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Experimental investigation of low-voltage spark ignition caused by separating electrodes

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ABSTRACT

Electric arcs pose an ignition hazard in the presence of flammable gas mixtures. Electrical equipment to be used in such hazardous environments shall therefore satisfy strict safety requirements, through the use of internationally standardized explosion protection methods as e.g. “Intrinsic Safety”, documented in the IEC 60079-11 Standard.

This “Intrinsic Safety” is verified by using a stochastic empirical procedure, using a “Spark Test Apparatus” connected to an electrical energy source. The apparatus generates electrical discharges between a separating tungsten anode and a cadmium cathode enclosed in a test cell filled with flammable gas atmosphere. The connected electrical circuit is considered intrinsically safe if no ignition results within a defined number of contacts. However this procedure suffers from variability and poor reproducibility.

The goal of this work is to investigate the relationships between such arc discharges and the ignition of the gas. The measurement is technically challenging, as the physical processes occur in different time scales (ns, µs, ms) and the physical dimensions are small (µm). Additionally the ignition process can also damage the experimental equipment.

An important prerequisite for such discharges is a sufficient degree of electrode surface wear. Microscope images show such electrode surfaces as well as the presence of metal whiskers. These inhomogeneous rough surfaces are compared by the means of Abbott curves.

A spectral analysis of the radiation from the electrical discharge shows, that the main substance is cadmium vapour.

The electrical characteristics of these arcs are characterised by voltage, current and length curves. For constant currents from 74 to 270 mA up to a voltage of 40 V, the transient arc lengths, voltages and currents were measured for arc discharges generated in a 21% Hydrogen-Air gas mixture. These initial results appear to correspond qualitatively to published curves for static arcs, however the accuracy of the measurements has to be improved.

Knowledge of these relationships between electrical, mechanical and ignition processes will ultimately make it possible to recognize discharges which most likely cause an ignition by their current and voltage waveforms. This will allow the development of a more reliable alternative, where discharges are electronically simulated.

1. Introduction

Separating or breaking electrical contacts are a major cause of incendive arcs in flammable gasses. The specification of safety critical maximum parameter values therefore plays a central role in the qualification of electrical circuits for use in explosive atmospheres. The determination of these maximum values for the explosion protection concept known as Intrinsic Safety is based primarily on incendive arcs produced in a “Spark Test Apparatus”, defined in standard IEC 60079-11 (2012). This apparatus evaluates the influence of the circuits’ current and voltage outputs on the ignition process.

In this paper, circuits supplied by 40 V rectangular current limited source are investigated. The abovementioned IEC standard

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does not provide any safety critical limits for this type of circuit. For circuits with linear (resistive) outputs, the standard specifies a maximum current of 57 mA, where a 1.5 safety factor (SF) is required and 83 mA for an SF of 1.0. Within these circuit limits, typical incendive discharge energies are between 18 and 100 μJ.

Under the IECEx system, measurements made with the Spark Test Apparatus were compared across many different certification laboratories worldwide, revealing an extremely high statistical spread of results. The disadvantages of the Spark Test Apparatus, other than poor reproducibility, are the use of toxic cadmium and flammable gas, as well as the high level of competence demanded for personnel undertaking the measurements. These difficulties have resulted in interest for developing an Electronic Spark Test Apparatus, which can be connected to the circuit under test and simulates the incendive spark electronically, evaluating safety with analysis of electrical parameters (Shekhar and Uber, 2015). For this purpose, the electrical and non-electrical parameters relevant to the spark ignition process must be measured and analyzed.

The initial investigations presented here are concerned with contact opening discharges resulting from a current limited voltage source.

To the best of the authors' knowledge, previous studies of incendive arcs in explosion safety did not consider the particular situation studied here as a whole. Certain parts of the process, such as the mechanical contact movement, have however been handled in depth by previous literature. The ignition process overall is described in the following sections.

2. Background

2.1. Overview of the arc formation process

At the start of the opening arc process, the tungsten wire slides over the rough surface of the cadmium block. Shortly after, the wire enters a groove, maintaining a distance of a few micrometers from the surface. The wire then continues to separate from the edge of the cadmium block. These phases of the contact movement are described in Fig. 1.

In the Spark Test Apparatus, the tungsten wire moves over the cadmium disc with varying velocities. In accordance with the standard, the wire must overlap the edge of the disc by 1 mm and therefore bends and straightens elastically during movement. In practice, with an overlap of around 0.7–1.2 mm the wire accelerates when straightening (i.e. separating from block) starting with a speed of 0 m/s to speeds of 26.8–31.1 m/s (Zalogin, 2006).

In the first phase of movement, the electrical contact results from a microscopic sized contact surface area (due to the surface roughness), which may also be covered with impurities such as cadmium oxide. As the contact surface area decreases, the current density increases. This leads to an increase in temperature, which, when high enough to melt the metal, produces a molten metal bridge between the contacts. This molten bridge can vaporize explosively when its temperature reaches the boiling point of the metal. Such temperatures can result even with relatively low contact voltages (eg. 0.7–2 V), depending on the contact material (Vinaricky, 2002; Slade, 2014).

In the transitional phase, where the contact distance is of the same order of magnitude as the mean free path of the surrounding gas (i.e: a few μm), a so called "short arc" plasma consisting mainly of metal vapor results. In this discharge electrons are released by field emission and thermionic emission can also result. By evaporation of cathode material additional charge carriers are also generated. Field enhancement through micrometer scale asperities, as well as areas with lower work function (such as grain boundaries or impurities), can also support the discharge (Rieder, 1967; Johannsmeyer, 1984). Additional cathode material can also be vaporized due to high current density in micro asperities. (Meysats and Proskurovski, 1989).

Around the electrodes, a space charge region of increased field intensity develops, with a thickness of around 0.1–1 μm. This is termed the fall region, and results in a fall voltage of 9.8 V near the cadmium cathode. A fall voltage can result from tungsten anode, but only with currents orders of magnitude higher than those studied here (Boxman et al., 1995). As the contact distance increases, higher voltages are necessary to maintain the arc (Rieder, 1967).

The phenomena described here have not yet been investigated in situations where they occur together. Electrical contact related studies considered mostly electrical processes and material parameters (Slade, 2014; Vinaricky, 2002). Other phenomena are considered in gas and plasma studies. Although some of these also examine arc voltages and currents, only static electrodes are considered (Rieder, 1967; Fridman and Kennedy, 2011). Previous work concerning plasma surface treatment technology also exists, however significantly higher currents are normally used in this application.

It is also important to note that none of these areas of study include the ignition of flammable gas mixtures. Spark ignition of gas mixtures is also well studied, particularly in internal combustion engine applications, however the discharges here involve high voltage gas breakdown (Schäfer, 1997).

After the discharge takes place, an expanding high temperature ignition kernel results. If the kernel reaches a sufficiently large radius and the necessary energy density is reached, the flammable gas mixture can ignite (Warnatz and Maas, 1993). For a mixture of 21% hydrogen in air (by volume), a minimum ignition energy of 17.2 μJ ± 2.3 μJ was measured, for an arc with electrodes 0.5 mm apart (Wähner et al., 2013).

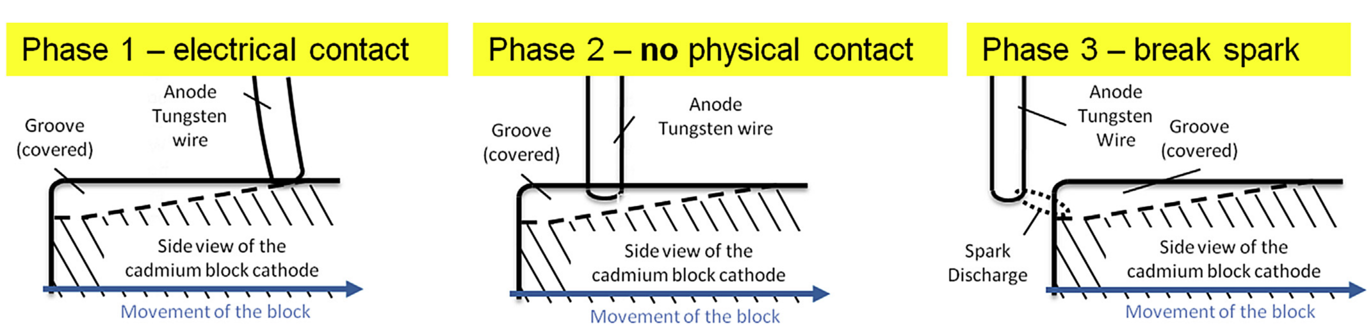

Fig. 1. Contact movement phases of an opening spark.

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