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Tribology Enabling Sustainable Transitions

Wear Mechanism Studies in Agriculture and Transportation

Maria Wojtowicz

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Abstract

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The transition towards more sustainable technologies is introducing new tribological challenges in a wide range of engineering applications. Changes in materials, operating conditions, and system design can alter contact conditions and wear behavior, making the selection and development of wear-resistant materials increasingly important. Achieving this requires a detailed understanding of the wear mechanisms governing material wear. However, such understanding is often difficult to obtain from full-scale testing due to high costs and the complexity of the resulting wear damage, while overly simplified laboratory tests may fail to accurately represent real applications.

The overall objective of this thesis was to develop test, evaluation, and analysis methodologies that enable detailed investigations of wear mechanisms in industrially relevant applications. The work focused on two tribological systems where the transition towards sustainable solutions has created new materials challenges: impact-sliding wear associated with unsuccessful gear shifts in electric vehicle non-synchronous transmissions, and soil-induced wear of agricultural tools, particularly tools designed for precision tillage.

For both applications, methodologies were developed that combined the advantages of controlled laboratory testing with a high degree of application relevance. In the transmission application, laboratory methods enabled systematic investigations of damage evolution under impact-sliding conditions. In the agricultural application, a novel mobile pendulum test was developed, allowing detailed studies of soil-induced wear directly under field conditions.

The results demonstrate that simplified test methods can provide valuable mechanistic insights, provided that the wear mechanisms remain representative of those occurring in the intended application. The developed methodologies enabled investigations that would have been difficult using either conventional field tests or highly simplified laboratory experiments alone. The knowledge generated contributes to a deeper understanding of wear processes and provides a foundation for the selection and development of improved wear-resistant materials for future sustainable technologies.

Keywords: Tribology, tillage, transmissions, tribological testing, wear mechanisms.

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Sometimes, the thought of coming home to you
is the only thing that keeps me going

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. Wojtowicz, M., Wiklund, U., Elo, R., Jacobson, S. (2026). A new experimental technique for assessing impact-sliding wear resistance of materials for non-synchronous transmissions. *Wear*, 586 (2026) 206476

II. Wojtowicz, M., Wiklund, U., Elo, R., Jacobson, S. (2026). Wear mechanisms of non-synchronous transmission couplings – case study using a novel impact-sliding test rig. *Submitted to Wear*

III. Wojtowicz, M., Bäckström, A., Heinrichs Lindgren, J., Elo, R., Wiklund, U., Jacobson, S. (2026) On the influence of coarse fractions and soil texture on the wear of steel tillage tools. *Submitted to Soils and Tillage Research*

IV. Wojtowicz, M., Elo, R., Heinrichs Lindgren, J., Wiklund, U., Bäckström, A., Jacobson, S. (2026) A new mobile pendulum test for detailed wear mechanism studies of tillage tools. *Tribology International* 220 (2026) 111931

V. Wojtowicz, M., Bäckström, A., Beste, U., Heinrichs Lindgren, J., Elo, R., Wiklund, U., Jacobson, S. (2026) Multi scale field-test investigations of wear mechanisms in agricultural tools: Comparison between conventional QT steel and AM tool steel. *Submitted to Tribology International*

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Author's contributions to the papers

Paper I	Part of planning, major part of experimental work, evaluation and writing
Paper II	Major part of planning, all experimental work, major part of evaluation and writing
Paper III	Part of planning, experimental work, major part of evaluation and writing
Paper IV	Major part of planning, experimental work, evaluation and writing
Paper V	Major part of planning, experimental work, evaluation and writing

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Abbreviations

AM	Additive manufacturing
EBM	Electron beam melting
SEM	Scanning electron microscopy
FIB	Focused ion beam
BIB	Broad ion beam
AFM	Atomic force microscopy
wt%	Weight percent
USDA	United States Department of Agriculture
FAO	Food and Agriculture Organization of the United Nations
QT	Quenched and tempered
EDX	Energy dispersive X-ray spectroscopy
EN	European norm
ISO	International Organization for Standardization
IUSS	The International Union of Soil Sciences
C	Clay
SCL	Sandy clay loam
SiL	Silt loam
SL	Sandy loam

1. Introduction

Modern society is currently undergoing a transition towards more sustainable technologies and engineering systems. New technical solutions and materials are being developed at an unprecedented pace to support this transition. However, what is often overlooked is how these new systems, environments, materials, and performance requirements alter the tribological conditions under which the components operate. In many cases, it is only after implementation that it becomes apparent that the new solutions result in contact conditions that the components and the materials no longer can withstand, resulting in accelerated wear, shortened service lives, and, ultimately, economic and environmental costs rather than benefits.

Consequently, material development must progress alongside technological development. However, the selection and development of materials suited to these new tribological systems require a deep understanding of the mechanisms governing wear. Achieving such an understanding is not always straightforward. Full-scale tests, which most accurately reproduce real operating conditions, are often costly and may generate highly complex worn surfaces, making detailed investigations of wear mechanisms difficult.

For this reason, tribological studies are frequently conducted using simplified laboratory test methods that produce less complex wear behaviors and enable systematic investigations of wear mechanisms and the influence of individual test parameters. However, it is essential that the wear mechanisms generated in such simplified tests remain representative of those occurring in the intended application. Otherwise, there is a risk that the connection to the real system is lost and that conclusions that have no relevance in actual operating conditions are drawn.

1.1 Research objectives

The overall objective of this thesis was to develop test, evaluation and analysis methodologies that enable detailed investigations of wear mechanisms in industrially relevant applications. Through a combination of simplified laboratory testing and application-relevant experiments, the goal was to generate new knowledge that can support the selection and development of improved wear-resistant materials.

The research focused on two main topics, both of which arise from needs of materials development that:

- Impact-sliding wear caused by unsuccessful shifting in electric vehicles when synchronising rings are removed from transmissions.
- Soil-induced wear mechanisms of agricultural tools in general and for tools aimed at sustainable shallow tillage in particular.

2. The mechanisms of wear

2.1 Wear and wear mechanism

Wear is the damage to one or more surfaces that occurs due to their interaction caused by their relative motion to each other. This damage often gradually results in material removal from one or both surfaces. Although the severity of wear can vary considerably, it is undesirable in most engineering applications.

Consequently, considerable effort is devoted to minimizing wear. One common approach is the use of lubricants, such as oils or greases, to reduce friction and surface damage. However, lubrication is not always feasible, particularly in open systems where the lubricant cannot be retained. Another strategy is to apply protective surface coatings, as is commonly applied to for example, cutting tools. Yet this solution is also limited to applications where the coating can withstand the operating conditions and is economically feasible.

When such approaches are not practical or sufficiently effective, the only remaining option is to employ materials with inherently higher wear resistance which can extend component lifespan. However, the selection and development of wear-resistant materials require a detailed understanding of how wear occurs in a given application. Therefore, a fundamental understanding of the mechanisms governing wear is essential for the design of more durable engineering materials and components.

2.2 Mechanically induced surface deformation

During sliding contact between metals, the material adjacent to the surface is subjected to heavy deformation, resulting in a characteristic cross-sectional appearance in which three distinct zones can often be identified, as shown in Figure 1. Zone 3 is located closest to the surface and consists of a heavily grain-refined layer, often containing oxides, transferred material, and other compounds present in tribological contact. Grain refinement may also occur at the boundary between Zones 3 and 2. Zone 2 consists of plastically deformed material, sheared in the direction of the counter surface. The shear strain is highest at the surface and gradually decreases with increasing depth into the material. This transition continues until Zone 1 is reached, which represents the unaffected bulk material [1].

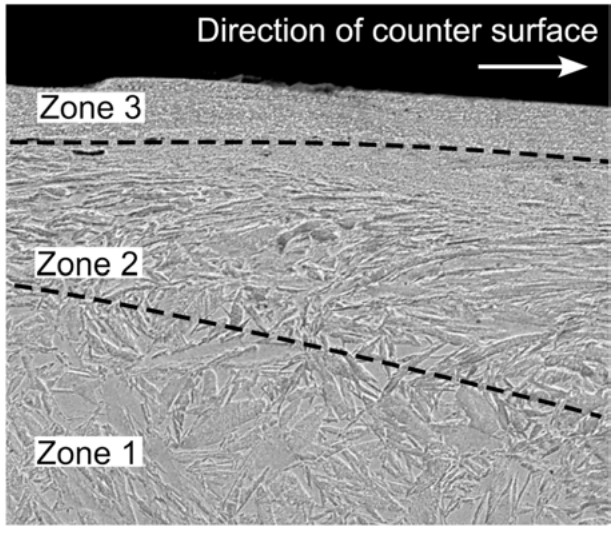

Figure 1: Cross section of a tribological surface with the three deformation zones indicated.

2.3 Wear mechanisms in impact and abrasive contacts

The focus of this thesis has been on wear mechanism investigations in two specific applications: impact-sliding wear in transmission couplings (**Papers I** and **II**) and abrasive wear in agricultural tools (**Papers III-V**). The specific contact conditions and a literature review of each topic are presented in later sections. Here, the fundamental wear mechanisms themselves are briefly described.

2.3.1 Impact-sliding wear

Impact contact occurs when a surface is repeatedly struck by one or more opposing surfaces. This type of contact often results in severe surface damage and wear. Impact contacts are commonly divided into two categories: normal impact and impact-sliding contact, the latter also referred to as compound impact. In normal impact, the contact occurs without any tangential motion, meaning that the only relative movement between the surfaces is in the impact direction. In contrast, impact-sliding contact involves both an impact component and a tangential sliding component.

The sliding motion can arise in several ways. For example, one of the contacting surfaces may possess a tangential velocity [2,3], one of the surfaces may be inclined such that sliding is induced during impact [4,5], or one of the

surfaces may be displaced by the impact force, thereby generating relative sliding [6,7]. The focus of this thesis is on impact-sliding contacts in steel components (**Paper I** och **II**).

In impact contacts, the active wear mechanisms can vary considerably depending on both the material properties and the contact conditions. Mechanisms such as adhesion, abrasion, plastic deformation, delamination of oxide layers, and fatigue-induced material detachment have all been reported in the literature [8,9]. A common characteristic of these contacts is the presence of a heavily deformed near-surface region, where both Zones 2 and 3 are typically observed. Furthermore, the formation of oxides on all or parts of the contact surface is frequently reported [10–12].

Several wear mechanisms have also been identified for impact-sliding contacts. One commonly reported mechanism involves the formation and subsequent delamination of surface oxides, generating wear debris particles [2,7,13–16]. These particles may subsequently contribute to abrasive wear of the contacting surfaces.

The severe plastic deformation associated with impact-sliding contacts can also result in material extrusion in the sliding direction and the formation of shear tongues. When these shear tongues fracture or detach from the surface, they generate additional wear debris [7,11–15]. Furthermore, the deformation process can cause substantial changes in component geometry, even when relatively little material is removed from the contact.

Cracking and fatigue-induced material removal resulting from subsurface crack propagation are also commonly reported wear mechanisms in impact-sliding contacts [2,4,7,13,14,16]. Different terminology has been used in the literature to describe such fatigue-induced damage, including delamination, spallation, and pitting. Yang *et al.* [10] for example, describe delamination as crack propagation occurring primarily within Zone 3, whereas spallation is associated with crack growth extending deeper into Zone 2. Other authors only use the term pitting [17] , but the various terms are often applied inconsistently throughout the literature.

In this work all fatigue-induced material removal is referred to as pitting, and then the location and path of crack propagation is described in detail.

2.3.2 Abrasion wear

Abrasive wear occurs when hard asperities or particles slide against a softer surface, creating scratches. Two forms of abrasion are commonly distinguished: two-body abrasion, in which the particles or asperities are fixed, and three-body abrasion, in which the abrasive particles are more or less free to move between the surfaces. Two-body abrasion is generally considered more

severe, whereas three-body abrasion is often milder. [18] Abrasive wear is the main focus in **Paper III-V.**

Plowing refers to the formation of scratches without the immediate removal of material. In this case, the abrasive particle slides against the surface and deforms the material, pushing it downward and sideways to form ridges. Although no material is directly removed, repeated plowing can eventually lead to material loss through micro fatigue. [1]

Cutting scratches occur when the deformed material is removed from the surface in the form of a chip. In reality, pure cutting rarely occurs. Instead, the scratches formed are typically the result of a combination of both plowing and cutting mechanisms. [18]

During abrasion, high shear strains are introduced into the material. The stress is highest at the surface and decreases with increasing depth. The shear deformation also causes work hardening of the material. Both the shear strain and the depth of the affected material are proportional to the scratch depth. [1]

The abrasiveness of particles depends on several parameters, including the hardness of both the particles and the counter-surface, the particle shape (particularly their sharpness), and the attack angle between the particles and the surface. [1]

The abrasive wear resistance of a material depends on several material properties, of which hardness, and particularly the hardness difference between the abrasive particles and the worn material, is among the most influential. Nevertheless, there are other microstructural features, such as hard carbide particles embedded in a tougher metallic matrix, that can significantly improve wear resistance, while still preserving the toughness of the material. As a result, materials containing carbides often exhibit superior abrasion resistance compared with materials of similar bulk hardness [1].

Part I – Impact-sliding contact and the transmission

3. Introduction – Part I

3.1 The Synchronization system and the lack of it

Conventional transmission systems often incorporate a synchronization system which function is to match the rotational speeds of the input and output shafts during gear shifting. For a gear to engage successfully, the rotational speeds of the two shafts must be approximately equal. If this condition is not met, impacts may occur between the coupling sleeve and coupling spline in the transmission. Such impacts can result in severe impact wear and may significantly reduce the service life of the affected components [19–21].

However, synchronization systems consist of several additional components, which increase both the size and weight of the transmission. They also increase the time required to complete a gear shift, as synchronization must be achieved before engagement can occur. Historically, this has not represented a major limitation. However, the increasing demand for reduced emissions and improved energy efficiency has placed new requirements on heavy-duty transportation. The development of heavy electric vehicles has further intensified the need for efficient and lightweight drivetrain components, including transmission systems [22–26].

One proposed approach to improve transmission efficiency and vehicle drivability is to eliminate the synchronization system altogether. This would reduce transmission weight and enable the design of more compact transmission systems. In addition, gear-shifting times could be shortened, potentially resulting in improved efficiency and drivability [27–31].

In such, non-synchronous transmission system, gear engagement would rely solely on a coupling sleeve, a coupling spline, and a precision control system. However, successful gear engagement in such a system requires a controlled difference in rotational velocity between the coupling sleeve and the coupling spline during shifting. If the shift timing is slightly incorrect, impacts may occur between the sleeve and the spline, resulting in repeated impact loading which can lead to severe wear [32,33].

3.2 Impact contact in non-synchronous transmission systems

During such impact-siding events in non-synchronous transmission, instead of locking into place, the teeth of the coupling sleeve strike the teeth of the coupling spline near the edge of the teeth causing high contact pressures, plastic deformation and wear. The sleeve teeth then slide across the spline teeth until they, ideally, engage in the next available slot. Consequently, an impact-sliding contact occurs between the teeth of the coupling sleeve and the coupling spline, resulting in wear of both components. As wear progresses, the teeth become increasingly rounded, which increases the likelihood of subsequent impact-sliding events where the teeth fail to engage upon first contact.

This type of engagement failure has been investigated previously, both in synchronized and non-synchronized transmissions. However, most studies have focused on numerical modelling and optimization of the shifting process itself [19,21,27–29,32–34]. In contrast, relatively few studies have examined the tribological aspects of this contact. Although wear of bronze synchronizer rings [35] and impact-sliding wear in dog gears [36] has been reported in the literature, a deeper understanding of the wear mechanisms in impact-sliding contact in non-synchronous transmissions is still lacking.

Such knowledge is essential for the selection and development of materials capable of withstanding the severe contact conditions encountered during repeated impact-sliding events. Therefore, further research is required to improve the understanding of the underlying wear mechanisms and their influence on component durability in non-synchronous transmission systems.

3.3 New impact sliding test rig

Although impact-sliding contacts in non-synchronous transmissions have received limited attention in the literature, impact and impact-sliding wear have been extensively studied using a variety of laboratory test configurations. These include ballistic impact tests [37,38], hammer-type impact tests [39,40], and reciprocating impact-sliding tests [41,42]. Despite this variety of experimental approaches, most existing test rigs are unable to adequately reproduce the contact conditions encountered in non-synchronous transmissions. Typical limitations include insufficient contact pressures, excessively short sliding distances, or overly simplified contact geometries.

To address these limitations, the Tribomaterials Group at Ångström Laboratory developed a novel impact-sliding test rig specifically designed to replicate the contact conditions experienced in non-synchronous transmissions (Figure 2a). The rig enables the investigation of wear mechanisms under

realistic contact geometries, contact pressures, and impact-sliding conditions relevant to the intended application (presented in **Paper I**).

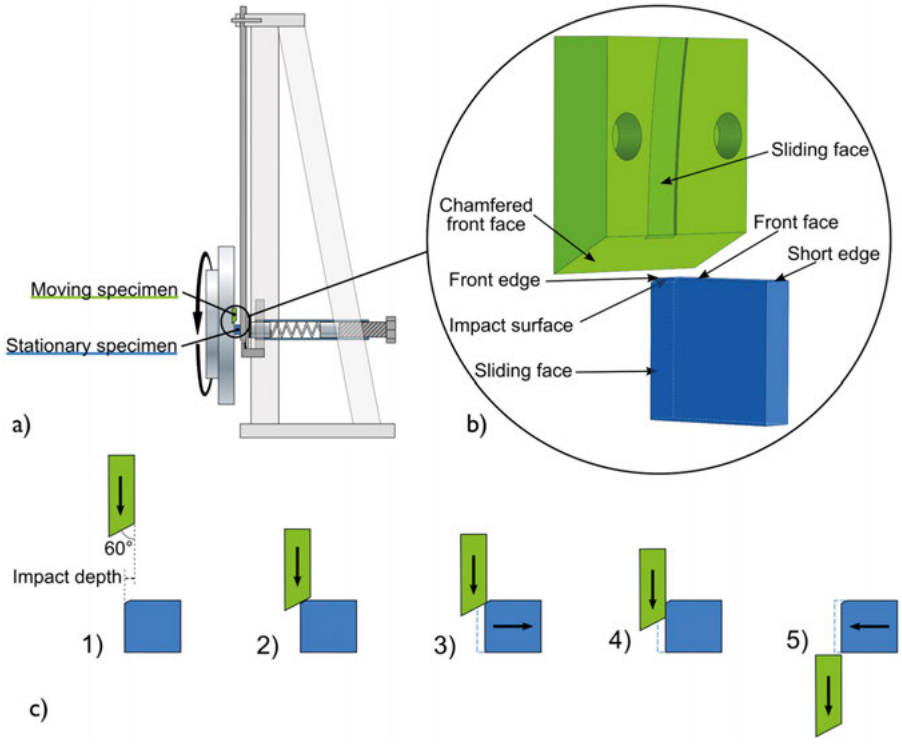

Figure 2: a) Illustration of the impact-sliding rig which consists of a specimen holder disc (1), specimen holder arm (2), piston (3), spring (4) and screw (5). b) Moving (green) and stationary (blue) specimens. c) Impact sequence where the chamfered front edge of the moving specimen approaches (1) and impacts (2) the front edge of the stationary specimen eventually causing the formation of an impact surface on the stationary specimen. The arm then moves to the right in the image allowing the moving specimen to slide along the now formed impact surface (3) and then slide over the front edge and enter a flat-on-flat contact between the sliding faces of both specimens (4). Eventually the specimens slide out of contact (5).

The newly developed rig was designed to be mounted on an industrial lathe. A specimen holder disc is attached to the lathe chuck, allowing up to eight specimens to be mounted simultaneously. As these specimens rotate together with the lathe, they are referred to as the *moving specimens*. The rotational speed of the lathe can be controlled and corresponds to the relative speed difference between the coupling sleeve and spline in a transmission system.

The main test component of the rig is a single stationary specimen mounted on an arm where a normal load can be applied with a spring-loaded piston. The compression of the spring and hence the normal load can be adjusted with

a screw. The arm is free to move to the right in Figure 2, away from the moving specimens during contact. Prior to testing, a specific impact depth is established by introducing a controlled overlap between the rotating specimens and the stationary specimen, as illustrated in Figure 2c1. Lubrication is provided continuously throughout the test by applying a small amount of oil to the moving specimens during each revolution.

The sequence of an individual impact event is illustrated in Figure 2c and remains essentially identical throughout the test. Three distinct stages can be identified. First, the chamfer of the moving specimen strikes the front edge of the stationary specimen (Figure 2c2), generating an impact and initiating sliding along the impact surface that is continuously formed during testing (Figure 2c3). Subsequently, the stationary specimen is pushed to the right, allowing a flat-on-flat sliding contact to develop between the sliding surfaces of the two specimens (Figure 2c4). The duration of this stage is considerably longer than that of the initial impact event. Finally, the specimens slide out of contact and separate (Figure 2c5).

The moving and stationary specimens utilized in this work are illustrated in Figure 2b. The moving specimens were all made of a MoCr steel case hardened to 62 HRC (S1). They had a rectangular 25 x 25 x 7 mm shape with one front face forming a 60° chamfer. The stationary specimens were made of three different steels. One was the same as for the moving specimens (S1) and the other two were NiCrMo steels case hardened to 62 (S2) and 59 (S3) HRC. S2 had a slightly lower alloy content than S3. The stationary specimens were shaped as 15 x 15 x 4 mm blocks with with all edges rounded to a 0.1 mm radius.

The specimen holder arm was also instrumented with strain gauges, enabling the impact force associated with each impact event to be measured. An example of such force curve is presented in Figure 3. The impact can be clearly identified as a sharp force peak at the beginning of the curve, corresponding to the initial collision between the specimens. This is followed by the sliding contact between the sliding faces of the specimens, producing a more prolonged, but smaller force. Finally, the force decreases to zero as the specimens slide out of contact and separate.

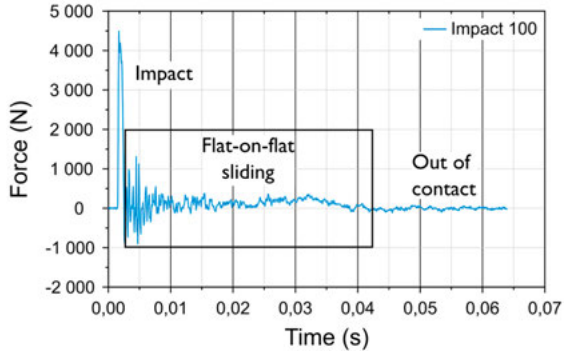

Figure 3: An example of a force curve for one single impact with the initial impact, flat-on-flat sliding and out of contact indicated in the image.

4. Contributions – Part I

4.1 Investigating the wear mechanism in transmission couplings (Paper I-II)

As previously discussed, the wear mechanisms associated with impact-sliding contacts in non-synchronous transmissions remain poorly understood. To address this knowledge gap, the Ångström Tribomaterials Group, together with the author of this thesis, developed the experimental methodology presented in this work. The methodology was specifically designed to utilize the newly developed impact-sliding test rig for detailed investigations of the underlying wear mechanisms (**Paper I**). It was subsequently applied to generate a deeper understanding of the mechanisms governing wear in impact-sliding contacts representative of those encountered in non-synchronous transmissions. (**Paper II**).

4.2 Methodology

All experiments were performed using identical test parameters, which were deemed suitable for the application. The chosen parameters generated wear mechanisms similar to those observed in real non-synchronous transmission while maintaining reasonable test durations and avoiding excessive contact severity that could result in specimen overheating. The selected test parameters were: an impact depth of 1 mm, two moving specimens, a moving specimen velocity of 1 m s^{-1}, an impact frequency of 3 Hz and a normal load of 650 N.

To validate the relevance of the test method for studies of impact-sliding wear in non-synchronous transmissions, the surface damage produced by the rig-tested specimens was compared with the damage observed on a coupling sleeve obtained from a full-scale industrial transmission test.

Wear was quantified using two complementary approaches. First, the mass loss of the specimens was determined by weighing the specimens before and after testing. Second, the length of the impact surface was measured, preferably in cross-sections although it could also be assessed from surface observations. The use of two wear metrics provided not only a more

robust assessment of wear but also helped distinguish the contributions of different wear mechanisms.

The force signals obtained during testing were analyzed in terms of both the maximum impact force and the friction force generated during flat-on-flat sliding. The maximum impact force was determined as the average of the peak force values from ten consecutive force curves. The friction force was calculated from the flat-on-flat sliding stage by averaging the force over 200 data points collected towards the end of this stage. The reported friction force was likewise calculated as the mean value from ten consecutive impact events.

To obtain a deeper understanding of the wear process and its evolution throughout a test, tests of varying lengths were conducted. In addition, selected tests were stopped for weight and surface analysis at predefined intervals before they were continued with the same specimens at the same position to enable a more detailed investigation of the wear progression. The complete range of test durations is presented in Table 1.

Table 1: Test lengths utilized in this work. The number of impacts between stops are indicated in the right column.

Final test length (impacts)	Imaging stops at (impact)
10 000	-
50 000	-
200 000	50 000, 100 000, 150 000
10 000 interrupted	2, 4, 10, 50, 200, 500, 1000, 3000, 5000, 7000

To obtain a comprehensive understanding of the wear mechanisms, both surface and cross-sectional analyses were performed. The cross-sections were prepared mechanically and positioned approximately at the center of the impact surfaces of the stationary specimens after 10 000, 50 000 and 200 000 impacts.

Hardness profiles were measured in the cross-sections along an approximately 45º line from the original front edge and extending into the bulk material by Vickers microhardness indentation with 1 kg load. These measurements were used to estimate both the magnitude and depth of the strain hardening induced by the repeated impact-sliding contact.

4.3 Results and discussion

To assess whether the newly developed rig could be used for wear mechanism investigations of impact-sliding contacts in non-synchronous transmissions, it

first had to be validated that the rig was capable of reproducing the wear mechanisms observed in the real application (**Paper I**). This validation was performed using the test parameters described in the methodology section.

The wear mechanisms present on an S1 coupling sleeve subjected to full-scale transmission testing were examined using SEM. As shown in Figure 4, an impact surface was formed on the teeth of the sleeve. This surface exhibited characteristic damage features, including pitting, shear tongue formation, and large fractures. Similar observations were made on specimens tested in the newly developed rig using both stationary and moving specimens manufactured from S1 steel (Figure 5).

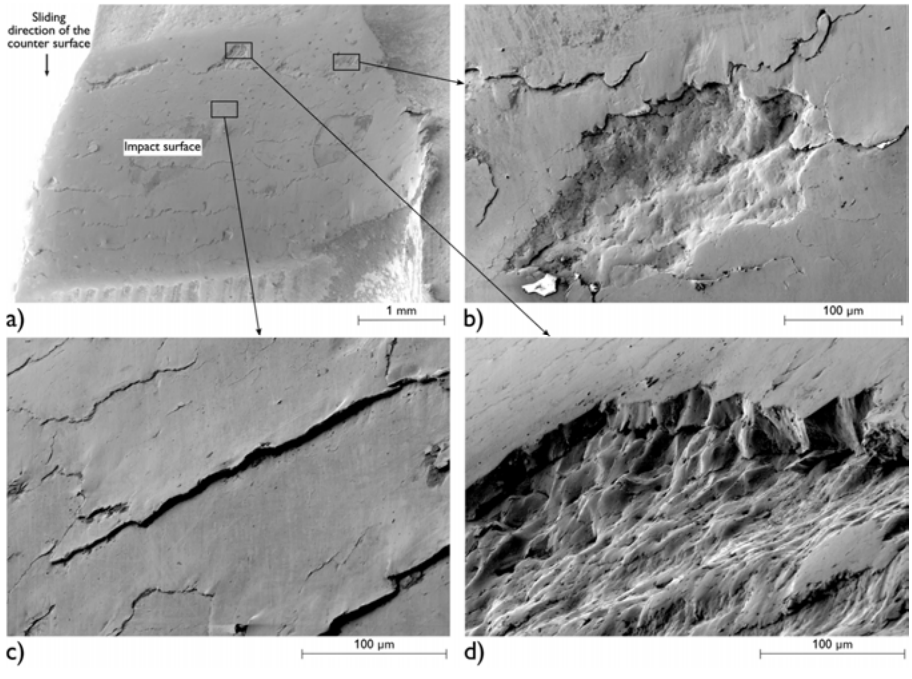

Figure 4: Observed wear mechanisms after 300 000 shift in a full-scale industrial test utilizing an S1 sleeve. a) A wide impact surface could be seen at the edge of the tooth. b) Pitting. c) Tongues formed by shear deformation. d) Small fracture.

Although the geometry and dimensions of the rig specimens differ from those of actual coupling sleeve teeth, the most significant difference between the rig and a full-scale transmission test is that not every gear shift results in an impact event. Despite these differences, the wear mechanisms observed in both cases were remarkably similar. The rig was therefore considered capable of reproducing the wear mechanisms relevant to non-synchronous transmissions and suitable for detailed wear mechanism studies.

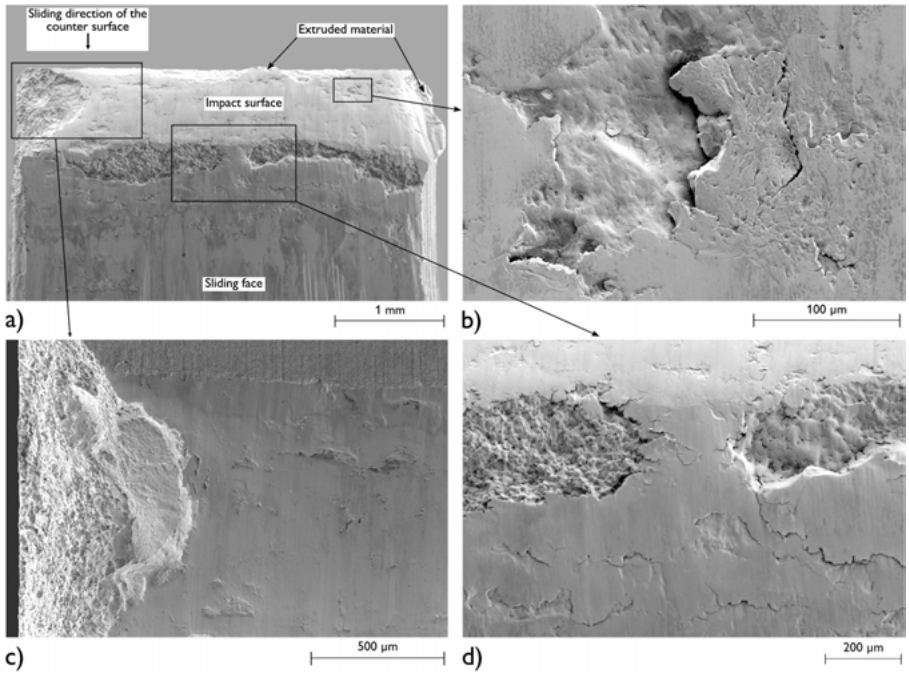

Figure 5: Wear mechanisms observed on an S1 stationary specimen from a 50 000 impact rig test. a) An impact surface was formed on the front of the specimen. b) pitting. c) Large fracture and d) small fractures and tongues formed by shear deformation.

After establishing the relevance of the new impact-sliding rig, it was used to investigate how the wear mechanisms varied as the number of impacts during a test increased (**Paper II**). A combination of 10 000 and 200 000 impact tests with stops according to Table 1 were performed using stationary specimens manufactured from S2 steel. These tests revealed that the wear rate decreased dramatically from a relatively high initial value during the first impacts to a very low value that was about 25 000 times lower after 200 000 impacts, see Figure 6b and d.

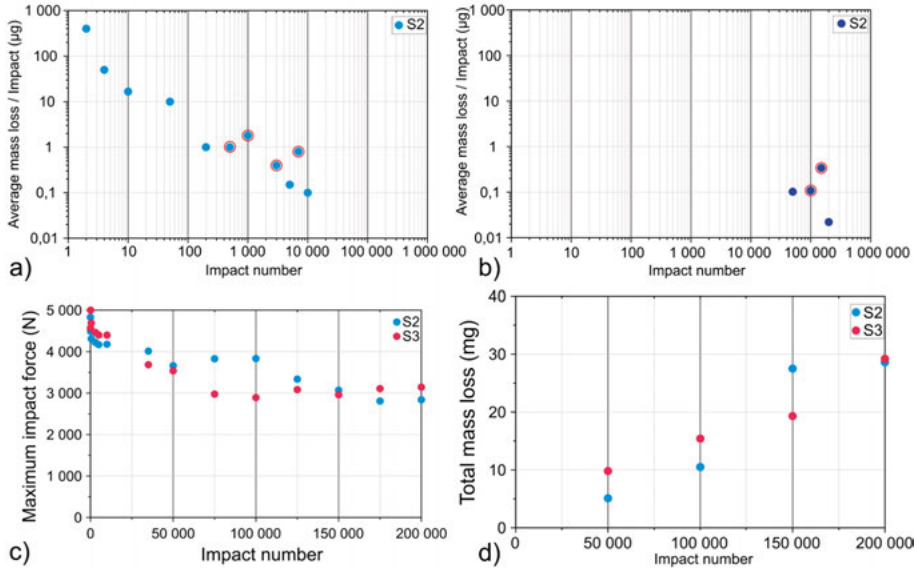

Figure 6: a) Wear rate given as average mass loss per impact (since the last data point) for a S2 10 000 impact test. b) Average mass loss per impact for a S2 200 000 impact test. c) Maximum impact force measurement for S2 and S3 200 000 impact tests. Accumulated mass loss for S2 and S3 200 000 impact tests.

Surface imaging and the wear rate showed that the most severe damage occurred during the initial stages of a test. During the first few impacts, a large piece of material was sheared off from the front edge of the stationary specimen, where the impact occurred, see Figure 7. Significant material flow was also observed, resulting in the formation of numerous shear tongues. Material removal occurred when these tongues either fractured or were displaced beyond the edge of the impact surface. This mechanism was found to dominate the wear process during approximately the first 3 000 impacts.

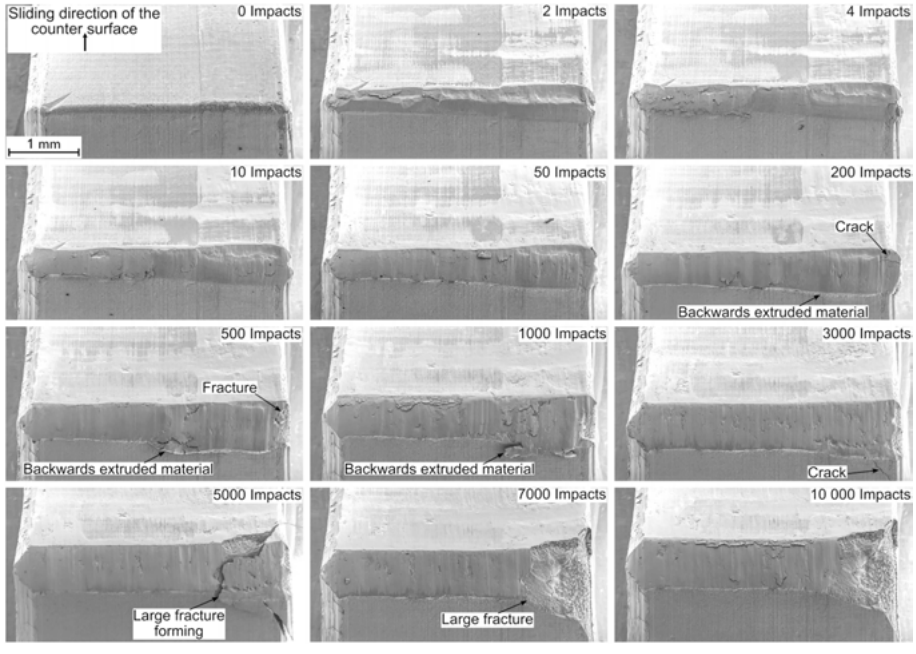

Figure 7: Wear progression for a S2 10 000 test stopped at 2, 4, 10, 50, 200, 500, 1000, 3 000, 5 000, 7 000 and 10 000 impacts. In the beginning of the test a large material fragment is removed. Then the impact surface is formed through plastic deformation, backwards extruded material, pitting and large fractures.

After approximately 3 000 impacts, pits began to appear on the impact surface. The occurrence of these pits increased with test duration.

Cross-sectional analyses of S2 specimens from 10 000, 50 000 and 200 000 impact tests revealed that the impact surface gradually developed a more convex shape as the test progressed, see Figure 8. Simultaneously, the chamfer angle slowly approached 45°. The impact force (Figure 6c) also decreased from about 5 000 N to 2 000 N after about 150 000 impacts.

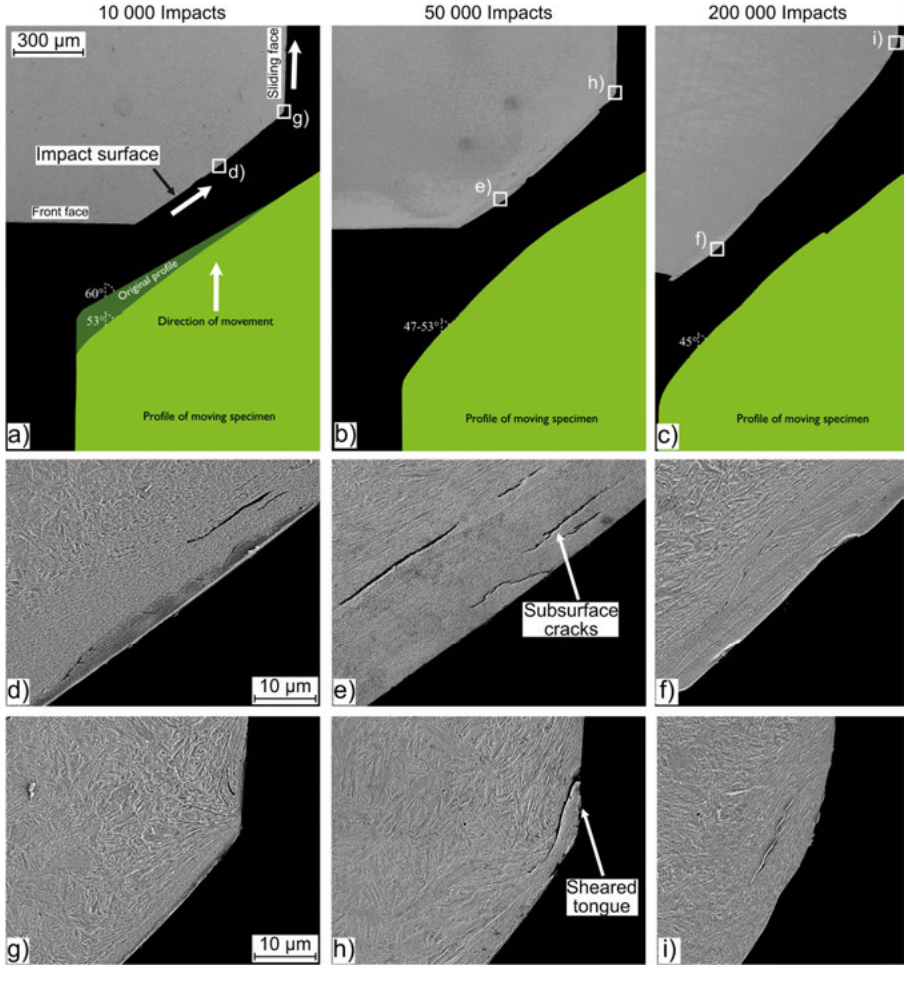

Figure 8: Cross section of the impact surface of S2 stationary specimens after 10 000, 50 000 and 200 000 impacts. a-c) overview images with the profiles of the moving specimens indicated. d-f) Higher magnification of the impact surface closer to the point of impact. g-i) The transition between the impact surface and the sliding face.

Cross-sectional observations further showed that the subsurface material beneath the impact surface underwent severe plastic deformation, resulting in the formation of deformation Zones 2 and 3. Zone 3 became partially oxidized and gradually developed into a layered tribofilm as the test progressed (see Figure 9). In addition, crack initiation and crack propagation were observed either within Zone 3 or at the interface between Zones 2 and 3 (see Figure 8). When these cracks eventually led to material detachment, the pits observed on the impact surface were formed.

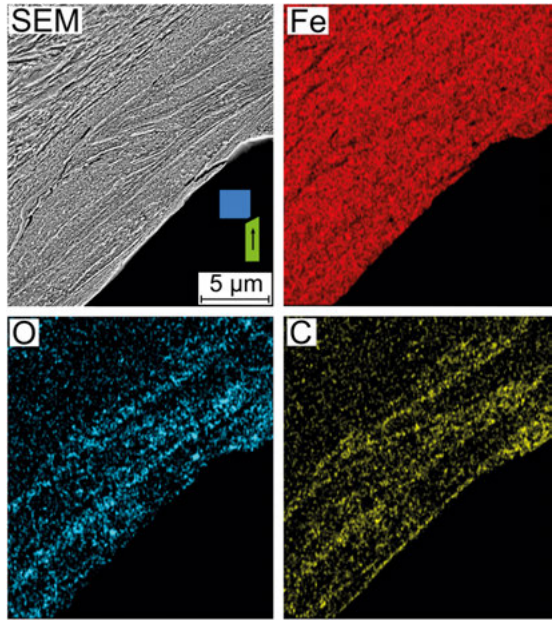

Figure 9: Elemental map analysis of Fe, C and O of a S2 200 000 impact test. The map shows enrichment in C and O in some regions of zone 3. The enriched and not enriched layers are stacked in alternating layers, forming a tribolayer.

The wear mechanisms were divided into two categories, frequent, small-scale and rare, large-scale. One of the large-scale mechanisms that was observed and that is shown in Figure 10 was the backwards extrusion caused by gradual plastic deformation of the material in that direction opposite to the direction of the moving specimen, caused by the percussive impacts. Although this mechanism occurred relatively infrequently, it was observed in both shorter and longer tests. Another rare large-scale event that could be observed was the large fractures (see Figure 7 after 7000 impacts), that occurred throughout all tests until about 150 000 impacts.

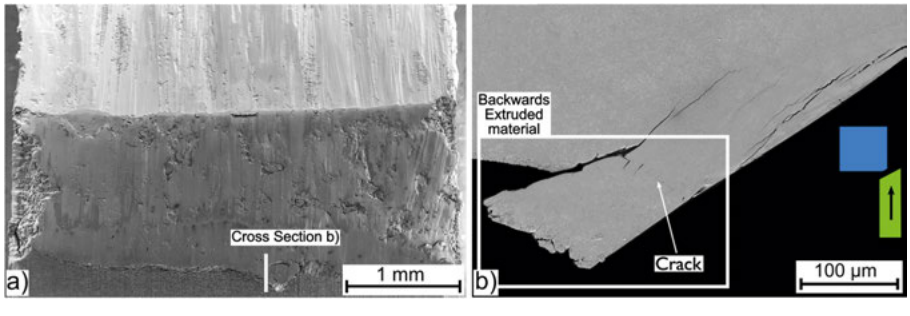

Figure 10: a) Overview of the S2 stationary specimen after 200 000 impacts with an overhang caused by the backwards extrusion visible. b) The indicated cross-section where the overhand is visible.

The small-scale events were the shear tongue formation and fatigue-related damage leading to pit formation. Smaller pits formed by cracks propagating within zone 3 could be observed as well as larger pits formed by the crack propagation in-between Zones 2 and 3, see Figure 11.

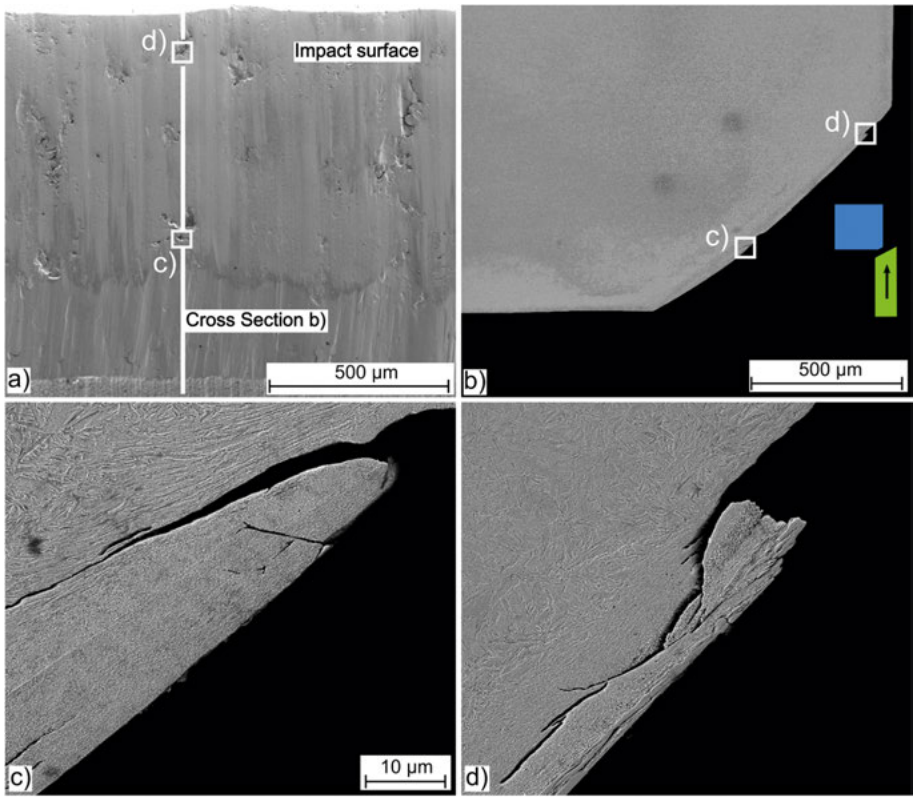

Figure 11: a) Top view of the impact surface of the S2 specimen after 50 000 impacts. b) overview of the cross-section of the impact surface. c-d) Formation of tongues and crack propagation between zone 2 and 3 that in d) lead to pit formation.

The rig was also used to compare two NiCrMo steels with slightly different chemical compositions (steel S2 and S3), see Figure 12. Although the materials exhibited similar overall behavior, some important differences were identified. One of the steels displayed greater resistance to plastic deformation, but large fractures were observed along the short edges of the impact surface. These large fractures occurred relatively infrequently but resulted in substantial material loss. Although the wear mechanisms varied slightly, the total mass loss after 200 000 impacts was the same for both materials (see Figure 6d).

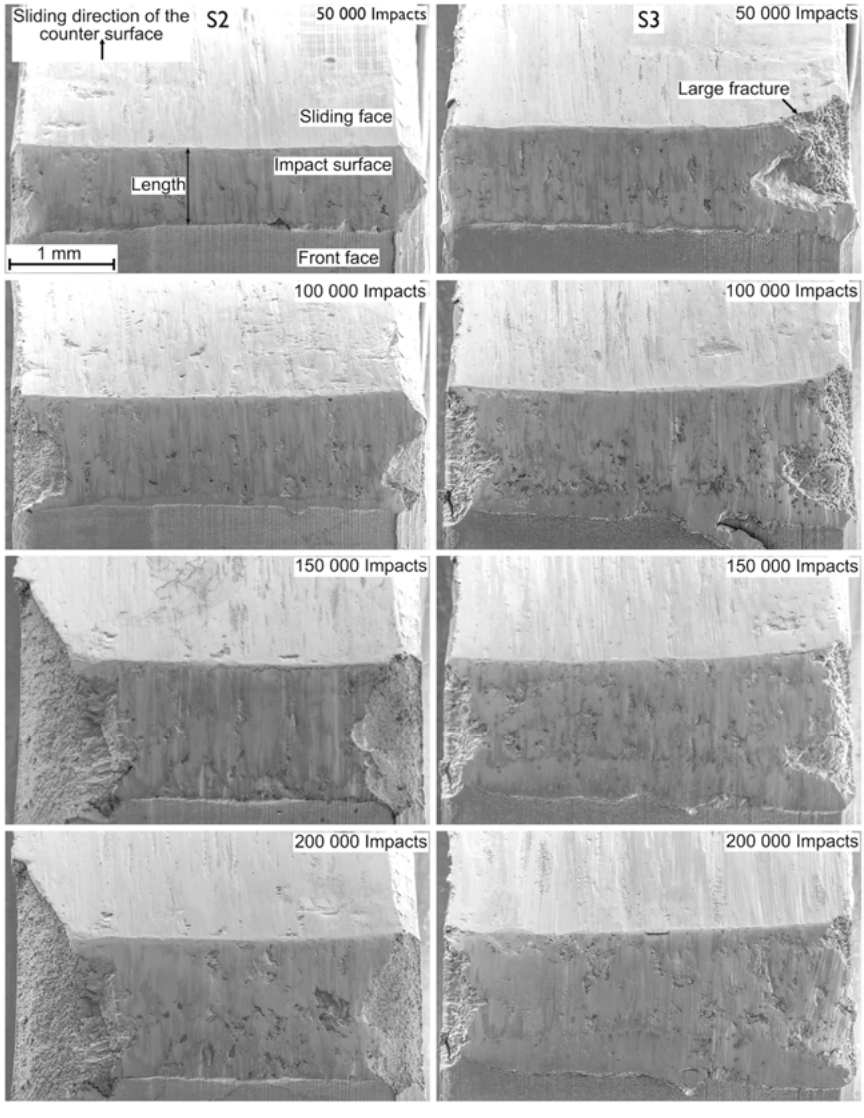

Figure 12: Appearance of the impact surface of specimens S2 and S3 after 50 000, 100 000, 150 000 and 200 000 impacts. The length of the impact surface is increasing faster on the S3 specimen, but more significant large fractures are formed on the S2 specimen.

Overall, the results demonstrate that the developed rig successfully reproduces the wear mechanisms observed in full-scale transmission testing while enabling a level of wear mechanisms investigations that would be difficult to achieve under full-scale industrial test conditions. The rig therefore provides a valuable tool for improving the understanding of wear processes in transmission couplings and for supporting the development of more wear-resistant materials for future non-synchronous transmission systems.

Part II – Wear of tillage tools

5. Introduction – Part II

5.1 Tillage

Agriculture has been an important part of human society for millennia, not least because it is essential for providing food for a growing global population. Approximately 1.1 billion hectares of agricultural fields around the world are being used for the cultivation of temporary crops, and a large part of those require some kind of soil tillage before crops can be sown [43]. Soil tillage involves loosening, turning, and aerating the soil, as well as cutting existing roots and crop residues, and is performed to create favorable conditions for crop establishment and growth.

As agricultural practices continue to evolve towards more efficient and environmentally sustainable approaches, conventional plough-based systems are increasingly being replaced by modern tillage methods that cause less soil disturbance and require lower fuel consumption, while still producing a suitable seedbed for cultivation. One such method causing less soil disturbance and at the same time providing a faster and fuel-efficient tillage is cultivation using combined or tine cultivators [44,45].

A wide range of implements are used for soil cultivation. These include sweeps, discs, and tine points, the latter being the primary focus of this work. The geometry of tine points can vary considerably depending on their intended application and manufacturer. An example of a tine point is shown in Figure 13 (the point used in **Papers III** and **V**). The shape of these tools is of great importance, as it directly influences the resulting tillage performance [46–48].

Figure 13: Example of a standard tillage point used in this study before exposure to soil abrasion.

Agricultural fields consist of soil containing, among others, abrasive mineral particles that continuously wear the tools during operation, gradually altering their shape. This wear does not only reduce tool service life and increase operating costs, but the resulting changes in tool geometry can also impair tillage performance and ultimately adversely affect the seedbed and ultimately crop establishment, particularly in modern agriculture, where precision dependent techniques are increasingly used. Changes in tool geometry may also increase draft forces and thereby fuel consumption [49]. In an increasingly unpredictable climate, the periods during which soil conditions are optimal for cultivation may also be limited and fleeting. Consequently, minimizing downtime associated with the replacement of worn tools during these periods is of great importance.

Therefore, to improve the efficiency of agriculture, more wear-resistant tool materials are required. However, developing such materials is challenging without a thorough understanding of the mechanisms governing wear.

5.2 Soil

To have any chance of understanding the wear of agricultural tools, it is first necessary to establish a basic understanding of how complex soil is as a material. Approximately half of the total volume of soil consists of pores (of which up to 40 % can be filled with water), around 5 % is organic matter, and

the remainder is composed of mineral particles with a wide range of sizes. The particle size distribution can also vary considerably between different locations. To facilitate the description and classification of soils, mineral particles are commonly divided into distinct size classes. Several classification systems exist, for example USDA, FOA and a Swedish classification. In this work, a combination of the Swedish classification and FAO classification systems was adopted, resulting in six particle size classes and eleven subclasses, as presented in Table 2.

The relative proportions of the three particle size classes clay, silt and sand, in this work called the fine earth fraction, strongly influences the properties of the soil. A soil consisting predominantly of clay exhibits characteristics that differ substantially from those of a soil dominated by sand or silt. Consequently, soils are commonly described in terms of texture classes, where each texture class is associated with a distinct set of properties. These relationships are often illustrated using a soil texture triangle [50]. In general, clay-rich soils tend to be cohesive, difficult to till, and capable of retaining large amounts of water, whereas sandy soils are loose, easy to cultivate, and have poor water retention [51,52]. Silty soils typically exhibit properties intermediate between those of sandy and clay soils where they often pose relatively high water-holding capacity while remaining easier to cultivate than clay-rich soils, but the properties vary depending on the ratios of sand and clay in the soil.

Table 2: The size classes of soil, as a combination of the Swedish classification system [53] and the FAO classification system [50].

	Separate classes	Separate subclasses	Size (mm)
Fine earth fraction	Clay		< 0.002
	Silt	Fine silt	0.002 – 0.006
		Medium silt	0.006 – 0.02
		Coarse silt	0.02 – 0.06
	Sand	Fine sand	0.06 – 0.2
		Medium sand	0.2 – 0.6
		Coarse sand	0.6 – 2
Coarse fragment fraction	Gravel	Fine gravel	2 – 6
		Medium gravel	6 – 20
		Coarse gravel	20 – 60
	Stone		60 – 200
	Boulder	Boulder	200 – 600
		Large boulder	600 – 2000

In addition to differences in particle size distribution and composition, soil exhibits two additional levels of structural organization. One of these is soil aggregation, where individual particles are bound together to form aggregates. Aggregate formation depends largely on soil properties, such as texture and organic matter content, but is also influenced by factors including soil pH and biological activity [53].

Further, soil structure is related to soil compaction and porosity. These properties may vary considerably depending on the characteristics of the soil, the mechanical loads applied to it, its moisture content, and the type of vegetation and soil organisms present.

5.2.1 Soil analysis

The particle size distribution of the fine earth fraction in a soil can be determined using several different methods. One of the most common approaches is to divide the soil into the fractions clay, silt, and sand (according to the subclasses presented in Table 2) using sieve and sedimentation analyses. This approach is commonly used for soil texture determination and was employed in Papers III and V in accordance with ISO 11277 (2009).

Other methods are also available, including a hydrometer method and a pipette method. In addition, laser diffraction techniques, such as the LA-950, can be used to obtain more detailed particle size distribution. The latter method was employed in **Paper IV**, after which the procedure described by Faé et al. [54] was used to calculate the corresponding contents of clay, silt, and sand. Compared with conventional interval-based methods, laser diffraction provides a much more detailed characterization of the particle size distribution, as it can detect particles ranging from approximately 10 nm to 2 mm and distinguish size differences as small as a few tens of nanometres.

In contrast to the fine earth fraction, there is no widely adopted method for quantifying the content of coarse fragments in agricultural soils. The contents of fine and medium gravel (see Table 2) are commonly determined using sieving procedures, whereas larger fragments are rarely quantified in a systematic manner. Both the IUSS and FAO systems rely primarily on visual assessments, where the abundance of coarse fragments is estimated using predefined percentage classes. Even though these methods don't disturb the soil, such assessments can be difficult to perform accurately in agricultural fields and therefore provide only approximate estimates.

In geotechnical engineering, coarse fragment content is often determined by excavating large soil volumes and measuring or counting all fragments within the sampled volume. However, this approach requires extensive excavation and would cause unacceptable damage to agricultural fields. Therefore, a novel

method developed by the co-authors was employed in the present work, as described in **Paper IV**. This method enabled a more practical and quantitative assessment of coarse fragment content under agricultural field conditions.

5.3 Wear of tillage tools

Wear of agricultural tools is generally characterized as relatively mild abrasive wear. Worn surfaces are typically characterized by long, continuous scratches with a wide range of sizes, from several hundred micrometers down to a few tens of nanometers, as shown in Figure 14. A significant proportion of these scratches are filled with retained soil material. In addition, large areas of the worn surface are covered by adhered soil, consisting predominantly of clay particles smaller than 2 µm. Together with the complexity of the soil, these features result in a highly complex surface morphology, making detailed analyses of the underlying wear mechanisms challenging [55]. As a result, smaller scratches, which individually contribute less damage, are often overlooked. However, it is difficult to determine the extent to which these features contribute to the overall material degradation. Furthermore, the mechanisms responsible for the formation of the different types of scratches are difficult to identify from such analyses.

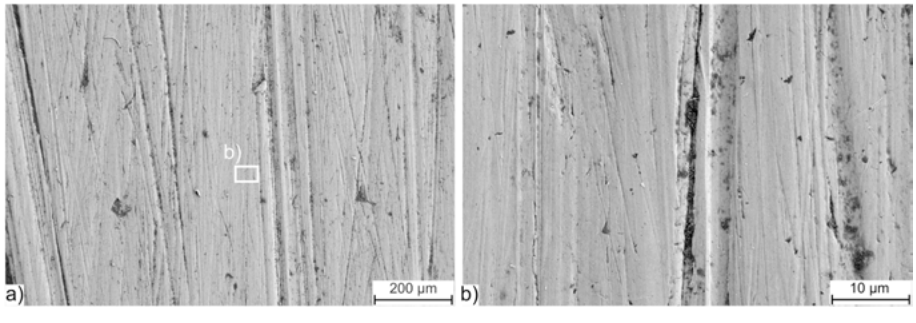

Figure 14: SEM images of the worn surface of a tine cultivator point after tilling 4 ha, at low, a), and high, b), magnification. Even though there is a wide range of scratch widths, indentation sizes, and amount of transferred material it still results in a similar visual appearance at both magnifications, despite the 20X difference in scale. This indicates large variations and a highly complex surface appearance.

The majority of the literature on the wear of agricultural tools focuses on the quantification of wear as mass loss or volume loss, typically through comparisons of different materials or soil conditions. These studies have shown that the wear rate of soil-engaging tools is influenced by several soil properties, including soil texture [56–61]. In particular, soils with higher sand contents have been shown to be more abrasive, resulting in increased wear

rates of agricultural tools [58,59,62]. Furthermore, tool wear has been shown to depend on the soil moisture content. In general, increasing the water content reduces the wear rate [59,63,64]; however, this relationship is not always observed and may vary depending on the soil composition and operating conditions [59]. In addition, wear rates are affected by both the cultivation speed and the working depth [61]. The wear rate is also influenced by the content of the coarse fragment fraction in the soil, and studies have shown that increasing amounts of coarse fragments lead to increased wear [64,65]. Consequently, agricultural tools are subjected to highly complex wear conditions in soil environments.

The wear mechanisms causing the wear of tillage tools are still not fully understood. One approach that has gained acceptance is the analysis of wear mechanisms through the study of surface penetration depth. This approach is based on the work of Hokkirigawa *et al.* [66,67], who, through single-asperity scratch testing, demonstrated that the relationship between scratch width and scratch depth can be linked to the underlying wear mechanism.

This approach has subsequently been applied to worn surfaces of agricultural tools by several authors [68–71]. However, field-worn cultivator points differ substantially from the conditions encountered during single-asperity scratching. In addition, the worn surfaces are generally in a steady-state condition, meaning that the original surface geometry and reference level are no longer preserved. Furthermore, such analyses are often based primarily on the largest scratches present on the surface, which may not be representative of the overall wear process.

When it comes to the wear mechanisms of the coarse fragment fraction, simplified laboratory studies have shown that both the size and the abundance of coarse fragments influence wear [72]. The large scale surface damage has also been contributed to the presence of coarse soil fragments [73,74]. However, research in this area remains limited, and the understanding of how coarse fragments contribute to wear is still at an early stage.

Due to the variety of parameters that affect the wear and complex wear appearance, complementary methods are required to achieve a more comprehensive understanding of the wear mechanisms acting on agricultural tools. One such attempt was made by Napiórkowski and co-workers, who investigated the morphology of worn surfaces [55]. However, they concluded that the high complexity of field-worn surfaces makes detailed studies of the wear mechanisms challenging.

To overcome these limitations, several laboratory test methods have been developed to study the wear of agricultural tools, including test using different abrasive media and test setups [75–77]. Although such methods allow the

influence of individual parameters on wear during tillage operations to be investigated in a controlled and systematic manner, they do not fully reproduce the complex nature of tillage in real soil. Consequently, the wear mechanisms occurring under field conditions cannot be replicated completely [57,78,79].

There is therefore a need for alternative approaches to investigating the wear mechanisms of agricultural tools that preserve the essential characteristics of field worn tools while providing a less complex worn surface. Such approaches would facilitate detailed studies of individual wear events and enable a more comprehensive understanding of the mechanisms governing wear in agricultural soils.

5.4 Tested materials

In this work, cultivator points and 38 x 25 x 15 mm block specimens manufactured from a quenched and tempered boron steel according to EN 10083-3-27MnCrB5-2, designated QT steel, were used as the reference material for agricultural tools (**Papers III-V**). In addition, cultivator points partially covered with the additively manufactured steel Vibenite® 130, produced by electron beam melting (EBM) by VBN Components AB, hereafter referred to as AM steel and block specimens of the same AM steel were used to investigate the influence of carbides on the soil-induced wear of these tools (**Paper V**). The chemical compositions of both materials are presented in Table 3. Both materials had similar hardness of about 520 and 560 HV0.3.

Table 3: The wt% composition of QT and AM steel used in this work.

	QT steel	*AM steel*
C	0.25–0.30	0.4
Si	0.10–0.40	1.0
Mn	1.10–1.30	0.4
Cr	0.20–0.50	5.2
V	-	1.0
B	0.0008–0.0050	-
Fe	balance	balance

6. Contributions – Part II

6.1 Investigating the influence of coarse particle fraction on the wear of tillage tools (Paper III)

As already mentioned in the introduction, there is still a knowledge gap regarding how different soil properties are linked to the mechanisms responsible for the wear of agricultural tools. This gap is particularly evident for larger fragments such as gravel and stones. While it is established that coarse fragments increase the wear of agricultural tools, the exact ways in which they affect material degradation are not yet fully understood. Further research is therefore needed to achieve a comprehensive understanding of the influence of the coarse fraction on wear.

6.1.1 Methodology

To investigate the influence of coarse fragments on wear, while maintaining realistic and relevant test conditions, field testing during normal tillage operations using a TopDown 500 cultivator were implemented. Typical operating conditions in this region involve driving speeds of 11 to 13 km/h and a working depth of about 15 cm, although these parameters may vary between operators and field conditions.

Field testing was selected because coarse fragments such as gravel and stones occur relatively infrequently compared to the fine earth fraction, making their interaction with tillage tools difficult to reproduce under laboratory conditions. In addition, one of the objectives was to study the behavior of these particles in different soil textures, which are also challenging to replicate realistically in laboratory environments.

All tests were conducted during autumn tillage operations in 2024 and 2025. An analysis of the weather conditions showed no major differences between the two seasons. Standard QT steel cultivator points were used in fields with varying soil textures and contents of coarse fragment fractions. However, all test fields were located within a 15 km radius of Överum, a town in southern Sweden, in order to minimize the influence of climatic variation between sites. An overview of the soil textures and coarse fraction contents of the tested fields is presented in Figure 15.

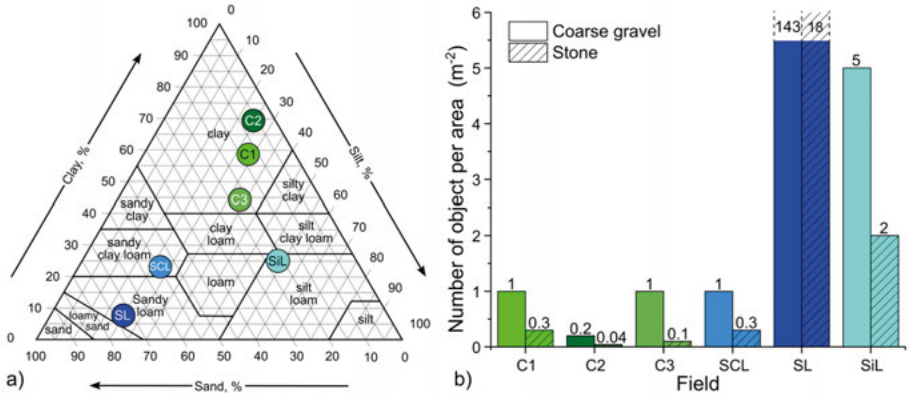

Figure 15: a) All fields included in this study marked on a soil texture triangle. b) Number of coarse fraction fragments, including coarse gravel and stones, identified in the six study fields. No objects larger than 200 mm were identified during the coarse fragment fraction analysis.

The damage observed on cultivator points from fields with similar soil textures but different coarse fraction contents, as well as from fields with similar coarse fraction contents but different soil textures, was compared in order to isolate and investigate the influence of the coarse fraction. Particular emphasis was placed on determining whether soil texture affects the damage caused by the coarse fraction. This aspect has received limited attention in previous research and could contribute to a better understanding of the wear mechanisms responsible for the large variations in wear rates observed between different fields.

The material characterization consisted of a combination of surface analyses and investigations of the combined thickness of deformation Zone 2 and 3 in order to provide a more comprehensive assessment of the effect of the coarse fraction on the wear of tillage tools. Surface morphology was examined using SEM to evaluate the occurrence of large scratches. The depth of these large scratches was further investigated using profilometry. Prior to analysis, the profilometry data were filtered using a Gaussian spline high-pass filter with a cut-off wavelength of 3000 µm to minimize the influence of large-scale shape changes and enhance the contribution from scratches.

The thickness of the deformed zone was examined in etched cross-sections, where the grain structure was revealed to facilitate identification of the deformation depth. The cross-sections were prepared approximately 5 cm from the tip of the cultivator point and oriented at an angle of 30° relative to the scratch direction. This orientation allowed the flow of potentially sheared material to be observed while reducing the risk of analyzing only a single scratch.

The surface layer along the entire cross-section was then imaged using SEM at 50 different positions spaced 0.4 mm apart (corresponding to 0.2 mm

in the direction perpendicular to the scratch direction). The thickness of the deformed zone was defined as the combined thickness of the fine-grained layer and the underlying region containing severely elongated grains. This thickness was measured at all 50 positions, after which the values were sorted according to magnitude to facilitate comparison and analysis.

6.1.2 Results and discussion

The proposed approach made it possible to investigate the influence of the coarse fraction under real field conditions. For example, it was shown that different amounts of coarse fragments in soils with relatively similar textures resulted in differences in the occurrence of large and deep scratches, where increasing the amount of coarse fragments also increased the amount of large scratches (see Figure 16a-d). It was also demonstrated that the thickness of the deformed zone increased with increasing stone content in soils of similar texture (see Figure 16e-f). These observations suggest that the coarse fraction is primarily responsible for the large-scale damage observed on the tested points.

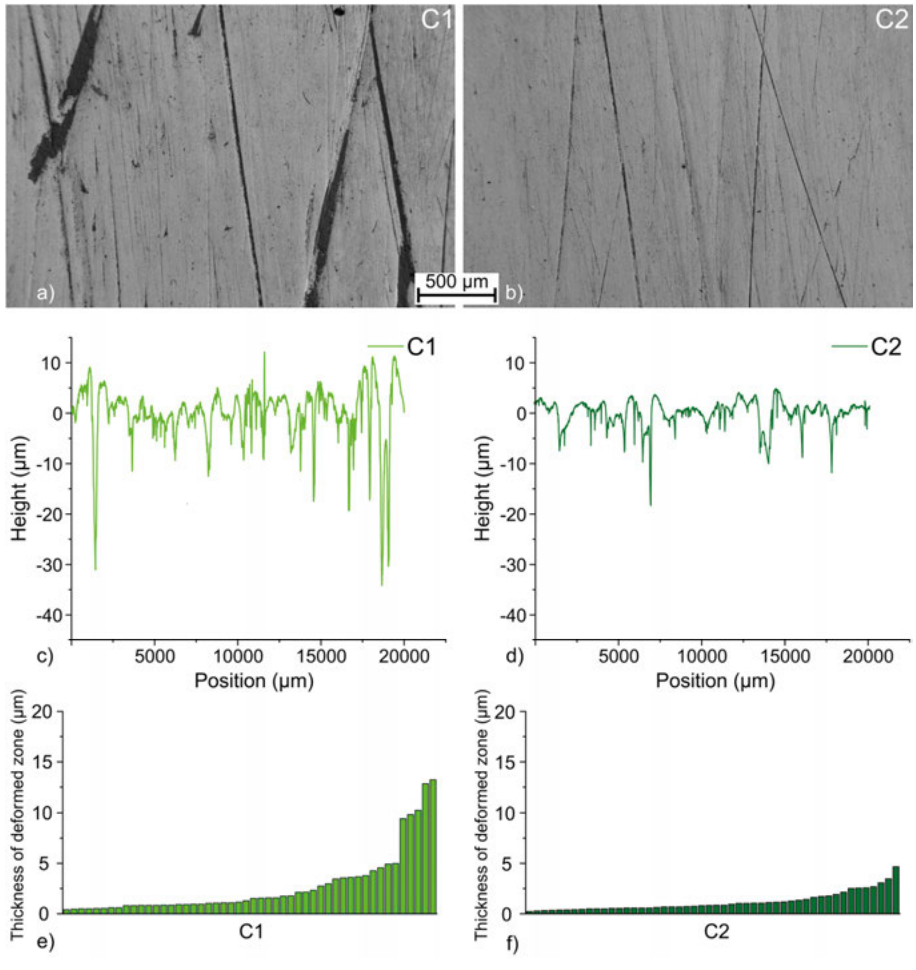

Figure 16: a-b) SEM images representing the wear of the front face from C1 and C2 points. In these images the scratch direction is from the top of the image moving towards the bottom. c-d) Optical profilometry surface profiles of the worn points after testing in the two fields. A Gaussian spline filter with a cut off period of 3000 µm has been applied to the profiles to enhance the differences in groove depth, groove density and overall surface morphology between the two points. e-f) Thickness of the deformed zone from mechanical cross-sections, sorted by size.

By comparing soils with similar amounts of coarse fragment fractions but different soil textures, it was also possible to study how the coarse fragments behave in different soil environments. The results showed that fields with different soil textures, but similar coarse fragment fraction contents, exhibited different amounts of large and deep scratches (Figure 17a-d). A similar trend was observed for the thickness of the deformed zone. Soils with a higher sand content, and thus a looser soil structure, produced smaller and shallower scratches as well as a thinner deformed zone. These findings demonstrate that

soil texture plays a decisive role in determining the extent of damage that the coarse fraction can inflict on the material where sandy, loose soil cannot constrain the coarse fragments to the same degree as soils with larger amounts of clay and silt.

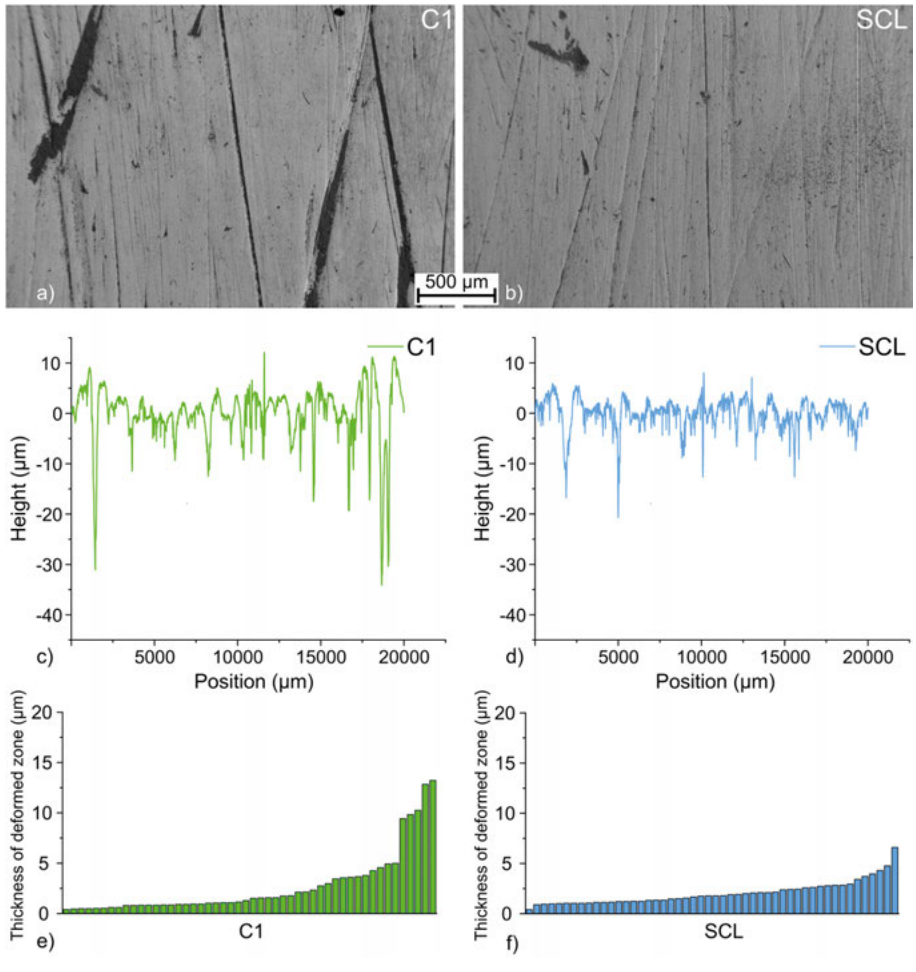

Figure 17: a-b) SEM images representing the wear of the front face from C1 and SCL points. In these images the scratch direction is from the top of the image moving towards the bottom. c-d) Optical profilometry surface profiles of the worn points after testing in the two fields. e-f) Thickness of the deformed zone from mechanical cross-sections, sorted by size.

However, these investigations were conducted under field conditions. Although considerable effort was made to monitor and control the test parameters and operating conditions, field testing inherently involves uncertainties. Soil texture, stone content, moisture conditions, and operator driving parameters may vary between tests or even throughout a single test. This represents the

main limitation of field testing and highlights the need for studies of soil-induced wear under more controlled conditions.

Nevertheless, despite the complexity associated with field tests, the approach proved successful at highlighting different wear behaviors between fields with different soil compositions and for drawing conclusions regarding the behavior of the coarse fragment fraction. Furthermore, it was shown that, when assessing soil-induced wear, it is not sufficient to consider only the amount of coarse fraction present in the soil, but also the properties of the surrounding soil as they influence the extent of damage caused by the coarse fragment fraction.

6.2 Influence of the soil properties on the wear mechanisms of agriculture tools (Paper IV – V)

The above-mentioned approach is highly suitable for studying the influence of large fragments, which are responsible for the large scale damage to the material. However, the surfaces of field-tested cultivator points are far too complex for detailed investigation of the more frequent, locally less severe wear caused by the three main soil fractions: clay, silt, and sand. To enable such detailed studies, including the relationship between small particles and scratch size as well as analyses of wear mechanisms, a simpler surface appearance is required. Such surfaces can only be produced through simplified and more controlled testing methods.

6.2.1 Methodology

6.2.1.1 Mobile pendulum rig

A new mobile pendulum rig was designed by the Ångström Tribomaterials Group, with contributions from the author. Subsequently, a methodology for conducting pendulum testing in agricultural fields and for analyzing the resulting wear damage was developed by the author.

The pendulum rig consisted of a four-legged frame and a pendulum arm with an adjustable length (Figure 18). A specimen could be mounted at the lower end of the arm. To account for the complex soil properties that are difficult to reproduce under laboratory conditions, the experiments were conducted directly in agricultural fields. As the pendulum rig was mobile, it could

easily be transported between fields with different soil characteristics, enabling wear studies under a wide range of relevant field conditions.

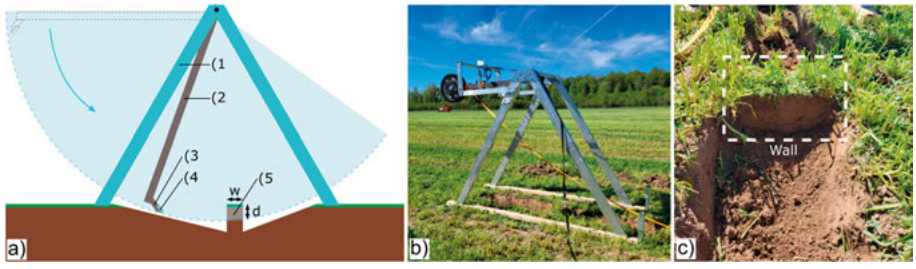

Figure 18: a) Schematic illustration of the pendulum rig with 1) the stand, 2) pendulum arm, 3) specimen shoulder, 4) mounted specimen and 5) the wall (with thickness w and impact depth d) illustrated. b) The rig as its used in an agricultural field. c) A wall prepared for the pendulum test.

A pit was excavated to create a soil wall with a thickness (w) through which the pendulum arm with the specimen could pass. A thickness of 15 cm was selected as a compromise, providing sufficient wear damage for subsequent analysis in less abrasive soils while remaining thin enough for the pendulum arm, at a practical operating weight, to penetrate the entire soil wall even in heavy soils.

The impact force and impact velocity could be adjusted by varying the length of the pendulum arm and the mass attached to it. Both the force and the velocity were calculated rather than directly measured. The calculations were based on the potential energy of the pendulum prior to release. As the pendulum reached the wall at the lowest point of the pendulum swing, the force of the arm could be estimated according to Equation 1.

$$E_i = E_p \tag{1}$$

where E_i is the kinetic energy and E_p is the potential energy. The velocity of the arm could subsequently be calculated by applying the parallel axis theorem, as shown in Equation 2

$$v_i = R\omega = R\sqrt{\frac{2mgh(1-cos(\theta))}{I}} \tag{2}$$

where v_i is the velocity at the lowest arm position, R is the length of the arm, ω is the angular velocity of the arm, m is the mas of the arm, g is the gravitational constant, h is the distance from the center of rotation to the center of

mass of the arm, θ is the arms angle of deviation from vertical and I is the total moment of inertia of the arm.

The specimens used in this study were polished to a mirror finish, resulting in a final surface roughness of Ra = 0.001 µm. In addition, the final polishing step was performed such that the remaining polishing scratches were oriented perpendicular to the direction of the scratches expected to form during the tests. This preparation maximized the ability to identify and investigate even very small scratches in detail.

A single pendulum test produced long scratches of varying sizes on the specimen surface. The number of scratches generated by a test through a 15 cm soil wall varied between soils; however, the scratch density was always sufficiently low that scratches rarely overlapped, leaving only a portion of the specimen surface affected. An example of a surface after a single pendulum test is shown in Figure 19a. In contrast, after testing through three consecutive 15 cm soil walls, a significant portion of the surface was covered by scratches, and substantial scratch overlap could be observed for some specimens.

To validate the relevance of the damage produced by the pendulum rig, and to determine whether the wear mechanisms correspond to those observed during field testing with a cultivator, a short cultivator test with a test distance of only 10 m was conducted (**Paper V**). Although the surface produced by the cultivator test exhibited a greater number of scratches, due to the considerably longer test distance, the characteristics of the scratches were similar to those observed on the pendulum specimens, see Figure 19. Based on these observations, the pendulum test was considered a suitable, simplified method for studying the wear caused by the fine earth fraction in agriculture soil.

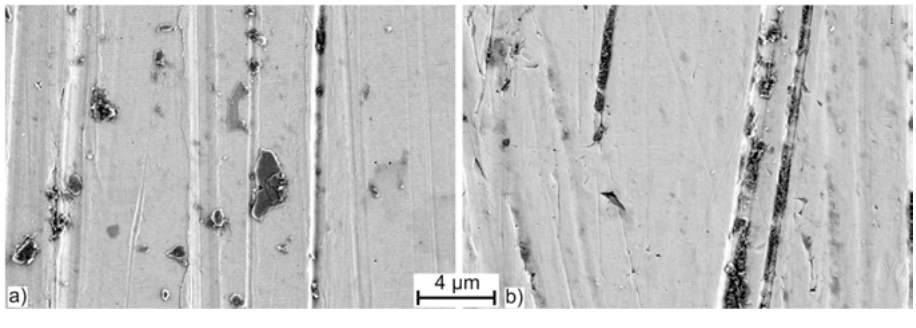

Figure 19: a) An SEM image of the QT steel specimen surface after a pendulum test (from Paper V). b) An SEM image with the same magnification of a QT steel point surface after short, 10 m, cultivator field test in the same sail as a).

6.2.1.2 Scratch analyses

A methodology was subsequently developed for the analysis of scratch widths, and for classifying scratches according to whether their character was

dominantly cutting or ploughing. Such a method was necessary because the large variation in wear features present on soil-worn specimens also results in scratches that are too small to be reliably captured using common surface characterization techniques, such as optical profilometry, which allow the analysis of large surface areas. At the same time, a relatively large surface area had to be examined in order to capture a sufficient number of scratches and thereby represent the broad range of wear features generated by soil. Consequently, techniques offering higher lateral resolution, such as AFM, were not suitable because their limited scan area makes the analysis of sufficiently large regions impractical.

To satisfy these requirements, SEM imaging was performed at a magnification corresponding to a pixel size of 23 nm. Long image strips perpendicular to the scratch direction were acquired to cover a total surface length of 5 mm, making it possible to capture a substantial portion of the variation in scratch sizes present on the worn surfaces. The analyzed area was further divided into five sections to evaluate the statistical variability of the wear features across the surface (**Paper V**).

The classification according to the scratch character without the need for cross-sectional analysis was based on the appearance of the scratches in SEM images acquired from the top surface of the specimens. As illustrated in Figure 20, the classification focused on the morphology of the scratch bottom and the ridges formed alongside the scratches. The proposed methodology was validated through cross-sectional analyses performed using broad ion beam (BIB) milling.

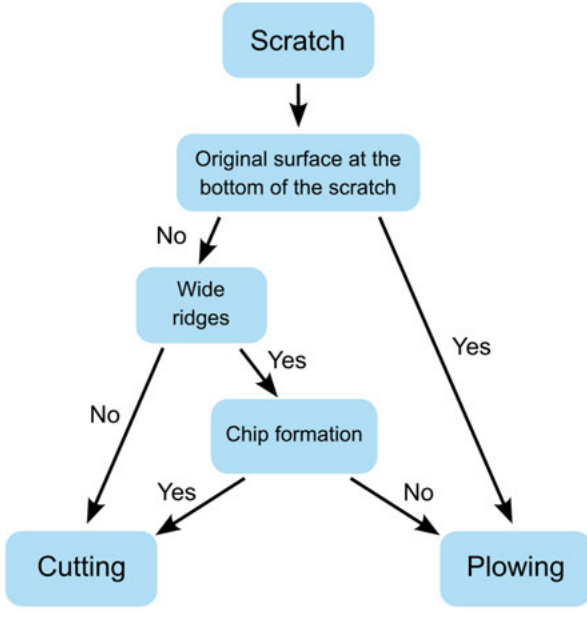

Figure 20: Schematic illustration of how the dominant scratch character was determined.

6.2.2 Results and discussion

By using this approach, it was possible to show, for example, that two soils with different sand contents produced both different numbers of scratches and different scratch size distributions. While the majority of the total scratch width on specimens worn by the soil with lower sand content was associated with scratches smaller than 1.5 µm, scratches of this size accounted for only 26 % of the total scratch width after testing in the soil with higher sand content. Further, scratches wider than 7 µm constituted only 2.5 % of all scratches, yet accounted for 25 % of the total scratch width (Figure 21). These results show that the relative contribution of small scratches is much greater in soils containing smaller particles, whereas a higher sand content leads to more severe surface damage and a greater contribution from larger scratches (**Paper IV**).

It was also shown that an increased soil water content resulted in fewer scratches compared to drier soil, and that the scratch size was reduced. However, the effect of soil water content was less pronounced than the differences observed between soils with high and low sand contents (**Paper IV**).

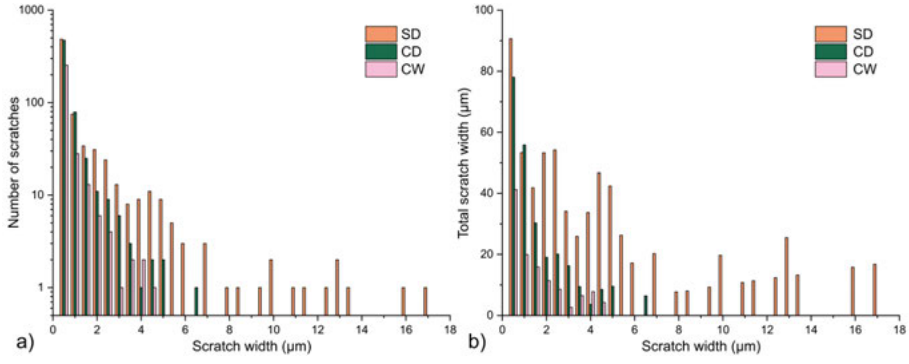

Figure 21: a) Number of scratches for the sandy-, dry clay- and wet clay soils. Note the logarithmic scale on the y-axis. All scratches were grouped into 0.5 µm bins. b) Total scratch width within each bin for the three soils.

It was also demonstrated (**Paper IV**) that the proposed scratch classification could be successfully applied to the results obtained from the pendulum tests. The proportion of cutting scratches increased with increasing sand content, and the majority of the largest scratches were classified as cutting scratches, see Figure 22. An increase of soil water content however had no clear effect on the scratch type.

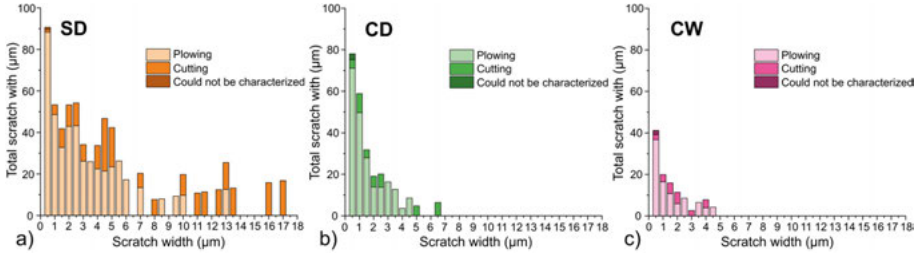

Figure 22: Total scratch width of the plowing, cutting and unidentified scratches measured in the a) sandy soil, b) dry clay soil and c) wet clay soil. The scratch widths are grouped in 0.5 µm bins.

This method was also used to demonstrate that a material with a hardness similar to that the QT steel, but containing hard carbides (AM steel), exhibits significantly higher resistance to soil-induced wear (**Paper V**). Detailed studies of the influence of carbides on the wear mechanisms associated with the fine earth fractions in soil were enabled. The results showed that the presence of carbides greatly reduced the overall surface damage (Figure 23), affecting both the number and the size of scratches formed on the surface.

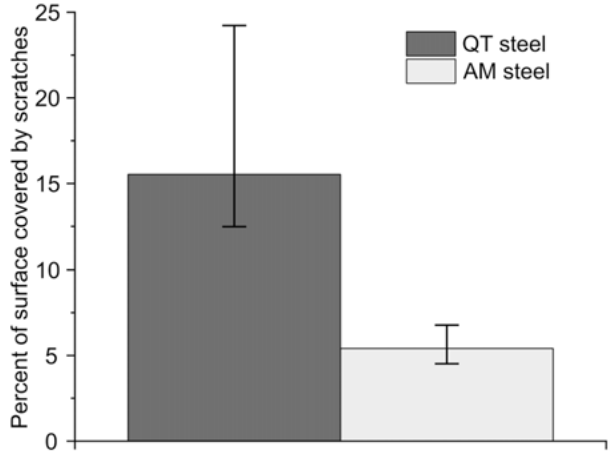

Figure 23: Percentage of the analysed specimen surface covered by scratches for QT steel and AM steel specimens calculated using the total scratch width. The results were obtained using the pendulum rig in a loam field with the test length of 15 cm (one repetition). The mean value was calculated using five 1 mm analysed areas of the specimens. The error bar shoves the maximum and the minimum values of the analysed stripes.

By subsequent analysis of these two materials, where the primary difference was the presence of carbides in one material and their absence in the other, it was possible to identify the mechanisms responsible for this behavior. Carbides located in the path of an abrasive particle can alter the soil particle's position relative to the surface, effectively "pushing it back" as illustrated in Figure 24. This can either reduce the size of the resulting scratch or prevent its formation altogether.

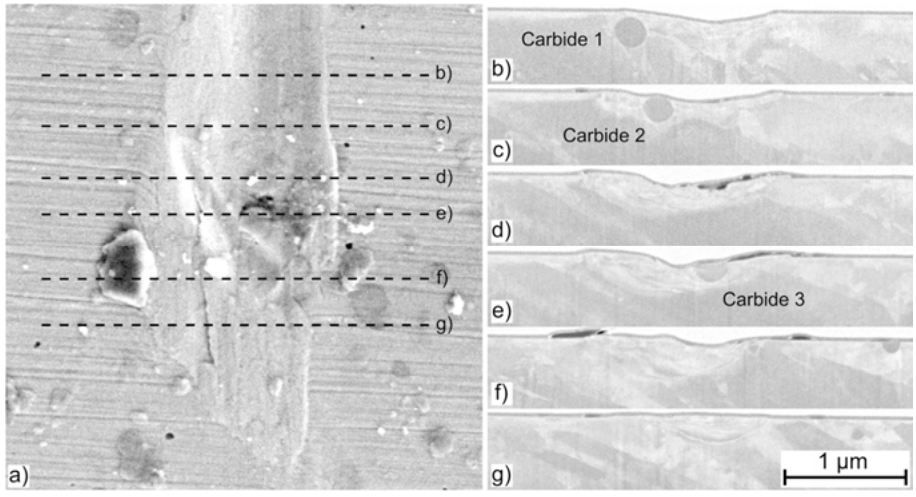

Figure 24: Focused ion beam (FIB) cross section of a scratch on the AM steel where the soil particle was interrupted by carbides. b), c) and e) show several carbides that affect the path of the soil particle, eventually leading to the disruption of the scratching process. By f) (after 3 carbides) the depth of the scratch is significantly reduced and by g) the scratching has subsided.

These results show that the pendulum tests offer several advantages compared with field testing of cultivator points. Despite the short sliding distance, sufficient surface damage is generated to enable meaningful wear analyses. At the same time, the limited exposure produces a less complex surface morphology, enabling the investigation of individual scratches and wear events. The observations made during the pendulum tests would not have been possible to obtain from specimens subjected to traditional field testing.

Furthermore, the short test distance minimizes variations in soil conditions during testing. This makes it possible to characterize the soil directly at the test location and establish more reliable correlations between soil properties and the resulting wear mechanisms. Consequently, pendulum testing provides a controlled approach for investigating the fundamental mechanisms governing soil-induced wear while retaining the use of natural soil as the abrasive medium, avoiding the need to reproduce complex soil characteristics, a task that is particularly challenging given the heterogeneous nature of soil and its structure.

7. Final remarks

7.1 Conclusive summary

The most significant conclusions drawn from the five papers included in this thesis are:

- A new impact-sliding test rig reproducing wear mechanisms representative of those observed in full-scale industrial transmission was developed. The rig enables faster and more cost-effective testing and detailed investigations of both wear mechanisms and the influence of a wide range of test parameters. (Paper I)

- The test rig was used to perform detailed wear mechanism studies, revealing that the wear rate can decrease by up to 25 000 times during a test because of transitions in the dominant wear mechanism. Furthermore, the observed wear processes could be divided into two categories: frequent small-scale wear events and rare large-scale wear events. (Paper II)

- Field testing under conditions representative of cultivator tillage demonstrated that both the content of coarse soil fragments and the soil texture in which they are embedded strongly influence the wear mechanisms of tillage tools. (Paper III)

- A mobile pendulum test was developed for detailed investigations of soil-induced wear in agricultural tools. The method enabled study of small-scale wear mechanisms at a level rarely achieved in studies of soil-induced wear and was used to demonstrate the influence of soil moisture content and particle size distribution the wear. (Paper IV)

- It was demonstrated that the pendulum test reproduces wear mechanisms relevant to field conditions and provides a suitable platform for detailed wear mechanism studies. The method was used to investigate the influence of hard carbides on abrasive wear in soil, showing that carbides reduce both the number and severity of abrasive scratches. (Paper V)

7.2 Concluding remarks

This thesis reports on the development of new methodologies for studying wear mechanisms in two industrial applications, where the transition towards more sustainable operation has introduced new challenges for the tribological systems involved.

The work presented in this thesis demonstrates that a deeper understanding of the governing wear mechanisms can be achieved through a careful balance between simplification and application relevance. While simplified test methods are often necessary to enable detailed mechanistic studies, it is essential that they continue to reproduce the wear mechanisms of the real application. By maintaining this balance, the developed methodologies made it possible to obtain insights that would have been difficult or impossible to achieve using either full-scale tests or highly simplified laboratory experiments alone. Such insights are essential for the of more suitable materials development of new materials tailored to meet the requirements of tomorrows sustainable technology.

Populärvetenskaplig sammanfattning

Vi befinner oss mitt i en global omställning mot ett mer hållbart samhälle. Nya tekniska lösningar utvecklas i snabb takt inom allt från transporter och energiproduktion till jordbruk och industri. Samtidigt som dessa innovationer bidrar till minskad miljöpåverkan ställer de ofta nya och högre krav på materialen som används i systemen.

Ett vanligt problem är att material som fungerat väl i äldre system inte alltid klarar de nya förhållandena. Komponenter kan då nötas snabbare än förväntat, vilket leder till ökade kostnader, mer underhåll och större materialförbrukning. I värsta fall kan en lösning som är tänkt att vara mer hållbar istället leda till ökade miljömässiga och ekonomiska kostnader. Tyvärr är detta ofta en eftertanke och man tar sällan med nötning som en aspekt när nya system utvecklas.

För att utveckla mer nötningsbeständiga material krävs en förståelse för de mekanismer som orsakar nötningen. Detta är dock en utmaning. Nötning påverkas av hela systemet där den uppstår, och verkliga driftförhållanden är ofta mycket komplexa och svåra att återskapa i laboratoriemiljö. Samtidigt är fullskaliga tester ofta både tidskrävande och kostsamma.

I denna avhandling har två exempel studerats där utvecklingen mot mer hållbara system har medfört nya krav på materialens nötningsbeständighet.

Det första exemplet är kopplingshylsor i framtidens elektriska lastbilar. För att öka fordonens räckvidd eftersträvas lägre vikt och högre effektivitet i transmissionssystemen. Ett sätt att uppnå detta är att använda växellådor utan traditionell synkronisering. En sådan lösning kan dock leda till kraftiga slag mellan komponenter vid växling, vilket orsakar nötning på komponenterna. För att dessa system ska kunna användas i praktiken krävs därför material som bättre tål denna typ av belastning.

Det andra exemplet är jordbruksverktyg som används för jordbearbetning. I takt med att jordbruket blir allt mer precisionsstyrt ökar kraven på verktygens prestanda och livslängd. När verktygen nöts förändras deras geometri, vilket kan påverka bearbetningsresultatet negativt, särskilt i ett precisionsjordbruk. För att möjliggöra ett mer effektivt och hållbart jordbruk behövs därför verktyg som behåller sina egenskaper under längre tid.

Syftet med arbetet har varit att utveckla metoder som gör det möjligt att studera nötningsmekanismer på en detaljerad nivå samtidigt som testerna

fortfarande är representativa för verkliga användningsförhållanden. Detta gjordes för båda områdena som nämndes ovan.

För transmissionsapplikationen utvecklades en ny laboratoriemetod som var baserad på en ny, tidigare utvecklad glidande labbuppställning. Denna användes för att studera glidande slagkontakt som liknade den som kan uppstå i växellådor utan synkronisering. Metoden visade sig kunna återskapa de nötningsmekanismer som uppstår i verkliga växellådor, samtidigt som den möjliggjorde mer detaljerade studier än vad som är möjligt i fullskaliga tester. Tester med den nya metoden visade att nötningstakten förändras kraftigt över tiden. Nötningstakten minskade och blev nästan 25 000 gånger mindre från testets början till dess slut, samtidigt som de dominerande nötningsmekanismerna gradvis övergick från kraftig plastisk deformation till utmattningsrelaterade mekanismer. Man kunde även dela in mekanismerna i två grupper ofta förekommande småskaliga och sällan förekommande storskaliga.

För jordbruksverktygen utvecklades en metod som kombinerar fältförsök med en mobil, förenklad pendeluppställning. Pendeluppställningen kunde endast göra väldigt korta (15 cm långa) tester som gjorde mekanismerna lätta att studera. Samtidigt genomfördes försöken i riktiga fält vilket gjorde att mekanismerna stämde överens med verkligheten. Metoden visade sig kunna återskapa de nötningsmekanismer som orsakas av jordens vanligaste partiklar, sand, silt och lera. Samtidigt möjliggjorde den detaljerade studier av hur jordens sammansättning och fukthalt påverkar nötningen. Resultaten överensstämde väl med tidigare observationer från långvariga fältförsök.

Fältstudierna visade också att sten och grovgrus har stor betydelse för nötningen av jordbruksverktyg. En ökad mängd grova partiklar ledde till mer omfattande skador på verktygen. Resultaten visade dock även att effekten av sten och grovgrus är starkt beroende av jordens övriga sammansättning. Samma mängd grova partiklar kan därför ge upphov till mycket olika nötning beroende på jordtyp.

Sammanfattningsvis visar avhandlingen att det är möjligt att utveckla testmetoder som både förenklar komplexa nötningsprocesser och samtidigt bevarar de viktigaste egenskaperna hos den verkliga applikationen. Genom sådana metoder kan nötningsmekanismer studeras på en detaljnivå som tidigare varit svår att uppnå. Den kunskap som kan fås är avgörande för utvecklingen av framtidens nötningsbeständiga material och kan därmed bidra till den fortsatta omställningen mot ett mer hållbart samhälle.

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