Maintenance-related major accidents in the metal industry: The combustible dust challenge

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The process industry has seen many major accidents over the years and several literature point at maintenance as one of the contributing factors. In this paper, some selected major accidents in the metal sector are analyzed to see how maintenance has influenced their occurrence. The Work and Accident Process (WAP) classification scheme is used as the basis for the analysis. This paper aims to give to metalworkers and others involved in risk management an insightful learning from accident. The paper builds on a review of literature, including accident investigation reports. Learning from these accidents is expected to stimulate attention on applicable safety strategies such as inherent safety (e.g. factory layout design to limit the accumulation of dust in high-risk zones), procedural strategy (e.g. good housekeeping), passive strategy (e.g. use of blast walls) and active strategy (e.g. use of gas, smoke, heat or flame detectors to mitigate risk). Engineering cybernetics, among other disciplines, find application in the control of the risk associated with dust explosion as discussed under recommendations.

Keywords: Maintenance, Major Accident, Work and Accident Process, Combustible Dust, Risk

Introduction

The metal sector of the process industry has experienced several major accidents in the form of major explosion and major fire with serious damage to human life and physical asset **(**CSB, 2006). For some of these accidents, maintenance is a contributing factor. Generally, maintenance is reported to be responsible for between 30% and 44% of all major accidents in the hydrocarbon and chemical process industry (HSE, 1987; Okoh and Haugen, 2014).

The Work and Accident Process (WAP) classification scheme will be used to analyze a set of major accidents in the metal sector. WAP is an integration of failure in the maintenance work process (i.e. Deficient planning/scheduling/fault diagnosis, deficient mobilization/shutdown, deficient preparation for maintenance, deficient performance of maintenance work, deficient startup and deficient normal operation) and failure in the accident process, which is decomposed into Active failure (i.e. Lack of barrier maintenance, barrier maintenance error, maintenance introducing new hazards and maintenance being an initiating event for an accident scenario) and Latent failure (i.e. Deficient regulatory oversight, deficient risk assessment, deficient implementation of requirements, deficient management of change, deficient documentation, deficient design/organization/resource management, unbalanced safety and production goals, deficient monitoring of performance, deficient audit, and deficient learning) (Okoh and Haugen, 2013, 2014).

The objective of this paper is to enable the management and staff of the metal industry identify what can go wrong in relation to maintenance (an important activity for preventing failures and promoting dependability) and what the consequences are. This is the first step in the prevention of maintenance-related major accidents in the industry (Okoh and Haugen, 2013).

The rest of the paper of the paper is structured as follows. Accident cases from the metal industry will be analyzed. Next and finally, comes discussion and conclusion.

Accident Cases in the Metal Industry

Case 1: Kawasaki Tennessee Aluminum Dust Fire (April 24, 2017)

On April 24, 2017, at Kawasaki Tennessee plant in the U.S., a major fire occurred from clogged aluminum dust at a large funnel (dust collector), a part of a fan system for dust removal from the production area (Moore, 2017).

Major hazard: Aluminum dust (*Combustible dust*)

Work process influence: Poor schedule for evacuating dust from dust collector (*i.e. deficient planning/scheduling/fault diagnosis*).

Accident process influence: Active failure - Maintenance of the dust collector was inadequate (*i.e. lack of barrier maintenance*)

Case 2: Hoeganaes Metal Dust Fire and Hydrogen Explosion (May 27, 2011)

On May 27, 2011, Hoeganaes Gallatin facility in Tennessee (USA) experienced a hydrogen gas explosion, followed by metal dust flash fires, leading to three fatalities and two injuries; the leaking gas was not tested and mistaken for Nitrogen, and in a bid to repair the leak, the removal of a gas-line trench cover using a forklift equipped with a chain on its forks created sparks which ignited the hydrogen and metal dust (CSB, 2012).

Major hazard: Hydrogen gas and iron dust (Combustibles)

Work process influence: Gas untested (*i.e. deficient planning/scheduling/fault diagnosis*), Use of forklift fork with chains (*i.e. deficient performance of maintenance work*)

Accident process influence: Active failure – Creation of spark by use of forklift fork with chains (*i.e. maintenance being an initiating event for an accident scenario*); Latent failure – Irregular inspection of pipes in the trench (*i.e. deficient risk assessment*), no testing to identify the type of gas leak (*i.e. deficient risk assessment*), no job hazard analysis (*i.e. deficient risk assessment*), no training of workers on hazard recognition (*i.e. deficient design/organization/resource management*), failure to learn from near-misses (*i.e. deficient learning*),

Case 3: Hoeganaes Metal Dust Fire (March 29, 2011)

On March 29, 2011, during the replacement of igniters on a band furnace at the Hoeganaes Gallatin facility in Tennessee (USA), an engineer using a hammer mistakenly lofted large amounts of combustible iron dust from flat surfaces of the furnace, leading to his being engulfed in flames that caused him severe burns (CSB, 2012).

Major hazard: Iron dust (*Combustible dust*)

Work process influence: Use of a metallic hammer rather than a mallet (*i.e. deficient performance of maintenance work*)

Accident process influence: Active failure – Creation of spark by use of metallic hammer on metallic surfaces in the presence of combustible dust (*i.e. maintenance being an initiating event for an accident scenario*); Latent failure – No effective overhaul in relation to dust containment and housekeeping procedures following the combustible dust testing of 2009 (*i.e. deficient implementation of requirements*), no job hazard analysis (*i.e. deficient risk assessment*), no training of workers on hazard recognition (*i.e. deficient design/organization/resource management*)

Case 4: Hoeganaes Metal Dust Fire (January 31, 2011)

On January 31, 2011, during the restart of the motor of a bucket elevator at the Hoeganaes Gallatin facility in Tennessee (USA), vibrations from the elevator dispersed combustible iron dust into the air, leading to the severe burn of two workers and their subsequent death; the restart was done based on a wrong inspection result, after it was suspected that the bucket elevator had gone off-track (CSB, 2012).

Major hazard: Iron dust (*Combustible dust*)

Work process influence: Incorrect observation from inspection (*i.e. deficient planning/scheduling/fault diagnosis*).

Accident process influence: Active failure – Fire almost immediately after the restart of the elevator motor (*i.e. maintenance being an initiating event for an accident scenario*); Latent failure – No effective overhaul in relation to dust containment and housekeeping procedures following the combustible dust testing of 2009 (*i.e. deficient implementation of requirements*).

Case 5: AL Solutions, Inc., Metal Dust Explosion and Fire (December 9, 2010)

On October 9, 2010, at AL Solutions, Inc., New Cumberland, WV (USA), a metal dust explosion occurred during the processing of Zirconium in a defective blender, killing three workers and injuring one; Sparks or heat generated between the blender blades (metal surface) and sidewall (metal surface) ignited the zirconium dust (CSB, 2014).

Major hazard: Titanium and Zirconium dust (*Combustible dusts*)

Work process influence: Blender remained defective in spite of maintenance carried out on it earlier (*i.e. deficient planning/scheduling/fault diagnosis*).

Accident process influence: Latent failure - No dust collection system for reduction of hazards of metal dust explosion (*i.e. deficient risk assessment*), Non-adherence to the practices recommended in NFPA 484 for controlling combustible metal dust hazards installation (*i.e. deficient implementation of requirements*), OSHA did not carry out a Combustible Dust NEP inspection at the company before the 2010 incident despite the company's history of near-misses (*i.e. deficient regulatory oversight*).

Case 6: Hayes Aluminum Dust Explosion (October 29, 2003)

On October 29, 2003, at Hayes Lemmerz International-Huntington, Inc. (Hayes) facility, Huntington (USA), an aluminum dust explosion occurred in a scrap re-melting system, which killed one employee, burned two employees, destroyed the dust collection equipment and damaged other equipment; the restart by maintenance personnel of the dry chip feed system led to the formation of a crust in the vortex and a subsequent overflowing of chips into the spark box in the dust duct, where a fire started, leading to an explosion (CSB, 2005).

Major hazard: Aluminum dust (*Combustible dust*)

Work process influence: No inspection to deal with why the chip system was releasing excess dust (*i.e. deficient planning/scheduling/fault diagnosis*).

Accident process influence: Active failure - Maintenance in the chip processing and dust collector area was insufficient (*i.e. lack of barrier maintenance*); Latent failure - No formal training for operating and maintaining the chip-processing and dust collection systems (*i.e. deficient design/organization/resource management*), no study about the excessive dust that was leaking from the chip system (*i.e. deficient risk assessment*), ineffective design of dust collector system (*i.e. deficient design/organization/resource management*), non-adherence to National Fire Protection Association (NFPA) 651 guidance on dust collector design and installation (*i.e. deficient implementation of requirements*), no formal documentation for investigation and follow-up of preventive actions in relation to aluminum dust fire incidents (*i.e. deficient documentation*), flame-retardant clothing not worn during routing work near the melt furnace (*i.e. deficient risk assessment*).

Case 7: Jahn Foundry Resin Dust Explosion (February 25, 1999)

On February 25, 1999, at Jahn Foundry Corporation in Massachusetts (USA), there was resin dust explosion in the shell mold area, propagating a flame through the building, which dispersed settled dust, leading to a major secondary explosion, killing three workers and injuring nine (CSB, 2006).

Major hazard: Resin dust (*Combustible dust*)

Work process influence: Insufficient maintenance of the gas burner system (*i.e. deficient planning/scheduling/fault diagnosis*), insufficient housekeeping to minimize the accumulation of resin in the venting duct (*i.e. deficient planning/scheduling/fault diagnosis*).

Accident process influence: <u>Latent failure</u> – Inadequate design of the gas burner system (*i.e. deficient design/organization/resource management*).

Case 8: Dust Explosion in a Silicon Grinding Plant at Bremanger, Norway (1972)

In 1972, a dust explosion occurred at a silicon powder grinding plant in Norway, killing five and injuring four workers, and destroying most of the process equipment and wall panels; during partial shutdown of the plant for repair, a small hole was made with a cutting torch in a steel pipe used for silicon powder transportation while the pipe was yet uncleaned, and this led to the ignition and explosion of dust (Eckoff, 2003).

Major hazard: Silicon dust (*Combustible dust*)

Work process influence: Silicon powder not evacuated from steel pipe prior to hot work (*i.e. deficient preparation for maintenance*).

Accident process influence: <u>Latent failure</u> – No job hazard analysis (*i.e. deficient risk assessment*).

Discussion and Recommendations

Most of the maintenance-related major accidents analyzed in this paper involved metal dust (the major hazard). Generally, metals account for more than 20% of dust explosions, and will burn or explode if finely pulverized and dispersed in adequate concentrations (CSB, 2006; Eckoff, 2003). Metal dust settle on surfaces, unsealed spaces, dust collectors, etc., during the intentional manufacturing of metal powder coatings, machining (e.g. turning, drilling and milling) of a semi-fabrication, polishing of finished products (Li, Yang et al., 2016), handling of very small particles, or the processing of scrap metal (CSB, 2005).

Based on the analysis of the accidents in relation to the Work and Accident Process (WAP) classification scheme, some factors that influence maintenance-related major accidents in the industry are revalidated as follows:

1. *The maintenance work process:* Deficient planning/scheduling/fault diagnosis, deficient preparation for maintenance and deficient performance of maintenance work.
2. *The accident process:* Lack of barrier maintenance and maintenance being an initiating event for an accident scenario (active failures), and deficient risk assessment, deficient regulatory oversight, deficient implementation of requirements, deficient design/organization/resource management, deficient documentation, deficient learning (latent failures).

Besides, other factors that might influence metal dust explosion may be classified in relation to materials technology, manufacturing process, equipment design and factory layout as follows (CSB, 2006; Eckoff, 2003, Hydro, 2012):

1. *Materials technology:* Particle size, shape of material, etc. are influencing factors.
2. *Manufacturing process:* Moisture content, ambient humidity, oxygen available for combustion, the concentration of dust in the air, etc. are also influencing factors.
3. *Equipment design:* Design of potlines, dust collectors and other material handling systems can influence the accident as well.
4. *Factory layout:* Flat surfaces, crevices and hard-to-clean areas also form part of influencing factors.

However, the “equipment design” and “factory layout” categories in the latter classification can be considered also as maintenance-related with respect to maintainability (i.e. the ability of an item to be maintained). These are similar to “deficient design/organization/resource management” of the latent failure sub-category of the accident process part of the WAP scheme.

There must be the concurrent presence of dust suspension and confinement in addition to fuel, oxygen and ignition (i.e. dust explosion pentagon) for a dust explosion to occur (CSB, 2006). Intense burning occurs in suspended dust, and confinement promotes pressure buildup (CSB, 2006). Removing either the suspension or the confinement hinders explosion, but fire may still occur in the presence of fuel, oxygen and ignition (i.e. fire triangle). Most of the accident cases analyzed in this paper are linkable to poor housekeeping in relation to dust collectors. According to Zalosh et al. (Zalosh, Grossel et al., 2005), dust collectors are involved in over 40% of all dust explosions. Another report of combustible dust incidents in North America puts this figure at over 30% for 2016 alone (Cloney, 2006).

Equipment that usually contain significant quantity of dust must be designed for maintainability (Okoh and Haugen, 2013a); i.e. there should be ease of evacuation of dust. Besides, the layout of the factory also should be planned for maintainability (Okoh and Haugen, 2013a); dust removal as part of maintenance should be promoted. These will prevent secondary dust explosion which occurs when accumulated dust on surfaces is lofted and ignited by a primary explosion (CSB, 2006; Eckoff, 2003). Primary explosion itself occurs when a dust suspension within a confined space is ignited and explodes (CSB, 2006; Eckoff, 2003).

Considering the high significance of the aforementioned statistics, it is recommended to pay closer attention to dust collectors. Maintenance of this equipment should be scheduled at optimal intervals. Grinders, hoppers and mixers are also linked to several accidents and should be considered diligently as well (CSB, 2006). Regarding maintaining the factory in relation to dust removal, the strict and regular application of 5S methodology is recommended, whereby the "Seiso" element will help reduce accumulation of dust.

In addition, it is recommended that maintenance workers are trained to recognize the hazards they face in the course of their work in the metal industry. This will help improve their personal safety, situational awareness and prevent major accidents. A task-specific work permit, which contains a list of hazards that maintenance and production personnel are responsible for, should also be used. This should be signed to authorize the start of work and closed out after work execution.

Maintenance leaders should be trained also in the development/deployment of Work Safety Analysis (WSA) for every maintenance work to be carried out in the plant. The aim of the WSA is to anticipate hazards that are inherent or that could be created in a task and workplace and to define control measures. This should be used to modify any existing standard maintenance procedure to fit a specific maintenance task. It is important also in the case of the maintenance of systems that have undergone modification.

Furthermore, the use of WAP-FMEA (Work and Accident Process Failure Modes and Effects Analysis), i.e. a process FMEA (or PFMEA) consisting of the maintenance work and accident process (Okoh and Haugen, 2013, 2014), is suggested for the prevention of maintenance-related major accidents in the metal industry. A WAP-FMEA could be developed for a specific metal industry during the development of standard maintenance procedures and updated for every relevant modification/change. The WAP-FMEA will determine how accidents might occur in relation to maintenance in the plant, how likely such an event would be, how severe it would be and what to do to mitigate the risk.

Finally, in addition to the aforementioned recommendations which encompass safety strategies such as inherent safety strategy (e.g. factory layout design to limit the accumulation of dust in high-risk zones) and procedural strategy (e.g. good housekeeping), passive strategy (e.g. use of blast walls) and active strategy (e.g. use of gas, smoke, heat or flame detectors to mitigate the risk of fire) are also highly recommended. In the case of the detectors, high sensitivity, high accuracy, speedy response and high audibility are some important parameters to consider. Considering gas detection, oxygen detectors can be installed to monitor oxygen concentration during normal operation and be automated to trigger nitrogen release into the high-risk zone to displace atmospheric oxygen, thus reducing the concentration of the oxygen from the normal 21% to far below the limiting oxygen concentration (LOC) of the combustible dust. This significantly reduces the probability of having an explosion, since oxygen, one of the elements in the dust explosion pentagon, is being controlled. This is possible with the knowledge and application of engineering cybernetics. Besides, the smoke, heat or flame detector will warn people to act to reduce the risk of fire.

Conclusion

Some selected major accidents involving dust have been analyzed in this paper. Metal dust explosion is a typical unwanted event in the metal sector and accounts for a large proportion of dust explosions in the process industry. This significant statistics indicates the need to look thoroughly into this sector to determine the underlying and contributing causes of such a major accident, in order to prevent the reoccurrence.

In pursuit of the objective of learning from accident, the Work and Accident Process (WAP) classification scheme has been used to analyze a set of major accidents in the metal sector. WAP is a combination of the maintenance work process failures (i.e. Deficient planning/scheduling/fault diagnosis, deficient mobilization/shutdown, deficient preparation for maintenance, deficient performance of maintenance work, deficient startup and deficient normal operation) and the accident process, which is decomposed into Active failure (i.e. Lack of barrier maintenance, barrier maintenance error, maintenance introducing new hazards and maintenance being an initiating event for an accident scenario) and Latent failure (i.e. Deficient regulatory oversight, deficient risk assessment, deficient implementation of requirements, deficient management of change, deficient documentation, deficient design/organization/resource management, unbalanced safety and production goals, deficient monitoring of performance, deficient audit, and deficient learning).

In this paper, the factors that influence dust explosion in relation to maintenance in the metal industry have been revealed together with recommendations for managing the risk. From the number of accidents analyzed, though small, the following have been established as some of the factors that influence maintenance-related major accidents in the metal sector: Deficient planning/scheduling/fault diagnosis, deficient preparation for maintenance, deficient performance of maintenance work (Based on the maintenance work process) and Lack of barrier maintenance and maintenance being an initiating event for an accident scenario, deficient risk assessment, deficient regulatory oversight, deficient implementation of requirements, deficient design/organization/resource management, deficient documentation, deficient learning (Based on the accident process). The recommendations proposed cover improvements in procedures, materials technology, manufacturing process, equipment design, factory layout design and the selection/deployment of safety barriers such as gas, smoke, heat and flame detectors.

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