Fundamental studies on dynamic wear behavior of SBR rubber compounds modified by SBR rubber powder

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Abstract

The aim of this study is focused on the experimental investigation of dynamic wear behavior of carbon black filled rubber compounds comprising pristine styrene butadiene rubber (SBR) together with incorporated SBR ground rubber (rubber powder). We also analyzed and described quantitatively the service conditions of some dynamically loaded rubber products, which are liable to wear (e.g. conveyor belts, tires). Beside the well-known standard test method to characterize wear resistance at steady-state conditions, we used an own developed testing equipment based on gravimetric determination of mass loss of rubber test specimen to investigate the influence of rubber powder content on dynamic wear depending on varying impact energy levels. Incorporation of SBR rubber powder in SBR rubber compounds increases wear. With increasing rubber powder content the wear at steady-state conditions progressively increases. However, the level of wear at dynamic loading conditions increases only once, but stays constant subsequently even with contents of incorporated rubber powder.

Keywords

Rubber, Rubber Powder, Wear Behavior

Introduction

Reinforced rubber materials are mainly used in technical applications, such as tires and conveyor belts, where high energy absorption ability is required [1]. Energy absorption due to hysteresis caused by breakage and re-aggregation of the rubber-filler-network is known as a significant contribution to energy dissipation effects [2]. In practice, technical rubber products are mostly cyclically loaded in contact with more rigid materials (e.g. sharp edged bulk materials, road surface asperity) and thus exposed to dynamic impact scenarios. Therefore, energy dissipation appears. Energy dissipation levels are significantly high at the smallest contact areas, promoting failure mechanisms, like crack initiation and crack propagation processes [3, 4]. Figure 1 schematically shows the typical expiration of rubber failure of conveyor belt top covers and tire treads due to dynamic mechanical loading.

The failure behavior of rubber products is caused particularly by formation of micro-cracks due to impacting foreign objects with considerable higher E-modulus in comparison to rubber (e.g. gravel, roots, etc.). Following crack initiation, its propagation will lead to both fatigue and abrasive wear at the rubber surface after a high number of loading cycles.
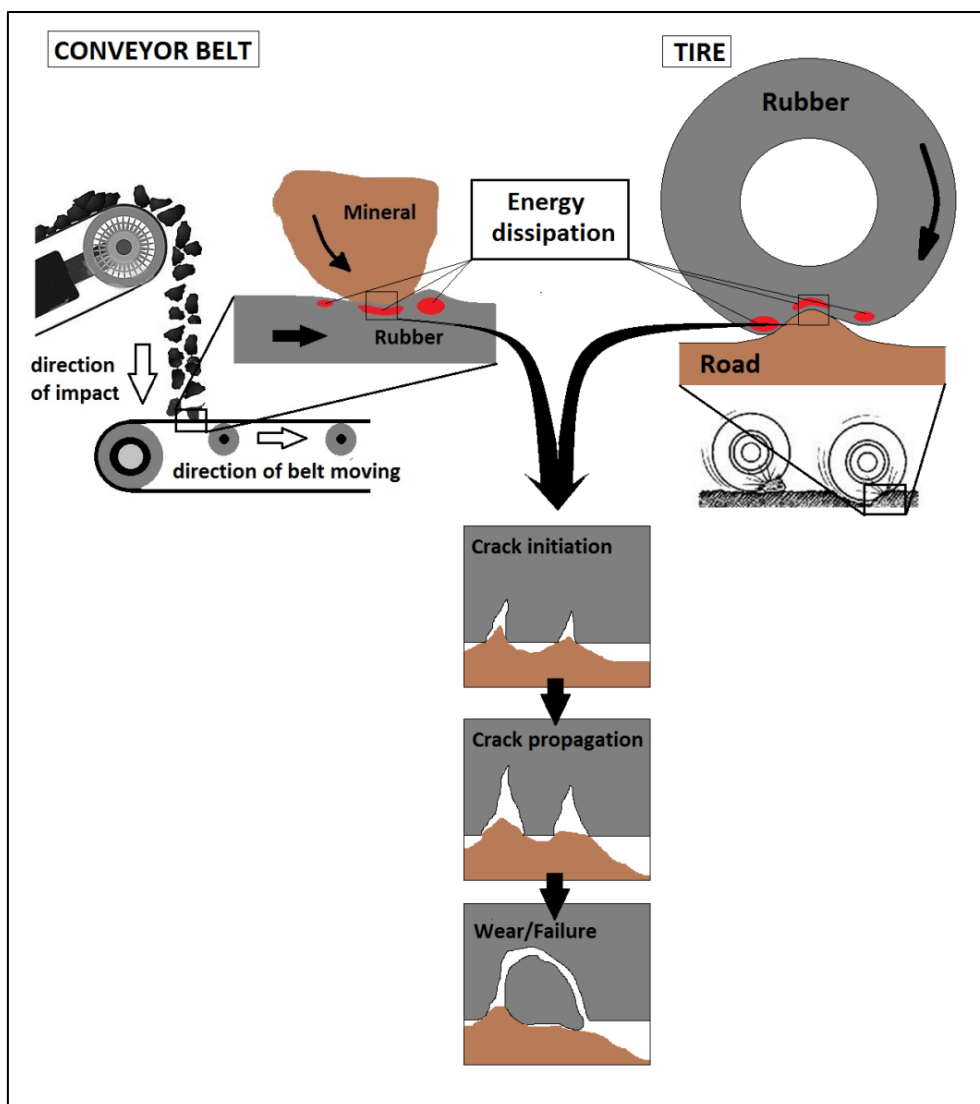

Figure 1: Mechanical loading and failure process of conveyor belt top covers and tire treads

Conveyor belt top covers as well as tire treads (especially in case of off-road and all-terrain tires) are used in hard terrain and thus exposed to very high mechanical loadings. Therefore special rubber compounds typically based on natural rubber (NR), styrene butadiene Rubber (SBR) or a blend of both are required. NR as well as SBR are – in comparison with other rubber types – denoted by high tensile and tear strength, high E-modulus and high wear resistance. Thus, NR and SBR are commonly used for technical applications [1].

Rubber materials as typical weakly cross-linked polymeric systems cause difficulties regarding resource-efficient recycling methods. A promising way of rubber recycling is grinding exhausted rubber products into fine rubber powder. By using an efficient technology of incorporation of rubber powder into fresh rubber compounds, rubber powder is qualified to form physical bonds with fresh rubber matrix material, because of its highly structured surface, where layers of bound rubber might be evolved. If the mechanical grinding process of exhausted rubber would provide high enough stresses beyond the chemical bonding energy of the carbon-sulfur-bonds – which are the weakest in cross-linked rubber materials – reactive polymeric chain ends could emerge and thus even chemical bonds between rubber powder particles and fresh rubber matrix might be possible. Few investigations regarding the utilization of high quality rubber powder as rubber substitute for fresh rubber compounds of the same rubber type have been done yet [e.g. 5-7]. The specific surface area of rubber powder particles, its surface structure, its polymeric nature and its content in the rubber compound influence the adherence of rubber powder to fresh rubber matrix. Thus the processability as well as the mechanical properties of rubber powder modified rubber is determined by these properties. Especially the incorporation of rubber powder into fresh rubber compounds of the same rubber type let quasi-static mechanical parameters (tensile strength, modulus) only slightly decrease, whereas fatigue behavior may even be improved, e.g. by higher crack growth resistance evoked by incorporated rubber powder particles [7]. Nevertheless, investigations of mechanical properties and especially the wear behavior of rubber powder modified rubber are still required.

The aim of this work was to prove the influence of rubber powder considering the wear behavior of rubber powder modified rubber materials at steady-state as well as dynamic loading conditions. Therefore, the standard abrasion test due to DIN ISO 4649 was applied to determine the abrasion resistance at steady-state (quasi-static) conditions and a dynamic testing apparatus based on the previous work of Beatty & Miksch [8] was applied to characterize dynamic wear behavior associated with *Chip & Cut* effects.

Materials

In this study Styrene-Butadiene-Rubbers (SBR), Buna 1500 and Buna 1723, were filled with carbon black N339 (surface area 90-95 m^2/g). Curing was done by a typical sulfur-accelerator-system (Table 1). The original rubber compound without modification was prepared; three further compounds were modified by incorporation of rubber powder based on SBR with different contents (10 phr, 30 phr, 50 phr).

The applied rubber powder was produced by ultra-high pressure water-jet-milling of exhausted conveyor belts. The rubber powder granulometry was declared by the supplier (Mitteldeutsche Umwelt und Entsorgung GmbH, GER) to be less than 400 μm. The highly structured surface of the applied rubber powder is visible by the scanning electron microscope (SEM) image in Figure 2.
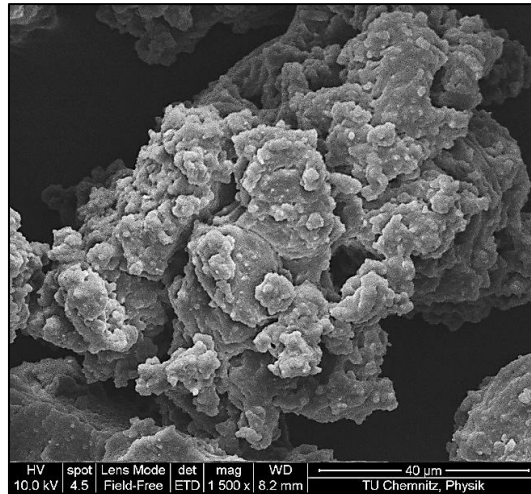
Figure 2: Scanning electron microscopy of ultra-high pressure water-jet-milled rubber powder particles (magnification 1500 x)

The different compound formulations used in this work are shown in Table 1. Rubber compounds were mixed in two stages: Firstly, the mixing of rubber, rubber powder and several ingredients was done using a Banbury mixer; secondly, for adding the curatives a two-roll mill was used. Curing of specimens was performed in a heat press (RUCKS Maschinenbau GmbH, GER) at 180°C and 10 MPa according to the rheometric properties determined due to DIN 53529.

Table 1: Rubber compound formulations

Compound designation	RP-00	RP-10	RP-30	RP-50
Ingredients	[phr]	[phr]	[phr]	[phr]
SBR Buna 1500	70			
SBR Buna 1723	40			
Carbon Black N339	50			
Rubber Powder	0	10	30	50
Zinc Oxide	4			
Stearic Acid	1			
Vulkanox 4010 NA/LG	2			
Vulkanox HS/LG	1			
Varazon 5998	1			
Tudalen 65	10			
Sulphur	1,5			
Sulfenax TBBS	1,5			

Experimental Details

Two different testing methods were performed to characterize the wear behavior of rubber powder modified rubber materials at steady-state and dynamic loading conditions. All wear experiments were run for cured rubber at room temperature and 50% humidity.

Steady-State Wear Test

Investigations of wear behavior at steady-state loading conditions were performed using an abrasion tester due to DIN ISO 4649. Figure 3 illustrates the testing equipment: A cylindrical test specimen moves at a rotating barrel covered by an abrasive-coated paper with constant feed rate (1 m.s^{-1}) and constant loading force (10.0 N) over a defined testing length (40 m). The abrasion resistance was investigated by gravimetric determination of mass loss of test specimen after the complete loading process.
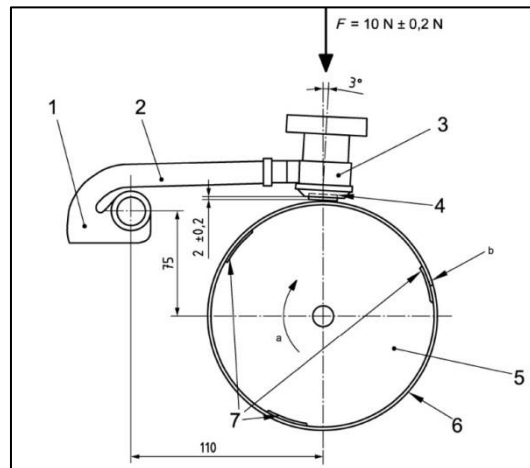

Figure 3: Abrasion tester according to DIN ISO 4649; 1 - Carriage, 2 - Actuating arm, 3 – Fixing system for test specimens, 4 - Test specimen, 5 – Cylindrical barrel, 6 – Abrasive-coated paper, 7 – Fixing system for abrasive-coated paper

Dynamic Wear Test

In this work dynamic wear tests were carried out using an own-developed prototype of a *Chip & Cut*-Tester. Previous investigations evaluated the measuring procedure to be suitable for simulating the impact scenario occurring for instance by deflection of a moving conveyor belt penetrated by falling sharp edged materials [8-11].
Figure 4 shows the measuring principle of the *Chip & Cut* Tester. The normal force F_L is induced by a static load with variable weight. A multiphase motor leads the actuating arm *1* to swing from the bottom to the upper position; and reverse. Due to the driving of the multiphase motor the oscillating arm *2* is hold in the upper position at given time. Thus, varying loading conditions of moving test specimen in accordance to real applications can be simulated. The oscillating arm *2* with the ceramic cutting tool *3* (CORUN doo, SRB; type TNGN-220616) drops due to free fall and impacts the revolving rubber test specimen *4*. The cutting process proceeds in the range of milliseconds and is repeated for a certain testing time with a defined frequency based on loading conditions occurring in the field. Within this testing procedure the cyclic mechanical loading leads to failure processes at the rubber surface, because crack initiation as well as crack propagation appears. The wear resistance is characterized by the determination of mass loss of the test specimens. Therefore, the test specimens were weighed before and after the *Chip & Cut* experiments. During the experiments wear debris occurs at the rubber test specimen surfaces, which have to be cleaned by air brushing.
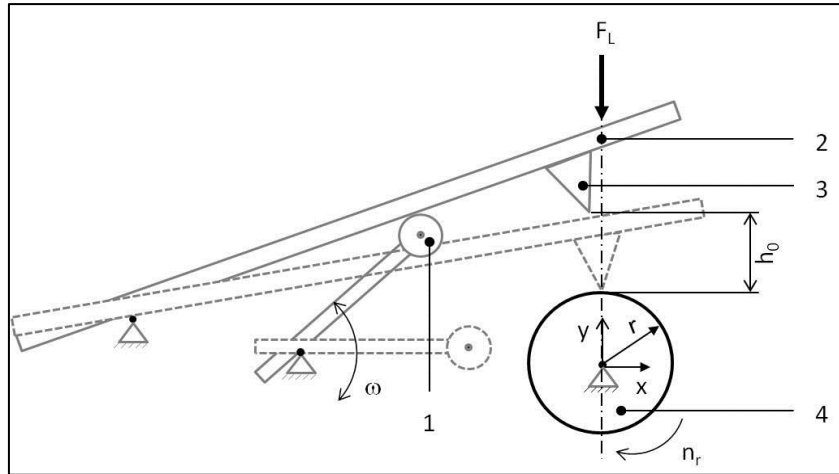
Figure 4: Principle of the *Chip & Cut Tester*; 1 - Actuating arm and multiphase motor, 2 - Oscillating arm, 3 - Ceramic cutting tool, 4 - Test specimen; F_L - Force, h_0 - Drop height, r - Radius n_r - Rotation speed of test specimen, ω - Acting frequency

In this study, cylindrical test specimens with radius 27.5 mm and thickness 13.0 mm were analyzed over a time period of 360 sec. The loading conditions were defined with GAUSSIAN pulse frequency of 1 Hz, pulse width 100 ms, dropping height 20 mm, rotation speed of the sample 700 rev.min^{-1} (4 m.sec^{-1}) – simulating a typical moving velocity of conveyor belts and low-speed tires, respectively. In this work static loading force is the single parameter affecting the testing conditions varying between two levels: 4.8 N and 10.5 N.

Results

To evaluate and to compare the results of both steady-state and dynamic wear test the experimental data for rubber based on each compound are depicted as relative mass loss considering the total contact time of the abradant or penetrator at the rubber surface for the entire testing procedure. This total contact time is quantified for the steady-state wear test to be 142 s. For the dynamic wear test the total contact time of 36 s results from 360 s test duration with 360 single contacts of the penetrator (1 Hz) for 100 ms each.

Steady-State Wear Test

The relative mass loss due to the abrasive wear process during DIN-Abrasion test of applied rubber is shown in figure 5. Increasing rubber powder content causes higher mass loss of rubber in comparison to the mass loss value of unmodified rubber. Whereas, incorporation of low rubber powder contents (≤10 phr) the mass loss stays stable.

Dynamic Wear Test

The relative mass loss data of applied rubber tested under varied dynamic loading conditions is shown in figures 6 and 7. Both illustrate a substantial increase of mass loss for rubber caused by incorporation of rubber powder. Thus, even low rubber powder contents (10 phr) distinctly decrease the dynamic wear resistance of rubber. On the other hand the relative mass loss stays almost constant independently of the value of rubber powder content.
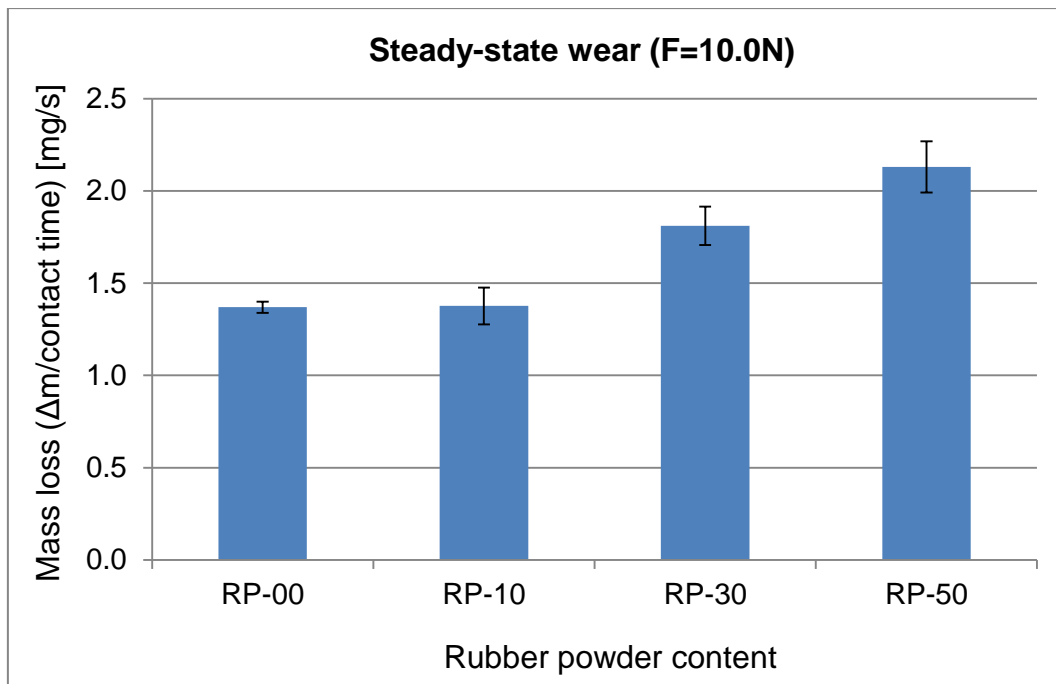
Figure 5: Mass loss of rubber compounds with different rubber powder content at steady-state wear according to DIN ISO 4649 (loading force F = 10.0 N)
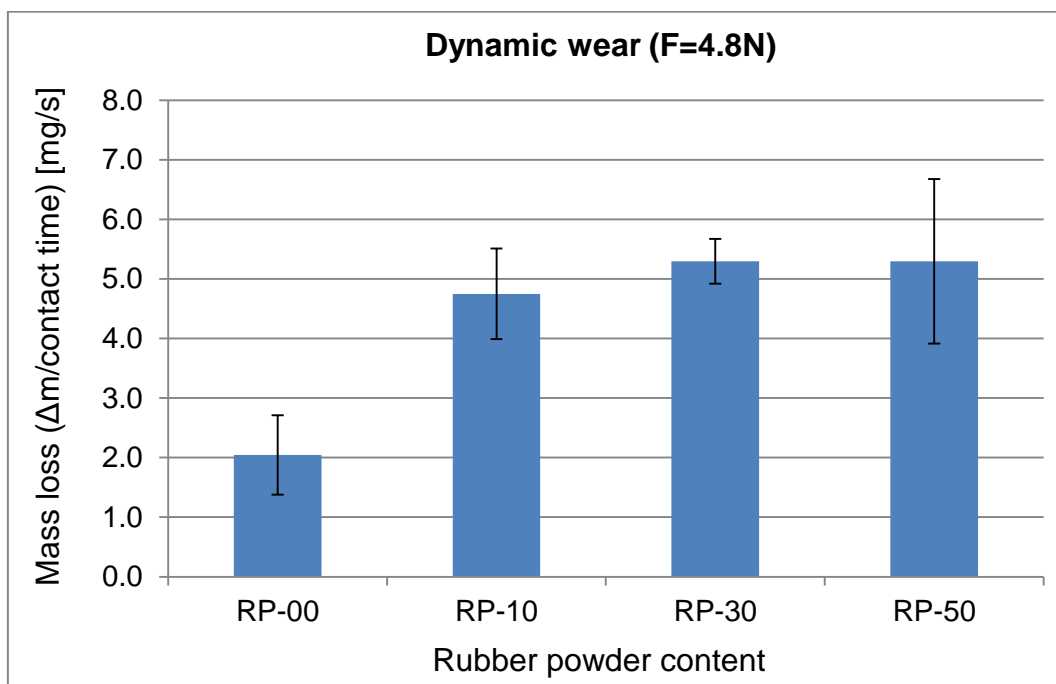

Figure 6: Mass loss of rubber compounds with different rubber powder content at dynamic wear simulation *Chip & Cut* behavior (loading force F = 4.8 N)
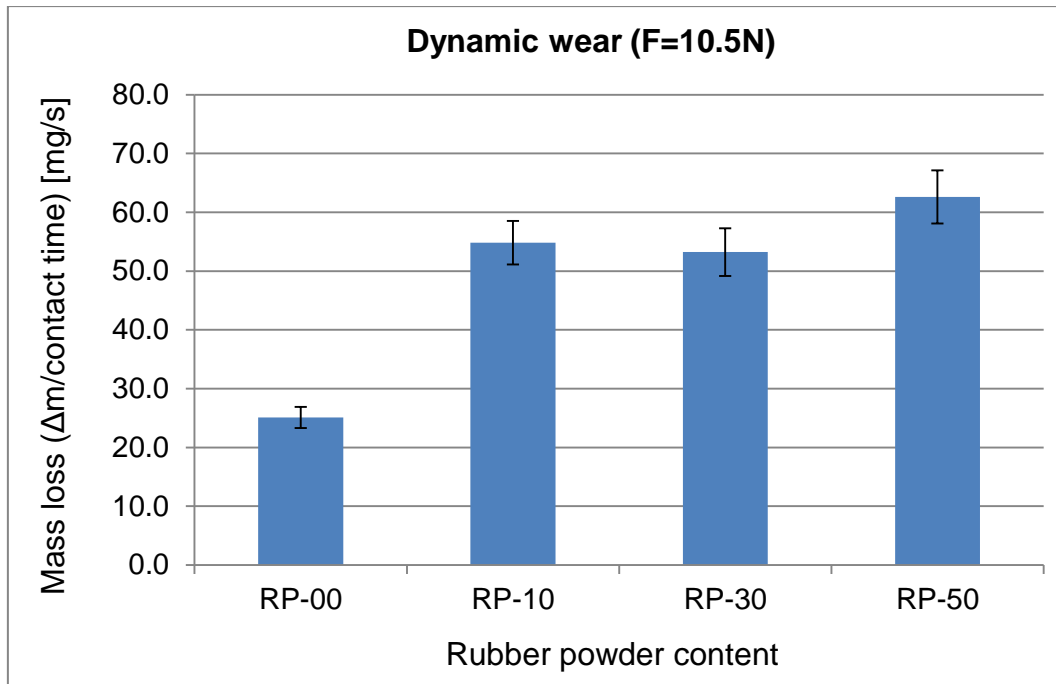
Figure 7: Mass loss of rubber compounds with different rubber powder content at dynamic wear simulation *Chip & Cut* behavior (loading force F = 10.5 N)

Discussion

The experimental data point out the wear behavior of cured rubber modified by different rubber powder contents substantially depend on the type of loading. Expectedly, dynamic loading conditions cause higher relative mass loss values in comparison to steady-state conditions. This is due to higher energy impact levels caused by the cyclically hitting penetrator. Figure 8 contrasts the surface and ridge formation of rubber test specimen depending of the kind of loading.

Moreover, the relative mass loss levels depend on the amount of loading force and impact energy, respectively. Higher impact energy levels will lead to higher mass loss values, because of higher mechanical degradation of the polymer-filler-network.
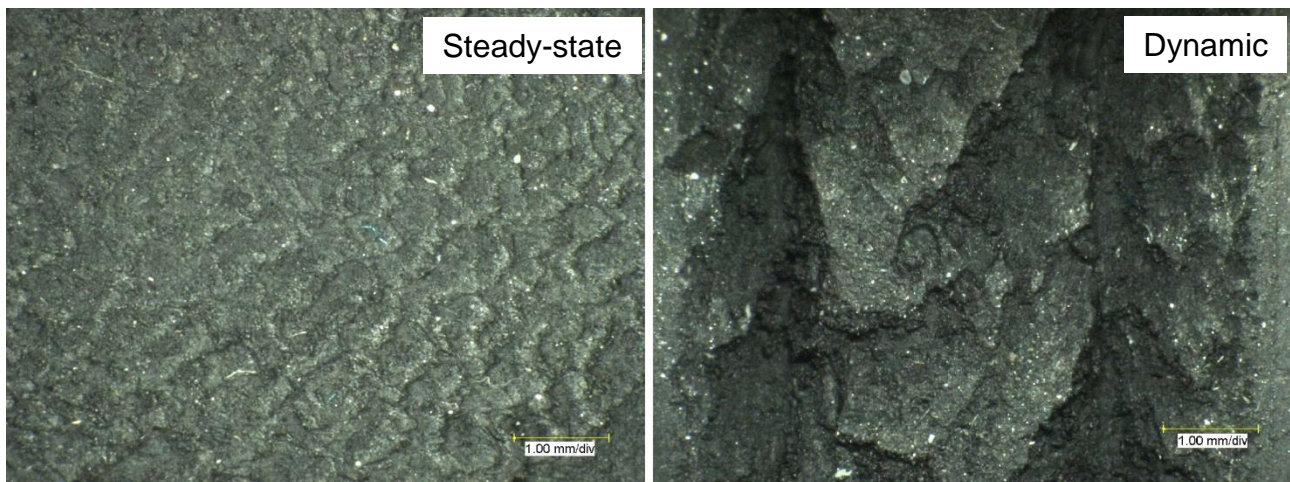

Figure 8: Comparison of rubber surfaces considering the loading type: Rubber surface of RP-00 after steady-state wear test (left) and rubber surface of RP-00 after dynamic wear test (right) with considerable higher macroscopic roughness. Light microscopy, magnification 50x.

Furthermore, the wear behavior of rubber, considering the influence of incorporation of rubber powder into fresh rubber materials, becomes apparent. The decrease of wear resistance of rubber with increasing content of rubber powder can be seen. Especially the wear resistance of rubber at dynamic loading conditions substantially decreases by incorporation of rubber powder. This might be due to insufficient bonding of rubber powder particles and fresh rubber matrix material. Poorly bonded particles will cause cavities, where crack initiation and crack propagation occur in consequence of mechanical deformation. The increase of mass loss with increasing rubber powder contents correlates with abrasion pattern occurring at test specimen surfaces (Fig. 9). Higher sizes of ridges visualized by light microscopy photography indicate increasing wear due to enhanced tearing of particles from the rubber surface [12, 13].
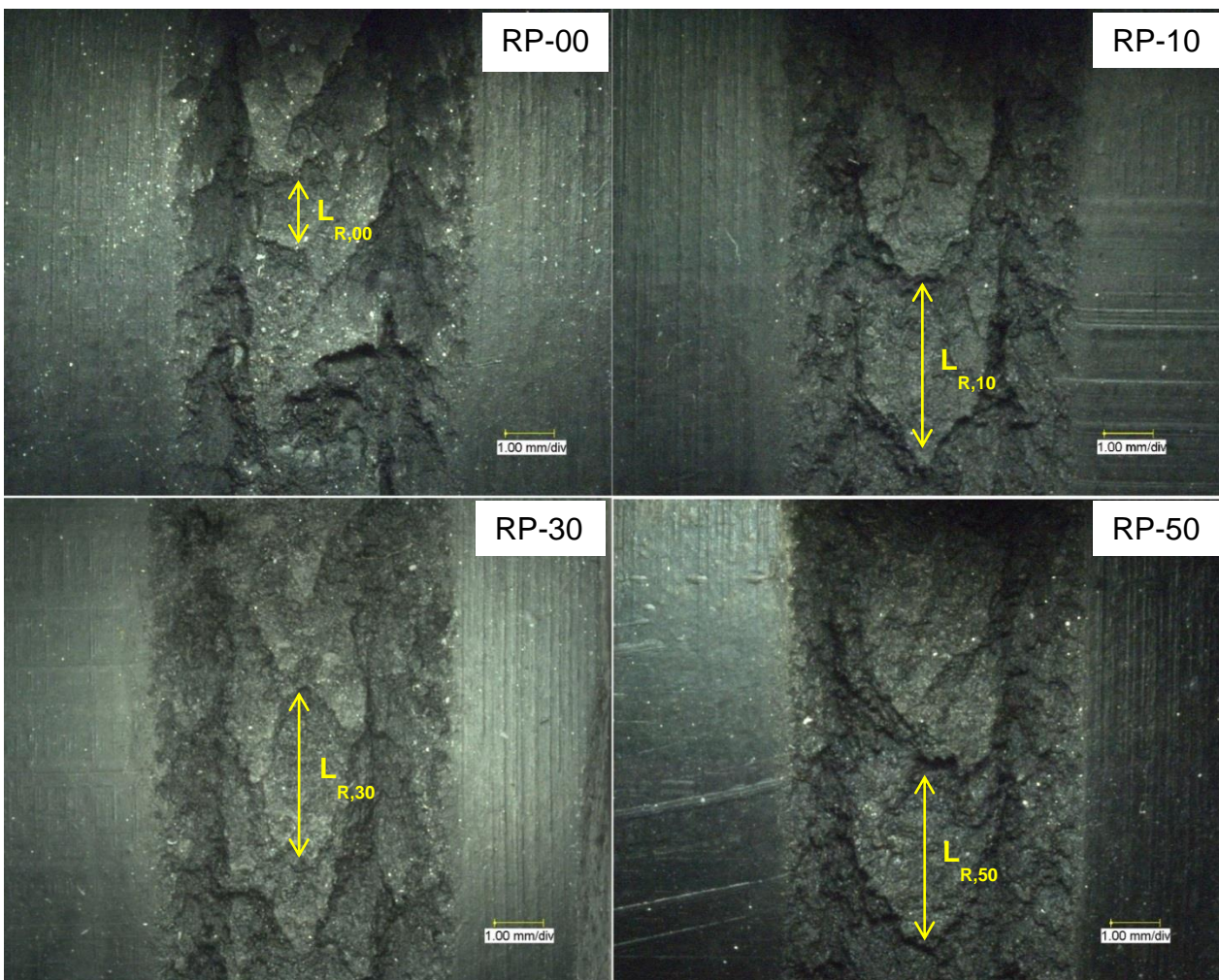

Figure 9: Comparison of rubber surfaces after dynamic wear test considering the RP-content (RP-00, RP-10, RP-30, RP-50): Significantly larger ridges at test specimen surfaces of rubber containing rubber powder. Light microscopy, magnification 25x.

Table 2 summarizes ridge sizes at rubber surfaces depending on the rubber powder content. High rubber powder contents (≥10 phr) lead to a significant decrease of wear resistance in comparison to unmodified rubber compounds, but stay stable at a comparable high level. Indeed, received data imply the existence of a percolation threshold of rubber powder content affecting the dynamic wear resistance of rubber powder modified rubber. We suppose that rubber powder contents above this percolation threshold lead to the development of weaker clusters of comparable large rubber powder

particles (0-400 μm) due to less physical and chemical interlinking because of the high ratio of rubber powder particles compared to fresh rubber matrix material.

Table 2: Comparison of ridge sizes depending on the rubber powder content

Rubber	RP-00	RP-10	RP-30	RP-50
Ridge designation	$L_{R,00}$	$L_{R,10}$	$L_{R,30}$	$L_{R,50}$
Average Ridge Size [mm]	1,39	3,38	3,35	3,43

Conclusion

Wear behavior of rubber distinctly depends on the loading scenario. Taking into account that loading conditions of highly deflected and harsh rubber applications, such as conveyor belts and tires, are predominantly of dynamic nature, we suggest the abrasive wear test (*Chip & Cut* test) for characterization of specific rubber applications, such as off-road tries or conveyor belts.
The incorporation of high contents of rubber powder (≥10 phr) into fresh rubber materials has a negative influence on the wear resistance. This might be due to insufficient bonding between the rubber powder particles and the fresh rubber matrix material. Active participation of rubber powder particles on mechanical deformation caused by external loadings is only possible, when a stably linked polymer-filler-network is established. In this context the characterization and targeted improvement of interlinking of rubber powder particles in rubber matrix materials will be further investigated. Furthermore, additional work will be done regarding the correlation between abrasion pattern occurring after wear tests, especially ridge formation and ridge length, and fracture mechanical parameters, such as crack propagation rate etc., in consideration of the applied rubber type.

Acknowledgement

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