Experimental research of the mechanical properties of the round drive belts made of thermoplastic elastomer

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Abstract. A lot of the industrial machines use belt transmission for power transfer. These mechanisms often use the round belts several millimetres in diameter, which are made of the thermoplastic elastomers, usually polyurethane. The mandatory step in their production process is bonding of belt ends, which is often performed by the butt welding, using the hot plate. In general, this operation comprises two main mechanical interactions between belts and the automatic welding equipment. The first one is a compression, performed by shaped grippers during heating and joining step. Compression proceeds both along the axis of the belt and in the radial direction. The second of them is shearing, performed by cutting edges, during belt preparation and flash removing step. Shearing is present both in a plane which is tangential to the belt outer surface and also in a plane which is perpendicular to the axis of the belt. To correctly develop the model of the whole welding process, both the proportionality modulus and the shear modulus are required. The paper demonstrates the procedure of the experimental determination of these parameters, with some assumptions which are valid for the hot plate welding process. There were presented the results of the compression test in the axial and radial directions, and results of the shearing test. Finally, the values of proportionality and shear modulus as a function of test parameters are presented.

1. Introduction

Drive belts, both employed in conveyors and drive systems, are commonly used in machine building. Transportation technology utilizes drive belts with full cross section as well as perforated strands in vacuum transportation of light objects [1–4]. Whereas in the category of drive belts, the most commonly used are: flat belts, toothed belts and shaped belts (e.g. V-shaped or round). Toothed belts are employed both in simple transmission units as well as in non-classical solutions, e.g. with variable ratios [5–9]. Shaped belts, in particular the round and V-shaped, are commonly used in drive system technology and are most commonly made of rubber [10, 11] or elastomers based on polyester or polyurethane [12, 13]. Their common usage in industrial machinery calls for an efficient manufacturing process which is usually carried out in two stages [14]. First, a long belt strand is manufactured, subsequently it is cut down to desired length; finally, its ends are permanently joined together to form an endless belt. In most examples, closing the circuit of belts made of thermoplastic elastomer is achieved by hot plate butt welding. The process is relatively inexpensive and utilizes simple technological solutions [15].

The butt welding of polymers is commonly practiced in the automotive industry and civil engineering, e.g. in the process of joining: tanks for utility fluids, lamp enclosures, engine instrumentation [15, 16] and pipes [17, 18]. Studies were performed for the hot welding of different
polymer materials, including: acrylonitrile butadiene styrene copolymer (ABS) [19], poly(methyl methacrylate) (PMMA) [20], polycarbon (PC) [21], as well as polypropylene (PP) [22].

The authors began design works on a device for automated butt-welding of drive belts utilizing the to improve manufacturing efficiency [13]. In order to verify the construction design assumptions, the examination of the process began together with the study to identify the influence of hot-welding parameters on the quality of joint [23, 24]. It was assumed that the item to hot weld will be a polyurethane TPU C85A belt, commonly offered by drive belt manufacturers [25].

The hot plate butt-welding process, in general terms, can be divided into 5 stages, which include axial pressing of the belt end towards the hot plate as well as the belt ends towards one another [23, 26, 27]. Additionally, the examined technological process calls for preparing the strand for secondary processing after the welding process is finished. These activities include, among others, cutting the belt down to required length as well as shaving the flash from the bond. Therefore, there are three types of mechanical stress which the belt material is subject to during the bonding process:

- knife shearing of the belt when its correct length is determined,
- axial compression of the belt under elevated temperature conditions,
- shearing of belt material during removal of the flash.

It is difficult to find accurate information regarding this method of joining flexible polyurethane materials in available literature, these materials are considered as part of the hyper-flexible group, with additional possibility of plasticization under elevated temperature conditions. Moreover, the range of known material constants for the examined plastic materials is very large [28]. In addition, the belt’s material, similar like other non-classical materials i.e.: natural shredded materials [29, 30] or glue [31] can have some mechanical properties, which cannot be predicted during classical models analyzing. Consequently, the examination of the mechanical properties of the belt material was carried out, in particular the values during: stretching, compression and shearing were tested.

2. Study methodology
The testing was carried out on a MTS Insight 50 kN durometer, equipped with instrumentation adapted to the methodology of the current examination. For each testing case, the force on the movable durometer jaw and its displacement were registered. Additionally, actual dimensions of prepared samples were taken. The repeatability of obtained results was considered to be satisfactory, therefore the number of repetitions for each type of examination and sample was limited to three.

In the order of priority, examination of sample characteristics during stretching was performed for the following types of samples:

- dumbbell-shaped, type 1B as per PN-EN ISO 527-2, die cutout from a flat conveyor belt with full cross-section and nominal thickness of \( t = 4 \text{ mm} \) and width at narrow point equal to \( b = 10 \text{ mm} \). The samples were cutout along the longer, reference belt edge,
- cylindrical shaped with nominal diameter \( d = 4 \text{ mm} \), cut from a drive belt with circular cross-section with the same diameter,
- cylindrical shaped with nominal diameter \( d = 12 \text{ mm} \), cut from a drive belt with circular cross-section with the same diameter.

Basic parameters of the stretching examination are provided below in table 1.

Sample surfaces were not subject to any mechanical processing apart from cutting to size. The manufacturer of the drive and conveyor belts declares that the manufacturing material for the three belt types from which the samples were taken has an identical chemical composition. However, one needs to take into account the difference in manufacturing technology for round and flat belts which may affect the actual mechanical properties of the final product.

In all cases, the distance between the durometer jaws was 108 mm and was used as the basis for calculating relative elongation. The samples were stretched up to elongation \( \varepsilon_r = 300\% \). The testing station together with an example dumbbell-shaped sample are provided in figure 1.
Table 1. Testing parameters of belt stretching.

| Parameter                                | Designation | Value  |
|------------------------------------------|-------------|--------|
| Dimensions of the narrow lateral cross-section of the dumbbell shaped sample | $b$ (mm) $\times$ $t$ (mm) | 10 $\times$ 4 |
| Circular sample diameter                 | $d$ (mm)    | 4, 18  |
| Testing velocity                         | $v_r$ (mm min$^{-1}$) | 60     |
| Total sample length                      | $l_t$ (mm)  | 150    |
| Distance between the durometer jaws      | $l$ (mm)    | 108    |
| Limit elongation                         | $\varepsilon$ (%) | 300    |

Figure 1. Testing station during the elongation testing of the dumbbell sample together with a sample taken from a flat belt: 1 – movable jaw of the MTS durometer, 2 – immovable jaw of the MTS durometer, 3 – dumbbell shaped sample.

During the subsequent stage of the examination, the following compression tests were performed on the belt material:

- axial and radial compression of the circular sample with diameter $d = 4$ mm and height $h = 6 \pm 0.2$ mm, cut from drive belt with circular cross-section and identical diameter,
- axial and radial compression of the circular sample with diameter $d = 18$ mm and height $h = 27 \pm 0.2$ mm, cut from drive belt with circular cross-section and identical diameter,
- compression in the normal direction of the belt surface of a sample taken from a flat belt with thickness $t = 4$ mm, in form of a cylinder with diameter $d = 10 \pm 0.2$ mm, die cut from a flat conveyor belt with the same diameter.

Quasi-static compression was performed with velocity of $v_c = 1$ mm min$^{-1}$, until strain $\varepsilon_c = 30\%$ was achieved. In the case of cylindrical samples taken from belts with circular cross-section, the faces after cutting were polished so that the deviation from the right angle between the belt axis and the face was lower than 0.1 mm. The length of the samples cut from the round belt complies with the below formula:

$$h = 1.5 \cdot d,$$

therefore the distribution of compressive stress along the transverse cross-section of the belt is approximately even, but also limits the possibility of buckling [32]. Additionally, the sample faces in contact with the clamping discs were lubricated in order to limit the influence of friction on load distribution in the sample. The lower support of the samples during compression was self-aligning, which limited the influence of any possible deviation from the right angle of the face and sample axis on the measured results.
Under the same conditions, radial compression of samples taken from the belt with circular cross-section and axial compression of samples cut from the flat belt was performed. In the course of the examination, two types of clamping discs were used, depending on sample size. The testing station during compression of samples is provided at figure 2.

![Testing station during belt compression](image1.png)

**Figure 2.** Testing station during belt compression; a – radial compression of sample with diameter \( d = 4 \) mm, b – radial compression of sample with diameter \( d = 18 \) mm, c – axial compression of sample with diameter \( d = 10 \) mm taken from a flat belt, d – radial compression of a sample with diameter \( d = 18 \) mm; 1 – clamping disc for small samples, 2 – self-aligning support plate, 3 – clamping disc for samples with higher diameter, 4 – sample.

![Belt shearing testing station](image2.png)

**Figure 3.** Belt shearing testing station: 1 – moving blade, 2 – supports, 3 – sample, 4 – counter blade.

During the subsequent stage of examination, shearing tests were carried out for samples:
- circular with diameter \( d = 4 \) mm, taken from a drive belt with circular cross-section,
- rectangular with width \( b = 10 \) mm and thickness \( t = 4 \) mm, die cut from a flat conveyor belt.

The examination was carried out on the testing station for shearing (figure 3).
Quasi-static shearing was carried out with moving blade velocity \( v_t = 1 \text{ mm s}^{-1} \) and dynamic shearing with velocity \( v_t = 8 \text{ mm s}^{-1} \). The sample was placed between two supports (2 and 3) and rested on the counter blade (4). In order to minimize the influence of bending on the results of the shearing, the gap between the moving blade (1) and counter blade (4) was set to 0.05 mm. Additionally, both supports (2 and 3) were fitted with clamps to immobilize the sample.

3. Result analysis

Elongation curves (stress - relative strain) for the three types of examined samples are provided on Figure 4. The characteristics vary, in particular when both cylindrical samples are compared. However, an important shared characteristic is that the belt could not be broken in the course of the experiment. Furthermore, it was observed that the sample stretches uniformly along its entire length. Another shared feature in all the obtained characteristics is the prominent non-linearity, with two points of inflexion of the elongation curve. It is therefore evident that the material cannot be modeled with a classical characteristic of a flexible-plastic material. This is a characteristic feature of thermoplastic elastomers under load in room temperature conditions. An analysis of the obtained characteristic proves that the material calls for utilizing a more complex model for hyper-flexible materials, e.g. Neo-Hookean, Mooney-Rivlin or Ogden’s model.

It is interesting that the obtained characteristics during stretching differ depending on the geometric form of the examined sample, which does not occur for classic metal materials. However, in this case, the established elongation characteristic is influenced by the manufacturing technology of the belt from which the sample was taken, which is different for round and flat belt cross-sections. Additionally, taking into account the difference between elongation curves for cylindrical samples with different diameters, it is probably that the cooling speed for the belt semi-product during its manufacturing affects the segregation of polymer chains and their bonding.

![Figure 4](image_url)

**Figure 4.** Averaged elongation characteristics of the examined polyurethane samples.

Additionally, consider the value scale for the resulting stress together with the employed examination methodology. For relatively low force values (causing stress lower than 10 MPa) the accuracy of, e.g.: force measurement system of the durometer, sample length and diameter, has a significant influence on
the obtained results in comparison to the examination of characteristics of metals, where the results are higher by at least an order of magnitude.

Based on the determined elongation characteristics, the longitudinal elasticity modulus for the material was established. Taking into account the initial stretching range for $\varepsilon_r < 2\%$, which is approximately linear. In this case, the elasticity modulus is equal to the value to the proportionality coefficient of the line formula describing this section. It was assumed that the matching of the graph line to the examined value range, described with the correlation coefficient $R^2$, should be at least 0.98. Therefore, the calculated values of the elasticity modulus are equal to (table 2).

Table 2. The value of longitudinal elasticity modulus during stretching.

| Sample                                      | Designation     | Value  |
|---------------------------------------------|-----------------|--------|
| Circular, diameter $d = 4$ mm               | $E_{rr4}$ (MPa) | 25.839 |
| Circular, diameter $d = 12$ mm              | $E_{rr12}$ (MPa)| 37.207 |
| **Average value for circular samples**      | $E_{rAVG1}$ (MPa)| **31.523** |
| Dumbbell shaped with rectangular cross-section and dimensions $4$ mm $\times$ $10$ mm | $E_{rr}$ (MPa)  | 36.510 |
| Total average value                         | $E_{rAVG2}$ (MPa)| 33.185 |

The average value for all samples and average value for circular samples was determined. At this stage of research works, such samples are sufficient as an informational reference point to determine the mechanical characteristics during stretching of belts made of this material.

Compression testing results in form of characteristics of compression stress–strain relation, for the three types of examined samples is provided in figures 5–7.

![Figure 5](image-url)

**Figure 5.** Averaged compression characteristics of the examined circular samples with diameter $d = 4$ mm for axial and radial compression.

Based on the averaged compression graph line for circular samples with diameter $d = 4$ mm (figure 5), it is possible to determine that in the examined strain range $\varepsilon_r < 30\%$ the characteristic for this material is close to linear, both in axial and radial direction.
Figure 6. Averaged characteristics of compression for selected circular samples with diameter \(d = 18\) mm, for axial and radial compression.

In the case of circular samples with diameter \(d = 18\) mm (figure 6), the characteristic for compression stress - strain relationship is less linear in comparison to the sample with lower diameter (figure 5), it is similar to the sample taken from a flat belt (figure 7).

Figure 7. The averaged compression curve in the normal direction for the surface of the circular sample, diameter \(d = 10\) mm taken from a flat belt with thickness \(t = 4\) mm.

What draws our attention is the phenomenon of the different graph line for the compression characteristics for different directions: radial and axial, in the case of circular samples. This suggests that the mechanical characteristics of this material are not isotropic. It is the authors’ opinion that this phenomenon is attributable to different methods of manufacturing for these types of finished belt product. The temperature gradient during the manufacturing of the extruded circular belt may cause...
a directional segregation in the macromolecule chains and the bonds between them. In the macroscopic scale, this causes an anisotropy in the mechanical characteristics of this product.

The longitudinal elasticity modulus during compression was established. The linear range for the compression characteristic was accounted for, at \( \varepsilon_c < 5\% \). It was assumed that the elasticity modulus is described with a directional coefficient to approximate this range, and its matching described by the correlation coefficient value \( R^2 \), should be at least 0.98. The determined values of the modulus are presented in Table 3.

### Table 3. Longitudinal elasticity modulus values during compression.

| Sample                              | Axial modulus | Radial modulus |
|-------------------------------------|---------------|----------------|
|                                     | Designation   | Value          | Designation   | Value          |
| Circular, diameter \( d = 4 \) mm   | \( E_{ca4} \) (MPa) | 33.590         | \( E_{ca4} \) (MPa) | 14.677         |
| Circular, diameter \( d = 18 \) mm | \( E_{ca18} \) (MPa) | 45.883         | \( E_{ca18} \) (MPa) | 17.823         |
| **Average value for circular samples** | \( E_{caAVG} \) (MPa) | **39.736**     | \( E_{caAVG} \) (MPa) | **16.250**     |
| Flat, diameter \( d = 10 \) mm, from flat belt, thickness \( t = 4 \) mm | \( E_{cf4} \) (MPa) | 31.501         | -             | -              |
| Total average value                 | \( E_{caAVG2} \) (MPa) | 35.619         | -             | -              |

The average longitudinal elasticity modulus value for circular samples can be calculated from the formula:

\[
E_{AVG} = \frac{E_{caAVG1} + E_{caAVG2}}{2} = \frac{39.736 + 16.250}{2} = 27.993 \text{[MPa]}
\]  

(2)

The average value differs by 12.6\%, from the longitudinal elasticity modulus (31.523 MPa), calculated from the elongation curve for round belts.

Figures 8 and 9 demonstrate the characteristics of shearing stress as a function of shear angle, obtained during the shearing tests of the belt for two shearing speeds and two types of samples.

**Figure 8.** Averaged dependence between the shearing stress \( \tau_s \) and shear angle \( \gamma \) for a circular belt and two shear velocities \( v_s \).
Figure 9. Averaged dependence between the shearing stress and $\tau$, shear angle $\gamma$ for flat belt with rectangular cross-section and two shear velocities $v_t$.

The results of shear testing (figures 8 and 9) are characterized by a satisfactory degree of result repeatability for different sample types. This indicates that the testing method was correctly selected and that the sensitivity is low for the shearing stress–displacement angle characteristics of the sample shape. It is important that the stress during dynamic sharing ($v_t = 8 \text{ mm s}^{-1}$) is slightly higher than during quasi-static shearing ($v_t = 1 \text{ mm s}^{-1}$). However, the difference in maximum values does not exceed 10%.

The elasticity modulus during shearing was identified. It was assumed that it is described with a directional coefficient of a graph line approximating the linear range of the characteristic of stress–strain angle of $\gamma < 2 \text{ rad}$. It was furthermore assumed that the matching of the graph line and the characteristic in the examined range, described by the coefficient of correlation $R^2$, should be equal to at least 0.98. The calculated modulus values are provided in table 4.

### Table 4. Determined values of the transverse elasticity modulus of the examined material.

| Shear velocity | Designation | Value | Designation | Value |
|----------------|-------------|-------|-------------|-------|
| $v_{t1}$ (mm s$^{-1}$) | 1 | $v_{t8}$ (mm s$^{-1}$) | 8 |
| Sample:              |             |       |             |       |
| Circular, diameter $d = 4 \text{ mm}$ | $G_{41}$ (MPa) | 11.204 | $G_{48}$ (MPa) | 12.255 |
| Rectangular, dimensions $4 \text{ mm} \times 10 \text{ mm}$ | $G_{101}$ (MPa) | 12.804 | $G_{108}$ (MPa) | 15.037 |
| Average value         | $G_{AVG1}$ (MPa) | 12.004 | $G_{AVG8}$ (MPa) | 13.646 |

In analyzing the stretching and shear tests results, the value of Poisson’s coefficient for the material was calculated. Considering that two different types of belts were used in the examination, it was calculated separately for dumbbell shaped samples and circular samples. The longitudinal elasticity modulus at stretching and transverse elasticity modulus during quasi-static shearing was accounted for. The value of Poisson’s coefficient for the sample with circular cross-section is equal to:

$$v_r = \frac{E_{AVG1}}{2 \cdot G_{41}} - 1 = \frac{31.523}{2 \cdot 11.204} = 0.407, \quad (3)$$
whereas for the flat sample:

\[ \nu_f = \frac{E_{eff}}{2\cdot G_{101}} - 1 = \frac{36.510}{2 \cdot 12.804} = 0.426, \]

The difference between the determined coefficient values is 5%. Therefore, the average Poisson’s coefficient value for this material is:

\[ \nu = \frac{\nu_r + \nu_f}{2} = 0.416. \]

This constitutes the expected value for this type of material which is rubber-like.

4. Conclusions

Analyzing the results of the performed examinations, one needs to point out that they do not provide an unambiguous, accurate information regarding the material constants for the tested belts. According to common knowledge, the longitudinal modulus during stretching or compression, the transverse modulus and Poisson’s coefficient exhibit a constant value, regardless of shape and dimensions of the examined sample. This phenomenon applies in particular to classical materials with elastic-plastic characteristics, e.g. metals. For the examined polyurethane belts, this characteristic is not observed.

The causes for this phenomenon can be as follows:

- the mechanical characteristics of the examined plastic material vary non-linearly, therefore its behavior under loads affected during the examination can be significantly different from the generally assumed standards for elastic-plastic materials,
- the samples examined were taken from different products available in the offer of the belt manufacturing company. The differences in mechanical characteristics of the circular and rectangular samples can be therefore explained by difference in manufacturing technology of this types of belts, caused by geometrical properties, and therefore we observe the differences in mechanical properties of samples coming from different belt types,
- anisotropy of mechanical characteristics of samples with circular cross-section, this can also result from the manufacturing technology of the belts. Supposedly, during the cooling of an extruded belt, as a result of temperature gradient, the chemical bonds are segregated and the macromolecular chains become directionally oriented, which causes the difference between the mechanical parameters along the axial and radial direction,
- for stretching tests, the difference in results may be caused by the use of non-normalized circular samples, without a narrow section. In such a case, the belt deformation in the durometer jaws may cause a decrease in the registered force value, in particular at low strain values,
- in the case of compression tests, the difference in results for the axial and radial direction can be caused by the employment of non-normalized methodology of belt compression in the perpendicular direction to the external surface. However, one needs to point out that it is highly problematic to prepare a circular or rectangular sample that is oriented radially in relation to the initial belt axis. It would require to use injection, casting or mechanical processing technologies which would significantly affect the mechanical parameters of the material in comparison to the original belt.

Despite the fact that examination results failed to deliver accurate information regarding specific values of strength characteristics of the material, they provided information regarding its behavior under load. One needs to consider in particular the anisotropic character of this material as was indicated during the examination of the linear thermal expansion [23]. Additionally, to further studies, it is required to select a reference shape and dimensions of the sample, identical for all tests on the material, including the examination of the technological process of welding. This ensures comparability of results during all the tests carried out for the same technological process.
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