Comparative analysis of requirements for industrial cleanliness in mechanical engineering

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Abstract. In this work, the author shows the results of the study of the nomenclature base for industrial cleanliness in domestic sources and compares them with foreign analogues used in related fields of activity. With a detailed analysis of the standards, one can conclude that they are similar. The study presents universal methods for achieving a given surface cleanliness of technological equipment, which allow obtaining a result that meets the requirements of both domestic and international standards.

1. Introduction
A clean room is a room in which a certain number of different particles and their size are artificially maintained in the air. We are talking about dust, large aerosol vapors, various microorganisms and the like. Such rooms are designed, created and operated in such a way that the minimum amount of such particles gets inside them, they should not accumulate there in any case [1].

Clean technologies are widely used in the manufacture of medical devices that are designed to penetrate the human body or interact with an open wound. About 40% of the global market for medical equipment and surgical instruments are produced using clean technologies [2].

In mechanical engineering technology, these technologies are also often used. In connection with the rapid development of nanotechnology and a decrease in component parts at the enterprises of the instrument-making industry, the need for the use of complexes of "clean" rooms has significantly increased. At some production sites, the presence of people is completely excluded ("deserted technologies"), since even the slightest air pollution can provoke a critical defect in manufactured products, for example, a separate microcircuit or the entire device as a whole. The most important task of "clean" technologies at instrument-making enterprises is to prevent the production air pollution with the smallest particles, as well as to create sterile, safe and controlled production conditions. A properly designed complex of "clean" rooms allows you to minimize the number of defective devices and computers, as well as guarantee the production of quality products.

Along with nanotechnology, when using 3D printing technologies, air purity and temperature also play a key role [3-5].

The main documents of the design regulatory framework include:
- GOST ISO 14644-1-2002 ("Clean rooms and associated controlled environments");
- GOST R 51752-2001 ("Industrial cleanliness. Provision and control in the development, production and operation of products").
These standards reflect the requirements for the concentration of suspended particles per unit volume of the air, air exchange rate, air flow rate, temperature and humidity, noise level in industrial premises, etc.

2. Literature review

In mechanical engineering, assembly and testing complexes located at large test sites include large-volume clean rooms (up to 30,000 m$^2$) of P8 purity class according to GOST R 50766-95, which corresponds to the 100,000 purity class of the US Federal Standard FED-STD-209D and clean areas of a smaller volume, where the P7 purity class according to GOST R 50766-95 is provided, which corresponds to the purity class 10000 of the US Federal Standard FED-STD-209D.

This section provides an overview of the main regulatory documents and outlines the main requirements of domestic and foreign regulatory frameworks for ensuring and controlling the cleanliness of technological equipment for clean rooms.

Requirements for ensuring industrial cleanliness during manufacture, assembly, testing are set out in OST 92-0300-86 “System for ensuring industrial cleanliness of industry products. General requirements”.

In the United States, an extensive program has been developed to control surface contamination of products and ground equipment, which includes both government and industrial standards for determining the criteria for surface cleanliness and methods for their control. The following standards used in the preparation of products in mechanical engineering are of interest:

- NASA / JSC SN-C-0005 standard - contains the pollution control requirements applicable to spacecraft and ground support equipment, and includes a description of the "apparent cleanliness" levels and procedures for their determination;
- US military standard MIL-STD-1246C "Product Cleanliness Levels and Contamination Control Program" - sets requirements for product surface cleanliness based on particle size distribution and number of particles per square foot.

The main foreign documents defining standard methods for sampling and testing to determine the degree of contamination by levels of surface cleanliness are:

- ASTM E1216 - Standard Sampling Method for Determining Microparticle Contamination on a Surface Using a Belt Collector;
- ASTM E1234 - Standard Methods for Sampling, Transport and Installation of Non-Volatile Residue (NVR) Sample Plates;
- ASTM E1235 - Standard Test Method for Implementing the Gravimetric Method for Calculating Non-Volatile Residue (NVR) Concentration.

Let's consider in more detail the requirements of the US standards MIL-STD-1246C and NASA / JSC SN-C-0005.

3. Purity criteria

The cleanliness levels are the criteria for determining surface cleanliness according to US MIL-STD-1246C.

The standard establishes the following terms and definitions:

- Cleanliness level - the established maximum permissible maximum pollution for a specific area of the surface;
- Contamination control - any action taken to control the level of cleanliness;
- Particles - foreign substances of organic or inorganic origin that affect the quality of the technological process;
- Non-volatile Residue (NVR) - A soluble substance left on a surface after a volatile liquid evaporates. The quantitative content of non-volatile residue is controlled;
- Particle size is the maximum linear size or diameter of a particle in microns.

Examples of designation of surface cleanliness levels according to the US Military Standard MIL-STD-1246C:
a) "MIL-STD-1246C. Level 200 " - determination of the surface cleanliness only by microparticles;
b) "MIL-STD-1246C. Level 200F " - determination of the surface cleanliness by two indicators: microparticles (200) and non-volatile residue (F);
c) "MIL-STD-1246C. Level F " - determination of surface cleanliness only by non-volatile residue (F).

Examples of particles are: metal shavings, pile, pieces of foam rubber, rubber, fibers, soil and coal dust, peeling paint, etc.

An example of a non-volatile residue (NVR) is: detergent residue, fingerprints, splashes and lube oil stains.

The cleanliness level of the surfaces of technological equipment must correspond to the cleanliness class of the room in which it will be used.

The NASA / JSC SN-C-0005 standard establishes the levels of surface cleanliness without counting the number of microparticles and gives criteria for their determination:

a) The level of "visible cleanliness" (Visibly Clean) - the visible cleanliness of the surface when observed with the naked eye (except for vision correction), expressed in a certain way. This requirement is usually accompanied by a description of the verification method (for example, when viewed at close range using oblique white lighting of a certain intensity or under normal lighting):
   VC0 - Check for cleanliness using an incident light of 50-75 Ftc. The tested surface must be observed with the naked eye (except for vision correction) from a distance of 0.6-1.5 m;
   VC1 - Check for cleanliness using an incident light of 50-75 foot candel. The surface to be checked must be observed with the naked eye (except for vision correction) from a distance of 0.3-0.6 m;
   VC2 - Check for cleanliness using incident light of 100-125 foot candel. The surface to be tested must be observed unarmed.

   Maximum number of characters: 5,000. To continue translating, use the arrows. VC2 - check for purity using incident light of 100-125 foot candle. The surface to be tested must be observed with the naked eye (except for vision correction) from a distance of 0.15-0.45 m; [one]

b) "Visibly Clean + Ultraviolet" level - "visible cleanliness" level (as defined above) controlled by ultraviolet light with a wavelength of 3200-3800 A (320-380 nm) [6-7].

4. Cleaning methods with specified cleanliness requirements

"Rough" cleaning. This method is used to obtain a surface cleanliness visible to the naked eye (except for vision correction). Coarse cleaning removes such contaminants as welding scale, corrosion, oxide films, residues of oils, fats, and accumulation of soil and coal dust from the surface. Coarse cleanliness levels generally require no inspection other than visual inspection. The method is a normal production process and usually does not require high cleanliness in the production area and is carried out by the equipment manufacturer in a safe manner.

The following types of cleaners can be used to eliminate the most severe forms of contamination by the equipment manufacturer:

- acid cleaners (hydrochloric, sulfuric, phosphoric acids with various additives) - used to remove such types of contaminants that cannot be removed using other types of solvents;
- alkaline cleaners (technical pure alkali, alkaline solutions containing nitrate or phosphorus) - used to remove organic or inorganic contaminants such as grease, ground dust, scale, metal oxide film;
- "mild" cleaners (alkaline soap, emulsion cleaners, surfactants) - used to remove contaminants such as oil, grease, grease, ground dust;
- organic solvents (acetone, alcohol) - used to remove organic contaminants;
- tap water and deionized water - used to remove residues of the substance formed as a result of the use of cleaning solutions or as a result of washing off the contaminant.

This method is more suitable for cleaning metal structures. For non-metallic, it is mainly destructive. Rubber products and products made from plastics can change their shape, porosity after using acidic, alkaline and organic solvents [8].
The "rough" cleaning method can be recommended for removing a large amount of dirt accumulated during storage and transportation of large-sized equipment without packaging or in unsealed packaging [9].

It is recommended to use industrial detergents as cleaners to remove organic and inorganic contaminants such as oil, grease, soil and coal dust.

Cleaning is carried out in special rooms using a large amount of aqueous solution or water.

Table 1 shows the recommended methods of "rough" cleaning of surfaces, depending on the surface material and the type of surface contamination.

**Table 1. Methods of "rough" cleaning of surfaces, depending on the surface material and the type of surface contamination.**

| Surface material | Type of contaminated surface | “Rough” cleaning method |
|------------------|------------------------------|-------------------------|
|                  |                              | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Aluminum         | Mechanical processing or lack of covering. | X | X | X | | | | |
|                  | Lack of thermal oxidation. | X | | | | | |
|                  | Protective film covering | | | | | | |
|                  | Weld joint scale, corrosion or high temperature acidification | | | | | | |
|                  |                              | X | X | X | X |
| Bronze (brass)   | Mechanical processing or lack of covering. | X | X | | | | |
|                  | Lack of thermal oxidation. | X | | | | | |
|                  | Protective film covering | | | | | | |
|                  | Weld joint scale, corrosion or high temperature acidification | | | | | | |
| Stainless steel  | Scale-free surface | | | | | | |
|                  | Weld joint scale, corrosion or high temperature acidification | X | X | X | X | X | X |
| Carbon steel     | Scale-free surface | X | X | | | | |
|                  | Weld joint scale, corrosion or high temperature acidification | X | X | X | X | X | X |
| Non-metallic surfaces | As usual | | | | | | |
| Electroplated surfaces, other metals | As usual | X | X | X |

Notes:
1 "X" is the recommended surface cleaning method (in sequence from left to right).
2 Methods of "rough" cleaning: "1" - mechanical removal; "2" - degreasing with an organic solvent; "3" - flushing with alkaline cleaner and tap water; "4" - washing with detergents and tap water; "5" - washing with acidic solution and tap water; "6" - flushing with neutralizing substances and tap water; "7" - washing with distilled water; "8" - drainage.

"Fine" cleaning. This method is used to achieve a surface cleanliness level that is higher than that obtained by the "rough" cleaning method. It is thanks to the "fine" cleaning that the surfaces of the equipment should look "perfectly" clean. "Fine" cleaning is carried out under conditions of simultaneous monitoring of the environment and is designed to remove particles, films, fibers, biological and other
forms of contamination that are difficult to distinguish with the naked eye, but which can lead to a
deterioration in the technical characteristics of an object or technological process.

Substances or solvents used for "fine" cleaning should not react with the equipment surface material,
cause obvious or latent deterioration of the technical characteristics of the equipment being cleaned and
should not degrade the quality parameters of the air environment in the room. [ten]

For "fine" cleaning it is recommended to use as cleaners:
- compressed air;
- flakes or granules of carbon dioxide;
- distilled water;
- surfactants;
- compressed inert gas (with mandatory control of maximum permissible concentration of gas);
- organic cleaners.

Liquids for "fine" cleaning should be thoroughly filtered and their properties controlled. When
choosing liquids for "fine" cleaning, one should take into account the physicochemical properties of the
pollutant to be removed and the surface on which the cleaner is applied [11], the possibility of the surface
material of the object being cleaned to react with the cleaning agent, the degree of danger of each
cleaning liquid to human health and the environment. media, waste disposal method, including draining
the cleaning liquid, and the possibility of its reuse after preliminary cleaning and filtration [12].

Methods for "fine" cleaning:
- a) cleaning with a solution - the surface to be cleaned is washed with detergents, aqueous solution or
  solvents;
- b) spray cleaning - cleaning with an aqueous solution under pressure;
- c) acoustic cleaning:
  1) ultrasonic cleaning (15 ... 100 kHz) - is used for surfaces of complex configuration (surface erosion
  is possible during cleaning);
  2) mega-acoustic cleaning (over 100 kHz) - the most effective for surfaces of simple geometry;
- d) cleaning with steam - the surface is exposed to hot vapors of the solvent, which, condensing on
  the surface, washes away the dirt. This method is effective for removing soluble contaminants and can
  be used as a drying method. Ineffective for removing microparticles;
- e) circular rinsing and drying - applied only after using another cleaning method. The item to be
  cleaned is rinsed during its slow rotation, then the rotation is accelerated to the maximum value. High
  angular velocity accelerates the movement of liquid droplets that wash away particles with the help of
  shear stress; rinsing liquid also flows down from the surface and the surface is dried;
- f) electropolishing and chemical polishing - the product is immersed in a specially prepared solution
  necessary for etching the base material of the surface, which makes the surface smooth and flushes out
  all dirt particles that have penetrated into all surface irregularities. The solutions used must be pre-
  filtered, then the surface is washed with distilled water to remove the remaining solution.

It should also be noted other methods of "fine" cleaning associated with the use of argon flakes,
chemically highly active substances, plasma and ozone using ultraviolet radiation, which are more
suitable for cleaning the surfaces of parts made using 3D printing tools [13].

5. Methods for measuring purity used in mechanical engineering
Measurement methods are based on counting the number of microparticles and non-volatile residue and
are conventionally divided into:
- a) Direct Measurement Method - Direct measurement analyzes the surface of interest by calculating
  the concentration of microparticles and non-volatile residue (NVR) using a microscope. This method is
  the most accurate, but it can be applied only if the optical characteristics of the surface make it possible
to implement such a check;
- b) Method using IR spectroscopy.
  The method has a high resolution (sensitivity) and allows you to determine the type of pollutant.
The method options are:
1) discs transparent to infrared radiation are placed near the controlled surfaces and then, without additional processing, are examined by methods using an IR spectrophotometer. The disadvantage of this method is the need for a very fast study, since the penetration of disc materials into the studied pollution is possible, which leads to an error in the results;

2) a photographic plate-sample is placed near the controlled surface, then the contaminated plate is moistened with a special solution, dried under an IR lamp until the solvent evaporates, the remaining few drops are transferred to a disc made of sodium chloride transparent for IR radiation and examined using an IR spectrophotometer.

Application of methods using technical measuring instruments requires significant financial, time and material costs for the purchase of special control equipment and consumables, staff training. In some cases, an additional clean room is required for the measurement processes.

The quality of the liquids used for cleaning surfaces should be determined by the amount of the total residue, which should not exceed 0.001% by weight. The most frequently used solvents abroad are isoprene alcohol, petroleum ether, methyl ethyl ketone and other solvents.

The surfaces of the operated equipment of the cleanliness class P8 are considered clean:

   a) After wiping them with clean coarse calico napkins moistened with ethyl alcohol. The indicator of cleanliness is the absence of traces of contamination on the cloth.

   The cleanliness of the napkin (presence or absence of traces of contamination) is determined with the naked eye (except for vision correction) under working light, which corresponds approximately to the particle level "750" and the "D" cleanliness level for non-volatile residue.

   This method is recommended for the control of contamination of equipment surfaces (stored or transported in a dustproof and moisture-proof package) and surfaces with metal coatings.

   b) After visual inspection with the use of special lighting means to achieve the levels of "clean in appearance by particles" or "clean in appearance by non-volatile residue".

Today, mainly private organizations are engaged in the development of complex methods for teaching the design or operation of clean rooms, which could interest employees of technological services of enterprises of the microelectronic, pharmaceutical, food industries; heads of medical institutions; managers and specialists of design and construction organizations [14].

Also, when designing complex special units, possible degrees of contamination during operation are not taken into account. With rare exceptions, chemical maps or conclusions on ensuring environmental safety are being developed, which in the modern world may not be enough for the uninterrupted functioning of heavy machinery [15-18].

6. Conclusion

Application of methods using technical measuring instruments requires significant financial, time and material costs for the purchase of special control equipment and consumables, staff training. In some cases, an additional clean room is required for the measurement processes.

In accordance with the requirements, the control of the microclimate parameters (temperature, humidity, dustiness) of the clean room and clean zones must be carried out continuously by the microclimate parameters monitoring system on a daily basis or after operations that pose a risk of contamination, for example, equivalent levels of carbon compounds, levels of cleanliness of surfaces of technological equipment according to microparticles and non-volatile residue.

From the above requirements, it follows that contamination in clean rooms and areas of test facilities should be minimized, since without this, a functioning clean room will not be certified for a given cleanliness class.

To meet the requirements for minimizing contamination from process equipment, newly designed and all previously developed equipment (operated in clean rooms) must be certified for compliance with industrial cleanliness requirements.

Surfaces that will be used in the clean room must be visually checked for compliance with the "visually clean non-volatile residue" level.
For technological equipment operated in clean areas of test complexes of P7 cleanliness class according to GOST R 50766-95 (which corresponds to 10000-100000 cleanliness classes according to FED-STD-209D), the surface cleanliness should be subject to more stringent control:

1) Compliance with the level of "visible purity" + ultraviolet (Visibly Clean + Ultraviolet) - the level of "visible purity" is checked (as shown above) and control is carried out using ultraviolet light with a wavelength of 3200-3800 A (320-380 nm).

If any sign of fluorescence is found, re-clean it. If the fluorescence has not decreased, it is necessary to find out the source of the fluorescence - contamination or the main material of the element. For this, fine cleaning methods are used without particle counting.

2) Compliant with US MIL-STD-1246C cleanliness level with microparticle count and non-volatile residue (NVR) - plate sampling method.

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