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Contamination Control for Sensitive Products in the Era of Electrified Vehicles

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Abstract

With the growing trend toward electric vehicles, technical cleanliness is also taking on a more prominent role. Insufficient component cleanliness can lead to more frequent or more serious defects, and although contamination control tools and techniques are well known, they are not widely used in production. This article describes how contamination control can be systematically planned and integrated into existing production processes. Contamination control is not a stationary state, but rather a dynamic search for Points of Interest (POI). Only when all POIs have been identified does contamination control become continuous monitoring, which ultimately allows the cleanliness requirements specified in the customer-supplier relationship to be verified.

Keywords

Contamination control; particle; electronic; vehicle; safety

1. Introduction

As electrification in the automotive industry progresses, a new era of mobility seems to be emerging, which is already becoming evident in the fields of autonomous driving, connected driving and electric drives [1].

When it comes to new technologies, people tend to be averse to taking risks and consequently have a greater need for safety [2]. Drive batteries or high-voltage components can pose an added risk to the occupants of electric vehicles. Short circuits can cause fires or explosions due to the high voltages involved [3,4]. Among others, these can be triggered by collisions [5] or particulate contamination [6].

The fact that particulate contamination can cause malfunctions or failures is not new [7–9]. As early as 2010, the automotive industry developed a guideline for reducing or monitoring particulate contamination in assembly processes [10]. Component cleanliness inspections are indispensable in this regard [11,12].

The cleanliness inspections are carried out in the laboratory by a specialist and are extremely time-consuming [13]. As a result, in practice only approx. 0.002% - 2% of manufactured parts are tested for cleanliness, meaning that at least 98% of components leave the factory without being tested. This estimate applies to many companies in the automobile industry which manufacture safety-critical components.

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Contamination control becomes inevitable in order to avoid vehicle recalls associated with the risk of shorting due to particles. The ever-increasing miniaturization of electronic circuits and product complexity is constantly increasing the pressure to act.

At present, the automotive industry is faced with the challenge of making contamination control an integral part of quality planning and assurance. Attempts to do so have so far been unsuccessful because the necessary know-how is not equally distributed along the supply chain. This article helps to establish a common understanding and approach by explaining basic aspects of contamination control from an operational perspective.

2. State of knowledge and practice

The number of automotive components which are produced in cleanrooms is constantly rising (e.g. cameras, displays, battery cells, microelectronics, etc.). It therefore seems logical to implement procedures for monitoring airborne contamination [14] or methods for evaluating surface cleanliness [15]. However, there are two reasons why this may not be appropriate. Firstly, there is a discrepancy as regards the relevant particle sizes: a) 0.1 µm to 5 µm in ISO 14644 [16] and b) 5 µm to > 3000 µm in VDA 19.1/ ISO 16232 [11,12]. Secondly, the cleanliness of products manufactured in cleanrooms is not taken into account in the ISO 14644 series of standards [17].

However, contamination control in the automotive and electronics industries is aimed at product-specific cleanliness, which is based on a product's functions or sensitivity [18] and thus differs from other industries and standards. For example, in IEST-STD-CC1246E (formerly: MIL-STD-1246C), product cleanliness levels are defined in a more general way, which can be conducive to the implementation of contamination control [19,17] which can be beneficial when implementing contamination control.

The goal of contamination control is to limit the contamination that occurs during production to a level that is acceptable for the product [20,21].

The first step is to define cleanliness targets for the product [22] as well as for the assembly processes and areas [23]. At the beginning of the product life cycle, this can be achieved with the help of failure mode and effects analysis (FMEA), [22,24] something which is rarely done in practice.

Once the production line is completed, the analyses can be performed to monitor compliance with the defined targets. The early detection of out-of-control events helps to reduce reject rates [25]. In ASTM E1548, some procedures (in connection with aerospace) are mentioned for

- sampling surfaces using the tape lift method, which is comparable to the particle stamp technique from VDA 19.2 [10] (see Figure 5),
- sampling products with the spray flush method, which is comparable to the extraction method of pressure rinsing from VDA 19.1/ ISO 16232 [11,12] or
- analyzing the particle load obtained by one of the two previously-mentioned sampling methods using the light microscope. However, this is technically outdated compared to the automated process described in VDA 19.1/ ISO 16232 [11,12]. [26]

Although some techniques are similar, the aerospace industry differs significantly from the automotive industry, which is cost-sensitive and manufactures in large series. The automotive industry's dilemma is, on the one hand, to produce dependable or safe modules - which is associated with high cleanliness requirements - while on the other hand, to minimize production times and costs. The economic optimum corresponds exactly to the cleanliness requirement which ensures that a component will just still function correctly. So-called fault injection tests are suitable for this purpose [27]. According to the understanding of [22] and [23], robust product design is already an integral part of contamination control.

This holistic understanding of contamination control is far removed from actual practice in the automotive industry. For this reason, the following article is limited to the point in time when the product design has been fixed and the production line is about to go into series production. With the production part approval process (PPAP), there is a need to establish conformity to something that usually has not yet been defined.

3. Initial situation

The following section describes Phases I and II based on the example of the electronic control unit (ECU) for the current generation of hydraulic/ electronic brake control units (HECU), see Figure 1. The procedure can also be applied without restriction to other mechatronic or electronic components.

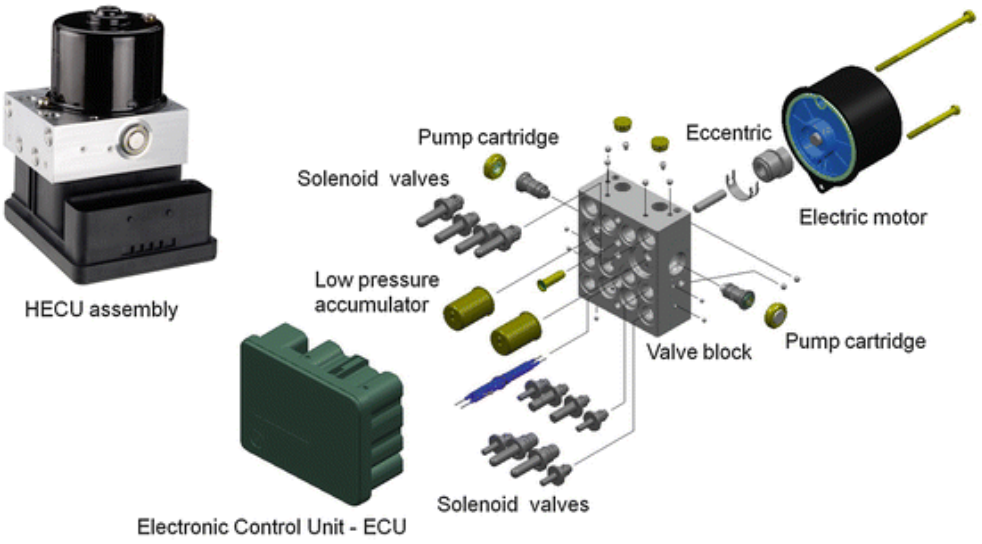

Figure 1: Exploded view of the brake control unit [28]

The HECU controls the anti-lock braking system, electronic vehicle stabilization, and autonomous emergency braking. If the unit has to intervene for any reason, the brake pressure is individually adjusted by the hydraulic valves on each wheel. Particles in the electronics or hydraulic valves could cause a malfunction or failure and cause an accident.

Figure 2 shows the assembly processes for the ECU. This article does not go into further detail about the surface mounted technology line (SMT line) or test line. The risks of particles being generated or transferred on these lines is lower compared to the back-end line.

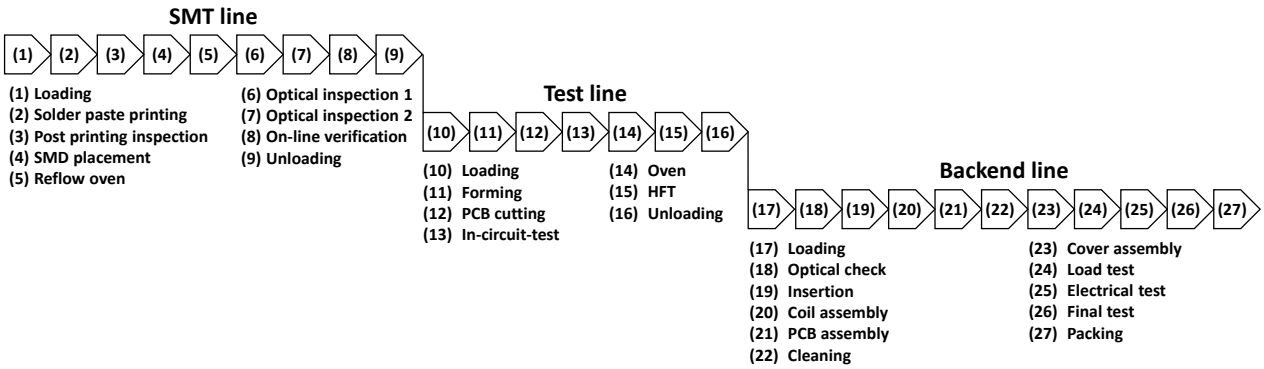

Figure 2: Process chain for assembling the ECU

For the purpose of this article, only Size Class F (100 - 149 µm) is discussed, with a maximum permissible amount of 64 particles. The approach presented here can be transferred to the other size classes. Further criteria are indispensable to complete the cleanliness specification:

a) After which process step does the cleanliness specification apply?
b) To which control areas does the particle size distribution refer?
c) How often must cleanliness be checked?

Unfortunately, in practice these criteria are specified far too rarely, resulting in a potential conflict between the manufacturer and the customer. For example, without specifying a), it is often assumed that cleanliness applies to the End of Line (EOL) - i.e. after Process (27). This assumption is incorrect and a sign of insufficient knowledge about technical cleanliness. The ECU is already closed after Process (23), meaning that only the exterior would be accessible for a cleanliness inspection. If b) is also not specified, this could already cause the conflict to escalate.

The ECU cleanliness specification applies after Process (22), see Fig. 4. Once the cover has been mounted, the relevant inside area is no longer accessible. A cleanliness inspection would then require a mechanical opening of the ECU housing, which is associated with additional residues from the breakage. It is impossible to distinguish between residual assembly particles and residues from the breakage. Therefore, the cleanliness of a component has to be specified at a point where it can be inspected. The particle increase from Process (23) is typically hidden from view**.**

However, additional cleaning processes can also improve cleanliness elsewhere, for example if an EOL cleaning step is not feasible. Since cleaning is a key process, it should always be monitored, cf. Annex A.B.1 in [10]. Consequently, the cleaning processes in Phase I do not need to be taken into account.

In Phase I, expectations and results are constantly compared through new analyses, which gives this phase an iterative character. Conclusions can be drawn from the comparison, which in turn can lead to further tests. Phase I is complete when only little or no further knowledge can be gained.

4. Phase I

The aim of Phase I is to identify critical particle sources or processes. A process is considered as critical if it significantly contributes to the accumulated contamination of the product or if the cleanliness specification is not met.

Depending on the amount of value added and the complexity of the product, Phase I can rapidly become extremely time-consuming or cost-intensive. Therefore, the iterative refinement of the search grid (from coarse to fine) is a compromise to economic constraints, see Figure 3. If a company has little or no experience in this field, expert advice should be sought from production line operators, logistics specialists, etc.

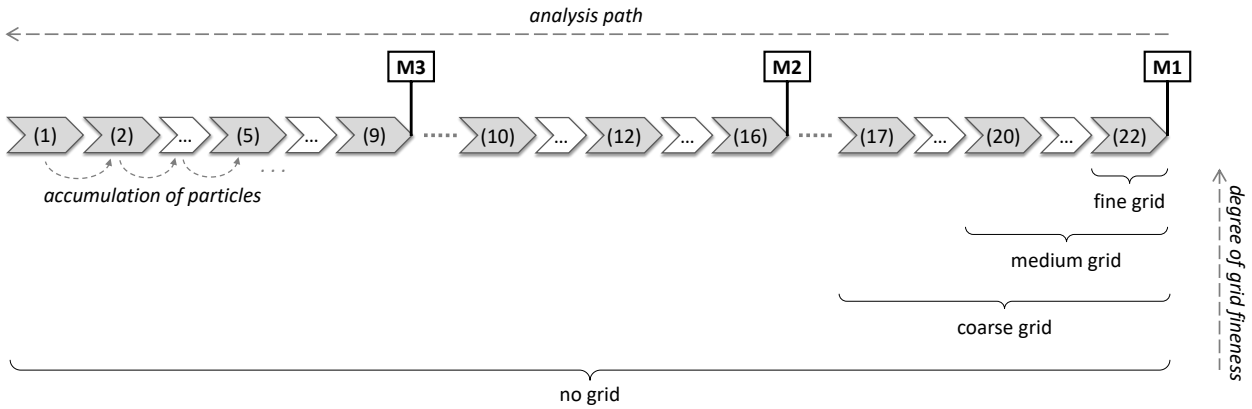

Figure 3: Approach for analyzing the process chain

How much the search grid needs to be refined or which processes should still be examined can only be seen from the previous analysis cycle. The initial analysis cycle could consist of the measurements M1, M2 and M3. In a second cycle, processes (21), (20) and (19) could then be analyzed etc. However, a complete (fine grid) process chain analysis as shown in Figure 4 is rarely found in practice.

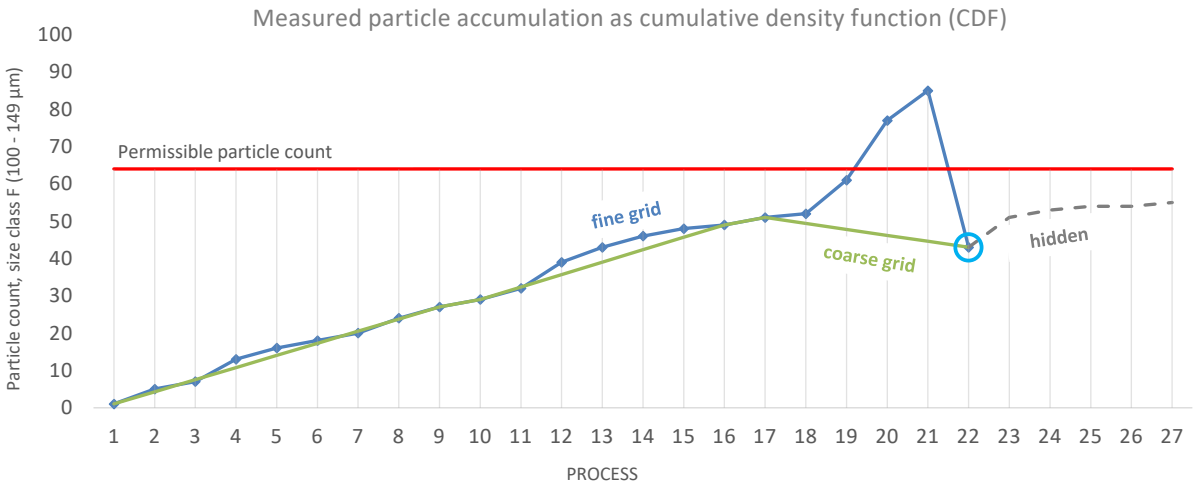

Figure 4: Information density in relation to the search grid

The methods and tools used in Phase I and Phase II are largely identical. Nevertheless, the results from Phase I are not suitable for ratings in the customer-supplier relationship. The analyses carried out in Phase I have an exploratory character, enabling the maximum amount of information to be gained about the process chain as quickly as possible. The following tools can be used in Phases I and II:

Particle traps are an inexpensive and simple tool for measuring the cleanliness of the environment or processes. Particles settling on the adhesive surface are fixed by the adhesive tape and can be analyzed automatically with a light microscope after the trap has been deployed for a certain period of time, such as 5 working days, see Figure 5. [10] Instead of particle traps, particle deposition counters can also be used, which provide measurement data in real time [29].

Particle stamps are a further inexpensive and simple tool for determining the cleanliness of surfaces. The tape is used to remove contamination from the surface, which in turn can be analyzed automatically with a light microscope, see Figure 5. [10]

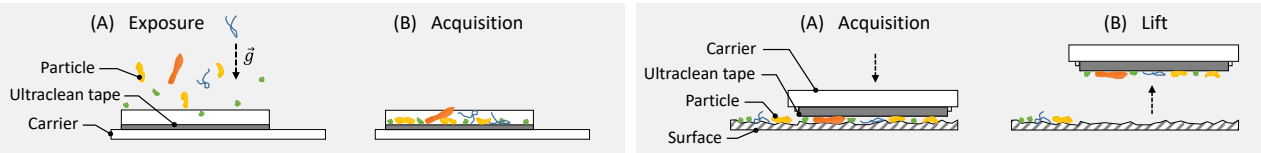

Figure 5: Left: particle trap, Right: particle stamp [30]

Component cleanliness inspections are used to verify the level of cleanliness specified in the customer-supplier relationship and provide the best results as a direct evaluation method. In Phase I, a simplified procedure can be implemented. In Phase II, the component cleanliness inspections must be performed exactly according to VDA 19.1 or ISO 16232. [11,12]

Tracer components tend to be used at the end of Phase I, when the previous results are verified by measuring the contamination generated by the process step. This is done by cleaning the assembly or its individual components in the laboratory until no further residues can be extracted. The assembly then has a defined

state of cleanliness, which can be verified in a cleanliness inspection. The assembly is then ready for processing. After the assembly step, another cleanliness inspection is performed, see Figure 6. [10]

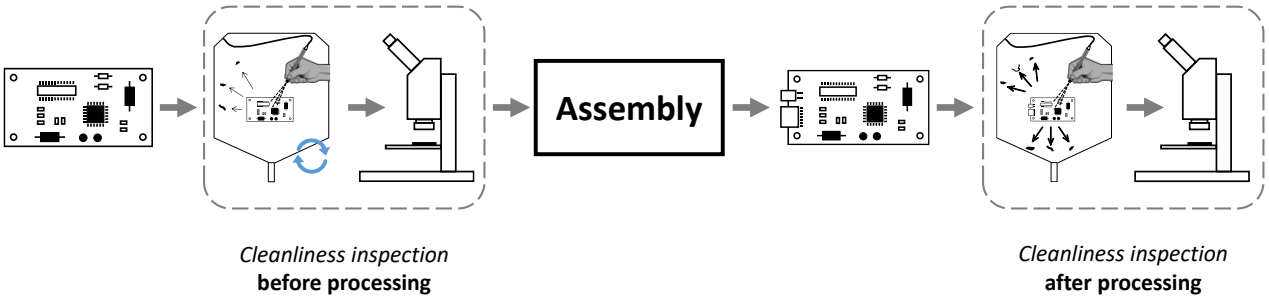

Figure 6: Application of tracer components

Tracer particles have specific properties that make them distinguishable from ordinary contamination in the manufacturing environment. Tracer particles are suitable, for example, for evaluating cleaning results or for visualizing the transfer of contamination due to logistics processes. Figure 7 gives examples of tracer particles.

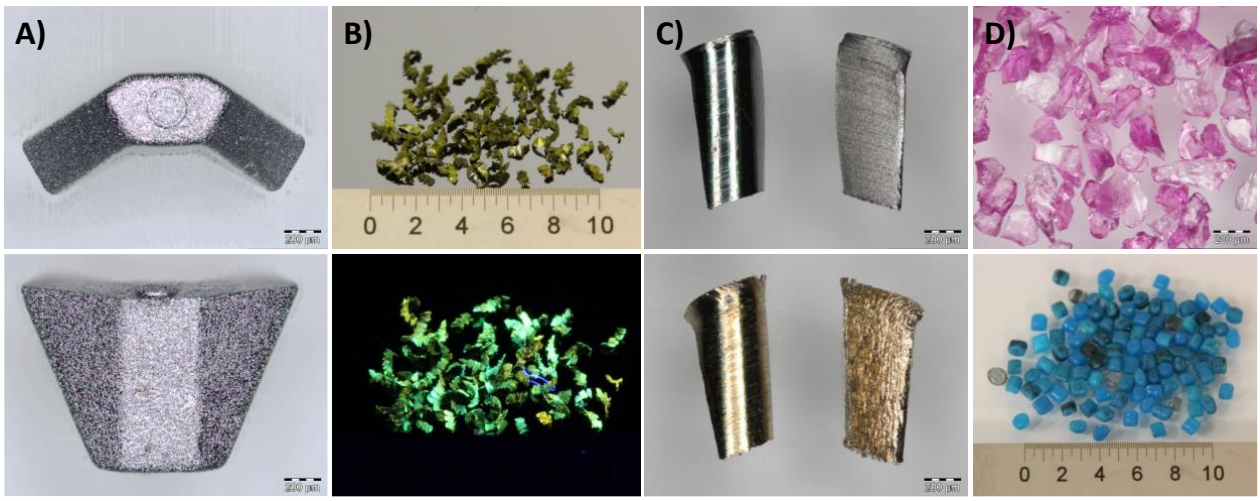

Figure 7: Tracer particles. A) Regular shapes [31]. B) Fluorescent [32]. C) Milled chips [33]. D) Blasting material.

Besides the correct use of the tools, the type of information required from the respective analysis is another important factor. For example, a particle trap mounted underneath the conveyor belt can supply information about the quantity of particles emitted in this area. However, this information is of little help in assessing the cleanliness of the ECU. Such approaches may be useful in Phase I but should be verified by component cleanliness inspections in a further iteration.

Difficulties arise when examining the data from a statistical point of view. As opposed to other features that can be specifically produced, values tend to fluctuate much more when it comes to technical cleanliness, see Figure 8. This is because technical cleanliness is strongly influenced by random events. Therefore, a once-only assessment of component cleanliness is not sufficient.

Verifying inspection results also has another advantage. Should contradictory results arise, information deficits can be better identified, thus stimulating the development of new or further process analysis techniques. Only when additional analyses fail to deliver any further information can the process chain analysis in Phase I be concluded.

The minimalistic approach is a consequence of the high cost pressure prevailing in the automotive industry. However, this does not mean that analyses should be dispensed with. In the case of supplied parts, it is not

only their state of cleanliness when they are ready for dispatch at the supplier's and at the point of use that must be monitored. The cleanliness of these parts should also be monitored on arrival at the customer's.

For instance, the coils actuating the hydraulic valves are monitored not only before shipment at the supplier's but also on receipt at Continental and again at Process Station (20). This makes it possible to find out whether the particles originate from internal logistics processes, from external logistics processes or from the supplier's production process.

5. Phase II

Phase II is aimed at long-term process monitoring and at reducing particle sources / emissions. As a rule, Phase II commences once series production is up and running. The respective tools and analysis sites are already known from Phase I. The frequency of analyses should be determined primarily by the cleanliness specification. If no information is given, the frequency of inspection should be in the range of 0.002% - 2% of the products manufactured. The long-term reduction of particle sources or emissions is achieved through three fields of action:

Intervention limits enable steps to be taken at an early stage if cleanliness levels show signs of worsening. An intervention limit can be set after about 30 analyses have been conducted. Several procedures can be used. Figure 8 shows three possible intervention limits. IL #1 corresponds to Quantile 3 and represents a clear intervention threshold that would trigger an alarm at 25% of all values. IL #2 corresponds to the 1σ level known from quality control. IL #3 is an intervention limit that is well suited for technical cleanliness and mostly applied by vehicle manufacturers and first-tier suppliers in practice. This is obtained from the point where x intercepts with F(x) of the empirical CDF.

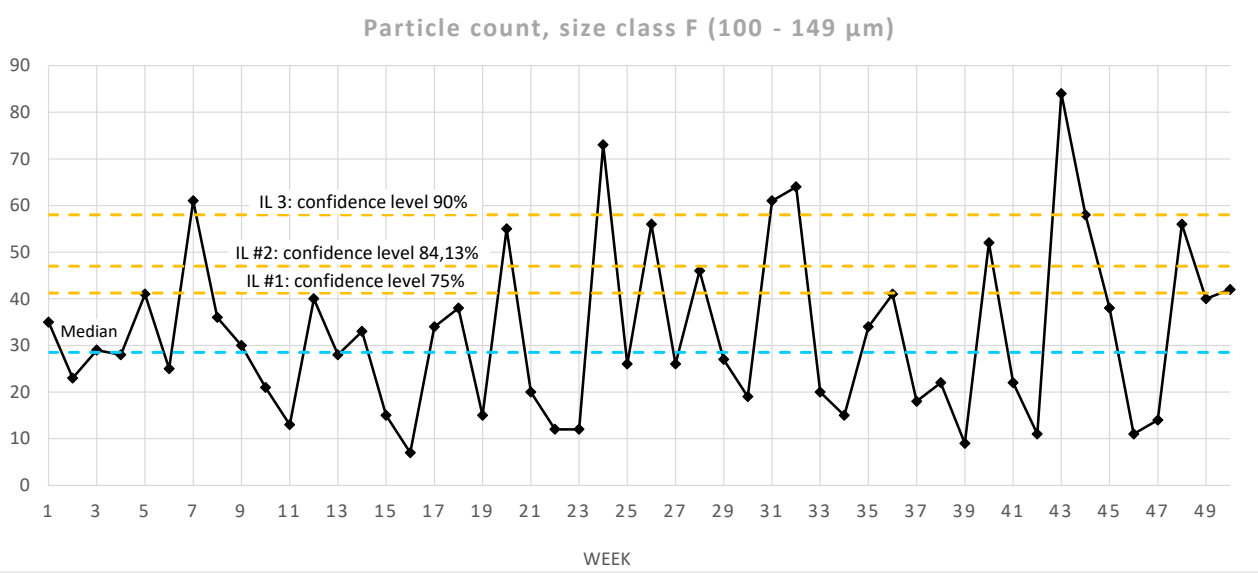

Figure 8: Selection of recommended intervention limits

The intervention limit chosen depends on company preferences. At present, there is no standardized regulation or convention on this. However, choosing a high sigma level, as pursued by quality control, is not recommended. As the sigma level increases, the warning threshold decreases.

Staggered analyses can increase sensitivity and allow faster intervention. This results from the causal relationships observed between the processes due to particle accumulation. Instead of always measuring Processes (22), (21) and (20) on a Monday, it would be better to measure Process (22) on a Monday, Process (21) on a Wednesday and Process (20) on a Friday.

Particle galleries make it easier to identify particle sources. In addition to light microscopic analyses, spectroscopic analysis methods are also used. The origin of particles can be derived from material data. Scanning electron microscopes with energy dispersive x-ray (SEM/EDX) or laser-induced breakdown spectroscopy microscopes (LIBS) are suitable for identifying inorganic particles. Fourier-transform infrared microscopes (FTIR), on the other hand, can be used to identify organic particles.

6. Summary and Outlook

Contamination control might be established since decades in aerospace or semiconductor industry. But the automobile industry needs a divergent approach in this field to be successful in a price sensitive milieu. For that purpose, this article describes the method to establish contamination control in the automobile industry.

Phase I reflects an explorative survey to understand the severity of impacts that is the basis for a lean monitoring in phase II. The method can be applied to any automobile component. In this work, the phases were explained on the example of the hydraulic brake control unit (HECU). It was found that multiple iterations were needed with varying measurement techniques to conclude if a process is relevant (critical) in terms of its added proportion to the cumulative contamination, typically found in the product, end of line. The information density illustrated in Figure 4 is not common so that a very economic approach (coarse grid) could end up in wrong conclusions. But the example of the HECU showed, that the limit violations of process 20 and 21 are finally not critical, when followed by an efficient cleaning process. In return, process 22 is relevant for the monitoring instead of process 20 and 21.

However, the comparability of different measurement techniques was not discussed in this work, but is still an issue, when Phase I is carried out. It is questionable, if the same amount and size of contaminants that were found in particle traps would have been found in the product as well, to name only one. Some of the measurement techniques can be only used for trend analyses, when compared to a component cleanliness specification. Nevertheless, particle traps or stamps are cheap tools for single or multiple process monitoring and usually the preferred choice in the automobile industry. There are particle deposition monitoring systems available that could measure the sediment in or near real time [34,35]. But they are sometimes too big to fit in a machine, too expensive for the aspired measurement frequency or do not present the desired information [36].

A further development of contamination control in the automobile industry requires more handy solutions as described in [37] for example and a higher degree of automation as presented in [38] to gain more information in less time. Nevertheless, new technical solutions should be able to provide the same information as a microscope, i.e. actual shape and dimension of a contaminant.

As long as there are not such technical solutions available, this paper provides a method for an economic oriented contamination control that might be of interest for all manufacturers of safety relevant automobile components.

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Biography

Patrick Brag (*1980) has been project manager for technical cleanliness at the Department of Ultraclean Technology and Micromanufacturing at the Fraunhofer Institute for Engineering and Automation (IPA) since 2011. Dipl.-Wirt. Ing. Patrick Brag was a member of the VDA 19 Part I standardization committee (2014-2015) and has been a PhD candidate since 2021. He is also a trainer and consultant for technical cleanliness in the worldwide automotive industry.

Bálint Balogh (1980) has dedicated his career to the Automotive industry. Since 2015 he has been the member of the Executive management at Continental Automotive Hungary Ltd. He demonstrates strong commitment in leading the company to success: first as the Leader of the Laboratory (2010-2015), then as the Head of Quality Management (2015-2021), and currently as the Head of Focus Factory Automotive Plant Budapest. He was graduated in Electrical Engineering MSc at Budapest University of Technology and Economics and continued his academic journey as a PhD student at the Department of Electronics Technology.

Peter Gordon, PhD (*1976) is associate prof. at Dept. of Electronics Technology, Faculty of Electrical Engineering and Informatics, Budapest University of Technology and Economics. He is the co-founder of EFI-labs, specialized in material and failure analysis of electronic products. He is also the co-founder of Center of Particle Control (CPC), which is the competence center for technical cleanliness in Hungary.