IGNITION OF EXPLOSIVE ATMOSPHERES BY MECHANICAL EQUIPMENT

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Ignition of explosive atmospheres by mechanical equipment is a problem in many industries and has led to a large number of incidents including those that have been classified as Major Accidents with serious effects(1). The European ATEX Directives (94/9/EC(2) and 1999/92/EC(3)) are designed to improve the control of hazards in explosive atmospheres by a number of means, one of which is the control of all ignition sources, including those from mechanical equipment.

This paper discusses the problem of ignition by mechanical equipment and identifies factors that may be of importance in assessing mechanical systems for use in explosive atmospheres. The parameters describing the mechanical generation of heat (power, energy, speed and load) during rubbing, grinding and impact are discussed together with how they might effectively be related to the ignition characteristics of explosive atmospheres. The discussion draws on data and findings from the MECHEX project (EU contract G6RD-CT-2001-00553) to illustrate possible approaches and problems, and where further investigation might be required.

INTRODUCTION

Ignition of explosive atmospheres by mechanical equipment occurs when energy supplied by equipment used for processing or conveying of material is converted into heat, usually as the result of a mechanical failure of the equipment or associated systems. Such events have led to a large number of accidents causing death, injury and financial loss(1).

Work is ongoing as part of the EU project MECHEX (MEChanical ignition Hazards in potentially EXplosive gas and dust atmospheres — EU contract G6RD-CT-2001-00553) to investigate the problem of mechanical ignition. The drivers behind the project are the European Directives 94/9/EC(2) and 1999/92/EC(3) concerned with the control of explosion hazards in the workplace. They define clear Essential Health and Safety Requirements (EHSR's), which must be met, including the control of all potential ignition sources.

Analysis of the physical processes that lead to ignition by mechanical equipment shows that there are at least three key stages:

i. Production of heat by conversion from kinetic energy.
ii. Transfer of heat to the surrounding explosive or flammable atmosphere.
iii. Ignition of the explosive or flammable atmosphere.

The first stage of this sequence is the area that offers the greatest potential for preventing ignition of an explosive or flammable atmosphere by possibly limiting the power/energy fed into the conversion process. In general, the friction processes that need to be considered are rubbing (long duration friction between surfaces producing a hot surface), grinding (long duration friction producing hot surfaces and sparks) and impact (short duration friction producing short duration transient hot surfaces and sparks), or a combination of these. Fundamental studies of friction such as Jaeger[(4)] and Kragelsky et al[(5)] show that the power dissipated in the contact region is dependent on material properties, such as hardness, melting point and thermal conductivity, and the conditions of the actual friction event such as rubbing speed, contact force and contact area. This is discussed further later in this paper in relation to work carried out as part of MECHEX.

The second and third stages listed above involving the transfer of heat and then ignition of the explosive/flammable atmosphere are difficult combustion problems in their own right and have undergone considerable study in relation to ignition by other types of hot surface (Laurendau[6], Carleton et al[7], Ungut[8] and Powell[9]). Depending on the situation or industrial process, the ignition may involve:

– A combustible dust layer ignited to produce smouldering and then flaming (smouldering nests – see Reference 10), which in turn may then ignite a surrounding dust/gas/vapour or hybrid explosive atmosphere.
– An explosive atmosphere ignited directly by a hot surface. This situation may then be further categorised to consider the situation of a potentially large volume in which strong convection currents and mixing can take place. The ignition source could be the hot surface produced at the contact point or a sub-millimetre burning spark or particle both of which would need to be at temperatures well above the auto-ignition* (minimum ignition temperature for dusts) temperature. At the other extreme, we must also consider the potential for a situation where the geometry/confinement and power input are such that the whole volume of explosive atmosphere can be heated and ignition can occur at close to the auto-ignition temperature.

The main focus of the MECHEX project has been on the problem of the generation of heat (stage 1 above) as this is the area where most practical steps could be taken to control the potential for ignition. However, for a complete solution the problems of heat transfer/kinetics of ignition will probably also need to be addressed.

*Auto ignition temperature, or safety characteristic ignition temperature, although not an intrinsic parameter, is widely used to assess the susceptibility of an explosive atmosphere to ignition by a hot surface under other conditions – see for example references 6 and 7.

FRICTIONAL RUBBING AND GRINDING

In this paper frictional rubbing refers to a process that involves prolonged contact between surfaces that are moving relative to one another. This process generates heat at the interface between the two surfaces and under extreme conditions plastic deformation of one or other of the surfaces. Analysed qualitatively, the temperatures generated are primarily dependent on the material properties, such as hardness, melting point and thermal conductivity, and the conditions of the actual friction event such as rubbing speed, contact force and contact area.

Depending on the conditions during the friction process, it may be that the forces in the contact zone are sufficiently high to result in grinding where material is removed from the contact zone in the form of hot chunks or particles (mechanical sparks). Where the materials are dissimilar, the softer lower melting material will produce a lubricating layer and limit the temperature generated in the contact zone.

The photograph in Figure 1 illustrates the hot spot at the contact point and the production of mechanical sparks during a test using the low speed rubbing machine test apparatus at HSL. This apparatus was designed to produce severe frictional rubbing at

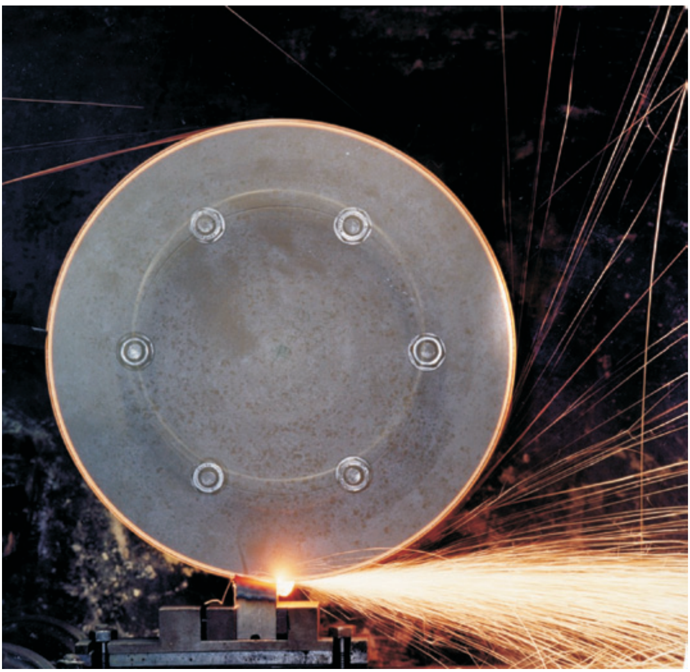

Figure 1. Photograph showing frictional and sparks and hot spot produced during a test at HSL

the contact point to produce ignition. It is essentially a modified lathe bed with the driven shaft terminating inside a 300 l vented explosion chamber. Note the slider (small sacrificial metal block) at the bottom of the disc and sparks produced at the contact point projected out to the right. Discs of different material and sizes can be attached to the shaft to achieve circumferential velocities between approximately 0.4 $ms^{-1}$and 20 ms^{-1}. 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 disc is driven by a 30 kW variable frequency AC induction motor via a v-belt pulley arrangement (ratios 2.28:1 and 6:1). The apparatus is fully instrumented to allow the powers, speeds and forces involved in the friction process to be measured. These parameters characterise the friction on a macro scale, the power dissipated in the friction process being equal to the product of contact load, rubbing velocity and the coefficient of friction. Using this relationship it is possible to calculate all of these parameters from the data obtained during a test. Note that the coefficient of friction is strongly dependent on temperature as summarised in Figure 2, which is taken from the experimental data discussed later in this paper.

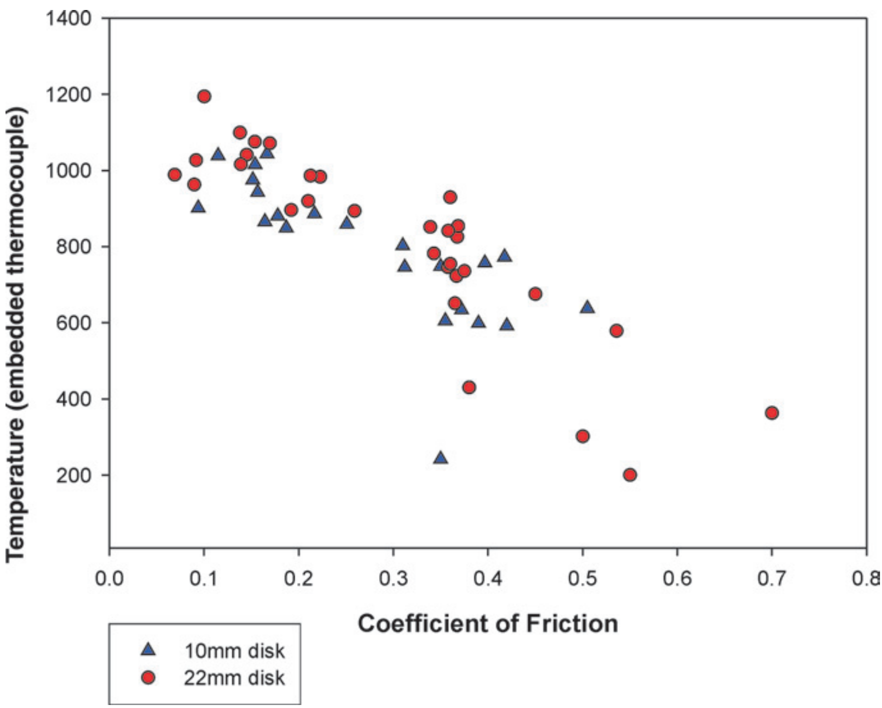

Figure 2. Plot of temperature (°C) against coefficient of friction for stainless steel from tests carried out at HSL

IGNITION BY FRICTIONAL RUBBING AND GRINDING

Ignition by friction is clearly dependent on the temperature generated in the contact zone, to produce a direct source of ignition, and as the source of hot particles that may increase in temperature as they burn in the air. As already discussed, as a primary measure surfaces must at least reach the auto-ignition temperature to theoretically have a chance of igniting an explosive atmosphere. However, a much more likely ignition process is by hot surface ignition as found in HSL's apparatus and shown in Figure 1. In such a situation the temperature for ignition is generally well above the auto-ignition temperature and depends on a number of variables including size and convective/conductive heat flow from the hot surface. Despite the work in this area (Laurendau[6], Carleton et al[7] and Ungut[8]) there is no easy to apply method for predicting the temperature for ignition by such a process, or for intermediate situations that fall between the extremes of a simple hot surface and auto-ignition that could potentially occur in mechanical equipment.

The effects of size and residence time (contact time between the hot surface and flammable atmosphere) are well known, and have been demonstrated many times in the HSL apparatus where the hot spot produced at the contact point is observed to be the ignition source in the majority of cases, rather than individual or even groups of sparks — effectively small hot surfaces typically smaller than 0.1 mm in diameter (Ritter[11]).

Proust and Raveau[(12)] have reviewed previous experiments where ignition has been produced in grinding and rubbing tests similar to those in the HSL apparatus. However, in these tests there was generally no measurement of the temperature in the contact zone, which is also discussed in reference 10. As part of the MECHEX project, a series of tests has been carried out to measure contact zone temperatures during frictional rubbing and grinding. These tests aim to simulate worst-case conditions for metal-on-metal rubbing and used a slider (small sacrificial block) and wheel constructed from duplex stainless steel, which was chosen for its hardness, high melting point and low thermal conductivity. Contact zone temperatures were measured across a range rubbing speeds and contact loads. The work was initially carried out at speeds up to 10 m/s[(13)] and has since been extended to 15 m/s as shown in Figure 3.

The contact zone temperatures were measured using a sacrificial 0.5 mm diameter K-type thermocouple inserted into the block. As the test proceeds, the thermocouple is destroyed but at the same time continuously re-welded into the surface of the block, combining with the surrounding metal in the contact zone. In addition to the contact thermocouple, the temperatures around contact zone were also monitored using thermal imaging, which is discussed later in this section.

An unusual feature of the contour plot in Figure 3 is the apparent peak in measured temperatures at the intersection of the 4 N/mm^2 and 10 m/s lines. This behaviour is not fully understood, but could simply be an artefact of the thermocouple operating at its limits, or equally could be a real effect associated with a change from simple heat generation in the contact zone to a more efficient grinding process, which removes material effectively from the contact zone without generating quite the same high temperatures.

It is clear that temperatures in excess of the auto-ignition temperature of many materials (e.g. $>300°C$ for class T3) are reached at moderate speed. Any conditions

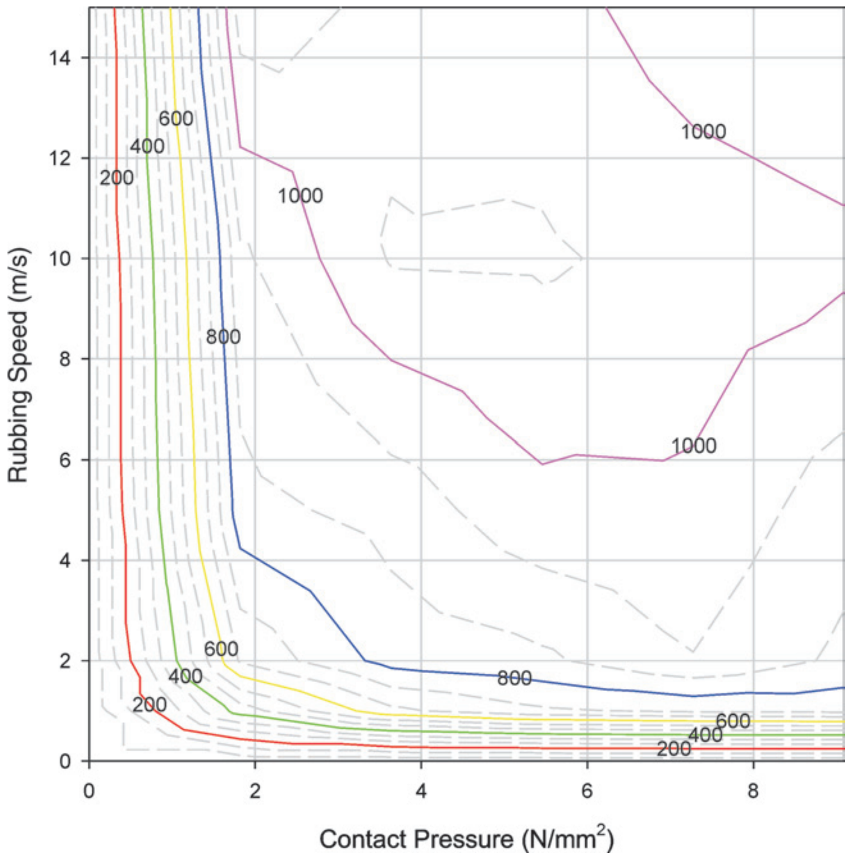

Figure 3. Contour plot showing contact zone temperatures (°C) measured as a function rubbing speed and contact pressure

above the 300°C contour in Figure 3 should then theoretically be presumed to potentially be incendive for T3. However, in many situations this would be too restrictive, and possibly should be relaxed if it could shown that volume or pseudo auto-ignition could not occur. However, there is still the question of how this would be decided.

To demonstrate this behaviour, tests have been carried out igniting propane (auto-ignition temperature 470°C), ethylene (auto-ignition temperature 430°C) and hydrogen (auto-ignition temperature 516°C) to obtain ignition at the lowest possible speeds. The conditions for ignition in these particular tests are summarised below:

- Propane: 1.75 kW and 1 m/s and a temperature of 750°C.
- Ethylene: 1.2 kW at 0.7 m/s (minimum speed of the system in its present form) and a temperature of approximately 650°C.
- Hydrogen: 0.7 kW at 0.7 m/s and a temperature of 530°C.

In all cases the ignition occurred from the hot surface, few sparks being produced under these low speed conditions. Again, the temperatures are above the auto-ignition temperature as expected except for the hydrogen test, which suggests that the thermocouple did not measure the highest temperatures produced in the contact zone.

Another important observation in the case of the propane test was that ignition occurred at the end of the test when the hot surface in the contact region was exposed to the explosive atmosphere. This observation is key and illustrates a point already discussed in relation to the size of the exposed hot surface. In addition, it also raises an important point that the explosive atmosphere needs to be able to contact the high temperatures to ignite, and the flame kernel formed then needs to be able to expand away from this surface without being quenched.

Depending on the circumstances of the frictional rubbing/grinding, processes which project hot material out of the contact zone are of key importance in determining whether ignition will occur or not. Such processes obviously include:

i. Exposure of the contact region to the explosive atmosphere.
ii. Spark production where hot particles are thrown some distance from the contact zone at high speed;
iii. 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;
iv. 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 (see Figure 4);
v. Conduction of heat from the contact region to adjacent surfaces to produce high temperatures.

From work using the HSL apparatus, ignition of explosive gas and dust atmospheres has been observed most regularly by mechanism *iv*, but also by *i, ii* and *iii*. For the case of dust deposits, mechanisms *ii* through to *v* have all been observed to cause ignition.

In general observations show mechanical sparks from steel against steel are a less effective ignition source than the hot spot. However, work is ongoing as part of the project to investigate mechanical sparks and compare the energy of sparks with the electrical spark ignition energies. The general finding from this work is that although the energy associated with mechanical sparks may be larger than the electrical spark Minimum Ignition Energy (MIE), the former are a less effective ignition source because of the lower temperatures attained. For more details see reference 12.

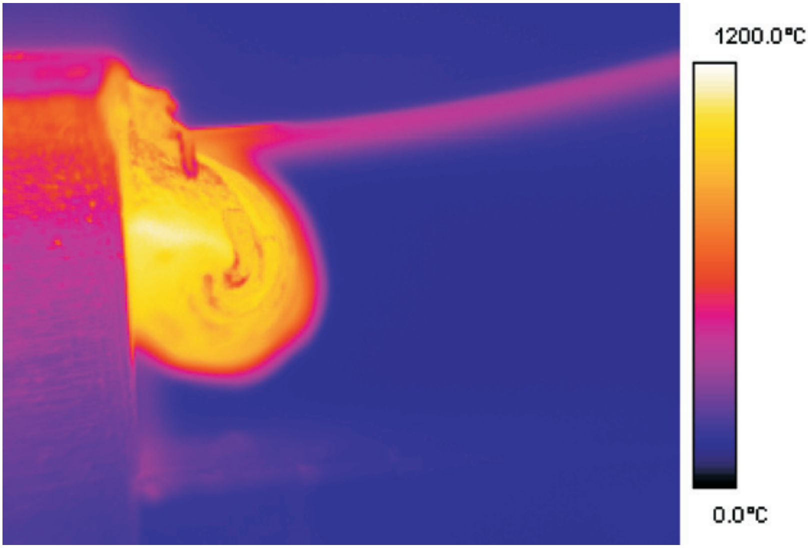

Figure 4. Hot burr formed at trailing edge of slider block

Although the assessment of the nature of potential ignition sources detailed in *i* to *v* above is important, the key parameter is the temperature in the contact region. While the data in Figure 3 is useful for assessing this under laboratory conditions, and demonstrates a number of interesting effects, it probably is not particularly easy to apply to real practical equipment. A more useful approach might be an assessment in terms of the operating power of a piece of equipment, or operating power density produced under specific fault conditions. This approach that has previously been used to assess hot surface ignition by electrical components and optical equipment in terms of a surface power density[7]. To begin to investigate this for ignition by friction, Figure 5 shows a re-plot of the data from Figure 3 as a function of surface power density assuming a fixed contact area. Temperature data points reflecting both the contact zone temperatures (contact thermocouple) and the maximum temperatures observed using the thermal imaging camera are included. The temperatures observed using the thermal imaging camera are based on an emissivity of 1 and so in reality are probably higher because of a lower emissivity.

The red line on the plot ($y = 200x$) is plotted to suggest a possible approach for using data such as this to assess the possibility of ignition. It is not a best fit. It is deliberately plotted to give an element of safety with regard to all temperature data up to approximately 450°C (T1). In theory it then should be possible to relate power density to surface temperature in the contact zone. What is obvious from this approach is that to keep the temperature down, the power density needs to be low which necessarily requires that

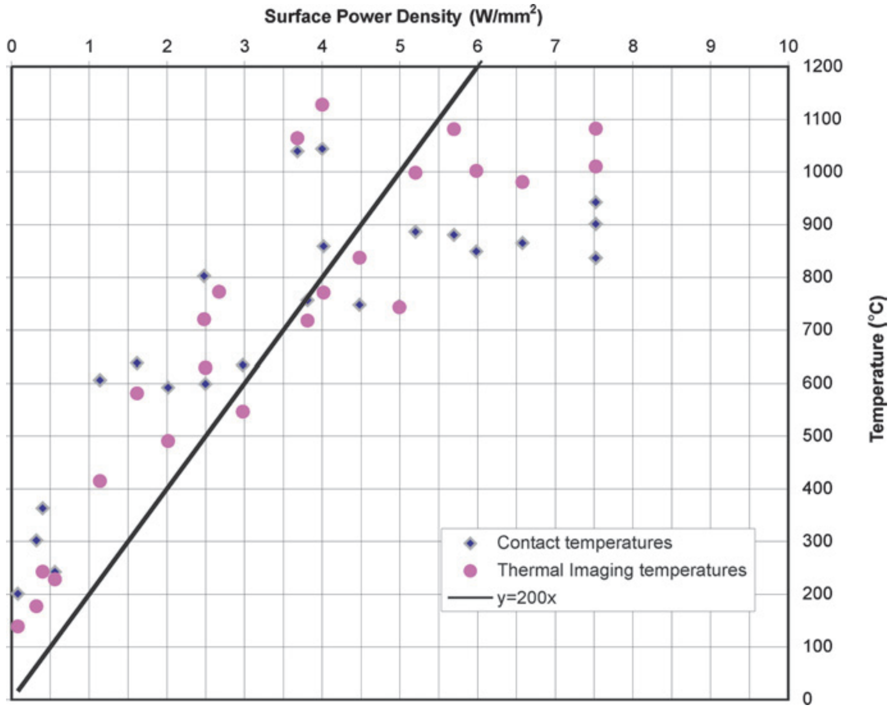

Figure 5. Plot showing temperatures as a function of power density

the contact areas are kept to maximum (advice also given in reference 14). This has implications for equipment and how it might be designed to minimise the risk of ignition.

On closer analysis of this approach, a major obstacle appears to be how to assess or define the contact area that might occur under fault conditions to allow a power density to be calculated. For optical or electrical systems this was quite straightforward. However, for mechanical systems it is more difficult because of size uncertainty and the transient nature of any surface created as the result of a fault that may occur in mechanical systems.

An additional problem with this approach is that for small areas it predicts very low ignition powers. In reality there is likely to be a minimum ignition power, which will apply to a broad range of conditions as found with optical equipment. However, further work is required to identify and quantify this situation.

In addition to the work at low speeds, a limited number of tests have also been carried out at a relatively high speed (15 m/s) and intermediate load of 3.6 N/mm^2. These tests are summarised in Figure 6 and clearly show the advantages of using softer materials to minimise the temperatures generated in the contact zone. Note however,

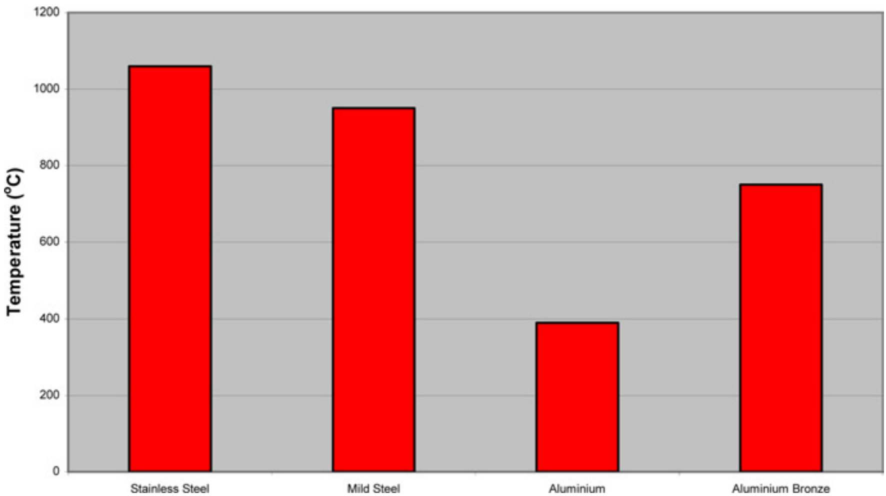

Figure 6. Temperatures generated between a stainless steel wheel and sliders of other metals at 15 m/s and 3.6 N/mm^2

that the softest material used, aluminium, can introduce other serious hazards with regard to impact with rusty steel and the thermite reaction which is highly incendive and has been demonstrated to cause ignition of dust deposits/clouds[15].

SUMMARY

As part of the MECHEX project work has been carried out investigating rubbing and grinding to measure temperatures in the contact zone, demonstrate ignition and investigate a possible approach for relating the power of equipment to ignition temperatures of explosive atmospheres. The complexities of how the incendive high temperatures generated in the contact zone may be exposed to the explosive atmosphere have been discussed, along with possible practical problems associated with the size and transient nature of the hot surfaces produced by mechanical equipment.

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