Explosion Hazards of Aluminum Finishing Operations

Jérôme Taveau [a,b], Simone Hochgreb [c], Saul Lemkowitz [d], Dirk Roekaerts [b,e]

[a] Fike Corporation, Blue Springs, MO, USA
[b] Section Fluid Mechanics, Department of Process and Energy, Delft University of Technology, Delft, The Netherlands
[c] Department of Engineering, University of Cambridge, England, United Kingdom
[d] Department of Chemical Engineering, Delft University of Technology, Delft, The Netherlands
[e] Section Multiphase & Reactive Flows, Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands

Abstract

Metal dust deflagrations have become increasingly common in recent years. They are also more devastating than deflagrations involving organic materials, owing to metals' higher heat of combustion, rate of pressure rise, explosion pressure and flame temperature.

Aluminum finishing operations offer a particularly significant hazard from the very small and reactive aluminum particles generated, and thus require high attention to details of operation and explosion safety management.

This paper presents available statistics on metal dust explosions and studies the specific explosion hazards of aluminum finishing operations. The analysis of seven case studies shows that the proper design, monitoring and maintenance of dust collection systems are particularly important. Furthermore, the isolation of deflagrations occurring in dust collection systems, as well as good housekeeping practices in buildings, are critical safeguards to avoid the occurrence of catastrophic secondary explosions.

Keywords: dust; deflagration; accidents; metals; aluminum; finishing operations

Email: jerome.taveau@fike.com

Nomenclature:
ΔH_c heat of combustion (kJ/mole O_2)
K_{St} deflagration index (bar.m/s)
MAP   mono ammonium phosphate
MEC   minimum explosible concentration (g/m^3)
MIE   minimum ignition energy (mJ)
MIT   minimum ignition temperature (°C)
P_{max} maximum explosion pressure (barg)
P_{red} reduced explosion pressure (barg)
SBC   sodium bicarbonate
T_f flame temperature (°C)

1. Introduction

Dust explosions have been a hazard for as long as mankind has been processing, storing and transporting bulk materials and powders.

Most of the reported accidents in the past have involved organic products, mainly because most of the combustible materials in commerce are organic, but this trend is changing due to the increased use of metals in the automotive, electronics and emerging 3D-printing industries. Furthermore, metals also enter into the composition of plastics, rubber, fibers, paints, coatings, inks, pesticides, detergents, and even drugs; they are used for the catalysis of major chemical reactions (Grignard, Claus, Haber and Fisher-Tropsch), and are being explored as a possible clean alternative to fossil fuels.

Among metals, aluminum has been involved in a considerable number of severe explosions in recent years. Indeed, aluminum is commonly used in the industry, as well as extremely sensitive to ignition sources and reactive if finely divided. This poses important challenges to conventional explosion prevention and protection methods.

The present paper analyzes seven particular accidents that occurred in aluminum finishing facilities (Table 1) and presents some lessons learned and recommendations.

Table 1. Accidents involving aluminum polishing operations analyzed in this article. All involved propagation of an initial deflagration into the dust collection ducting and back into the work area.

Case study	Country/Year	Ignition	Fatalities	Injuries
1	USA (1920)	Mechanical impact	6	Numerous
2	Europe (2005)	Mechanical impact	8	
3	USA (1987)	Unknown		6
4	Italy (1999)	Self-heating	1	2
5	Italy (2000)	Mechanical impact		3
6	USA (2003)	Unknown	1	6
7	China (2014)	Self-heating	146	114

2. Statistics of metal dust explosions

Metal dust deflagrations have become increasingly common, and have led to severe accidents in recent years. Yet statistics on dust explosions are difficult to obtain since plants do not disclose accidents to the public, unless a major event has occurred.

Following several major dust explosions, the Chemical Safety Board (CSB) published a dedicated study in 2006: 281 dust explosions were reported between 1980 and 2005 in the USA, killing 119 workers and injuring 718 (Chemical Safety Board, 2006). Metal dusts were involved in 20% of these accidents.

Moreover, the last three out of four CSB combustible dusts investigations were related to metal dusts (Chemical Safety Board, 2005, 2012 & 2014):

- 2003: Huntington, Indiana (aluminum, 1 fatality, 6 injured),
- 2010: New Cumberland, West Virginia (titanium, zirconium, 3 fatalities, 1 injured),
- 2011: Gallatin, Tennessee (iron and hydrogen, 1 fatality, 7 injured).

According to the Center for Chemical Process Safety (2005), FM Global identified 19 explosions involving metal dusts between 1985 and 1995, representing 13% of all accidents (Febo, 2001).

Metal dust deflagrations have also been regularly reported in Europe, Japan, and more recently China:

- Thirteen percent of explosions involved metal dusts in Germany for the 1965-1980 period (Beck & Jeske, 1982; Eckhoff and Alfert, 1988). Statistics also show that the average number of both injuries and fatalities were comparatively high for the metal dust explosions, primarily involving aluminum. About 65% of the metal dust explosions occurred in dust extraction and grinding systems. A significant fraction, about 15%, also occurred in mills, mixers and sieving machines. Of these, 60% were initiated by mechanical sparks. According to a later study (Jeske and Beck, 1987), 44.1% of metal dust explosions occurred in dust collecting units, where the main ignition sources were mechanical friction or sparks, corresponding to 49.4% of the investigated cases. Six aluminum dust explosions occurred between 1981 and 1985, with 6 injuries and no fatality,
- In the United Kingdom, a total of 18% of explosions involved metal dusts for the 1979-1988 period (Lunn, 1992),
- In Japan, 24% of explosions involved metal dusts, causing as much as 27% of injuries and 39% of the fatalities for the 1952-1995 period (Nifuku et al. 2000). Matsuda (1993) reported a sharp increase in accidents involving metal dusts between the periods 1971-1980 (23.6%) and 1981-1990 (42.9%). He concludes that a large number of dust explosions in Japan were caused by metal dusts, especially aluminum and its alloys, which are the most common material involved,
- Similarly, seven explosions involving metal dusts have been reported by Yan & Yu (2012) in China during the period 2009-2011 alone, five of them involving aluminum, with a total of 11 fatalities and 54 injuries. Other metal dust explosions in China have been reported by other sources (2009: Wuxi, Jiangsu, polishing; 2010: Wenzhou, Zhejiang, motorcycle/car accessories polishing; 2011: Lishui, Zhejiang, car polishing; 2011: Chengdu, computer polishing (aluminum); 2011: Wenzhou, Zhejiang, polishing (2 events); 2011: Shanghai, computer polishing (aluminum); 2012: Wenzhou, Zhejiang, lockset polishing; 2012: Shenzhen, Guangdong, metal products polishing). Most events have involved polishing of aluminum parts. In 2016, two explosions involving aluminum dust occurred in Shenzhen, Guangdong, in a bike accessories polishing facility, and in Jiangmen, Guangdong, in a cookware manufacturing facility.

Figure 1 summarizes the evolution of the number of metal dust explosions in the USA, along with the more recent cases reported in China.
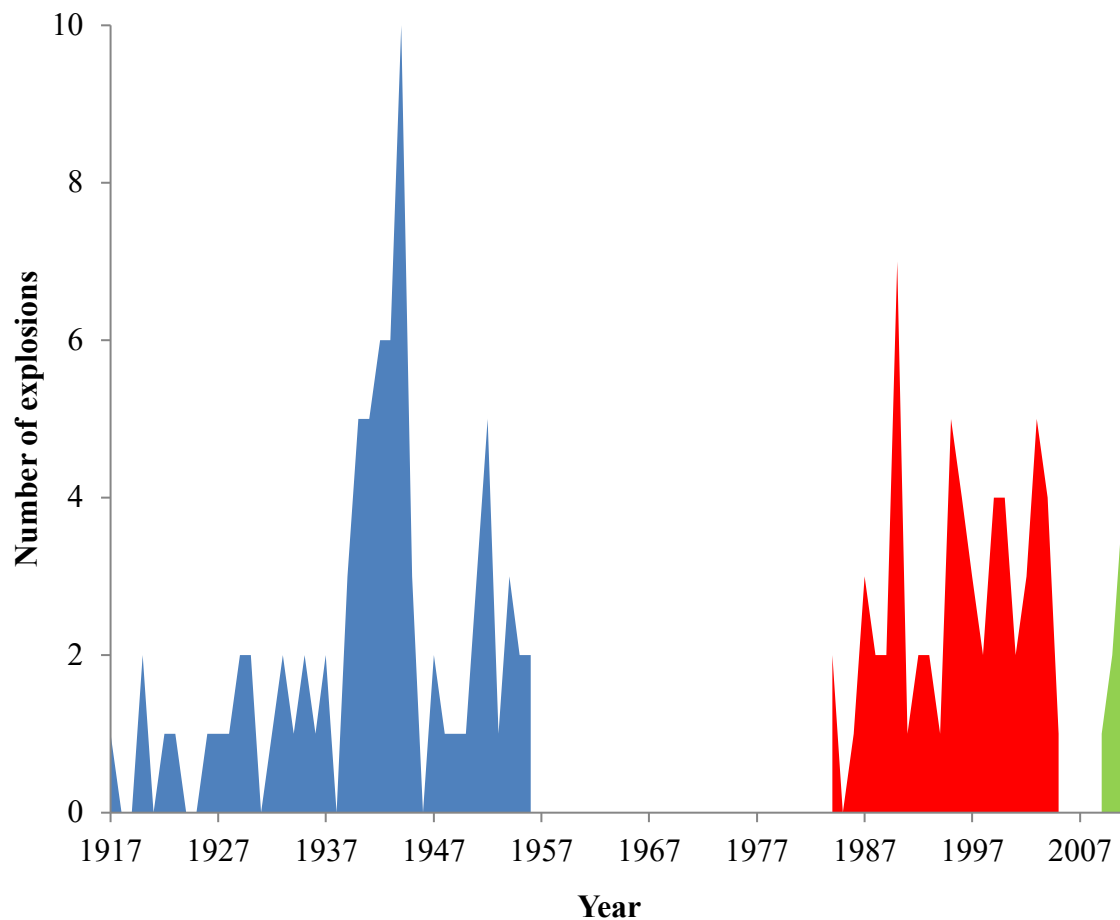

Figure 1. Occurrence of metal dust explosions according to NFPA (1917-1956) in blue, CSB (1984-2005) in red, and Yan & Yu (2009-2011) in green

The occurrence of metal dust explosions is clearly directly related to the manufacturing activity, as exemplified by the high number of metal dust explosions during the World War II period.

3. Case studies

3.1 Case study 1 (USA)

One of the first documented aluminum dust deflagration was reported by Price and Brown (1922) in the USA. The accident took place in the polishing workshop of a manufacturing plant located in Manitowoc, Wisconsin, on February 26th, 1920. Aluminum dust was drawn away from the polishers into a suction system which discharged into the open air. A heavy piece of steel wire fell into the exhaust pipe and struck the fan, striking sparks which ignited the dust. The explosion propagated back through the suction system and into the room (Figure 2), causing an explosion which was so violent that it was heard at least two miles from the plant, killing six operators.

An explosion of aluminum dust in a plant at Manitowoc, Wis., on February 26, 1920, resulted in the death of 6 girls and injuries to a number of others. Note, extending from the fan exhaust at right of picture, a piece of heavy wire that in some unknown manner was introduced into the fan thereby producing the necessary spark to ignite the aluminum dust. The girl operators were occupying the chairs at the work bench shown in the picture.

Figure 2. Picture of the manufacturing plant located in Manitowoc, Wisconsin (Price & Brown, 1922) showing the work stations

3.2 Case study 2 (Europe)

A very similar case to the Manitowoc explosion that happened many years after is discussed in a booklet published by the International Social Security Association (ISSA, 2005). The explosion took place in a facility where finishing work of cast aluminum parts was ongoing (Figure 3). The working stations were all equipped with a central dust collection connected to an extraction fan and a water-filled dust separator placed outside the building. Ignition was initiated by the shock of an air flap falling into the fan, causing an initial explosion in the ducting. The explosion propagated within the recirculating air ducting, which blew and ignited dust into the grinding room, and killed all eight workers. The grinding building was completely destroyed. The recommendations in the ISSA booklet highlighted the importance of avoiding a recirculating air system, unless the ducting is equipped with an explosion isolation system that can prevent the flame from propagating back to the building in case of an explosion.
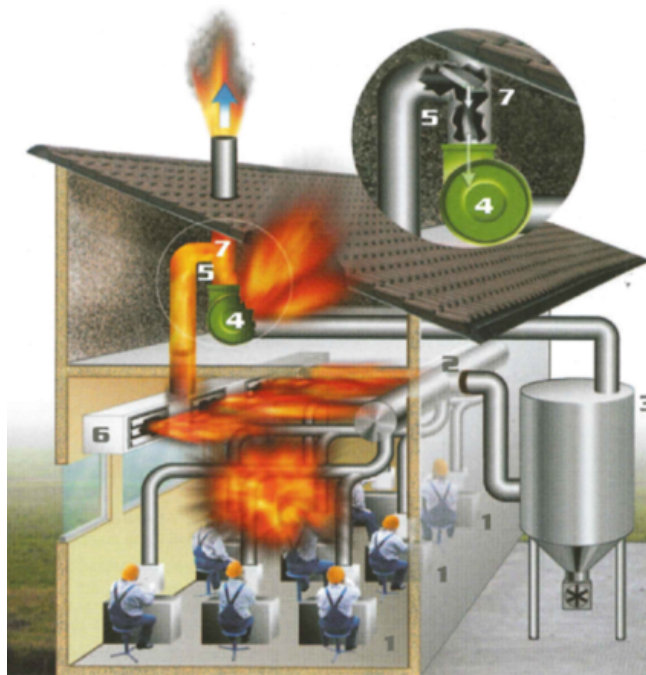
Figure 3: Aluminum dust explosion in a grinding room (ISSA, 2005)

3.3 Case study 3 (USA)

May and Berard (1987) report the case of a company manufacturing molding strips that experienced three accidents. Automated brushing and buffing machines were used to finish the extruded aluminum strips. After the two first incidents, the company decided to relocate the two dust collectors associated with the brushing operation to a dedicated room separated from the work area by a concrete block wall. The cyclone-filter bag units discharged into this room and the concrete block wall had openings to allow cleaned air to be recirculated back into the work area. At the opposite side of the dust collection room was a wall intended to blowout in case of a dust explosion. Approximately 60 feet of duct connected six brushing machines to each of the two collectors. Six workers were hospitalized when one of the brushing dust collectors exploded. The explosion blew out the weak wall, shifted the top row of concrete blocks in the dust collector room, and propagated back through the collection system where it knocked duct work to the floor and injured the six workers. Although exact cause of the ignition remains unknown, examination of a parallel duct which was connected to the same machines was found to contain l to 3 inches of dust build-up within its length, indicating insufficient transport velocity.

3.4 Case studies 4 and 5 (Italy)

Cavallero et al. (2004) report two aluminum dust explosions that occurred in two small surface finishing processes:
- The first accident (1999) occurred in a factory that performed polishing of coffee percolators using three multi-stage machines. Each machine had eight working stations (each one connected to a dust collector) where corundum belts of various grain sizes were used to polish the artefacts. Three ducts collected the powder from the three machines to

convey it to an abatement plant, using a wet type scrubber. The explosion took place while two machines where working and one was being cleaned by a worker. The blast destroyed the suction plant, the whole building and the wet abatement plant which was located outside, including the roof and the structure of the building, resulting in one death and two injuries. According to the investigators, the decrease in the water level inside the scrubber resulted in a lowering of the abatement efficiency. Wet dust stuck to the demister, the pressure drop increased, the speed of the air inside the ducts decreased and some powder settled and then exploded, perhaps due to overheating of the wet powder which attached to the demister, or due to the ignition of the powder settled inside the ducts during the cleaning operations,

- A second accident (2000) took place in a small factory in the North-West of Italy (Marmo et al., 2015) where polishing and other surface finishing operations were routinely conducted on aluminum coffee pots using sixteen grinding machines. The dust was captured through sixteen drawholes and sent to a cyclone followed by a bag filter. The filter was equipped with four overpressure relief panels hinged to their upper parts, which were weighed down with four metallic 1.2 kg plates. The explosion destroyed the equipment and threw ejected equipment beyond 60 m. Three workers were slightly injured. The first deflagration happened inside one of the grinding machines and was caused by the breakage of one belt. Sparks and burning particles were aspired by the abatement plant, causing the aluminum dust to ignite in the lower part of the cyclone, giving rise to the first major explosion. The cyclone collapsed and the pipes connected to the machines broke, releasing aluminum dust in the work areas. The flame front propagated to the bag filter, causing a second more violent explosion. Figures 4 shows the bag filter before and after the event.

Figure 4a. Bagfilter before the aluminum dust explosion (Marmo et al., 2015)

Figures 4b and 4c. Bagfilter before after the aluminum dust explosion (Marmo et al., 2015)

Further details regarding these accidents can be found in (Lembo et al., 2001) and (Marmo et al., 2015).

Lembo et al. (2001) report that during the period 1990-2000, 6 explosions occurred among the 27 aluminum dust finishing facilities in Northern Italy, resulting in two fatalities and sixteen injuries.

3.5 Case study 6 (USA)

On October 29th, 2003, a deflagration started in the dust collector of a cast aluminum automotive wheels manufacturing plant located in Huntington, Indiana, and propagated to a drop box, interconnected pipes and finally to the plant (Figure 5). The deflagration caused major damage to the dust collector: the vent panels and three maintenance doors were blown open, the top section of the housing was dislodged and the cleanout section was distorted. According to the Chemical Safety Board (2005) which investigated the accident, this damage shows that the venting was not sufficient to prevent structural damage to the dust collector caused by the overpressure generated in this accident. The drop box, on the other hand, failed and fractured into several large pieces (Figures 6).
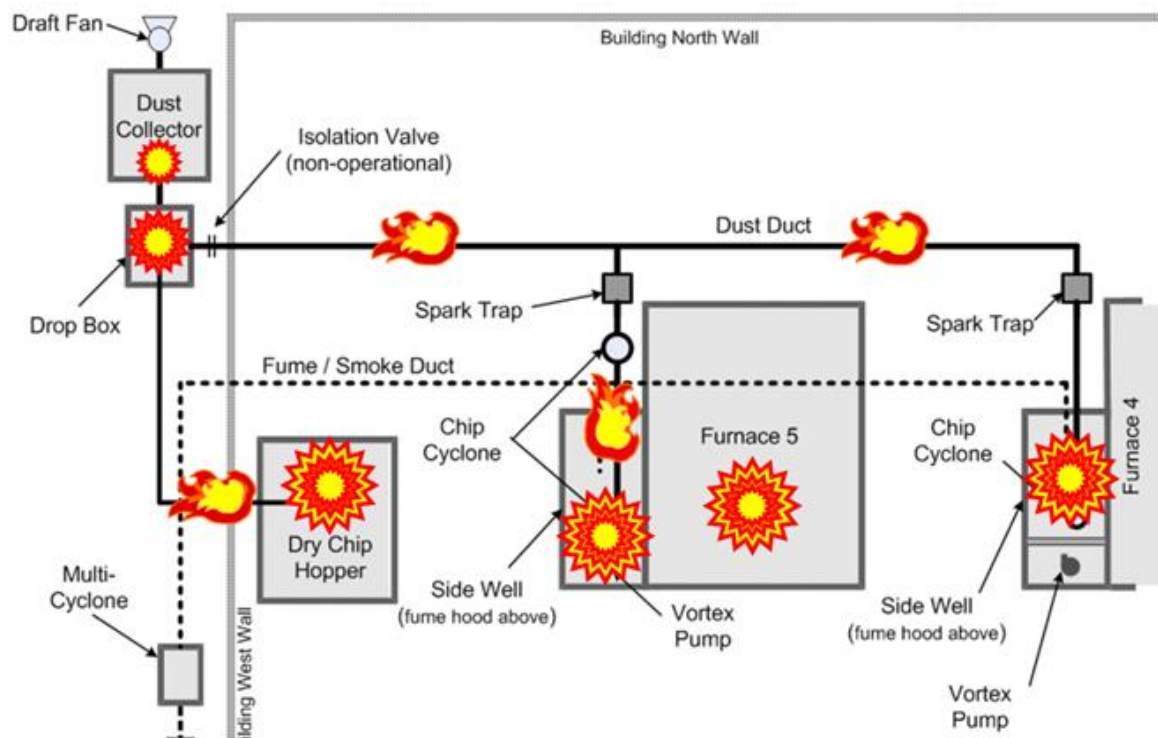
Figure 5: Assumed sequence of events (from top left): ignition in the dust collector, larger explosion in the drop box and propagation to other process areas (adapted from the Chemical Safety Board, 2005)

Figure 6a. Damage to the dust collector (Chemical Safety Board, 2005)

Figure 6b. Damage to the drop box (Chemical Safety Board, 2005)

Figure 6c. Damage to the interior of the facility (Chemical Safety Board, 2005)

Some dust was sampled from the top of an electrical enclosure, yielding a deflagration index K_{St} = 131 bar.m/s, which is a moderate value for aluminum. It was not possible to determine the source of ignition, but investigators found some signs of poor maintenance of the dust collection system. An isolation gate valve was installed in the 20-inch line outside the building, close to the drop box (Figure 5). However the valve actuator had been disconnected because of operational problems and employees were not aware that this valve was intended to isolate the pipe in case of a dust deflagration.

3.6 Case study 7 (China)

On August 2nd, 2014, an aluminum dust deflagration took place in an automotive parts factory of Jiangsu province, killing 146 people and injuring 114 people (Li et al., 2016). The explosion was heard several kilometers away, and shattered glass up to 500 meters away (Figures 7).
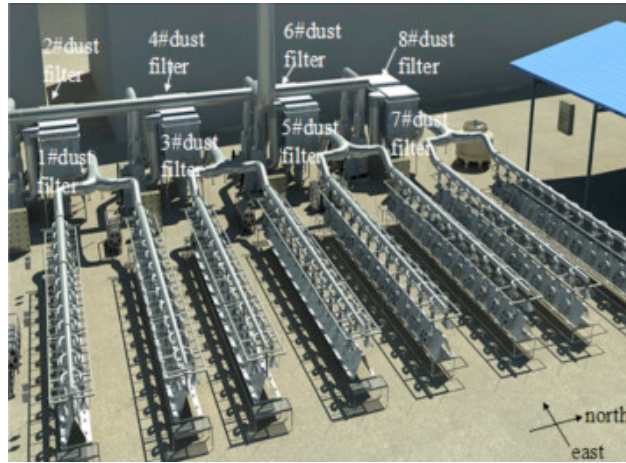
Figure 7a: Production lines with work stations (Li et al., 2016)
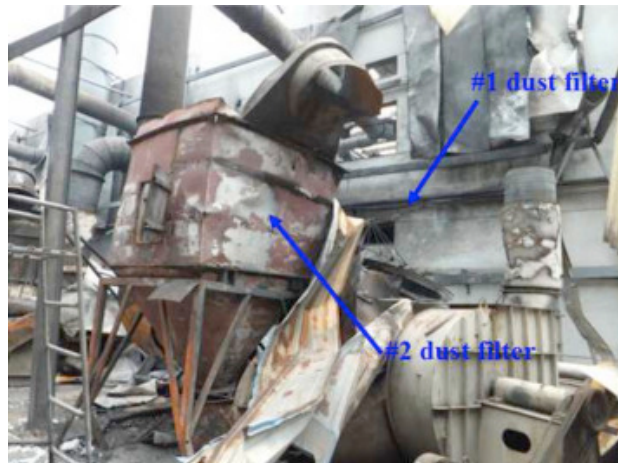

Figure 7b: Damage to the dust collectors (Li et al., 2016)

Figure 7c: Damage to the production lines and work stations (Li et al., 2016)

Figure 7d: Damage to the eastern wall of the main building (Li et al., 2016)

The investigation concluded that the primary deflagration started in a dust collector located outside, which then propagated into the main building via the dust extraction system. Ignition was determined to be the self-heating of aluminum dust in a collecting barrel below one of the dust collectors. Some dust samples were collected across the facility. The results of tests using the collected powders are given in Table 2. The authors underline that the presence of explosion isolation systems in the ducting would have limited the consequences of the deflagration substantially. They also point out the difficulties of isolating deflagrations involving highly reactive dusts, especially when dust collectors and work rooms are separated by short distances.

Table 2. Ignitability and explosibility parameters of the collected powders (Li et al., 2016).

MEC (g/m^3)	MIE (mJ)	MIT (°C)	K$_{St}$ (bar.m/s)	P$_{max}$ (barg)
40	7-11	540	250	11

4. Lessons learned and recommendations

The case studies reviewed in the previous paragraph clearly illustrate the severe explosion risk presented by systems used to collect fines from aluminum finishing and polishing operations, and thus for the following reasons:

- finishing and polishing operations generate very fine particles,
- dust collectors inherently concentrate the smaller particles and employ pulse jet cleaning, which periodically generate dust clouds and thus a dust explosion hazard in presence of an ignition source;
- both ignition likelihood and explosion severity sharply increase as aluminum particle size decreases. As an example, Figure 8 introduces 2 different sets of experiments showing the effect of decreasing aluminum particle size on the deflagration index K_{St}.
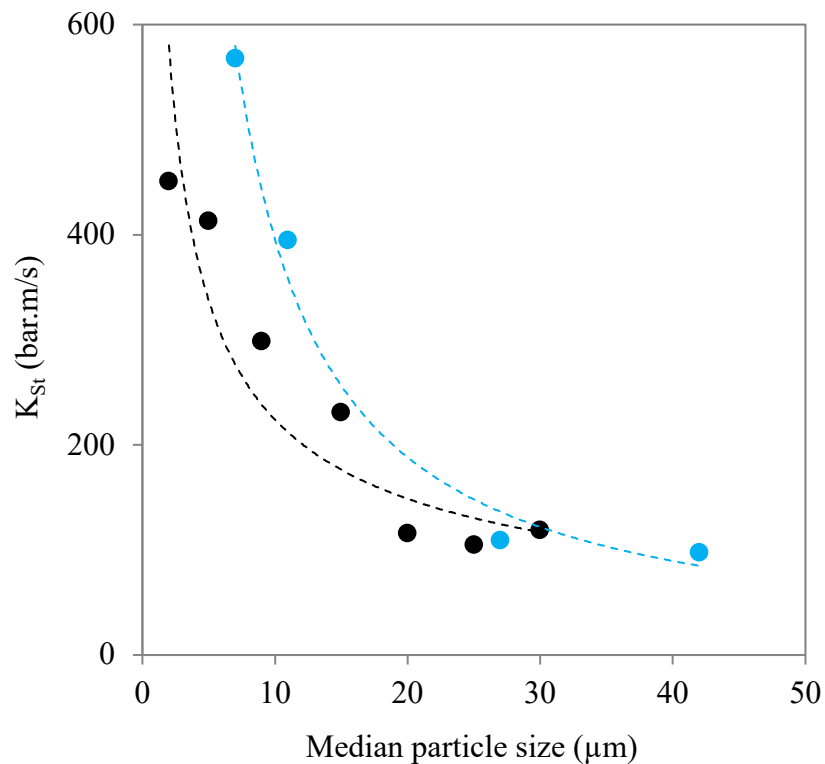

Figure 8: Evolution of the deflagration index K_{St} with particle size for micrometric aluminum dust (0-50 microns) according to Dufaud et al. (20-L sphere; 2010) in blue and Castellanos et al. (36-L vessel; 2014) in black

Figure 9 gathers these seven case studies into a single diagram, starting from the assumed ignition (left, in yellow) down to the final consequences of the accident. Numbers in brackets indicate the case study under consideration, while potential safeguards are represented as green barriers along the diagram, and will be discussed one by one in the following paragraphs.
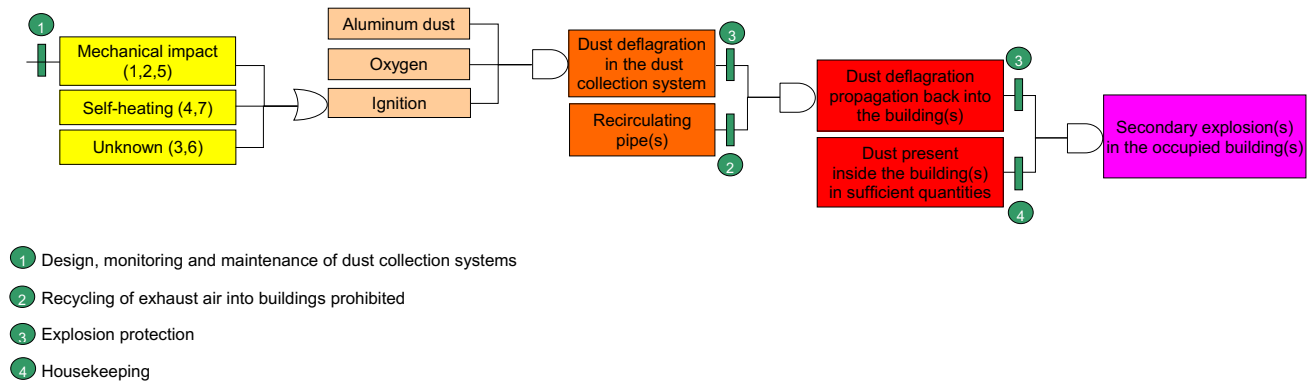
Figure 9: Simplified representation of the seven case studies

4.1 Design, monitoring and maintenance of dust collection systems

Detailed guidance for the safe design and operation of industrial plants handling metal dusts is available in NFPA 484 (2015), including important safety recommendations for dust collecting systems.

Wet-type abatement systems are generally preferred to dry-type dust collectors since they offer an inherently safer design. However, they need to be monitored and maintained properly: in case study 4, the decrease in the water level inside the scrubber resulted in a lowering of the abatement efficiency, leading to a decrease in conveying velocity, which ultimately allowed some powder settle, possibly overheat and explode.

Dry-type dust collection systems are subject to the same requirements: in case studies 1 and 2, loose parts became effective ignition sources. A minimum velocity throughout the conveying system should also be provided to avoid powder to accumulate and create explosive situations.

4.2 Recycling of exhaust air into buildings

NFPA 484 (2015) prohibits the recycling of exhaust air from dry-type dust collectors into buildings. Indeed, this practice can create very hazardous situations (without the implementation of appropriate measures such as deflagration isolation and good housekeeping) and lead to disastrous secondary explosions with numerous victims due to the high thermal radiation associated with aluminum dust fireballs (Figure 10). It has, unfortunately, been confirmed by the case studies reviewed in this paper.

Figure 10. Vented aluminum dust explosion test
illustrating the very high emissivity of aluminum flames (Holbrow et al., 2000)
©Crown Copyright, Contains public sector information published by the Health and Safety
Executive and licensed under the Open Government Licence
Courtesy of Paul Holbrow, Health and Safety Laboratory, UK

4.3 Explosion protection

The high values of flame temperature (T_f), explosion pressure (P_{max}), deflagration index (K_{St}) and heat of combustion (ΔH_c) presented in Table 3 for aluminum indicate a greater hazard than typical carbonaceous dusts (Taveau, 2014), and brings new challenges to standard explosion protection methods.

Table 3. Physical properties of aluminum compared to other metals and carbonaceous dusts (NFPA 484, 2015; Eckhoff, 2003).

Element	T_f (°C)	P_{max} (bar)	K_{St} (bar.m/s)	Oxidation products	ΔH_c (kJ/mole O_2)
Al	3,790	11.2	515	Al_2O_3	1,100
Mg	3,340	17.5	508	MgO	1,240
Si	2,970	10.2	126	SiO_2	830
Fe	2,220	5.2	50	Fe_2O_3	530
Zn	1,800	7.3	176	ZnO	700
C	~1,500	~8	~200	CO_2, H_2O	400

NFPA 484 (2015) just started to specifically address metal dusts explosion hazards through the following recommendations:
- to use caution when applying NFPA 68 (2013) and NFPA 69 (2014) standards requirements to metal dusts, since the provided design rules for explosion venting, suppression, and isolation are based on K_{St} values and might not be suitable for certain combustible metal dusts (Annex A),
- to justify that the considered explosion protection system is suitable for the specific hazard with experimental evidence (Annex A),
- to show that the isolation devices are compatible and effective with the material collected (chapter 9).

4.3.1 Explosion venting

Some cases analyzed in this paper, and especially case studies 5, 6 and 7 where the dust collection systems experienced severe damage, suggest that vent sizes were underestimated. While it is hard to conclude categorically without more information regarding the vent design (e.g. size, specific mass, static opening pressure), the explosibility of the dust (K_{St}, P_{max}) and the assumed enclosure strength, this undersizing may be related to a scaling issue with metal dusts, and particularly aluminum (Taveau, 2014; Taveau and Seidel, 2015; Taveau, 2015a; 2015b).

Published experiments of vented aluminum dust deflagrations, for volumes of 2.6 m^3 and 18.5 m^3, have led to much higher reduced pressures than predicted by venting equations (Taveau et al., 2013; Taveau, 2013; Taveau, 2014).

A recent incident, referred in a public input to NFPA 68 2013 edition (Luzik, 2015), further questions the scalability of aluminum dust explosibility parameters. The dust involved in this incident was an aluminum alloy with a tested K_{St} = 186 bar.m/s. While the installed vent area (20.4 ft^2) exceeded the required vent area per NFPA 68 (17.9 ft^2), the dust collector experienced significant structural deformation during the deflagration (Figures 11), suggesting that the internal pressure was higher than calculated.

Figure 11a: Dust collector before the deflagration (Luzik, 2015)

Figures 11b and 11c: Dust collector after the deflagration: filters blown through the vents (Luzik, 2015)

Figure 11d and 11e: Dust collector after the deflagration: deformation of the reinforced wall and access doors (Luzik, 2015)

4.3.2 Explosion isolation

While explosion venting protects the enclosure from structural damage, it is the role of explosion isolation to prevent the primary deflagration from propagating through interconnected pipes, especially when these pipes lead to work stations or occupied areas.

There has been only little information reported on the propagation and isolation of aluminum deflagrations due to the technical difficulty of conducting such experiments at a large scale.

Bartknecht (1989) reports some explosion propagation and isolation tests carried out in a 30-m long, 400-mm diameter pipe closed at one end using cornstarch (K_{St} = 210 bar.m/s; P_{max} = 9.7 bar) and aluminum dust (K_{St} = 625 bar.m/s; P_{max} = 11.4 bar) at a concentration of 500 g/m^3. The

flame was twice as fast in the case of aluminum, and the pressure was increased by more than a factor 10 after 20 meters. This illustrates well the challenges associated with the isolation of aluminum dust explosions, both in terms of response time and pressure resistance required for the isolation device.

Chemical isolation was demonstrated in this pipeline using detection at 1 m and the extinguishing barrier at 10 m. The suppressant conditions were not specified; however, it appears that 12 kg of Mono Ammonium Phosphate (MAP) were injected. The flame did not cross the barrier, and the pressure was reduced to approximately 3 barg. In a related test with a 33 m pipe and a 2.4-m^3 initiating vessel causing flame jet ignition, the velocity and pressure at 30 m exceeded 3,000 m/s and 36 barg respectively.

Attempts to use mechanical isolation at 10 m or greater led to massive deformation of the gate. The installation of vents, with an area of 4.5 times the cross section of the pipeline, was effective at reducing the pressure at the mechanical valve. Placement of vents at 20 m intervals was effective at keeping the pressure below 10 barg.

Tests were conducted by Fike Corporation at DMT GmbH testing site in the system shown in Figure 12 (Going and Snoeys, 2002). This layout was based on a 5 m^3 initiating vessel, a DN 400 pipe, an aluminum dust with $K_{St} > 300$ bar.m/s and a maximum valve placement distance of 14 m. Tests indicated that the deflagration transitioned into a detonation within the pipe between the vessel and the explosion isolation valve; pressures up to 30 barg and flame speeds over 450 m/s were measured. The explosion isolation valve did stop the explosion flame from propagating down the pipe; however flames escaped through pipe gaskets and valve parts as a result of the excessive heat and pressure.

A combined system was developed by adding 2 chemical isolation containers at 4 m from the vessel, each containing 8.2 kg of SBC (sodium bicarbonate). This chemical barrier suppressed enough of the flame front so that the pressure at the isolation valves was decreased to an acceptable level, 15 barg, thereby allowing the isolation valve to completely block the flame without being damaged. This combination of chemical and mechanical isolation techniques was therefore proven to be a method to safely isolate a metal dust explosion without release of flame or combustion products.
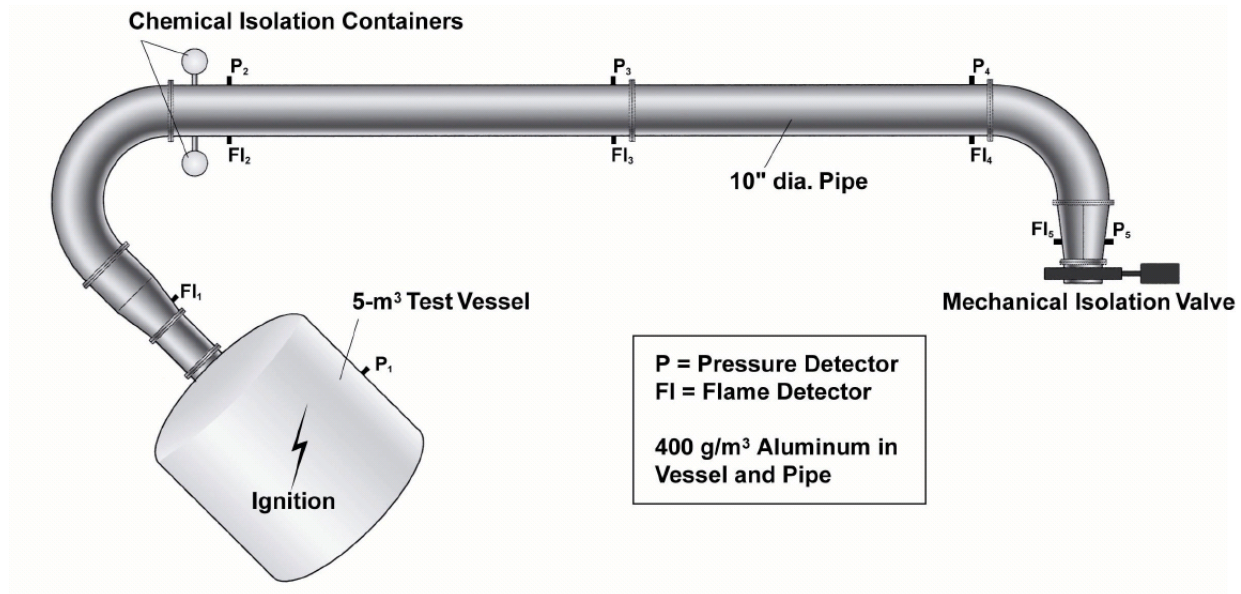
Figure 12: Test layout for 5-m^3 initiating vessel and pipe isolation

Further tests (Taveau et al., 2013) have been performed with aluminum dust (K_{St} = 680 bar.m/s, P_{max} = 11.6 barg) using a new version of the gate valve (with a stronger design and better sealing capabilities at high temperatures) first on a DN 150 pipe connected to a 1-m^3 contained vessel (Figure 13). The valve was able to stop the explosion both for ignition near the pipe and ignition at the vessel center, without chemical isolation. Pressure spikes up to 40 barg were measured just upstream of the closed valve, but did not damage it.

Figure 13: Mechanical explosion isolation of an aluminum dust (K_{St} = 680 bar.m/s) deflagration initiated in a 1-m^3 contained vessel (Taveau et al., 2013)

The most recent large scale tests involving a 5-m^3 vented vessel (for a P_{red} up to 0.9 barg) connected to a DN400 pipe and conducted with aluminum dust (K_{St} = 450 bar.m/s, P_{max} = 10.1 barg) were also successful (Figure 14).

Figure 14: Mechanical explosion isolation of an aluminum dust (K_{St} = 450 bar.m/s) deflagration initiated in a 5-m^3 vented vessel (Fike Corporation)

4.4 Housekeeping

Often referred as the last safeguard in a facility handling combustible dusts, housekeeping seems an easy task but is often neglected.

Even if small quantities of aluminum dust escape from the dust collection systems into the main work rooms of the factory per day, significant quantities may accumulate on floors, process equipment, shelves and other surfaces over time.

An effective housekeeping program is absolutely crucial in order not to fuel the primary explosion, and therefore prevent the development of secondary dust explosions, for example as experienced in the catastrophic explosion in China in 2014.

Frank and Holcomb (2010) provided some general guidance to deal with dust leakages and dust accumulation. Very simple indicators, such as white crosses on the floor, can be used to detect dust accumulation.

5. Conclusions

Metal dust deflagrations have happened all over the world and represent a significant and growing proportion of accidents. Statistics show that they give rise to a high death rate due to the high temperatures of metal dust flames.

Aluminum is the most common metal fuel involved, and also one of the most hazardous. Finishing and polishing are one of the most dangerous operations, as they generate the smallest and most reactive particles.

The analysis of seven explosions that occurred in aluminum finishing facilities provides useful insight. A typical accident involves a fault or process upset in a dust collecting system, leading to the initiation of a deflagration and its propagation through the recirculating air system back into the work area where operators might be present.
Adequate design, monitoring and maintenance of dust collection systems are all critical aspects for the safe operation of plants handling aluminum powders. In addition, explosion isolation is needed to prevent the flame from propagating back to the buildings and causing fatalities or injuries.

Additional research is clearly needed in the area of explosion protection for aluminum dust collector applications. Case studies 5, 6 and 7 especially show severe damage to the dust collectors and suggest that vent sizes have been underestimated.
The apparent lack of scalability of metal dusts explosion severity, which could lead to the undersizing of mitigation systems, should be the subject of further investigations.

References

Bartknecht, W., 1989. Dust explosions: course, prevention, protection. Springer-Verlag, Berlin.

Beck, H., Jeske, A., 1982. Dokumentation Staubexplosionen. Analyse und Einzelfalldarstellung, Berufsgenossenschaftliches Institut für Arbeitssicherheit Report BIA 4-82.

Castellanos, D., Carreto-Vazquez, V.H., Mashuga, C.V., Trottier, R., Mejia, A.F., Mannan, M.S., 2014. The effect of particle size polydispersity on the explosibility characteristics of aluminum dust. Powder Technology 254, 331-337.

Cavallero, D., Debernardi, M.L., Marmo, L., Piccinini, R., 2004. Two aluminum powder explosions that occurred in superficial finishing plants. In: International Conference on Probabilistic Safety Assessment and Management, PSAM 7, Volume 6, pp. 3402-3407.

CCPS, 2005. Guidelines for safe handling of powders and bulk solids. Center for Chemical Process Safety, American Institute of Chemical Engineers, New York.

Chemical Safety Board, 2005. Investigation report, Aluminum dust explosion, Hayes Lemmerz International, Inc., Huntington, IN. Report No. 2004-01-I-IN.

Chemical Safety Board, 2006. Combustible dust hazard study. Report No. 2006-H-1.

Chemical Safety Board, 2012. Hoeganaes Corporation: Gallatin, TN, Metal dust flash fires and hydrogen explosion. Report No. 2011-4-I-TN.

Chemical Safety Board, 2014. AL Solutions, Inc., New Cumberland, WV, Metal dust explosion and fire. Report No. 2011-3-I-WV.

Dufaud, O., Traoré, M., Perrin, L., Chazelet, S., Thomas, D., 2010. Experimental investigation and modelling of aluminum dusts explosions in the 20 L sphere. Journal of Loss Prevention in the Process Industries 23, 226-236.

Eckhoff, R.K., Alfert, F., 1988. Fire and explosion hazards in the production and handling of aluminium powder. Christian Michelsen Institute, CMR report n° 88/02103-1.

Eckhoff, R.K., 2003. Dust explosions in the process industries. 3rd edition, Gulf Professional Publishing.

Febo, H., 2001, FM Global, personal communication to S.S. Grossel.

Frank, W.L., Holcomb, M.L., 2010. Housekeeping solutions, Dust explosion hazard recognition and control: new strategies. Kansas City, October 20-21.

ISSA, 2005. Dust explosion incidents: their causes, effects and prevention. Examples 2, 3 and 10. International Social Security Association, ISSA Prevention Series n° 2051.

Going, J.E. & Snoeys, J., 2002. Explosion protection with metal dust fuels. Process Safety Progress, Volume 21, 305-312.

Holbrow, P., Hawksworth, S.J., Tyldesley, A., 2000. Thermal radiation from vented dust explosions. Journal of Loss Prevention in the Process Industries 13, 467-476.

Jeske, A., Beck, H., 1987. Dokumentation Staubexplosionen. Analyse und Einzelfalldarstellung, Berufsgenossenschaftliches Institut für Arbeitssicherheit. Report BIA 2-87.

Lembo, F., DallaValle, P., Marmo, L., Patrucco, M., Debernardi, M.L., 2001. Aluminum airborne particles explosions: risk assessment and management at Northern Italian factories. ESREL Conference, 85-92.

Li, G., Yang, H.-X., Yuan, C.-M., Eckhoff, R.K., 2016. A catastrophic aluminium-alloy dust explosion in China. Journal of Loss Prevention in the Process Industries 39, 121-130.

Lunn, G.A., 1992. Dust explosion prevention and protection, Part 1, Venting, 3rd Edition, Institution of Chemical Engineers, Rugby, UK.

Luzik, S., 2015. Public input to NFPA 68, 2013 edition. December 18, 2015.

Matsuda, T., 1993. Dust explosion incidents in Japan. Proceedings of the Second IUPAC-Workshop on Safety in Chemical Production, pp. 256–261.

Marmo, L., Piccinini, R., Danzi, E., 2015. Small magnitude explosion of aluminum powder in an abatement plant: a telling case. Process Safety and Environmental Protection 98, 221-230.

May, D.C., Berard, D.L., 1987. Fires and explosions associated with aluminum dust from finishing operations. Journal of Hazardous Materials 17, 81-88.

NFPA, 1957. Report of important dust explosions. A record of dust explosions in the United States and Canada since 1860. Boston, MA.

NFPA 484, 2015. Standard for Combustible Metals. National Fire Protection Association, Quincy, MA, USA.

NFPA 68, 2013. Standard on Explosion Protection by Deflagration Venting. National Fire Protection Association, Quincy, MA, USA.

NFPA 69, 2014. Standard on Explosion Prevention Systems. National Fire Protection Association, Quincy, MA, USA.

Nifuku, M., Matsuda, T. and Enomoto, H., 2000. Recent developments of standardization of testing methods for dust explosion in Japan. Journal of Loss Prevention in the Process Industries 13, 243-251.

Price, D.J., Brown, H.H., 1922. Dust explosions: theory and nature of, phenomena, causes and methods of prevention. National Fire Protection Association, Boston, MA.

Taveau, J.R., Vingerhoets, J., Snoeys, J., Going, J.E., Farrell, T.M., 2013. Explosion protection with metal dust fuels: new experimental evidence. In: 7th International Seminar on Fire & Explosion Hazards, pp. 820-829.

Taveau, J., 2013. Explosion protection for metal dusts. Presentation to NFPA 484 committee, June 17th, Quincy, MA.

Taveau, J., 2014. Combustible metal dusts: a particular class. In: Mary Kay O'Connor Process Safety Center, Seventeenth International Symposium, pp. 594-606.

Taveau, J., Seidel, R., 2015. Explosibility and large-scale venting tests with 4 metal powders. Presentation to NFPA 484 committee, August 26th, Knoxville, TN.

Taveau, J., 2015a. Scaling-up metal dusts explosion severity. Presentation to NFPA 68 committee, September 9th, Quincy, MA.

Taveau, J., 2015b. Metal dusts explosibility testing in 20-L sphere and 1-m^3 vessel. Presentation to ASTM E27 committee, November 19th, Tampa, FL.

Yan, X.Q. & Yu, J.L., 2012. Dust explosion incidents in China. Process Safety Progress 31, 187-189.