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Flame phenomena in nanogrinding process for titanium and iron

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ABSTRACT

Minimum ignition energies of nano-iron and nano-titanium, both of which are extremely sensitive materials, are less than 1 mJ. A factory nanogrinder was operated for 15 min; the temperature increased from 44.25 °C to 46.25 °C and the relative humidity decreased from 47.5% to 36.1%. No combustion occurred at air speeds of 14.7 m/s and 23.5 m/s when 20 kg of micro-sized iron powder was mixed with 200 g of 35-nm iron powder particles in the grinding machine for 40 min. Grinding a mixture of 20 kg micro-titanium powder and 200 g of 35-nm titanium powder particles at an air speed of 14.7 m/s for 40 min did not generate a combustion reaction. However, combustion did occur 5 min after the initiation of a 23.5-m/s airflow, suggesting that the occurrence of combustion is related to the airflow speed. Combustion occurred when the electrostatic volts in the plastic hose of the grinder reached 2.3 kV. The combustion process lasted for approximately 0.1798 s and the temperature at this location increased from 25 °C to 130 °C. The pre-exponential factor (min^{-1}) was 3.18×10^{15} and the activation energy was 185.32 kJ/mol.

1. Introduction

The process of delivering nanograde metal by a high-speed gas is often subject to high explosion risk. For example, in Taiwan, the probability of an explosion during the grinding of nanograde metal powders is as high as 100% (Wu & Chang, 2007).

The principle of nanogrinding is to make use of the impact and collision forces of material particles that are continuously driven by airflow to comminute large-sized particles into fine grains. Nanograde metals are susceptible to explosion because their minimum ignition energies (MIEs) are very low. For example, the MIEs of nanograde titanium, iron, and aluminum are less than 1 mJ (Wu, Chang, & Hsiao, 2009). Presently, Eckhoff is developing equipment that can measure MIEs of less than 1 mJ in metal powder (Randeberg & Eckhoff, 2007) (Eckhoff & Olsen, 2010). Electrostatic charges may ignite nanometal powder. In a recent accident in a Taiwanese laboratory, electrostatic charges of approximately 1.8 kV ignited a fire when an operator moved 75-nm Ti particles from a polyethylene bag to a plastic plate (Fig. 1).

The maximum explosion pressure is denoted as P_{max}. The maximum rate of pressure rise $(dp/dt)_{max}$ was obtained when P_{max} was used at different concentrations of dust. The P_{max} values of 210-nm and 100-nm aluminum particles measured with a 20-L sphere are 12.5 and 11.2 bar g, respectively. Their deflagration index (K_{St}) values are 449 and 536 bar m/s, respectively (Holbrow et al., 2010). Bouillard et al. measured the P_{max} values of 100-nm and 200-nm Al to be 8.2 and 9.5 bar, and K_{St} to be 362 and 673 bar m/s, respectively (Bouillard, Vigne, Dufaud, Perrin, & Thomas, 2010). The P_{max} values of 35-nm and 100-nm Al are 7.38 and 12.5 bar, and the K_{St} values are 349 and 296 bar m/s, respectively (Wu, Kuo, Wang, Wu, & Hsiao, 2010; Wu, Ou, Hsiao, & Shih, 2010; Wu, Ou, Peng, et al., 2010).

The 20-L sphere probably disturbs the flame propagation and thermal mechanisms by absorbing radiation (wall-quenching effect) (Dufaud, Vignes, Henry, Perrin, & Bouillard, 2011). There are three possible explanations for these results: (1) preignition of the dust cloud from friction/impact during the injection/dispersion of the tested powder; (2) oxidation of the particle surface; and (3) agglomeration/coagulation of the primary particles (Eckhoff, 2011).

The explosion of nanoparticles has been tested by passing air through the bending tube (Wu, Kuo, et al., 2010; Wu, Ou, Hsiao,et al., 2010; Wu, Ou, Peng, et al., 2010). Four different air velocities were used in the experiment: 13, 8.5, 6.5, and 3.5 m/s. Titanium powder ignited spontaneously at all of the airflow velocities. The iron powder ignited at all velocities except 3.5 m/s.

The purpose of this research was to explore conditions such as changes in the temperature, humidity, electrostatic charge, and air speed that triggered the ignition of titanium and iron in a grinder. A high-speed camera was used to capture photos at the instant when

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Fig. 1. Fire triggered by electrostatic charges when Ti-75 nanoparticles in polyethylene bag were taken from plastic plate.

fire was ignited. In addition, a temperature sensor was used to test the temperature changes during combustion to obtain kinetic parameters.

2. Materials and methods

2.1. Chemicals and experimental equipment

2.1.1. Chemicals

Metal powders of different particle sizes used in the present research were obtained from Yong-Zhen Technomaterial Co., Ltd. The experiments used 20 kg each of micro-iron and micro-titanium and 200 g each of nano-iron and nano-titanium powders. Material specifications are listed in Table 1.

2.1.2. Equipment

a. The nanogrinder (Fig. 2) was manufactured by Hsin Fang Co., Ltd. This equipment uses a roller to squeeze the powder granules to form small dust particles. The particles are then spun in a cyclone to separate the nanoparticles. Larger particles are transferred back to the grinder.

b. The EFM022 electrofield meter produced by Kleinwächtere was used. Measurement was performed once every 10 min.
c. The FASTCAM SA3 high-speed camera manufactured by Photron was used to capture the photographs. The maximum speed was 200 kHz with a sampling speed of 1/5000 s. The high-speed camera was used to study the fire/explosion of fine particles in the grinder by capturing every instant in the process.
d. A thermocouple produced by Omega was used for temperature measurements. The measurement point was on the hose located at the cyclone entrance (Fig. 3).
e. ASAP 2010, produced by Micrometrics, was used to measure the specific surface areas of the particles.

2.2. Experiments

Micrometal and nanometal powders were mixed in the grinder and ground to confirm the combustion of nanoscale material.

2.2.1. Measurement of temperature, humidity, and electrostatic charge in grinder

(a) To measure changes in the grinder temperature and the humidity of the cyclone, 20 kg of micro-iron powder was added at an air speed of 14.7 m/s and grinding pressure of 900 kg/cm^2.
(b) To measure the electrostatic charge, the EFM022 electrofield meter was used once every 10 min at locations A, B, C, and D, as shown in Fig. 1.

Table 1
Specifications of micro- and nano-titanium and iron powders.

Type of sample	Range of diameter	Average diameter[a]	Surface area[b] (m^2/g)
Micro- and nano-titanium powders			
30-nm Ti	15–45 nm	30 nm	60
45-μm Ti	20–70 μm	45 μm	0.15
Micro- and nano-iron powders			
15-nm Fe	10–20 nm	15 nm	75
150-μm Fe	75–220 μm	150 μm	0.06

[a] The average particle size was calculated by using projections from a scanning electron microscope. The confidence interval was 99% with a sample size of 100 particles.
[b] Specific surface area was measured by ASAP 2010.

Fig. 2. Grinder. Electrostatic charge was measured at locations A, B, C, and D.

2.2.2. Measurement of combustion temperature and photograph

A high-precision fine-wire thermocouple was used in this experiment to measure the temperature variation during combustion; photographs were captured using a high-speed camera to observe the combustion phenomena. The measurement location with the thermocouple (location 3 in Fig. 3) was decided on the basis of the maximum electrostatic volt measured with the electrofield meter.

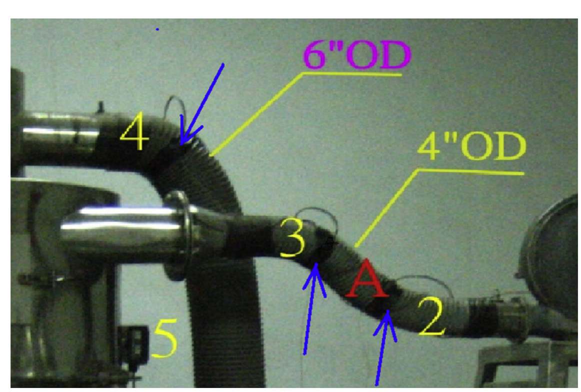

Fig. 3. Thermocouple is at position 3. Humidity meter is at position 5.