Particles Contamination in Battery and Electric Vehicles Systems: from safety to sustainability

Public report

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Content

1. Summary

Technical Cleanliness Analysis (TCA) plays a critical role in the quality control of components in the automotive industry. TCA assesses chemical and particulate contaminants, typically originating from the manufacturing process. As the automotive industry strives for safer and even more durable vehicles, the importance of TCA has grown, especially with the changes motivated by the electrification of drivelines. This transition has significantly impacted how TCA is conducted and will continue to do so in the future.

A standard TCA involves two key steps: particle extraction from components and microscopic analysis. The particles are analysed by size, type (such as normal or fibres), and reflective properties to classify them as metallic or non-metallic. These steps are essential for ensuring cleanliness standards are met.

Historically, TCA was developed to meet the needs of traditional automotive manufacturing, primarily focused on combustion engines. Liquid-based particle extraction methods, using surfactants or organic solvents, became the dominant approach due to their efficiency. Particle analysis based on size and hardness was deemed sufficient to ensure cleanliness in these systems.

However, with the growing adoption of electric vehicles (EVs) and the replacement of internal combustion engines (ICE) with electric motors (EM), TCA has had to evolve. The pace of this change, though, has lagged behind the rapid increase in EV production. Challenges in TCA now include studying the behaviour of particles in electrified systems, such as the impact of magnetic fields and electrochemical reactions, the influence of electric currents in lubricated systems, and the effects of particles on EV powertrains, including wear mechanisms. The role of conductive fibres and metallic particles in battery systems and potential short-circuits also presents new complexities for TCA.

The objective of this work was to enhance knowledge in all aspects of TCA, particularly in relation to EVs. This involved investigating wear mechanisms, particle interactions with magnetic fields, new extraction techniques, and advanced analytical methods where particles are classified based on their molecular and atomic structures.

The result of this work is a comprehensive literature review, which highlights the need for further advances in TCA. It also emphasizes the importance of large-scale, focused research projects to address specific challenges such as wear mechanisms, electrical failures, and the analysis of particles in EV systems.

2. Sammanfattning på svenska

Teknisk renhetsanalys (eng. TCA) spelar en avgörande roll för kvalitetskontroll av komponenter inom fordonsindustrin. TCA bedömer kemiska och partikelföroreningar, som vanligtvis härrör från tillverkningsprocessen. Eftersom fordonsindustrin strävar efter säkrare och ännu mer hållbara fordon har vikten av TCA ökat, särskilt med de förändringar som drivs av elektrifieringen av drivlinor. Denna omställning har stor påverkan på hur TCA utförs och hur det ska utföras i framtiden.

Historiskt sett utvecklades TCA för att möta behoven inom traditionell fordonsproduktion, som främst var inriktad på förbränningsmotorer. Partikelanalyser baserade på partiklarnas storlek och hårdhet ansågs tillräckliga för att säkerställa god renhet i dessa system.

En standardiserad TCA involverar två viktiga steg för att säkerställa att renhetskraven uppfylls: Partikelextraktion från komponenterna och mikroskopisk analys. Partiklarna analyseras utifrån storlek, typ (t.ex. normala eller fibrer) och reflekterande egenskaper för att klassificera dem som metalliska eller icke-metalliska.

I och med den ökade tillverkningen av elfordon och ersättningen av förbränningsmotorer med elmotorer, har TCA varit tvungen att anpassas och utvecklas. Anpassningen har dock inte hållit jämna steg med den snabba ökningen av elfordonproduktionen. Utmaningarna för TCA omfattar studier om partiklars beteende i elektrifierade system, såsom effekterna av magnetfält och elektrokemiska reaktioner, påverkan av elektriska strömmar i smorda system och partiklars effekter på drivlinor i elfordon, inklusive slitage. Ledande fibrer och metalliska partiklar i batterisystem och potentiella kortslutningar utgör också nya komplexa utmaningar för TCA.

Målet med detta arbete var att öka kunskapen inom alla aspekter av TCA, särskilt i relation till elbilar.

Det finns fyra olika typer av slitageprocesser i tribologiska system: abrasion (slitage genom nötning), vidhäftning, ytfattig och tribokemiskt slitage. Bland dessa processer är partikelabrasion den vanligast förekommande tribologiska system, där repning är den vanligaste skademekanismen. Dock kan tribokemiskt slitage bli en större faktor på grund av elektriska strömmar, då partiklar kan påverkas av elektrokemiska reaktioner. Ström påverkar även smörjmedlets egenskaper, vilket kan leda till ökat slitage.

Partikelinteraktioner med magnetfält kan också spela en roll i slitaget på elmotorernas komponenter. Metalliska eller magnetiska partiklar, som vanligtvis lossnar från komponenter på grund av vibrationer och gravitation, kan fastna under längre tid och öka slitaget.

I batterier och batterisystem är slitage inte den mest allvarliga skadeprocessen, men kortslutning kan uppstå om ledande partiklar finns närvarande. Även om det är osannolikt att små ledande eller metalliska partiklar orsakar kortslutning, behöver långa metalliska partiklar, eller polymerer med ledande egenskaper, identifieras vid partikelanalyser.

I elektriska system är det många komponenter som inte kan rengöras med vätskor. Vätskebaserade metoder för partikelextraktion, med hjälp av ytaktiva ämnen eller organiska lösningsmedel, blev dominerande i den traditionella fordonsindustrin på grund av dess effektivitet, men i elfordon är dessa extraktionsmetoder ibland olämpliga, eftersom de kan skada komponenter eller skapa risker under ett tekniskt renhetstest.

Därför är det inte tillräckligt att endast analysera hårda och mjuka partiklar. Det krävs också utveckling av nya extraktionsmetoder och avancerade analysmetoder där partiklar klassificeras baserat på sin molekylära och atomära struktur, för att kunna fastställa renhetskraven för batterier och komponenter i elfordon.

Resultatet av detta arbete är en omfattande litteraturöversikt som understryker behovet av ytterligare utveckling eller anpassning inom TCA. Den belyser också behovet av större forskningsprojekt för att hantera specifika utmaningar som slitageprocesser, elektriska fel och analys av partiklar i EV-system.

3. Background

Climate changes are one of the biggest risks for the continuation of all types of living beings as we know today. The increasing emissions of greenhouse gases accelerated the global warming and the point-of-no-return, where its impacts will be irreversible and even more extremes, is coming closer and closer. Therefore, fast developments of new technologies that decrease the effects of human activities on the climate are urgent.

One of the main gases that contributes to the greenhouse effect and is for very long time considered the biggest villain in common knowledge is CO_2. CO_2 is naturally occurring in nature, but the increased emissions due to the burning of fossil fuels, ethanol, and biodiesel caused an unprecedent accumulation of CO_2 in the atmosphere. This accumulation disrupted the weather patterns, resulting in extreme events, such as heat waves, draughts, and storms, directly impacting people’s lives and essential human activities such as agriculture.

Decarbonization has become more than just a popular word and became a need to ensure a sustainable future for this and next generations. One of the major efforts in this direction is the decarbonization of drivelines, which means the replacement of internal combustion vehicles (ICE) with more sustainable alternatives like electric vehicles (EVs). The replacement of traditional power sources with, mainly, electrochemical devices (batteries and fuel cells) is called electrification.

Electrification of drivelines is now the focus for several developed countries, including Sweden. Due to that, the International Energy Agency estimates that the number of EVs by 2030 will reach about 240 million unities [1]. Only in the USA, the number of EVs has increased exponentially from 22 000 in 2011 to a projected 5 700 000 unities in 2024 [2]. Today, Li-ion batteries are the preferred energy storage system in many applications [3].

Differences between EVs and traditional vehicles go far beyond the battery, i.e., the power source. The engineering of the entire motor and the transmission is different, which directly impacts the production lines. This means that significant changes must be implemented to address this new technology demands, and this impacts the whole production chain: from raw materials to quality control of components. EVs are built with sensitive electronic components, high voltage systems, and advanced battery technologies. Such components set a new level of cleanliness control, since the presence of electric currents, transient and permanent magnets, and use of less lubrication will directly impact the interaction of components with particulate contaminants.

Particulate contaminants, or particles, is the main subject of study in Technical Cleanliness (TC) analyses. Particles are small pieces of organic, inorganic, natural or synthetic matter found everywhere, and are usually harmless. However, in several industries, particles pose a great danger to moving parts, sealings, tubing, junctions etc. Therefore, actions to remove and keep particles away from sensitive components and the analyses of particles as contaminants became common practices in a large variety of processes.

Particles can be presented in all shapes and sizes, ranging from submicrometric scale to few millimetres. They are constantly formed during regular industrial activities, or by the simple fact of opening and closing doors, walking, moving objects etc.

Today, the most used standards in the automotive industry are the VDA 19.1 [4] and ISO16232 [5] for TC analyses inspections and VDA 19.2 [6] for technical cleanliness in assembling sites. From these standards, several internal standards for specific components have been created in all production lines where TC plays an important role. Until now, standards have been focusing on the traditional automotive industry, i.e., on vehicles moved by ICE, and little has been discussed about TC in EVs standards.

4. Purpose, research questions and method

The purpose of this work is to identify methods to improve TCA in the manufacturing of EVs. Although not directly influencing the carbon footprint of road vehicles, TCA is crucial to avoid early failures specifically caused by particles, and to increase durability of vehicles' components. TCA is therefore a critical industrial procedure to increase safety and reliability of EVs, making them even more cost-efficient and attractive to consumers.

However, particles are contaminants present in all manufacturing steps and it is therefore important to answer the following questions:

- Where do particles pose risk for components or systems in EVs?
- Which type of particles are critical for a normal function of a system?
- When (which process) creates harmful particles?
- What contamination level (number of particles) is dangerous?
- How to remove particles from essential components?

In this work, question related to TCA in electrification of drivelines have been addressed with focus on the role of particles in critical systems such as: electric motor, powertrain, shafts, bearings, batteries, battery modules, and battery packs. The study involved understanding the wear mechanisms of particles in moving parts and their effects in batteries, battery systems and battery packs.

The project was developed based on routine meetings with the project partners, who guided and influenced the actions along this project. During the meetings, the partners provided valuable information to work package leaders, who took the initiative to search for answers for the challenges the industry is facing in TCA on EVs. From these discussions, the idea was to develop a literature study, where wear and damage mechanisms caused by particles are on focus, as well as to investigate particles extraction methods, and advance analysis systems (including in-line and on-line solutions) to accelerate TCA to render the manufacturing process faster and more sustainable. Another decision was to book meetings with analysis systems manufacturers, for deep discussion with cutting-edge specialist about the future of image analysis systems and their role in TCA.

5. Objective

The original objectives of this project were to establish appropriate technical cleanliness requirements and to identify cleanliness methodology and standards for their assessment in EV industry. In this pre-study project, the ambitions were:

- to build-up knowledge on the critical contaminants in batteries and electric vehicles,
- to build-up network with battery and electric cars manufacturers and particles analysis systems developers in Sweden,
- identified, beyond battery failing, where technical cleanliness is most important for the electric vehicles industry,
- Identify needs, actions and activities as well as identify stakeholders and consortium for a full-scale project.

In the completion of a full-scale project, the following is expected:

- Identified particles which are harmful to electric vehicles,
- Identified new techniques (if needed) to identify and quantify particles,
- Provide a comprehensive document about cleanliness in electric vehicles.
- Directions and guidelines for cleanliness assessment
- How to handle cleanliness in the value chain in a production line

During this project, the ambitions were slightly changed, though the core objectives were maintained. The initial project had a focus on the TCA on battery production and battery systems assembly, but it was noticed that there was a knowledge gap between wear/damage mechanisms and the role of particles, and therefore, this subject became dominant in the literature study proposed. Also, the objective to build-up a network including Swedish EV manufacturers and particle analysis system developers, was changed to a more insightful discussion with overall detection systems and analysis equipment developers, to bring this knowledge to a full-scale project. Another change was to investigate and to include in the literature survey

6. Results and deliverables

The main result from this pre-study is a mini review report that was distributed among the project participants. This review report contained information on wear mechanisms, effects of particles on wear, effect of electrification on wear (including unwanted currents formation in different tribological systems), particles in electrified systems, battery safety, effect of particles in batteries, a general description of technical cleanliness analysis methods, advanced analysis methods, and in-line analysis methods. The report was also presented to the partners as a slide show (power point presentation), where there was a session for questions and comments.

Some of the main parts of the review report is here outlined.

6.1. Wear mechanisms

Wear is the name given to the damage caused by two surfaces in mechanical contact with each other [7]. Wear affects basically all tribosystems, with dramatic economic impacts in the industry. Zum Gahr [7] classifies wear into four main types: adhesion, abrasion, surface fatigue, and tribochemical reactions. Adhesion wear occurs when sliding surfaces adhere, leading to material transfer and increased friction. Abrasion results from surface protuberances or particles causing damage. Surface fatigue arises from repeated stress, leading to cracks and material loss. Tribochemical wear involves chemical reactions due to friction, influenced by environmental factors like humidity and temperature.

6.2. Effect of particles on wear

Investigating the effects of particles on wear is an intricate science. However, understanding the mechanism of wear caused by particles is probably the most important factor to stablish accurate technical cleanliness requirements. Particles play an important role in components wear into a system. Particles take part in two-body or three-body abrasion, where they are the abrasive material. Particles effects on abrasion has been studied by addition of artificially made wear material [8], simulating the wear mechanism using well-defined silicon abrasive tips [9], interrupted pin-on-disk tribological tests [10, 11], ball-on-disk wear tests [12], by computational simulations of polyhedral particles abrasion [13].

6.3. Particles in electrified systems

Particles pose a risk in tribological systems through the three-body wear mechanism, but research on wear cause by particles in electrified systems is limited. No specific studies focus on particle effects in such environments. Electrification influences wear and particle interactions with magnetic fields. While magnetism has shown positive effects on wear resistance in ferromagnetic materials [14, 15], but the impact of magnetic particles is still unclear. However, knowing that such particles will be attracted by magnetic fields formed during the passage of electric currents (transient) or to permanent magnets (as that present in EV motors), the tribological system can be seen as a “close tribological system”, i.e., the particles will not be easily removed by vibrations or gravitation effects. In such systems, the wear can be twice as high as that in systems where particles are constantly removed by external forces [12].

6.4. Effect of particles in batteries

Safety is a key word in EVs’ battery systems. Faulty battery cells are the dominating factor, and then can be divided in two types [16]: progressive fault and sudden fault. Progressive fault, as the name suggests, is related to cell degradation caused by chemical and electrochemical side reactions, which develops along the time. Sudden faults occur instantaneously and are more dangerous since they are unpredictable.

Among several reasons, short-circuits are the number one risk for sudden failures [16], but particles contamination from inadequately production processes is one critical source of sudden spontaneous combustion [17]. Mohanty et al. [18] showed that the addition of small metallic particles affects the discharge patterns, and that different metals affect the battery capacity differently. More recently, Sun et al. [19] have shown that a Cu particle as small as 100 µm can be damaging, as overtime dissolution and redeposition reactions made the particle larger, causing a short circuit.

6.5. In situ inspection methods

One part of this project was to discuss possibilities to perform cleanliness analysis in situ, i.e., without the need to take random samples from the production line and analysing them in the cleanliness laboratory. However, such methods can be complicated. Particles that sit on the outside of components can be firmly attached to the component’s surface by oils, grease, or electrostatically, or they can also be trapped in places of difficult access, like threads, corners or cavities. Defining one simple analysis method is therefore challenging, but some commercial available equipment have been discussed.

- The QIII SM™ , QIII ST™, and QIII SX™ Surface Particle Detector are equipment produced by Pentagon Technologies which are designed to extract and analyse particles in loco. The detection limit is as low as 0.1 µm up to 125 µm [20].

- PartSens® is a portable surface particle counter ISO 16232 and VDA 19 Part 2 compliant. It directly measures and counts particles, or any other contamination on surfaces. The equipment uses *glancing light technology* which is a lighting condition that originates when incident light shines at specific angles on a surface, revealing/highlighting irregularities, in this case, particles. The software is capable of automatically count, measure, and classify particles ≥ 25 µm, differentiating between metal and fibres.
- ParticleArt is one of the most innovative methods to analyse particles from a surface. This is because ParticleArt is an App that works in any smartphone with Apple or Android systems. The method is very simple: a particle trap strip is used to remove particles from a target sample and the App uses the smartphone camera to analyse the particles.

With the composition of the Review Report based on a literature survey, discussion with technical cleanliness experts, analysis systems developers and manufacturers, the main questions related to this project have been addressed, and the objectives nearly fulfilled. Remaining questions opened up for the possibility to apply for research projects where the main challenges related to particle analysis and cleanliness methods can be explored deeply.

7. Dissemination and publications

7.1. Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The literature study led to increased knowledge in wear and damage mechanisms caused by particles and how electrified systems can modify and change particles/systems interactions.
Be passed on to other advanced technological development projects	X	At least three research projects will be based on the findings in this project.
Be passed on to product development projects	X	The partners involved will benefit on the learnings, and measure to enhance TCA, based on the knowledge brought by this project are already starting.
Introduced on the market		

Used in investigations / regulatory / licensing / political decisions		

7.2. Publications

No publications have been planned so far.

8. Conclusions and future research

Technical Cleanliness is crucial for quality control in sensitive systems, as particles can cause unpredictable damage. However, in the electrification of drivetrains, most cleanliness standards are absent. This study surveyed literature on particle-induced damage, focusing on wear mechanisms from Zum Gahr's work [7]. In electrified systems, electricity may worsen particle-driven wear if magnetic fields trap particles [21], preventing their removal. The study identified potential hazards in battery systems, where particles can cause sudden failures through electrode perforation or contamination.

Current particle extraction methods, such as pressure rinsing and air jet extraction, and detection methods like light microscopy, were evaluated, highlighting their limitations, particularly in detecting transparent or white particles. Alternatives were proposed, but further testing is needed. This work provides a comprehensive overview of cleanliness in EVs, outlining challenges and offering insights, though further research is necessary to establish robust standards for safer, more sustainable electric vehicles.

In this study, it was demonstrated that the safety and reliability of EVs depends on a better understanding of the effect of particles in their tribological systems and in battery systems. Therefore, the following future works are proposed:

- EV tribological systems
  - Particles wear mechanisms in EVs shafts and bearings
  - Effect of magnetic fields on metallic particles
  - Interaction between magnetic particles and tribological systems
- Battery systems
  - Damage mechanisms caused by particles
  - Risk for short-circuits caused by conducting particles
  - Effects of conducting or non-conducting fibres in battery modules or packs
  - Long-term effects of particles in sealed-for-life systems
  - Particles extractions based on dry extraction
- General
  - Technical cleanliness requirements
  - On-line cleanliness techniques for quick particles contamination assessment

- Improved particles detection and composition analyses

9. Participating parties and contact persons

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10. Bibliography

[1] L. Jiang, X. Diao, Y. Zhang, J. Zhang and T. Li, "Review of the Charging Safety and Charging Safety Protection of Electric Vehicles," *World Electric Vehicle Journal,* p. 184, 2021.

[2] E. S. Forcast, "EVAdoption," 8 May 2021. [Online]. Available: https://evadoption.com/2030-20-million-more-ice-vehicles-will-be-on-the-roads-in-the-us-than-in-2021/. [Accessed 21 03 2024].

[3] Y. Li, P. Zhao och B. Shen, "A review of new technologies for lithium-ion battery treatment," *Science of the Total Environment,* vol. 951, p. 175459, 2024.

[4] VDA-19.1, Quality Management in the Automotive Industry Part 1: Inspection of Technical Cleanliness, Frankfurt: Henrich Druck + Medien GmbH, 2015.

[5] *Road Vehicles - Cleanliness of Components and Systems,* ISO 16232:2018, IDT, 2018.

[6] VDA-19.2, Quality Management in the Automotive Industry Part 2: Technical Cleanliness in Assembly, Frankfurt: Henrich Druck + Medien GmbH, 2015.

[7] K.-H. Zum Gahr, Microstructure and Wear of Materials, Amsterdan: Elsevier Science Publishers B.V., 1987.

[8] M. Binder, F. Klocke and B. Doebbeler, "Abrasive wear behavior under metal cutting conditions," *Wear,* Vols. 376-377, p. 165, 2017.

[9] R. Gåhlin och S. Jacobson, ”The particle size effect in abrasion studied by controlled abrasive surfaces,” *Wear,* vol. 224, p. 118, 1999.

[10] F. P. Benincá, C. M. Romero, R. M. Camporez, C. A. Rosa Neto, N. F. Strey och C. Scandian, ”Evolution of morphology, microstructure, and hardness of bodies and debris during sliding wear of carbon steels in a closed tribosystem,” *Waer,* vol. 523, p. 204809, 2023.

[11] T. Hisakado, K. Miura och H. Suda, ”Effects of debris transfer and abrasive particle damage on the abrasive wear of hardened bearing steel,” *Wear,* vol. 247, p. 24, 2001.

[12] S. Hanke, I. Samerski, J. Schöfer och A. Fischer, ”The role of wear particles under multidirecional sliding wear,” *Wear,* vol. 267, p. 1319, 2009.

[13] D. V. De Pellegrin och G. W. Stachowiak, ”Simulation of three-dimensional abrasive particles,” *Wear,* vol. 258, p. 208, 2005.

[14] T. A. Stolarski och Y. Makida, ”Influence of permanent magnetic field on wear performance of dry sliding contacts,” *Wear,* vol. 271, p. 1109, 2011.

[15] A. F. Yetim, H. Kovaci, M. Aslan and A. Celik, “The effect of magnetic field on the wear properties of a ferromagnetic steel,” *Wear,* vol. 301, p. 636, 2013.

[16] B. Zou, L. Zhang, X. Xue, R. Tan, P. Jiang, B. Ma, Z. Song och W. Hua, ”A Review on the Fault and Defect Diagnosis of Lithinum-Ion Battery for Electric Vehicles,” *Energies,* p. 5507, 2023.

[17] X. Kong, L. Lu, Y. Yuan, Y. Sun, X. Feng, H. Yang, F. Zhang, J. Zhang, X. Liu, X. Han, Y. Zheng and M. Ouyang, “Foreign Matter Defect Battery and Sudden Spontaneous Combustion,” *eTranportation,* p. 100170, 2022.

[18] D. Mohanty, E. Hockaday, J. Li, D. K. Hensley, C. Daniel och D. L. Wood III, ”Effect of electrode manufacturing defects on electrochemical performance of lithium-ion batteries: Congnizance of the battery failure souces,” *Journal of Power Sources,* vol. 312, p. 70, 2016.

[19] Y. Sun, Y. Yuan, Y. Lu, M. Pu, X. Kong, L. Lu, H. Wang, X. Han och M. Ouyang, ”Life-cycle evolution and failure mechanisms of metal-contaminant defects in lithium-ion batteries,” *Journal of Power Sources,* vol. 557, p. 232591, 2023.

[20] Pentagon Technologies, ”pen-tech.com,” P5i Ltd, [Online]. Available: https://pen-tec.com/qiii-surface-particle-detection. [Använd 30 May 2024].

[21] F. He, G. Xie och J. Luo, ”Electrical bearing failures in electric vehicles,” *Friction,* vol. 8, p. 4, 2020.