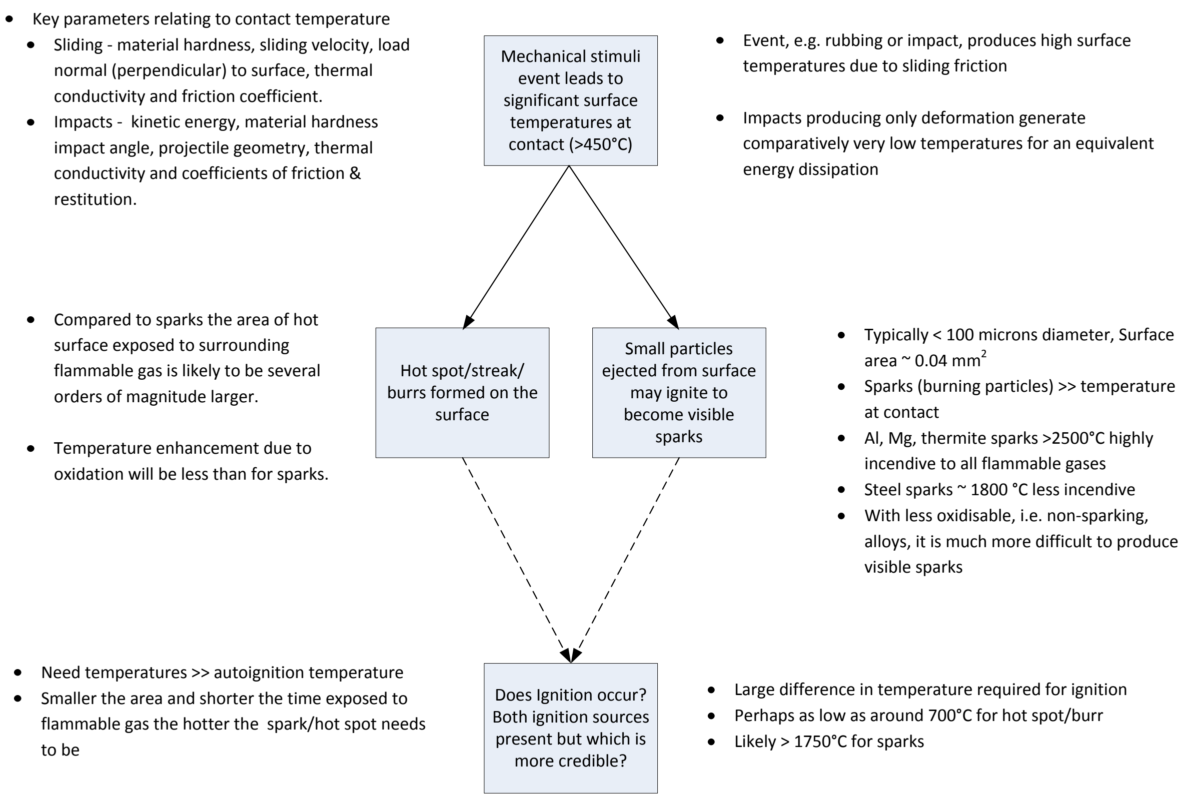
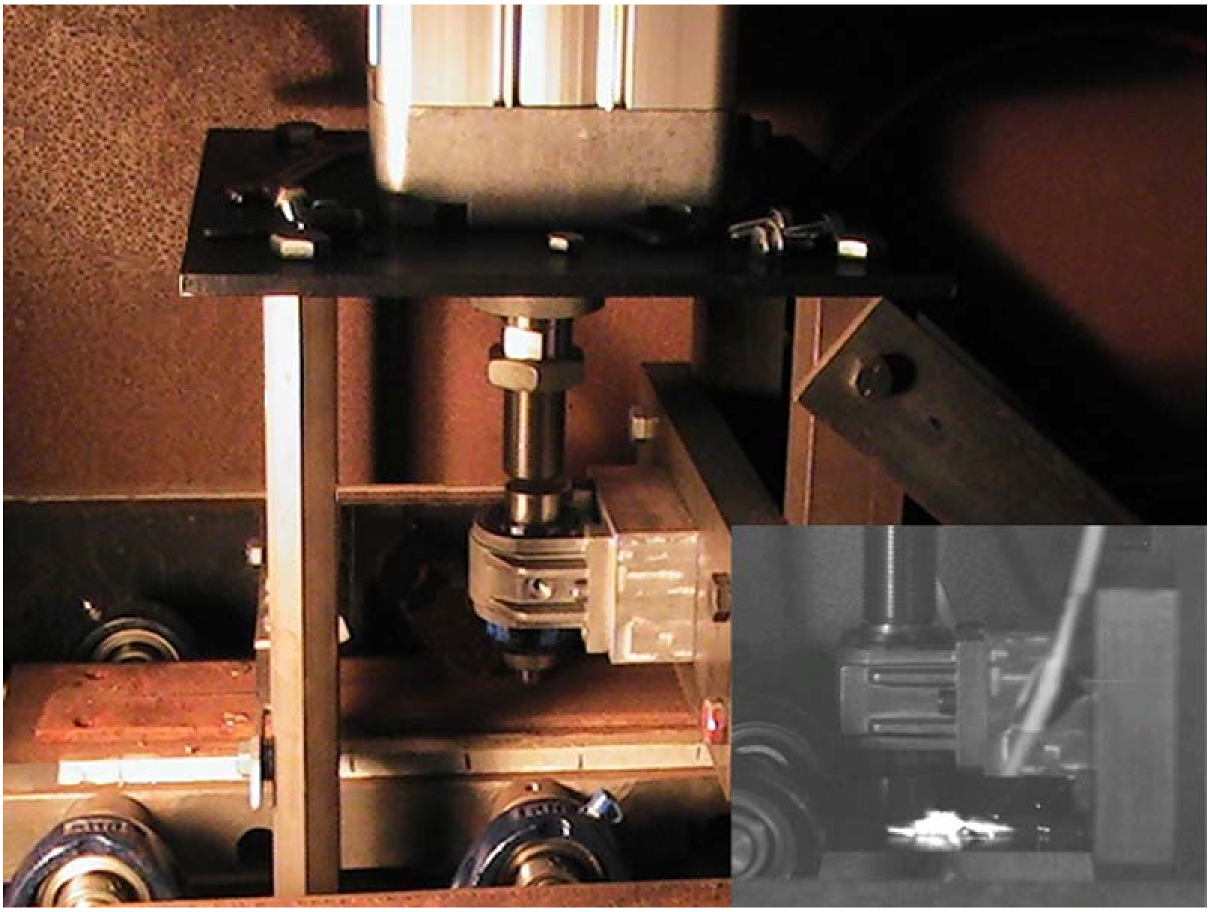
Ignition of Flammable Atmospheres by Mechanical Stimuli

As readers of HazardEx will be well aware, following the introduction of the ATEX 95 and 137 directives, there are now requirements on both manufacturers of equipment and employers to consider the likelihood of ignition flammable atmospheres from mechanical impacts/sliding. The aim of this article is not to review legislative requirements, as these are well discussed elsewhere, but to provide insight into the ignition mechanism and relevant research literature to assist those needing to make such assessments. It is certainly not the intention to advocate ignition source control as an appropriate hazard management strategy, particularly with easily ignited gases like hydrogen- this needs to be decided on a case by case basis. Guidance in the design standards i.e. [1] has improved from earlier versions, but still does not convey very well the likely influence of parameters such as material hardness, load, velocities and impact angle.

The Explosion and Fire Group at LSBU have carried out a programme of work on mechanical ignition over the past 15 years to gain an understanding of the influence of the various parameters on ignition likelihood. The process can be broken down into a number of stages as illustrated by the Figure below.



There are a number of key stages leading to ignition, each one complex. Experiments on mechanical ignition have been undertaken since the early 1800's, yet the specification of usable criteria is still a challenge. The first step in the ignition process is the generation of high surface temperatures which mostly results from sliding friction confined to a very thin surface layer. For impacts relevant to this discussion the work partitioned into deformation of the bulk material can effectively be ignored since it would typically amount to only a few tens of degrees celsius temperature rise. Prediction of the temperature due to sliding is not as straight forward as might first be imagined and the study of 'wear and friction' - Tribology is a science in its own right. When two surfaces rub together, contact occurs not over the whole surface but on high points or asperites, the real contact area typically being much less than the apparent area. As the normal load is increased the real contact area also increases so that the frictional force is often observed to be independent of the apparent contact area - Frictional force is proportional to the real contact area and real contact area is proportional to load. This already creates a complexity – what is actually meant by any representation of surface temperature? Each contact point will have a temperature distribution and if sufficient in number/closely spaced they will interact with each other. Neither, the individual contact points or the surface as a whole is at a single uniform temperature. Additionally, the contact points are not always evenly distributed and hot spots can occur. In many practical situations, components can have sufficient movement such that even at the macro scale rubbing doesn't occur over the whole nominal contact area. In any case, what is important is the temperature and area/size of hot material that can be exposed to the flammable gas i.e. at the trailing edge of the contact or particles ejected (which may then go on to burn and increase in temperature). The image below show an apparatus designed and constructed at LSBU for high load sliding ignition tests, with inset showing the onset of ignition of a hydrogen/air mixture.



A convenient and pessimistic assumption, appropriate to many practical situations, is to assume that rubbing occurs over a theoretical contact area, which is defined by the load, L, divided by the Hardness, H, of the material. This in effect provides a theoretical maximum frictional flux for a given material and load. Applying equations for non-steady state heat transfer for a contact between a stationary pin and a moving surface it can be shown [2] that the temperature generated at the point of contact will be proportional to:

- Friction coefficient, μ
- Hardness, $H^{0.75}$
- Sliding velocity $V^{0.5}$
- Normal Load, $L^{0.25}$

and inversely proportional to

- Thermal conductivity, $k^{0.5}$
- Density, $\rho^{0.5}$
- Heat capacity, $c_p^{0.5}$

It can be seen that the various parameters are raised to different powers where the higher the power the greater is the relative influence. E.g. a 2 times increase in sliding velocity would result in a higher surface temperature than would doubling of the load. The above also highlights the importance of material properties, for example, a tool steel (Hardness 700HV, ρ=7800 kg/m^3, k=40 W/mK,) might well be expected to produce twice the temperature rise of a CuBe alloy (Hardness 350 HV, ρ=8100 kg/m^3, k=64 W/mK) under the same sliding load and velocity (due to friction at the point of contact). In the case of mechanical impact, the situation is clearly more complex as the load is not uniform with high peak forces occurring. Sliding will also depend on impact angle, friction and restitution coefficients, etc, but the relative importance of the above parameters might well be expected to be similar.

High surface temperatures produced at the contact point is the first stage of the ignition process. However, if there is sufficiently high load/velocity sparks, will also be produced at the contact point. Whether it is the ejected sparks or the hot spot/molten bead at the contact that is the cause of ignition is a difficult question to answer.

The sparks (e.g. from steels) are often very much hotter than the impact/rubbing surface due to oxidation/burning but in order to cause ignition they need to be at a considerably higher temperature since they are much smaller and will be moving at significant velocity (>10 m/s) through the flammable atmosphere. Particles ejected from non-sparking metals are much less oxidisable with little enhancement in temperature.

In experiments at LSBU (with metals not including light alloys) it has always appeared that ignition has occurred at the trailing edge of the contact point. E.g. the image below shows the impact of a 30 Kg stainless steel headed projectile onto a mild steel plate at 5.6m/s in air, which is of sufficient severity to cause ignition (initial Kinetic energy 480 J). In similar tests with a flammable atmosphere, high speed video images point towards the ignition occurring at the molten bead of material visible in the Figure. However, many other experimental investigations have focused more on the incendivity of the sparks produced and it is undeniably true that sparks can also be a source of ignition. It is also interesting to note that, unlike for electric discharges, mechanical ignition occurs most easily in lean flammable mixtures and that this is likely a result of the effect of oxygen concentration on spark/surface temperatures.

Considering the published data it might be speculated that, for a particular contact temperature, higher loads, lower velocities & less reactive metals favour ignition by hot spot whereas with lighter loads, higher velocities & more reactive metals ignition by sparks would be more likely.

The observation of visible sparking (though certainly an indication of a possible hazard) does not necessarily mean that ignition will occur. The ignition probability associated with the sparking could in some circumstances be very small. Grinding sparks were once (ca 1880) utilised as a means of 'safe' illumination in mines. There were, however, still ignitions, albeit infrequent, which introduces a further complication with regards to testing/specifying criteria. That is, in practice, ignition from whatever source is often observed to be probabilistic in nature in that under what appears to be identical conditions it sometimes occurs and sometimes not. A plot of ignition probability versus energy (or other criterion) is typically S shaped and from the point of view of hazards analysis it is often the lower tail of the S that is of interest. As loads (or impact energies) and sliding velocities decrease the observed ignition frequency will decrease and while it is relatively easy to observe when ignition probability is say 0.1 for a given mechanical interaction, it is not usually practical to determine when it decreases to e.g. 10^{-5} since this would involve a great number of tests. Safety factors need to be applied to data observed for higher ignition probabilities and establishing the magnitude of such factors is not easy.

While the above discussion helps in understanding the nature of the problem, it does not immediately focus on the magnitude of interactions that could cause ignition.

In relation to the design of equipment for flammable atmospheres the most usable guidance is that contained within BS EN13463-1. This sets minimum impact energy criteria above which ignition is deemed to require consideration (although not necessarily likely or even possible in the specific scenario being considered). Guidance (for single impact events) is given in terms of impact energies for different gas groups and different zones of use (reflecting the probabilistic nature of impact ignition and frequency of flammable atmosphere). In the case of group IIB gases and category 2G equipment the energy limits are quoted as 20J for steels or 250J for non-sparking materials.

However, in many practical situations the limits cited can appear to be very pessimistic and could easily be orders of magnitude less than required to cause ignition. For example in drop weight experiments at LSBU [3] with a 7kg stainless steel headed projectile and stainless steel target, ignition was not obtained in 15 tests with impact energies of 500J. A magnesium headed projectile dropped onto a rust free mild steel surface likewise gave no ignitions in 15 tests at an impact energy of 365J. Both were with hydrogen/air mixtures and at a near optimum impact angle of 45°. If a projectile were to fall vertically onto a horizontal surface without sliding, the energy required for ignition would likely be orders of magnitude higher. Ignition, at energies approaching those in the standard, is only likely where the frictional heat flux is maximised. For example, in LSBU tests with magnesium particles impacted between two stainless surfaces ignition was obtained in 4 out of 15 tests at only 80J. Here, with much less deformation of projectile and target compared to magnesium onto mild steel, impact tests resulted in much higher frictional heat flux. Those familiar with the guidance in BS EN13463-1 will recognise how the influence of material properties and the effect of load and velocity features in the criteria presented.

Regarding ignition by sliding friction, criteria is given in BSEN13463-1 in terms of a sliding velocity of 1 m/s, above which ignition may be possible. While this is a reasonable rule of thumb, work reported by LSBU and more recently by Meyer [4], has indicated conditions below this velocity, where ignition can occur. Additionally, both studies have provided further evidence of the importance of thermal conductivity and also point towards the hot surface as the likely source of ignition during sliding.

It is clear from the above that a large body of research has been carried out into ignition from mechanical stimuli. Much of the earlier research can be found summarised in reviews by Powell [5, 6]. Reading these reviews, the wide range of situations that have been investigated and the range of energies, loads, materials for which ignition may occur can be seen. His later review is particularly useful providing more description of the ignition process(es).

The required conditions of impact energy for which ignition might actually occur in a real world scenario could often be considerably greater than the minimum values given in BSEN13463-1. In some cases higher limits may be allowed by other product standards, backed by many years of operational experience. Working with minimum values for design purposes may often be required, but if needing to assess the likelihood of ignition associated with the operation of existing process plant or maintenance operations, utilising minimum values could result in a pessimistic and ultimately costly assessment of the true risk. This is especially the case where an impact does not have a tangential/sliding component.

In such circumstances, guidance can with care be found in the published work but it is essential that such data is compared with due regard to differences between test data and the actual situation under consideration. For example, ignition energies determined for projectiles of a few grams travelling at ballistic speeds cannot be directly applied to projectiles of a few kg and those determined for projectiles of a few kg cannot be applied to projectiles of 10’s of kg. Similarly, impacts in which the geometry and freedom of movement acts to restrict motion can’t be directly compared in terms of initial potential energy with a freely falling projectile as the fraction of energy dissipated as friction (and frictional heat flux) could be substantially different. It should also be noted that in many tests investigating spark incendivity, the point of mechanical contact was deliberately not exposed to the flammable gas. This could be quite different in the case of a real world scenario.

However, in many cases where reasonably applicable data can be found, a knowledge of how various parameters/properties are likely to alter the results from test conditions can be used to help justify the relevance (or otherwise) of such data to a given situation e.g. show that it is likely to be pessimistic.

Ultimately, realistic assessment of ignition probability from mechanical interactions remains a considerable challenge. Recent studies following on from the introduction of ATEX have as yet failed to yield widely applicable useful predictive models. There has been some progress in establishing/predicting limiting criteria and prediction of surface temperatures but often at the expense of considerable conservatism when applied to many real situations. This is perhaps not surprising giving the complex multi-disciplinary nature of the problem, involving mechanics, tribology and combustion – each one challenging. While this article does not provide a simple solution for determining ignition probability it will hopefully provide those faced with assessment of mechanical ignition, insight into the ignition process and highlight sources of further information.

References

1. EN 13463-1:2009, Non-electrical equipment for use in potentially explosive atmospheres Part 1: Basic method and requirements.

2. Averill AF, Ingram JM, Battersby P, Holborn PG, Ignition of flammable hydrogen/air mixtures by mechanical stimuli. Part 1: Ignition with clean metal surfaces sliding under high load conditions, International Journal of Hydrogen Energy, 39(32) (2014) 18472-9

3. Jones, S., Averill, A.F., Ingram, J.M., Holborn, P.G., Battersby, P., Nolan, P.F., Kempsell, I.D. and Wakem, M.J. Impact ignition of hydrogen-air mixtures. IChemE Hazards XIX, Manchester 27th-30th March 2006

4. Meyer L., Beyer M., Krause U., Hot surfaces generated by sliding metal contacts and their effectiveness as an ignition source, J Loss Prev. Proc. Ind. (2015), http://dx.doi.org/10.1016/jlp.2015.02.013

5. Powell F, Can non-sparking tools and materials prevent gas explosions, Gas Wasser, Abwasser, 66(6) (1986) 419-28

6. Powell F. Ignition of gases and vapors. Industrial and Engineering Chemistry 1969; 61: 29–37