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Metal Waste Dusts from Mechanical Workings – Explosibility Parameters Investigation

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The reactivity of metal scraps or fine particles, typical residual wastes of mechanical workings, is significantly high to cause violent deflagration when particles disperse in the air in the form of clouds. However, literature information is scarce regarding the explosive risks of mixtures of pure metals, oxides and other impurities (like waste dust) whereas the form the bulk of materials in abatement systems and bag filters in the metal industry. Mechanical working could produce a different type of dust, depending on the process, the source material, and the operating conditions, main differences are in the particle size distribution, oxide content and morphology of samples.
The present study investigates several samples of metal/oxide dust mixtures. The results of this work help to recognize the most hazardous dust in term of ignition sensibility when dispersing in clouds. The dust from sanding and welding processes fall into this group, while dust from laser-cutting does not ignite with standard ignition sources (like an electric arc or a hot wire). The work also aimed to establish a correlation between sample properties and explosibility parameters, like K_{ST} and P_{max}. The results indicate a direct proportionality between these values and the particle size distribution of samples (in particular with the d-tenth percentile of the mass distribution) and with the metal oxide content. Additional research is needed to assess the influence of other variables (morphology, chemical composition) and the actual hazards related to different mechanical workings to prevent and mitigate explosive events.

1. Introduction

Metal finishing processes are at high explosion risk. However, no precise classification of the hazard of different process exist. This work is an attempt in that direction according to the explosibility hazards of the dust. A dataset containing data about several samples collected at different metal workshops is discussed, with the aim to provide risk assessment guidelines to workshop owners and operators.
Current statistics of accidents (Yuan et al., 2015) confirm that metal finishing is at high explosion risk. Prevention and mitigation measures to reduce explosion hazards were recently discussed by Taveau (2018) with focus on Aluminium dust which recently came in the spotlight because of a major accident occurred in an automotive parts factory, in China (Li et al., 2016) and by Amyotte et al. (2016). However, other metals are hazardous as well (though in general with lower KST values), as the two accidents occurred at the Hoeganaes facility in Tennessee, US (CSB, 2012) demonstrate. One of the critical issues in explosion risk assessment of metal dust is sample characterization. Dust is often an undesired by-product to get rid of, with little or no control over its characteristics. Metal finishing operations may imply thermal alteration (as in the case of laser cutting) with consequent partial oxidation of the particles. Particle size distribution and particle shape are variables with no control as there is no interest in the dust quality, but unfortunately, they play a significant role on the properties of explosible dust (Marmo et al. 2015). In most cases, the metal dust found at the abatement plants are blends of different alloys as many different artifacts may be processed on the same plant at different times. Waste dust is often composed of partly oxidized metals, whose characteristics are influenced by the oxide content as well as by the working conditions.
Today still a scarce correlation between explosible properties and manufacturing process may be found in the literature. Blasting finishing samples are examined in the work by BGIA (2009), while Myers (2015) focused on the mitigation procedures to reduce explosion risk of polishing/buffing dust samples.

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Table 1: Metal dust-related accidents distribution versus the equipment involved, derived from Yuan et al. (2015)

Equipment/process involved	Percentage of cases (%)
Dust abatement system	43
Grinding/Polishing	18
Conveying system	11
Silos	7
Mixing	5
Furnaces	3
Milling/Crushing	5
Others	8

Metal artifacts are widespread. The use of light alloys, mainly based on aluminum, is thriving with apparently no limitations yet. Most of these artifacts need some exterior finishing or mechanical operations which produce dust. The most diffused unit operations are:

- ✓ Laser cutting
- ✓ Grinding
- ✓ Polishing/Buffing
- ✓ Blasting
- ✓ Welding

The process may profoundly influence dust morphology, dimension, and chemical nature. Dust from laser-cutting has typically a homogenous spherical morphology consequence of the melting provoked by the high temperature. Grinding is diffused in the process industry. It was involved in many accidents, as described by Edabat & Prugh (2007) and Marmo et al. (2004, 2015). Dust produced by grinding is a mixture of metal fines and swarfs in the form of shavings or aggregates. They often contain residues of the abrasive used. Polishing often results in the peculiar shaving-like shaped dust with poor contamination of abrasive residues. Dust generated from blasting is heterogeneous and made of particles of different shape: spheres, shavings or fibers. Dust from welding process is mainly made up of spongy and porous aggregates, often of a Nano-metric scale, with relevant contamination by other materials.

The dust unwillingly produced during metal manufacturing processes must be removed and abated in a proper collector system. A typical arrangement consists of several working points, connected to a dust abatement device via a pipes network. The most used abatement devices are bag filters and cyclones. Both these devices generally contain a flammable atmosphere as dust concentrates above the minimum explosible concentration (MEC) and represent the most significant hazard in this kind of plants. As underlined by Taveau (2015) tiny particles generated from finishing operations are collected in filters and concentrated above the MEC. Air jet-pulse cleaning used for removing dust from filters creates clouds inside the equipment and consequently an explosion hazard. Issues related to dust accumulation on filter and cake detachment procedures are reported by Zalosh (2014), who suggests an expeditious method to assess the explosion risk caused by the mass of the dust cake in the bag section. The method was successfully used by Marmo et al. (2015) to estimate cake deposit in bag-filters in the Italian episode of Aluminum finishing dust explosion (also reported in Taveau, 2018).

The proper airflow must be maintained in the piping network to prevent dust deposit formation. A speed of 20 m/s or higher may fit this purpose. A drop in the airspeed may cause dust deposit which increases the explosion hazard. Blowers are located downstream of the dust abatement device(s), to avoid dust entering in contact with the rotor.

Besides these general considerations, a vital issue of dust explosion hazard assessment is dust characterization. The data presented in this paper may help to identify the processes and dust at significant hazard.

2. Dust analysis

A dataset containing some properties of metallic waste dust was published recently (Marmo et al. 2017). Here the dataset is enriched with new data and morphological analysis. The dust samples were collected at finishing metal workshops in Italy. Table 2 reports the origin of the samples. Each sample was subjected to a morphological characterization (see Table 3), and to the measurement of explosibility parameters as described in section 2.1.

Table 2: Metal dust samples distribution respect to production process

Finishing process	Percentage of samples (%)
Metal recovery	23
Abatement system	13
Sand/shotblasting	13
Grinding	10
Foundry waste	10
Laser cutting	6
Welding	3
Polishing	3
Others	19

Table 3: Metal dust characterization tests

Parameter	Standard/Methodology	Unit of measure
Moisture	ISO 562:2010	Weight %
PSD by Sieving	Internal procedure 08/2014 (see below)	Weight %
PSD by Laser diffraction	ISO 13320:2009	Weight percentiles
BZ flammability class	VDI 2263-1	-

Details of the analytical procedures may be found in Marmo et al. 2017. An acid attack to obtain complete dissolution, followed by an ICP-MS (Inductively coupled plasma-mass spectroscopy) was used to determine the chemical nature of the samples and their oxide content

Dust samples collected at metal finishing workshops are rarely pure elements: the majority consists of a mixture of alloys, finishing components (such as abrasive materials from grinding, polishing tools) or other contaminants, depending on the type of manufacturing process that produces the dust.

Oxidation of metals is the consequence of chemical processes, air exposure or is a direct consequence of finishing operations, like thermal treatments, such as laser cutting. All the samples investigated are partly oxidized, so metals are both present as oxide and as metallic elements. Metal bounded to oxygen is no more available to oxidation and acts as an inert material, reducing reactivity. It will be assumed, on a weight basis, that the 100% minus the content of metallic elements equals the oxide content. The Metal Cation Weight Fraction (MCWF, as detailed in Marmo et al., 2017) is the total metal content measured by chemical analysis (MCWF accounts for metallic element and the metal bonded to Oxygen).

2.1 Explosibility properties assessment

Flammability investigation of samples was performed using the Speditive Explosibility Test (SET, see Danzi et al., 2016 and Marmo et al., 2017 for the complete procedure) and measuring the maximum pressure (P_{max}) and deflagration index (K_{ST}). SET is composed of two parts: “room temperature” and “high temperature” tests. The Room temperature tests were conducted in a Hartmann tube. A continuous arc and a glowing wire were used as an ignition source to ensure the most severe ignition conditions. The High-temperature tests were carried out in a GG furnace at 800 °C and with a hot plate to test for layer auto-ignition at 400 °C

For comparison with ISO/IEC 80079:2016, last flammability check in the 20 l Siwek sphere with 2*1kJ igniters was done as well. Maximum pressure (Pmax) and deflagration index (KST) were measured in the 20 l Siwek sphere according to UNI EN 14034-1:2011. Simex chemical igniters were used (2*5kJ).

3. Results and discussion

The results are presented in Table 4. Dust classified as EA (Explosible at Ambient test) are prone to explode as a continuous arc, or a glowing wire ignites them in the Hartmann tube. The samples classified EA came from sand/shot blasting and welding processes, plus a sample collected from the processing stream of an Aluminum pieces manufacturer. Samples from blasting are composed of particle clusters. Leaves-shaped particles and residue of the abrasive are often present. Oxide content is variable, the highest value set at 22%, which includes the Aluminum oxide (Corundum) usually adopted as abrasive spherical particles. K_{ST} value of these samples is generally high and somehow related to the finest particle fraction (d_{10} in the PSD obtained by laser granulometry), as shown in Figure 2. One single sample collected at a welding station was quite surprisingly classified EA as well although it was sampled at a high-temperature process. This sample had a

KST value of 94 bar m/s and had a low d10 of 1.04 µm. The Scanning Electron Microscope (SEM) imaging revealed this dust is made by nano-metric aggregates with a spongy structure of Fe and Ferric oxide.
Most of the samples belong to EH (Explosible at High-temperature tests) class. These come from a different type of finishing, mainly grinding or are samples collected from abatement system. Grinding dust are typically made up by little scraps (leaves and foils) due to the handling operation of the grinder (Figure 2, right). Among these, dust produced by grinding of aluminum artifacts are, as expected, the most hazardous. One of these exhibited the highest K_{ST} value measured in this work. The aluminum content of the sample was 74%, and d_{10} was 16.5 µm.

Table 4: Metallic dust explosibility results

Sample #	Dust origin	MCWF	d10	SET class	20-L sphere tests		
	-	% wt.	µm	-	Pmax (bar)	K_{St} (bar·m·s^{-1})	2 kJ
1	Laser cutting	48.0	2.63	NE	0	0	N[1]
2	Waste from steel work-piece manufacturing	69.3	10.42	EH	0	0	N
3	Laser cutting	59.9	1.32	NE	0	0	N
4	Grinding	61.8	2.21	EH	5.7	53	P
5	Welding	88.1	1.03	EA	5.9	94	P
6	Sandblasting	94.0	7.83	EA	3.8	122	P
7	Grinding, sandblasting	81.3	4.69	EA	2.5	20	P
8	Waste from bearings production	82.4	7.17	EH	4.4	23.8	N
9	Abatement	70.1	7.59	EH	0	0	N
10	Sandblasting	89.2	26.76	EH	3.1	4	P
11	Sandblasting	77.8	11.44	EH	4.2	33.5	P
12	Polishing	88.1	-	NE	0	0	N
13	Abatement	66.1	1.68	EH	0	0	N
14	Grinding	74.3	16.55	EH	7.25	140	P
15	Descaling process	0.82	1.07	NE	ND[2]	ND	ND
16	Metal recovery	0.51	1.78	NE	ND	ND	ND
17	Foundry waste	0.69	0.48	NE	ND	ND	ND
18	Foundry waste	0.75	0.66	NE	ND	ND	ND
19	Foundry waste	0.67	0.56	NE	ND	ND	ND
20	Aluminum work-piece manufacturing	ND	17.53	EA	7.4	83.4	P
21	Laminating process waste	ND	2.05	EH	3.5	24.6	P
22	Processing	ND	3.06	EH	ND	ND	ND
23	Processing	ND	3.86	EH	ND	ND	ND
24	Processing	ND	3.10	EH	ND	ND	ND
25	Metallic waste recovery	ND	3.33	EH	ND	ND	ND
26	Metallic waste recovery	ND	3.67	EH	ND	ND	ND
27	Inerting	ND	2.28	EH	ND	ND	ND
28	Argalum powder	ND	2.81	NE	ND	ND	N
29	Pyrolytic treatment	ND	2.05	EH	ND	ND	ND
30	Pyrolytic treatment	ND	2.01	NE	ND	ND	N
31	Abatement	ND	21.68	EH	ND	ND	ND
32	Foundry waste	ND	0.53	NE	ND	ND	N
33	Foundry waste	ND	0.57	NE	ND	ND	N
34	Shotblasting	ND	12.03	EH	3.8	40.7	P

[1]: Negative outcome to explosion criteria (P is positive)
[2]: Not determined, whether for insufficient sample amount or poor dispersibility in the 20L sphere

Most of the samples classified Non-Explosible (NE) came from laser cutting and recovery of foundry wastes. In general, these dusts have a high oxide content (greater than 50%, more significant for foundry waste, around 90%), but even small PSD, with d_{10} often lower than 5 µm (Figure 2a). Laser cutting samples are mainly composed of spherical particles strongly oxidized. Dust samples from foundry waste are all classified as NE, due to their oxidized nature, although exhibiting very low d10, up to 0.5 µm. A single sample coming from the polishing process has been classified NE, unexpectedly concerning literature data and case studies of explosions involving these type of operations (Marmo et al., 2004 or in Myers, 2008). This dust had a peculiar fibrous nature (see Figure 2b). This feature mainly reduces the dispersibility of the sample by an air blast, which may be the reason for its low reactivity. No dispersion was possible in the G-G furnace. Ignition criteria were not met in the 20 L sphere either with 2*5kJ or 2*1kJ chemical igniters.

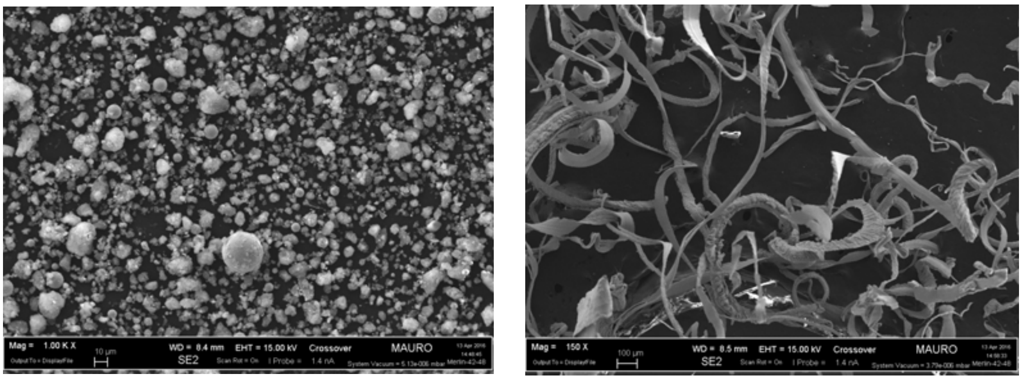

Figure 1: 1000X, Sample from Laser-cutting (a) and polishing (b)

In general, d_{10} seems to have a significant influence on K_{ST} of explosible samples. A comprehensive explosibility assessment should, therefore, consider also the metal content as a relevant factor together with the d_{10} value. A tentative plot was presented in Marmo et al. (2017) and reported here as Figure 3 which accounts for both variables. It seems that maximum K_{ST} is inversely proportional to d_{10}. Stahmer and Gerhold (2016) proposed similar result concerning mean diameter. Samples constituted by Aluminum show always higher K_{ST}, even if their oxide content is more significant than other dust, mostly composed by Iron alloys. This result may be a consequence of the high reactivity of aluminum respect to many other metals. Among iron alloys dust, a sample (coming from blasting) exhibit a slight lower KST than Al dust sample from grinding (122 bar m/s against 140), but with an MCWF slightly higher (90% against 70%). Also, the sample coming from welding had a high KST, with a relatively high metal content (94 bar m/s and 82% respectively).

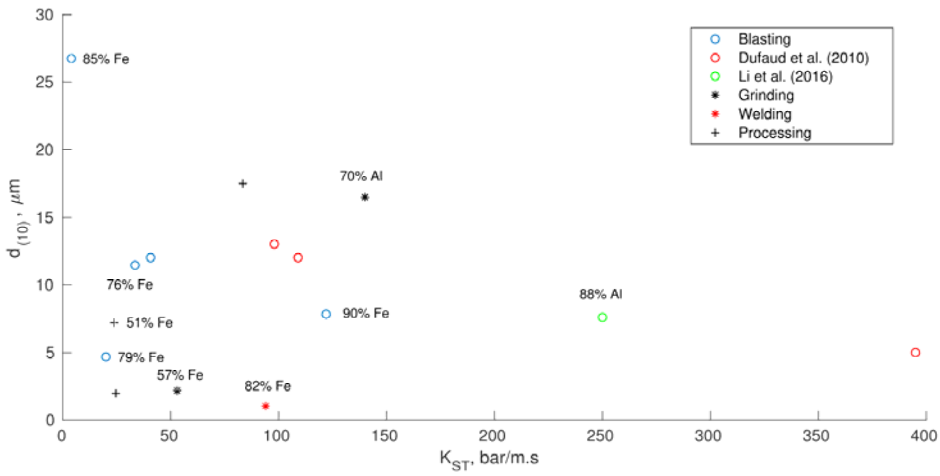

Figure 2: K_{ST} values vs. $d_{(10)}$ and MCWF for some samples in this work and comparison with literature results.

4. Conclusions

The present work reports the assessment of explosibility parameters of several samples of dust coming from the metal finishing industry. Different characterization procedures and flammability tests were adopted to investigate whether dust coming from specific finishing processes could be more prone to explode than others, with the general idea that dust that ignites at ambient tests is more hazardous than dust that ignites at high temperature. Though the number of samples is still limited (further data are needed) some considerations could be done:

Metal dust coming from foundry waste are generally oxidized and not explosible, Sand/shot-blasting and grinding workshops could generate explosible dust, with relative high K_{ST} (although all samples belong to ST_1 class), Dust collected in abatement system should be regarded carefully, depending on their chemical characterization.
Most samples tested should be considered EH (according to SET, Danzi et al. 2016), i.e., sensitive to ignition sources like high-temperature surfaces or ambiances, rather than ignition at room temperature;
Chemical composition is a clear telling factor: Aluminum-based samples seemed to exhibit higher KST, even with a higher oxide fraction than Iron based.
These results may be used as a guideline for explosion risk assessment in metal workshops. As expected the less hazardous activities are foundry and laser cutting wastes. Shot blasting and grinding must be regarded as hazardous to highly hazardous. The chemical nature and the particle size (mostly d10) are key factors to determine the hazardous level. Oxide content decreases reactivity to a great extent. The low oxide content may be the main reason for the weak or very weak reactivity of dust produced by laser cutting.

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