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# IGNITION OF FLAMMABLE GASES AND VAPOURS BY FRICTION BETWEEN FOOTWEAR AND FLOORING MATERIALS*

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## Summary

For pedestrian locomotion, friction between footwear and flooring materials is necessary. What is not, perhaps, realised is that friction between two surfaces can produce temperatures approaching the lower of the melting points of the two materials. In circumstances where material is transferred from one surface to the other, temperatures near the higher melting point may be realised. Thus, with many everyday materials, temperatures approaching 1500° C are possible.

Sparks are pieces of the hot surfaces ejected into the atmosphere. Those from materials that do not burn or oxidise in the atmosphere begin to cool as soon as they are formed. Certain materials, however, oxidise rapidly and their sparks can attain temperatures approaching 3000° C.

Such hot surfaces or sparks produced in the vicinity of flammable gases or vapours can lead to fires and explosions.

Tests of 'hobnails', tungsten carbide studs and 'non-sparking' materials, using a machine that can simulate a glancing kick, in flammable mixtures are described. Other materials that are used for footwear and flooring are discussed from the point of view of frictional ignition of gases and vapours.

## Introduction

In an attempt to reduce accidents attributed to slipping, Ramsay and Senneck [1] tested a variety of sole and floor materials for "grip". Their results showed that, under their test conditions, boots with rubber or composition soles gave a very good grip on clean, dry surfaces such as steel, concrete and PVC conveyor belting. However, if the surfaces were smeared with mud or grease the grip was very much reduced. Hobnailed leather soles gave a more consistent grip than rubber-soled boots, but had a much lower grip on clean, dry surfaces. The grip of hobnailed boots on steel was particularly poor.

Ramsay and Senneck's method of overcoming these problems was to fit the soles and heels with tungsten carbide-tipped studs of the type used in car tyres for motoring on ice. Although the grip was not as good as that of rubber-soled boots on a clean dry surface, their tests showed that the grip of boots fitted with tungsten carbide studs was hardly affected by mud or grease, and was consistently better than the grip of hobnailed boots.

With tungsten carbide studded boots it was, for example, possible to walk up and down a 1 in 4 greased steel slope. User trials have been described elsewhere [2]. At least one manufacturer fits purpose-designed studs during manufacture and such boots are now in use in a number of industries in Britain.

The question that did arise, however, was whether the use of such boots introduced an ignition hazard in flammable atmospheres. It is not intended to discuss the ignition hazard from static electricity produced by friction between footwear and flooring materials.

The ignition hazard considered is that introduced by hot surfaces or sparks that may be produced when the frictional forces necessary for pedestrian locomotion are overcome.

**Production of hot surfaces and sparks by friction and the relative ease of ignition of the different gases and vapours by friction**

Whenever two materials slide over each other, mechanical energy is expended in doing work against friction; the energy so dissipated is transformed into heat at the rubbing surfaces. In this way hot surfaces are produced whose temperatures do not usually exceed that of the lower of the melting points of the two materials. It is in this way too that high temperatures are produced if sliding occurs during impact between two materials (e.g. glancing impact). The situation is more complicated if wear and transfer of material takes place between the two surfaces undergoing friction. In such circumstances it is possible for temperatures approaching the higher of the two melting points to be attained. Sparks are the visible hot fragments of either material torn off during continuous rubbing or impact. Some materials, when heated, oxidise on contact with the ambient atmosphere, and can produce sparks whose temperature increases as they pass through the atmosphere. Sparks of this nature are produced by lighter 'flints' (cerium alloy), the light metals (aluminium, magnesium and titanium) and the heavier metals, hafnium and zirconium.

Although there has been no systematic classification of flammable gases and vapours into groups by ease of ignition by frictionally heated surfaces, sufficient is known [3] to suggest that the grouping used for electrical apparatus used in explosive atmospheres (e.g. BS 5345 : Part 1 : 1976)* can be used as a reasonably accurate guide to the ease of ignition by friction. Thus propane—air (representing Group IIa) is more easily ignited than methane—air (representing Group I, mining). Ethylene—air (representing Group IIb) is more easily ignited

*British Standard 5345 : Part 1 : 1976. Code of practice for the selection, installation and maintenance of electrical apparatus for use in potentially explosive atmospheres.

than propane—air, and hydrogen—air (Group IIc) is more easily ignited than ethylene—air.

Finally, with all flammable gas—air mixtures examined so far, it is found that the mixture most easily ignited by friction is usually close to the lower limit of flammability. The same appears to apply for ignition by hot surfaces.

As far as is known, there has been no previous study of the possible ignition of flammable atmospheres by glancing kicks from footwear. There is, however, much useful information amongst tests carried out by other investigators for different purposes. This other information, where it concerns materials used for footwear or flooring, will be discussed later.

## Frictional ignition tests on boot studs

The rubbery soled boots, into which tungsten carbide-tipped studs had been inserted, had a steel toepiece. It was therefore necessary to distinguish between sparks produced by the toepiece and the studs.

In preliminary tests, it was found that sparks could be produced, both with the toepiece and the studs, when Darley Dale sandstone or rusty mild steel was given glancing kicks. (Darley Dale sandstone is a massive quartzitic rock containing about 70% by volume of quartz and having a dominant quartz particle size of 250 $\mu$m. Its compressive strength is 90 MPa (13,000 lb/in$^2$).) Visually, the sparks from the steel toepiece appeared to be the more incendive. Photographs, both cine and still, were taken in an attempt to show these differences. By this means it was found that a typical speed, when the brightest sparks were being produced, was about 7.6 m/s. A footballer's foot may move at up to 3 times this speed, but he would not be kicking the floor!*

## Ignition of methane—air mixtures by glancing impact

*Impact machine*

An extended series of experiments was carried out in methane—air mixtures with an impact machine (see Fig. 1). In this machine a horizontal arm is held against a stop whilst its driving spring is pre-tensioned by an electric motor. When the arm is released, the hammer head at the end of the arm moves in an arc of a horizontal circle, 0.91 m in diameter. The specimen, fixed vertically below the head, strikes a single glancing blow on the chosen target, whose angle of inclination to the horizontal is adjustable. The width of the target material, and therefore the maximum distance over which the specimen is in contact with it, is 75 mm.

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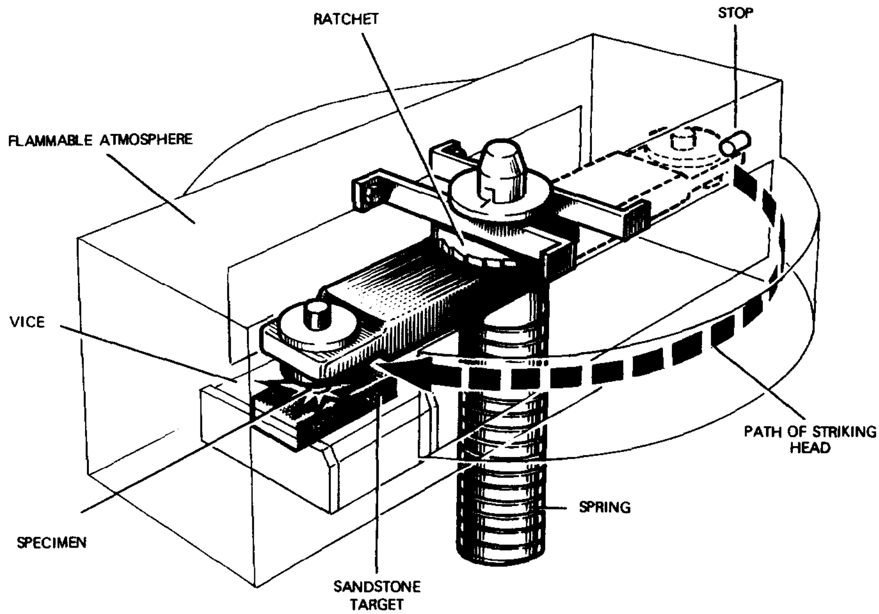


Fig. 1. Frictional impact machine.

*Initial experiments*

Initial experiments took place with a tungsten carbide tipped stud, machined to fit into one end of a steel rod, as the specimen.

After a series of experiments in which a Darley Dale sandstone target produced one ignition of a 7% methane—air mixture, tests were made in which the target was rusty steel. Although sparking was produced, it was fairly obvious that the chance of ignition with the rusty steel was less than that with a sandstone target.

*Experimental conditions*

Experiments were therefore carried out with sandstone as the target material. Variables included the angle of inclination of the target, and the number of impacts, both with the specimen, and on the same part of the target. The specimen was either the tungsten carbide tipped stud, a part of a toepiece, mild steel, silver steel (British Standard 1407: 1970)* or a hobnail. Any changes made in the angle, or number of impacts on a spot, were attempts to produce the brightest and most incendive sparking or flash as assessed visually.

The speed (or energy) of the specimen at impact was also adjustable, and

*British Standard 1407 : 1970. High Carbon bright steel (silver steel).

TABLE 1

Boot stud hazard, impacts on Darley Dale sandstone in 7% methane—air mixture

| Material [typical hardness VPN (10 kg load)] | Speed (m/s) and energy (J) available at impact | Target angle(°) | Number of non-ignitions | Number of ignitions | Total no. o impacts |
|---|---|---|---|---|---|
| Tungsten carbide tipped stud [1100] | 9.4, 255 | 2 | 259 | 1 | 500 |
| | | 4 | 150 | 0 | |
| | | 6 | 90 | 0 | |
| | 6.4, 117 | 1 | 50 | 0 | 500 |
| | | 2 | 300 | 0 | |
| | | 4 | 50 | 0 | |
| | | 6 | 50 | 0 | |
| | | 8 | 50 | 0 | |
| Hobnail [230] | 9.4, 255 | 2 | 95 | 0 | 500 |
| | | 4 | 63 | 0 | |
| | | 6 | 109 | 0 | |
| | | 8 | 100 | 0 | |
| | | 10 | 50 | 0 | |
| | | 12 | 83 | 0 | |
| | 6.4, 117 | 2 | 50 | 0 | 500 |
| | | 4 | 100 | 0 | |
| | | 6 | 100 | 0 | |
| | | 8 | 199 | 1 | |
| | | 10 | 50 | 0 | |
| Silver steel (BS 1407 : 1970) [270] | 9.4, 255 | 2 | 49 | 0 | 91 |
| | | 10 | 35 | 0 | |
| | | 12 | 7 | 0 | |
| | 10.1, 289 | 12 | 6 | 1 | 7 |
| Mild steel [140] | 9.4, 255 | 2 | 83 | 0 | 108 |
| | | 4 | 25 | 0 | |
| | 10.1, 289 | 2 | 24 | 0 | 48 |
| | | 12 | 24 | 0 | |
| Toe piece (steel) [200] | 9.4, 255 | 1 | 10 | 0 | 50 |
| | | 2 | 33 | 0 | |
| | | 4 | 5 | 0 | |
| | | 6 | 2 | 0 | |

TABLE 2

Impact of various materials on Darley Dale sandstone in 7% methane—air, 3% propane—air, 4% ethylene—air and 15% hydrogen—air mixtures

| Specimen material | Energy available (J) | Percentage ignitions and 95% confidence limits | | | |
|---|---|---|---|---|---|
| | | 7% Methane—air | 3% Propane—air | 4% Ethylene—air | 15% Hydrogen—air |
| Tungsten carbide | 225 | 0.2 (0—1.1) | | | |
| stud | 117 | 0 (0—0.7) | 1.8 (1.1—3.1) | 26 (22—30) | |
| Hobnail | 225 | 0 (0—0.7) | | | |
| | 117 | 0.2 (0—1.1) | 25 (22—28) | 43 (38—47) | |
| Silver steel | 255 | 0 (0—4.1) | | | |
| (BS 1407 : 1970) | 289 | 14 (0.4—58) | | | |
| Mild steel | 255 | 0 (0—3.4) | | | |
| | 289 | 0 (0—7.6) | | | |
| Toepiece (steel) | 255 | 0 (0—7.1) | | | |
| Aluminium bronze | 117 | 1 (0.1—5.4) | 24 (15—32) | 82 (74—89) | |
| Copper beryllium | 117 | 2 (0.3—7) | 20 (12—29) | 83 (75—90) | |
| Tool steel (hammer head material) | 117 | 1 (0.1—5.4) | 24 (15—32) | 73 (64—82) | |
| Silver steel | 117 | 1 (0.1—5.4) | 4 (1—10) | 72 (63—81) | |
| Fused quartz | 117 | | | 10 (2.2—26.5) | 100 (59—100) |
| Lamp glass (heat resisting) | 117 | 0 (0—1.4) | 2.8 (1.1—6) | 5.5 (1.9—12.4) | 47 (23—72) |
| Bottle glass | 117 | | | 0.72 (0.1—3.9) | 39 (28—52) |

depended on the energy stored in the driving spring. In general, only about one third of the available energy was dissipated during impact.

A total of 1000 impacts for both the studs and hobnails on sandstone, 500 at the initial impact speed of approximately 9.4 m/s and a further 500 with the speed at impact of approximately 6.4 m/s were carried out. Even with the reduced energy (approximately half the previous), the flashes or sparks produced were still much more intense than those obtained by kicking. The tests are summarized in Table 1.

These tests showed that the hazard in methane—air with tungsten carbide tipped studs was very small, and similar to that with hobnails. The energy and speeds necessary to cause ignition with either stud or hobnail are considered sufficiently large for it to be unlikely that a spark from a glancing kick could ignite methane—air.

## Tests with propane—air and ethylene—air mixtures

The ignition hazard with the more easily ignited gases and vapours of Group IIa and IIb have also been studied in the impact machine. Table 2 shows the results of impacts against sandstone, in methane—air, propane—air and ethylene—air mixtures for the tungsten carbide studs, hobnails, silver steel (BS 1407 : 1970), mild steel, and the steel toepiece material. In addition, tests carried out on the so-called 'non-sparking' materials aluminium bronze ('non-sparking' hammer material) and copper beryllium ('non-sparking' chisel material), in which they were compared with steel (steel hammer) and silver steel, are included. Table 2 is completed with the results of tests on fused quartz, electric lamp glass and bottle glass. The latter three were also tested in hydrogen—air mixtures. All these impacts took place under similar conditions with the specimen under test given a glancing impact onto sandstone with the energy available as shown in the table.

To enable comparisons to be more easily made, the results of all the tests with sandstone, including those in Table 1, are shown as the percentage ignitions, together with (in brackets) their 95% confidence limits. Thus, for example, for the impact of tungsten carbide studs on sandstone in 4% ethylene—air, Table 2 shows the percentage ignitions in the tests as 26, and the 95% confidence limits as 22 and 30. With those materials with which fewer experiments were carried out, the confidence limits are, naturally, wider.

'Chrome steel' and 'brass' specimens have also ignited methane—air mixtures in the impact machine, the former with a probability as high as 38% in impacts at steeper target angles i.e. in which more energy was dissipated during impact. 'Chrome steel' impacting onto silicon carbide (grindstone material) also ignited methane—air (15% (7—27%)).

Tests in which the target material was steel (usually rusty steel) are summarized in Table 3. Although far fewer tests have been carried out (hence the wider confidence limits) it is clear that ignitions were much more difficult to produce than when the target material was sandstone.

TABLE 3

Impact of various specimens on steel targets (energy available 117 J)

| Specimen material | Target material | Percentage of ignitions and 95% confidence limits | | | |
|---|---|---|---|---|---|
| | | 7% Methane—air | 3% Propane—air | 4% Ethylene—air | 15% Hydrogen—air |
| Steel (case hardened EN36) | Steel (case hardened EN36) | 0 (0—1.2) | | | |
| Aluminium bronze | Rusty mild steel | | | 0 (0—31) | |
| Copper beryllium | Rusty mild steel | | | 0 (0—31) | |
| Tool steel (hammer head) | Rusty mild steel | | | 90 (55—100) | |
| Silver steel (BS 1407 : 1970) | Rusty mild steel | | | 0 (0—31) | |
| Mild steel | Rusty mild steel | | 0 (0—5.9) | 13 (6—25) | 42 (28—58) |
| Spring steel cable clip | Rusty mild steel | | | 25 (10—45) | |

Glancing impacts in the machine of a titanium alloy onto a metal working file produced burning particles that ignited methane—air and propane—air with ease. The burning particles can be easily demonstrated by hitting titanium alloys by hand against a file. Hafnium and zirconium produce such particles even more easily, and will produce these burning sparks with light glancing hand blows against aluminium oxide coated abrasive cloth, sandstone, cement and concrete.

## Other tests involving materials used for flooring

The results of frictional ignition tests on many other materials, including many that are likely to be used for catwalks, floors, decks and runways, have been reviewed [3] and the conditions under which ignitions were or were not obtained, catalogued.

Such materials are the light metals, steels, 'non-sparking' metals, grindstone materials, rocks, concrete and asphalt aggregates, bricks and clay tiles. The light metals deserve special mention because with them so little mechanical energy need be expended to cause ignition. Their failing is, of course, the 'thermite' reaction that occurs between them and many oxides, particularly rust. Rocks and rocklike materials can be frictional ignition hazards if they are capable of remaining strong at the high temperatures required for ignition. Those that melt, soften or decompose at lower temperatures are therefore less of a hazard. Low melting point metals give ignitions with rocks because they can become contaminated with embedded grains of rock.

Experiments similar to those described here have been carried out by Schultz and Dittmar [4]. In an impact machine with a total available energy of 240 J, they obtained ignitions of propane—air and other Group IIa vapours (with benzene—air, 177 J was sufficient to cause ignition), when carbon steel was impacted onto carbon steel. Hydrogen—air could be ignited with the impact of steels when the total energy was only 3.4 J. In tests with 'non-sparking' metals impacting onto rusty steel, they ignited hydrogen—air with aluminium bronze, copper—beryllium and a hard nickel—silicon—copper alloy.

## Discussion

Instances of ignitions of flammable gases or vapours attributable to frictional effects from footwear have been recorded. Palmer [5] mentions 3 ignitions of petrol and 1 of a pyrotechnic mixture attributed to the impact of boot nails on concrete. We have knowledge of an ignition of an ether—oxygen mixture that occurred as the operative concerned moved his feet to maintain his balance. He was wearing 'anti-static' clogs, the rubber heels of which were fixed with steel nails. The floor was described as 'terrazzo' with 9 mm 'marble' set in a sand/cement matrix. The contact of a nail with the floor was thought to be a possible cause of the ignition.

On the basis of our experience and the tests already described, the worst possible materials from the point of the frictional ignition risk are those that produce burning particles when struck against hard or abrasive surfaces — these materials would include titanium, cerium, hafnium and zirconium.

Next, in degree of hazard, are magnesium and its alloys — because a 'thermite' reaction can be initiated between magnesium and rusty steel and even silica (sand). Aluminium is a little less of a hazard (it does not react with silica), but both magnesium and aluminium (and their alloys) can leave smears on rusty surfaces which can, if struck by almost any hard materials (possibly even hard rubber and plastic), produce a thermite flash [6].

In contact with steel surfaces, whether rusty or not, mild steel, iron and tungsten carbide are unlikely to be a hazard in methane—air, and are, at most, a very low hazard in propane—air and a possible hazard in ethylene—air. Hard steels must, however, be regarded as more of an ignition risk. In contact with steel surfaces the 'non-sparking' copper alloys offer increased safety from ignitions over steel.

Where steel on footwear is in contact with quartzitic materials, such as sandstone, granite, or clay tiles, brick and concrete or asphalt (containing these materials), the risk of ignition is small in methane—air, but ignition is possible in propane—air and very likely in ethylene—air; the 'non-sparking' materials offer no advantage whatsoever. The lowest risk with these footwear and floor materials appears to be with tungsten carbide. It goes almost without saying that catwalks and ladders should not be made of light metal, for the reasons already given.

Not mentioned, so far, are the 'non-slip', 'slip-resistant' and 'non-sparking' surfaces or coatings for floors. Many of these consist of a resin base (often polyester) in which hard particles are embedded. The particles or grit may be sand, or crushed flint (i.e. quartz), glass, silicon carbide or similar materials for 'non-slip' floors. Once commercially available coating that has come to our notice, described as 'sparkproof', consists of resin, portland cement and calcined bauxite chips. It produced sparks and visible hot surfaces, however, when held against a grindstone and cannot, therefore, be regarded as 'completely safe' during impact.

Many of the non-slip coatings are used in situations where flammable gases and vapours are likely to be present, such as on oilrigs, aircraft carriers, seagoing oil tankers and on floors in general, ramps, loading docks etc. Many are claimed to be resistant to oil, petrol and other hydrocarbons. The little experience we have of these coatings and our knowledge of quartzitic rocks may be of some help in selecting safer coatings for floors. Just as the most hazardous quartzitic rocks are those that have a strong cementing matrix, and in which the volume of quartz is high (with naturally occurring rocks, these tend to be those in which the dominant particle size is also large), one would expect a high particle concentration, large particle size and high melting point particles to make a coating more hazardous as far as ignitions are concerned, but in most circumstances they would probably not be as likely to produce ignitions as would a strong, highly quartzitic sandstone.

It would appear that the only way to avoid the frictional ignition of gases and vapours by sparks from floors would be to use materials incapable of sustaining the relatively high temperatures required for such ignitions.

Such materials that come readily to mind are plastics, resins and rubber. However, even with these materials, there are other possible hazards; for example, prolonged, continuous rubbing may set the materials themselves alight and, unless special measures are taken, they may present a risk of electrostatic sparking.

## Acknowledgement

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