under study in the light soil mass is lower than that of 38GSA steel. PUR2 polyurethane had the highest abrasive wear resistance (8.6 times higher than steel) in these conditions. The material marked as PUR1 proved to be much less resistant to abrasive wear in the light abrasive mass; however, its resistance was still 3.5 times greater than that of the reference material.

Polyurethane materials were less resistant to wear in the heavy soil mass than 38 GSA steel. The abrasive wear resistance index for PUR2 polyurethane was ca. 15% of its value for steel in the heavy abrasive mass. The abrasive wear resistance index for PUR2 polyurethane reached 31% of its value for steel in the heavy abrasive mass. Such great differences in the resistance index in various abrasive masses may be attributed to the methods of use. To this end, sample surfaces were observed under a microscope.

**Fig. 3. Abrasive wear resistance index of materials under study in various abrasive masses**

Rys. 3. Wskaźnik odporności na zużycie ścierne badanych materiałów w różnych masach ściernych

![Fig. 3. Abrasive wear resistance index of materials under study in various abrasive masses](image-url)
grains with many degrees of freedom, which affect the surface by sliding against it, rolling, and impacting. Cyclic contact stress in surface layers of friction elements that work together causes material fatigue and consequent local loss of cohesion and pitting. Fatigue wear manifests itself by surface cracking followed by chipping off fragments of material. Fig. 5a shows visible cracks on the material surface. These cracks can propagate inwards, causing volume fatigue (Fig. 5b). This process is intensified in the harder materials (PUR1).

No cracks reaching inwards were observed on the surface of PUR2; whereas, surface fatigue in the form local pitting is more visible (Fig. 6).

The effect of loose abrasive grains results in the accumulation of stress in the surface layer of the polyurethanes under study. It results in fatigue cracking and chipping off of pieces of the surface. In fatigue wear, pitting does not occur until the limit number of cycles and the fatigue limit is exceeded for individual micro-areas of the material. The abrasive wear resistance index for the polyurethanes was much higher in these conditions (360% to 900%) than for the steel.

![Fig. 4. Micrograph of a polyurethane sample surface worn in a light abrasive soil mass (SEM microscope): a) PUR1, b) PUR2](image)

Rys. 4. Mikrofotografia powierzchni próbek poliuretanowych zużywanych w lekkiej glebowej masie ściernej (mikroskopia SEM): a) PUR1, b) PUR2

![Fig. 5. Surface of PUR1 polyurethane worn in the light abrasive soil mass: a) fragment of surface chipped off as a result of cracking, b) surface crack propagating inwards](image)

Rys. 5. Powierzchnia poliuretanu PUR 1 zużywana w lekkiej glebowej masie ściernej: a) odrywanie fragmentu powierzchni w wyniku pęknięcia, b) pęknięcie powierzchni propagujące w głębokę materiał

![Fig. 6. Surface of PUR2 polyurethane worn in light abrasive soil mass](image)

Rys. 6. Powierzchnia poliuretanu PUR 2 zużywana w lekkiej glebowej masie ściernej

A softer material (PUR2) is more susceptible to elastic strain, which resulted in its higher resistance to abrasive wear in the light abrasive mass than PUR1 polyurethane.
The abrasive effect of a heavy abrasive mass with a large portion of silts and clay (ca. 77% in abrasive mass) is different. Combined with moisture, silt forms a sticky substance that binds together both small (clay) and larger (sand or gravel) abrasive particles, thus limiting their degrees of freedom. Abrasive grains bound together make a rough surface in contact with a sample surface. Processes of wear by bound abrasive grains take place. A sample surface worn by an effect of heavy abrasive surface is shown in Fig. 7.

When a material is worn in this type of environment, a higher material hardness favours abrasive resistance. Scratches and grooves cut out and pressed out by abrasive grains were detected on the surface of samples made of PUR1 (Fig. 7c). Numerous traces of deformation (pushing away) of the surface layer, which manifests itself as “waves” on the surface, were observed in PUR2 polyurethane (Figs. 7b and 7d). This process is accompanied by chipping off the crests of the “waves,” which results in greater material loss compared to a harder material removed by scratching (Figs. 7a and 7e). Such a folded wear surface (Fig. 7b) is typical of resilient plastics which work against a rough surface of an antibody [L. 15]. In this case, the heavy abrasive mass was the rough antibody. The polyurethane materials were less resistant to abrasive wear than the steel in these conditions. Their resistance reached 15-31% of the steel resistance to abrasive wear.

CONCLUSIONS

1. Tribological properties of polyurethanes under abrasive wear in abrasive soil masses vary and depend on the type of abrasive mass.
2. A light abrasive soil mass brings about wear with loose abrasive grains, which generally cause fatigue of the material surface. Due to resilience of polyurethanes, the effect of abrasive particles causes mostly elastic strain deformations and plastic strain, which manifests itself as scratches on the surface only to a small extent. Effects of loose abrasive grains on the surface of polymer materials cause surface and volume fatigue wear.
3. Wear with bound abrasive grains takes place in heavy abrasive masses. An increase in the hardness of polymer materials resulted in better wear resistance in this abrasive mass. The heavy abrasive mass caused plastic deformations in soft polyurethanes in the form of characteristic waves.

![Fig. 7. A micrograph of the surface of samples worn in heavy abrasive mass: a) and c) PUR1 polyurethane, b) and d) PUR2 polyurethane](image)
REFERENCES