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An investigation of an ignition of flammable gaseous mixtures with mechanical sparks

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ABSTRACT

This article describes a method for testing the safety of construction materials with respect to mechanical sparks (spark safety). This method was tested on examples of various materials and flammable gases. Hydrogen, acetylene, petrol, methane and LPG were used as the flammable gases. Various types of steel, aluminium, and copper and aluminium alloys were used as the construction materials. On the basis of the experiment a criterion for spark safety was proposed.

1. Introduction

It is well known that particles formed as a result of a counteraction of moving surfaces can be heated to high temperatures depending on the sizes of these particles and the composition of the gaseous environment. These temperatures can be so high that they radiate in the visible part of spectrum. Such particles are called mechanical sparks and can be produced as a result of friction or the striking of moving bodies. Mechanical sparks are one of the most frequent ignition sources for flammable gaseous mixtures.

A series of normative documents contain requirements for the application of spark safety materials in cases where flammable gaseous mixtures can be produced, owing to accidents [1–4]. However, the normative documents determining a testing procedure for a determination of the spark safety of the construction materials are not complete. For example, documents [1,2] only contains common regulations for spark safety. The standards [3,4] contain method for testing of materials on spark safety in the case of friction or collision separately. But in practice at malfunctions of equipment both friction and collisions can take place quite simultaneously, and no method for testing was proposed for this case. There is a recommendation [5] which was used successfully for more than 10 years for the determination of the spark safety of construction materials. This study is aimed at an improvement of the method [5].

2. Background

An analysis of earlier works on investigations into ignition capability of sparks obtained from collisions and/or friction was published in [6,7]. Now we will consider more modern studies.

An experimental investigation of the ignition capabilities of mechanical sparks was performed [8]. It was found that the mechanical sparks in 30–50% of accidents were the cause of industrial fires and explosions, and this peculiarity does not change over time. This situation is also caused by the knowledge of such an ignition source. Therefore, in [8], mechanisms of dissipation of mechanical energy into heat at collisions and frictions, as well as probable mechanisms of ignition of gaseous mixtures with mechanical sparks, are considered.

In the experiments in [8] a set-up with a rotating wheel of a diameter 10 or 30 cm was used. The wheel was in contact with a horizontal plate of sizes 7×7 or 25×25 mm^2. Linear velocity of a part of the wheel contacting the plate was in the range of 0.2–20 m/s, with a load 5000 N. The temperature of the plate was measured by means of thermocouples and an infrared pyrometer. The wheel was made of tempered steel. The plate was made of tempered or non-tempered steel, aluminium and its alloys, quartz. According to estimations of the authors [8], the pressure in the zone of a contact was several MPa.

It was found that hot solid particles produced by friction had a typical size of several hundred microns. The temperature of the horizontal plate at the power of 4 kW was up to 1000 °C for the wheel of diameter 30 cm, and 500 °C for the wheel of diameter 10 cm. According to the estimations [8], nearly 80% of the energy released by friction was dissipated via thermal conductivity. The heated particles (mechanical sparks) had a mass in the range of

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0.07 to 7.5 g, depending on conditions of friction and the type of materials. The frequency of particle formation was near several tens per second. Approximately 1% of the released energy was spent on particle formation.

For an investigation of the mechanical sparks produced as a result of collisions an experimental set-up with a target in the form of a steel plate of size $5 \times 70 \times 45\ cm^3$ was used, and the investigated body collided with this target. The target was inclined at an angle of 60°, in order to produce optimal conditions for spark formation. The velocity of collisions was in the range of 5–50 m/s. The collision was registered by means of video camera. A colliding body was a cylinder of diameter 18 mm and length 5 and 20 cm, made of steel, copper and aluminium.

It was found that the temperature in the place of a collision can reach 600–700 °C, and then drops substantially after 2–3 ms. Typical pressures in the place of the collision can reach several hundred MPa; that is, this pressure is twice the order of magnitude than pressures from friction. As a rule one particle of 2–4 min in size is formed, which moves with a velocity close to the velocity of the collision. The temperature at the place of the collision does not depend on the cylinder length and is determined mostly by the collision velocity.

An ignition resulting from friction and/or collision can be realized as a result of three mechanisms:

a. ignition by a hot surface in place of friction and/or collision;
b. ignition owing to the heating of a flammable gaseous mixture in a confined space, as a result of heat released by friction and/or collision;
c. ignition caused by mechanical sparks produced by friction and/or collision.

It was found that mechanism (a) is the main one.

On the basis of the experiments, the authors [8] made the following conclusions. In the case of friction, ignition always occurs quite near the surface heated by the friction. The ignition temperature does not correlate to the standard auto-ignition temperature. The power released by the friction is usually several per cent of the total power. In order to obtain a high enough temperature for ignition a time interval of not less than several seconds is usually required. Maximum temperature in the friction zone depends strongly on the power released, owing to the friction.

In the case of a collision, ignition takes place by means of a hot surface. The possibility of ignition is determined not by the kinetic energy of the collision, but by relative velocity.

The particles produced as a result of friction and/or collision have a low capability of igniting the flammable gaseous mixtures in comparison with the hot surface. The temperature of this surface is the most important parameter.

The ignition of methane–air mixtures by mechanical sparks produced by light metals and alloys was investigated in [9]. It was found that the ignition from friction is caused by a hot surface and mechanical sparks (hot fine particles). Ignition is more probable from the friction of bodies made of light alloys and the surface of rusty steel. Experiments have been carried out in which the mechanical sparks were produced from the free-falling of the tested specimen on to the surface of rusty steel. Four specimens were tested (Table 1).

The specimen had a length of 50 and a diameter of 60 mm. The energy of collisions was regulated by the mass of the specimen and its height over a target. The target was a plate made of rusty steel, with horizontal sizes $400 \times 160\ mm^2$ and a thickness of 12 mm. The specimen and the plate were located in a chamber of volume 1 m^3. Maximum height from the specimen and the plate was 4 m. The specimen fell on to the plate at an angle of 45°. The chamber was filled with a methane–air mixture of the required composition.

Table 1
Compositions of specimens made of light alloys.

No.	Chemical compositions of the specimens (%)										Type
	Si	Fe	Cu	Mn	Zn	Ni	Ti	Cr	Mg	Al	
1	11.5	0.9	0.3	0.4	0.3	0.1	0.2	0.2	0.2	The rest	Al–Si
2	0.4	0.5	1.6	0.3	5.5	–	0.2	0.2	2.5	The rest	Al–Mg–Zn
3	0.2	0.3	0.1	0.6	0.2	0.2	0.2	0.2	4.5	The rest	Al–Mg
4	0.3	–	0.3	0.2	1.0	–	–	–	The rest	3.0	Mg

The probability of the ignition's dependence on the a height of the fall of the specimen, of mass 14 kg, for various mixture compositions, was measured. The most easily ignitable mixtures contained 6.5–7% methane in air. A probable reason for this peculiarity is the reaction of oxygen for the oxidation of the particles. For a 4 m height and the optimum methane concentration, the probability of ignition is close to 90%. For 3 and 2 m heights this probability is equal to 60 and 25%, respectively. The ignition probability depends on the roughness of the surface and the mass of the specimen. If this mass is lower than 5 kg and the height is lower than 4 m no ignition takes place. The authors concluded that the ignition probability is not determined by the mass of the specimen and its height separately, but by the potential energy of the specimen.

On the basis of the investigations in [9], the following conclusions can be made:

1. collisions of specimens made of light alloys and steel have a high ignition capability, owing to the formation of a hot surface heated additionally by the exothermic reaction of the light alloys with rusty steel.
2. The height of the fall of the specimens is one of the most important parameters determining the ignition capability.
3. Collision energy, which results in an ignition probability of 50%, can be used for the evaluation of the ignition capability.
4. The availability of Mg in light alloys substantially increases the ignition capability.

The investigation [10], aimed at the exploration of the influence of a footwear material and the material of a floor on the ignition capability of gases and vapours by mechanical sparks. A hot surface and mechanical sparks are produced. These mechanical sparks in a process of their movement can be additionally heated, owing to a reaction with air. Lean gaseous mixtures have a higher ignition capability. Mechanical sparks with a high ignition capability usually occur in the case of light metals (alloys of cerium, aluminium, magnesium, and titanium) and sometimes in the case of heavy metals (hafnium, zirconium).

At present there is no systematic classification of flammable gases and vapours on their ignition capability by mechanical sparks. The classification connected with explosion-proof electrical equipment can be only used very approximately.

Experiments were carried out to model the ignition of gaseous mixtures of methane–air (7% CH_4) with mechanical sparks from the collision of footwear with a flooring material. The typical velocity of the sliding collision was 7.6 m/s. The experiments were performed with specimens made of steel and tungsten carbide. Nearly 500 collisions were made with the velocity 9.4 m/s, and 500 collisions with the velocity 6.4 m/s. Nearly 33% of the collision energy was dissipated into heat. It was found that quartz as a flooring material has a much greater ignition probability than metals.