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Two and three-body abrasion resistance of rubbers at elevated temperatures

W. Molnar[a,*], A. Nevosad[a], H. Rojacz[a], K. Adam[b], H.-J. Henze[c], M. Rodríguez Ripoll[a], E. Badisch[a]

[a] *AC2T research GmbH, Viktor Kaplan-Straße 2C, 2700 Wr. Neustadt, Austria*
[b] *voestalpine Stahl GmbH, voestalpine-Straße 1, 4020 Linz, Austria*
[c] *Sempertrans GmbH, Averdunkshof 3, 47447 Moers, Germany*

ABSTRACT

Conveyor belt systems are a major option, when it comes to the transport of large quantities of loose goods. During operation, their rubber belts undergo wear due to tribological interaction with the transported good and scrapers The kind of wear in practise can vary strongly and may be classified as two or three body-abrasion. This work investigates the two and three body abrasion performance of rubber belts using two well-established normed tests, namely ISO 4649 and ASTM G65 tests. Since in some applications, such as in the steel industry the transported goods can be at higher temperatures, both normed tests are modified to account for temperatures up to 200 °C.

The gained information and wear rates from these tests, including Shore A hardness and nano-indentation, gave insight in the wear loss, materials parameters and the respective wear mechanisms. The ASTM G65 showed a 3-body-abrasion mechanism, which causes wear by adhesion of rubber to the employed abrasive. The ISO 4649 showed a 2-body-abrasion mechanism, which causes wear by “tongue-rupture”. The mechanism are still present at higher temperatures although the characteristic wear patterns become less pronounced with increasing temperature. Regarding the application, the ASTM G65 test better simulates the wear caused by loose good rolling freely on the belt, while the ISO 4649 is more suitable for describing the scraper belt contact.

1. Introduction

If there is a need to transport large quantities of solid bulk goods on a continuous basis, conveyor belts are an attractive solution. Currently, such conveyor systems can be realized at small sizes, like often encountered at a supermarket checkout, or at large scale going up to 98 km in length, transporting phosphates from the Bou Craa mine in Africa [1]. Currently the longest single flight belt is situated in Bangladesh with 17 km in length [2]. Other fields of application include the cement or steel industries, shipyards and power plants [3].

Needless to mention, the upkeep of such a system is essential and ways are sought to increase the lifetime of wear parts. In this regard, probably the most important part of the whole conveyor system is the belt, which can make up to 30–70% of the costs calculated over the lifetime of the system [4]. The wear of the belt during operation can be principally attributed to two sources, namely the transported good at the loading point, which wears down the rubber belt primarily in the centre [5], and the scrapers, whose primary function is the removal of adhesive goods from the belt in order to keep the belt clean. The latter is particularly relevant since the damage on about a third of the premature worn belts originate from improper adjusted scrapers [6].

There are two categories of abrasive wear: two- and three-body abrasion. During abrasion, the part experiencing the most wear is normally denoted as first body, while the second body directly or indirectly imparts forces through relative motion, which cause the first body to wear. A third body is introduced into the contact when particles either form autogenously during the wear process or by an external source [7]. The third body can consist of debris, lubricants, entrained particles or even reactive chemicals. The abrasion behaviour of rubbers in datasheets is typically specified using 2-body abrasion tests (ISO 4649 norm in almost every case) [8]. Additionally, scratch testing at nano- and macroscale simulating a hard particle abrading the surface [9,10] exists. In contrast, in typical operation, 3-body abrasion is encountered more often [11–13]. Abrasion can also be divided into high- and low stress abrasion [14]. It is considered high stress abrasion when the abrasive found in the contact features sharp edges, which can be either created by breaking of the abrasive itself within the contact area due to the presence of high contact stresses or as distinct feature of either the second or third body. Still the kind of test can utterly influence the performance of rubbers or polymers in general. Evans and Lancaster’s work [15] give a good example, as low-density polyethylene showed the lowest wear rate out of 18 different polymers against rough mild steel, but the highest against coarse corundum paper.

In most cases, commercial rubber belts consist of blends of several elastomers like natural rubber (NR), polybutadiene rubber (BR) or styrene-butadiene rubber (SBR). However for high temperature applications (> 70 °C) ethylene propylene (EPM) or ethylene propylene diene (EPDM) based rubbers are frequently used. Wear related

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[*] Corresponding author.
E-mail address: molnar@ac2t.at (W. Molnar).

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investigations of EPDM rubbers were conducted by Felhös et al. [16] by using a Pin-on-Plate, Roller-on-Plate and an oscillating cylinder setup. Felhös et al. measured wear volumes ranging from 0.1 mm^3 to ~ 10^{-5} m^3/Nm depending on the amount of carbon black and test apparatus used. Also the difference in wear between fretting and rotating or rolling testing was shown when fretting produced only 1/15 of the wear the other tests generated. Other investigations were made by Findik et al. [17] on NR/SBR blends with a Pin-on-Drum tribometer. Wear volumes in this case ranged around 100 mm^3. In a previous work [18], the wear behaviour of different, commercial SBR-based rubber belt mixtures were investigated with the 2-body abrasion ISO 4649 tester and the 3-body ASTM G65 tester at room temperature. The results showed a good correlation of wear with tensile strength in case of 2-body-abrasion and tear strength in case of 3-body-abrasion.

Regarding the temperature sensitivity of rubbers, an increase in temperature significantly changes mechanical properties [19] and wear volume [20]. Fundamental investigations of rubber friction at elevated temperatures (up to 60 °C) were made by Schallamach [21] and revealed an exponential increase of rubber friction with decreasing temperature. A more recent and extended work on rubber friction at increased temperature was conducted by Baek et al. [22]. Rubber coatings were investigated in this work in a steel ball against rubber coating setup at temperatures from 20 °C to 150 °C and revealed increasing wear with rising temperature. Also a decrease in coefficient of friction with increasing temperature was shown. Still, temperature does not only affect rubber by softening it up and changing its mechanical properties, but also by oxidation. An extensive review on this topic was given by Li et al. [23], emphasising, that rubber degrades at every point in its lifetime, meaning synthesis, production and use. Rubber even oxidizes at room temperature as Gillen et al. showed [24]. The uptake of oxygen increases with increasing temperature and the amount of absorbed oxygen increases linearly over time. Celina et al. [25] also showed that different mechanisms can compete when rubber degrades at different temperatures. In practise, this represents the different reaction points which oxygen can attack: Sulphur bonds between the polymer chains, remaining double bonds or even the polymer chains themselves.

Hence, the aim of this work is to investigate the high temperature abrasion behaviour of rubber conveyor belts in 2-body abrasion (modified ISO 4649 tester) as well as in 3-body abrasion (modified ASTM G65 tester) in order to reveal the underlying wear mechanisms and understand the probable influence of mechanical characteristics.

2. Experimental

2.1. Materials

Commercially available conveyor belts from Sempertrans (Poland) were chosen, which are recommended for operation at elevated temperatures. An overview of the investigated samples are listed in Table 1. EPM features higher wear at room temperature than SBR, but is much more resistant to aging due to its peroxide crosslinking and lack of unsaturated double bonds. SBR on the other hand exhibits the mentioned double bonds, which are the anchor points for sulphur cross linking, but exhibits higher wear resistance at low temperatures.

Both samples were tested in as-delivered condition, as well as in aged condition, to investigate the role of rubber degradation by aging on abrasion performance at elevated temperatures. The aging procedure was conducted by placing the samples in a drying cabinet for 7 days at 150 °C in conventional air atmosphere.

Table 1
Rubber conveyor belt samples and their properties.

	Wear volume from data sheet [mm^3]	Breaking resistance [MPa]	Base polymer	Recommended temperature [°C]
Sample A	max. 130	> 12	EPM	< 180
Sample B	78	> 20	SBR	< 150

2.2. High temperature two- and three-body abrasion tests

A modified ISO 4649 tester, denoted as ISO 4649M, (Fig. 1a) was equipped with a heating collar around the sample holder to heat the sample to the desired temperatures of 150 °C, 175 °C and 200 °C. An important difference compared to the standardized ISO 4649 test was that instead of the 2 mm overlap of the sample, which the norm requires, 3 mm were required for inserting the thermocouple into the sample. This test represents a classical high stress 2-body abrasion test, as the sample is moved over a rotating drum with mesh 60 emery paper.

Concerning test temperatures, the samples were heated until the desired temperature was reached (usually 10–15 min), measured using aforementioned thermocouple. Testing parameters included a load of 10 N, rotation speed of the drum of 40 rpm and a linear sliding speed of 4.2 mm/rotation (according to the ISO 4649 standard). This amounts to a total test distance of 40 m. Two samples of a standardized test material were investigated before and after each test series to calculate the wear of the rubber mixtures according to the norm. As the ISO 4649 test is very widespread in the conveyor belt industry, it will serve as a reference for other tests.

The standardized ASTM G65 test was also modified with two heating systems, which are able to heat abrasive and sample independently, denoted as ASTM G65M (Fig. 1b). This setup was chosen to simulate a condition where the already warm belt is impacted by fresh hot good. The samples were heated to 70 °C, which is the temperature of the belt measured in an exemplary industrial application just before the hot good is loaded onto the belt. Abrasive (0.2–0.3 mm Ø; round, standardised AFS 50–70 sand from the US Silica company) was heated up to 160 °C respective 230 °C depending on the test series. The temperature of the samples during the tests, which was measured with a thermocouple located 1 mm aside from the wear track in a depth of 1 mm, reached values of 125 °C and 150 °C respectively. This test represents a classic low stress 3-body-abrasion test, where a rubber wheel (80 Shore A) causes wear to a sample by sliding abrasive particles through the contact. The flow of abrasive is high enough to separate sample and wheel, constantly providing a dynamic layer of abrasive particles. Further testing parameters are 130 N load, 2.43 m/s sliding speed and a test distance of ~ 1420 m.

For every condition and test, there were at least three samples tested to ensure a statistically solid average value. Range bars indicate the deviation from the average in the diagrams. After testing, wear debris from both tests were collected and investigated by an optical microscope to confirm wear mechanism published in literature. To quantify the softening process of the rubber at elevated temperatures, pieces of conveyor belts were put into an oven and heated up. Starting from 25 °C the temperature was increased in steps of 25 °C and the Shore A hardness was measured for both samples.

2.3. Micro-mechanical testing via nano-indentation

To show the influence of one hard particle abrading the surface and to get a deeper insight into micro mechanics of rubber wear mechanisms, two-body abrasion at room temperature was further simulated within a Hysitron® TI900 tribo-indenter utilising a diamond Berkovich-tip. To evaluate the static materials hardness and Young's modulus [26], load controlled indents were performed at 250 µN with a load- and unload time of 5 s. At least 10 valid indents were performed at 3 different areas (50 × 50 µm) on the samples (initial state and aged state).

For the evaluation of stresses at which the on-set of wear occurred, nano-scratching was performed. The used load cycle and displacement