

# **Influence of loading conditions on the dynamic wear of rubber**

Nikolas Ryzí

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2. Výroba kaučukových směsí na bázi NR, BR a SBR s variací obsahu plniva na bázi aramidových vláken v porovnání s klasickými plnivy
3. Vulkanizace zkušebních těles a vzorků pro strukturní pevnost, dynamického šíření trhliny při cyklickém pulsním zatěžování a pro měření oděru při dynamickém zatěžování
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L.S.

doc. Ing. Roman Čermák, Ph.D.  
*děkan*

prof. Ing. Berenika Hausnerová, Ph.D.  
*ředitel ústavu*

Příjmení a jméno: Ryžec Nicolas

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## **ABSTRAKT**

Předložená práce se zabývá problematikou opotřebení pryže při dynamickém zatěžování, kterému mohou být vystavovány běhouny pneumatik během použití v náročných terénních podmínkách. V první kapitole teoretické části byly popsány základní faktory, které mají vliv na opotřebení běhounu pneumatiky. Druhá kapitola se zabývá souhrnem současných metodik testování pryží a byl představen mechanismus oděru běhounu pneumatik v těžkém terénu, který se nazývá cut and chip (CC). Pro experimentální část byly zvoleny dvě pryže na bázi gumárenských směsí s variací typu kaučuku. Tyto pryže byly podrobeny základním analýzám pro popis standartních mechanických vlastností. Primární část experimentální práce je poté zaměřena na vliv variací okrajových podmínek dynamického zatěžování a na jejich výsledném dynamickém oděru. Pro tyto analýzy byla zvolena metoda charakterizující odolnost proti opotřebení při dynamickém zatěžování. Výsledky prokázaly výrazně odlišné chování použitých pryží právě v souvislosti s typem kaučuku a jednoznačný přínos této metodiky k simulaci oděru reálného běhounu pryže v laboratorních podmínkách.

Klíčová slova: Pryž, gumárenská směs, oděr, pneumatika, běhoun, Cut, Chip

## **ABSTRACT**

This thesis deals with the problematics of dynamic wear of cured rubber compounds under dynamic loadings, to which tire treads may be exposed during their performance in off-road conditions. In the first chapter of the theoretical part the basic factors that affect the wear of tread were described. The second chapter describes summary of current methods of cured rubber compounds testing and mechanism of tread wear in off-road conditions which is called cut and chip (CC). For the experimental part, two cured rubber compounds based on uncured rubber compounds with a variation of the rubber were chosen. These cured rubber compounds were tested for fundamental mechanical properties. The primary part of the experimental chapter is then focused on the influence of variations of boundary conditions of dynamic loadings and their resulting dynamic wear. For these analyses was used method to characterize the wear resistance under dynamic loadings. The results showed significantly different behaviour of used cured rubber compounds in context with variations of rubber and the contribution of the chosen method to simulate real tread wear in laboratory conditions.

Keywords: Rubber, rubber compound, wear, tire, tread, Cut, Chip

*“There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.*

*There is another theory which states that this has already happened.”*

Douglas Adams

Thank you all for...

...the Pure Child...

...and you above all.

I hereby declare that the print version of my Bachelor's thesis and the electronic version of my thesis deposited in the IS/STAG system are identical.

# CONTENTS

<b>INTRODUCTION .....</b>	<b>9</b>
<b>I THEORY .....</b>	<b>10</b>
<b>1 WEAR AND ABRASION OF TIRES .....</b>	<b>11</b>
1.1 TIRE DESIGN .....	11
1.1.1 Tread .....	13
1.2 TIRE MANUFACTURING MATERIALS .....	14
1.2.1 Rubber .....	14
1.2.1.1 Natural Rubber .....	14
1.2.1.2 Styrene Butadiene Rubber .....	15
1.2.1.3 Polybutadiene Rubber .....	15
1.2.2 Vulcanization system .....	15
1.2.2.1 Vulcanization agents .....	15
1.2.2.2 Activators of vulcanization .....	16
1.2.2.3 Accelerators .....	16
1.2.2.4 Vulcanization retarders .....	16
1.2.3 Fillers .....	17
1.2.3.1 Carbon black .....	17
1.2.4 Antidegradants .....	19
1.2.5 Lubricants .....	19
1.3 FRICTION AND WEAR MECHANISMS .....	19
1.3.1 Friction .....	20
1.3.1.1 Friction factors .....	20
1.3.1.2 Friction measurement .....	22
1.3.2 Wear .....	22
1.3.2.1 Adhesive wear .....	23
1.3.2.2 Fatigue wear .....	23
1.3.2.3 Abrasive wear .....	23
<b>2 TESTING METHODS .....</b>	<b>26</b>
2.1 TEST METHODS BASED ON STEADY STATE LOADING CONDITIONS .....	26
2.1.1 Bussen-Schlobach method .....	26
2.1.2 Du Pont-Grasseli method .....	27
2.1.3 Akron-Croydon method .....	28
2.1.4 Dunlop-Lambourn method .....	29
2.2 TESTING METHODS BASED ON DYNAMIC LOADING CONDITIONS .....	29
2.2.1 Beatty-Miksch Cutting and Chipping tester .....	31
2.2.2 Experimental Chip-Chunk method .....	32
<b>II ANALYSIS .....</b>	<b>33</b>
<b>3 PREPARATION OF SAMPLES .....</b>	<b>34</b>
3.1 RUBBER COMPOUND RECIPES .....	34
3.2 PREPARATION OF COMPOUNDS .....	34
3.3 PREPARATION OF TESTING SAMPLES .....	35
<b>4 EXPERIMENTAL METHOD .....</b>	<b>36</b>



4.1	BASIC MATERIAL CHARACTERIZATION .....	36
4.1.1	Hardness test .....	36
4.1.2	Tensile test .....	36
4.2	CUT AND CHIP ANALYSES .....	36
4.2.1	Testing device .....	36
4.2.2	Tools.....	40
4.2.3	Boundary conditions of analysis .....	41
4.2.3.1	Force and speed .....	41
4.2.3.2	Contact time .....	41
4.2.3.3	Tools .....	42
4.2.3.4	Aramid content .....	42
<b>5</b>	<b>RESULTS AND DISCUSSION.....</b>	<b>43</b>
5.1	HARDNESS TEST .....	43
5.2	TENSILE TEST .....	43
5.3	CUT AND CHIP ANALYSES .....	43
5.3.1	CC resistance for NR and SBR under different loading conditions.....	43
5.3.1.1	$F_N = 100N$ .....	44
5.3.1.2	$F_N = 125N$ .....	45
5.3.1.3	$F_N = 150N$ .....	45
5.3.1.4	$F_N = 175N$ .....	46
5.3.1.5	$F_N = 200N$ .....	47
5.3.1.6	Summary.....	48
5.3.2	Influence of varied tip radius of the tool on CC resistance of NR and SBR .....	50
5.3.3	CC resistance for NR and SBR for different contact time $t_s$ .....	51
5.3.4	CC resistance for NR and SBR with different Aramid content .....	52
	<b>CONCLUSION .....</b>	<b>54</b>
	<b>BIBLIOGRAPHY .....</b>	<b>55</b>
	<b>LIST OF BBREVIATIONS .....</b>	<b>57</b>
	<b>LIST OF FIGURES .....</b>	<b>59</b>
	<b>LIST OF TABLES .....</b>	<b>61</b>

## INTRODUCTION

With the expanding rubber industry and the use of rubber products, the demands on their functionality and low prices are growing. These aspects are reflected in an effort of the efficient and economic development of rubber materials with the desired properties.

Rubber products are used in many everyday applications, due to their unique properties. Each of these applications places different demands on the rubber for both mechanical properties and durability. The essential use of rubbers is in dynamic applications where there is a long-term dynamic stress on the component, which is mostly in contact with diverse surface causing additional wear. The most important part that falls into the category of dynamically stressed parts is a tire.

The main function of the tire is transferring forces between the vehicle and the road where the main element of the tire is subjected to friction and wear. The properties of the tire and the factors affecting it in use have a major impact on its durability, safety, type of use and the ultimate economic aspect of use. Therefore, their development and testing, targets the desired wear resistance properties and the researching of tire and manufacturing rubber compounds behaviour in different environments and under different load circumstances. To determine the degree of resistance of tire and rubber compounds to a certain type of wear, wear tests are used. These tests must be selected adequately for the problem, which is under the investigation.

The aim of this thesis is to describe the state of the art in laboratory methods for dynamic wear testing of rubber compounds and determine the influence of different loading conditions applied on dynamic wear behaviour of fundamental rubber compounds.

## **I. THEORY**

## 1 WEAR AND ABRASION OF TIRES

Wear and abrasion of tires is the inevitable loss of rubber material during rolling and sliding contact of tires with road. This contact results mainly in fatigue cut growth and the peeling off of small rubber particles. [1]



Figure 1: Worn tire [1]

Wear of tires is strongly influenced by the conditions of tire application, because different abrasion mechanisms appear in dependence of loading, road texture, weather conditions and operation usage. These mechanisms result in different surface topographies of the abraded tread materials implying that the classification of tire surface wear is closely related to the topography on the worn surface. [1]

Wear of tire surface is mainly influenced by three factors:

- Tire design
- Conditions
- Tire materials

### 1.1 Tire design

Tire design deals with geometrical and functional part of tire production. Tire is essentially a cord-rubber composite and together with rim and valve forms vehicle wheel. The assembly thus formed is filled with pressure medium and works on principle of pressure vessel. Tires have plies of reinforcing cords extending horizontally from bead to bead, on top of which is

a belt located below the tread. The belt cords have low extensibility and are made of steel or fabric depending on the tire application. [2,3]

Tires can be divided into categories based on vehicle applications, tire design and condition use but regardless of the design or application of the tire, all tires must full-fill a basic set of functions throughout its lifetime: [2,3]

1. Provide load-carrying capacity
2. Provide cushioning and dampening
3. Transmit driving and braking torque
4. Provide cornering force
5. Provide dimensional stability
6. Resist abrasion
7. Generate steering response
8. Have low rolling resistance
9. Provide minimum noise and minimum vibration
10. Be durable throughout the expected life span

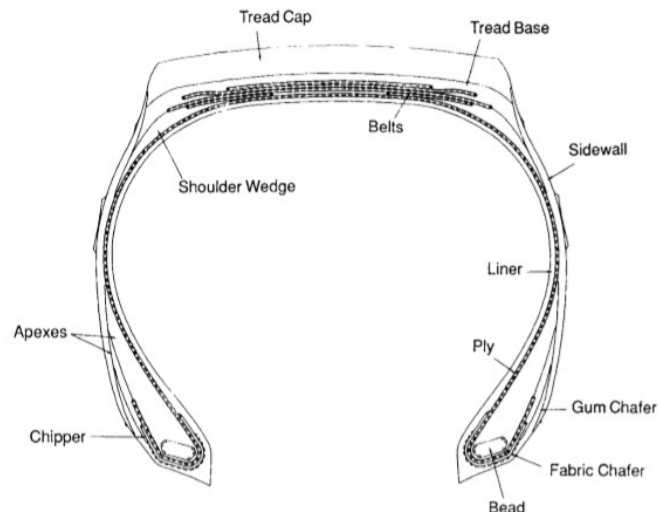


Figure 2: Component of a radial truck tire [2]

To meet all requirements in list above tire is an assembly of a series of parts, each of which has a specific function in the service and performance of the product. Figure 2 illustrates the key components of a tire: [2,3]

- Tread
- Belts
- Shoulder belt wedge

- Sidewall
- Liner
- Plies
- Beads
- Bead area components

Even though most of the tire parts are exposed to some kind of wear during their lifetime tread is in direct contact with the road and obstacles that may occur during their performance and must resist the main part of wear acting on tire therefore it is the main focus of wear and abrasion study. [2,3]

### 1.1.1 Tread

Tread is the wear resistance component of the tire provided with tread pattern which is in contact with road. It must provide traction, wet skid, good cornering characteristics with minimum noise generation, low heat build-up, perfect wear resistance and adhesion. In practice, the casing usually consists of a two-layer tread. The top layer has a very high wear resistance while the bottom layer is constructed with the least hysteresis losses under dynamic stress.

Hysteresis is directly proportional to tire temperature, which means that low hysteresis losses result in low tire temperature stress. The upper part must provide a long service life with sufficient road adhesion, while the inner part is designed to reduce rolling resistance and protect the ply and belts from mechanical damage of the tire. [2,3]



Figure 3: Tread [21]



The rubber compound for tread consists of rubber polymer and other ingredients which each has a different function and impact on product. These includes fillers, vulcanization system, antidegradants, lubricants and other ingredients in the precise ratio. [2,4]

## **1.2 Tire manufacturing materials**

As described above tire is assembly of many different parts with different required properties and material content. Each of the rubber parts of tire is meant for its own purpose therefore their compound mixture diverse in used materials and their amounts

In this chapter we will focus on materials used in tread rubber compounds and their possible wear and abrasion resistance effect on product. [5,2]

### **1.2.1 Rubber**

The rubber is the most important part of the compound and the carrier of essential properties therefore choosing of a rubber is based on their basic properties such is mechanical properties, chemical resistance and its temperature range of application.

For tread applications Natural Rubber (NR), Styrene Butadiene Rubber (SBR), Polybutadiene Rubber (BR) are the most used as well as their precisely designed combination. [2,5,6]

#### ***1.2.1.1 Natural Rubber***

Production of Natural Rubber (NR) begins by harvesting milky liquid called latex primarily collected from rubber trees. This latex consists of water, polyisoprene, and small amounts of other substances such as carbohydrates and proteins. It can be processed by various procedures primarily by coagulating with formic or acetic acid to gain coagulum which is then squeezed between rollers to remove excess water and dried by hot smoke.

Vulcanized product made from NR have high mechanical strength, very good abrasion resistance and dynamic mechanical properties. An NR vulcanizate has an excellent elasticity, thus most of the kinetic energy of an impact particle is converted into deformation of the vulcanizate which then releases the energy by returning to its original undeformed state. Range of temperature resistance of NR vulcanizate begins at the region of -57 °C where its stiffness shows a considerable increase and ends in the region of 75 °C which is its high temperature heat aging resistance limit for continuous use. [5,6]

### ***1.2.1.2 Styrene Butadiene Rubber***

Styrene butadiene rubber (SBR) is static copolymer of butadiene and styrene and it is derived from petroleum oil. The final SBR properties depends on content of styrene and position of butadiene (1,4 or 1,2). SBR can be prepared by radical polymerization in emulsion (E-SBR) or anionic polymerization in solution (S-SBR). [5,6]

In comparison with NR, vulcanizates made from SBR have poor mechanical properties. The raw rubber elastomer must have reinforcing fillers, such as carbon black, in order to gain good mechanical strength and at the same time the filler increases hardness. The properties of SBR and their weather and chemical resistance are broadly similar to NR apart of the upper temperature heat aging resistance limit which is little higher. [5,6]

### ***1.2.1.3 Polybutadiene Rubber***

Polybutadiene Rubber (BR) is made from butadiene which is built-in in three different configurations during polymerization: cis-1,4 ; trans-1,4 and 1,2 (vinyl).

Even though this is a significant elastomer it is most commonly used as a blend with other rubbers as it is in tread compounds. Properties are very much dependent on the architecture of the repeating unit in the polymer chain. [5,6]

## **1.2.2 Vulcanization system**

The main function of vulcanization system is to modulate the polymer by forming crosslinks between the chains in short period of time. The vulcanization system is usually composed of a vulcanization agent, an accelerator, an activator and an inhibitor. These parts are added into compound in low concentration in phr units. [5,7]

### ***1.2.2.1 Vulcanization agents***

The vulcanization agent is the basic component of the vulcanization system. The most used and the most important reagent is elemental sulfur which is only applied to unsaturated rubbers. [5,8]

#### **1.2.2.1.1 Sulfur**

Essential requirement for usage of sulfur as vulcanization agent is the presence of unsaturated bonds. It reacts with the raw rubber elastomer forming cross-links between the polymer

chains, resulting in a more dimensionally stable, less heat-sensitive and elastic product with very good properties in dynamic loading.

Using sulfur as vulcanization agent allows extensive control of vulcanization kinetics and freedom to the design of the recipe as well as possibility to control the length of the sulfur cross-links. [5,6]

### ***1.2.2.2 Activators of vulcanization***

The main purpose of activators is to increase efficiency of sulfur cross-linking under the same conditions of vulcanization. Combination of ZnO and stearic acid are most often used as activators of sulfur vulcanization. [5]

### ***1.2.2.3 Accelerators***

The function of accelerators is accelerating the vulcanization process as well as increasing efficiency of the sulfur bonding. This increasing of efficiency results in improving properties of the vulcanizate, especially aging resistance and higher temperature resistance. [5,8]

Accelerators can be divided into groups:

- Slow – amines, guanidines
- Fast – thiazoles, sulfaamides, mercaptides
- Very fast – tiuramy
- Ultra accelerators – xanthates and dithiocarbamates

In tire industry guanidines (DPG), sulfaamides (CBS, TBBS) and mercaptides (MBT) are the most used accelerators. [4]

### ***1.2.2.4 Vulcanization retarders***

Vulcanization retarders increases processing time of mixture by slowing down process of vulcanization. [5,8]

Retarders can be divided into groups:

- Inorganic – MgO, PbO
- Organic – Adipic acid, Sebacic acid, Sodium acid and others

### 1.2.3 Fillers

Fillers increase the stiffness of rubber in various degrees depending on quantity and quality of the fillers. The properties of cured rubber compounds are affected not only by the filler content but also by its structure and particle size. [2,5,8]

According to effect on the properties of the vulcanizate fillers are classified as:

- a) Reinforcing – increases tensile strength, structural strength and abrasion resistance (fine particles, precipitated silica – Particles size 0,01 to 0,1  $\mu\text{m}$ )
- b) Semi-reinforcing – increases tensile strength, structural strength, but do not improve abrasion resistance (coarse particles, hard kaolin, precipitated  $\text{CaCO}_3$  – Particles size 0,1 to 1  $\mu\text{m}$ )
- c) Non-reinforcing – does not improve the properties of vulcanizate (talc, soft kaolin,  $\text{CaCO}_3$  – Particles size 1 to 10  $\mu\text{m}$ )

Incorporation of reinforcing fillers such as carbon black improves stiffness and strength of rubber therefor the abrasion resistance is improved by suppressing tearing of the rubber under the sliding contact. Incorporation of silica and carbon black reduces the abrasion loss of the natural rubber materials notably, whereas rice husk ash shows no effect with filler loading. This improvement is probably due to the greater surface area and better filler-rubber interfacial adhesion resulting in an improved abrasion resistance. Fine particles actually reflect their greater interface between the filler and the rubber matrix and, hence, provide a better abrasion resistance than the coarse ones. [9]

The worn surfaces of the rubber compounds filled with carbon black having smaller particle size and a more developed structure showed narrower spaced ridges and better abrasion resistance. It means that smaller particle size and better structure development of carbon black resulted in improved abrasion resistance. [9]

#### 1.2.3.1 Carbon black

Carbon black is one of the most significant fillers used in the rubber industry. It is primary used for its reinforcing effect but their secondary properties as UV light absorption, thermal conductivity and protection against sun light degradation are equally important.

Carbon black can be qualitatively described by a series of properties:

- Particle size (surface area)

- Particle size distribution
- Particle structure (particle aggregates DBP Absorption)
- Surface activity (chemical composition and energy ratios on the surface of the particles)

An increase in a carbon black aggregate size or structure will result in an improvement in cut growth and fatigue resistance. A decrease in particle size results in an increase in abrasion resistance and tear strength, a drop-in elasticity, and an increase in hysteresis and heat build-up. [5,8]

From tire testing of the selected carbon black types were noted the following points:

- Reduction of carbon black loading lowers tire rolling resistance. At a constant black loading, an increase in oil level will increase rolling resistance but also improve traction.
- Increasing black fineness raises both rolling resistance and traction.
- An increase in the broad aggregate size distribution decreases the tire rolling resistance with constant surface area and DBP.
- Tread-grade carbon blacks can be selected to meet defined performance parameters of rolling resistance, traction, wear, etc.

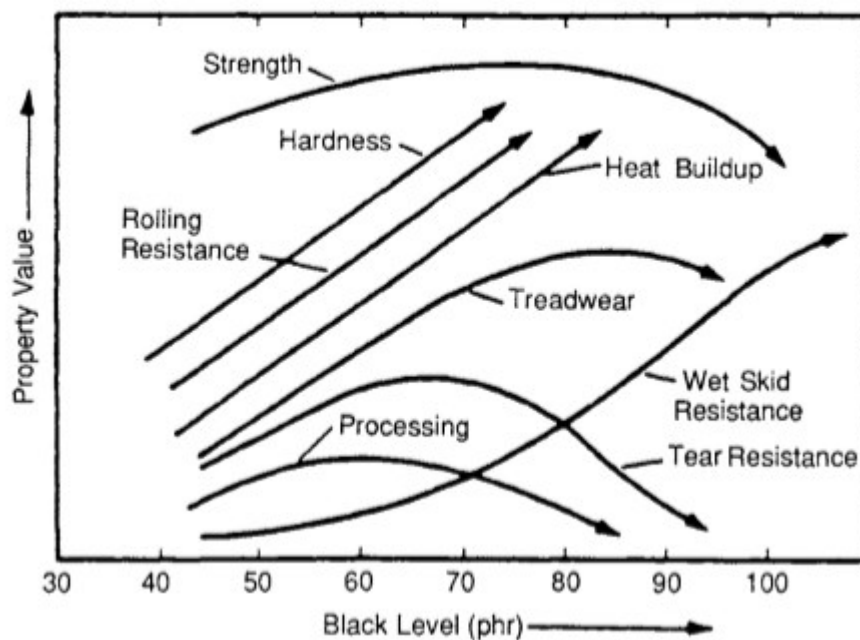


Figure 4: Effect of carbon black volume on compound properties and final rubber behaviour [2]

Figure 4 illustrates the general trends for tread-grade carbon black loading and the effect on physical properties of compound. As level of carbon black increases, there are increases in compound heat build-up and hardness and, in tires, an increase in rolling resistance and wet skid properties. Tensile strength, compound processability, and abrasion resistance, go through an optimum after which these properties deteriorate. [2,4]

#### **1.2.4 Antidegradants**

Over time, the degradation by external conditions appears. It can be caused by numerous influences, such as the effects of UV radiation, heat, oxygen, ozone, mechanical stress. [1,6]

The aging process can be slowed down by using antidegradants which are divided into:

- a) UV absorbers
- b) Antioxidants
- c) Antiozonants

#### **1.2.5 Lubricants**

Lubricants greatly reduce friction on smooth surface but the effect is smaller on rough surface. Changes in friction properties of rubber are possible by adding substantial amounts of standard lubricants, but this reduces strength, especially at high temperatures. In spite of reduction of vulcanizate strength, their abrasion resistance can be excellent. When a lubricant is applied, a much finer pattern develops and the rate of abrasion is much lower. [9]

### **1.3 Friction and wear mechanisms**

Friction and wear are two interrelated processes. Friction is an integral part of mechanical processes of wear therefore friction and wear can be studied and measured simultaneously during the same experiment. In tire industry friction (slip resistance) and wear forms two most important parameters. However, in laboratory testing these two parameters are considered separate processes regardless of small amount of standardized friction test procedures, while wear standardized test procedures are widely spread and can be found in almost all rubber laboratories. [5,10]



### 1.3.1 Friction

Friction of rubber is very complicated process which occurs when two surfaces are in contact. Generally speaking, friction consist of two parts:

- a) Adhesive friction
- b) Hysteresis friction

Adhesive friction is caused by repeated formation of molecular bonds between surfaces during friction, while hysteresis friction results from dynamic deformation of the vulcanizate in which mechanical energy loos occurs. However, the friction value also depends on external factors like surface roughness as well as on internal factors namely viscoelastic behaviour of the vulcanizate. [5,10]

#### 1.3.1.1 Friction factors

External friction occurs when two bodies are together in relative motion. The surfaces of these bodies can either be in simple touch or there can be normal force actively pushing one surface against the other. During the body surface movement, a resistive force forms and counteracts against the relative movement of surfaces. The resistance force is perpendicular to the normal force and they are defined as: [5,10]

$$F = \mu \cdot F_N \quad (1)$$

Where:

F – Friction force [N]

$F_N$  – Normal force [N]

$\mu$  – Friction coefficient [-]

The friction coefficient is in this example proportionality constant which does not depend only on normal force but also on the roughness and adhesion of both surfaces in contact. For common materials friction coefficient use to be constant but for rubber vulcanizates it depends on more factors such are total surface area in contact, normal force, speed of movement and temperature. [5,10]

The friction coefficient can be divided by the form of which surfaces move:

- a) Sliding friction coefficient
- b) Rolling friction coefficient



Figure 5: Sliding and rolling friction [22]

Sliding friction coefficient is defined by equation (1). Rolling friction coefficient is defined by equation (2) where the balance of moments applies.

$$F \cdot R = N \cdot e_m \quad (2)$$

Since no material is perfectly smooth, but its surface has many inequalities, it has to be distinguished between the apparent and the actual surface area in contact. The actual contact area is much smaller, than the actual contact area. The friction force is therefore directly proportional to the actual contact surface area. [5,10]

Depending on the character and condition of the surface, friction can be divided into hysteresis and adhesive.

$$F = F_h \cdot F_a \quad (3)$$

Where:

$F_h$  - Hysteresis friction

$F_a$  - Adhesive friction

Hysteresis friction expresses the deformation of inequalities on the surface of the softer component by the harder component. Adhesion friction is compared to hysteresis friction less significant. It occurs at each contact of the surfaces of the two bodies (effects of low molecular forces). [5,10]

As were written above friction laws depends on more factors for rubber vulcanizates than for common materials on which the equations (1) and (2) applies. In case of rubber vulcanizates, the friction coefficient decreases with increasing normal force and is highly dependent on composition of compound. Another difference is so called stick-slip effect in which the friction decreases rapidly with increasing speed. [5,10]

### 1.3.1.2 Friction measurement

Friction is measured between two surfaces in contact which move relative to each other. Generally, the friction measuring device consist of two bodies whose surfaces are in contact, moving device and system which indicates friction force. [5,10]

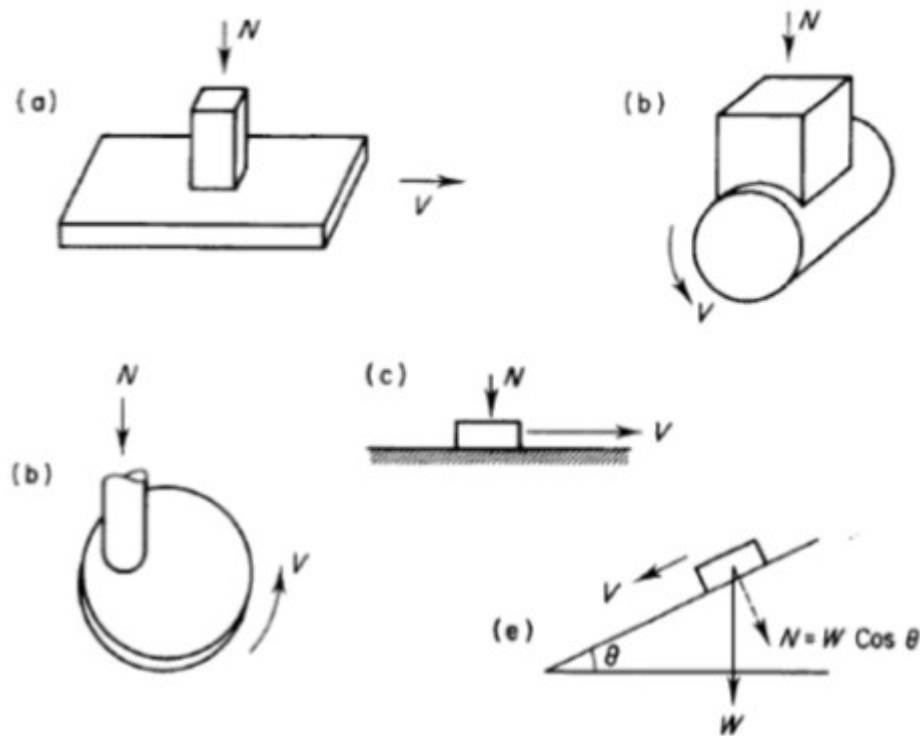


Figure 6: Friction measuring methods: a – linear track, b – shaft, c – dragging, d - roller with rotating disc, e - inclined plane [21]

Figure 6 schematically shows some of friction measuring methods. The most common method is 2c – dragging the sample. This method is very simple however dragging of sample against solid support may result in tilting of sample therefore the test result may be affected. [5,10]

### 1.3.2 Wear

Wear mechanisms acting on tread of a tire depends on terrain in which is tire used. Basically it means, that scale and type of wear on smooth terrain highly differs from wear which occurs during off-road or poor road conditions where the tires can get in contact with gravel, uneven road surface and diverse objects such as rocks, branches or various fragments. [11]

The main wear mechanisms influencing tread can be divided into three categories depending on the way wear occurs:

- Adhesive
- Abrasive
- Fatigue

#### ***1.3.2.1 Adhesive wear***

Adhesive wear occurs when two functional surfaces are in relative motion and pressed together by a force. Adhesion is caused by the strong adhesion forces between the materials in contact. Adhesive forces cause adhesion and the formation of micro-joints which are continually formed and disappear during the relative motion. Adhesive wear is characterized by the transfer of material from one surface to another. [10,12]

#### ***1.3.2.2 Fatigue wear***

Fatigue wear occurs in long-term cyclic deformation which results in change of stiffness and strength. It is accompanied by the formation of cracks below the surface of the material (pitting) and subsequently to the separation of material particles. [10]

#### ***1.3.2.3 Abrasive wear***

While fatigue wear occurs on smooth roads with minimal microstructure abrasive or cutting wear appears with increasing road harshness and higher force loads. [1]

Abrasive wear is a very intensive degradation process. It is caused by the effect of the hard and rough surface of the second body or by the effect of the hard particles in the material when the two functional surfaces are in contact. Abrasive wear is characterized mainly by scoring and cutting off the surface of the material. [10,12]

The vast majority of abrasive wear is caused by mechanical abrasion, but chemical degradation is an important role as well. Due to chemical degradation the vulcanizate loses its properties, thereby the mechanical abrasion is simultaneously increased. [5,10,13]

Depending on the type of movement of the vulcanizate, the mechanical abrasion can be divided into:

- a) Dragging motion
- b) Rolling motion

#### 1.3.2.3.1 Dragging motion

Two different abrasion types can occur during the dragging motion:

- Own abrasion – it is based on movement of vulcanizate over rough surface while the surface of the vulcanizate remains despite the volume loss smooth.
- Pattern abrasion – it differs from own abrasion by forming system of equilibrium grooves on surface of vulcanizate during the abrasion. Grooves are perpendicular to the dragging direction.

##### *1.3.2.3.1.1 Own abrasion*

The own abrasion can be observed when the specimen is rotating with respect to the dragging direction therefore the pattern does not form. Surface roughness of material is very important for own abrasion since the real contact surface between vulcanizate surface and rough surface is given by places where protrusions of both surfaces are in contact. Stress concentration starts at the point where both surfaces are in contact. The moving protrusion rolls the vulcanizate surface layer in front of it causing a creation of tensile stress on the sides of the groove. If the tensile stress overcomes mechanical strength of rubber it results in creation of crack on surface of vulcanizate what may cause in total tear of the material. Creation of crack releases the cumulated tension and process starts over again nearby. [9,14]

##### *1.3.2.3.1.2 Pattern abrasion*

Dragging of vulcanizate over rough surface without allowing specimen to rotate results in creation of abrasive patterns which may resemble waves. During the abrasion these waves bends and at a certain phase the ridge of the wave is torn off and the groove restores on the lower layer of vulcanizate. During abrasion, the waves move along the rubber surface in the direction of movement. The speed at which the waves move increases with the load. The size of the patterns depends on the load and roughness of the surface. In the case of pattern abrasion, the wear of the vulcanizate is greater than under the same conditions at own abrasion. This is due to the fact that during pattern abrasion larger particles are torn from the surface. [9,14]

#### 1.3.2.3.2 Rolling motion

Rolling of vulcanizate over rough surface results in some cases in slipping effect. Slippage occurs when the friction in the front area of contact is greater then the tangential stress which

acts on vulcanizate. During rolling motion dragging motion appears. Deformation energy starts to accumulate in vulcanizate because of dragging motion. This energy is exhausted on to friction work during the dragging motion. The hysteresis of the vulcanizate causes that part of the deformation energy is lost. Due to the loss of deformation energy there is less energy left to carry out the friction processes. Vulcanizate wear decreases with increasing deformation energy losses. [9,14]



## 2 TESTING METHODS

Methods for wear resistance testing of treads are very time consuming and economically demanding. They are carried out with already made tires in testing laboratories or on testing roads during driving tests. However important these tests are their complexity resulted in an effort to find method in which would be possible to test properties of different rubber compounds in short periods of time carried out on small samples. [15]

### 2.1 Test methods based on steady state loading conditions

These wear resistance testing methods works on the principle of constant loading of specimen on the abrasive surface. They usually result in weight loss of the test specimen after the test. However, when comparing wear resistance for different rubber materials, weight loss is often converted to volume loss and the wear resistance is then expressed as volume loss in mm<sup>3</sup> obtained under standardized conditions.

For increasing of the reliability of the wear results, the test conditions must be precisely defined and results of tested sample compared to the results of standardized sample obtained under the same conditions. [5,14]

When compared to a standardized sample, abrasion resistance can be expressed as:

$$\text{Wear resistance index (\%)} = \frac{V_S}{V_R} \cdot 100 \quad (4)$$

Where:

$V_S$  – volume loss of standardized sample [mm<sup>3</sup>]

$V_R$  – volume loss of tested sample [mm<sup>3</sup>]

#### 2.1.1 Bussen-Schlobach method

The method is based on a cylindrical sample with diameter of 16 mm and height of 6-10 mm which is abraded on a roller with abrasive coating. The test sample is inserted into a casing which is clamped in a sleeve on the pendulum slider. The rider mounted on the pendulum allows longitudinal movement of sample over rotating cylinder. Also, the sample is rotating around its own axis. The weight of the rider and the sleeve with casing is adjusted so that a force of 10 N which is a 1 kg load is applied to the test sample surface.

The test sample with casing is attached to the rider so its surface is perpendicular to the surface of the cylinder and protrudes 2 – 2,5 mm from the pendulum. Rotation of cylinder is started and the test sample is dragged over cylinder. As abrasive element on cylinder is used standard abrasive paper with corundum grains of defined size whose sharpness must be examine before each use of a standardized rubber sample. Weight loss of a standardized mixture on such surface after completion a total path of 40 m and force loading of 10 N should range from 180 to 220 mg. First, a standardized sample is tested, then three test samples and again standardized sample. The average rubber wear values is 6 mm<sup>3</sup> per 1 m of the path. [14,16]

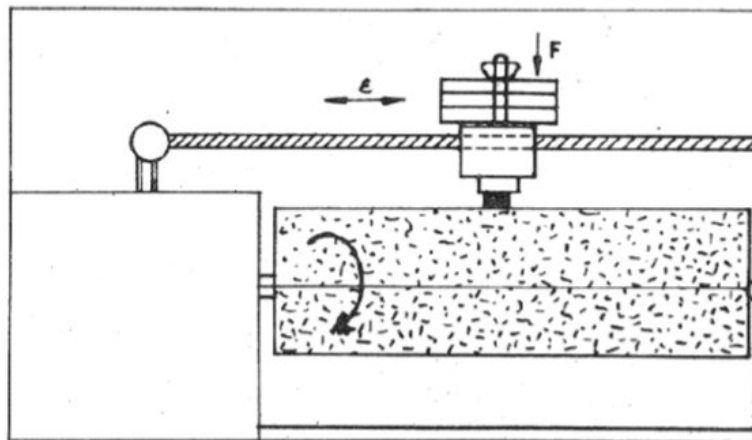


Figure 7: Bussen-Schlobach method [16]

### 2.1.2 Du Pont-Grasseli method

For this method 20 mm square cross section samples with height of 10 mm are used. The samples are provided with clamping part. Two samples are attached into the clamping part of instrument which presses them by constant pressure of 0,045 MPa on the abrasive disk of annular shape. Abrasive disk speed is 37 RPM. A new abrasive disk is used for each set of testing samples thereby the conditions remains same for next measurement.

The method begins by testing a pair of standardized samples, then two pairs of test samples and finally a pair of standardized samples. The abrasion period is selected according to the test samples. The more resistant material the longer is period of abrasion (3 – 5 minutes). The average rubber wear values are 10 mm<sup>3</sup> per 1 m of the path. [14,16]

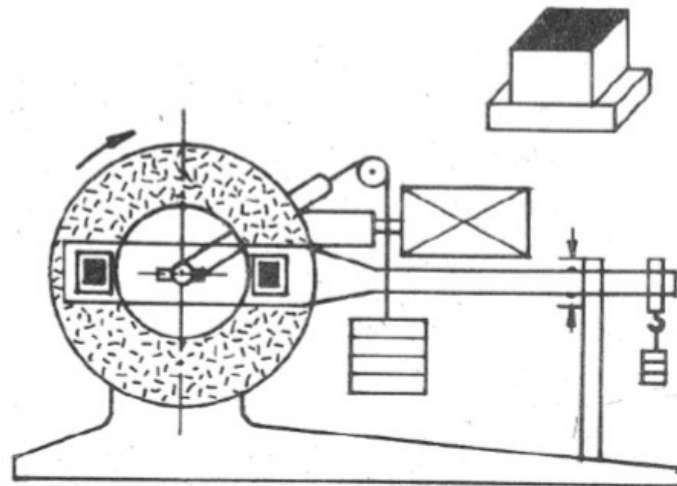


Figure 8: Du pont-Grasseli method [16]

### 2.1.3 Akron-Croydon method

A hollow disc with outer diameter of 64 mm, inner diameter of 43,6 mm and thickness of 12,7 mm is used as the test sample. Test sample is slid onto the shaft and rotates at a speed of 250 RPM. Carborundum disc is pressed on the testing sample by pressure of 0,28 MPa under the angle of  $15^\circ$ . The test is carried out by first testing the standardized material sample, then two test samples and finally two standardized samples. Abrasion resistance is determined as the volume loss of material per 1000 revolutions. [14,16]

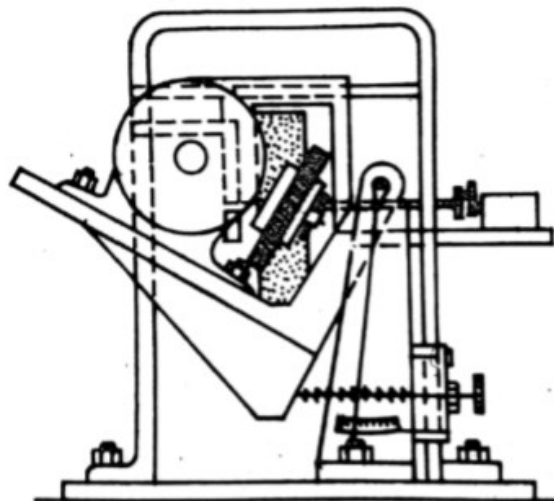


Figure 9: Akron-Croydon method [16]

### 2.1.4 Dunlop-Lambourn method

The method and test samples are similar to previous Akron-Croydon method. Test sample is a hollow disc with outer diameter of 64 mm, inner diameter of 43,6 mm and thickness of 10 mm which rotates at speed of 600 RPM. The corundum disk which is provided with separate propulsion is pressed onto the test sample. Slippage occurs at the point of contact due to different speeds and has a value of 16% for commonly performed tests. Test procedure is same as in Akron-Croydon method. Abrasion resistance is determined as the volume loss in  $\text{cm}^3$  per 1 km of the path. [14,16]

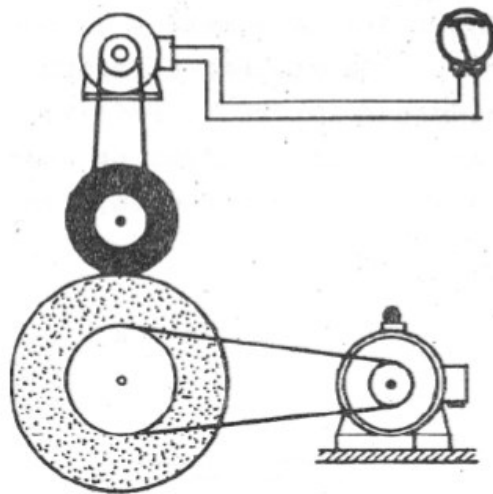


Figure 10: Dunlop-Lambourn method [16]

## 2.2 Testing methods based on dynamic loading conditions

Previously introduced methods deals only with static loads. However, if it comes to actually simulate real driving conditions it must be taken into account that behaviour of a car and structure of a roads are not static and constant. Therefore, new methods with dynamic loads had to be invented. [11,17]

These methods deals with phenomenon called chip and cut (CC) behaviour. This behaviour occurs when tread surface is exposed to concentrated, sliding impacts during diving over mm-scale asperities. These sliding impacts results in large normal and shearing stresses which can cause damage even chipping material from the surface. [11,17]

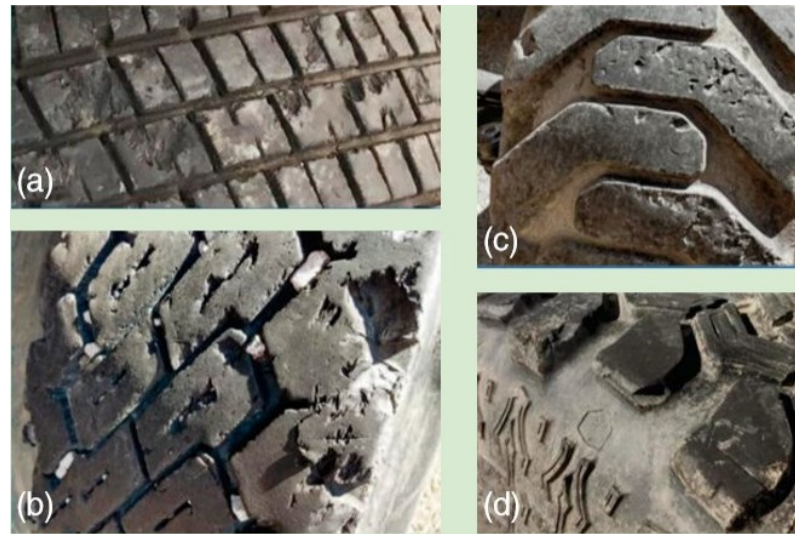


Figure 11: Examples of various extents of chip and cut damage to the treads of:  
 a,b – TBR/heavy truck tires, c – OTR/construction vehicle tire, d – mud-terrain  
 light truck tire [17]

Tire application where CC behaviour occurs most often include off-the-road tires for agriculture, all-terrain light truck tires, and heavy truck tires in poor road conditions. These tires comes into contact with a wide range of surfaces and textures, and the tread is exposed to sharp asperities while the tire transmits complex vehicle forces through the contact path. [18,19]

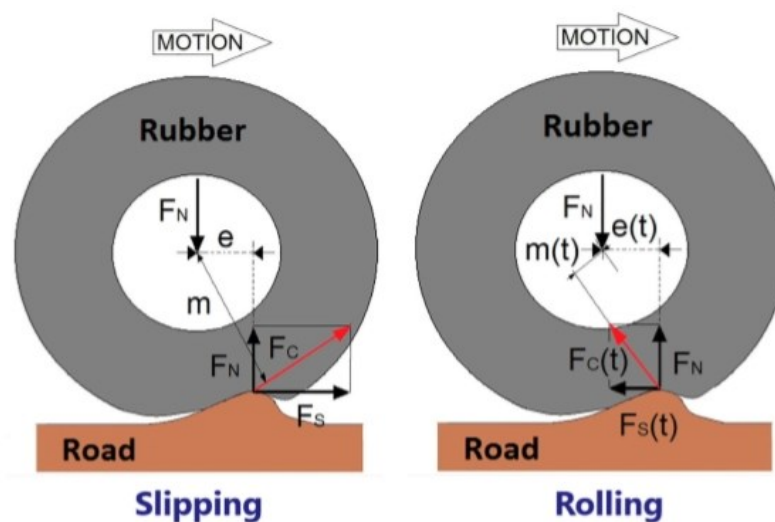


Figure 12: Schematic visualization of forces on a tire moving across an asperity, where the left diagram demonstrates slipping and a rolling process is shown on the right. The normal force ( $F_N$ ), shear force ( $F_s$ ), and resultant force ( $F_C$ ) are

shown along with the shift in centre of normal load (e) and the actuating moment (m). [11]

Picture 12 shows interaction of tire and road asperity for rolling and slipping. Slipping generates higher shear forces than rolling, and the shear force direction in slipping promotes more crack opening and growth. [11]

### 2.2.1 Beatty-Miksich Cutting and Chipping tester

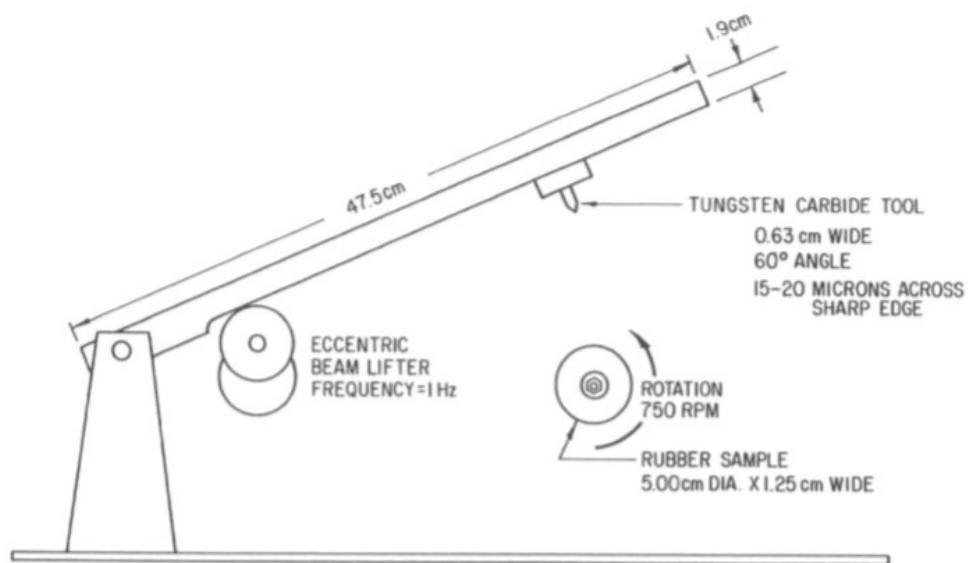


Figure 13: Beatty-Miksich Cutting and Chipping tester [20]

This method was introduced by Beatty and Miksich in 1982 and laid the foundation for future development of new testing methods for chip and cut behaviour. Method is based on sharp tool impacting rotating rubber sample of hollow disc geometry. Tool is attached to arm which is lifted in desired frequency by eccentric beam lifter. Force of an impact is determined from weight of an arm with tool and height from which it impacts. Rotation speed of a sample was selected 750 rpm. Impacting tool over time creates a groove in sample. The size of a groove and weight loss of sample are two resulting parameters which describes chip and cut resistance of rubber compound. [20]

### 2.2.2 Experimental Chip-Chunk method

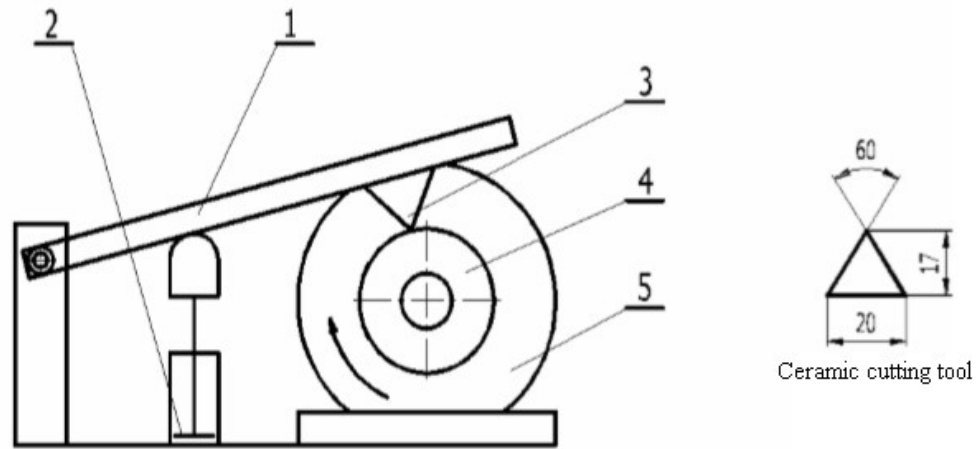


Figure 14: Experimental Chip and Chunk method [15]

This method has the identical principle as Beatty and Miksch cutting and chipping tester. Test sample is a hollow disc with outer diameter of 55 mm, inner diameter of 15 mm and thickness of 13. Test sample is clamped with nuts and clamping washers with spikes to prevent slipping into the shaft groove. The shaft is driven by an electric motor. Rotation speeds of sample can be chosen between 500, 750 and 910 RPM. The cutting tool then impacts the sample and gradually cuts off the material resulting in forming groove in the sample. The size of a groove produced by the cutting tool over time and weight loss is a measure of wear.

Unfortunately, interactivity of this device rests only on speed of sample eventually tool geometry. This means small range of possible loading conditions. [15]

Generally, the bot introduced methods are based on the determination of the weight loss after the impacting of the sharp tool. However, from the industry it has been approved that the weight loss parameter does not contribute to the understanding of the CC phenomenon and the ranking of the weight loss does not correspond with the field tests realized on real tires. Thus a new testing method and equipment were necessary to be developed and evaluated to be simulating the real process of tire in lab conditions and finally to determine the CC behaviour quantitatively based on physical parameters. Such testing method and equipment has been developed and firstly introduced by Stoczek at al in [11] and the equipment is used for the conducting of experimental part of this diploma thesis.

## **II. ANALYSIS**



### 3 PREPARATION OF SAMPLES

#### 3.1 Rubber compound recipes

Two rubber compounds were used for study of dynamic wear of rubber (Table 1). First based on natural rubber (NR) and second based on styrene butadiene rubber (SBR). As a filler carbon black (CB) N330 was used.

Table 1: Recipe of compounds in phr

	<b>SBR</b>	<b>NR</b>
Master Batch	<b>E-SBR 1500</b>	100
	<b>SMR20 NR</b>	-
	<b>N330 CB</b>	50
		50
Final Batch	<b>Zinc oxide</b>	2
	<b>Stearic acid</b>	1
	<b>Sulfur</b>	2
	<b>TBBS</b>	2
	<b>6PPD</b>	1
	<b>Total phr</b>	<b>158</b>

#### 3.2 Preparation of compounds

Rubber compounds were mixed in two steps. Both of these steps were performed in an internal mixer SYD-2L. First the master batch was prepared with a rotor speed of 50 rev min<sup>-1</sup>, mixing chamber temperature of 100 °C. and fill factor of 0,7. First the polymer (NR or SBR) was mixed for 1 min. Then CB was added and mixed with polymer for 3 minutes to reach a drop temperature of 150 °C. The master batch was then milled and sheeted with a two-roll mill at temperature of 60 °C. In second step, the final batch was prepared using rotor speed of 35 rev min<sup>-1</sup> with a mixing chamber temperature of 70 °C. First the master batch compound was mixed for 1 min followed by adding the complete vulcanization system and mixed for 2 more minutes, with a drop temperature of 110 °C. Then the final batch was milled and sheeted with a two-roll mill at 60 °C.

Before further use the final batches were stored for 24 hours.

### 3.3 Preparation of testing samples

The curing characteristics including  $T_{90}$  the time to reach 90% of final cure state were evaluated at 160 °C. The test samples were hollow discs of the geometry given in Figure 15 prepared in the mold of the required geometry. Samples were prepared by pressing in the heated LabEcon 300 hydraulic press at temperature of 160 °C and pressure of 150 kN with curing time  $T_{90} + 1$  minute per 1 mm of the thickness.

## 4 EXPERIMENTAL METHOD

### 4.1 Basic material characterization

#### 4.1.1 Hardness test

The measurement was performed according to the standard ČSN ISO 7619-1. Device was used Hardness tester Shore A. Test specimen is formed by three layers of plate with dimension 12,5 x 12,5 x 0,2 mm.

#### 4.1.2 Tensile test

The test was performed according to the standard ČSN ISO 37. Device which was used was Testometric M350-5CT. A dumbbell-shaped specimen (ISO 37- TYPE 2) was used.

### 4.2 Cut and Chip analyses

#### 4.2.1 Testing device

Measurement of rubber wear resistance under the dynamic load was performed on the rubber samples using the Instrumented Chip and Cut Analyzer ICCA™ (Coesfeld GmbH, Germany). Mechanical principle of ICCA shown in Figure 15 used for measurement is illustrated in Figure 16. [11]



Figure 15: Photograph of instrumented chip and cut analyser (left) and diagram of rubber sample geometry (right). [11]

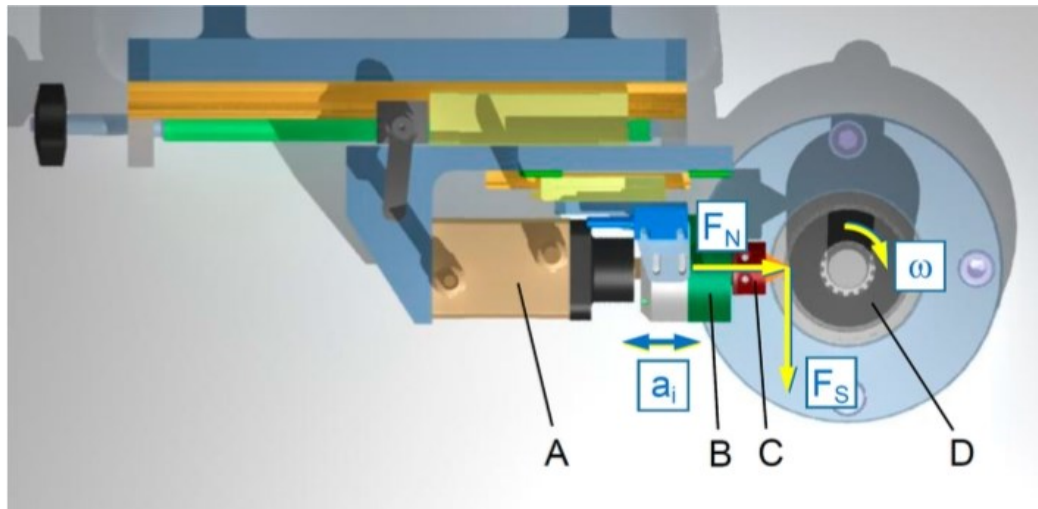


Figure 16: Schematic of ICCA measuring principle, with: pneumatic actuator (A), two-axis load cell (B), holder + impactor (C), and cylindrical rubber test specimen (D). [11]

The main advantage in measurement with chip and cut analyser is based on range of defined, measured, controlled and calculated parameters. The types of input parameters and output parameters are listed in Table 2 along with their ranges and units. The range of variable loading conditions of this instrumented method is critical to generating laboratory data that can predict the CC behaviour in complex rubber applications like tire treads. [11]

Testing with the ICCA is based on rotating the rubber sample fixed in rotatable clamping device using a safety sleeve and impacting the sample with a stainless-steel tool with specific frequency. The rotation speed, impacting normal force, frequency, and contact (sliding) time with the rubber surface can all be independently controlled. All of these parameters including tool must be chosen proportionally to problem that is investigated to gain valuable results. The main characteristic factor that is evaluated from the results is the CC propensity,  $P$  illustrated for two compounds with different CC resistance in Figure 17. [11]

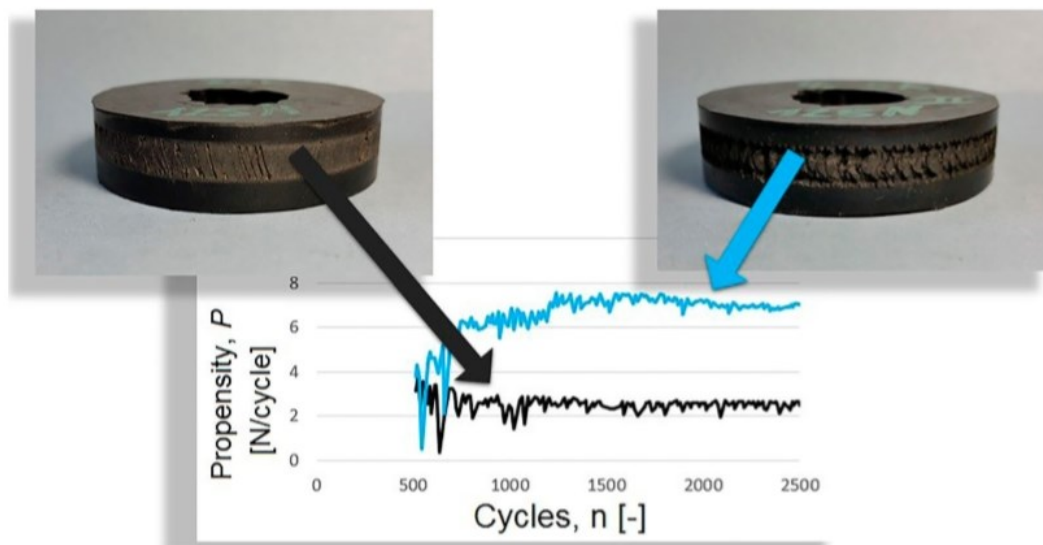


Figure 17: Examples of  $P$  versus  $n$  for two compounds with different CC resistance.

[11]

The parameter  $P$  describes the roughness of a materials surface which reflect the CC resistance. Simply, less CC resistance of material evokes more roughness and larger shear forces  $F_s$  recorded by a load cell. The parameter  $P$  is then determined from integrating the fluctuation in mentioned shear force  $F_s$  over a number of impact cycles using equation (5) where  $f(\max)$  and  $f(\min)$  are illustrated in Figure 18. A higher the value of  $P$  relate to lower CC resistance. [11]

$$P = \frac{\int_0^n f(\max)dn - \int_0^n f(\min)dn}{n}, \left[ \frac{n}{\text{cycle}} \right], \quad (5)$$

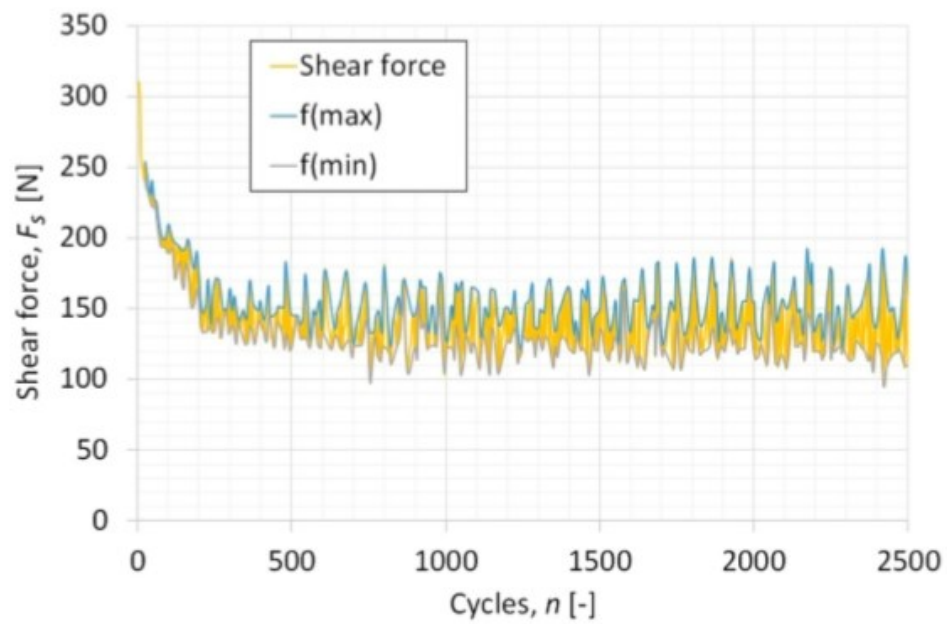


Figure 18: Determination of the CC propensity ( $P$ ) from the shear force fluctuations. [11]

Table 2: List of parameters for instrumented chip and cut analyser (ICCA).

Parameter	Range	Unit	Parametre type			
			Defined	Measured	Controlled	Calculated
Rotation speed, $\omega$	100-1500	rev min <sup>-1</sup>	✓	✓	✓	
Impact frequency, $f$	0-10	Hz	✓	✓	✓	
Number of impact cycles, $n$	0 to undefined	-	✓	✓	✓	
Contact time, $t_s$	20 to permanent	ms	✓	✓	✓	
Normal force, $F_N$	0-500	N	✓	✓	✓	
Shear force, $F_s$	0-900	N		✓		
Resulting force, $F_c$	Calculated	N				✓
Depth of indentation, $a_i$	0-20	mm		✓		
Friction distance, $a_f$	Measured	mm		✓		
Normal energy, $E_N$	Calculated	J				✓
Shear energy, $E_s$	Calculated	J				✓
Friction coefficient, $C_f$	Calculated	-				✓
Chip and cut propensity, $P$	Calculated	N/cycle				✓

#### 4.2.2 Tools

As written above as impactor is used a stainless-steel tool described in Figure 19. It is designed to simulate asperities with which the tread can come together during performance.

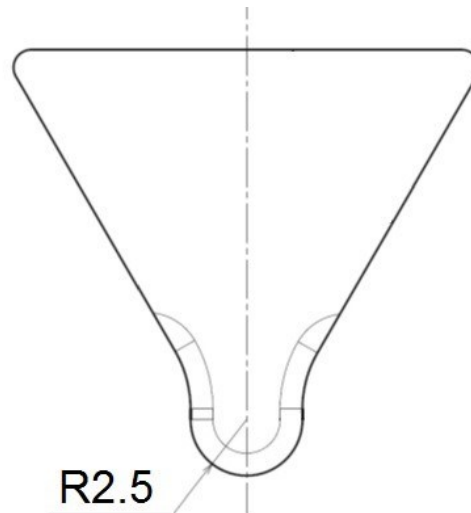


Figure 19: Stainless-steel impactor tool no. 4. [11]

For measurement 5 varied tools with different tip radius were used. The smaller the tip radius is the sharper object it simulates. Tools are listed in Table 3.

Table 3: List of used impacting tools.

Tool no.	Main radius
1	R 1
2	R 1,5
3	R 2
4	R 2,5
5	R 3



Figure 20: Picture of impacting tools.

### 4.2.3 Boundary conditions of analysis

#### 4.2.3.1 Force and speed

In the first measurement the normal force  $F_N$  and rotation speed  $\omega$  were varied according to Table 4. Contact time  $t_s$ , number of impact cycles  $n$  and impact frequency  $f$  were constant. As impactor was used tool no. 4. Measurement was conducted in three series of samples for each NR and SBR.

Table 4: List of boundary condition for first measurement.

Sample no.	$F_N$ [N]	$\omega$ [rev min <sup>-1</sup> ]	$t_s$ [ms]	$n$ [-]	$f$ [Hz]
1	100	150	30	4000	5
2	125	150	30	4000	5
3	150	150	30	4000	5
4	175	150	30	4000	5
5	200	150	30	4000	5
6	100	200	30	4000	5
7	125	200	30	4000	5
8	150	200	30	4000	5
9	175	200	30	4000	5
10	200	200	30	4000	5
11	100	250	30	4000	5
12	125	250	30	4000	5
13	150	250	30	4000	5
14	175	250	30	4000	5
15	200	250	30	4000	5

#### 4.2.3.2 Contact time

The second measurement was based on variations of contact time  $t_s$ , normal force  $F_N$  and rotation speed  $\omega$  according to Table 5. Number of impact cycles  $n$  and impact frequency  $f$  were constant. As impactor was used tool no. 4. Measurement was conducted in one series of samples for each NR and SBR.

Table 5: List of boundary condition for second measurement.

Sample no.	$F_N$ [N]	$\omega$ [rev min <sup>-1</sup> ]	$t_s$ [ms]	$n$ [-]	$f$ [Hz]
1	100	150	60	4000	5
2	100	150	40	4000	5
3	150	200	60	4000	5
4	150	200	40	4000	5
5	200	250	60	4000	5
6	200	250	40	4000	5



#### 4.2.3.3 Tools

The third measurement was based on variations of tools and normal force  $F_N$  according to Table 6. Normal force  $F_N$ , contact time  $t_s$ , rotation speed  $\omega$ , number of impact cycles  $n$  and impact frequency  $f$  were constant. Measurement was conducted in one series of samples for each NR and SBR.

Table 6: List of boundary condition for third measurement.

Sample no.	Tool no.	$F_N$ [N]	$\omega$ [rev min <sup>-1</sup> ]	$t_s$ [ms]	$n$ [-]	$f$ [Hz]
1	1	100	200	50	4000	5
2	2	100	200	50	4000	5
3	3	100	200	50	4000	5
4	4	100	200	50	4000	5
5	5	100	200	50	4000	5

#### 4.2.3.4 Aramid content

The final measurement was based on variations of aramid content in compound mixture. Aramid content and load conditions are given by Table 7. Measurement was conducted in three series of samples for each NR and SBR.

Table 7: List of boundary condition for fourth measurement.

Aramid content [phr]	$F_N$ [N]	$\omega$ [rev min <sup>-1</sup> ]	$t_s$ [ms]	$n$ [-]	$f$ [Hz]
0	200	150	50	4000	5
5	200	150	50	4000	5
10	200	150	50	4000	5
15	200	150	50	4000	5

## 5 RESULTS AND DISCUSSION

For the characterization of compounds, the following tests were performed: Hardness test, Tensile test and Dynamic wear resistance analysis.

### 5.1 Hardness test

Hardness test was carried out for the basic characterization of used materials according to description in Chapter 4.1.1. The determined data are listed in Table 8.

Table 8: Results of Hardness test

Sample	Hardness Shore A
NR	57,0 ± 0,7
SBR	64,4 ± 0,5

### 5.2 Tensile test

Tensile test was then carried out according to description in Chapter 4.1.2. The results are listed in Table 9.

Table 9: Results of Tensile test

Sample	Stress at 100% elongation [MPa]	Stress at 300% elongation [MPa]	Stress at break [MPa]	Strain at break [%]
NR	2,0 ± 0,2	8,9 ± 0,8	22,9 ± 3,1	599 ± 63
SBR	2,5 ± 0,1	10,9 ± 0,5	21,9 ± 1,6	501 ± 32

### 5.3 Cut and Chip analyses

For characterization of CC resistance of samples made from NR compound and SBR compound described in Chapter 3.1 under the different loading conditions was used CC analysis presented in Chapter 4.1.

#### 5.3.1 CC resistance for NR and SBR under different loading conditions

Because of the scale of loading conditions given by Table 4 results will be divided into five categories by normal force  $F_N$  and a summary will be made at the end of the chapter.

5.3.1.1  $F_N = 100N$

For the first series parameter P was measured for loading  $F_N = 100N$  and rotation speeds  $\omega_1 = 150$  rpm,  $\omega_2 = 200$  rpm and  $\omega_3 = 250$  rpm.

Both NR and SBR parameter P values illustrated in Figure 21 and Table 10 resulted similar with no greater fluctuations. Rotation speeds under the small loading force had no greater influence on the test and its results.

However the approximately similar results in parameter P the surface of the samples differs. NR samples surface illustrated in Figure 28 showed beginning of cracks under distinct angles and two inner lines representing footprint from the tool. SBR samples surface illustrated in Figure 28 showed no visible cracks.

Both compound samples showed slight wear but no cutting or chipping of material.

Table 10: Results of propensity P under loadings 1,6 and 11.

Sample no.	NR CC propensity P [n/cycle]	SBR CC propensity P [n/cycle]
1	$6,8 \pm 0,8$	$6,9 \pm 0,3$
6	$5,2 \pm 0,8$	$7 \pm 1$
11	$5,3 \pm 0,4$	$9 \pm 2$

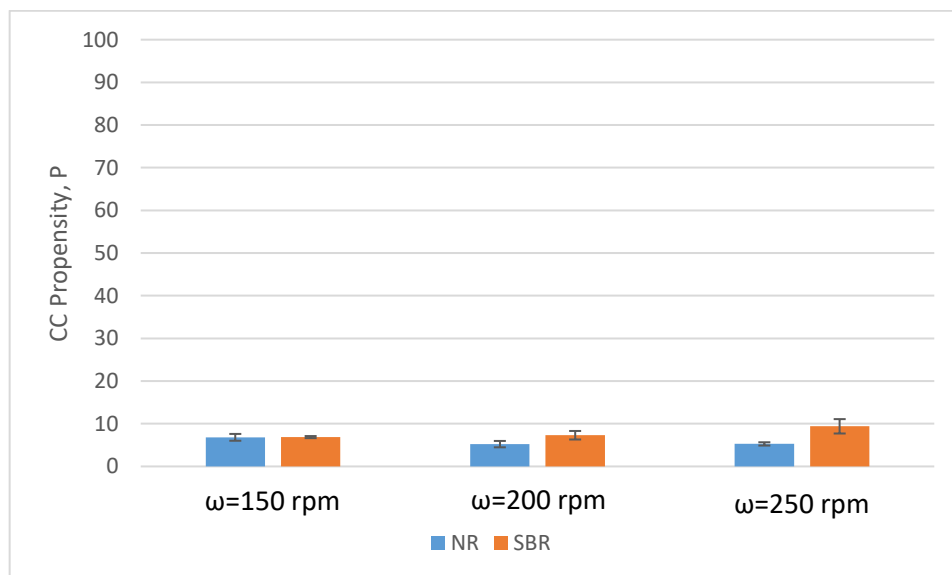


Figure 21: Graphical representation of CC Propensity, P results under loadings 1,6 and 11.

**5.3.1.2  $F_N = 125N$**

For the second series parameter P was measured for loading  $F_N = 125N$  and rotation speeds  $\omega_1 = 150$  rpm,  $\omega_2 = 200$  rpm and  $\omega_3 = 250$  rpm.

Both NR and SBR parameter P values illustrated in Figure 22 and Table 11 increased proportionally compared to the first measurement with no larger differences among two compounds. Wear of NR samples as resulting parameters is greater with crack crossing and two inner lines representing footprint from the tool but still it safe to say it is only surface wear with no chipping. For SBR samples few C shaped cracks emerged across the surface but with no additional material removal.

Table 11: Results of CC propensity P under loadings 2,7 and 12.

Sample no.	NR CC propensity P [n/cycle]	SBR CC propensity P [n/cycle]
2	15 ± 4	7 ± 1
7	11 ± 4	11 ± 4
12	11 ± 3	7,6 ± 0,5

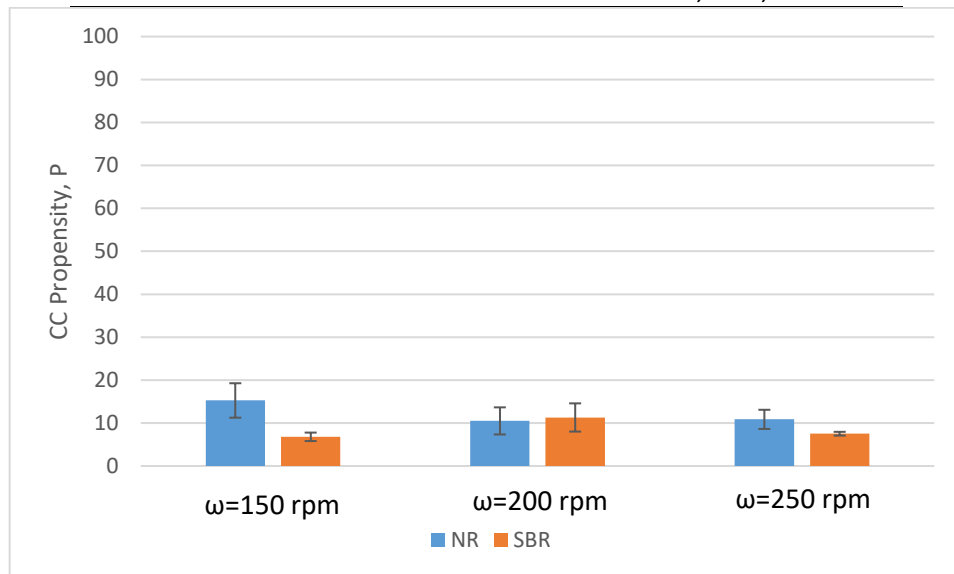


Figure 22: Graphical representation of CC propensity P results under loadings 2,7 and 12.

**5.3.1.3  $F_N = 150N$**

For the third series parameter P was measured for loading  $F_N = 150N$  and rotation speeds  $\omega_1 = 150$  rpm,  $\omega_2 = 200$  rpm and  $\omega_3 = 250$  rpm.

Under the loading of  $F_N = 150N$  behaviour of the rubber compounds started to differ. While SBR samples continued the trend of parameter P values illustrated in Figure 23 and Table

10 increased proportionally NR samples showed large increase of parameter P. As Figure 23 shows NR compound behaviour was greatly affected by rotation speeds. This disparity in parameter P values is caused by greater disproportionate in shearing force  $F_s$  described in chapter 4.1 during the measurement of NR samples. These results are supported by Figure 28 which shows great wear of NR samples where large particles were cutted off from their surface in comparison with almost non chipping on SBR samples surface.

Table 12: Results of CC propensity P under loadings 3,8 and 13.

Sample no.	NR CC propensity P [n/cycle]	SBR CC propensity P [n/cycle]
3	25 ± 4	15 ± 4
8	39 ± 5	11 ± 3
13	46 ± 7	11 ± 2

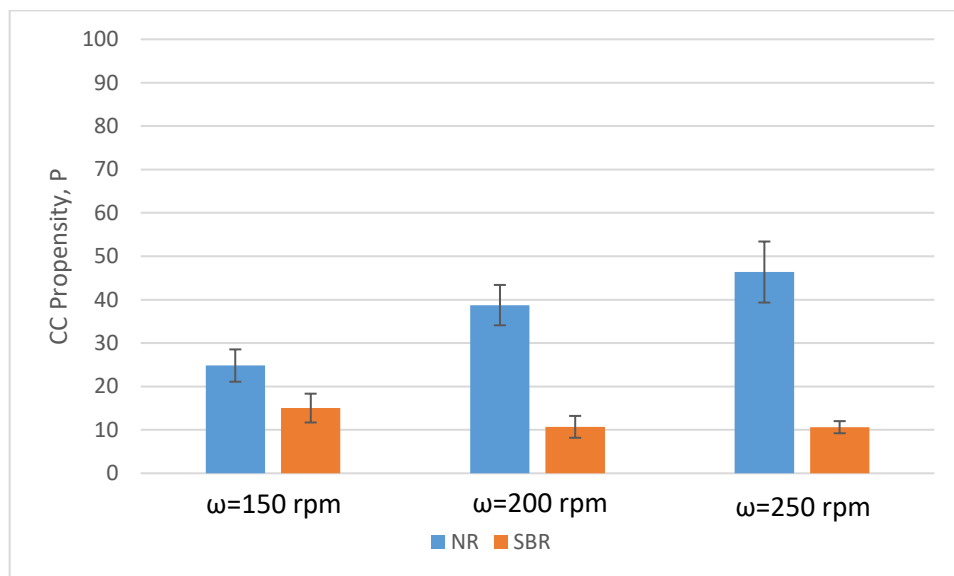


Figure 23: Graphical representation of CC propensity P results under loadings 3,8 and 13.

**5.3.1.4  $F_N = 175N$**

For the fourth series parameter P was measured for loading  $F_N = 175N$  and rotation speeds  $\omega_1 = 150$  rpm,  $\omega_2 = 200$  rpm and  $\omega_3 = 250$  rpm.

As the third series could be looked at as breaking point for NR behaviour the fourth series is especially important for a change in behaviour of SBR samples. The grow of parameter P of SBR could be described as far as critical as the Figure 24 and Table 13 shows. Multiple parameter P increase is caused by beginning of removal of large chips of material during the

measurement as shows Figure 28 and therefore large disproportionate in shearing force  $F_s$ . Behaviour of NR samples is very interesting as well. While the samples NR<sub>9</sub> and NR<sub>14</sub> continued the trend the NR<sub>4</sub> sample kept the same behaviour as sample in the third series NR<sub>3</sub> therefore the dynamic wear resistance wasn't affected by increase in loading.

Table 13: Results of CC propensity P under loadings 4,9 and 14.

Sample no.	NR CC propensity P [n/cycle]	SBR CC propensity P [n/cycle]
4	26 ± 5	53 ± 6
9	64 ± 10	40 ± 4
14	68 ± 10	60 ± 20

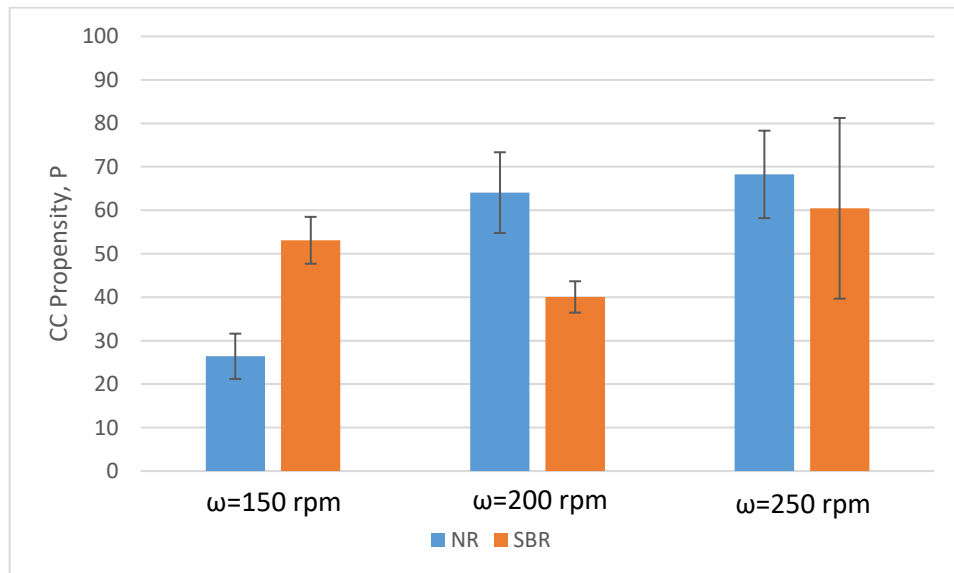


Figure 24: Graphical representation of CC propensity P results under loadings 4,9 and 14.

### 5.3.1.5 $F_N = 200N$

For the last series parameter P was measured for loading  $F_N = 200N$  and rotation speeds  $\omega_1 = 150$  rpm,  $\omega_2 = 200$  rpm and  $\omega_3 = 250$  rpm.

The last measurement was in terms of large chip and cut behaviour on both rubber compounds but in different way of process. While the cutting off of NR material remained primarily in path of a tool and cracks didn't emerge beyond this boundary the cracks on surface of SBR samples emerged beyond and material was removed even from beyond the tool path as shown in Figure 28 Parameter P results illustrated in Figure 25 and Table 14 shows a very interesting behaviour of NR<sub>5</sub> sample which acted the same way as NR<sub>3</sub> and NR<sub>4</sub>.

Table 14: Results of CC propensity P under loadings 5,10 and 15.

Sample no.	NR CC propensity P [n/cycle]	SBR CC propensity P [n/cycle]
5	19 ± 8	61 ± 10
10	63 ± 2	74 ± 2
15	83 ± 10	78 ± 6

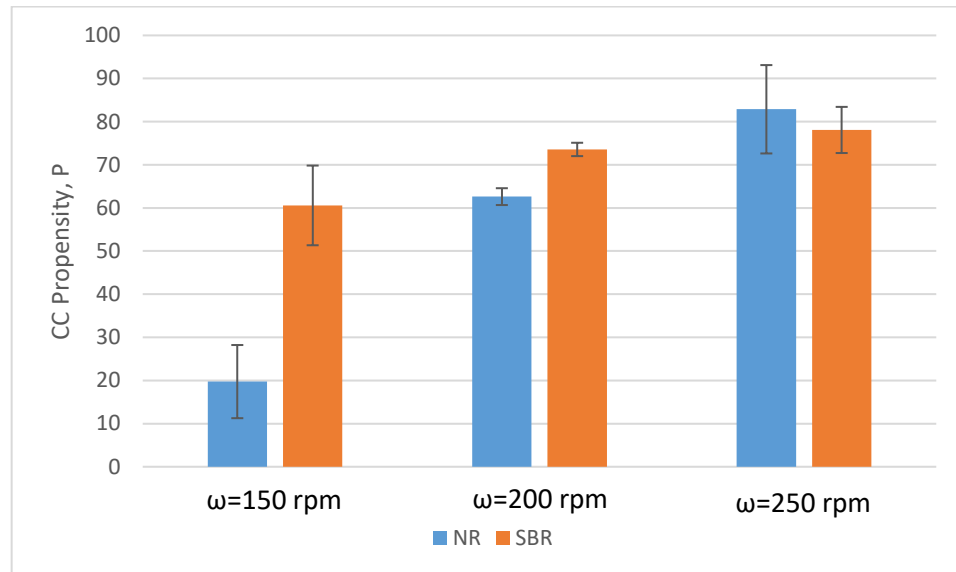


Figure 25: Graphical representation of CC propensity P results under loadings 5,10 and 15.

### 5.3.1.6 Summary

According to Figure 26 and Figure 27 the CC propensity P rises for NR proportionally to combination of  $F_N$  loading and  $\omega$  rotation speed. While the CC propensity is steady until the breaking point where  $F_N = 175\text{N}$  loading was applied for the SBR compound. After this loading point SBR showed very poor dynamic wear resistance independent on the rotation speeds. The most interesting region of NR behaviour is under rotation speed of  $\omega = 150$  [rpm] where the increasing loading had no significant effect on dynamic wear of samples. Generally, the results are showing very systematically, that the SBR material is more resistant against CC mechanism at region of lower applied normal forces, however over the value 150 N the CC resistance decreases rapidly compare to NR. Thus, the NR material is much more resistant against CC mechanism in the higher region of applied normal forces compare to SBR.

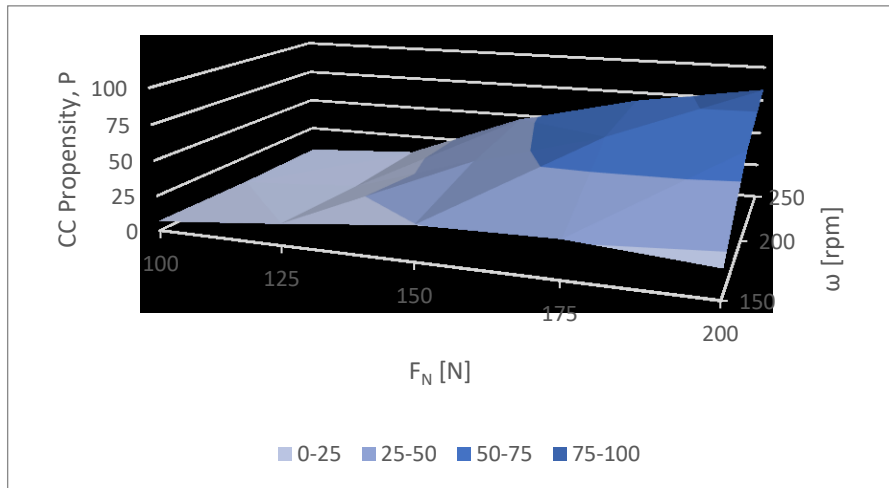


Figure 26: Graphical representation of CC propensity P overall results for NR.

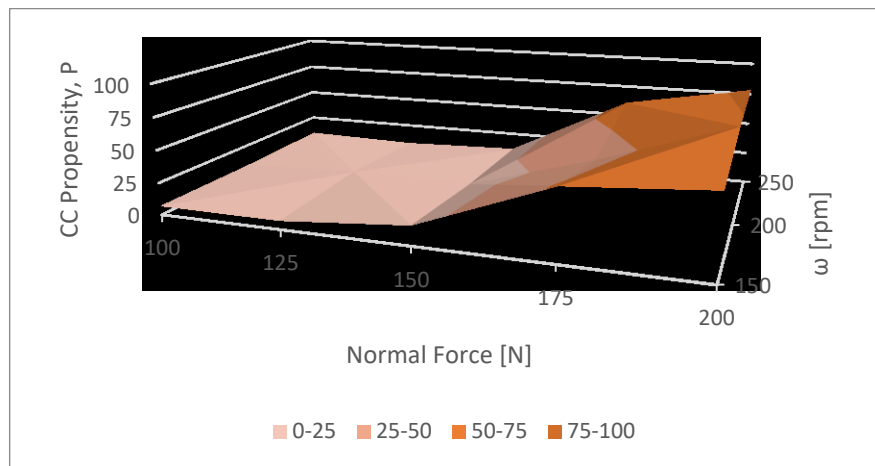


Figure 27: Graphical representation of CC propensity P overall results for SBR.

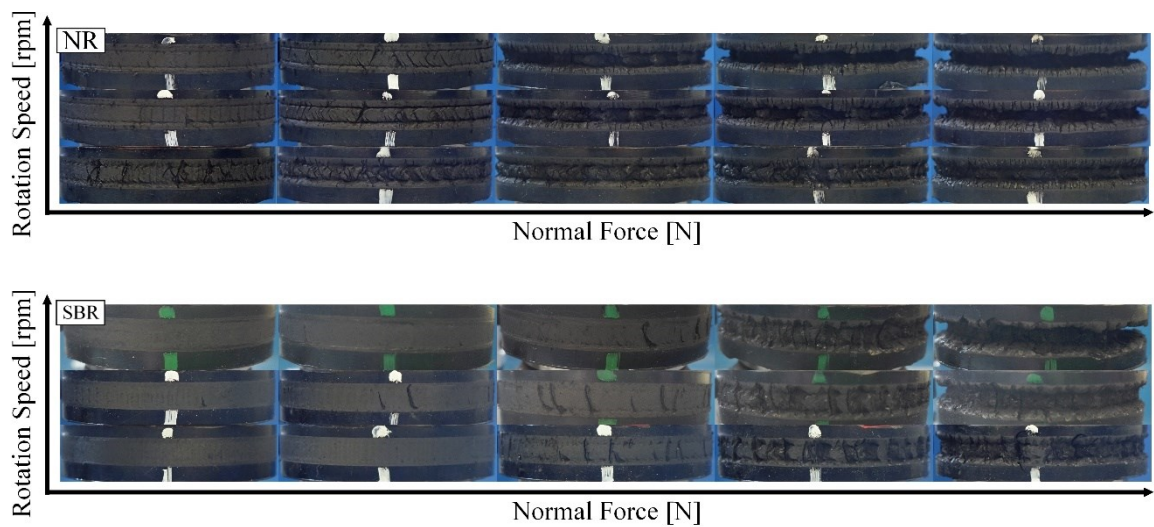


Figure 28: Images of worn NR and SBR samples compared to  $F_N$  [N] and  $\omega$  [rpm] loading.



### 5.3.2 Influence of varied tip radius of the tool on CC resistance of NR and SBR

Measurement was conducted under loading conditions given by Table 6.

In the beginning it is important to state that this measurement was conducted for NR samples and SBR samples in one series under the one loading condition. Therefore the results are rather exemplary and informative for future study. However the trends of compounds behaviour observed in first measurement approximately matched and may be related for this test.

The measurement results illustrated in Figure 29 proved assumption that the sharper the impacting tool is the greater and intense wear appears which cause a large disproportionate in shearing force  $F_S$  and therefore the parameter  $P$  increases for both NR and SBR samples.

Extreme differences between NR and SBR samples behaviour for third and fourth tool are very interesting. From pictures of worn samples in Figure 30 can be assumed that the cracks on NR surfaces emerged very fast and led to intense cutting off of material while the SBR surfaces under small loading force  $F_N = 100\text{N}$  resisted much better against the formation of deep cracks which would cause chipping.

Results from first measurement indicate that usage of greater loading force  $F_N$  together with sharper tools would cause very different behaviour of SBR samples.

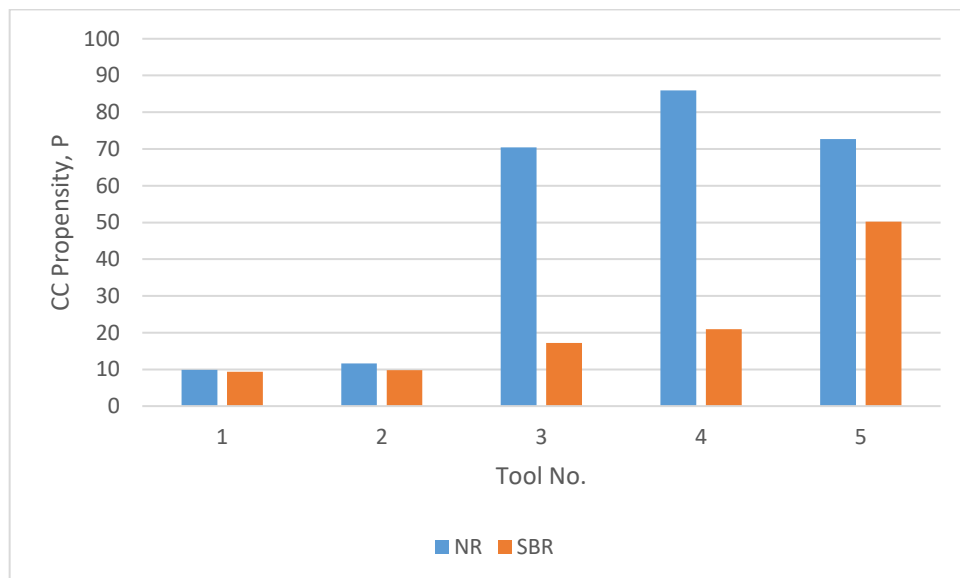


Figure 29: Graphical representation of CC propensity  $P$  results for different impacting tools.



Figure 30: Images of worn NR and SBR samples for different impacting tools.

### 5.3.3 CC resistance for NR and SBR for different contact time $t_s$

Measurement was conducted under loading conditions given by Table 5

As in chapter describing influence of different tools it is important to state that this measurement was conducted for NR samples and SBR samples in one series. Therefore the results are as well rather exemplary and informative for future study.

Measurement proved that longer the contact time  $t_s$  is the greater wear on samples occurs. Differences are mainly under higher loading conditions. Which is caused by a large disproportionate in shearing force  $F_s$ .

Results illustrated in Figure 31 and 32 shows more significant drop of parameter P for NR then for SBR.

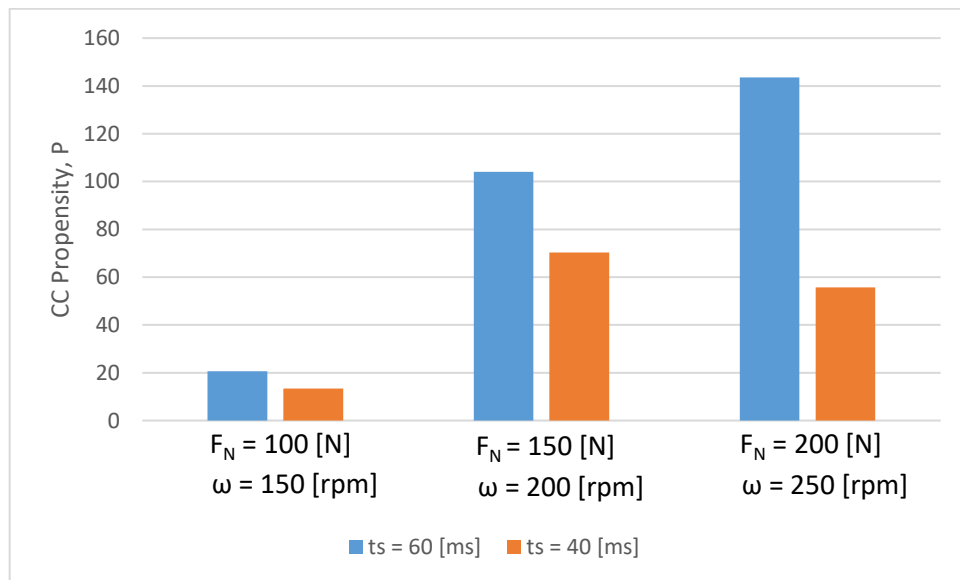


Figure 31: Graphical representation of CC propensity P results for NR under different contact time  $t_s$ .

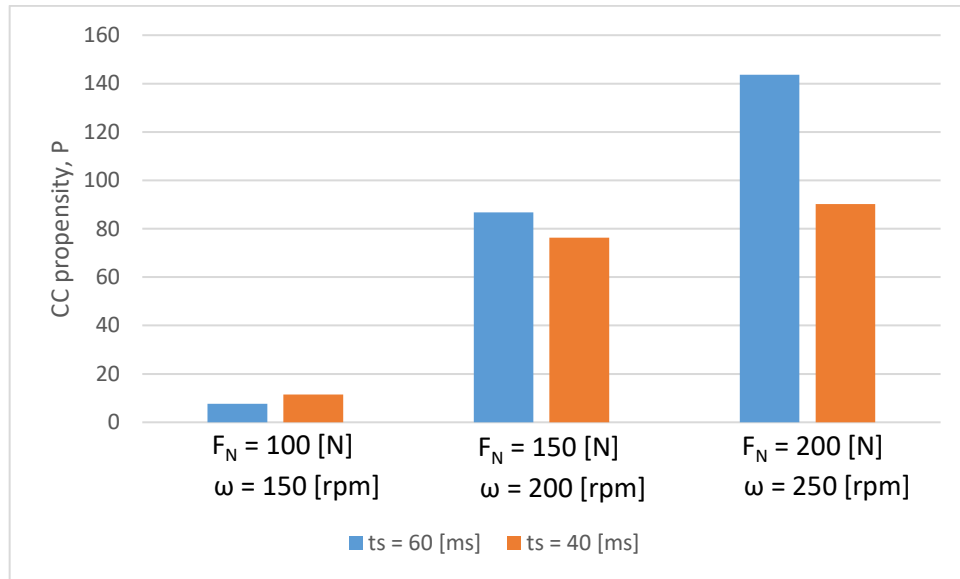


Figure 32: Graphical representation of CC propensity P results for SBR under different contact time  $t_s$ .

#### 5.3.4 CC resistance for NR and SBR with different Aramid content

Measurement was conducted under loading conditions given by Table 7.

Results illustrated in Figures 33 and 34 and Table 15 shows extensive negative influence of aramid content on CC resistance for NR samples while CC resistance for SBR samples was slightly improved.

Table 15: Results of propensity P for different aramid content.

Aramid content	NR CC propensity P [n/cycle]	SBR CC propensity P [n/cycle]
0	$19 \pm 8$	$61 \pm 10$
5	$47 \pm 6$	$53 \pm 8$
10	$47,5 \pm 0,6$	$48 \pm 3$
15	$43 \pm 6$	$45 \pm 3$

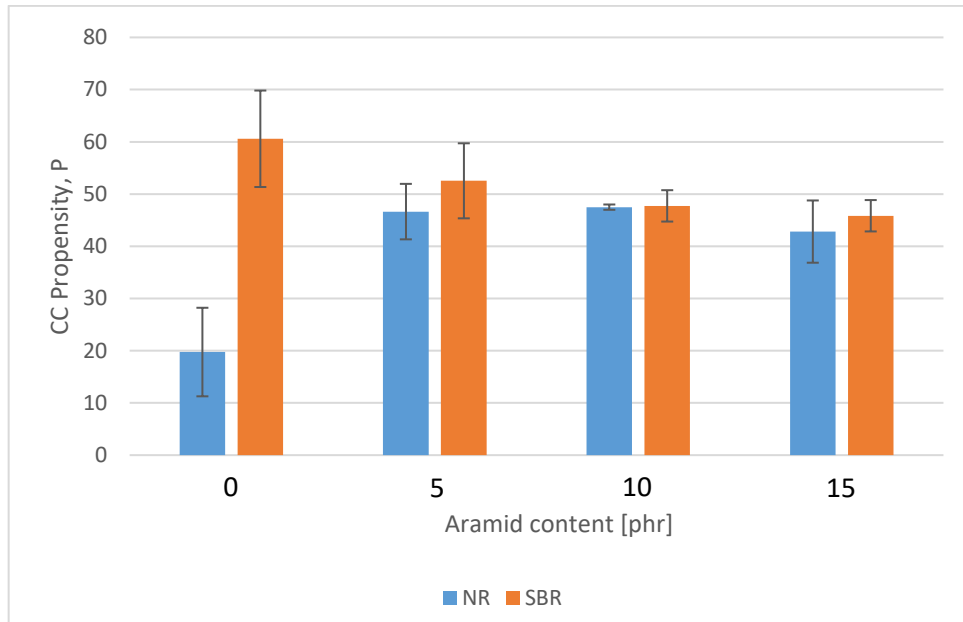


Figure 33: Graphical representation of CC propensity P results for different aramid content.



Figure 34: Images of worn NR and SBR samples for different aramid content.

## CONCLUSION

This thesis deals with rubber wear resistance under different dynamic loadings for CB-reinforced rubber compounds of NR and SBR used in tread manufacturing process. Thesis includes measurement of fundamental material properties and advanced material characterization of CC resistance. Measurement of CC resistance was divided into four categories based on variations of normal force  $F_N$  and rotation speeds  $\omega$ , variations of impacting tools, variations of contact time  $t_s$ , and variations of aramid content in rubber compound.

Measurement proved fundamental differences between NR and SBR compounds dynamic wear resistance. This different behaviour was more significant under higher loading forces combined with low rotation speeds where NR compound kept its high dynamic wear resistance while SBR compound showed great increase in wear.

Measurement of variation of impacting tools confirmed the assumption that the sharper the impacting tool is the greater and more intense wear appears. Significant differences between compounds behaviour indicates that this assumption was more significant for NR compounds than SBR compounds which kept their high wear resistance under the small loading force.

Measurement of variations in contact time  $t_s$  proved that longer the contact time  $t_s$  is the greater wear on samples occurs. Differences were observed mainly under higher loading conditions.

The last measurement proved negative influence of aramid content in NR compound on its wear resistance while slight improvement on SBR compound wear resistance.

Overall results showed significant differences between NR and SBR compounds behaviour. NR compound wear resistance seemed to be more affected by changes applied in last three measurement while SBR compound wear resistance kept similar trends obtained in first measurement. These findings represent a necessity of knowledge of environment in which would the tread compound be used as well as need of reliable, fast and cheap testing method to determinate its possible behaviour before manufacturing given by Instrumented Chip and Cut Analyzer.

Within the range of thesis and processing of the results, it was decided to not conduct experimental measurement described in points four and five of the assigned topic of the thesis.

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**LIST OF BBREVIATIONS**

NR	Natural Rubber
SBR	Styrene Butadiene Rubber
BR	Polybutadiene Rubber
PHR	Number of parts per hundred pieces of rubber
F	Friction force [N]
$\mu$	Friction coefficient [-]
$F_h$	Hysteresis friction
$F_a$	Adhesive friction
$V_S$	Volume loss of standardized sample [mm <sup>3</sup> ]
$V_R$	Volume loss of tested sample [mm <sup>3</sup> ]
ČSN	Czech technical standard
ISO	International Standard Organization
ICCA	Instrumented Chip and Cut Analyzer
CC	Chip and Cut
$F_N$	Normal force [N]
$F_S$	Shear force
$\omega$	Rotation speed [rev.min <sup>-1</sup> ]
f	Impact frequency [Hz]
n	Number of impact cycles [-]
$t_S$	Contact time [ms]
$a_i$	Depth of indentation [mm]
$a_f$	Friction distance [mm]
$E_N$	Normal energy [J]
$E_S$	Shear energy [J]
$C_f$	Friction coefficient [-]



P Chip and cut propensity [N/cycle]

R Radius

NR<sub>1-15</sub> Natural Rubber sample; 1 to 15 according to boundary conditions

SBR<sub>1-15</sub> Styrene Butadiene Rubber sample; 1 to 15 according to boundary conditions

## LIST OF FIGURES

Figure 1: Worn tire [1].....	11
Figure 2: Component of a radial truck tire [2].....	12
Figure 3: Tread [21].....	13
Figure 4: Effect of carbon black volume on compound properties and final rubber behaviour [2] .....	18
Figure 5: Sliding and rolling friction [22] .....	21
Figure 6: Friction measuring methods: a – linear track, b – shaft, c – dragging, d - roller with rotating disc, e - inclined plane [21].....	22
Figure 7: Bussen-Schlobach method [16].....	27
Figure 8: Du pont-Grasseli method [16].....	28
Figure 9: Akron-Croydon method [16].....	28
Figure 10: Dunlop-Lambourn method [16] .....	29
Figure 11: Examples of various extents of chip and cut damage to the treads of: a,b – TBR/heavy truck tires, c – OTR/construction vehicle tire, d – mud-terrain light truck tire [17].....	30
Figure 12: Schematic visualization of forces on a tire moving across an asperity, where the left diagram demonstrates slipping and a rolling process is shown on the right. The normal force ( $F_N$ ), shear force ( $F_s$ ), and resultant force ( $F_C$ ) are shown along with the shift in centre of normal load ( $e$ ) and the actuating moment ( $m$ ). [11] .....	30
Figure 13: Beatty-Miksch Cutting and Chipping tester [20] .....	31
Figure 14: Experimental Chip and Chunk method [15] .....	32
Figure 15: Photograph of instrumented chip and cut analyser (left) and diagram of rubber sample geometry (right). [11] .....	36
Figure 16: Schematic of ICCA measuring principle, with: pneumatic actuator (A), two-axis load cell (B), holder + impactor (C), and cylindrical rubber test specimen (D). [11].....	37
Figure 17: Examples of P versus n for two compounds with different CC resistance. [11] .....	38
Figure 18: Determination of the CC propensity (P) from the shear force fluctuations. [11] .....	39
Figure 19: Stainless-steel impactor tool no. 4. [11].....	40

Figure 20: Picture of impacting tools. ....	40
Figure 21: Graphical representation of CC Propensity, P results under loadings 1,6 and 11. ....	44
Figure 22: Graphical representation of CC propensity P results under loadings 2,7 and 12. ....	45
Figure 23: Graphical representation of CC propensity P results under loadings 3,8 and 13. ....	46
Figure 24: Graphical representation of CC propensity P results under loadings 4,9 and 14. ....	47
Figure 25: Graphical representation of CC propensity P results under loadings 5,10 and 15. ....	48
Figure 26: Graphical representation of CC propensity P overall results for NR. ....	49
Figure 27: Graphical representation of CC propensity P overall results for SBR. ....	49
Figure 28: Images of worn NR and SBR samples compared to $F_N$ [N] and $\omega$ [rpm] loading. ....	49
Figure 29: Graphical representation of CC propensity P results for different impacting tools. ....	50
Figure 30: Images of worn NR and SBR samples for different impacting tools. ....	51
Figure 31: Graphical representation of CC propensity P results for NR under different contact time $t_s$ . ....	51
Figure 32: Graphical representation of CC propensity P results for SBR under different contact time $t_s$ . ....	52
Figure 33: Graphical representation of CC propensity P results for different aramid content. ....	53
Figure 34: Images of worn NR and SBR samples for different aramid content. ....	53

**LIST OF TABLES**

Table 1: Recipe of compounds in phr .....	34
Table 2: List of parameters for instrumented chip and cut analyser (ICCA). .....	39
Table 3: List of used impacting tools.....	40
Table 4: List of boundary condition for first measurement. ....	41
Table 5: List of boundary condition for second measurement. ....	41
Table 6: List of boundary condition for third measurement. ....	42
Table 7: List of boundary condition for fourth measurement.....	42
Table 8: Results of Hardness test.....	43
Table 9: Results of Tensile test.....	43
Table 10: Results of propensity P under loadings 1,6 and 11.....	44
Table 11: Results of CC propensity P under loadings 2,7 and 12. ....	45
Table 12: Results of CC propensity P under loadings 3,8 and 13. ....	46
Table 13: Results of CC propensity P under loadings 4,9 and 14. ....	47
Table 14: Results of CC propensity P under loadings 5,10 and 15. ....	48
Table 15: Results of propensity P for different aramid content.....	52