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Mechanical Sparks as an Ignition Source of Gas and Dust Explosions

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Mechanical sparks and friction are one of the most common causes of ignition of flammable gas and dust clouds. Mechanical sparks can arise due to processes involving friction, grinding or impact and can occur e.g. in case of disturbances in rotating equipment causing the rotating parts of the machinery (repeatedly) to come into contact with each other at relative high speeds. Also, application of hand tools such as drills, grinding machines, welding and cutting torches and hammers can lead to the generation of mechanical sparks. Single impact sparks may arise due to collisions between two objects.
Accident statistics concerning dust explosions occurring in Germany indicate mechanical sparks and friction as the ignition source in 32.7 % of the incidents (Jeske and Beck, 1997). Billinge (1979) presented an overview of 66 incidents where gases or vapours were ignited by something referred to as frictional ignition. 68 % of the reported incidents were caused by impact, 20 % by friction and 12 % by cutting and grinding operations. Generally, speaking it is unclear whether the ignition occurred by mechanical sparks or by a hot surface generated by the impact/friction. The fraction of gas and vapour explosions ignited by mechanical sparks and frictional heat is unknown.
Mechanical sparks are caused by friction, rubbing or single or multiple impacts of objects of similar or dissimilar materials causing small parts of this material to be torn loose. These small pieces of material are due to the energy absorbed hot and may during their flight start burning resulting in very high temperatures. Melting and evaporation of this mechanical spark may cause it to burst increasing its surface area and thereby its incendivity. This article reviews work performed addressing ignition of gas and dust clouds by mechanical sparks and friction. The review starts from the work performed in connection with coal mine explosions performed in the 1950's and 1960's and works published since then. The majority of the reviewed literature concerns experimental work but also theoretical studies have been included in the review.

1. Mechanisms

Mechanical sparks are small particles, which due to the impact between two objects are torn loose from the surface of one of the two colliding objects. The kinetic energy is turned into heat and deformation work. The heating of the particle may cause the particles to become visible. If the material of the particle is flammable the heating of the particle may cause the formation of an oxide layer around the particle whereas the inner part of the particle will melt. The melted kernel may ignite and burn causing also the oxide layer to melt. The combustion may cause the temperature to be that high that the oxide layer evaporates (Ritter, 1984). Mechanical spark generation is dependent on the pressure with which the one object is working against the other, the relative speed between the objects, the friction coefficient and the hardness of the materials involved. The particle size of mechanical sparks depends on the hardness of the material. High hardness results in small particles but if the temperature of the material increases the hardness decreases causing particle sizes to increase.
There is a minimum speed for generation of sparks depending on the pressure with which one object is working against the other, the materials of the objects and the relative speed. Figure 1 shows an example for different steel objects being ground and rubbing against each other. The Figure also shows the relative speed at which the steel objects start glowing.

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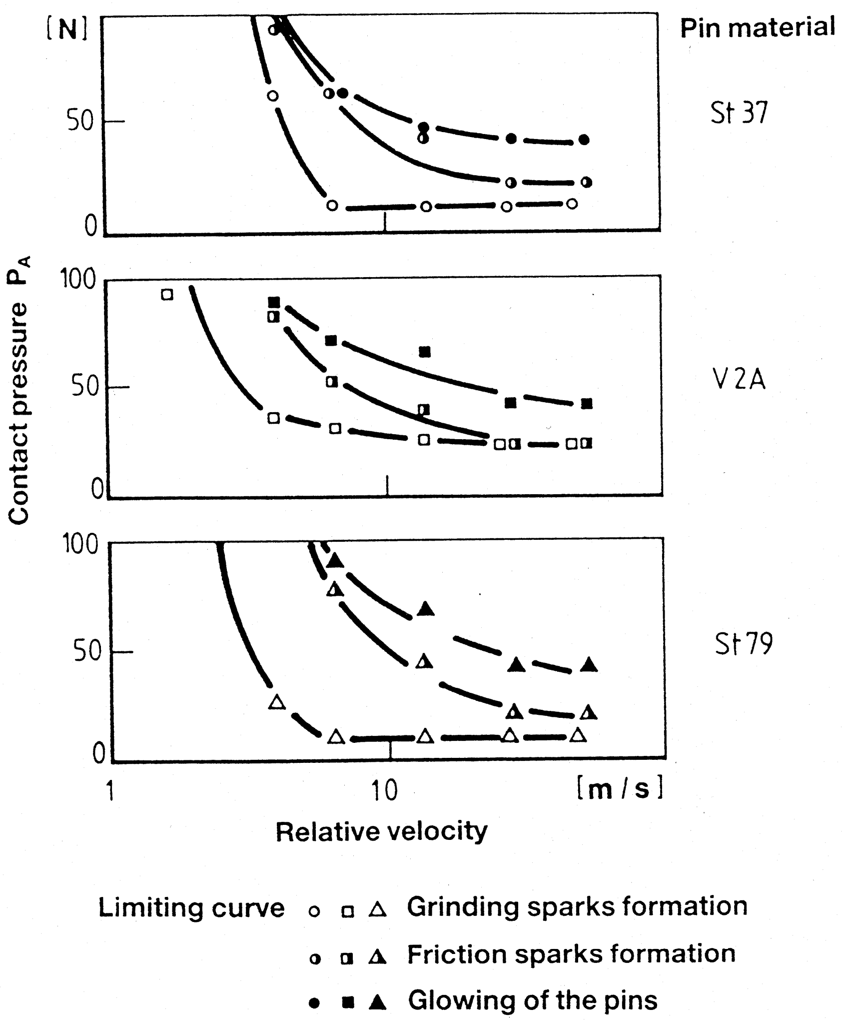

Figure 1: Relative velocity of steel pins being ground or rubbing needed to generate grinding sparks, friction sparks or glowing of one of the objects as a function of the pressure with which one object is working against the other (Bartknecht, 1982)

Apart from the oxidation and combustion of the particles the heat transfer to the surroundings per unit of distance travelled increases with decrease of the speed of the particle and due to bursting of particles (e.g. due to evaporation) causing the surface area of the particle to increase.
The temperature of mechanical sparks vary depending on the forces involved generating the sparks, the relative speed between the contacting objects and the size and material of the sparks. Ritter (1984) reported temperatures above the boiling point of the material in question (e.g. for iron ~3200 °C). Boczek et al. (1983) using a grinding wheel measured mechanical spark temperatures in the range of 1727 – 2127 °C for steel (above the melting point but far below the boiling point). The shape of the particles was either spherical or those of shavings. Comparable temperatures were reported by (Hardt, 1954) for a big number of steel types. The maximum temperature of shavings was approximately 350 °C.

Mechanical sparks may also involve conditions where the contacting surfaces react together. An example of such a reaction is one between aluminium and an oxide such as rusty steel which is referred to as the thermite reaction:

$$Fe_2O_3\,(s) + 2\,Al\,(s) \rightarrow Al_2O_3\,(s) + 2\,Fe\,(s)$$

This reaction is exothermic, releasing heat, making such mechanical sparks more incendive.

According to Rogers et al. (2006) rubbing produces long duration hot surfaces and generally none or only a few sparks. Grinding also produces long duration hot surfaces, generally with large numbers of sparks depending on the material. Tests performed indicate that hot material around the frictional hot surface (e.g. trailing edge burr) is a much more potent ignition source than sparks. The efficacy of the ignition source produced depends on the power, load, speed, size and coefficient of friction associated with the friction process and the confinement of the equipment in which the hot surface is produced. Hawksworth et al. (2004) investigated especially the hot surfaces generated by rubbing. A wheel constructed from duplex stainless steel, which was chosen for its hardness, high melting point and low thermal conductivity could operate achieving circumferential velocities between 0.4 m/s and 20 m/s. Sliders of different materials are brought into contact with the edge of the spinning disc with a controlled force of up to 5000 N.
The temperature of the contact zone between the disc and the slide as a function of the rubbing speed and the contact pressure was measured showing that ignition at a hot surface would theoretically be possible at relatively low speeds depending on the auto-ignition temperature of the fuel. Temperatures > 1000 ºC were measured for speeds exceeding 6 m/s or contact pressures exceeding 1.5 N/mm^2. Where the materials are dissimilar, the softer lower melting material will produce a lubricating layer and limit the temperature generated in the contact zone. Several possible ignition mechanisms were identified:

- Exposure of the contact region to the explosive atmosphere.
- Spark production where hot particles are thrown some distance from the contact zone at high speed;
- Production of larger hot chunks which are thrown from the contact zone at lower speed but in many ways represent a more potent ignition source because of their size;
- Hot burrs formed on the trailing edge of the contact zone, which remain attached to the stationary surface and progressively become larger as the rubbing continues
- Conduction of heat from the contact region to adjacent surfaces to produce high temperatures

Lorenz et al. (2015) showed that during experiments investigating the effects of friction between two steel surfaces that approx. 20 % of the energy put into the steel surfaces is used for heating, 3 % in generation of metal sparks 20 % in loss of energy by radiation, 33 % in loss by convection and 25 % in loss by conduction. Still, extrapolation of the experimental results using a model it could be shown that incendive hot surfaces can be generated also at relative speeds of < 1 m/s.

2. Ignition tests

There are numerous articles addressing ignition of gas, vapour and dusts by mechanical sparks. Early investigations were devoted to safety in coal mines. Below some investigations have been described briefly.
(Dittmar 1965) describes experiments reported by K. Gaulrapp and Feber (Zündung brennbarer Gas/bzw. Dampf/Luft-Gemische, Arbeitsschutz, 7, 97, 1944) presenting a systematic investigation of the incendivity of steel sparks generated by grinding. The sparks were generated by pressing hardened carbon steel rods against an aluminium oxide wheel with a force of 2.105 N/m^2. The outer velocity of the wheel was 10 m/s. The incendivity of the steel sparks was investigated for a number of fuels: ammonia, acetylene, ethylene, carbon monoxide, methane, hydrogen, butane, butylene, propane, propylene, acetaldehyde, acetone, ethyl alcohol, ethyl ether, benzene, petrol, n-hexane, methanol, n-pentane and carbon disulphide. The various gases and vapour were investigated over a wide range of concentrations. The steel sparks appeared incendive for acetylene, ethylene, carbon monoxide, hydrogen and carbon disulphide. For these gases the lowest ignitable concentration often coincided with the lower explosion limit. The upper flammable limit was however far below the upper explosion limit of these respective gases and vapours with the exception of carbon disulphide, which could still be ignited by the steel sparks at a concentration of 50 % carbon disulphide and air. The upper explosion limit of carbon disulphide is 50 % v/v (Kuchta 1985).
(Dittmar 1965) also report on experiments performed by Voigtsberger, P. (Zündfähigkeit von Schleiffunken gegenüber explosiblen Gas/ und Dampf/Luft-Gemischen, Arbeitsschutz, 191, 1955). He performed mechanical spark incendivity experiments with different steel types. He used an aluminium oxide wheel with an outer velocity of 22 m/s pressing the steel with a pressure of 105 N/m2. The tests were performed using hydrogen-air mixtures. The concentration range over which the mechanical sparks were able to ignite the hydrogen-air mixtures were used as a measure of incendivity. The lower explosion limit was similar for all steel types whereas the upper explosion limit where the mechanical sparks still were able to ignite varied.
(Dittmar 1965) reports a direct relationship between the size of the mechanical spark particles generated and the range of concentrations that can be ignited. The size of the particles was at its turn shown to be related to the crystalline structure of the steel. When the hardness of the various parts of the crystalline structure varies considerably, the size of the particles appears directly related to the size of the harder parts of the structure.

(Schulz F. 1963) report on single impact sparks and their incendivity against hydrogen-air mixtures. The impact sparks concern low angle impacts (streaking) with an energy of 3.4 J. The impact occurred against an anvil of rusty steel and one made out of granite.

The tests performed with the combination steel-rusty steel resulted in ignition in the concentration range of 4.9-5.0 – 13.7-13.8 % v/v for two steel qualities with differing hardness. It was concluded that for this combination pieces of the anvil were torn loose and not from the impacting materials explaining the result of the test. For the steel-granite combination the mechanical sparks were torn loose from the impacting steel and the concentration range over which the sparks appeared incendive was 5.0-43 % v/v hydrogen-air indicating that hot burning steel particles were generated.

Powell (1969) in his review of gas and vapour ignitions, has produced tables showing the incendivity of ignition sources (metal, stones) produced by a range of impact and rubbing situations for a number of gases and vapours.

Ritter (1984) and Bartknecht (1982) report on experiments performed with three types of mechanical sparks: frictional sparks, grinding sparks and single impact sparks.

The frictional sparks were generated by moving a small part of a fine file against a piece of flint over a distance of 10 mm. During the movement the fine file was pressed with a force of 88.3 N against the flint using a spring. The speed of the fine file was 1 m/s resulting in a duration of the spark generation of 10 ms. The tests revealed that the frictional sparks (flint) could ignite several gases (butane, propylene, propane, hydrogen, methane) over a large range of concentrations. They also showed that using the respective ignition energies necessary to ignite the boundary concentrations for the range of concentrations where flint sparks are incendive and plotting those as a function of the auto-ignition temperature of the fuels (in °C) single relationships were found which indicated a borderline between gases and vapour which can be ignited by flint and which cannot. According to Bartknecht (1982) and Ritter (1984) similar relationships could be defined for grinding sparks and single impact sparks. For generation of the grinding sparks a grinding wheel with an outer velocity of 35.3 m/s was applied. 4 mm diameter rods of different materials could be pressed against the grinding wheel with a force that was varied between 2.46 N and 88.3 N. The tests showed that the most optimal conditions to obtain ignition were found when the outer velocity of the grinding wheel was chosen to be 8.8 m/s and with a force pressing the rods against the grinding wheel of 36.8 N. To avoid hot surfaces from being generated the grinding duration was limited to 20 ms.

For the flammable gases the results show that the lower concentration ignition limit of grinding sparks of flint are very similar to those seen for frictional sparks of flint. Again, it was shown that single relationships between minimum ignition energy and auto-ignition temperature could be defined indicating a borderline between gases and vapours which can be ignited by flint and which cannot. Ritter (1984) showed this for grinding sparks of different materials: iron, titanium, zirconium and flint. Similar tests performed with stainless steel (type V2A) did not lead to any ignition event. Ritter (1984) also showed that the relationships obtained for the various grinding sparks could be used directly for assessing the incendivity of mechanical sparks of dust-air mixtures.

For single impact sparks 6 mm diameter rods of different materials were mounted onto a rotating wheel. The speed of the tip end of the rods was 35.3 m/s at a maximum impacting onto a plate of which the angle could be varied. The material of the rods and plate could be varied.

The combination steel-steel (hardened steels) did lead to sparks but not to any ignitions. This was different for the combination aluminium or titanium and rusty steel which led to ignitions. Ignitions were also obtained for single impact sparks of titanium rods impacting on plates of steel types St 37 and 1.2842.

Using the results of early studies (Konschak and Voigtsberger, 1957; Schulz and Dittmar, 1963) some of the relationships suggested by Ritter (1984) were verified. For this verification published data on the minimum ignition energy of gases and vapours was used. Figure 2 shows the incendivity of grinding sparks of steel (from Konschak and Voigtsberger, 1957) versus the relationship suggested by Ritter (1984). The agreement can be described as satisfactory. This is however not the case for single impact sparks involving aluminium and rusty steel (termite reactions). The relationship suggested by Ritter (1984) does not seem to be conservative when comparing to the results obtained by Schulz and Dittmar (1963) as is presented in Figure 3.

Ritter (1984) also states that the same relationships can be used to assess the incendivity of dust-air mixtures. There is unfortunately very little data (no information on minimum ignition energy as a function of concentration of published data) available to verify the relationships for dusts. In his review Lunn (2000) expressed his doubts wrt the appropriateness of the suggested relationship for thermite sparks igniting dust clouds based on experiments reported by Gibson et al (1967).

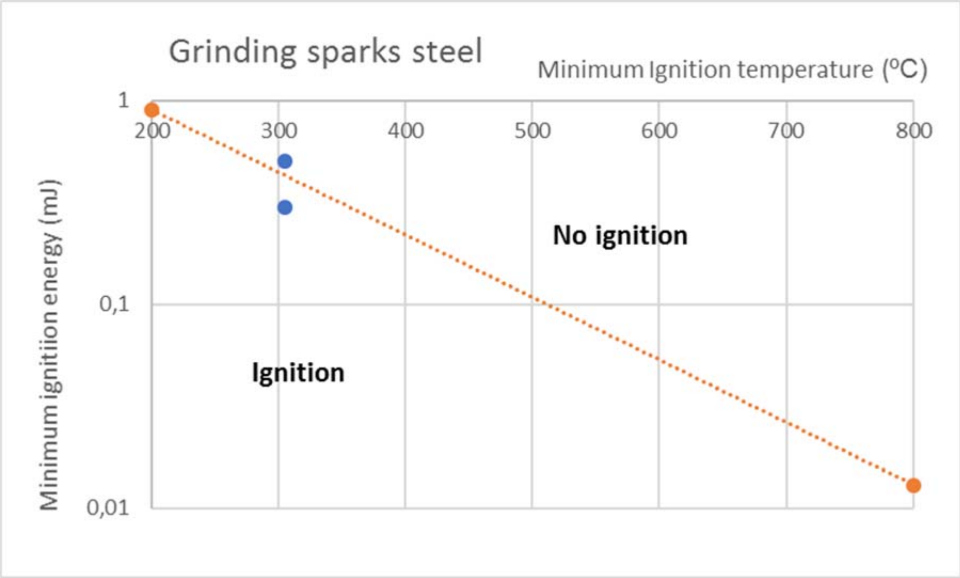

Figure 2: Relationship distinguishing between fuels that can be ignited by steel grinding sparks and those that cannot as suggested by Ritter (1984) compared to results by Konschak and Voigtsberger (1957).

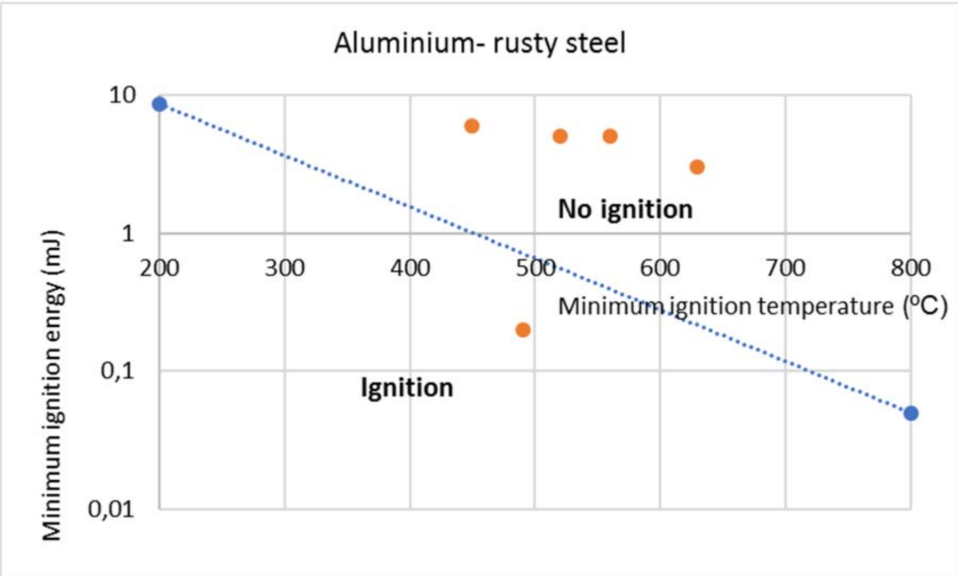

Figure 3: Relationship distinguishing between fuels that can be ignited by steel grinding sparks as suggested by Ritter (1984) compared to results by Schulz and Dittmar (1963).

According to Meyer et al (2015) the occurrence of mechanical sparks due to friction processes cannot occur without the generation of hot surfaces. Prior to the occurrence of mechanical sparks, hot surfaces are always developed. As a result and supporting the work reported by Rogers et al. (2006) and Hawksworth et al. (2004) conclusions regarding the incendivity of mechanical sparks need to be made with care. This in spite of the fact that many authors made efforts to prevent hot surfaces from occurring. Meyer et al (2015) developed limiting power densities (surface pressure (N/mm^2) vs relative velocity) for the ignition of hydrogen, ethylene, diethyl ether, propane and pentane/air mixtures for friction processes with stainless steel showing that also at relative velocities < 1 m/s ignition at hot surfaces are possible. Holländer et al (2016) showed that also impact sparks generate hot surfaces. The authors investigated impacts between stainless steel components showing that hydrogen-air mixtures were mainly ignited by the hot surfaces not the mechanical sparks. Acetylene-air mixture on the other hand were more often ignited by mechanical sparks. The probability of ignition increases with increasing kinetic energy.

3. Conclusions

Mechanical sparks have been indicated to be the cause of many explosion incidents. The current review tried to give an impression on the large number of investigations available. A comparison of studies performed in the 1950's and 1960's with criteria suggested by Ritter (1984) show that the criterion suggested for steel grinding sparks is satisfactory whereas the one suggested for aluminium-rusty steel impact sparks tends to underpredict the incendivity of such sparks.
More recent research indicates that ignition due to friction or single impacts may have occurred to hot surfaces instead of mechanical sparks.

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