IGNITION OF DUST CLOUDS AND DUST DEPOSITS BY FRICTION SPARKS AND HOTSPOTS

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Evaluating the effectiveness of mechanical ignition sources in igniting dust clouds and deposits is a major problem when assessing the risks in powder handling plants. This paper describes the results obtained in the recent European collaborative project, MECHEX, with explosible dusts. These involved both friction and impact ignition tests with different dusts including coal, maize starch, calcium stearate, suphur and sawdust as well as hotspot tests. using both large hotspots in dust deposits and small laser heated hot particles in dust clouds. The experimental work was carried with the aim of providing guidance for inclusion in European Standards on mechanical equipment for use in potentially explosive atmospheres. Although still inconclusive, the results obtained provide further information for understanding the complex problem of frictional ignition.

INTRODUCTION

Mechanical ignition sources occur when solid surface either impact briefly or rub together over longer period. Friction, grinding and impact can produce sparks and hot spots capable of igniting explosive atmospheres. When explosible dusts are present an additional danger is that dust deposits may be ignited at the contact surface and subsequently act as an ignition source for an explosible dust atmosphere.

The friction processes which can occur in rotating machinery can be divided into rubbing, grinding and impact. Rubbing produces long duration hot surfaces and generally none or only a few sparks. Grinding also produces long duration hot surfaces, generally with large numbers of sparks depending on the material. Evidence from the MECHEX project [1–3] indicates that, for gas or vapour explosive atmospheres, hot surfaces at and around the frictional contact point (e.g. trailing edge burr) are a much more potent ignition source than sparks. The efficacy of the ignition source produced depends on the power, load, speed, size and coefficient of friction associated with the friction process and the confinement of the equipment in which the hot surface is produced. In relation to the latter, there is also the possibility of a pseudo auto ignition whereby a contained volume of the explosive atmosphere is heated to the auto ignition temperature, this is discussed further by Proust [2]. For explosive dust clouds this is unlikely to occur however for dust deposits the pre-heating by frictional heat is a common occurrence particularly when the friction source is embedded in the powder.

Although friction is a frequent cause of ignition of explosive atmospheres [4,5], in contrast to gas atmospheres, it is difficult to carry out laboratory tests which directly simulate the practical situation with explosible dust clouds. Hence in the MECHEX project, the friction grinding and impact processes have been analysed in order to classify the potential types of ignition sources which can occur and these have been simulated in the laboratory tests with dust clouds and dust deposits. This approach allows a more fundamental investigation into the underlying phenomena which occur, however it does have a major limitation in that the complex interactions which can occur when dust is present in the mechanical contact process are not taken into consideration. Ignition tests have therefore also been made which more directly simulate the practical situation.

TYPES OF IGNITION SOURCES

The types of ignition sources which occur include on the one hand hot surfaces due to longer duration friction or rubbing and on the other hand mechanical sparks from shorter but usually higher speed grinding or impact which consist of a few metal particles up to an extended cluster of heated particles which have a high temperature and may also be themselves "burning" in the air. Even the term "single impact" does not mean that there is a single heated particle. It usually means an arrangement such as the drop weight test where an object impacts against an inclined plane. Tests have shown that this "single-impact" produces a hot spot at the point of contact and additionally several heated metal particles.

In this work ignition tests with powders have therefore been carried out using simulated sparks produced by the controlled laser heating of fine particles, larger electrically hot spots; sparks and hot surfaces produced by a grinding wheel and single impact tests.

CHARACTERISTICS OF THE DUSTS USED

The following dusts have been used in the tests of mechanical ignition: Sulphur, Wood Dust, Maize Starch, Calcium Stearate, Coal, Aluminium and Bio-Waste. Some of the explosion characteristics measured using standard tests are given in Table 1.

IGNITION OF DUST CLOUDS BY SIMULATED SPARKS

Simulated sparks were produced by the laser heating of a coating of iron black on the tip of an 1000 μm diameter optical fibre. The final thickness of the coating cannot be controlled during its preparation and has to be determined after drying of the coating. Typical values ranged from 250 to 900 μm. The temperature of the simulated spark (coating) was

Table 1. Explosion characteristics of dusts used in ignition tests

Dust	5 mm layer ignition °C	5 cm cube Ramp ignition °C[1]	MIE mJ[2]	Kst bar m/s	Pmax bar	Cloud ignition °C
Bio-waste	300	135	>1000	69	5.7	480
Coal dust	225	115	>1000	70	7.5	450
Maize starch	440	208	100	110	9.2	480
Sawdust	315	181	10	115	9.2	470
Calcium stearate	>450	316	10	130	8.7	560
Sulphur	260	–	3	151	6.8	280
Aluminium	>450	–	3	415	11.2	600

[1]Exotherm onset temperature determined when the powder sample in a 5 cm cube wire basket is heated in an oven at 0.5 °C/min.
[2]Capacitative spark.

measured by a two-line pyrometer before starting the test. The applied output power of the laser was varied from 1 W to 6 W and the temperature measured.

Ignition tests were carried out using the simulated spark in a modified Hartmann-Tube to generate the dust cloud as shown in Figure 1. The power was varied tuntil the ignition/no ignition boundary was determined. At the end of the experiments with one

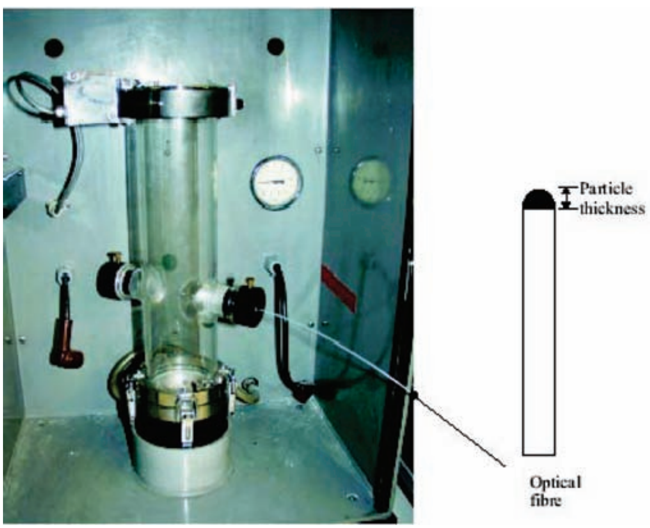

Figure 1. Modifed Hartmann-Tube for experiments with simulated sparks

type of dust the temperature of the coating was measured again in order to ensure the temperature measured previously has been applied during the whole experiment. Control experiments were also carried out with a thermocouple embedded in the tip of the coating. The results showed good agreement between the two measured temperature values.

The experiments were carried out with the following dust atmospheres: Sulphur, Wood Dust, Maize Starch, Calcium Stearate, Coal and Aluminium. For each dust weights of 0.5, 1.0 and 1.5 g were used. All dusts could be ignited in the experiments performed in the Hartmann tube with an applied laser power ranging from 1 W to 6 W. The main difficulty in realising this series of experiments was the poor reproducibility of the coating preparation. It was therefore not possible to develop a clear relation between particle size, particle temperature and the ignitability of a dust atmosphere Figure 2 shows typical results obtained with aluminium showing the variation of temperatures of ignition and non-ignition with particle thickness.

The results shown in Figure 2 show that there is only a small variation of the temperature required for ignition with particle thickness. This was observed for all of the dusts tested. Table 2 lists the minimum temperature of ignition and the maximum temperature of non-ignition for the different dusts used. With sulphur ignition occurred in all tests and no non-ignition temperature value was determined.

IGNITION OF DUST DEPOSITS BY HOTSPOTS

Ignition tests of dust deposits have been carried out using both electrically heated hot spots of ca. 2 cm diameter and laser heated particles of ca. 1 mm diameter prepared as above.

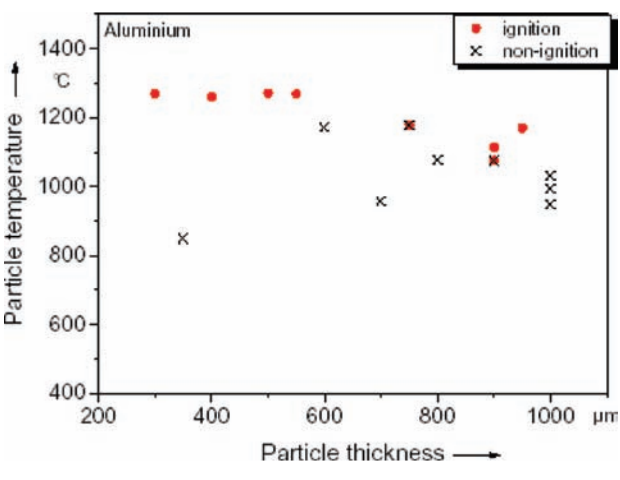

Figure 2. The ignition characteristics of aluminium dust in dependence of particle size and particle temperature

Table 2. Maximum and minimum temperatures for ignition/non-ignition

Dust	Maximum temperature non-ignition	Minimum temperature ignition
Aluminium	1173°C	1075°C
Calcium stearate	1256°C	1214°C
Coal	820°C	820°C
Maize starch	1391°C	1391°C
Sawdust	1351°C	1351°C
Sulphur	–	512°C

The larger hot spots were placed in the centre of a 10 cm wire basket containing the powder while the laser heated particles were placed in the centre of a 5 cm wire basket. Thermocouples were placed in the powder to detect ignition. Figure 3 shows the experimental set-up for the tests with the laser heated particles.

The applied output power of the laser used was about 4 W. The power of the laser radiation that comes through the optical fibre to the coated tip was measured to be round 70% of the laser output power, so that the actual laser power used for the heating of particles was in the range of 2.8 W (all further data are 70 % of the output power). Table 3 shows the coating temperatures measured by the pyrometer at this adjustment. After the adjustment of the laser power and the temperature measurement the coated end of the optical fibre is placed in the middle of the copper basket that is filled with the dust powder. The heating duration of the particle was 10 s to 20 s.

Tests with the laser heated particles were carried out using Coal, Sulphur, Calcium Stearate, Sawdust and Maize Starch. In all tests the temperature measured just above the

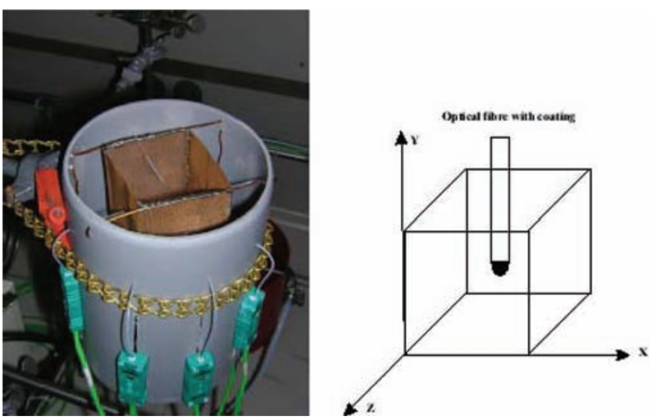

Figure 3. Experimental set-up with the basket for ignition tests of dust deposits

Table 3. Coating thickness and maximum temperature measured by the pyrometer

Dust	Experiment	Coating thickness	Coating temperature
Coal	1	660 μm	1150 °C
Coal	2	620 μm	1450 °C
Sulphur	1	780 μm	1270 °C
Sulphur	2	350 μm	1250 °C
Sawdust	1	400 μm	1200 °C
Sawdust	2	350 μm	1300 °C
Calcium stearate	1	500 μm	1180 °C
Calcium stearate	2	350 μm	1380 °C
Maize starch	1	500 μm	1125 °C
Maize starch	2	350 μm	1175 °C

hotspot increased rapidly when the power was switched on quickly reaching the temperature measured in air. A typical temperature trace is shown in Figure 4.

For all the dusts tested except for sawdust the temperature near the heated particle then increased slowly reaching a value ca. 30 °C above the "air" temperature. After switching of the laser the sample rapidly cooled back to room temperature After cooling it was found that no sustained oxidation had taken place rather that the sample had melted (or in the case of coal "ashed") away from the hot spot. Only in the case of Sawdust was the hot spot capable of initiating sustained propagation of smouldering

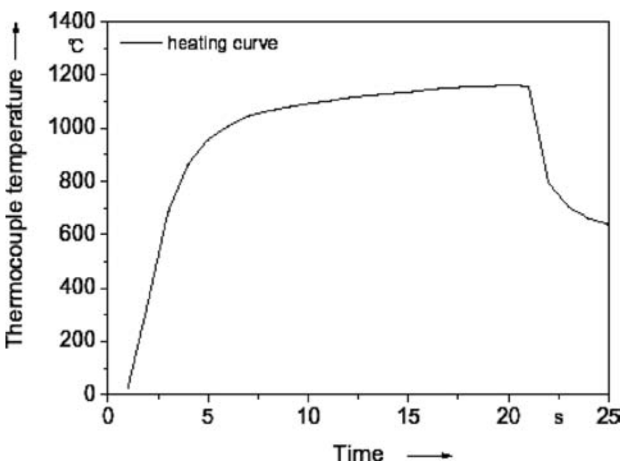

Figure 4. Typical temperature trace for experiments with laser heated particles

Table 4. Ignition/non-ignition powers and surface temperatures with 2 cm hotspot

Dust	Non-ignition temperature	Non-ignition power	Ignition temperature	Ignition power
Sawdust	173 °C	5.42 W	203 °C	5.85 W
Coal dust	170 °C	4.3 W	211 °C	4.90 W
Bio waste	181 °C	5.34 W	238 °C	5.75 W
Maize starch	171 °C	4.66 W	270 °C	5.8 W

which spread through the complete sample with a temperature of ca 500°C after the laser was turned off.

In the tests with larger hotspots, ignition or smouldering was also observed with Sawdust, Coal Dust and Maize Starch as well as with a sample of Bio-waste. Similar powers were used (1 to 6 W) though the surface temperature of the hotspots were much lower. Table 4 shows for different dusts the power and surface temperature of the hotspots which just did not cause ignition.

A typical result of the hot-spot ignition tests is shown in Figure 5 for Maize Starch. It can be seen that the ignition is clearly evident though this often occurs after a prolonged period of time, in this case more than 400 min.

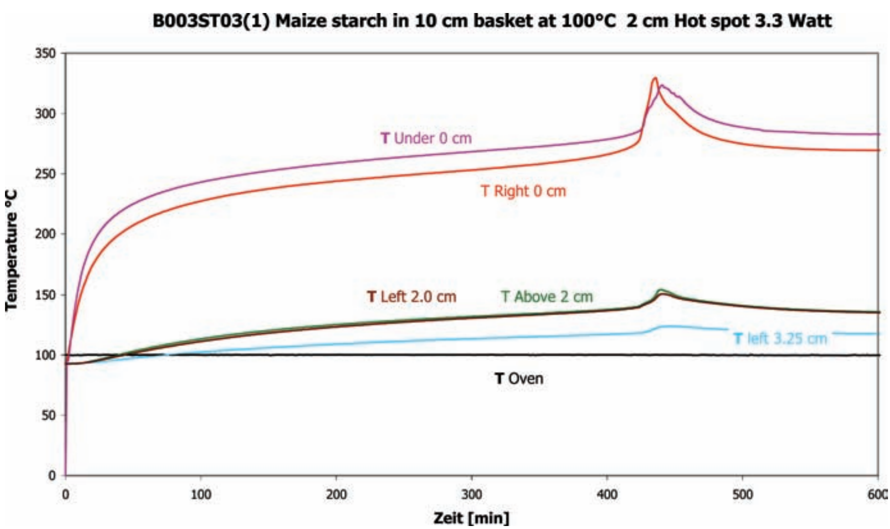

Figure 5. Typical result showing ignition by a 2 cm hotspot

As can be seen from Figure 5, the ignition/non-ignition boundary with the larger hotspots were determined not only at room temperature but also with the wire basket containing the powder at elevated temperatures namely 50 °C and 100 °C.

The power required for ignition decreases markedly (by a factor 2) as the temperature is raised from room temperature of 20 °C to 100 °C. The results for the dusts tested is shown in Figure 6. It can be seen that there appears to be an approximately linear relationship between the power required for hot spot ignition and the powder bed temperature. Also shown on the graph are the measured isothermal ignition temperatures for 10 cm cube. For Maize Starch and Sawdust the linear trend continues to the ignition temperature of the powder bed when the hot spot power is zero, i.e. no additional energy is required to cause ignition. However for the other two dusts tests, namely Coal and Bio-waste, this trend is not observed.

Anomalous results were obtained with Calcium Stearate. As with the tests with the small laser heated hot spots the tests with the larger hotspots also produced melting and additionally the formation of a hard "baked" mass around the hot spot but without ignition. Charring of the Calcium Stearate sample only occurred when a cartridge heater (dia. 1 cm length 4 cm) was used with a power of 110 W and with the powder preheated to 200 °C. (Figure 8) When the power was switched on to the heater its surface temperature rose to more that 500 °C however no self sustaining reaction occurred and although charred (See Figure 7) the temperature fell rapidly to the oven temperature when the heater power was switched off.

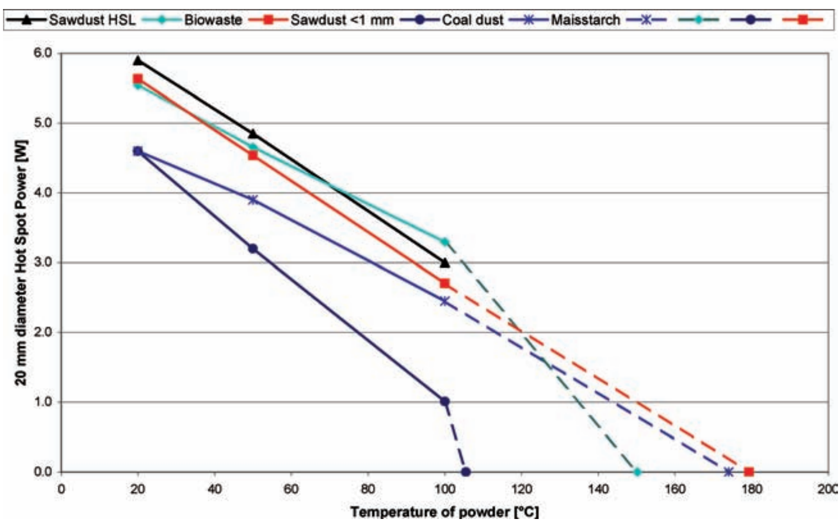

Figure 6. Power required for ignition by a 20 cm hot spot at different powder bed temperatures including ignition temperatures for 10 cm cube of the powder

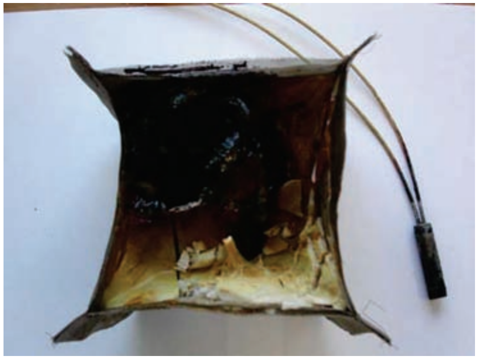

Figure 7. Charred calcium stearate after hot spot test at 200 °C and 111 W

IGNITION BY GRINDING SPARKS/HOT SURFACES

As with tests carried out in the MECHEX project on the ignition of gas atmospheres [1–3], the Low-Speed-Rubbing-Machine was used for the test programme with dusts. This apparatus has a variable speed rotating Steel wheel which rubs against a sacrificial steel slider block with an imbedded thermocouple. For the tests with dusts a small tray was

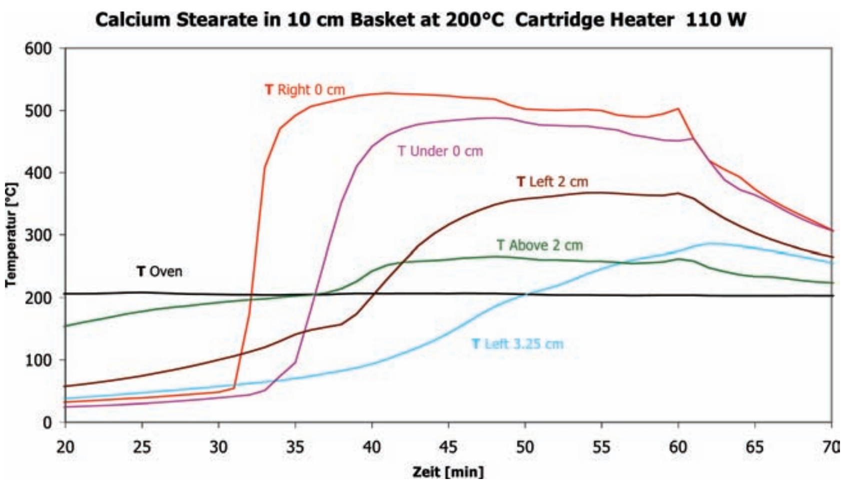

Figure 8. Experimental trace of hotspot ignition test with calcium stearate in oven at 200 °C with a power of 111 W

manufactured (see Figure 9) that could be attached the 'slider' test piece. This enabled a layer of dust to remain in contact with the hot surface or burr that was produced during the test.

The testing was conducted using contact loads and rubbing speeds that were required to achieve a range of temperatures within the contact zone similar to the layer ignition temperatures of the dusts. The mode of burning if any around the mechanically produced hot spot was observed.

This work has made it possible to see if a mechanically produced hot spot whose temperature was close to that of the LIT of a dust was capable of igniting a dust layer. Tests were carried out with Maize, Wood Dust, Calcium Stearate and Coal Dust. The tests aim were to detect the initiation of smouldering in the dust deposits, and secondly flaming. A range of different conditions (load and speed) were applied in order to observe the effects of temperature and block deformation on the ignition of the dust deposits. The results are shown in Table 5.

Further tests were performed directing sparks from low speed rubbing machine into an angled tray of dust. A number of different arrangements were tried, the most suitable of these is shown in Figure 10.

Here the tray, with Perspex viewing windows, contains a 5 mm dust layer with an area equivalent to a standard 100 mm dust layer test. Varying the speed and load controlled the intensity of the sparks produced and directed into the dust in the tray. Conditions for ignition at relatively low velocities ($\sim$1 m/s) are of particular interest and the work concentrated on low velocity limits for ignition. The results for the ignition tests with the different dusts are given in Table 6.

IGNITION BY SINGLE IMPACTS

Tests have also been carried out using an impact machine in which a compressed air canon fires a projectile at an inclined plate. High speed photography was used to observe the

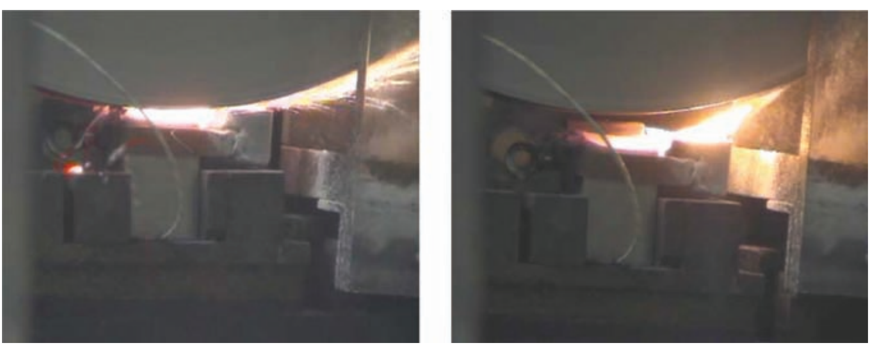

Figure 9. Test arrangement for ignition of dust deposits (calcium stearate) by direct contact with hot surface showing flaming of deposits as wheel and slider separated

Table 5. Results of ignition tests by hot surface from grinding/rubbing

Max temp in contact zone °C	Burr temp °C identical test	Burning mode observed	Duration of test	Duration at max temp	Speed m/s	Load kN	Test no
Wood dust (LIT = 315 °C)							
851	681	Flame			2	5	99
645	485	sustained smouldering	10 min	5 min	1	12	112
433	380	sustained smouldering	15 min	10 min	1	1	113
384	228	None	15 min		2	0.4	120
Calcium Strearate (LIT >450 °C) (melts)							
943	945	flaming on surface layer	11 sec	3 sec	5	5	118
590	485	starting to melt close to block	10 min	6 min	1	2	119
Maize Starch (LIT 440 °C)							
997	945	flame	14 s	3 sec	5	5	114
575	485	smouldering	10 min	5 min	1	2	115
Coal dust (LIT 225 °C)							
533	485	no combustion observed	10 min	5 min	1	2	116
871	945	flame after test	15 sec	2 sec	5	5	117

Figure 10. Wood dust ignition by spark shower showing tray used for spark ignitions of dust layers

Table 6. Burning modes observed following ignition tests with spark showers

Dust layer	Speed (m/s)	Load (kN)	Burning mode
Sawdust	5	5	Flaming
Sawdust	5	1	Short lived smouldering
Maize	5	5	No sustained burning
Coal	5	5	Transient flaming
Calcium stearate	5	5	Sustained flaming

point of impact. This showed that such impacts also produce "sparks" or burning fragments of metal as shown in Figure 11.

Tests were carried out using the impact machine to try and ignite various dusts. A dust layer were held in the target area and impacts with projectiles having different kinetic energies were made. The results are given in Table 7.

It was only possible to ignite Sulphur Dust up to the limit of the machine of ca 220 J though it should be recognised that the dust layer is dispersed by the shock waves at the point of impact such that it is unlikely that an optimum dust atmosphere is present.

DISCUSSION

The capability of mechanically generated sparks or hot-spots to ignite dust clouds has been investigated previously by many researchers. The results obtained from the MECHEX project provide additional insight into the mechanisms which occur in this complex process.

The results from the single impact confirm previous results obtained by Eckoff [6] who showed that impacts with energy up to 20 J were non incendive. The present work extends this limit to much higher values.

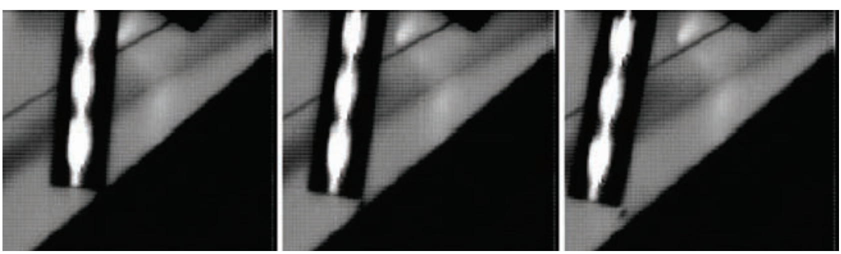

Figure 11. Production of a fragment during the impact of a 20 cm long steel rod on a stell target with an impact velocity of 7 m/s

Table 7. Ignition results of dust layers subjected to real impacts

Dust	Kinetic energy before impact J
Calcium stearate	>218
Sulphur	$134 < E < 147$ with ignition
Sawdust	>217
Coal	>188
Aluminium	>221

Ignition tests by simulated sparks (laser heated particles) showed that all dusts could be ignited though the temperature of the particle that was required is much higher than the dust cloud ignition temperatures. The ranking of ignitability approximately follows the ranking of the minimum ignition energy values for the dust. Such high temperature sparks are in practice mainly obtained with sparks from light metals which burn in air with high temperatures.

The high temperatures required support to a certain degree the results developed by Ritter and others [7] who rank the ignitability of a dust cloud by friction sparks on the basis of the minimum ignition energy and the dust cloud ignition temperature. However the tests with the grinding wheel show that this ranking does not take into account the complexity of dust ignition processes. The continuous stream of sparks was able to generate sustained burning with Calcium Stearate but not with Maize Starch. However in contrast, the hot surface or burr next to the grinding wheel produced smouldering at lower temperatures with the Maize Starch compared to Calcium Stearate.

In the case of ignition of dust deposits, the small laser heated particles were, with the exception of Sawdust, unable to initiate smouldering or combustion even though the particles had a high temperature. Similar power values (1–6 W) with larger hotspots produced ignition even though the surface temperatures were much lower. It appears that the high surface power density and high temperatures of the small particles rapidly oxidised or melted the surrounding layer of powder without generating a propagating reaction. Rather an insulating layer was generated around the small hotspot.

Again the complexity of dust ignition processes is shown by the results obtained for Calcium Stearate. No sustained ignition was obtained with the hotspots even when a power of 111 W was used and a powder bed had a temperature of 200 °C which is near to the thermal stability onset temperature. In contrast in the tests with the grinding machine ignition was readily obtained in a process which appears to involve melting/vaporisation followed by ignition.

The power required for hot spot ignition decreases as would be expected as the temperature of the powder bed is increased. The powers required for ignition are extremely low and it seems unlikely that a limit value of power whereby ignition does not occur can be given. In assessing the risk of ignition of powder deposits from friction of mechanical equipment it is necessary to consider not only the total power but also the temperatures that are produced. Results from other parts of the MECHEX project provide insight into the relationship between speed, power and temperature and these should be considered together with the actual configuration of the equipment and the characteristics of the dusts involved.

In summary it can be seen that single impacts are extremely unlikely to cause ignition and that the rule of thumb value used for many years that ignition is unlikely if the contact speed is less than 1 m/s provides a reasonable assessment of the ignition risk provided both the powder is not susceptible to rapid decomposition and that the powder is not trapped between the rubbing surfaces. This latter condition is not evaluated by the current tests where only friction between two direct contacting metal surfaces is considered. A separate assessment is required if the powder can be pressed between two surfaces and subsequently heated.

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