CLEANLINESS TEST FOR VARIABLE PACKAGING SOLUTIONS IN THE AUTOMOTIVE SUPPLY CHAIN

JAN PEČMAN[1], VLADIMIR LUPTAK[2]

Abstract

Technical cleanliness is at the centre of attention in more and more sectors of the automotive industry. Its importance primarily lies in the need to ensure the correct function of components and it is necessary to take into account that impurities can affect the assembly and proper functioning of other components if they are connected together in the working circuit. Requirements for technical cleanliness vary according to the type and function of components and can be divided into two basic areas – chemical cleanliness (for example, lubricant contamination) and particulate cleanliness (particles and fibres). So-called clean production must include all areas up until final assembly – production, assembly, storage, transport and the packaging itself. In process chains, measures are taken to minimise contamination or particle generation to achieve a continuous and controllable standard of cleanliness. A special section is the cleanliness of the cable connectors, which is dealt with in this article. The introduction describes the current state of science and research in this field and then summarises the standard requirements in the automotive environment and the basic possible consequences of connector contamination. This is followed by a case study showing the possibilities of preventing contamination by particles and fibres, including a discussion of the effectiveness of these measures.

Keywords: technical cleanliness; automotive industry; quality management; supply chain

1. Introduction

Technical cleanliness means sufficiently low contamination of technical components that are sensitive to harmful particles or pollution by liquid substances. In the case of particulates, if the contamination is so low that there are no short-term or long-term functional limitations and damage to the system, it is considered to be sufficiently clean in terms of technical cleanliness [12]. In the case of electrical connectors, according to the ZVEI (technical cleanliness in electrical engineering) directive, "technical cleanliness" means the absence of particles (metallic, non-metallic, fibres, etc.) on components that may affect the manufacturing process (e.g. welding) [19]. The production of

[1] Institute of Technology and Business, Department of Transport and Logistics, Okružní 517/10, 37001, Czech Republic, e-mail: pecmy@seznam.cz

[2] Institute of Technology and Business, Department of Transport and Logistics, Okružní 517/10, 37001, Czech Republic

parts, assemblies and systems sensitive to contamination in terms of technical cleanliness takes place within so-called clean production. It is necessary to take into account the complex environment, including the area of production, assembly, cleaning, packaging, storage and transport in the entire supply chain from raw materials and final assembly [10]. An integral part of the solution of technical cleanliness are operators and their clothing. Throughout the process chain, in order to achieve the defined technical cleanliness specifications, measures must be taken at each step of the process to avoid or minimise the following effects [1]:

- contamination by particles from the external environment,
- particle transfer through the process chain,
- formation of particles in the production process.

Technical cleanliness deals with particles with a size from 15 μm to 1,000 μm as standard. Different types of particles need to be taken into account both when assessing the potential effects of damage to the assembly and when defining appropriate measures to prevent and minimise, in particular:

- fibers,
- non-metallic particles,
- metal particles,
- abrasive particles.

A fibre is generally considered to be a particle whose thickness corresponds to ten times its length. Premises in which clean production takes place are referred to as clean sections according to VDA 19 part 2 [6]. These are divided according to the level of cleanliness into four basic types [20]:

- unregulated area (SaS0),
- clean zone (SaS1),
- clean area (SaS2),
- clean room (SaS3).

Due to technical developments in the automotive industry, the Industry Association for Technical Cleanliness (TecSa) [8] identified cleanliness problems as early as the early 1990s [21]. For example, anti-lock braking systems (ABS) or direct injection systems in diesel vehicles were sensitive to contamination. Therefore, many manufacturers have required the development of technical cleanliness specifications and methods of demonstrating compliance with these specifications due to the need for standardisation. This led to the creation of an industrial association, which in the summer of 2001 was renamed TecSa - Technical Cleanliness. Between 2001 and 2004, a comprehensive set of rules was developed. It sets out how to proceed in product cleanliness tests in the automotive industry. The following are defined [24]:

- extraction process,
- analytical methods,
- documentation of test results.

The set of rules was named "VDA 19 Testing of Technical Cleanliness - Particle Contamination of Functionally Relevant Automotive Parts/1st Edition 2004". Similar rules, which are described in the international counterpart for VDA 19, are as well in ISO 16232

[13], which was published in 2007. These two sets of rules are fully compatible. Over ten years of working with VDA 19, it enabled the acquisition of new knowledge and important experience. At the same time, however, the needs and requirements of industry have changed over the years. Against this background, the need for a revision of VDA 19 was questioned in 2012 and the relevant topics were categorised and prioritised. Based on these results, an industrial network TecSa 2.0 was subsequently established at the end of 2012, in which more than forty companies in the field prepare relevant topics in working groups. The revised volume VDA 19, Part 1 (or also VDA 19.1) has been available since May 2015 [1]. A large proportion of the approximately one hundred items have also been adopted by the Industry Association for Cleanliness (MontSa). The MontSa Montage Cleanliness industry association was founded under the leadership of the Fraunhofer Institute IPA. The aim was to create a new guide for planning or the optimisation of processes and procedures in assembly rooms sensitive to contamination cleanliness and requiring cleanliness in their surroundings. This was to prevent particle contamination throughout the process chain. These guidelines were intended to be addressed to production planners and quality managers, and after two years of work, a directive was issued entitled VDA Volume 19 Part 2, Technical Cleanliness in the Assembly – Environment, Logistics, Personnel and Assembly Facilities, 1st Edition 2010 [19].

2. Calculation of the Level of Contamination

In order to effectively implement the requirements set out in the above standards, it was necessary to spread awareness of them to all levels, divisions and processes. Every single person, from the technical director to the production operator, must be aware of the importance of technical cleanliness. Rules, processes and procedures that must be integrated in the earliest possible phase of product implementation, must be defined and optimised. For example, the Component Cleanliness Code developed by Thomas Magnets GmbH [15] is strictly based on VDA 19. This company decided to indicate the cleanliness of components using the Component Cleanliness Code (CCC). This meant that both internal component cleanliness requirements (cleanliness analyses, documentation, drawings) and external cleanliness requirements (drawing, specifications, customer and supplier communication, etc.) refer to components by default, not to the cleanliness area. The indication therefore uses size classes supplemented by the transcoded number of particles, related to the total surface area of the components. The calculation of the level of technical cleanliness is then the result of an analysis carried out by accredited laboratories. The preparatory part of the analysis consists of the extraction of impurities (usually by rinsing with demineralised water), filtering, drying and weighing the sample obtained, which is schematically shown in Figure 1. An example of a dried filter after extraction is shown in Figure 2.

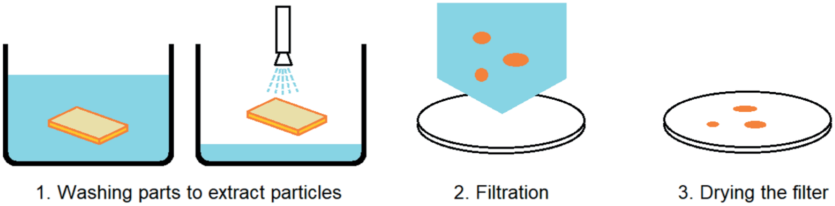

Fig. 1. The principle of extraction

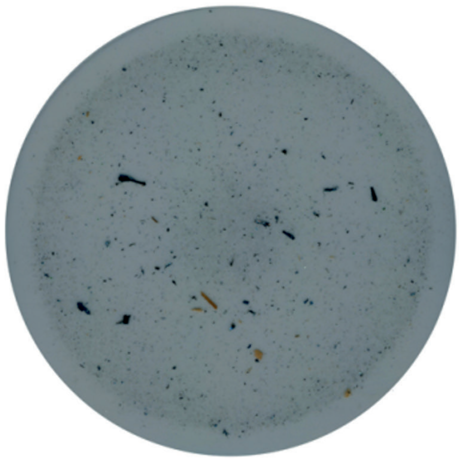

Fig. 2. Dried filter with particles trapped during extraction

The next part of the analysis is the inspection of the obtained sample. With the help of optometric devices, the number and size of particles and fibres, their character is usually identified and their material is possibly detected [18]. From the obtained values, the component cleanliness code is then calculated and the limits are checked according to the given regulation (usually a production drawing or documentation). A very important part of the analysis is the virtual inspection of particles (for example, clumps of fibres very often form on the filter, which optometric instruments may distinguish as just one large particle). The results of the analysis are assessed and incorporated into the protocol [26].

2.1. Determination of CCC – Component Cleanliness Code

For most cleanliness standards, an abstract number is displayed instead of the actual number of particles measured (or extrapolated). Furthermore, the level of contamination for each particle size class is checked. This is the second level of classification, but this time, the particles are not classified according to their size. Classes are determined by the number of particles in a given class. These levels of contamination allow a simple and quick comparison of different cleanliness measurements, although this is sometimes too simplistic.

Typical levels of contamination are specified in ISO 16232:

- Level 00: no particles on a surface area of 1,000 cm2,
- Level 0: less than 1 particle on a surface area of 1,000 cm^2,
- Level 1: more than 1 but less than 2 particles on a surface area of 1,000 cm^2,
- next levels (from 2 to 11) according to Figure 3 and Figure 4,
- Level 12: more than 2,000 but less than 4,000 particles on a surface area of 1,000 cm^2.

These levels of contamination are set for most international standards and are usually similar for each size class (e.g. for ISO 16232) [7] but may be determined differently for each class. Some standards limit the representation of measured product data to a short description only. This cleanliness code depends on the standard and consists of size classes and levels of contamination of the found particles. Below is an example of a cleanliness code. The cleanliness code form only applies to ISO 16232. Other standards specify a different cleanliness code. The first "A" indicates normalisation to a sample surface area of 1,000 cm2. Adjacent classes with the same level of contamination can be combined [21].

Class	Particles absolute	Particles per 1000 cm^2
B	1476	2059.0
C	598	834.2
D	179	249.7
E	94	131.1
F	5	7.0
G	2	2.8
...	...	...

Particles	Contamination level
...	...
2 to 4	2
4 to 8	3
8 to 16	4
16 to 32	5
32 to 64	6
64 to 130	7
130 to 250	8
250 to 500	9
500 to 1000	10
1000 to 2000	11
2000 to 4000	12
...	...

Fig. 3. Example of contamination levels for ISO 16232 (A) – contamination levels are displayed in the red area

Particle	Size
…	…
571	63 µm
572	165 µm
573	78 µm
574	23 µm
…	…

Range	class	Count
5 µm to 15 µm	B	2059.0
15 µm to 25 µm	C	834.2
25 µm to 50 µm	D	249.7
50 µm to 100 µm	E	131.1
100 µm to 150 µm	F	7.0
150 µm to 200 µm	G	2.8
…	…	…

Particles	Contamination level
…	…
2 to 4	2
4 to 8	3
8 to 16	4
16 to 32	5
32 to 64	6
64 to 130	7
130 to 250	8
250 to 500	9
500 to 1000	10
1000 to 2000	11
2000 to 4000	12
…	…

Fig. 4. Example of cleanliness code for ISO 16232 (A) – the resultant component cleanliness code (CCC) for this example is A (B12/C10/DE8/F3/G2/HIJ00)

The real purpose of the cleanliness analysis is to measure contamination and describe the results according to the selected standard. The approval and control of maximum values is not always part of the cleanliness inspection process. The maximum limit is specified in the inspection configuration. It can be the absolute number of particles or the maximum code of cleanliness. This value is checked during the examination of the filter membrane and is immediately displayed when the maximum permitted value is exceeded. The operator has the opportunity to completely stop the measurement process and examine the source of contamination. Size classes are according to VDA 19 and ISO 16232 and are dependent upon individual requirements; size ranges can be combined or omitted depending on the specifications of the components. The total cleanliness requirements can be further applied to the transport unit or production batch in a given time horizon. As already mentioned, continuity plays an important role in technical cleanliness, as the standard of cleanliness may vary not only in individual batches, but may also depend, for example, on the season.

2.2. Technical Cleanliness in Packaging Management

The long-term trend in the packaging economy is aimed at reducing so-called one-way packaging, which is supported by, among others, the requirements of the European Union [3]. In order to be able to reuse the packaging while meeting the requirements for technical cleanliness, it was necessary to integrate cleanliness control sections and washing lines into the supply chains. In addition to ensuring cleanliness, this link in the supply chain is also responsible for sorting damaged or destroyed packages. Furthermore, standards have been developed that exclude the use of materials that can adversely affect technical cleanliness from the production chains (e.g. wooden packaging, including pallets and paper boxes). If it is necessary to use these materials, it is then necessary to introduce additional measures that protect both the components themselves and production facilities with specific cleanliness requirements from contamination. The actual handling of packaging materials must therefore be defined and observed. A specific area of packaging are blisters for storing individual components in boxes. These blisters, one-way or multi-way, are subject to analysis, particularly in the form of abrasion, which releases particles to stored products and can cause them to become contaminated. In principle, packages could be interpreted as areas with special requirements for cleanliness.

2.3. Technical Cleanliness in Electronics Production

The current trend in electronics is the quest to reduce energy consumption and obtain the longest possible service life. For example, components with higher input impedances are installed to reduce the power consumption of electronic assemblies. In addition to the benefits of these assemblies when used in battery or accumulator-powered systems, it offers the use of highly durable components [17]. The disadvantage of using these economically active components is that reduced energy consumption is associated with very low signal currents and, as a result, it increases sensitivity to external influences, such as leakage currents [9]. These can be caused by moisture (reduction of the insulation resistance of mounting surfaces and especially solder masks, particularly in combination with hygroscopic contamination), or they can be caused by existing contamination by particles or fibres between open contacts or conductor paths. In the case of moisture-related leakage currents caused by hygroscopic (inclusive water-absorbing) impurities and particles or fibres, the reduction of the self-drying potential of the circuit also plays a decisive role. The self-drying potential is largely determined by the heat losses caused by the output. In addition to shortening the air and surface distances, some other error possibilities may occur in the case of insufficient particle cleanliness on electronic assemblies. Due to the above possible causes of errors in the event of particle contamination, the electronics manufacturing process should be planned and operated in such a way as to keep the number of potentially harmful size or type particles sufficiently low to not disrupt subsequent assembly operations during the manufacturing process. Both conductive (metallic) particles and non-conductive (non-metallic) particles or fibres can have a detrimental effect [22]. In the case of metal particles, it is mainly oxidation due to aging or exposure to external influences which leads to their reduced conductivity.

The risk potential of metal particles lies in the oxidation that arises with advancing age. If the resulting oxide layer leads to a reduction in the conductivity of these particles or chips, voltage faults in the given electrical circuit may occur. The risk potential of non-metallic particles or fibres lies is in varying polarity on their surface, which can lead to an increase in their hygroscopicity and thus to an increase in the conductivity of these particles. In the event of condensation, electrochemical migration (ECM) may occur. Due to the increased use of components with low power consumption and the associated low current load, it is necessary to evaluate materials and processes with regard to the potential risks of contamination (particles, chips, fibres, organic films, etc.). This requires a risk assessment approach that holistically records ionic, film and particulate contamination [23]. In addition to the risk assessment, contamination also poses a major challenge for determining component life. On this scale, impurities on the assembly in particular significantly change the resistance of the circuit to moisture. The first approach to life calculation is life prediction models based on statistical values. The standard of ZVEI (Zentralverband Elektrotechnik - und Elektronikindustrie) association "Technical cleanliness in electrical engineering" is generally used for the production of electronic components [11]. In addition to the classic field of application in mechanical engineering, the topic of particle contamination on printed circuit boards and assemblies is increasingly focused on the electronics industry. Even a small amount of particle contamination can significantly increase the risk of failure of manufactured electronic assemblies, and thus failure of the entire product [9]. The approach and methodology, as described in VDA 19 part 1 and part 2, described in general, so that can be applied to a whole range of materials and processes in the automotive industry [16]. The guidelines "Technical cleanliness in electrical engineering" issued in 2013 by ZVEI specifically deal with component cleanliness testing and planning of production areas for printed circuit boards and electronic assemblies. This guideline provides recommendations for testing, measuring and evaluating particulate matter and particulate contamination on assemblies [14]. Both the cleanliness test according to VDA 19 and the issues addressed in VDA 19, part 2, concerning the planning and optimisation of cleanliness-related production areas are examined here specifically in terms of the production of electrical, electronic and electromechanical components as well as printed circuit boards and specified electronic assemblies. The advantage of this coordination and the definition of a cleanliness test procedure, which specialises in the field of electronics production, is that above all, the comparability of the results of the analyses of parts and components from electronics production is significantly increased.

This shows how these results of cleanliness analyses can be classified and statistically interpreted, leading to targeted information on the risks of contamination in the respective production steps. Due to the large number of combinations of possible particles (with respect to material and shape) and the arrangement of the assembly, the setting of general limit values for the maximum loading of the particles was omitted. It is therefore appropriate to carry out a separate risk assessment for each individual case, which may serve as a basis for a discussion between the supplier and the customer on the setting of limit values [13]. The main topics addressed in the ZVEI guidelines on technical cleanliness in electrical engineering can be summarised as follows:

- detailed description of VDA 19,
- definition of particles and fibres,
- recommendations on how cleanliness analyses should be performed and results presented,
- taking into account cleanliness analysis results from statistics representation of the actual state of particulate matter in the manufacture of electrical, electronic and electromechanical components, printed circuit boards and electronic assemblies,
- consideration of possible sources of particulate matter in processes,
- presentation of (design) recommendations for particle reduction,
- notes on transport and logistics voltage for power electronics in the automotive industry.

Increased attention is currently being paid to the issue of technical cleanliness; this is especially true against the background of the use of power electronics in electromobility. For this reason, in 2014 the industry association "TecSa" added the delivery conditions "Technical cleanliness for high-voltage components" to the ZVEI directive "Technical cleanliness in electrical engineering". This so-called high-voltage directive for power electronics specifies, for example, aids for determining particle limits and minimum distances between electrical components [2]. The following conditions are set for the definition of particulate limits:

- The expansion of conductive particles should be less than half the minimum electrical distance.
- With regard to air distances and surface paths, due to the size of the conductive particles, electrical safety distances must not be undercut.
- Quantitative limits for size classes must be estimated at the beginning of the project and verified during the implementation of the series process.
- Non-metallic particles and fibres must be assessed for their risk. Possible consequences are insulation failures, mechanical blocking of contacts, optical attenuation/interruption of light barriers/light guides etc.

With regard to the special risk of air distances and high-intensity surface paths in high-voltage components and in combination with mechanical and electromechanical components should come the problems with contamination. Critical particles can be introduced into the process due to the large number of components (metallic/non-metallic components, electronics, packaging materials, etc.) and particles can also arise directly in the process during assembly steps. High voltage jumps and short circuits can be caused mainly by conductive particles. This risk is further increased by increasingly complex circuits and designs of power electronics [5]. The holistic approach to minimising the risk of particulate contamination under the high voltage directive covers the whole value chain from development to the production of a high voltage component, including the supply chain. An attempt was made to focus measures to introduce technical cleanliness on what is technically feasible and economically reasonable [25]. In order to achieve particle cleanliness, methodological approaches are shown to avoid particles throughout the production process and in logistics. In addition to the particle avoidance strategy, a possible way to meet the previously defined particle cleanliness requirements is to remove the particles at the end of production [3].

2.4. Methods of Ensuring Technical Cleanliness in the Production of Electronics

In general, two different approaches can be used to achieve technical cleanliness on electronic components or assemblies as well as on high-voltage components meeting the defined requirements [2]. One approach is to prevent contamination of components or assemblies throughout the process chain. This begins with the first planning of the assembly layout and must be taken into account from the purchase of supplier parts to transport to production and going through the various processes concerning production, packaging and sending to the final customer. To do this, it may be necessary to carry out all production in a clean room and harmonise the necessary logistics (locks, transport systems, protective clothing for employees, etc.) as well as the training and qualification of employees in order to avoid particles. In order to qualify production for technical cleanliness, an audit is first useful to determine the current state of cleanliness. In the next step, after evaluating the risks of particle contamination, first measures can be identified to improve the cleanliness of the particles during production, purchasing or logistics [27]. The second approach follows the strategy of removing particulate matter created during production in the supply chain (between the suppliers and the logistics), through an end-of-production-step cleaning process. This possibility can only be considered if it is guaranteed that the particles that are formed or introduced into the process chain do not lead to problems in this process chain. Another option is to combine the two mentioned strategies - particle avoidance and particle cleansing. This option should come into play especially when there are very high requirements for technical cleanliness, and therefore for reliability and durability. In addition to cleaning the assembly (low-voltage or high-voltage component), it may also be necessary to clean the production systems manually at certain process steps in order to meet the relevant cleanliness requirements of the final product; this is especially true if assembly production is designed as a clean process [4]. If the finished assemblies are not to be cleaned, it is necessary to minimise the introduction of particles into the production systems. For example, the brazing process itself can also be a source of particles, if the brazing frames and furnaces are not cleaned regularly. The burnt flux residues could form a solid layer on the solder frame, which peels off by mechanical action (movement by conveyor chains or manually by production staff) and, as a result, releases its particles.

3. Case Study

The case study deals with the possibilities for the protection of electronic components during transport in multiway packaging. Its goal was to choose the optimal packaging solution in terms of quality and price, because in addition to the demands on technical cleanliness, it is necessary to take into account the efficiency of the solution. The purpose of technical cleanliness is not to supply absolutely clean components but to achieve a continuous and measurable standard that can cope with the demands placed on components according to the technical specification. For the purposes of the case study, cable bundles with a diameter of 1.5 mm and a length of 220 mm with tinned terminations were selected as the subject of interest. The technical documentation shows that the requirements for technical cleanliness apply to the entire cable with the required level of cleanliness, given by the CCC code:

CCC: A (B12/C11/D10/EF8/G7/H4 I2/J00,

where a cleanliness analysis on the part of the supplier has shown compliance with this specification. Due to the potential uncertainty of the individual cleanliness of the transport crates, one standard automotive crate (RL-KLT 4147 length 400 mm, width 300 mm and height 147 mm) was chosen for the transport (Figure 5).

Fig. 5. Plastic crate

The crate was removed from the supply chain for research purposes, immediately after washing by a standard method to ensure the elimination of particles larger than 600 μm. Cleanliness analysis was performed after a transport test over a distance of 370 km. One production batch of cables was placed in the crate in three different ways: a bundle of cables in bulk (every 12 pieces held with fixing tape), a bundle of cables placed in a plastic bag (every 12 pieces held with fixing tape) and a bundle of 12 cables encased in stretch wrap (Figure 6):

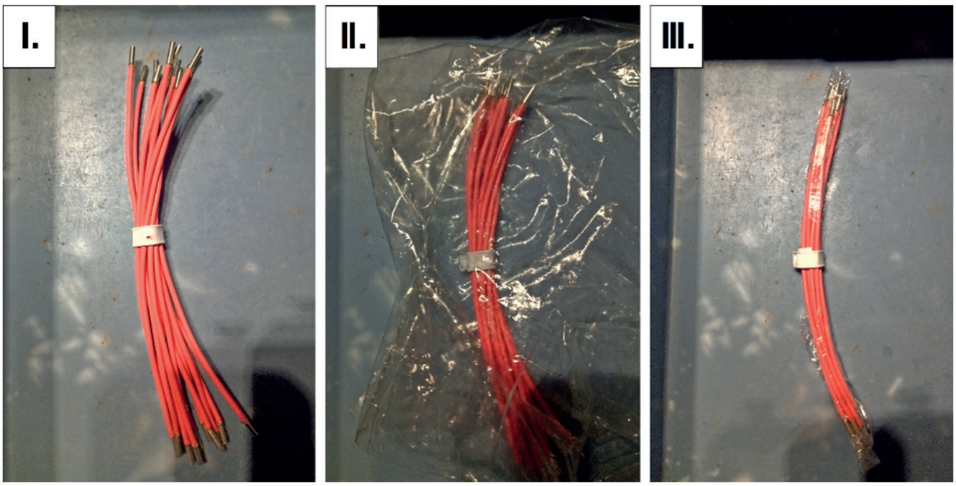

Fig. 6. Three types of packaging: I – in bulk; II – in polyethylene bag; III – in low-density polyethylene stretch foil

After transport, samples were taken for cleanliness analysis. The results of the analysis are summarised in Table 1.

Tab. 1. Results of the analysis of the cleanliness of individual types of packaging after the transport test

Type of package	CCC code	Result
in bulk	A(B12/C12/D11/EF9/G7/H5/I2/J2	not in specification
polyethylene bag	A(B12/C10/D9/E8/F7/G5/H3/I2/J00	in specification
low-density polyethylene foil	A(B12/C10/D10/E9/F8/G6/H4/I2/J1	not in specification

These result show that the required technical specification is met only by packing the cables in a plastic bag. Factors influencing the result are mainly determined by the exposure of the cables to the environment in the carrier. Considering the difficult washing conditions and the action of external forces during transport, the option of bagging seems to be ideal. The transport of bulk cables is considered unsuitable in terms of the results of the cleanliness analysis. A variant in which the ends of the cables are wrapped in stretch film was analysed in more depth and it was found that excess dirt adhered to only the unprotected parts of the cables. However, these parts do not constitute a risk from the point of view of subsequent assembly in terms of ensuring the correct function of the cable, as long as the transmission of contamination to their ends is prevented. After performing a comparative analysis of cleanliness with the ends of the cable from the plastic bag, this solution even showed better results. In addition, this variant does not require the use of a cable tie to comply with the 12-piece dosing. Paradoxically, the technical specification does not allow the cleanliness analysis to be performed only on parts of cables. However, if this solution will be used, it is necessary to ensure such measures, that the cable terminations are not contaminated during the unpacking and assembly process.

4. Discussion and Conclusion

This article has summarised findings on the current state of technical cleanliness and influence. A thorough literature search was conducted, which summarised the approaches to solving the issue of technical cleanliness and support in regulations and standards for the technical sector of interest. Furthermore, the principle of performing cleanliness analyses and determining the universal code of cleanliness relating to components was described. The aim of the case study was to analyse the cleanliness of electrical wires in different types of packaging and to select the most suitable variant for use in the supply chain. Due to the nature of the products, only particle and fibre contamination was addressed. After considering the possible variants, one type of packaging was selected with the addition that, if necessary, the packaging can be further improved. However, the results of the analysis meet the required specification and in the case of compliance, even during long-term monitoring, no further increase in the level of technical cleanliness is considered necessary.

5. Nomenclature

VDA Association of Auto Industry (in German „Verband der Autoindustrie")
ISO International Organization for Standardization

6. References

[1] Association of the Auto Industry: VDA 19.2. 2015, ISBN: 978-80-02-02406-4.

[2] Agarwal K.A., Gupta J.G., Dhar A.: Potential and challenges for large-scale application of biodiesel in automotive sector. Progress in Energy and Combustion Science. 2017, 61, 113–149, DOI: 10.1016/j.pecs.2017.03.002.

[3] Calata J.N, Bai J.G., Liu X., Wen S., Lu G.: Three-dimensional packaging for power semiconductor devices and modules. IEEE Transactions on Advanced Packaging. 2005, 28(3), 404–412, DOI: 10.1109/TADVP.2005.852837.

[4] Conlon E., Devaraj S., Matta K.F.: The Relationship Between Initial Quality Perceptions and Maintenance Behavior: The Case of Automotive Industry. Management Science. 2001, 47(9) 1275–1291, DOI: 10.1287/mnsc.47.9.1191.9788.

[5] Dzezit A., Nagit G.: Research on importance of cleanliness in manufacturing reliable products for automotive. MATEC Web of Conferences. 2017, 112, 1–6, DOI: 10.1051/matecconf/201711209017.

[6] Elo L., Pekkkonen J., Rinkinen J.: Technical Cleanliness of Assembled Fluid Power Components. Fluid Power Systems Technology. 2014, 68–77, DOI: 10.1115/FPNI2014-7850.

[7] Emmerich J.: Criteria for Selecting the Correct Cleaning System. International Surface Technology. 2014, 7(1), 34–37, DOI: 10.1365/s35724-014-0228-5.

[8] Fahr M.: In-Line, Automated Particle Analysis Systems. International Surface Technology. 2020, 13, 36–37, DOI: 10.1007/s35724-020-0137-8.

[9] German Electrical and Electronic Manufacturers' Association (ZVEI): Retrieved on 15.12.2020 from https://www.zvei.org/en/.

[10] Gorzelanczyk P., Jurkovic M., Kalina T., Sosedova J., Luptak V.: Influence of motorization development on civilization diseases. Transport Problems. 2020, 15(3), 53–66, DOI: 10.21307/TP-2020-033.

[11] Gruszka J., Misztal A.: The new IATF 16949:2016 standard in the automotive supply chain. Research in Logistics & Production. 2017, 7(4), 311–318, DOI: 10.21008/j.2083-4950.2017.7.4.3.

[12] Habidin N.F., Zubir A.F.M., Conding J., Jaya N.A.S.L., Hashim S.: Sustainable manufacturing practices, sustaining lean improvements and sustainable performance in Malaysian automotive industry. World Review of Entrepreneurship, Management and Sustainable Development. 2013, 9(4), 444–459, DOI: 10.1504/WREMSD.2013.056755.

[13] International Standardisation Organisation: ISO 16232: Technical Norm: Road vehicles - Cleanliness of components and systems, 2018.

[14] Johnson R.W., Evans J.L., Jacobsen P., Thompson J.R., Christopher M.: The changing automotive environment: high-temperature electronics. IEEE Transactions on Electronics Packaging Manufacturing. 2004, 27(3), 164–176, DOI: 10.1109/TEPM.2004.843109.

[15] Koblenzer G.: Parts Cleaning for the Cars of Tomorrow. International Surface Technology. 2019, 12, 32–33, DOI: 10.1007/s35724-019-0050-1.

[16] Koblenzer G., Trumpf GmbH Co. KG (Holding): The Highest Standards of Technical Cleanliness. International Surface Technology. 2020, 13, 40–41, DOI: 10.1007/s35724-019-0084-4.

[17] Luptak V., Bartuska L., Hanzl J.: Assessment of Connection Quality on Transport Networks Applying the Empirical Models in Traffic Planning: a Case Study. 22st International Scientific Conference Transport Means 2018. Kaunas, Lithuania: Kaunas University of Technology, 2018, 236–240. ISSN 1822-296X.

[18] Petrillo A., Felice F., Zomparelli F.: Performance measurement for world-class manufacturing: a model for the Italian automotive industry. Total Quality Management & Business Excellence. 2019, 30(7-8), 908–935, DOI: 10.1080/14783363.2017.1408402.

[19] Pophaley S., Vyas R.K.: Plant maintenance management practices in automobile industries: A retrospective and literature review. Journal of Industrial Engineering and Management. 2010, 3, 512–541, DOI: 10.3926/jiem.v3n3.p512-541.

[20] Scheffler K., Schué A.: Reliable Analysis of Residual Dirt Particles. International Surface Techonology. 2011, 4, 56–57, DOI: 10.1365/s35724-011-0026-2.

[21] Seidel M., Loch Ch.H., Chahil S.: Quo Vadis, Automotive Industry? A Vision of Possible Industry Transformations. European Management Journal. 2005, 23(4), 439–449, DOI: 10.1016/j.emj.2005.06.005.

[22] Springer Fachmedien Wiesbaden.: Meeting the Highest Standards of Cleanliness. International Surface Technology. 2013, 6, 30–31, DOI: 10.1365/s35724-013-0145-z.

[23] Stopka O., Stopkova M., Lizbetin J., Soviar J., Caban J.: Development Trends of Electric Vehicles in the Context of Road Passenger and Freight Transport. XII. International Science-Technical Conference Automotive Safety. 2020, 1–8, DOI: 10.1109/AUTOMOTIVESAFETY47494.2020.9293526.

[24] Tian G., Chu J., Hu H., Li H.: Technology innovation system and its integrated structure for automotive components remanufacturing industry development in China. Journal of Cleaner Production. 2014, 419–432, DOI: 10.1016/j.jclepro.2014.09.020.

[25] Welke R.: Controlled cleanliness. Adhesion Adhesives & Sealants. 2016, 13, 32–33, DOI: 10.1007/s35784-016-0012-7.

[26] Zamani D., Dhane K., Mahdavi O., McBride M.A., Yan J., Shadman F.: Surface cleaning of small structures during spin rinsing of patterned substrates. Microelectronic Engineering. 2013, 108, 57–65, DOI: 10.1016/j.mee.2013.02.092.

[27] Zhang X., Yan J., Vermeire B., Shadman F., Chae J.: Passive Wireless Monitoring of Wafer Cleanliness During Rinsing of Semiconductor Wafers. IEEE Sensors Journal. 2010, 10(6), 1048–1055, DOI: 10.1109/JSEN.2010.2042443.