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BRINGING PARTICLES TO LIGHT

Particle contamination monitoring and cleanliness control are fundamental to micromanufacturing processes across diverse industries to achieve cost-effective production of high-quality and reliable microscale devices and components. However, practice learns that producing in an ISO class cleanroom does not automatically guarantee a clean manufacturing process or product. By implementing cleanroom environments in combination with continuous particle deposition monitoring, manufacturers can design closed-loop clean process validation and process improvement procedures to prevent particle defects that lead to yield losses. This article introduces technology for cleanroom validation and qualification on the workspace where it really matters, using a Particle Fallout Scanner (PFS) that continuously measures particles falling onto critical target surfaces.

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Introduction

Microtechnology drives many technological advancements and is enabled by the production of highly precise and miniaturised components and devices on (sub)micrometer and smaller scales. Its applications span across many high-tech industries, pushing the boundaries of what is possible with modern manufacturing techniques.

Particle deposition in cleanrooms is a critical concern in microtechnology manufacturing, as even minute contaminants can significantly affect the performance of microscale devices and cause considerable yield losses. The mechanisms by which particles (visible and invisible, see Figure 1) are generated, transported and deposited in cleanrooms involve various physical and environmental factors. Understanding and continuous quantitative monitoring of these mechanisms are required to develop effective particle contamination control strategies, provide direct feedback to cleanroom operators and maintain cleanliness of the manufactured products [1, 2].

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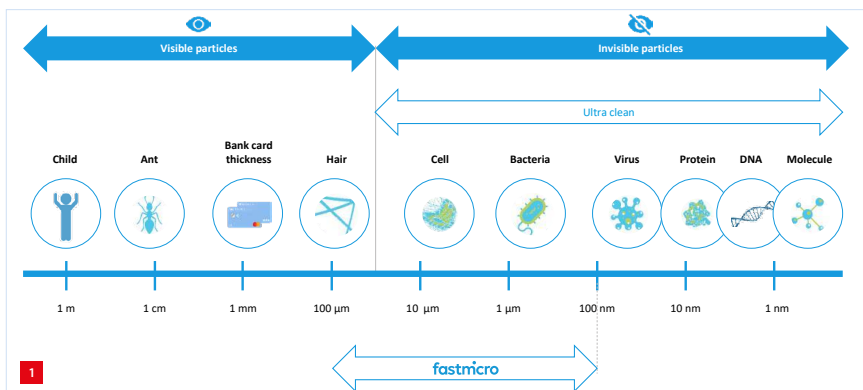
This article introduces the case for cleanroom qualification and process monitoring on the workplace itself, according to the standard ISO 14644-17: Particle deposition rate applications. This is achieved by using a Particle Fallout Scanner that continuously measures the particles falling onto critical target surfaces at the same particle-size levels down to 0.5 μm as those that apply for the Airborne Particles Counter (APC) measurements according to the ISO 14644-1 cleanroom standard.

Cleanroom standards in monitoring particle cleanliness

In micromanufacturing, cleanrooms are indispensable as they provide the contamination-controlled environment necessary to produce microscale devices and components. They enhance production yield, reliability and performance, while supporting advanced manufacturing techniques and compliance with stringent industry standards.

Effective management of particle deposition in cleanrooms involves understanding and controlling the various mechanisms that cause particles to settle on surfaces. By implementing comprehensive contamination control strategies, such as maintaining cleanroom airflow patterns, using appropriate filtration systems, minimising electrostatic charges, and following strict cleanroom operator procedures, manufacturers can significantly reduce the risk of particle contamination.

Unfortunately, particle contamination cannot be completely prevented. The air may be clean, but the contamination sources can come from the people, workspace and workflow in the cleanroom. A step closer to prevention is real-time monitoring and detection on critical surfaces. Parameters



Visible and invisible particles on the dimensional scale. (Source: H.D. Felton, "Long-term measurement of ultrafine particles in the Urban and Rural Environment", 2017)

such as surface cleanliness of product, tools and equipment, media and environment as well as air cleanliness and particle deposition rate should be monitored.

The International Organization for Standardization (ISO) provides an essential tool for defining and controlling the cleanliness levels inside a cleanroom.

ISO 14644 is a globally recognised standard that provides guidelines for the classification of cleanliness in cleanrooms and controlled environments. This standard establishes uniform criteria for allowable maximum particle concentrations based on particle size. It outlines methods for monitoring, testing and maintaining cleanroom environments to ensure compliance with specified cleanliness levels [3, 4].

While ISO 14644-1 serves as the foundational standard for cleanroom and controlled environment classifications, defining particle cleanliness levels based on airborne particulate contamination, ISO 14644-9 establishes the classification of surface cleanliness by particle concentration (SCP) for a size between 0.05 μm and 500 μm .

The fairly recent ISO 14644-17 introduces an important parameter, the particle deposition rate (PDR) level, that can be used to determine particle contamination risk on critical surfaces and predict the product cleanliness grade.

By adhering to these standards, manufacturers can set the quality norms to optimise their production environment, equipment and processes, to enhance product quality and mitigate particle contamination risks, ultimately achieving higher production yield and improving their environmental impact.

Importance of particle deposition control and monitoring

Particle contamination control and monitoring play crucial roles in micromanufacturing across various industries where precision, reliability and cleanliness are paramount. Applications include:

1. **Semiconductor manufacturing**
In wafer fabrication, even tiny particles can lead to defects in integrated circuits. Particle deposition control is essential during lithography, etching and deposition processes to ensure the integrity of patterns and features on wafers. In cleanroom operation, particle monitoring is critical for maintaining cleanroom environments in semiconductor fabs. Continuous monitoring enables identifying particle bursts and trigger contamination alarms, and ensuring production process compliance according to cleanliness standards.
2. **Biomedical devices and implants production**
Particle control is critical in the production of biomedical implants, such as pacemakers and orthopaedic implants, to prevent contamination that could lead to device failure or adverse biological

reactions in patients. Moreover, in micromanufacturing techniques used to produce precise drug-delivery systems, such as microneedles and microcapsules, particle monitoring ensures the cleanliness and integrity of these systems for safe and effective drug delivery.

3. **Optoelectronics and photonics**
Particle control is essential in the production of optical components, such as lenses, mirrors and fibre optics, to maintain optical clarity and performance. In microscale optical devices, particle deposition monitoring ensures the cleanliness of components used in telecommunications, sensing and imaging applications, which prevents performance degradation due to contamination.
4. **Aerospace and mobility**
Micromanufacturing is used to produce miniature components for aerospace and mobility applications, including sensors, actuators, fuel injectors and microelectronics. Particle control ensures reliability and functionality of these components in application areas where possible malfunctions cannot be tolerated.

Particle deposition rate monitoring for cleanliness control

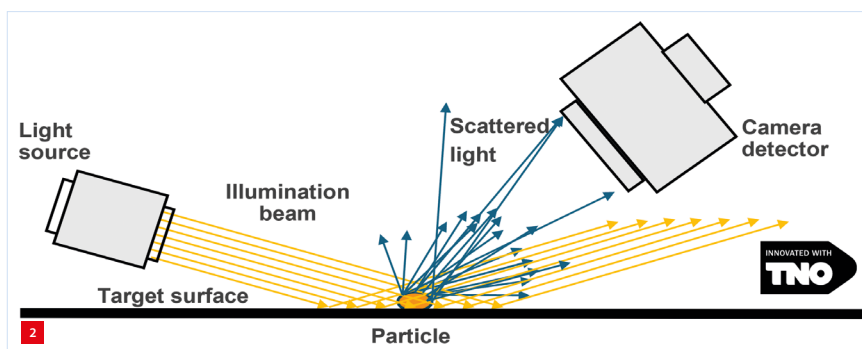
Particle deposition rate monitoring is used to detect, measure and analyse particulate contamination on surfaces within cleanroom environments. It plays a crucial role in maintaining and verifying the cleanliness standards required in micromanufacturing and other high-precision industries by monitoring deposition of particles over time.

Key attributes

1. **Detection and measurement**
 - Surface monitoring: assessing particle contamination on various surfaces, including workbenches, equipment and critical production areas.
 - Particle counting: counting the number of particles deposited on a defined surface area, providing data on contamination levels.
 - Size distribution: measuring and classifying particles based on size, typically ranging from a few nanometers to several micrometers.
2. **Data collection and analysis**
 - Quantitative data: providing quantitative data on the number and size of particles, which is essential for maintaining cleanroom standards.
 - Trend analysis: continuously or periodically monitoring surfaces, which helps to identify trends in particle deposition, enabling proactive contamination control.
3. **Automation and integration**
 - Automated scanning: allowing for consistent and repeatable measurements without manual intervention.
 - Data logging and reporting: using software for data logging, analysis and reporting, which helps in maintaining records for compliance and quality control.

Applications in micromanufacturing

1. Cleanroom certification, operation and maintenance
 - Routine monitoring: particle deposition rate monitoring is used for routine validation of cleanroom surfaces to ensure compliance with cleanliness standards such as ISO 14644.
 - Environmental control: help in verifying the effectiveness of air filtration systems, cleaning protocols and contamination control measures.
 - Sustainable operation: continuous measurement of actual particle contamination levels can be used to implement a closed-loop feedback and control system for cleanroom air filtration. A reduction in airflow refresh rate has the potential for energy consumption savings by a factor proportional to the power of three (i.e., power $P \approx \text{air flow } Q^3$)
2. Process control and optimisation
 - Identifying contamination sources in production: by pinpointing areas with higher particle deposition in situ, manufacturers can identify and address sources of contamination, such as equipment wear, operator handling or process inefficiencies.
 - Process improvement: continuous monitoring data supports process optimisation efforts by highlighting contamination trends and the impact of changes in procedures or cleanroom configurations.
3. Quality and assurance
 - Product integrity: ensuring that surfaces in contact with sensitive components remain free of particulate contamination is critical for maintaining product quality and reliability.
 - Regulatory compliance: documenting cleanroom conditions with data from a PFS helps demonstrating compliance with industry regulations and standards.
4. Feedback on operator behaviour inside the cleanroom
 - Direct feedback on the particle-generation effects of operator handling inside the cleanroom.
 - Making invisible particle contamination visible.
5. Product qualification
 - Validating the actual clean operation of products and machines can be executed via a duration test by measuring deposition rates, for instance below a robot.



An illustration of the Fastmicro scattering metrology.



The Fastmicro Particle Fallout Scanner.

Benefits of using a PFS

1. Enhanced cleanliness monitoring
Providing detailed and accurate information about particle deposition allows for better control and maintenance of cleanroom environments.
2. Improved product quality
Preventing particle-related defects in microscale manufacturing processes leads to higher-quality products.
3. Cost-savings
By identifying contamination sources early, a PFS helps in reducing downtime, rework, scrap and yield loss, ultimately saving costs.
4. Regulatory compliance
Meeting stringent industry standards and regulatory requirements ensures that manufacturing processes are up to par.

Fastmicro PFS

While standards have already been established as a guide to maintain the appropriate cleanliness, direct and continuous measurements of particle deposition give more insight and control over surface contamination. Fastmicro has developed a Particle Fallout Scanner (PFS) that can continuously and remotely monitor particles falling onto a target surface. The PFS is based on darkfield scattering metrology (Figure 2), a specialised optical technique used for particle detection and surface characterisation, particularly in environments where high sensitivity to small particles is required [5].

Main advantages

1. High sensitivity
By excluding direct light, darkfield scattering metrology enhances the visibility of small particles and surface features, providing high sensitivity to defects and contamination.
2. Enhanced contrast
The technique provides high-contrast images of scattered light, making it easier to detect and analyse small features and particles.

3. Non-destructive

It is a non-destructive technique that does not alter or damage the sample during inspection.

Some limitations

1. Precise set-up

The optical set-up for this technique requires precise alignment of the light source, sample and detector.

2. Size approximation

The size of the particles is estimated based on calibration measurements using polystyrene latex (PSL) particles with known size (certified by the National Institute of Standards and Technology, NIST).

3. Specificity

Darkfield metrology does not provide detailed information about the composition of detected particles, but the high sensitivity does provide fast particle detection and exact location information as a pre-scan to speed up throughput of follow-up root-cause analysis.

Overall, the Fastmicro PFS uses a powerful technique for detecting and analysing small particles and surface features with high sensitivity and contrast. Its applications in cleanrooms, semiconductor manufacturing, biological analysis, and material science make it an essential tool for maintaining the cleanliness and quality of microscale environments and products. Despite its complexity, the advantages it offers in terms of sensitivity and non-destructive analysis make it a valuable method in various high-precision industries.

Features and measurement capabilities

The Fastmicro Particle Fallout Scanner (Figure 3) is a compact and easy-to-use measurement tool. The PFS is interfaced to a computer via the Fastmicro Scanning Suite software which allows two log-in modes.

Under Operator mode, two measurement plots are given, namely 1) the particle deposition, which shows the number of particles detected at a particular time as well as the reference plot based on the expected particle deposition rate in relation to ISO 14644-17; and 2) the particle bin distribution, which indicates the cumulative count of particles per size bin.

With Supervisor access, additional real-time information on the measurement data can be retrieved, such as the matching of particles that appeared and disappeared over time as well as the relative size and corresponding locations. Moreover, the data (including the images) can be saved in an external folder for further processing and analysis.

The great strength of a low-detection-limit particle deposition measuring instrument such as the Fastmicro PFS is the ability to perform single or continuous measurements. In this way, data can be collected that not only provides



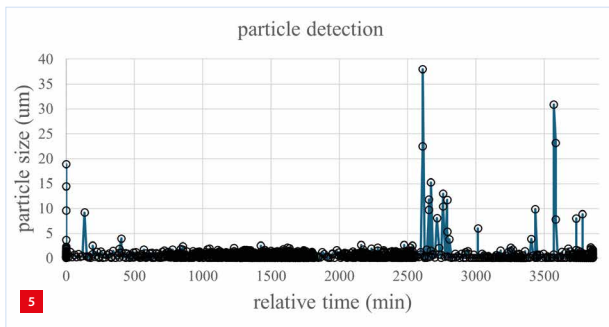
Exchangeable 2-inch witness wafer for extended cleanroom monitoring.

information about the final contamination of the surface, but also the rate at which it is contaminated.

As an additional use case, it is also possible to measure with an exchangeable 2-inch witness wafer (Figure 4). Such a witness wafer, used as a particle trap, can be placed at any location where the particle deposition must be determined and placed on the PFS after particle collection, so that the particle contamination measurement is done afterwards. By exposing this sample to the environment for a controlled period of time, and subsequently performing the particle count measurement in the scanner, it is possible to calculate the number of particles that have settled on average during this exposure period.

In both cases, after the particle deposition measurement, there is the possibility to do a follow-up with another measurement technique, such as optical or electron microscopy. This is in contrast to airborne particle counters, which can only take measurements of air flowing through the set-up at a particular time. With the particles collected using a witness sample, more extensive characterisation and analysis can be done to gather more information about the particle composition. This can give more insights in the possible cause or origin of the contaminants and consequently the specification of more accurate risk assessment.

With the Fastmicro PFS, it is possible to measure particle deposition with the same sensitivity as with the airborne particle counters. The number of particles with size $\geq 0.5 \mu\text{m}$ that fall out of the air and actually settle onto the adjacent target surface can be measured directly and continuously, which consequently leads to more accurate quantification of surface particle contamination. In addition, data collection and processing can be done in time intervals of 10 seconds or more, which results in a quick detection of the presence of unwanted particles.



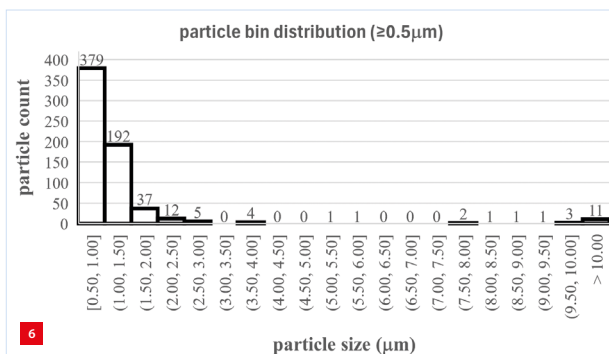
Example of continuous particle deposition monitoring.

Particle deposition rate measurement

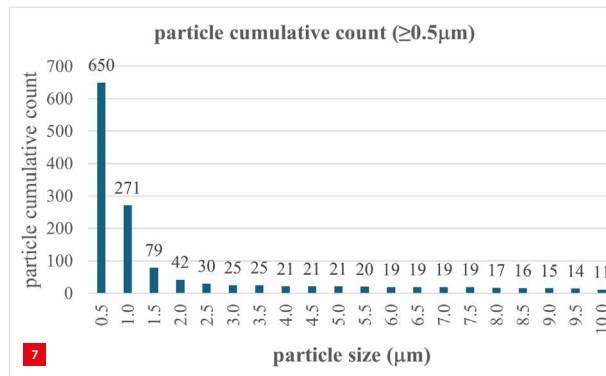
As an example of using the Fastmicro PFS to monitor particle deposition, a 2-inch witness wafer has been placed in the scanner to collect particles that settle on a working table inside a cleanroom (ISO class 6). Data collection was done continuously for almost three days. A plot of particle detection over time is given in Figure 5. A list of particles that appear on the wafer was recorded in an external file every 15 minutes. The time of appearance, particle size and location were saved.

It can be observed from the temporal plot that particles were already present on the wafer at the start of data collection. Most of the measured particles have size less than 5 µm. More particles bigger than 5 µm appeared during the latter part of data collection. In particular, there were a significant high number of big particles deposited around 2,600-2,700 min. Such data could be very useful in initiating an in-depth root-cause analysis of particle contamination, which could help in process evaluation and optimisation.

A histogram of the particle size is given in Figure 6. It shows that the particles are mostly with size between 0.5 µm and 1.0 µm, while particles bigger than 10 µm are also detected. A cumulative particle size distribution is shown in Figure 7. The graph indicates that particles with size bigger than 0.5 µm have been detected. Figure 8 gives a plot of the particle concentration as a percentage of total count, which indicates



Particle bin distribution for the measurement presented in Figure 5.



An example of a cumulative particle count for size $\geq 0.5 \mu\text{m}$ for a three-day continuous monitoring of a cleanroom.

that relatively more small particles have been detected than big ones. It can be noted that there is an exponential increase in the number of particles when their size becomes smaller than 1.0 µm. Moreover, the cumulative count of particles bigger than 2.0 µm is only less than 10% of the total number of detected particles.

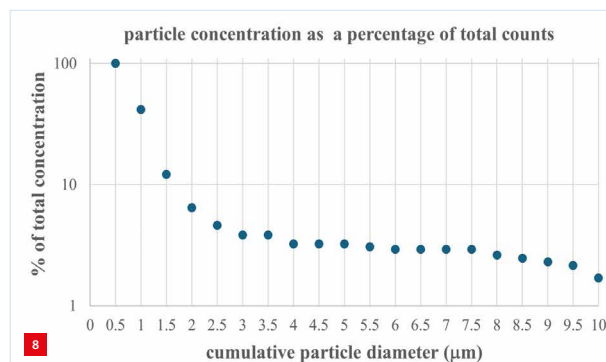
With the collected data, the particle deposition rate level L is determined using the following equation from ISO-14644-17 [3, 6]:

$$L = (R_D \cdot D) / 10$$

Here, R_D is the deposition rate of particles (in particles per m² per h) equal to or larger than the particle size D (in µm). R_D can be determined from the known number of deposited particles ($\geq D$) on a surface area a (in m²) over an exposure time t , using the equation:

$$R_D = N_D / (t \cdot a)$$

An example of the calculated values for approximately 24 hours of particle deposition measurements is given in Table 1. The estimated L value gives an indication of the ISO class in operation. For example, for $L = 1,000$ an ISO class limit of 5.5 for particles $\geq 5 \mu\text{m}$ is indicated [3].



Particle concentration as a percentage of total count for size $\geq 0.5 \mu\text{m}$, using the measurement data given in Figure 7.

Table 1

Example of determination of particle deposition rate R_D and particle deposition rate level L .

Particle size D (μm)	≥ 0.5	≥ 1.0
a (area on witness wafer, m^2)	$5.07 \cdot 10^{-4}$	$5.07 \cdot 10^{-4}$
t (exposure time, h)	23.75	23.75
N_D (Number of deposited particles)	126	60
R_D (particles $\geq D$ per m^2 per h)	10,470	4,986
Calculated L	524	499

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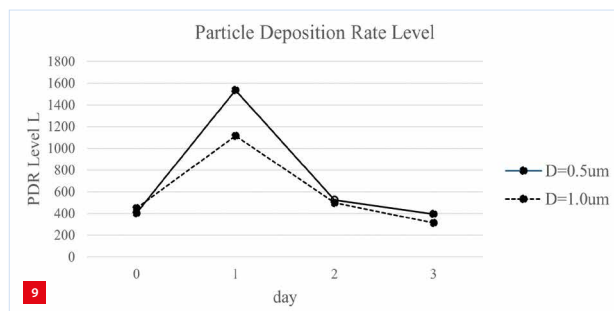
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An example of daily monitoring of the particle deposition rate L is given in Figure 9. Such a plot can give an indication of the general behaviour of particle deposition that can be used to assess compliance to a certain cleanliness standard.

Conclusion

In summary, cleanrooms are indispensable in micro-manufacturing because they provide a controlled environment that minimises contamination, thereby ensuring the high precision, reliability and quality required for the production of microscale and nanoscale devices. However, a cleanroom is not a clean product, hence continuous particle contamination control is essential. Airborne particulates are always present and spontaneously settle on adjacent surfaces. It is therefore inevitable to measure surface particle contamination continuously in order to constantly monitor the cleanliness of manufactured products.

With the Fastmicro Particle Fallout Scanner, it is possible to measure particle deposition with the same sensitivity as that of airborne particle counters. The number of particles with size $\geq 0.5 \mu\text{m}$ that fall out of the air and actually settle on a nearby surface can be quantified more accurately and continuously. Moreover, the real-time monitoring capabilities of the Fastmicro PFS enable other application use-cases, including reduction of energy consumption of operating cleanrooms and direct feedback to improve operator behaviour, which is also essential in maintaining a cleanroom environment that guarantees product quality and functionality.



An example of daily monitoring of particle deposition rate level using the measurement data provided by a Fastmicro PFS.



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