Challenges in the Assessment of the Cleanroom Suitability of Equipment and Materials

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Abstract

In the field of manufacturing engineering, cleanroom technology has become a key technology for a number of reasons. Without it, trends such as enhanced performance and miniaturization or the adherence to legal requirements would be impossible to maintain.

The main task of cleanroom technology is to reduce the amount of airborne contamination in manufacturing environments to an acceptable level. As the aim to control contamination in clean production facilities cannot be achieved by implementing cleanroom technology alone, a number of other measures need to be taken which also affect cleanliness levels. These measures are grouped together under the term "cleanliness technology" and include influencing factors such as personnel, logistics processes and manufacturing equipment, which together contribute significantly towards the contamination of a clean manufacturing environment. As today's trend towards increased automation continues, the subsystem of manufacturing equipment - including the materials used in its construction – has become the most important factor affecting cleanliness. In the meantime, the semiconductor industry calculates this to account for 40% of the total contamination.

Bearing this in mind, it is especially important to focus on equipment design, as this allows to consider and optimize cleanliness suitability early in the conception phase, e.g. by choosing appropriate materials or arranging components. Depending on the purpose of the equipment or the process to be carried out, the relevance of cleanliness factors such as particulate emission, cleanability, outgassing behavior, chemical resistance and microbiological properties need to be individually determined.

In order to be able to use such information in the design and optimization of cleanliness-suitable equipment, international standardization work is currently being carried out (e.g. the amendment of the ISO 14644 series "Cleanrooms and associated controlled environments") to determine the cleanliness- and cleanroom-suitability of equipment and materials realistically and comparably according to international practiced methods. The results gained from the standardized tests can be utilized effectively in equipment design if the information is made available via databases; these are practical tools which enable specific search queries regarding cleanliness-suitable materials and equipment to be made.

Key words: Cleanliness technology, cleanroom technology, cleanroom suitability, equipment, materials, particulate contamination, organic contamination, chemical resistance, biological resistance, microbicidity.

1. Cleanroom technology as a comprehensive and key technology

Cleanroom technology is a key technology in manufacturing which is being implemented in more and more different branches of industry [1].

The reason for this development lies in the following driving factors:

- enhanced performance
- miniaturization
- quality demands
- legal requirements
- product liability
- new technologies and materials
- operator safety

The need for cleanroom technology is demonstrated by way of the examples described in the following.

1.1. Enhanced performance, often in connection with miniaturization

Many semiconductor technological achievements form an indispensable part of our modern lives: personal computers, portable devices, cell phones, etc. These devices are simultaneously becoming smaller, more portable and increasingly powerful. This so-called "digital revolution" is based on Moore's law, an empirical observation of the fact that the number of transistors implemented in integrated circuits doubles approximately every 24 months, also associated with enhanced performance and smaller circuit line widths (Figure 1).

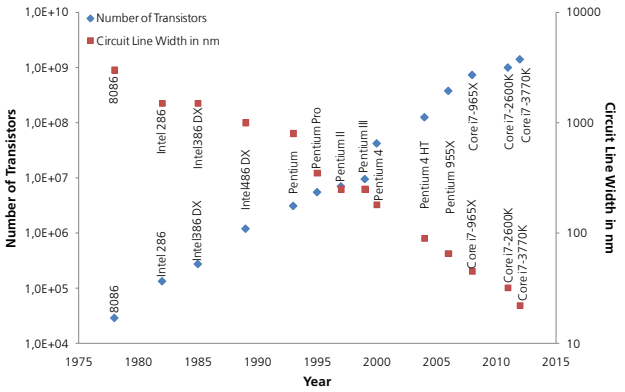

Figure 1. Development of line widths and the number of transistors in Intel processors

This trend has been upheld ever since 1965 when Gordon Moore, co-founder of Intel, made his bold prediction and is expected to remain valid until at least 2020 [3].

Continued miniaturization (currently 1.4 billion transistors with a line width of 22nm) results in even smaller "killer particle" sizes causing high failure rates and leading to non-profitable production. The same applies for molecular contamination and uncontrolled electrostatic discharge. In order to be able to fulfill Moore's law despite these problems, the use of leading edge cleanliness technology is required. However, this in turn causes the running costs of semiconductor factories to double every four years (often also called Moore's "second" law). To keep the price of semiconductor products affordable for the consumer without neglecting high quality demands, research concerned with the cleanliness suitability of manufacturing systems and equipment has become especially important [6].

Meanwhile, Moore's law and similar trends can also be applied to other microelectronic products, such as the storage capacity of hard disks, the pixel density of screens, etc. [5]. Thus, the microelectronics industry in general is also being confronted with similar challenges such as those described for semiconductor manufacture.

1.2. Legal requirements and product liability

Advancements in medicine are currently making an important contribution towards the demographic change: new methods of treatment, new drugs, operations and medical devices all require, amongst others, cleanliness technology, e.g. for the manufacture and implantation of medical products in order to reduce cross-contamination due to microorganisms and thus minimize the risk of infections of the patient. As patient protection is the principle consideration, national and international regulations have been compiled (e.g. Good Manufacturing Practice guidelines) which define highly-clean and sterile production environments. Due to the fact that the drug or medical device manufacturer is liable for his products, to avoid risks associated with costly damage claims it is also highly important from an economic point of view that such regulations are observed [7].

1.3. New technologies and materials

Today, the paradigm of "reduced CO_2 emissions" characterizes our mobility, especially with a view to minimizing the influence of man on our climate. In aviation, this is reflected in the use of new lightweight construction materials, for example, such as CFRP[1], GRP[2] or GLARE[3]. A similar development can be observed in the automotive industry. For example, in automotive industry alternative propulsion technologies such as the changeover to electric motors also demand the use of lightweight construction materials as well as new vehicle technologies. However, many of these new technologies are sensitive to particulate contamination, e.g. undesired particle inclusions in CFRP compounds can impair the contact of fibers with the matrix and lead to de-lamination effects. By implementing cleanroom technology, such undesired effects can be minimized.

1.4. Operator safety

When handling pathogenic substances (e.g. cytostatics) or hazardous microorganisms, cleanroom technology is utilized to protect the operator from becoming harmed by them. This can be achieved through the use of pressure cascades

[1] carbon-fiber reinforced plastic
[2] glass-fiber reinforced plastic
[3] glass-fiber reinforced aluminum

and other filter or barrier technologies (safety cabinets, isolators, etc.).

2. Cleanroom technology as a basis of cleanliness technology

In order to be able to fulfill the technical challenges mentioned, cleanroom technology to control airborne particulate contamination is fundamental. However, the use of modern cleanroom technology on its own is generally not enough to reduce the level of all process-critical contamination to a tolerable degree. Numerous other cleanliness measures need to be taken which are classified under the term cleanliness technology. Thus, cleanliness technology can be understood as chain of all measures required to reduce or prevent undesired influences on the product or operator (Figure 2 and [6]).

Figure 2. Aspects of cleanliness technology

If one considers the percentage of factors causing contamination in the semiconductor industry, as a result of automation it can be appreciated that manufacturing equipment and the materials used in its construction currently represents a main source of contamination, estimated with approx. 40% (Figure 3).

Figure 3. Factors affecting cleanliness in the manufacturing process

From the aspect of contamination control, the challenge of cleanroom manufacturing has therefore largely become a challenge for the equipment manufacturers. With traditional mechanical engineering experience, in the past equipment manufacturers were little concerned at all with the topic of cleanliness. Thus, today's equipment manufacturers need guidance to realize cleanliness-suitable equipment.

3. Assessment of cleanroom and cleanliness suitability

In order to be able to plan and manufacture "tailor-made" cleanliness-suitable equipment and products, firstly all the aspects relevant to a clean production need to be accurately determined. The investigation and evaluation of equipment in this regard is known as an assessment of **cleanliness suitability**. As all cleanrooms have specifications for maximum permissible particle concentrations, the most important aspect requiring consideration is that of particle emission. The corresponding assessment determines whether a piece of equipment is suitable for use in a cleanroom with a specific air cleanliness class. As a result, such an assessment is also known as **cleanroom suitability**.

However, when developing or optimizing equipment, it not only makes sense to qualify the complete system. It is also important to characterize the materials intended to be used in its construction from the point of view of cleanliness suitability, as this enables appropriate materials to be selected right from the start (priority approach). The most relevant cleanliness aspects can be assessed by implementing the standardized tests described in the following (in accordance with VDI 2083-17 [15]).

3.1. Particle emission

As most of the equipment used contains moving parts, it is important to consider the effect of frictional processes as a particle source more closely. In order to reduce particle generation to a minimum, it also makes sense to take this aspect into consideration when selecting suitable materials. To do this, the emission of particles from tribologically stressed materials is determined. In order to make a realistic assessment, the tribological stress simulates sliding or rolling frictional processes.

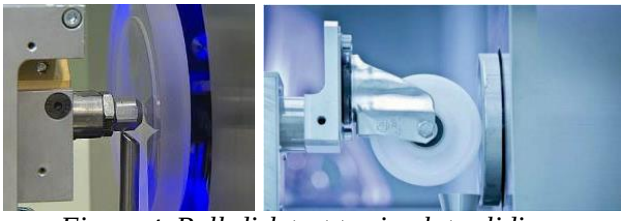

Figure 4. Ball-disk test to simulate sliding

friction (left) and roll-disk test to simulate rolling friction (rights)

Airborne particles generated by the frictional process are detected by a particle counter and correlated with air cleanliness classes in accordance with ISO 14644-1 [17]. This enables material pairings tested under the same stress parameters to be compared with one another and the results obtained to be used to select the most suitable material combinations (Figure 4).

3.2. Electrostatics

Due to the effects of electrical fields or frictional and separation processes on materials, electrostatic charges can be created ("triboelectric charging"). The charging potential of materials can be quantitatively determined. This enables appropriate electrostatically-conductive materials to be selected and damages caused by the uncontrolled release of electrostatic charges to be avoided, e.g. damage of structures on ICs or the attraction of particles to surfaces ("dust magnet").

3.3. Outgassing

Outgassing behavior describes both the quantitative and qualitative emission of volatile substances from materials. Today, this form of contamination represents an ever-increasing hazard for the semiconductor industry. Single molecules are capable of damaging products so badly that they can no longer be further processed, e.g. a single boron or phosphor molecule can sediment on a wafer and dope it in an undefined way.

By understanding the outgassing behavior of different materials, it is possible to specifically choose a material which has low or uncritical outgassing emissions. To investigate organic components (VOC), they are collected in test tubes and subsequently analyzed using combined gas chromatography–mass spectrometry (GC-MS) analysis (Figure 5).

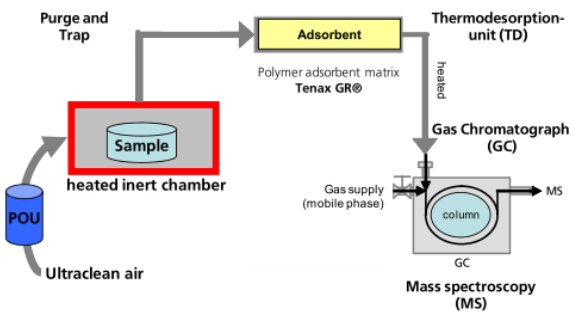

Figure 5. Diagram showing the test to investigate outgassing behavior

3.4. Chemical resistance

The chemical resistance test determines the compatibility of materials with certain substances such as cleaning agents, process chemicals and disinfectants. To assess chemical resistance, the material is first exposed to the test chemical. Any changes caused by the chemical are evaluated after defined periods of time have elapsed (ISO 4628-1 to -5 [20] and Figure 6).

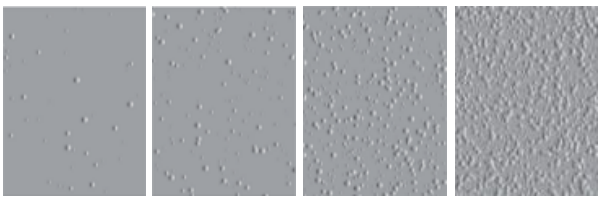

Figure 6. Alterations in a surface due to the effect of chemicals over a period of time (from left to right)

As all surfaces in cleanrooms generally have to be cleaned using cleaning agents and disinfectants at regular intervals, this test is an important assessment and selection criterion for all clean production facilities.

3.5. Cleanability

Cleanability describes the extent to which various forms of contamination (particulate, filmy, etc.) can be removed from a material surface under defined general test conditions (cleaning procedures, contamination quantities, roughness, etc.). The test ascertains the amount of contamination present on the surface before and after cleaning. With particulate contamination, an automated process with a light microscope or scanning electron microscope can be implemented; for organic filmy contamination, thermo-extraction with subsequent GC-MS analysis is used.

In conjunction with the chemical resistance tests, the cleanability of surfaces is as well an important assessment and selection criterion for all clean manufacturing environments.

3.6. Biological resistance

The term biological resistance describes the extent to which polymer materials can be damaged by microorganisms. This could result in microorganisms accumulating or colonizing on a material which can be used as a food source. Alternatively, the surface of the material may become altered by metabolic substances produced by the microorganisms. Carried out in accordance with ISO 846 [19], the test differentiates between the resistance of materials to fungi and bacteria respectively. The material is inspected and assessed after exposure to the microorganisms for a defined period of time (Figure 7). This assessment is especially important when selecting suitable materials for life science applications because the growth of microorganisms would contaminate products and could harm the consumer.

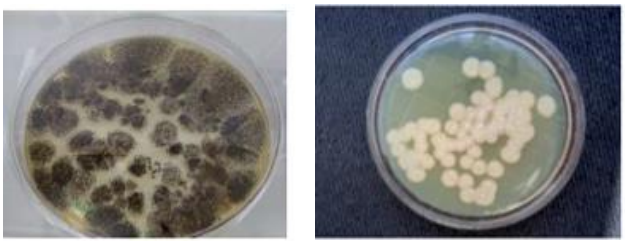

Figure 7. Growth of microorganisms

3.7. Microbicidity

The microbicidity test investigates the antibacterial effect of materials. To do this, selected microorganisms are applied to a material surface which has been treated with an antibacterial coating and to another surface of the same material which has not been treated (ISO 22196 [18]). An assessment is made after 24 hours by comparing the number of CFUs (colony-forming units) on the surfaces before and after the test. This enables microbicidal materials to be accurately evaluated. Consequently, surfaces can be used to reduce risks in areas where microorganisms represent a high contamination potential for the product.

3.8. Equipment design

In the planning and design of equipment for a clean production facility, cleanliness suitability can be influenced by making a targeted selection of suitable materials. Together with the consideration of general design criteria (position of components, airflow guidance, etc.), this enables cleanliness-suitable manufacturing equipment to be realized (Figure 8).

Figure 8. Cleanliness-relevant criteria for assessing cleanliness suitability (VDI 2083-17 [15])

3.9. Cleanliness suitability of equipment

In most cases, a final assessment of the overall system is carried out, e.g. in accordance with VDI 2083-9.1 [13], to obtain information about its cleanliness suitability and identify any optimization requirements. The tests described in this article, especially the particle emission test, are then carried out on the complete system under realistic conditions. In this way, cleanroom operators obtain information about the true suitability of operating utilities for their clean requirements which enables them to avoid undesired and costly production losses. Additionally, the manufacturers of operating utilities gain concrete knowledge about to how optimize their products effectively, e.g. by adapting the materials used or making constructional alterations.

4. Standardization work

Both VDI 2083 Part 9.1 [13], which assesses the overall system and VDI 2083-17 [15], which determines the cleanliness suitability of materials, are achieving increasing international recognition. These national standards have been developed in

close cooperation with industry, for example in the industrial alliance "Cleanroom Suitable Materials" (CSM). To make the standards more accessible to a wide international audience, the new work item proposal "Assessment of the Suitability of Equipment and Materials for Cleanrooms" was officially launched in July 2012 with the aim of transferring the contents of these standards to the ISO 14644 guideline series.

5. Exploitation of knowledge

As cleanliness suitability data is obtained in compliance with reproducible standardized procedures and is intended for public use, the results about materials as well as about equipment are stored in databases. This not only enables appropriate materials for cleanliness-suitable equipment to be selected by equipment manufacturers during the design phase but also cleanliness-suitable operating utilities to be selected for a clean manufacturing facility by the operator (Figure 9).

Figure 9. Database of the industrial alliance »Cleanroom Suitable Materials« [2]

6. Conclusion

Today, cleanroom technology is an essential part for many production technologies. With the aim of reducing airborne contamination in a manufacturing environment to non-critical levels, cleanroom technology relies on a range of accompanying measures which are grouped under the term of cleanliness technology. These measures include influencing factors such as personnel, manufacturing equipment and logistics processes, which all contribute decisively to the contamination of a clean manufacturing environment.

Due to the enormous contamination potential of manufacturing equipment and the materials used in their construction, it is especially important to be able to assess them with regard to their cleanliness suitability. On the one hand, the manufacturers of operating utilities can use this knowledge to design and optimize their equipment effectively. On the other hand, cleanroom operators can choose suitable operating utilities for their cleanliness requirements to avoid risking costly production losses.

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