IGNITION OF FLAMMABLE HYDROGEN/AIR MIXTURES BY CONTROLLED GLANCING IMPACTS IN NUCLEAR WASTE DECOMMISSIONING

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ABSTRACT

Conditions are examined under which mechanical stimuli produced by striking controlled blows can result in sparking and ignition of hydrogen in air mixtures. The investigation principally concerns magnesium thermite reaction as the ignition source and focuses on the conditions and thermo-mechanical parameters that are involved in determining the probability of ignition. It is concluded that the notion of using the kinetic energy of impact as the main criterion in determining whether an ignition event is likely or not is much less useful than considering the parameters which determine the maximum temperature produced in a mechanical stimuli event. The most influential parameter in determining ignition frequency or probability is the velocity of sliding movement during mechanical stimuli. It is also clear that the kinetic energy of a moving hammer head is of lesser importance than the normal force which is applied during contact. This explains the apparent discrepancy in previous studies between the minimum kinetic energy thought to be necessary to allow thermite sparking and gas ignition to occur with drop weight impacts and glancing blow impacts. In any analysis of the likelihood of mechanical stimuli to cause ignition, the maximum surface temperature generated should be determined and considered in relation to the temperatures that would be required to initiate hot surface reactions sufficient to cause sparking and ignition.

1.0 INTRODUCTION

During the course of nuclear waste decommissioning operations there exists the possibility of generating hydrogen in air atmospheres which could be ignited by some mechanical stimuli that results from the operations. Such mechanical stimuli can be associated with either normal operation of the decommissioning plant or be due to a fault condition which arises. It could include bodies falling under gravity to impact the waste containment vessel walls or machinery, sliding surfaces which produce excessive frictional heat or a controlled glancing blow or impact, such as for example, a robotic arm losing its control function.

Although in the past it was usual to use the concept of overall kinetic energy available in an impact or stimuli to characterise the likelihood of whether initiation of an ignition event can occur [1], with sparking due to glancing impacts, velocity is known to be an important parameter. At the former Safety in Mines Research Establishment, Buxton UK, Rae [2] investigated the ignition of methane/air by the glancing impact of metals on smears of light alloys formed on rusty surfaces causing a thermite reaction and sparking. He concluded that a light fast blow (250 g at 2.6 m/s with kinetic energy 0.9 J) can readily cause ignition whereas slightly slower, but much more ponderous impacts do not appear to do so. In contrast to this, where drop weight impacts on inclined plates are involved the minimum kinetic energy associated with initiation of thermite sparking is of the order of at least 20 to 40 Joules [1]. This apparent large difference or discrepancy in the kinetic energies involved, clearly requires further consideration. Proust et al. [3], in the development of a method for predicting the ignition of explosive atmospheres by mechanical stimuli, proposed some simple modelling for practical applications. It was considered that for impacts the relevant parameter for ignition is not the kinetic energy of the projectile but its velocity and the nature of the materials. This notion was supported by the previous observations of Rasuo and Zivkovic [4] who also suggested that the relevant parameter for consideration should be the velocity of the impact.

The nature of the corroded sludge beds in a nuclear waste containment is such that there will be very large amounts of partially corroded surface active or pyrophoric materials present. Of these, magnesium and its corrosion products are often the major constituent and represent the most likely source to initiate an ignition event.

The pyrophoric reaction that occurs when magnesium containing particles burn in air involves both oxygen and nitrogen

$$Mg + ½O_2 \rightarrow MgO \quad \Delta H = -598 \text{ kJ/mol} \tag{1}$$

$$3Mg + N_2 \rightarrow Mg_3N_2 \quad \Delta H = -461 \text{ kJ/mol} \tag{2}$$

Ignition will occur at temperatures exceeding about 500°C whereas if a thermite reaction is involved burning can be initiated at a lower temperature (~ 450°C).

$$3Mg + Fe_2O_3 \rightarrow 3MgO + 2Fe, \quad \Delta H = -981 \text{ kJ/mol} \tag{3}$$

The intensely exothermic reaction will result in temperatures of about 2500°C being reached with burning products spraying out in liquid form to generate a highly incendiary ignition source for flammable gas mixtures. Consequently, ignition of a flammable hydrogen in air mixture can result from a mechanical stimuli event, if a surface temperature is achieved that exceeds the initiating temperature for a pyrophoric surface reaction to occur.

This paper aims to examine and attempt to analyse the conditions under which mechanical stimuli produced by striking controlled blows can result in sparking and ignition of hydrogen in air mixtures. The investigation principally concerns the magnesium thermite reaction as the ignition source and focuses on the conditions and mechanical parameters that are involved in determining the probability of an ignition event.

2.0 DOUBLE PENDULUM GLANCING IMPACT APPARATUS AND EXPERIMENTAL METHOD

The apparatus constructed for the purpose of simulating glancing impacts was similar in its major design features to that used by Rae [2] in his study of the ignition of methane/air by the glancing impact of metals on smears of light alloys formed on rusty surfaces. Essentially, impacts occur due to a double pendulum system where one pendulum allows vertical freedom of movement of the striker on impact. As shown in the schematic diagram of the overall apparatus given in Figure 1, a hammer head made of mild steel with a screwed-in test tip to act as a striker was attached to the end of a 10 mm diameter steel hammer arm. The overall distance between the pivot for the hammer arm and the end of the test tip was 220 mm. A machined bronze bush was used to ensure that the hammer arm was able to swing freely with the minimum of friction.

Powerful springs wound from 3 mm diameter stainless steel rod were positioned on either side of the hammer arm and interlocked so that raising the arm to a horizontal position could give sufficient torque to accelerate the hammer head (at approximately ten times gravitational acceleration) to a velocity greater than 6 m/s when the tip reached the impact position. The torque of the made-up springs in the fully wound position was measured to ensure that each pair had similar properties. A typical torque reading for springs acting together in the release position was typically 7.2 Nm. The arm was fired using an air actuated solenoid that released the braided steel wire attached to the end of the hammer arm.

After release, the test tip struck a target plate at an angle which was preset by altering the protruding length of the test tip. The bronze bushed pivot for the horizontal arm allowed the hammer head a degree of freedom to lift away from the plate on impact and prevented embedding of the tip in the target surface. It was necessary to bolt steel plates (top plates) of sufficient mass onto the top arm to ensure that it was initially resting on its stop and that there was continued contact between the test tip and the plate surface during the impact period. The velocity achieved by the test tip at impact was altered by releasing the hammer arm from different raised positions.

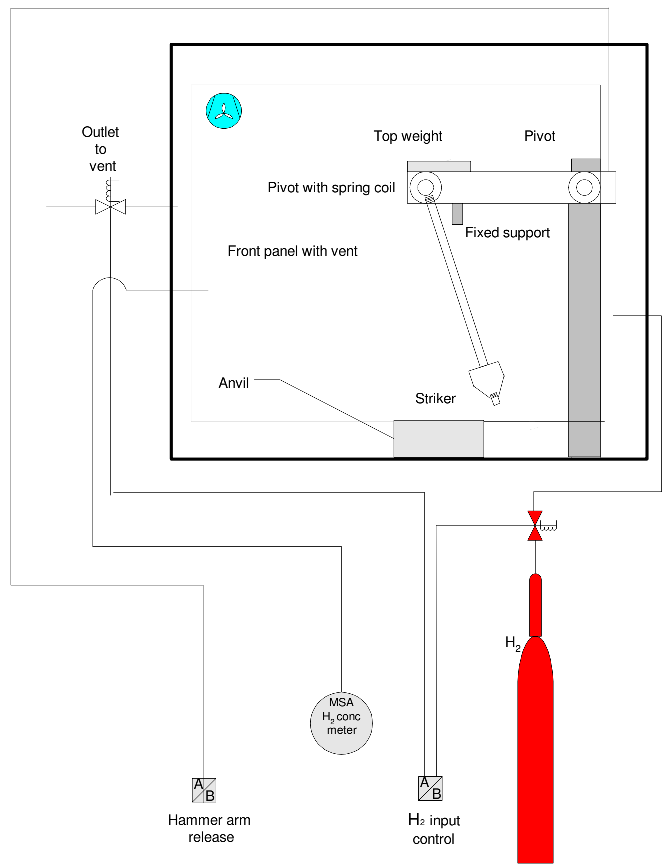

Figure 1. Double pendulum impact apparatus.

A high speed digital cine camera (Photosonic International Ltd) was used together with its associated "Phantom" software to supply a kinetic record of the impact and to determine the relevant angular and linear velocities. The high illumination lighting system necessary to give sufficient exposure without significantly raising the ambient temperature was provided by Dedocool Lighting. To accurately determine the impact angle, the test tip was lowered under tension onto the test plate and a still image was taken and analysed using the Phantom software.

Three test tips were prepared by heat treating threaded 0.4% carbon steel rods of approximately 5 mm diameter. All were initially heated to around 860°C in a muffle furnace and allowed to soak for 30 minutes before further treatment. A fully hardened tip was produced by quenching in water to produce a martensitic structure having a measured hardness of ~ 900 HV. The second tip was quenched similarly to the first but then tempered at approximately 250°C to produce a tempered martensite structure with hardness of ~ 680 HV. The remaining tip was normalised by allowing it to cool just outside of the furnace door. This tip was found to have a measured hardness of ~ 200 HV.

The target plate was machined from 100 mm diameter steel bar (BS 80A15 with measured hardness 170 HV) and allowed to rust naturally by exposure to exterior winter weather conditions in a central

London location for several months. Attempts to produce rusted plates in the laboratory using acidified solutions of hydrogen peroxide resulted in very thinly rusted plates which were found insufficient to interlock a magnesium smear and maintain a thermite reaction. Unlike the naturally rusted plates there was little pitting of the surface and only a small amount of light powdery rust particles could be detached from the surface. The surface of a typical naturally rusted plate is shown in Figure 2.

Figure 2. Naturally rusted surface produced by exposure to central London weather for several months. Magnification x 16.

Magnox metal (Al80: magnesium with 1% Al) was smeared onto the rusted surface by striking a chisel shaped piece of the material with a 0.45 kg hammer at an angle of approximately 60° to the horizontal. Confirmation that the surface coverage was sufficiently uniform to ensure that the test striker would always contact some Magnox on the surface during impact was obtained by examining the smeared surfaces under a side lit optical microscope with a digital capture system. A photomicrograph of a typical Magnox smeared surface is shown in Figure 3.

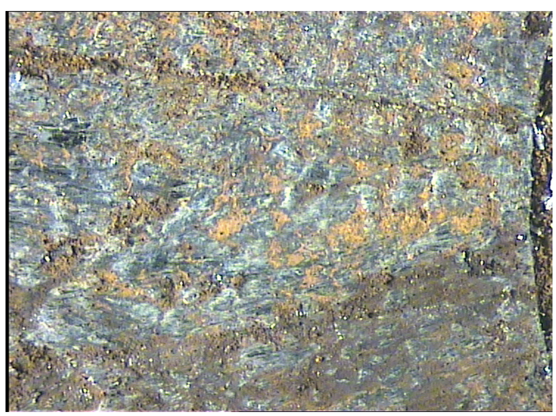

Figure 3. Photomicrograph showing a fully rusted and Magnox smeared surface Magnification x 16.

Using a simple arrangement with low friction pulleys a measure of the static friction coefficient between the striker tip and the rusty test plate was found to be approximately 0.6.

Hydrogen gas was introduced into the enclosure through a system of remotely controlled air operated valves and mixing accomplished using a compressed air operated fan assembly. The gas concentration was monitored by drawing off samples through a small bore brass tube which terminated in the near vicinity of the impact zone. Flammable gas concentration was measured using an AUER EX-METER 11 (P) analyser for combustible gases which was factory calibrated for hydrogen gas. This device allowed continuous monitoring of the gas concentration in the enclosure during mixing. The size of vent required for the chamber was determined so as to restrict the maximum overpressure that could develop to < 0.1 barg.

3.0 PRELIMINARY EXPERIMENTS USING THE DOUBLE PENDULUM APPARATUS TO DETERMINE THE APPROPRIATE PARAMETER RANGES TO CONSIDER

Initial experiments showed that ignition of hydrogen/air mixtures did not occur under test conditions when clean or rusted only surfaces were impacted. The tempered steel tip was impacted in turn onto clean and rusted target plates with the springs tensioned to give an impact velocity of ≈ 6 m/s. With impact angles ranging from between 4 to 10° and top plate weights of between 1.8 kg and 4 kg no ignitions or sparks were recorded in over thirty tests with hydrogen/air concentrations in the most easily ignitable range (15 to 22%). In all cases it was observed that there was slight bevelling of the test tip after impact and that very slight indentation of the target plate occurred indicating plastic deformation. It was noted that the smaller the glancing angle at impact, the longer was the overall length of the indentation, indicating that the lower normal impact force was resulting in a smaller degree of restitution. Experiments using the fully hardened steel tip with glancing impacts within the range 4 to 10° did not result in any ignition and were unsuccessful on account of the tip being brought to rest at impact, having become immediately embedded in the target plate. This rapid deceleration to zero velocity is associated with a high impulse force. It was also observed that there was no bevelling of the tip which would facilitate sliding. Clearly, virtually all of the deformation and $p\mathrm{d}v$ work (where $\mathrm{d}v$ represents the deformation volume) due to the normal impulse generated was being confined to the target plate material resulting in a constraining indentation crater. The velocity variation that occurred during the impact/contact period was examined using high speed digital imaging with a high frame per second rate. At an impact angle of 4° with the normalised tip no discernable reduction was observed whereas at 8° it was found that the velocity decreased by less than 10%. Increasing the angle of impact to 10° resulted in a velocity decrease of up to about 25% after the initial contact. The hardened and tempered tip had a greater effect on reducing the sliding velocity after impact.

Tests using solid Al80 Magnox test tips (HV 70) impacting onto rusty plates under various conditions of impact velocity and impact angle did not result in any observable thermite sparking or ignition of 15 to 22% H_2/air mixture. The tips were heavily deformed after impact particularly at velocities exceeding 6 m/s.

Tentative tests were carried out with Magnox smeared rusty plates to indicate which factors involved in the impact and the ignitions were of sufficient importance to be considered further in a factorial experiment. It was immediately apparent that the extent to which the target plate was rusty and the extent to which it was smeared with Magnox were both highly important factors. However, unless both the rust and Magnox particles are spread uniformly over the surface in such a manner as to ensure that every possible impact will involve contact with both reactants, sparking becomes a chance event dependent on the extent of the impact area. Because of the difficulty in representing the uniformity and distribution of rusting and smearing in a useful and meaningful way, it was decided to minimise variation as far as possible by carrying out all of the factorial experiments with highly rusted and heavily smeared plates. In effect it was assumed that these plates would always enable ignition to take place if the impact and energetic conditions allow it. However, it was not always found to be the case that sparking and ignition occurred during the first contact on impact.

Overall, from the preliminary experiments carried out with fully rusted and smeared plates it was concluded that the mass of the swinging hammer head has relatively little effect (over the range 0.22 to 0.43 kg) and that the factors most likely to be important in promoting ignition are; the glancing angle of impact, the velocity of the strike tip at impact, the hardness of the strike tip and the top plate mass. The hydrogen/air concentration was added to the list to give in total five main influencing factors. The initial experiments also indicated suitable values for high and low levels of the factors to be considered.

4.0 FACTORIAL EXPERIMENTAL DESIGN AND RESULTS

In order to explore which factors are most important in determining whether ignition of hydrogen/air mixtures occurs due to glancing mechanical impact of Magnox smeared rust layers, a "design of experiment" (DOE) approach was adopted. Using DOE with two levels for each parameter allows a relatively large number of variables to be considered in a consistent and economic manner. The factors and their parameter levels (designated as 1 or -1) for inclusion in the experimental design were as follows:

(a) Hardness of the impacting tip: (1) tempered 0.4% carbon steel 680 HV and (-1) normalised 0.4% carbon steel 200 HV.

(b) Hydrogen concentration in the gas mixture: (1) 8% and (-1) 15%.

(c) Glancing angle of impact: (1) 8° and (-1) 4°

(d) Impact velocity: (1) 6.7m/s and (-1) 3.9m/s

(e) Top plate mass (downwards acting weight on the vertically inclined striker tip)

: (1) 3.4 kg and (-1) 2.25 kg.

4.1 Factorial design

For five variables or factors, a full factorial (2^5) design would entail a total of 32 series of experiments being carried out. This would enable the five main effects with second and third order effects to be investigated. It was, however, considered unnecessary to include the higher order interactions so that a half fractionated design (2^{5-1} with two parameter levels having level V resolution was chosen. This kind of design allows full determination of the main order effects and if required second order interactions.

Although, there is an implicit assumption of linearity in the factor effects in this scheme, it is expected that the design will perform well even when the linearity assumption holds only very approximately [5]. Ten individual ignition tests were carried out to determine the frequency of ignition for each set of conditions leading to an overall total of 160 tests. Because this response is "fraction defective" arising from a binomial distribution with only two complementary alternatives (e.g. ignition or no ignition) and where frequency proportions are involved, it is beneficial to use an arcsine root transformation [5] before proceeding with the analysis of the results. This kind of transformation is satisfactory even when the results contain up to 75% of very low counts or zero proportions. The transformation does not change the relationship between the samples and data points but rather changes the scale on which the variables are measured and converts it to a normal distribution.

The organisation of the different combinations of experimental conditions employed in the runs followed the standard Yates order, the sequence of which was then randomised before carrying out the experiments.The experimental results were analysed with ANOVA to indicate the most important main effects and the residuals checked to confirm that there was no serious deviation from normality.

4.2 Procedure

The half fractionated experimental design (2^{5-1}) was generated and randomised to produce the final experimental scheme. Each set of the ten determinations necessary to obtain a measure of the ignition frequency, was carried out in the predetermined randomised run order. After each prescribed change of impact angle, careful verification of the angle was carried out and the stability of the assembly checked. The torque of the wound springs were checked after approximately every 30 tests to confirm that no significant changes had occurred during the testing. In all of the tests, target plates were used which had been exposed to the atmosphere and rusted under identical conditions. Every effort was made to achieve a similar and uniform smearing of Magnox on all the surfaces used. Two top plates were used to give the required top weights. A spring balance (Rapala 0 to 25 kg reading 0.01 kg) was used to determine the actual downward weights effective at the pivot for the hammer arm. These weights represent the normal force on the striking tip when the arm is in an exact vertical position. After each series of tests for a given set of conditions, an ignition frequency was recorded as the raw response variable.

4.3 Results and analysis

The experimental results obtained for the design are given in Table 1. For the reasons explained earlier, the ignition frequencies were transformed by taking the arcsine of the square root of each value and weighting the extreme values of 0 and 1 which become respectively $1/4n$ and $(n-1/4)/n$ where n = 10 in this case. These transformations are shown in the final column of the Table and were used in the analysis.

Table 1. Results of factorial design of experiment: ignition of H_2/ air by glancing mechanical impact

Run order	Standard order	Tip hardness (HV)	Concentration H_2/air (%)	Impact angle °	Strike Velocity (m/s)	Top Wt. (kg)	Ignition frequency	IgT*
1	12	680	8	4	6.7	2.25	0.6	50.76
2	8	680	8	8	3.9	2.25	0.1	18.43
3	6	680	15	8	3.9	3.4	0.2	26.56
4	15	200	8	8	6.7	2.25	0.7	56.78
5	11	200	8	4	6.7	3.4	0.6	50.76
6	16	680	8	8	6.7	3.4	0.7	56.78
7	4	680	8	4	3.9	3.4	0.3	33.21
8	5	200	15	8	3.9	2.25	0.3	33.21
9	9	200	15	4	6.7	2.25	0.9	71.56
10	3	200	8	4	3.9	2.25	0	9.1
11	14	680	15	8	6.7	2.25	0.8	63.43
12	1	200	15	4	3.9	3.4	0.1	18.43
13	13	200	15	8	6.7	3.9	1	80.89
14	2	680	15	4	3.9	2.25	0	9.1
15	7	200	8	8	3.9	3.4	0.2	26.56
16	10	680	15	4	6.7	3.4	0.3	33.21

* Arcsine root transforms (degrees)

To highlight the most important factors controlling the ignition frequency a main effects plot based on the data means is given in Figure 4.

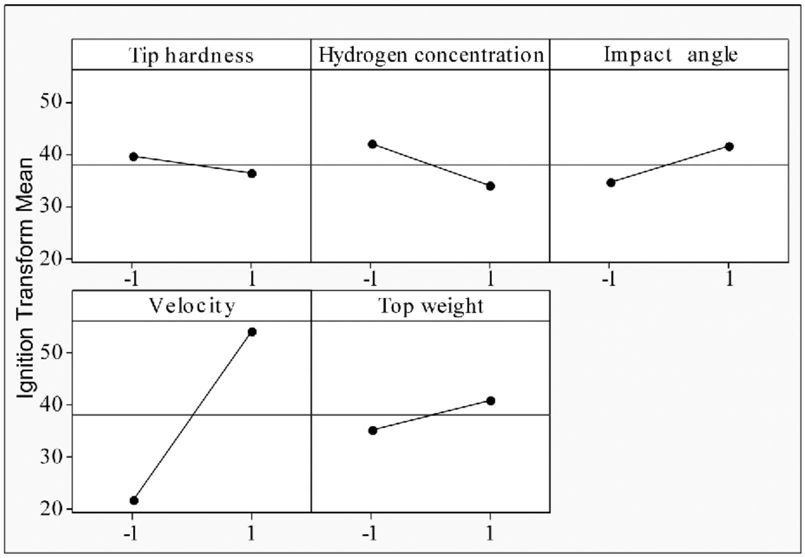

Figure 4. The main effects plots from the experimental design analysis.

It is clearly seen that the most important effect is the impact velocity followed to a considerably lesser extent by the other factors. Increasing hydrogen concentration from 8% (1) to 15% (-1) is associated with a higher probability of ignition as is increasing the top weight or the impact angle. Increasing the tip hardness on the other hand is shown to slightly decrease the likelihood of ignition. A Pareto chart is presented in Figure 5 to further facilitate visualisation of the contribution of the chosen factors to the ignition probability.

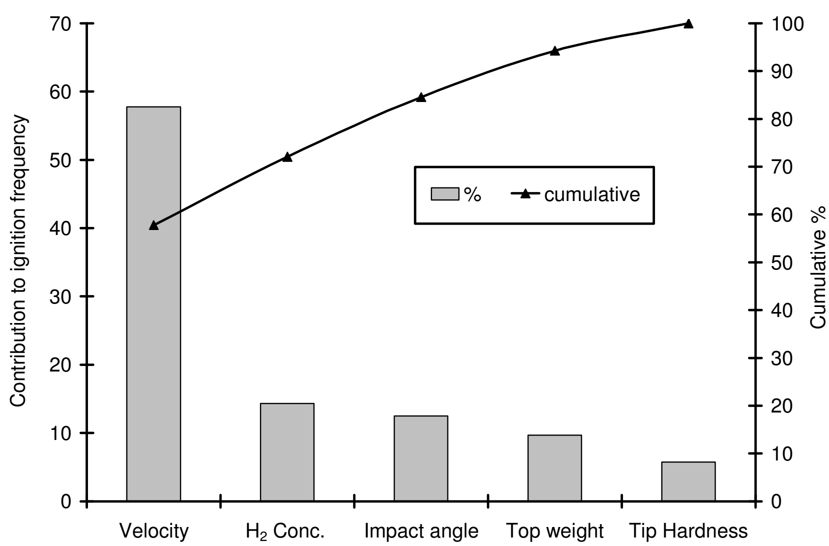

Figure 5. Pareto chart of the main effects of the factorial experiment showing the contribution of the variables to the ignition frequency.

High speed digital imaging was used to investigate the initiation of thermite sparking and ignition due to a glancing impact. The progress of a typical ignition sequence is shown in Figure 6.

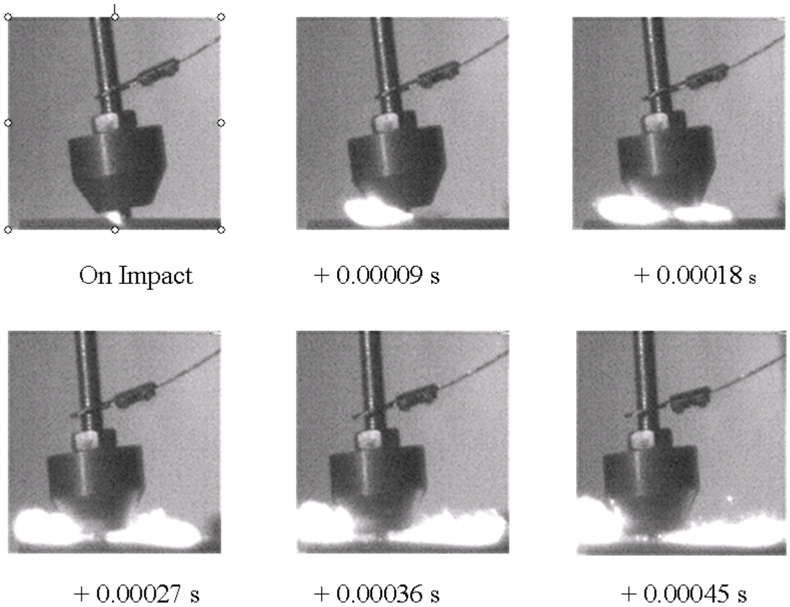

Figure 6. Progress of thermite sparking in a 22% H / air atmosphere produced by rust/Magnox reaction during glancing impact at an angle of approximately 7 degrees. 11,200 frames/s. Tip velocity -26.5 rads/s (~ 5.8 ms)

Sparking is observed in this case to occur within the first time frame after impact and burning of Magnox in the hot combustion gases can be seen to develop. This occurs within a fraction of a millisecond where it further appears that the hot gases may be causing some of the non-contacted or impacted areas of Magnox to also rapidly burn.

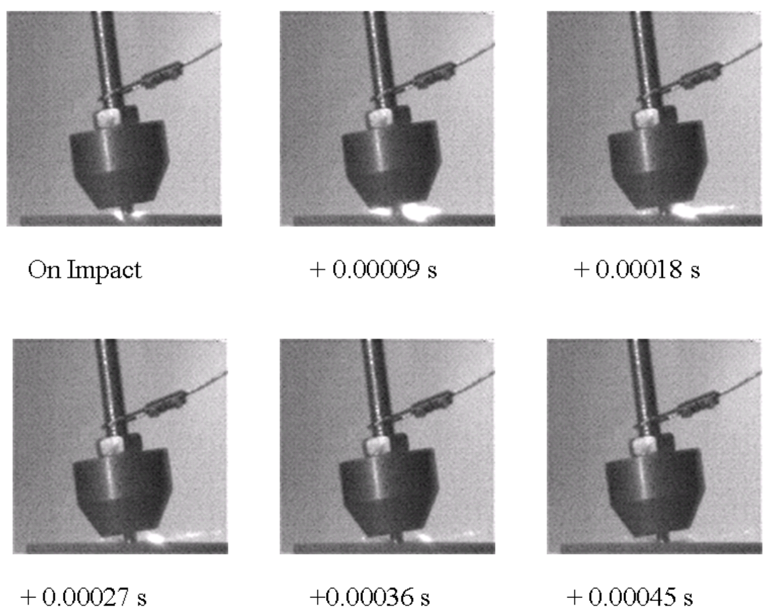

Figure 7. Progress of thermite sparking in air produced by rust/Magnox reaction during glancing impact at an angle of approximately 7 degrees. 11,200 frames/s. Tip velocity -27.3 rads/s (~ 6 ms)

5.0 DISCUSSION

It is clear from the results that the most important parameter influencing the ignition probability is the impact velocity and that the other factors have some influence but to a much lesser degree. From the preliminary experiments it was found that the weight acting downwards to load the striker tip had a significantly greater effect than the mass of the moving hammer head. This is not unexpected since the hammer head, even at the time of impact, is still being driven by the uncoiling springs. An increase in the hammer head mass would, however, contribute to additional momentum and this might be associated with slightly reducing deceleration of the tip as it impacts the plate. Increasing hydrogen in air concentration from 8% to 15% leads to an expected increase in the ignition probability in accordance with the known higher incendivity of the richer mixture. The increase of ignition likelihood with increase in the glancing angle may be attributed to some extent to the increase in the sliding contact time which occurs at the larger glancing angle. It is also the case that the nature of the impact and its impulse will also differ with the glancing angle since there will be a greater vertical displacement of the pendulum pivot at the larger angle. The normal mechanical loading on the tip will increase from the point of contact to a maximum at 0° (when the tip is vertically inclined) and will then decrease. Whilst in general, it would be expected that increasing the tip hardness will result in a greater likelihood of ignition occurring, this was not found to be the case. However, an associated effect of increasing the tip hardness is to reduce the resulting sliding velocity which will have a major influence in decreasing the ignition probability.

It was observed from the high speed digital imaging that the magnesium thermite reaction was rapidly initiated when conditions enabled it to occur. As can be seen from Figure 6, ignition of the gas mixture also commenced with very little delay once sparking had occurred indicating a high temperature ignition source. The temperature reached by burning magnesium as a result of the reaction is known to exceed about 2,500°C but a surface temperature greater than about 450°C would be sufficient for its initiation. The maximum or flash temperature generated between sliding surfaces can be deduced from a thermal analysis which takes into account the thermo- mechanical properties of the contacting surfaces together with the extent of the sliding velocity and its load. With glancing impacts there will be a reduction in the initial velocity arising from the impulse of force that occurs on impact. The impulse of force corresponds to the change in momentum of the hammer head during the impact and is given by the product of the mean force and the impact duration. After a short period, during which the impulse of force dissipates, sliding continues with little variation of velocity. It is apparent from the high speed imaging examination of the velocity variation after contact, that the force of impulse is of little consequence at low impact angle (4°) but becomes more significant at an impact angle of 8°. However, some understanding of the likelihood of ignition can be gained by considering the maximum surface temperatures generated during the sliding phase following the initial force of impulse. It has recently been demonstrated by Averill et al. [6, 7] (in a comparison of theoretical and experimental values) that it is possible to predict the maximum surface temperatures resulting from sliding mechanical stimuli by taking into account the main variables involved. Under conditions where there is rapid sliding so that a high Peclet number is applicable and where there is a high degree of plastic deformation as appertains here, the maximum surface temperature can be expressed by

$$\theta_{\max} - \theta_b = \frac{1.6 \mu p_f^{3/4} F_n^{1/4} v^{1/2}}{\pi^{1/4} (k \rho c_p)^{1/2}} \qquad \textbf{(4)}$$

where the symbols have the following meaning

c_p	specific heat
F_n	normal force
k	thermal conductivity
p_f	material flow stress in pure shear
v	velocity of sliding
μ	dynamic coefficient of friction

ρ density
θ_b bulk temperature
θ_{max} maximum (flash) temperature

It can be immediately seen that the sliding velocity is a more influential parameter than the loading force and that the coefficient of friction and the material flow stress are very important parameters in determining the surface temperature. The material flow stress in pure shear is included in the expression because it is directly related to the sliding contact area produced by plastic deformation.

$$F_n / \pi a_p^2 = p_f \qquad (5)$$

The Tresca maximum shear stress criterion suggests that in pure shear yielding will occur at a shear stress of $p_f = p_y / 2$ where p_y is the yield stress of the material. Taking this into account there is a simple and useful numerical relationship between indentation hardness (H) and the flow stress (p_f) which governs the onset of plastic behaviour [8].

$$H \approx 5.66\, p_f \qquad (6)$$

where H and p_f and are expressed in the same units (e.g. MPa). The measured hardness of the steel plate used in the experiments was 170 HV leading to a value for of 300MPa. Other values taken for the calculations were as follows; from the measured static friction coefficient of 0.6, a value of 0.54 was taken for the dynamic coefficient, for the steel k = 50 W/m·K, ρ = 7800 kg/m^3 and c_p = 465 J/kg·K.

From Table 1 it is apparent that the ignition frequency tends to be much higher with the level of velocity set at 6.9 m/s and with the higher level of loading (3.4 kg). At the lower velocity level the maximum ignition frequency found was 0.3 as compared to unity at the higher velocity. If the effect of the initial force of impulse is disregarded, comparison can be made between the maximum sliding temperatures estimated using equation (4) for level conditions of high velocity with high loading (708°C) and for low velocity with low loading (494°C). The higher flash temperature for the high velocity/loading condition, considerably exceeds that which is required to initiate the thermite reaction and is consistent with a high probability for ignition. In contrast, under the low velocity/loading condition the indicated flash temperature is not much above that required for the thermite reaction and so is consistent with the lower associated ignition probabilities.

It is interesting to consider the experimental finding that ignition did not occur under the test conditions when clean or rusty steel surfaces were employed. Comparing the maximum surface temperature that would have resulted from the tests (i.e around 700°C) with those required for hot surface ignition of hydrogen/ air mixtures suggests that ignition would be unlikely. In their work, Proust et al. [3] carried out hot surface ignition tests with a 10% H_2 /air mixture employing a rapidly heated-up 50 µm thick, 5mm x 20mm (100 mm^2) titanium strip. From their results, it can be considered that temperatures exceeding 700°C would be required for ignition to occur with ignition delays of between 3 to 10 ms. Given that (i) the maximum area of tip/plate contact during the glancing impact tests did not exceed about 75 mm^2 and (ii) the contact time was less than 3 ms, it is indicated that somewhat higher temperatures than 700°C would have been required for ignition to occur.

When determining the likelihood of an ignition event occurring during a glancing impact, it is clearly much more useful to consider the sliding velocity and loading involved together with the thermo-mechanical properties of the materials, rather than the kinetic energy just prior to the mechanical impact or event. The latter represents an overall quantity of which only a small part may be involved in initiating an ignition source. During a mechanical impact for example, part of the energy may be dissipated tangentially as friction, part normally to the surface resulting in possible plastic deformation and that which remains after the impact as potential energy of the moving body. This explains the apparent discrepancy in previous studies between the minimum kinetic energy thought to be necessary to allow thermite sparking and gas ignition to occur with drop weight impacts and constrained glancing blow impacts.

It is concluded that in any analysis of the likelihood of a mechanical stimuli to cause ignition, the maximum surface temperature that could be generated needs to be determined and considered in relation to the temperatures that would be required to initiate hot surface reactions sufficient to cause sparking and ignition. As described in previous work [6], prediction of surface temperature can be accomplished using Monte Carlo analysis to take into account uncertainty in the variables and parameters involved.

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