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Combustion properties of titanium alloy powder in ALM processes: Ti6Al4V

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ABSTRACT

The Ti6Al4V powder alloy combustion is studied in order to define dust explosion parameters for industrial safety and combustion mechanism for scientific analysis. No results exist in literature of dust explosion concerning titanium alloy like Ti6Al4V. Three different powders with different average particles size (around 13 µm, 26 µm and 55 µm) were studied. The interest comes from its wide use in metallurgy, especially for aeronautical, dental and defense applications. This paper reports the minimum ignition energy (MIE) of the alloy powders as a function of the concentrations. Hartmann tube apparatus was used in this way. Results can be synthetized as: 3.5 mJ for 13 µm, 4 mJ for 26 µm and 357 mJ for 55 µm particle size. When comparing the values of MIE for pure titanium (Ti) and pure aluminum (Al) powders, the alloy sensibility is near pure Ti. Severity parameters and temperature measured by IR pyrometry were investigated during 20 L spherical explosion vessel tests. Results shown 6 bar overpressure and rate of pressure rise at 546 and 474 bar/s for 13 and 26 µm respectively. In case of the powders average diameter around 55 µm, ignition occurred in only one condition: 1500 g/m^3. Temperatures were measured during explosion following two different scales: versus time and versus concentration.

1. Introduction

In recent years, the layer-by-layer manufacturing process seems to be used increasingly amongst the aeronautics, space or defense industries. These ALM (Additive Layer Manufacturing) processes use metal powders from metallurgical alloys commonly used in the mechanical industry. Among these metals, Aluminum (Al), Titanium (Ti), Silicon (Si) and Magnesium (Mg) are currently used in powder metallurgy and numerous studied were devoted to the hazards in their use with the possibility of dust explosions. In the concerned literature, surveys on the hazard of explosion of pure materials provide some data but few data is available in the case of alloys. Recently, on August 2nd, 2014 a dust explosion occurred in a large industrial plant for polishing various aluminum-alloy parts in Kunshan, China (Li et al., 2016). This disaster had shown that the risk of dust explosion must be studied for all alloys used in industries.

Titanium and its powder alloys present a risk of dust explosion in the metallurgical industry. In the field of risk with titanium powders, Wu et al. (2009) determined the minimum ignition energy (MIE) for pure titanium micro and nano-particles. For all nano-powders and 3 µm powders, the MIE are 1 mJ, 21.91 mJ for 8 µm and 45 µm and 18.73 mJ for 20 µm. Boilard (Boilard et al., 2013) studied the explosibility of micro and nano-titanium powders. Micro-titanium having average particle sizes of 150 µm, 45 µm and 20 µm, give maximum explosion pressure (P_{max}) of 5.5 bar (g), 7.7 bar (g) and 6.9 bar (g) respectively, and maximum rate pressure rise (K_{st}) of 23 bar m/s, 118 bar m/s and 114 bar m/s, respectively. MIE obtained with the MIKE 3 apparatus are 1–3 mJ for 150 and 45 µm powders average diameter and < less than 1 mJ for 20 µm and nano-titanium.

The Ti6Al4V alloy studied is made of 6% weight of aluminum 4% weight of vanadium and 90% weight of Titanium. In the scientific literature, we didn't find studies for the combustion of vanadium (V) powders, but many studies have been carried out for the combustion of pure aluminum in solid state. Using 20 L spherical vessel, Li et al. (2011) investigated the explosion characteristics of nano – pure aluminum powders. Using the Hartman vertical tube (1.2 L) apparatus (MIKE -3) (Choi et al., 2015), studied the minimum ignition energy of aluminum powders in the air and the variation of nitrogen concentration in the air. Concerning aluminum alloys (Bernard et al., 2017), studied ignition and explosibility of AlSi10 Mg alloy. Following the catastrophic explosion in China (Li et al., 2016), studied the explosion parameters of this alloy.

This paper defines the sensibility and severity parameters in case of dust explosion for Ti6Al4V alloy by using electric arc for ignition source. These results make it possible to set up safety systems around the environment of ALM machine, MIM technology or atomization. In

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Table 1
Ti6Al4V particles size.

	Dv (10) µm	Dv (50) µm	Dv (90) µm	D_{32} µm
Ti6Al4V 13 µm	8.31	13.02	20.48	12.29
Ti6Al4V 26 µm	11.88	26.42	44.30	22.07
Ti6Al4V 55 µm	39.56	55.56	76.18	51.28

addition, we propose a scenario with all steps that occur in the combustion in the Hartmann tube. The burning cycle of particle cloud during spherical 20 L explosion vessel tests was also analyzed.

2. Materials

Ti6Al4V ELI (Low Interstitial Elements) powders were manufactured by TLS Technik spezialpulver received in 2015. Three samples were selected with average diameters around 13, 26 and 55 µm. These three samples were characterized by laser granulometry (particle size distribution), SEM microscopy coupled with EDS (morphology and composition) before tests. TGA analysis completes the samples characterization for initial oxide amount estimation with (Baudry et al., 2007) method which was applied by (Bernard et al., 2017) for AlSi10 Mg alloy.

The particle size distribution was studied with the Spraytec Laser Granulometer provided by Malvern Instruments. The focal length of the lens is conditioned to 100 mm, which makes possible to measure the particles with diameters from 0.5 to 200 µm. The results of the particle size distribution for all three samples are shown in Table 1.

The SEM observations show that the particles are spherical, and the small particles are agglomerated with larger ones (see figures: 1-3). In Fig. 2, some particles are joined, with traces of sintering. The small particles stuck on larger ones are called “satellites”. The chemical analyzed by SEM coupled EDS showed in Table 2 that all powders correspond well to the referenced alloy of titanium according to ASTM F136 standards. Nevertheless, EDS method gives approximate information on chemical composition of particles.

Aluminum particles, like titanium particles, are often coated with their oxide which mitigates sensitivity and severity. Thus, this oxide amount needs to be measured for each powder. TGA analysis allows oxide measurement on the powders surface. We measured the increase in mass due to oxide formation in the air. This measure is achieved by oxidizing the powders in the air at variable temperatures during 2 h from room temperature to 1400 °C maximum. For calculations, it' considered that Al produces Al_2O_3 and Ti gives TiO_2. The vanadium contribution and other impurities is considered as negligible in the oxide formation due to their low concentration and the lack of data compared to Ti and Al. The following equation (1) is used:

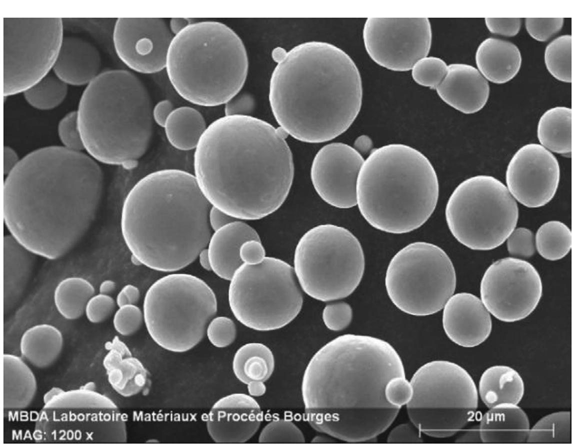

Fig. 1. SEM photography of Ti6Al4V 13 µm.

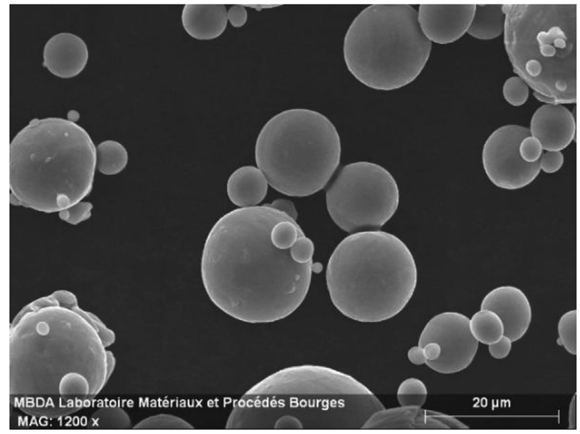

Fig. 2. SEM photography of Ti6Al4V 26 µm.

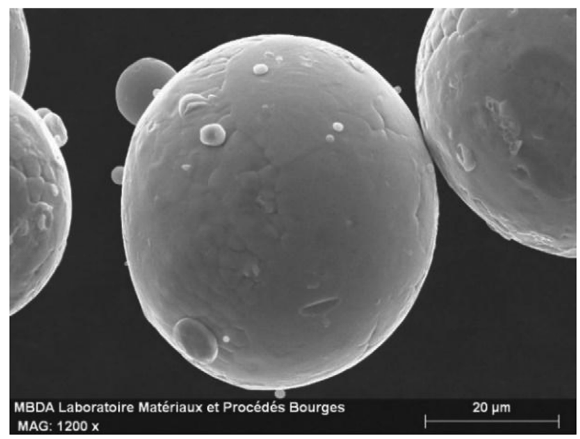

Fig. 3. SEM photography of Ti6Al4V 55 µm.

Table 2
Ti6Al4V powders compositions.

Elements	Ti6Al4V 13 µm	Ti6Al4V 26 µm	Ti6Al4V 55 µm	ASTM F136
Al (% wt)	6.25	6.30	6.40	5.5–6.50
V (% wt)	4.23	4.10	4.06	3.5–4.5
Others (% wt)	0.311	0.297	0.323	0.522
Ti (% wt)	balance	balance	balance	balance

$$2(1-y)T_i + 2yAl + \frac{1}{2}(4-y)O_2 \rightarrow 2(1-y)T_iO_2 + yAl_2O_3 \quad (1)$$

where y is the molar fraction of Al in the alloy and w the weight ratio of aluminum in Ti6Al4V alloy. Composition of the alloy is given in weight ratio, in the following way:

$$y = \frac{\frac{w}{M_{Al}}}{\left(\frac{w}{M_{Al}} + \frac{1-w}{M_{Ti}}\right)} \quad (2)$$

Finally, the weight ratio of oxide is given from equation (3):

$$X_{oxide} = 1 - \frac{2(1-y)}{(3+y)(1-w_{Al})}\frac{M_{Al}}{M_{O2}}\frac{\Delta_m}{m_o} \quad (3)$$

where M_{Al}, M_{Ti} and M_{O2} are the atomic weight of Al, Ti and O_2, Δm the mass increase due to oxidation and m_0 the initial mass of the sample into the TGA crucible. The results in Table 3 show around 5 % wt oxide for the powders.