Physico-chemical analysis and characterization of the flammability of metallic powders

Andrei Szollosi-Moța [1*], *Vasilica Irina* Nălboc[1] and *Asimina Iuliana* Toplician[1]

[1]National Institute for Research & Development in Mine Safety and Protection to Explosion – INSEMEX Petrosani, 32-34 G-ral. V. Milea Street, 332047, Romania

Abstract. When fine particles known as flammable powders are suspended in the air under specific circumstances, they have the potential to explode. There could be many serious fatalities, injuries, and structural damage as a result of a dust explosion. By being aware of the flammability parameters and the physico-chemical analysis for flammable powders and taking additional protective measures as a result of the occurrence of these kinds of catastrophic mixes, the risk of such incidents can be decreased. The goal of this study was to determine the flammability characteristics of two combustible powders, magnesium and aluminum powder. These characteristics included the lowest ignition temperature of the dust cloud and dust layer as well as certain physicochemical studies of the composition.

1 Introduction

Magnesium is the third most used metal in structural applications after iron and aluminum. Magnesium ignites at a temperature close to its melting point. In wire or powder form it burns when ignited in air giving rise to abundant smoke [1].

The structural and electronic characteristics specific to metals are due to the fact that the atoms are linked together by valence bands that are distributed over energy bands and no longer belong to each individual atom [2]. Magnesium particles produced during grinding operations and lightly moistened with water can generate enough heat to self-ignite and burn violently as the water breaks down into oxygen and hydrogen [3].

Reaction of flammable powders with oxygen:

$$\textit{Flammable powders} + \textit{Oxygen} = \textit{Oxides} + Q\ (\textit{heat}) \tag{1}$$

Ignited in air magnesium burns with a bright flame as it becomes incandescent due to the high heat of reaction. Aluminum is the most abundant metal in nature and the third element in the order of distribution of the elements. It is a silver-white metal, light compared to other metals such as iron. Heated to temperatures of about 700°C, powdered aluminum burns with a bright light.

* Corresponding author: andrei.szollosi@insemex.ro

Oxygen and magnesium combine in a chemical reaction to form this compound [4]. After burning, it forms a white powder of magnesium oxide. It is a strongly exothermic reaction with heat release of heat.

$$2Mg(s) + O2(g) \rightarrow \ 2MgO(s) + energy \tag{2}$$

Magnesium is also capable of reducing water to highly flammable hydrogen gas, which will be ignited by the excess heat given off by the reduction reaction.

$$Mg(s) + 2H2O \rightarrow \ Mg(OH)2(s) + H2\uparrow(g) \tag{3}$$

Magnesium also reacts with carbon dioxide to form magnesium oxide and carbon:

$$Mg(s) + CO2 \rightarrow \ 2MgO(s) + C(s) \tag{4}$$

Aluminum in reaction with oxygen forms aluminum oxide:

$$4Al + 3O2 = 2Al2O3 \ \Delta H = -1692 \ kJ/mol \tag{5}$$

The amount of heat released in this reaction is important. Due to its affinity, aluminum reacts with iron oxide, a reaction that is the basis of aluminothermy. This reaction is quite energetic, raising the temperature to over 2000°C.

If a mixture of aluminum powder and iron III oxide is ignited, the chemical reaction that takes place is as follows.

$$2Al + Fe2O3 = Al2O3 + 2 \ Fe + Q \tag{6}$$

The chemical combination of aluminum powder with oxygen gives rise to a strongly exothermic reaction.

The greater the contact surface of the air with the combustible materials, the easier the ignition. If non-combustible materials are divided into fine particles, they can become combustible, combustion sometimes occurs with explosion. The ignition mechanism and the combustion process can have the following explanation.

Aluminum reacts with water according to the reaction [5].

$$2Al + 6H2O = 2Al \ (OH)3 + 3H2\uparrow \tag{7}$$

Hydrogen in combination with oxygen in the air forms a detonating mixture.

The calorific value of aluminum powder is 7000 Kcal/kg, if exceeded. Metal powder collected during the processing of aluminum and magnesium materials or other combustible metal powders must be collected, as they are flammable.

$$Mg(s) + CO2 \rightarrow \ 2MgO(s) + C(s) \tag{8}$$

Oxygen and magnesium combine in a chemical reaction to form this compound. After burning, it forms a white powder of magnesium oxide. Magnesium gives up two electrons to oxygen atoms to form this powder product [6].

Fine aluminum powder is electrically charged and may cause fires due to electrostatic charging.

The following main groups of materials can cause a dust explosion:

- Metal powders and alloys (aluminum, magnesium, zinc, iron, titanium, etc.);
- Natural organic materials (cereal flour, wood, sugar, etc.);
- Synthetic organic substances (powders of plastic materials, organic pigments, pesticides, medicines, etc.)
- Coal and peat [7];

- Metal powders and alloys (aluminum, magnesium, titanium, zinc, iron, nickel, etc.).

Due to the high explosion severity of magnesium dust, explosion avoidance is the only practicable solution [8]. One of several important components in developing dust explosion prevention methods is MIT-DC. The GG furnace (one version is 216 mm long, while another has twice that length), the BAM-oven, a 1.2 L furnace, and a 6.8 L furnace can all be used to measure this parameter [9]. IEC rules in use today, however, advise using the GG furnace for MIT-DC determination [10]. As particle size dropped in the micro-small range in earlier investigations [11] utilizing a GG furnace to determine the MIT-DC of individual magnesium specimens, comparable results were found in trials with magnesium powder produced during the shredding of post-consumer waste in Japan. Chunmiao et al. (2013) measured the minimum ignition temperature (MIT) of magnesium powder layers for four different particle sizes: 6, 47, 104, and 173 m. While taking the melting and boiling of magnesium powder into account, a model was created to describe temperature distribution and how it changes over time. According to parameter study, MIT increased from 710 to 760 K as particle size increased from 6 to 173 m, but MIT reduced as dust layer thickness increased. The fact that the calculation took more than 5000 seconds to complete had little effect on MIT. The MIT of magnesium powder layers at different particle sizes demonstrated satisfactory agreement when comparing anticipated and experimental results [12].

2 Materials and methods

2.1. Determination of the minimum cloud ignition temperature of aluminum and magnesium powder

The minimum ignition temperature of magnesium powder clouds and aluminum scrap were tested in a Godbert Greenwald furnace. The stand used for testing includes a heating furnace, control system, compressed air storage tank, valve, powder storage enclosure, ignition observation mirror.

The furnace can maintain the temperature between 25-1000°C, the working method involves weighing a certain amount of powder, setting the temperature of the vertical furnace, pneumatically injecting the powder at high speed to create a dust cloud, determining the ignition and this is done visually. Clouds of metal powder obtained by swirling metal powders of aluminum and magnesium are inflammable.

The Godberg-Greenwald type furnace is a vertical furnace, having the bottom open to the bottom. The horizontal tube is connected to the powder sample dispensed by a glass observation chamber.

The powder to be tested is transferred from the sample into the furnace using compressed air. Dust ignition occurs when a flame is observed on the underside of the device, which is visible in the mirror below. The temperature is measured by two thermocouples connected to the Godberg-Greenwald furnace.

With the help of a balance, the necessary amounts of powder are weighed. By means of the pneumatic system, the powder is swirled and the powder particles come into contact with the hot furnace.

For the samples analyzed for this work the granulation was lower than 63 μm for both of the combustible powders.

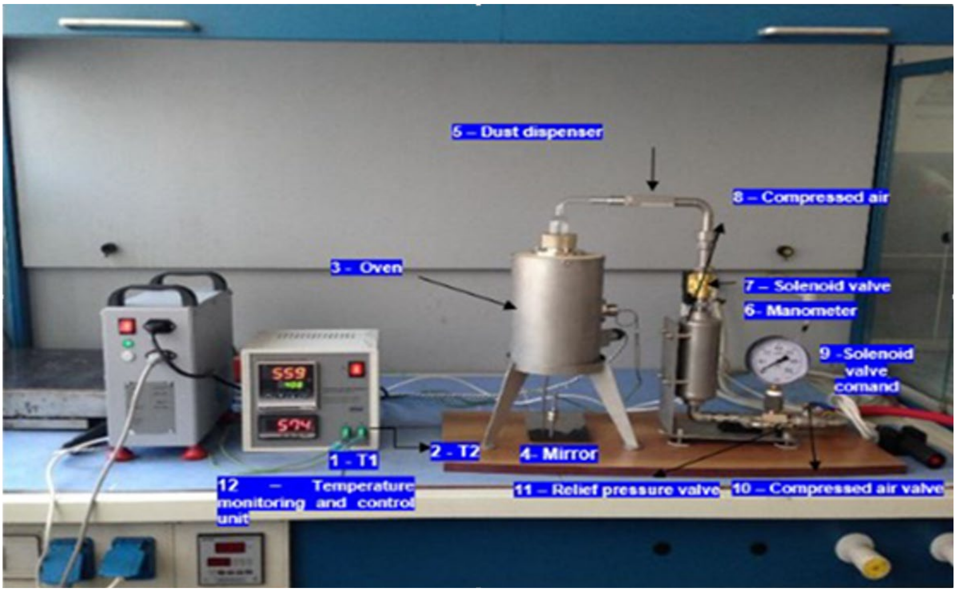

Fig. 1. Stand for determining the minimum ignition temperature of the dust cloud

2.2. Determination of the minimum ignition temperature of the dust layer

To determine the minimum temperature of a hot surface capable of igniting a layer of powder (5 mm thick).

The ignition of layer dust can be recognized when:

a) Glowing or flaming burning was observed or;
b) The measured temperature of the dust reached 450°C;
c) The measured temperature of the dust exceeded 250 K.

Fig. 2. Stand for determining the minimum ignition temperature of the dust cloud

During the test, the layer of flammable powder is placed in a metal ring with an inner diameter of 100 mm in a layer of 5±0.1 mm thickness. The temperature of the heated surface is set to the desired value.

2.3. FTIR Analysis of aluminum waste

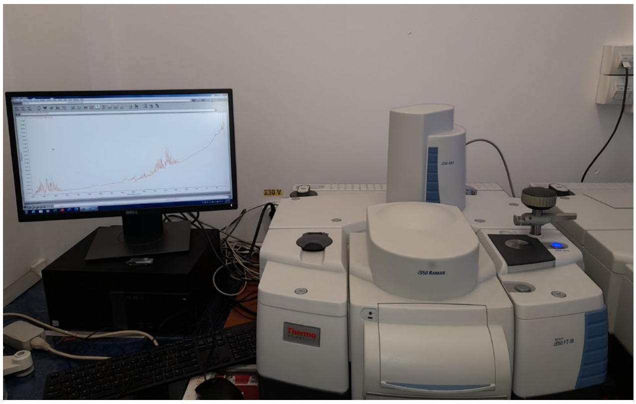

Fig. 3. FTIR spectrometer

The equipment used for the determination of the composition was Nicolet IS 50 Thermo-Scientific spectrometer (Figure 3) with the range 4000 – 400 cm^{-1}, and accuracy of 4 cm^{-1} ATR analysis method is a very useful method, which does not actually require a sample preparation, whether we are talking about a powder, film or even a smooth surface of the finished object. The analysis is no longer done by passing the IR beam through the sample, but by its reflection on the surface of the sample, the beam penetrating inside the sample approximately 1µm. The beam is directed to the window by means of an optical mirror system.

3 Results and discussion

Analyzing the spectrum obtained, it can be concluded that the material in the form of waste includes other substances such as water and organic substances such as amines, ammonia or alcohols (figure 4).

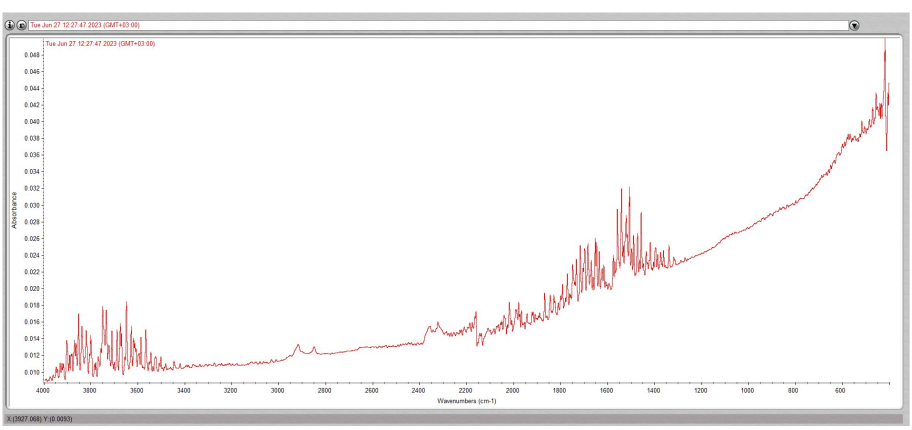

Fig. 4. ATR-FTIR spectra of aluminum waste

The results obtained for determining the minimum ignition temperature for metal powders can be found in Table 1.

Table 1.

Minimum ignition temperature of magnesium dust cloud	Minimum ignition temperature of aluminum waste dust cloud
550°C	470°C

Table 2.

Minimum ignition temperature of magnesium dust layer	Minimum ignition temperature of aluminum waste dust layer
More than 400°C	More than 400°C

The minimum ignition temperature for magnesium dust layer and aluminum waste dust layer was, accordingly with the condition in the working standard more than 400°C.

The most important factor is the chemical composition of the dust itself. During a dust explosion, the dust burns and combustion products are formed.

Defining parameters are:

- Granulation and particle size distribution: finer granules have a larger specific surface, the degree of contact with oxygen is greater and thus the risk of ignition and explosion is greater. As the grain diameter decreases, the flash point gradually decreases. The intensity of the dust explosion depends on the maximum pressure of the explosive gas (p_{max}) developed in the enclosed space, the explosion from the maximum rate of increase in pressure $(dp/dt)_{max}$ [13, 14].
- In addition to the explosive properties of the powders, the composition of the particles must be examined, a size of dust particles with flammable properties.
- Dust concentration: The moisture that the dust normally absorbs from the air increases the flash point of the powder, thus inertization is achieved, but in the case of magnesium or aluminum, extinguishing the ignited dust is not achieved with water due to the reaction when hydrogen is released [15, 16].

The results obtained for the magnesium dust showed a good correlation with the literature data.

4 Conclusions

The explosion of dust-air mixtures depends on:

- Chemical composition of the dust (powder);
- Dust concentration (minimum and maximum dust ignition concentration having particular significance);
- The degree of dispersion of the dust particles;
- Environmental conditions: temperature, humidity.

Among the dusts with the greatest risk of explosion, we mention: metal powders (magnesium, aluminum, titanium, zinc).

The minimum ignition temperature is also a key characteristic of powders and for explosion risk characterization.

The minimum temperature at which dust clouds ignite is considered to be very important in industries where explosions and fires may occur due to contact with hot surfaces.

The minimum ignition temperature is the lowest surface temperature capable of igniting a powder or dust dispersed in the form of a dust cloud. This is relevant for defining the maximum operating temperature of electrical equipment and mechanical equipment used in dusty environments.

Some metal powders are capable of self-ignition (self-ignition) and obviously, knowing the lowest temperature is important.

Again, reducing the particle size will increase the reactivity of the powder and consequently lower the minimum ignition temperature.

For the magnesium dust was obtained experimentally a temperature of 550°C for minimum ignition temperature of dust cloud and 470°C for minimum ignition temperature of dust layer, values that are well fitted with the literature data.

This work was carried out through the ”Nucleu” Program within the National Plan for Research, Development and Innovation 2022-2027, with the support of the Romanian Ministry of Research, Innovation and Digitalization, project no PN-23 32 02 01, title: Development of the knowledge level of the explosion parameters of gaseous and hybrid mixtures based on hydrogen, involved in the processes of obtaining and storage in order to reduce the explosion risk.

References

1. Yuan Chunmiao, Huang Dezheng, Li Chang, Li Gang, Journal of Hazardous Materials Issue 246-247 283-290 (2013)
2. Vignes A, Krietsch A, Dufaud O, Santandréa A, Perrin L, Bouillard J. of Hazard Mater. 2019 Nov 5; **379**:120767. doi: 10.1016/j.jhazmat.2019.120767. PMID: 31276924 (2019)
3. Jack Grubbs, Bryer C. Sousa, Danielle, **12**(4), 603 https://doi.org/10.3390/met12040603 Metals 2022, 12(4), 603 (2022)
4. I. Apostu, F. Faur, Research Journal of Agricultural Science, 50, **4** (2018)
5. Edith Beral, Mihai Zapan - *Chimie anorganica,* (Ed. Tehnica, Bucuresti, 1977)
6. M. Darie, T. Csaszar, S Burian, L. Moldovan, C. Colda, 22th International Multidisciplinary Scientific GeoConference SGEM 2022, **22**, Iss.1.1, DOI:10.5593/sgem2022/1.1/s06.077 *Small component ignition tests uncertainity estimation* (Albena, Bulgaria 2022)
7. G. A. Gaman, C. Lupu, G. D. Pupazan -*Proceduri și regulamente ale formațiilor de intervenție și exploatare în medii toxice/explozive/inflamabile*, ISBN 978-973-88753-6-4 (Ed. INSEMEX 2009)
8. G. Li, C.M. Yuan, Y. Fu, Y.P. Zhong, B.Z. Chen, Inerting of magnesium dust cloud with Ar, N2 and CO2, J. Hazard. Mater. 170 (2009) 180–183.
9. U. Krause, M. Wappler, S. Radzewitz, F. Ferrero, On the minimum ignition temperature of dust clouds, in: Proceedings of Sixth International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosion, vol. I, Dalhousie University, Halifax, NS, Canada, August 27–September **1**, 2006, pp. 68–76.
10. IEC 61241-2-1-1994, Methods for Determining the Minimum Ignition Temperatures of Dust. Part 2: Dust Cloud in a Furnace at a Constant Temperature, Central Office of International Electrotechnical Commission, Geneva, Switzerland, 1994, pp. 11–27.
11. G.K. Ezhovskii, E.S. Ozerov, Y.V. Roshchenya, Critical conditions for the ignition of gas suspensions of magnesium and zirconium powders, Fiz. Goren. Vzryva**. 15** (1979) 97–102.
12. Chunmiao Y, Dezheng H, Chang L, Gang L. Ignition behavior of magnesium powder layers on a plate heated at constant temperature. J Hazard Mater. 2013 Feb **15;**246-247:283-90. doi: 10.1016/j.jhazmat.2012.12.038. Epub 2012 Dec 28. PMID: 23314397.
13. G.D., Florea, N.I Vlasin, E. Ghicioi, A.B. Simon-Marinica A.B., Z. Vass, *Virtual simulation of initiating explosive atmospheres due to methane leakes*, International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM, ISSN: 1314-2704, Issue: 2.1, Page: 411-418, **20**, 10.5593/sgem2020/2.1/s07.05 (Albena Bulgaria 2020)

14. I. Nalboc, C. Lupu, M. Prodan, A. Szollosi-Mota, A. Jurca, 11th International Conference "Environmental Legislation, Safety Engineering and Disaster Management" Book of Abstracts ISBN 978-606-93873-1-3 *Experimental determination of explosion characteristics for aluminum powder derived from technological processes* (Cluj-Napoca, Romania 2016)
15. L. Kenneth Cashdollar -Journal of Loss Prevention, **13**, page: 183 -199, (2000)
16. J.M. Benson -The Journal of Southern African Institute of Mining and Metallurgy, **7A**, ISSN 2225-6253 (2012)