Toward modelling of frictional ignition

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ABSTRACT

This work is part of a European sponsored project named MECHEX **(GRD2-2000-30035)** which aims at providing a new insight and data about the ignition hazard induced by mechanical contacts classically termed as "grinding", "friction" and "impact" so that some sort of classification of mechanical equipments against this specific hazard could be issued. " Friction " and "grinding" might be understood as continuous mechanical solicitation whereas "impact" would be referred to as an instantaneous action such as that of a flying object striking freely on a fixed target. Within that scope, we undertook a detailed physical analysis of possible ignition mechanisms on the basis of precise measurements of hot spots, temperatures and fragments and tried to link them to the **thermomechanical** properties of the contacting bodies.

Introduction

It is recognised that **frictional** ignition is still a major cause of explosions in industry with a frequency ranging from 30 to 50 % **(Hawsworth** et **al., 2004a** and b). The objective of MECHEX project is to provide new insight and data about the ignition hazard induced by mechanical contacts classically termed as "grinding", "friction" and "impact" so that some sort of classification of mechanical equipments against this specific hazard could be issued that could help to apply the E.U. directives 94/9/CE and **1999/92/CE (Hawkworth** et **al.,** 2004a). This project gathers the effort of several major european institutes. Here will only be presented the input of the authors (for a general view of the subject see Hawsworth et **al.,** 2004a and b) mainly devoted to the physical analysis of both the dissipation of the mechanical energy into heat and of the subsequent flame initiation process.

Friction and grinding

Observations and preliminary analysis

Most available knowledge has been gained between 1930 and 1960 with main applications in coal mines. If most influencing parameters have been highlighted (for instance Powell, 1969), the global phenomenology seems outstanding, again justifying the present project.

Friction between two solid bodies is a process through which mechanical energy is transformed into heat. "Friction " and "grinding" might be understood as continuous mechanical sollicitation where both heat and effort have reached a steady state and may more or less be analysed by means of standard engineering approach. Experience reveals that heat is produced in the rubbing zone where the material is severely stretched and diffuses outwards. It is well know that the amount of heat evolved is in proportion of the applied force and sliding speed (Kragelskii, 1965). The maximum temperatures are observed after the thermal equilibrium has been reached when the two rubbing bodies do not represent any more a thermal sink as efficient as at the beginning when they were cold. Local liquefaction may be observed. Fragments are often produced either because of classical abrasion (asperities being torn away) or because of « **microcutting** » action in which process the sliding body acts more or less as a cutting tool. These fragments are the cause of « spark showers » (figure 1). A priori, ignition may either happen at the rubbing zone or around the sparks.

Figure 1 : example ofa « spark shower » fromRitter 1984

The analysis reveals that ignition may result from three different processes :

1. In direct contact with the hot rubbing zone whenever the local temperature is large enough according to the mechanism of the hot plate ignition as studied in preceding E.U. sponsored programme (Mc Geehin et al., 1994; Carleton et al., 1999). The experimental and theoretical evidence shows that the critical parameter is the temperature of the hot zone which can be linked to the standard ignition temperature of the ATEX ;
2. The power dissipated in friction may easily be of the order hundreds of Watts. If the friction is occurring in a **sufficiently** confined area, the mean temperature of the ATEX may rise and reach the **autoignition** point. This situation is well represented by the standard ignition temperature ;
3. The sparks may be a cause of ignition. However, since the initial temperature at the beginning of the flight should not be different from that of the rubbing zone, the spark are likely to constitute a preferential cause of ignition only if later in their flight, their temperature increases well above that of the rubbing zone. This may occur if the flying particles are able to burn. In this case, the ignition process may be linked to the spark ignition mechanism referring to minimum ignition energies.

A few «reasonable» data (Rae et al., 1959, 1960) have been extracted from the literature for validation purposes (table 1).

Source	ATEX	Wheel	Slider	Rubbing zone size (mm)	V (m/s)	**N (N)**
RAE	Methane-air	Sandstone : dia. 0.3 m, thickness 30 mm	Limestone cylinder : dia. 20 mm, height 20 mm	8 mm x 8 mm	1,6	444 to 727
RAE	Methane-air	Sandstone : dia. 0.3 m, thickness 30 mm	Limestone cylinder : dia. 20 mm, height 20 mm	7 mm x 7 mm	5,3	115 to 222
RAE	Methane-air	Sandstone : dia. 0.3 m, thickness 30 mm	Limestone cylinder : dia. 20 mm, height 20 mm	6 mm x 6mm	10,6	53 to 115
RAE	Methane-air	Sandstone : dia. 0.3 m, thickness 30 mm	Limestone cylinder : dia. 20 mm, height 20 mm	6 mmx 6 mm	16	53 to 115
RAE	Methane-air	Steel : dia. 0.3 m, thickness 30 mm	Steel cube : side width = 25 mm	25 mm x 25 mm	4,6	1300 to 2070
RAE	Methane-air	Steel : dia. 0.3 m, thickness 30 mm	Steel cube : side width = 25 mm	25 mm x 25 mm	9,2	500 to 1300

Table 1 : a few representative test results (V is the sliding speed and N the normal application force)

Proposed physical analysis

We separate the mechanical aspects describing the degradation of mechanical power into heat from the ignition process.

The informations available in the literature constitute a sound basis to establish a model. The tangential force, F, is classically linked to the normal force, N, through a friction coefficient, f, such that F= f.N. The prediction of f is somewhat difficult but it depends mainly on the material and, in many cases, $0.2 < f < 1$ for non lubricated rubbing. The power dissipated is then **q=f.N.**V. Jaegger (in **Kragelskii, 1965)proposed** an excellent mathematical treatment of the local temperature evolution of the heated zone as function of the rubbing parameters (figure 2) separating the fixed friction case where the rubbing point does not move (an axis rotating against a plate for instance) from the classical sliding friction where the rubbing zone moves (fixed slider on a rotating wheel). The problem can be solved if the mean temperature of the bodies can be known which can be done using the classical heat exchange laws with the atmosphere. The typical set of equation is then for a « fixed » friction :

$$\boxed{\Delta T_f = T_f - T_{body1} = rc/4 . v . q . R / (A . \lambda_1)}$$

with:

R : radius of hot spot, A friction area
λ_1 : heat conductivity of body 1
v fraction of heat **transfered** to body 1

$$\boxed{T_{body1} - T_{amb} = v . q / (h_1 . S_1) \text{ ibidem for body2}}$$

$$\boxed{V - h_1 . S_1 . (T_{body1} - T_{amb})] / [h_2 . S_2 . (T_{body2} - T_{amb})]}$$

with :

max (Ti) < T_{fusion}
hi heat exchange coefficients
S_i heat exchange areas

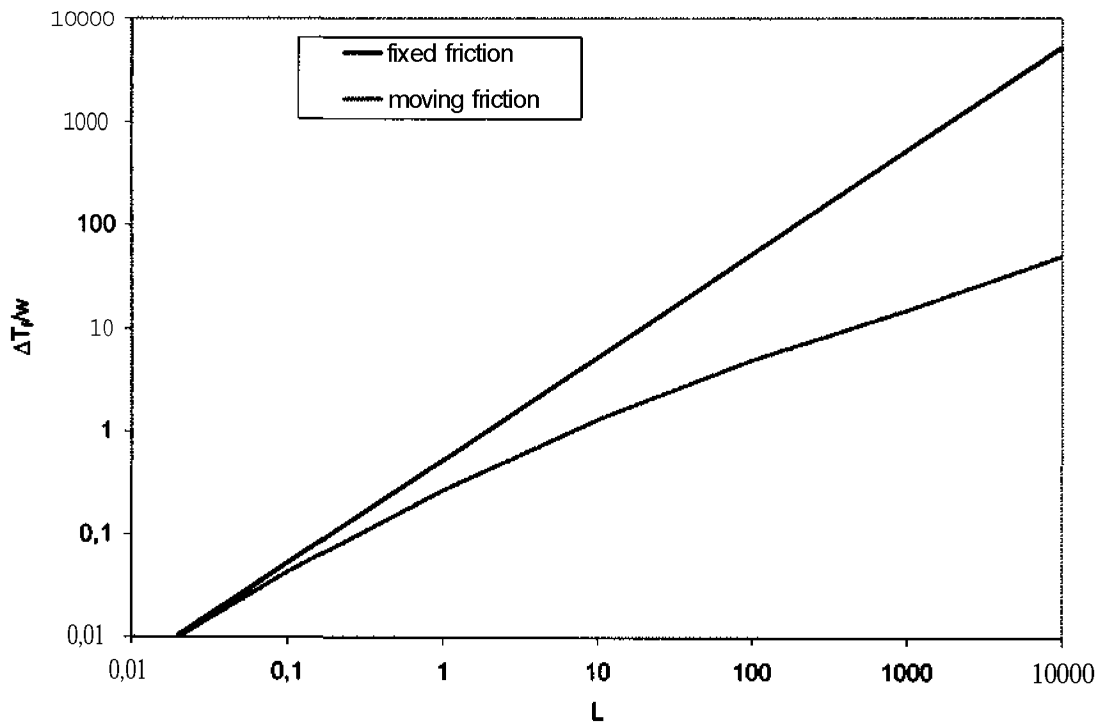


*Figure 2 : Temperature difference (ΔT_f) of the hot spot with the mean body temperature as function of $L = V.R/2.\alpha$, $w = \pi. q/A. \rho. c. V$, α is the mean thermal **diffusivity** of the bodies, c the **specific** heat, **and R** the typical size (radius) of the heated zone.*

About the production of fragments, criteria for differentiating abrasion and microcutting may be extracted from the following table.

Deformation endured	Elasto-plastic	rupture
Wear type	abrasion	microcutting
Contact pressure (p = F/f/ A)	$p < 10^{-2}.\ \sigma_{elast}.(r/\varepsilon)^3$	$P > 10^{-2}.\ \sigma_{elast}.(r/\varepsilon)^3$
Wear (mass)	$0,7.\rho.A.L.p/E$	$0,3.\rho.A.L.p/H$

Table 2 : type ofwear (fragmentproduction) ***with*** *L = friction length, E = Young* ***modulus,*** *H = Hardness, σ_{elast}=yield strength, r and s radius and height ofthe asperities*

In case of microcutting only very few fragments will be produced (a chip is cut) so that the size of the particle would be given by :

$$\boxed{dp \# (A . L . p/H)^{1/3}}$$

If classical wear is expected the size of the fragments should be between r (or e) and dp # $(A.L.p/ E)^{1/3}$.

The ignition aspect at the rubbing area (disregarding burning fragments for the moment) should be looked at through the hot spot ignition mechanism which has been extensively studied during the PROPEX project. One of the major findings is certainly that, in most situations, the critical parameter is the hot spot temperature which can be linked to the standard ignition temperature not only for gaseous ATEX but also for dust-air clouds (figure 3).

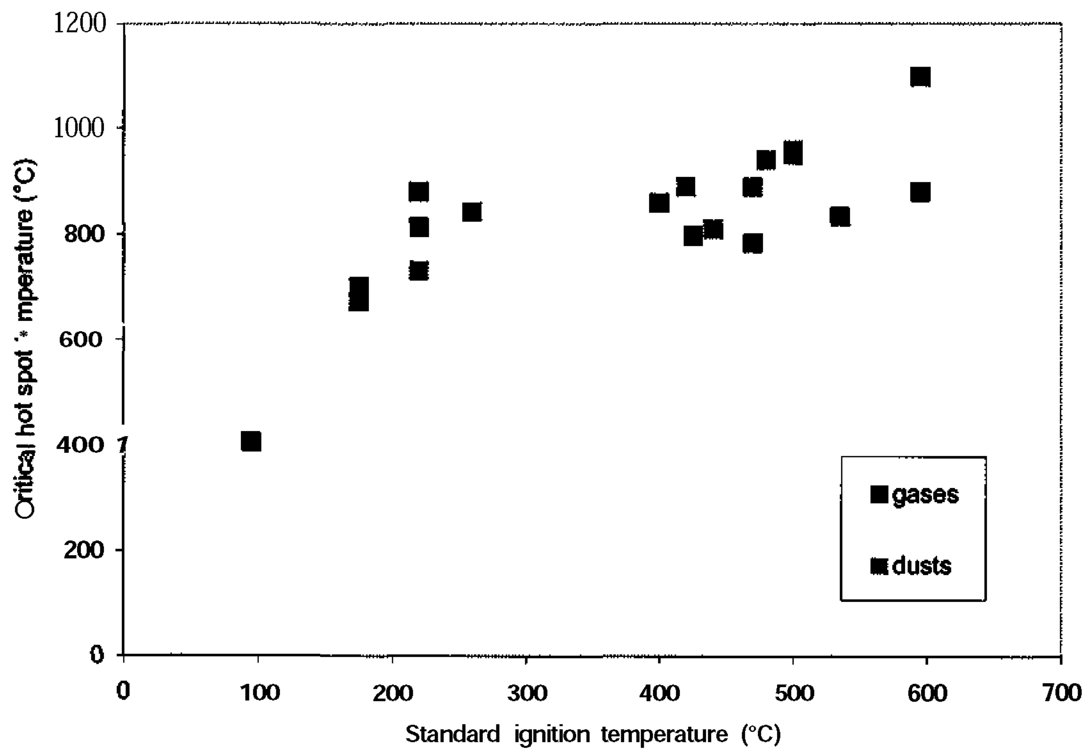


Figure 3 : correlation between the standard ignition temperature and the critical hot spot temperature for ignition for various ATEX

Comparison against experiments

The recent data from HSL (mid-term report) and those from **Ritter** (1984) may be used to try and validate this approach. HSL uses a 30 cm wheel rotating against a slider (25 mm). A comparison of

the predicted and measured rubbing temperatures (**Hawksworth** et **al.,** 2004a) is proposed on figure 4. The comparison is very encouraging bearing in mind that the rubbing area has been deduced from the experiments. The difficult point to solve is to be able to foresee this parameter from the theories of contact and to verify the effect of the size of the rubbing system which apparently affects the ignition risk. Work is currently under progress.

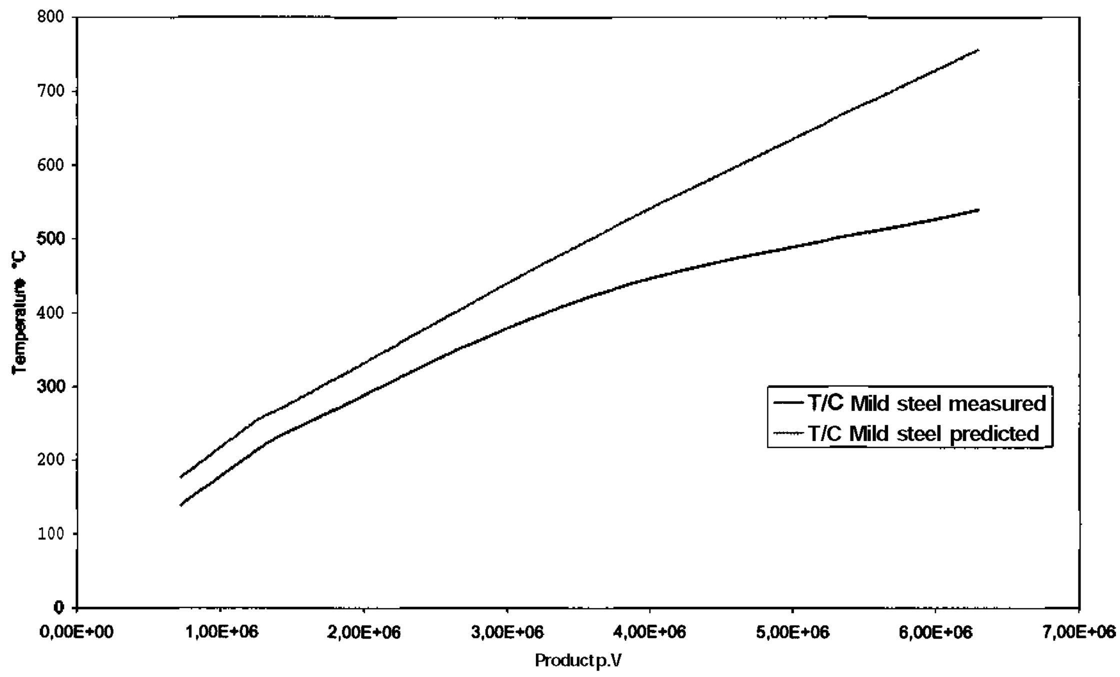


Figure 4 : measured and predicted rubbing temperatures from HSL data (present project)

About the size of the fragments, the results of Ritter, obtained at moderate loads (10 bars), suggest a classical abrasion and the size of the fragments, a few tens of microns, seem fully in line with the approach suggested above.

The remaining question is to see if the global model is able to reproduce the experimental data pertaining to frictional ignition (data of table 1). This comparison is proposed on figure 5 and seems again favourable.

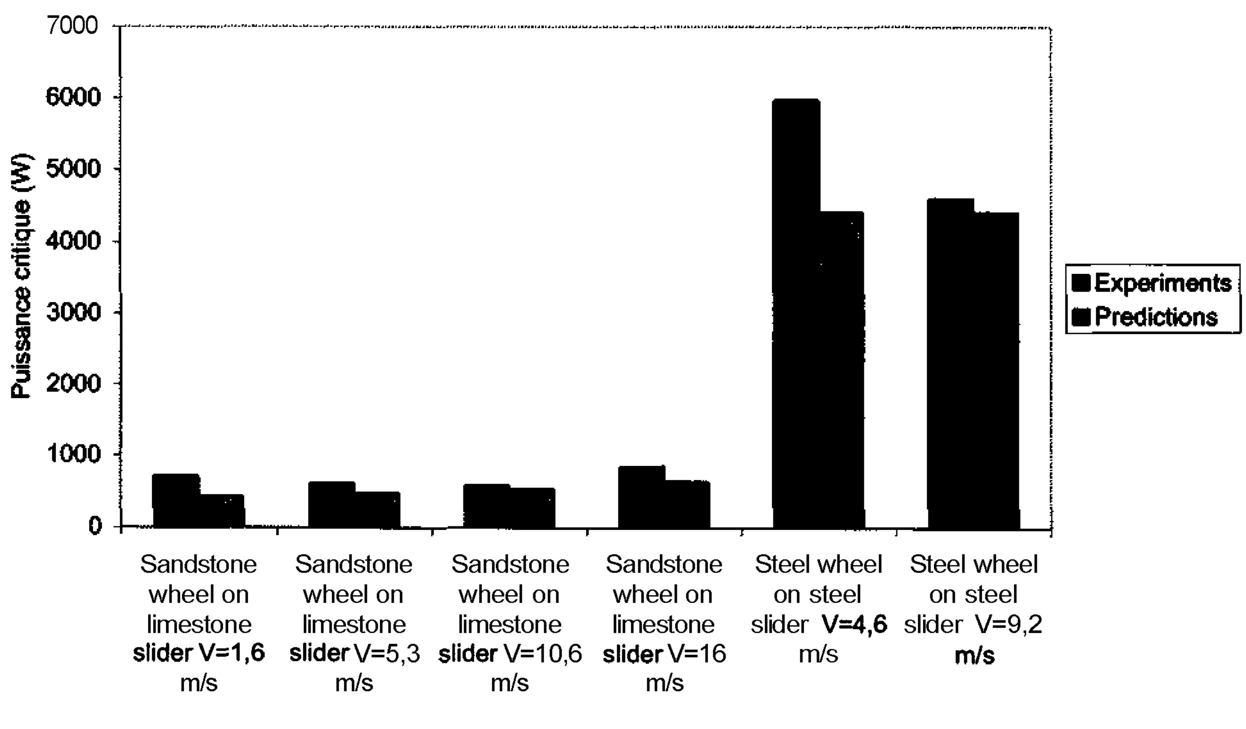


Figure 5 : comparison of prediction and experimental data on frictional ignition

Impacts

"Impact" would be referred to as an instantaneous action such that both the mechanical efforts and thermal phenomena are not in equilibrium. A good representation is the rebound of a flying object striking freely on a fixed target. A transient hot spot is produced in the contact zone. Sometimes, fragments are torn away from the surface.

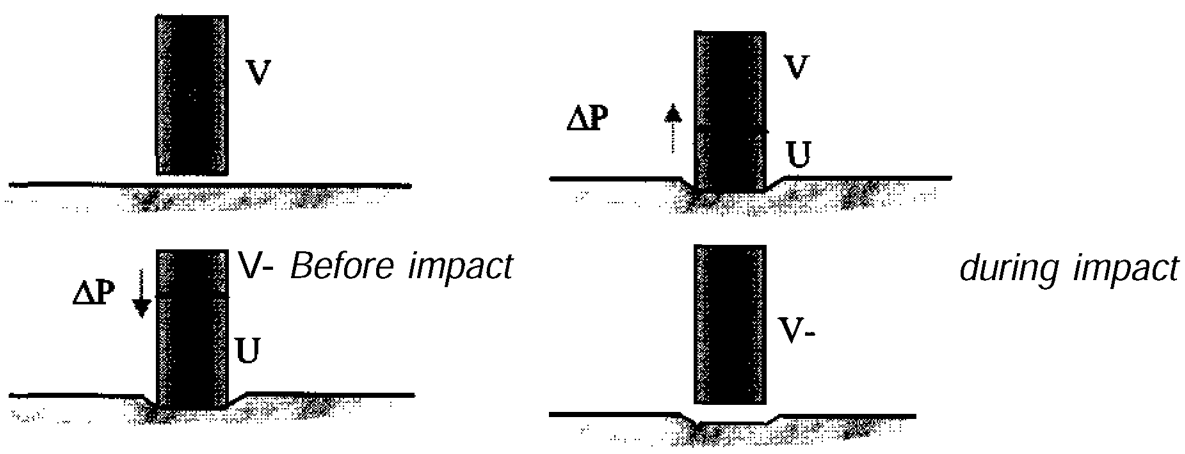
Apparently, ignition is mostly observed at the contacting point rather than around the flying fragments ("sparks"). Possible exceptions to this general rule arise when these fragments are able to burn either in air or in solide phase ("thermite" reaction). The ignition process seems to be closer to the classical spark-type than to hot surfaces although significant discrepancies with electrical spark-type if ignition seem to arise (Thomas, 1962 ; Rae, 1959 ; Rasuo et al., 1990). The link between this ignition process and the nature of the impact is unknown and reflects the very large scattering of experimental results (table 2).

Source	ATEX	Setup	D (mm)	Eci (J)
Thomas (1962)	15% Hydrogen-air	Steel ball on quartz	5,7	10
Thomas (1962)	15% Hydrogen-air	Auminium ball on steel	5,7	10
Thomas (1962)	15% Hydrogen-air	Steel ball on steel	5,7	60
Thomas (1962)	15% Hydrogen-air	Steel ball on aluminium	5,7	100
Thomas (1962)	15% Hydrogen-air	Auminium ball on rusted steel	5,7	2
Thomas (1962)	6,5 % Methane-air	Steel ball on steel	5,7	220
Thomas (1962)	6,5 % Methane-air	Auminium ball on clean steel	5,7	50
Titman (1954)	15% Hydrogen-air	Steel ball on sandstone	6,3	2
Titman (1954)	15% Hydrogen-air	Steel load (16,3 kg) on steel	160	400
Titman (1954)	6,5 % Methane-air	Magnesium load (16,3 kg) on rusted steel	260	50
Titman (1954)	6,5 % Methane-air	Aluminium load (16,3 kg) on rusted steel	220	100

Table 2 : some mechanical impact ignition results (D projectile diameter; Eci incident kinetic energy)

Physical analysis

A model has been developed by the authors based on the production and propagation of pressure waves in the impacting bodies during the rebound. Upon impact (figure 6), the interface between the projectile and the target is slowed down at speed U whereas the rest of the projectile keeps on going at V, the impact velocity. The projectile is progressively slowed down by a pressure wave propagating from the contact area to the opposite extremity of the body. U is a common deformation speed of the target and of the body. This wave is reflected back at the free extremity of the body as an expansion wave leaving the material at speed V-2.U behind.



Beginning of the rebound *rebound*

Figure 6 : deformations during normal impact

Very large pressures (10 MPa) may appear transiently (over a few microseconds) which may result in powerful friction if the impacting bodies are allowed to rub during this time. To this purpose the bodies must have the possibility to rub against each other, implying that sliding impact should be much more efficient than normal impacts as indeed observed experimentally. Representing this short friction as a classical friction in terms of speed, forces, deformations and strains, the model is developed and provides a mean to estimate the quantity of thermal energy produced in the contact zone (Ea) and the fraction of this energy which is being really transferred into the atmosphere (Egas). Local temperatures, contact areas and some other parameters are also available.

$$\boxed{Ea = 8\sqrt{2} \,.\, Cf / (e \,.\, (1+\varepsilon)^{3/2}) \,.\, \sin 2a \,.\, (\cos \alpha)^{1/2} \,.\, V\,(V / a_p) \,.\, Eci}$$

$$\boxed{Egas = Ea \,.\, 2 \,.\, \sqrt{(\lambda_g.\rho_g.c_g)} / [\sqrt{(\lambda_1.\rho_1.c_1)} + \sqrt{(\lambda_2.\rho_2.c_2)}]}$$

Where:

Eci, Ea, Egas stand respectively for the kinetic energy of the impact, thermal energy produced by the rubbing impact and thermal energy transferred into the atmosphere
a is the angle of impact
V, ap the velocity of impact and of the sound in the projectile
8 the ratio of the acoustic resistivities of the bodies
Cf the friction coefficient
Xi, Ci, pi, the thermal **conductibility,** specific capacity and specific mass of medium i (indice i = 1 and 2 for the bodies and g for the atmosphere)

It appears that only a very small fraction of the incident kinetic energy is really transferred as heat into the atmosphere (order of 1/1000) and that Egas is not a simple and constant fraction of Eci, which may explain at least partly the scattering in figure 6.

Given the nature of the efforts appearing in the contact zone, fragments may be produced under a "microcutting" action. This process need only a very small fraction of the kinetic energy (1/1000) and only a few chips are detached of typical size comparable to that of the contacting zone, leading typically to fragment diameters of a few hundreds of micrometers. These fragments may be launched at the sliding velocity of the impacting bodies and with an initial temperature equal to that in the contact area. If this temperature is large enough, burning of the fragments may be expected.

Classically two ignition modes are distinguished because their underlying physics are intrinsically different (Mc Geehin et al., 1994; Carleton et al., 1999): explosive atmosphere may be ignited either by to continuous heating by a hot surface at constant temperature or because of a local and instantaneous deposit of thermal energy ("spark"). For very short friction or impacts such that the thermal energy has been evacuated in laps of time comparable to ignition lags (presumably milliseconds or less), it is believed that the second mode of ignition would be more representative. The literature survey has however suggested that this may not be fully true. One reason may be that for most explosive atmospheres the optimum energy delivery time to obtain a minimum spark energy leading to ignition (MIE as measured experimentally for safety purposes) is of the order of a few microseconds. If characteristic times during impacts deviated strongly from this optimum, there are some indication suggested the required amount of energy would noticeably differ from MIE in an extend depending partly at least of the ratio real/optimum "spark" time. To our knowledge these aspects have not treated extensively up to now and no general rules are available. This work pertains to a further part of the present project. Another important question relevant to burning fragments is to be able to foresee the temperature at which runaway oxidation will occur. The analysis suggests that fusion of the combustible material would be a necessary condition. Further work is also needed on the subject.

Many aspects of the above model are speculative and constitutes a critical issue that cannot be verified by existing data. A specially designed setup had been designed basically to measure the thermomechanical aspects of impacts.

Experimental investigation

An experimental setup has been built. It basically consist of a free fall column thanks to which impacts between rods of different nature and a steel plate can be performed (figure 7).

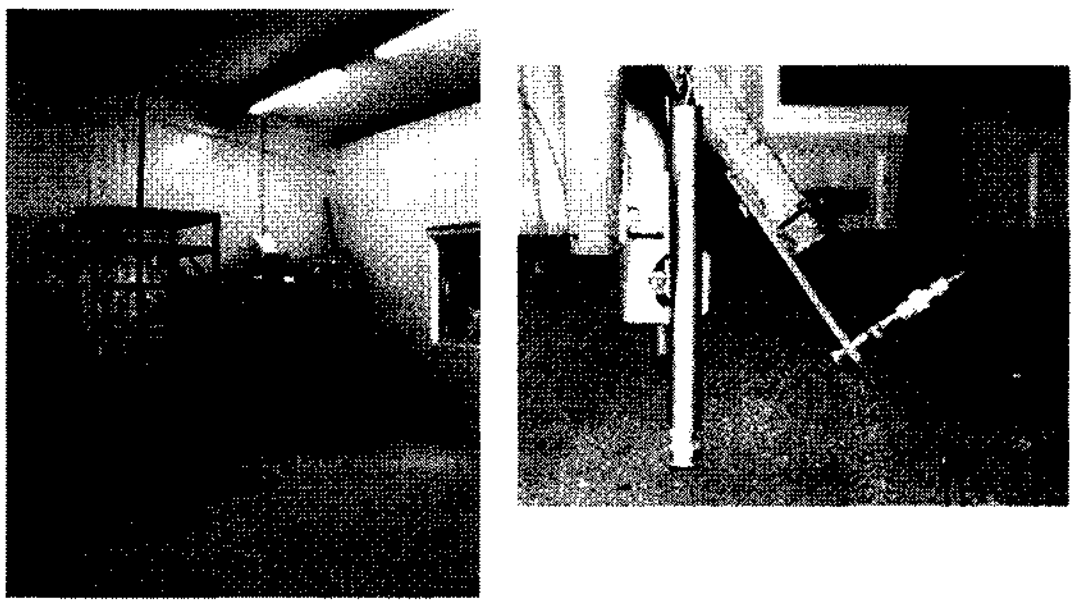


Figure 7 : views of the experimental setup

Much of the effort has been devoted to insuring a precise control of the conditions of impact and to the development of very fast thermal measurements. Temperatures are measured by means of fast **IR** pyrometer (**15 µs** rise time) and the part of thermal energy transferred to the atmosphere is derived from pressure measurements (photograph on the right in figure 7). The impact is also filmed at high speed to measure velocities and observe fragments if any. The target is a steel plate anchored on a rigid thick wood plate impeding flexion during impact. The impacting bodies are rods of different lengths (5 to 20 cm, diameter 15 mm) and different nature (steel, copper, aluminium). Typical impact velocities are in the range 5 to 10 **m/s.** A very good **reproducibility** has been obtained. Typical signals are shown on figure 8, in which the temperature is the red curve and pressure the blue one. On the pressure signal many high frequency vibrations can be seen and are attributed to mechanical waves propagating in the solids. Superimposed on them, adis tinct low vibration trace appears which is typical of thermal oscillations of the pocket of gas resulting from heat transfer from the hot spot in the friction zone. This latter part of the signal has been treated to estimate the quantity of thermal energy transferred to the atmosphere.

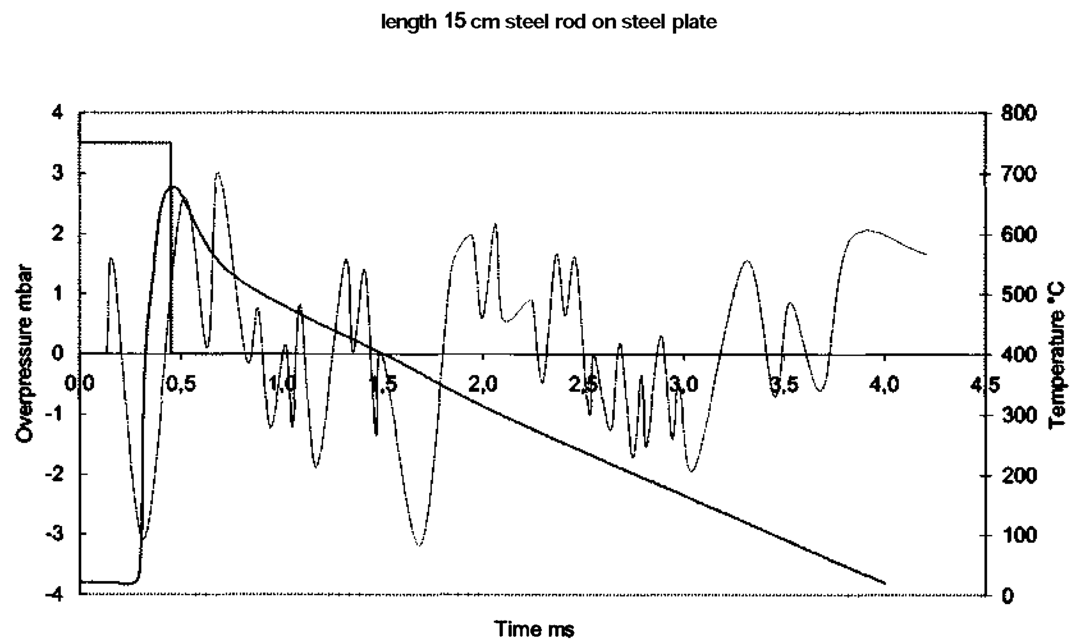


Figure 8 : typical signals resulting from the impact between a steel rod and the steel plate

For impact velocities in the range of a few m/s, a transient hot spot with a maximum temperature of the order of 700-800°C is produced with a typical duration measured in milliseconds. The area of the contacting zone is of the order a few mm^2 and the mass loss during the impact about 1 mm^3. High speed films has shown that very few fragments are produced. Typical value of E_{gas} are in the 1-10 mJ range for E_{ci} of the order of 1-10 J such that the ratio is of the order of 1/1000, fully in line with the predictions. The incidence of the nature of the bodies has been shown to be significant : softer material like copper tend to lead to larger deformations but smaller ratio Egas/Eci (three times smaller) as compared to a steel/steel configuration. This trend is coherent with the proposed analysis.

The following graphs (figure 9 and 10) show some comparisons between the calculations based on the proposed theory and the present measurements. The agreement may be judged qualitatively satisfactory, confirming the underlying physics at least about the mechanical aspects.

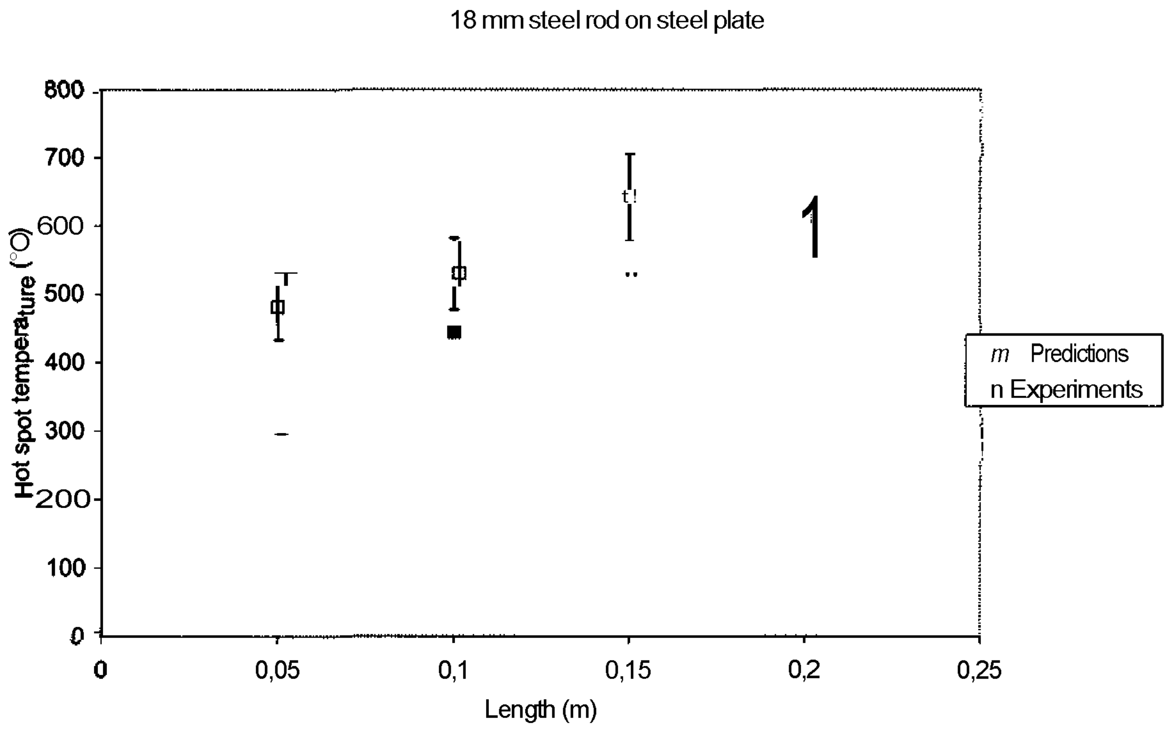


Figure 9 : hot spot temperatures for steel rods

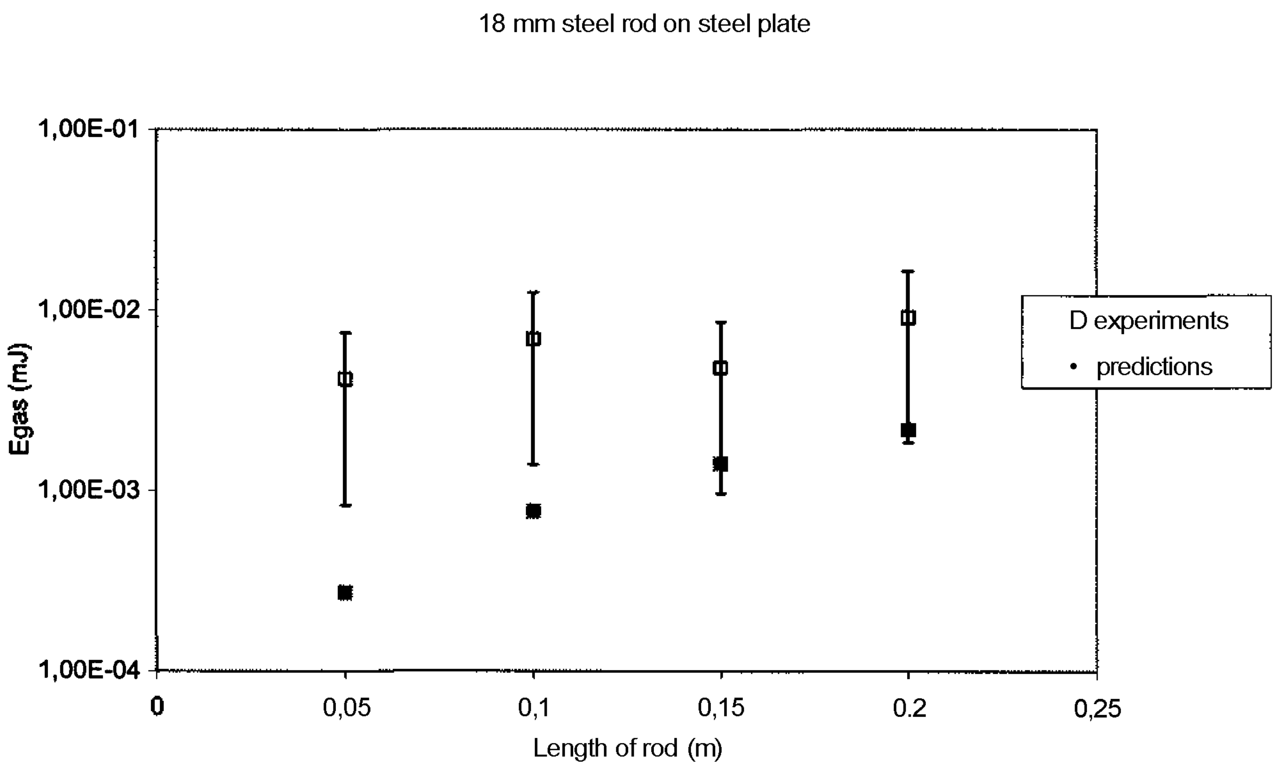


Figure 10: E_{gas} for steel rods

On the ignition side however, the typical time scale in which the thermal energy is being transferred to the atmosphere is in the range of milliseconds, which is much to large to permit the use without care of **MIE-based** criteria for ignition assessment, but which is much too small to justify the use of **AIT**-based criteria. This fully justifies a deeper insight into this ignition domain. An attempt to correlate the present modelling with available experimental data of figure 6 shows that the simple use of **MIE** to decide ignition occurs does show some links with the experiment if the energy transferred to the gas during the impact is at least 50 times the MIE (figure **11)** and, even with this ratio, the comparison is still not very good. An analysis of this would shortly be proposed along with dedicated experiments.

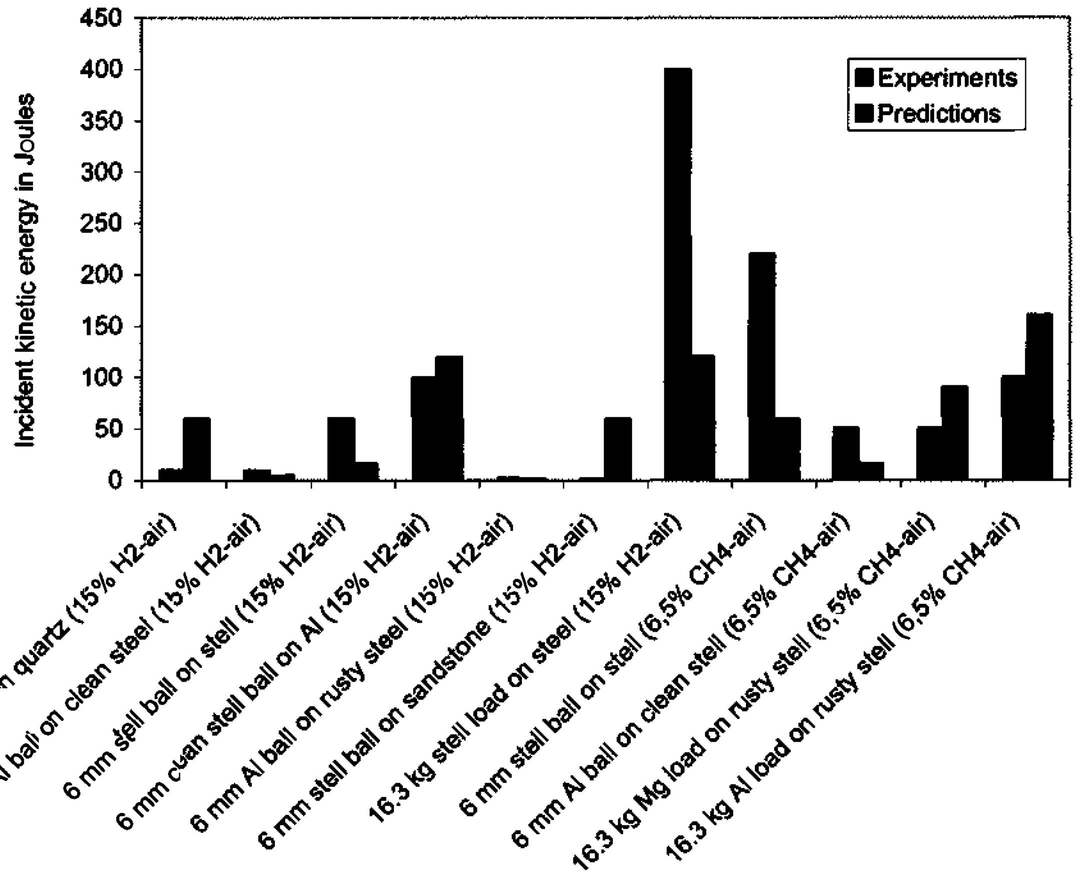


*Figure 11 : comparison of impact experiments and prediction with **Egas>50xMIE***

Conclusions

Herein are presented the results of a part of E.U. sponsored MECHEX project. The reader is referred to other papers for a global view of it **(Hawksworth** et **al.**, 2004a). A physical investigation of friction and impacts ignition hazard is proposed.

Friction (and grinding) are seen as established conditions of mechanical and thermal effects leading to the production of a local hot spot and of fragments with may burn inside the atmosphere. The question arising from the condition of ignition of these and related "thermite" reactions is left to a future part of the work. At for the remaining ignition mechanisms, we identified hot spot ignition and volumetric explosion when the explosive atmosphere happens to be sufficiently encapsulated around the friction zone. With rather simple engineering consideration, we reached a reasonable estimate of the underlying physics. In theory, ignition is possible whenever the local hot spot temperature in open atmosphere reaches roughly 700 °C. Enormous amounts of energy may not required for this (of the order of **1000** W for table 1) and the model does not suggest any clear limit in terms of sliding velocity provided the load is large enough and bearable by the machine. This is in contradiction with other opinions **(Bartknecht, 1988)** but seems to have been recently confirmed experimentally (Hawksworth et **al.**, 2004b).

Impacti s being defined by opposition to friction to tackle situations where efforts and thermal aspects are all transient. Here again a hot spot is produced during the rebound and fragments also. The physical picture is not as obvious as for friction and mechanical pressure waves have to be invoked. A satisfactory representation of the mechanical and thermal aspect is achievable on the basis of preliminary experiments. These need to be pursued with higher velocities to reach the ignition region. But it seems that the key is inside the ignition mechanism which does not appear to have been greatly investigated. To summarise the difficulty, ignition process is not through a classical hot spot nor a standard spark but in between. Much has to be done on that particular aspect.

Acknowledgement

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