

# Constructive and functional modernization of aluminum powder and paste production facilities in order to reduce risk of explosion

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**Abstract.** The present work aims to present functional constructive solutions of installations that produce aluminum powder and paste in technological process. Risk management in these Ex classified areas is closely linked to industrial development and awareness of the associated dangers. Classification of Ex areas refers to determination and marking of areas with explosion hazard in order to ensure the correct and safe use of equipment in these environments, in accordance with Directive 2014/34/EU and the legislative regulations in force. advantages.

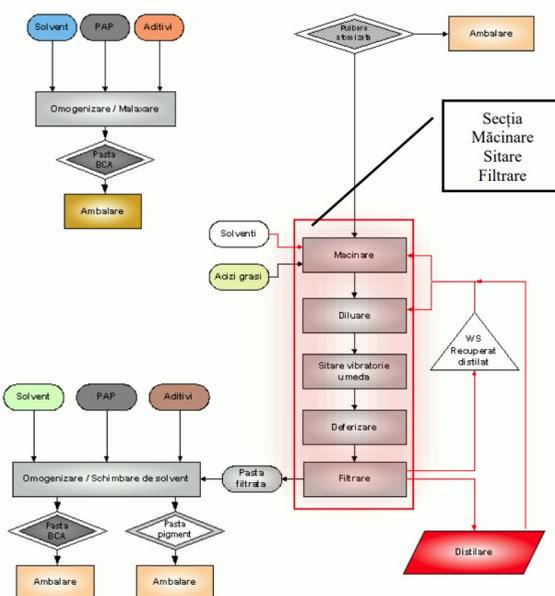
## 1 Introduction

The production of aluminum-based metallic pastes and pigments involves the use of volatile organic solvents (toluene, white spirit, acetone, etc.), which pose significant explosion, fire, and toxicity risks. This paper analyzes the technological processes, compares the hazards associated with different solvents, and proposes safety strategies in accordance with ATEX, [1, 2] and ISO standards. The results indicate that solvent selection and proper safety measures can substantially reduce industrial risks, [3].

The technology used for obtaining aluminum paste is a complex process consisting of several stages, as follows: grinding of atomized powder, wet vibratory screening, filtration of aluminum paste, homogenization of aluminum paste, packaging of aluminum paste, solvent exchange for AAC (autoclaved aerated concrete) aluminum pastes, recovery of ferrous metal waste, recovery of non-ferrous metal waste, and auxiliary activities, Figure 1. The first three stages of the technological flow for aluminum paste production are grinding, screening, and filtration of aluminum powders. The installation consists of tubular ball mills, a vertical mill, wet vibratory screens, plate and frame filters, pneumatic diaphragm pumps, agitated suspension tanks, solvent collection tanks, and exhaust fans.

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**Fig. 1.** Process block diagram.

The grinding of atomized aluminum powder consists in transforming particles with granulometry ranging from 50 to 200  $\mu\text{m}$  into lamellar powder with a thickness of 0.1 to 0.15  $\mu\text{m}$ .

It is well known that any metal has a certain level of activity, and the greater the surface area of the metal, the higher this activity becomes. This is particularly evident in the case of aluminum, which exhibits a high amphoteric character.

The substances used in the grinding process in tubular mills are: atomized aluminum powder, stearin or olein, toluene or acetone and dearomatized white spirit, each fulfilling different roles and characteristic, table 1 and table 2.

**Table 1.** Solvents properties.

Solvent	Flash Point (°C)	LEL/UEL (%)	Vapor Pressure (kPa, 20°C)	Toxicity (TLV, ppm)
Toluene	4,00	1,1–7,1	3,70	20 (neurotoxic)
White spirit	38–45	0,7–5,0	0,50	100 (irritant)
Acetone	-18,00	2,5–12,8	24,70	500 (irritant)

**Table 2.** Solvents properties.

Characteristic	Toluene	White Spirit	Aluminum Powder
Flash point	~4°C	~38-60°C	None (risk due to fine dust)
Lower explosive limit (LEL)	1.2% vol	0.6–0.8% vol	~40 g/m <sup>3</sup> in air

Characteristic	Toluene	White Spirit	Aluminum Powder
ATEX hazard classification	Zone 1 or 2 (gas, vapor)	Zone 1 or 2	Zone 20, 21 (combustible dust)
Type of risk	Flammable vapors, explosive atmosphere	Flammable vapors, less volatile than toluene	Explosive dust cloud, reacts with water/acids → H <sub>2</sub>
Volatility	Very high	Medium	Does not evaporate, but disperses easily
Toxicity	High (neurotoxic)	Medium	Low (but hazardous by inhalation)
Explosiveness	High (vapors)	Medium	Very high (dust cloud)
Chemical reactivity	Chemically stable but flammable	Chemically stable	Reactive with water, acids (produces hydrogen)
Typical protection measures	Ventilation, gas detection, ATEX equipment, inerting	Ventilation, leak control, ATEX equipment	Inerting, grounding, spark-free equipment, dust extraction

Note:

- **Toluene** creates explosive atmospheres (Zone 0/1) due to its low flash point and high vapor pressure.
- **White spirit** is more stable but still requires Zone 1/2 classification in enclosed spaces.
- **Acetone**, though highly flammable, poses a lower accumulation risk due to its lower vapor density than air.

The aluminum powder is the material to be ground; stearin or olein are fats soluble in white spirit, enabling the formation of a greasy solution that creates a protective film around the aluminum particle against oxidizing agents; dearomatized white spirit is an organic solvent used as the grinding medium. The grinding bodies are the balls inside the mill.

The discharge of aluminum paste slurry is done through the mill’s discharge outlet, which is equipped with a pneumatic pump system in order to avoid splashing during emptying. Due to the heat generated during the grinding process, cooling of the equipment is required; this operation is performed using recirculated water as a cooling agent.

After discharge, the mill is cleaned; the aluminum paste slurry is removed from the mill using pneumatic pumps and transferred to a dilution tank, from where the suspension is subjected to screening.

In this regard, after identifying the explosion hazard zones within the technological process for the production of aluminum powders and pastes, all electrical equipment used in these zones must be of Ex construction and must be properly maintained during their operational lifespan.

The screening process employs vibratory sieves. In this stage, the aluminum paste slurry obtained from the previous operation is sieved to remove aluminum particles that have not been sufficiently ground. The oversize material from the sieve is reintroduced into the grinding process.

The fractions obtained through vibratory screening using one or two-deck sieves have a homogeneous particle size distribution, and sorting by fraction is necessary for the subsequent production stages of various types of aluminum paste.

De-ironing (ferrous metal removal) is a complementary stage to screening and is specific to the production of certain pigment pastes with special shades that require iron content to be below 20 ppm. This is achieved using magnets mounted on the feed column of the filter press.

Next, the slurry is directed via pneumatic pumps to the filter presses. The equipment used are plate and frame filter presses. The pressing of the filter is performed using a hydraulic cylinder. The suspension introduced into the filter reaches the filter cloths, where the paste is retained and the solvent is discharged between the frames through the cloths.

The collection of aluminum paste is done in screw-equipped hoppers located beneath the filter. The screw conveyor is operated only after a drum has been placed under the discharge outlet.

The solvent resulting from the filter press is collected in a recovery tank and is then pumped—partially to a distillation unit (1–3 tons/day) and the remainder to the solvent storage tanks in the tank farm. The resulting paste is packed in sealed drums with removable lids.

Electrical installations operating in hazardous atmospheres have characteristics specially designed in order to make them suitable for operation in such atmospheres. It is essential, for safety reasons in these areas, that, during the lifetime of these installations, the integrity of such special features to be preserved; therefore, they require an initial inspection and either:

- a) subsequent regular periodic inspections, or
- b) supervision by qualified personnel

in accordance with EN 60079-17, [4] and, when necessary, also maintenance.

Installations in which flammable materials are handled or stored must be designed, operated and maintained so that all releases of flammable materials, and consequently the extent of hazardous areas, are kept to a minimum in terms of frequency, duration and quantity, whether the operation is normal or not.

It is important to check those parts of the production equipment and systems from which the release of the flammable substance may occur and to consider changing their design considering the reduction in the probability and frequency of occurrence of such flammable substances, of the quantity and level of releases.

The probability of the presence of a gaseous explosive atmosphere depends mainly on the degree of release and ventilation. This is identified as the hazardous area. The hazardous areas are split into: zone 0, zone 1, zone 2 and non-dangerous zone.

The extent of the area depends mainly on the physical and chemical parameters of the flammable material and on the production process.

The novelty of the paper is represented by presentation of the development of modular robots intended for use both in maintenance and repair activities, as well as in interventions in areas with fire and explosion hazard, where may occur toxic and/or explosive atmospheres.

## **2 Classification of hazardous areas in aluminum powder and paste production installations**

The SR EN 60079-10 standard "Explosive Atmospheres – Part 10-1: Classification of Areas – Explosive Gas Atmospheres" and Part 10-2: Classification of Areas – Combustible Dust Atmospheres provides recommendations for the classification of areas where the formation of explosive atmospheres of flammable gases may occur. In this context, the standard indicates both general and specific criteria for the zoning procedure of technological spaces. [5, 6].

Zoning of technological areas is a method of analysing and classifying the environment of a technological installation based on the probability of occurrence of explosive mixtures of flammable gas and air. This facilitates the appropriate selection of electrical equipment to ensure safe operation in such environments, also considering the characteristics of the gas and dust involved.

The classification of zones is based on long-standing practical experience. The classification of explosion hazard areas can be carried out based on two significant methods:

- the source-of-release method;
- the generalized method.

The source-of-release method relies on quantitative risk assessment, which leads to a more representative classification.

The generalized method is widely used and generally consists in addressing the hazard based primarily on the experience of the process engineer.

This method analyses each point from which flammable substances may be released in quantities sufficient to form an explosive mixture and aims to:

- reduce arbitrariness in zone determination;
- obtain a representative quantitative result.

Each potential source of release is identified and categorized separately, based on the associated level of risk and the frequency of occurrence:

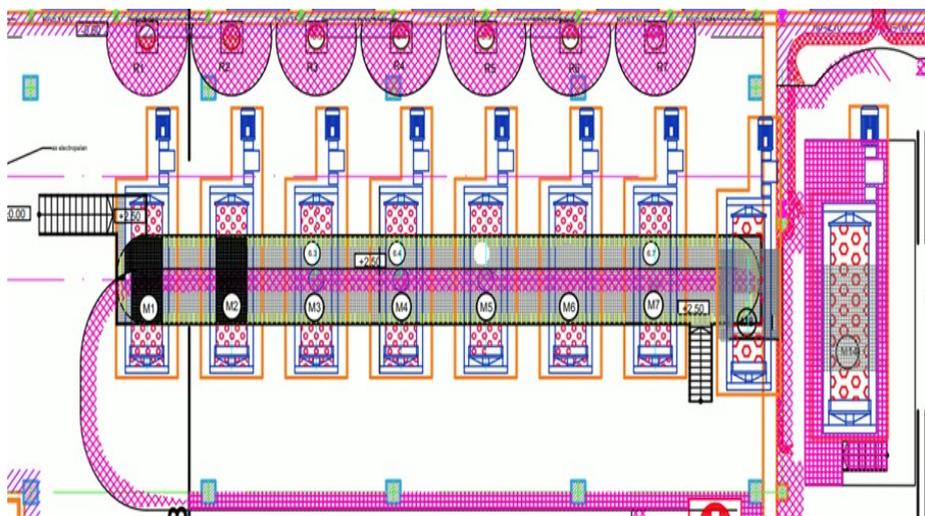
- Continuous release source (Zone 0): where releases occur for long periods (typically more than 1,000 hours per year).
- Primary release source (Zone 1): where releases are frequent or last for extended periods (typically between 10 and 1,000 hours per year).
- Secondary release source (Zone 2): where releases are infrequent and of short duration (typically less than 10 hours per year).

After identifying the release sources, the next step is to classify and determine the extent of the zones around them. In most cases, for well-ventilated areas, zoning performed according to the source-of-release method results in Zone 2 as the dominant area, with Zone 1 areas forming localized "islands" within them.

It is also possible for a Zone 0 area to exist within a Zone 1 area, but a Zone 0 area can never be located within a Zone 2 area.

The zoning method based on the source-of-release leads to a more accurate classification of the installation compared to the generalized method. Therefore, any changes in operation, equipment, or process procedures require a reclassification.

In the grinding, screening, and filtration stages of aluminum powder processing, both gas explosion hazard zones and dust explosion hazard zones are identified, as illustrated in figure 2, which shows a section of a production hall containing tubular ball mills, wet vibratory screens, and plate-and-frame filters.



**Fig. 2.** Zoning plan facility.

### 3 Hazard of Ex atmosphere formation in the production process

Due to the technological process involved in the production of aluminum powders and pastes, and the solvents used within this process, the risk of explosive mixture formation is extremely high. Therefore, it is crucial to consider the substances used in aluminum paste production and their physicochemical parameters.

Aluminum has a melting point of 660°C; thus, any temperature exceeding this threshold can easily lead to the ignition of aluminum powder.

When stored in piles or layers, aluminum powder is not explosive as such, but it can ignite from a source and burn with intense heat release, posing a significant fire hazard.

This process occurs as follows: the oxidation reaction, initiated by a source, is strongly exothermic. The air between the aluminum particles prevents the dissipation of the generated heat, leading to heat accumulation and subsequent particle ignition.

Contamination of aluminum powder increases the fire hazard when stored in layers or heaps. When contaminated with oil, the powder becomes prone to self-ignition. Self-ignition of aluminum powder, due to the heat generated by oxidation, may also occur on surfaces where particles tend to agglomerate.

Moisture significantly accelerates the self-ignition process. Aluminum powders can be ignited by open flames, mechanical or electrical sparks, short circuits, cigarettes, etc.

Fine aluminum powder has the property of accumulating electrostatic charges and can act as an ignition source for vapor-air mixtures due to electrostatic discharges.

When suspended in air, aluminum powder can form explosive mixtures (atmospheres). The simultaneous presence, in time and space, of such preformed explosive mixtures and an ignition source with sufficient energy and temperature can result in an explosion, which may be followed by a fire sustained by the present combustible materials.

In the aluminum paste production process, substances such as toluene or white spirit are used.

The installation for producing aluminum paste by mixing aluminum powder with solvents uses either pre-ground and dried powder to which solvent is added, or paste obtained from the grinding–filtration section.

Mixing of dry powders with solvents is carried out in Z-arm mixers, while the conditioning of existing paste is performed in a conical mixer.

According to safety standards on the zoning of technological areas, the primary safety principle is the elimination of either the explosive mixture or the ignition source. If this is not feasible, measures must be taken to reduce the probability of occurrence of either or both factors (ignition source and combustible atmosphere) to an acceptable level.

In the melting furnace area of the melting–atomization section, where the burner flame is a permanent ignition source, the only possible safety measure is to eliminate the formation of a flammable or explosive atmosphere. Therefore, classifying this area as Ex is not appropriate, neither from the perspective of the natural gas used as burner fuel, nor from the perspective of combustible dust presence.

To ensure safety in this technological space, all removable joints (flanges, couplings, unions, etc.) on the methane gas supply line to the burner must be checked at least daily to detect and eliminate any leaks.

Permanent flame monitoring must be ensured with an appropriate device that automatically shuts off the gas supply in case of flame extinction in the furnace.

Interlocking between the exhaust fan of the quenching tunnel and the compressed air supply circuit of the atomization lance must be implemented to avoid backward movement of aluminum particles into the furnace area.

During normal operation, the quenching tunnel constantly contains aluminum powder suspensions with concentrations depending on the distance from the point where the molten

metal stream meets the compressed air jet. It can be considered that during atomization, explosive concentrations of aluminum powder are continuously present in the quenching tunnel.

Moreover, the lower part of the quenching tunnel includes hopper compartments that permanently accumulate excessive and uncontrolled dust. Therefore, the entire volume of the quenching tunnel falls under Zone 20.

The technological area that includes the discharge openings of the hopper compartments is a partially open space.

Near these discharge openings, explosive aluminum dust suspensions ( $\geq 40 \text{ g/m}^3$ ) may occasionally occur for short durations. A Zone 22 is thus defined around these outlets.

This Zone 22 includes all three discharge points of the quenching tunnel as well as the discharge area of the cyclone with hopper.

The interior of the cyclone with hopper, which performs the first-stage separation of aluminum powder extracted from the tunnel, and the associated ducts connected to the fan and dust collector are classified as Zone 20.

A Zone 22 must also be defined around the cyclone's discharge point, which is located in an open space.

The interior of the bag filter located downstream of the cyclone is also classified as Zone 20.

Around the discharge points of the rotary screen, explosive dust suspensions may form due to the accidental swirling of powder deposits during product removal.

Therefore, a Zone 22 with a radius of 0.5 m around these discharge elements must be defined.

The interior of the cyclones and their associated hoppers are classified as Zone 20.

From the perspective of solvent vapors, in the aluminum paste production area, three zones have been identified.

The main vapor release source is the mixer.

The interior of the mixer contains liquid solvent, and subsequently the paste, which still contains approximately 30% solvent. For this reason, the interior of the mixer is classified as Zone 0.

Since the mixer inlet remains open for a period after emptying the powder drums, it is considered a primary release source, which defines a Zone 1 with a radius of 2.5 meters around the mixer inlet and extending to floor level (elevation 0.00 m).

The Zone 1 defined by possible leakages at the sealing gasket of the mixer lid and at the shaft seals of the mixing arms coincides with the Zone 1 defined by the mixer inlet emissions.

This area also accounts for cases when the mixer lid is opened for cleaning between batches.

It is assumed that before cleaning, the mixer is emptied, and any residual paste adhering to internal surfaces will not generate more vapors than during normal operation.

Zone 1, created by vapor release at the mixer inlet, is surrounded by a Zone 2 extending 1 meter vertically and 2.5 meters horizontally beyond the boundaries of Zone 1.

The number and extent of other Zone 2 areas, caused by smaller vapor releases (e.g., solvent drums placed near mixers), are included in the larger Zone 2 defined around the mixer inlet, which extends 5 meters around the mixer.

Due to the production process, described above, an important feature is maintaining proper ventilation in the production halls, [7], so a calculation was made for this, for a room with a volume of 100 cubic meters, as follows:

**Minimum Ventilation Rate Based on LEL**

To maintain concentration below **25% of LEL**:

$$C_{max} = 0,25 \times LEL \tag{1}$$

$$C_{max} = 0,25 \times 1,1\% \times = 0,275\% \text{ (2750 PPM)} \tag{2}$$

$$Q = \frac{G \times 10^6}{C_{max} \times \rho} \approx 58 \text{ m}^3/\text{h} \quad (3)$$

$$\rho = 3,2 \text{ Kg/m}^3 \approx 58 \text{ m}^3/\text{h} - \text{toluene density} \quad (4)$$

$$Q = \frac{0,5 \times 10^6}{2700 \times 3,2} \approx 58 \text{ m}^3/\text{h} \quad (5)$$

**With safety factor (k=4):**

$$Q_{final} = 58 \times 4 = 232 \text{ m}^3/\text{h} \quad (6)$$

**OSHA Air Change Method**

For solvents with flash points < 38°C (toluene), **20 air changes/hour** are required:

$$Q = 100 \text{ m}^3 \times 20 = 2000 \text{ m}^3/\text{h} \quad (7)$$

Conclusion: **2000 m<sup>3</sup>/h** is selected to meet both explosion prevention and health safety requirements.

**Duct Sizing and Pressure Loss**

- Air Velocity (v): 12 m/s (recommended for solvent vapors).

- Duct Diameter (D) and Pressure Loss:

$$Q = v \times A \text{ [m}^3/\text{h]} \quad (8)$$

$$A = \frac{Q}{v \times \frac{3600}{2000}} \approx 0,046 \text{ m}^2 \quad (9)$$

$$A = \frac{2000}{12 \times \frac{3600}{2000}} \approx 0,046 \text{ m}^2 \quad (10)$$

$$D = \sqrt{\frac{4 \times A}{\pi}} = 0,24 \text{ m (240 mm)} \quad (11)$$

$$Hf = \lambda \cdot \frac{L}{D} \cdot \frac{\rho \cdot v^2}{2} \text{ [Pa]} \quad (12)$$

Where:

-  $\lambda = 0.02$

-  $L = 10 \text{ m}$

-  $\rho = 1.2 \text{ kg/m}^3$

$$Hf = 0,02 \cdot \frac{10}{0,24} \cdot \frac{1,2 \cdot 12^2}{2} \approx 72 \text{ [Pa]} \quad (13)$$

**Pressure Loss:** ~100 Pa (including fittings).

**Fan Selection**

- **Flow Rate:** 2000 m<sup>3</sup>/h.

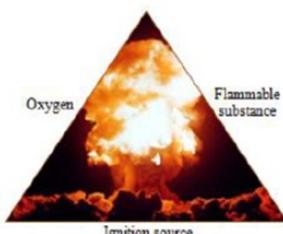
- **Pressure:** ≥100 Pa.

- **Recommended:** Centrifugal fan with Ex d IIB T4 certification.

## 4 Classification of hazardous areas in aluminum powder and paste production installations

Explosive atmospheres are defined as a mixture with air, under atmospheric conditions, of flammable substances in the form of flammable gases, mist vapors or combustible dusts, in which, after ignition, combustion is spread throughout the unburned mixture. To generate an explosive atmosphere, the flammable substance must be present in certain concentrations, between the Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL). Explosion limits of the substance may depend on pressure, oxygen concentration in the air and temperature. The mechanism of an explosion generated by a mixture of flammable gas, vapor or mist with air can be expressed by the well-known explosion triangle shown in Figure 3. Thus, the occurrence of an explosion is conditioned by the simultaneous presence of the following three factors, [8], [9]:

1. fuel (flammable gases, vapours, mists);
2. comburent (oxygen, oxidizing substances);
3. efficient ignition source for ensuring the activation of molecules in order to ignite and propagate the fast combustion reaction.

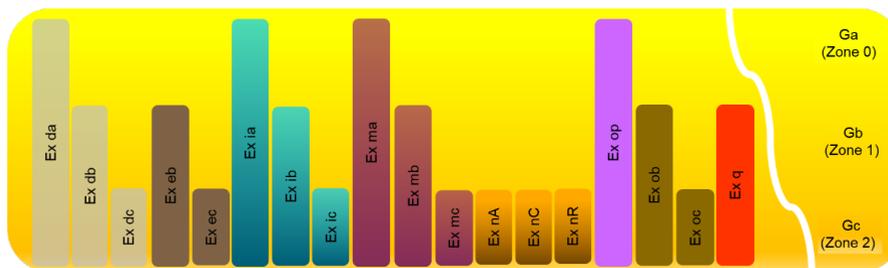


**Fig. 3.** The explosion triangle.

Ignition sources can be hot surfaces, sparks, short circuit, static energy, electric arcs, etc. Constructive solutions for the elimination of ignition sources are called protection types, Table 3, and the correlation between the types of protection and the hazardous zone is show in figure 4.

**Table 3.** Technical solutions and types of protection

Types of protection to explosion		Technical solution used
Symbol	Name	
Ex m	Encapsulation „m”	Separates electrical equipment or parts that are likely to cause explosive atmospheric ignition
Ex p	Pressurized enclosure „p”	
Ex q	Powder filling „q”	
Ex e	Increased safety „e”	Eliminates the ignition source
Ex n	Type of protection „n”	
Ex d	Flameproof enclosures „d”	Prevents the ignition from spreading throughout the mixture in hazardous area
Ex i	Intrinsic safety „i”	It limits electric energy in circuits



**Fig. 4.** The relationship between the types of protection and the hazardous zone.

A correlation of equipment category, classified areas and Equipment Protection Level (EPL) is summarized in Table 4.

**Table 4.** Correlation between the equipment category, the equipment EPL and corresponding area

EPL	Equipment group	Equipment Category (ATEX)	Zone
Ga	II	1G	0
Gb		2G	1
Gc		3G	2
Da	III	1D	20
Db		2D	21
Dc		3D	22

Considering these aspects and based on the data presented in the previous chapter, the equipment used and the corresponding types of protection must be properly selected and maintained in accordance with the applicable legislative standards regarding zoning, inspection, and maintenance of equipment.

## 5 Conclusions and recommendations

Due to the energy-intensive nature of the technological process, the following measures should be considered:

- **Toluene**, while efficient, requires strict safety measures due to high explosion risks.
- **White spirit** offers a balance between performance and safety.
- **Proper ventilation** (2000 m<sup>3</sup>/h) and ATEX-compliant equipment significantly reduce accident risks
- For the summer cooling system of the mills used in aluminum powder production, the motors operating these systems should be equipped with variable speed drives;
- Regarding the cooling of the installation, heat pumps should be used to reduce overall energy consumption;
- Due to the accumulation of aluminum dust, it is recommended to establish and strictly follow a cleaning schedule for all equipment used in the technological process;
- Given the solvents used in the technological process and the high temperatures generated, proper ventilation must be ensured in all technological areas where aluminum powders and paste are produced, stored, and packaged;
- Comparative studies are proposed with green solvents (e.g., limonene –  $C_{10}H_{16}$ ) in pigment production;
- Process optimization using nanomaterials to reduce solvent consumption.

Explosion prevention and explosion protection are of major importance for occupational health and safety, aiming to minimize both human and material losses.

This paper presents the mechanism of explosive atmosphere formation, the complex technological process, and appropriate equipment use solutions in accordance with the described application, with an emphasis on practical solutions and recommendations for the safe operation of the installation.

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