EXPERIMENTAL STUDY ON THE IGNITION OF HYDROGEN CONTAINING ATMOSPHERES BY MECHANICAL IMPACTS

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ABSTRACT

In international regulations on explosion protection mechanical friction, impact or abrasion is usually named as one of 13 ignition sources that must be avoided in hazardous zones with explosive atmospheres. In different studies it is even identified as one of the most frequent ignition sources in practice. The effectiveness of mechanical impacts as ignition source is dependent from several parameters including the minimum ignition energy of the explosive atmosphere, the properties of the material pairing, the kinetic impact energy or the impact velocity. By now there is no standard procedure to determine the effectiveness of mechanical impacts as ignition source. In some previous works test procedures with poor reproducibility or undefined kinetic impact energy were applied for this purpose. In other works, only homogeneous material pairings were considered. In this work the effectiveness of mechanical impacts with defined and reproducible kinetic impact energy as ignition source for hydrogen containing atmospheres was studied systematically in dependence from the inhomogeneous material pairing considering materials with practical relevance like stainless steel, low alloy steel, concrete, and non-iron-metals. It was found that ignition can be avoided, if non-iron metals are used in combination with different metallic materials, but in combination with concrete even the impact of non-iron-metals can be an effective ignition source if the kinetic impact energy is not further limited. Moreover, the consequence of hydrogen admixture to natural gas on the effectiveness of mechanical impacts as ignition source was studied. In many cases ignition of atmospheres containing natural gas by mechanical impacts is rather unlikely. No influence could be observed for admixtures up to 25% hydrogen and even more. The results are mainly relevant in the context of repurposing the natural gas grid or adding hydrogen to the natural gas grid. Based on the test results, it can be evaluated under which circumstances the use of tools made of non-iron-metals or other non-sparking materials can be an effective measure to avoid ignition sources in hazardous zones containing hydrogen, for example during maintenance work.

1.0 INTRODUCTION

Avoiding ignition sources (secondary explosion protection) is one of the basic measures for explosion protection according to the ATEX-directives [1]. Mechanically generated sparks (by friction, abrasion or single impact) are one of the typical ignition sources to be considered in the international regulations [2][3]. Ignition can be triggered during mechanical impact by particles separated from solid materials and possibly even heated up by means of oxidation processes or by the hot spot that is generated on the contact area [4][5]. Usually, the ignition sensitivity of fuel gases can be evaluated according to the minimum ignition energy (MIE) or the maximum experimental safe gap (MESG) [3]. For fuel gases like hydrogen with low MIE and low MESG allocated in the most critical explosion group IIC according to IEC 60079-0:2019[6] and ISO/IEC 80079-20-1[7] mechanical impacts must be considered as an effective ignition source in many cases. However, for fuel gases like methane with much higher MIE and MESG allocated in the least critical explosion group IIA, mechanical impacts are not an effective ignition source in many cases [3]. But the effectiveness of mechanical impacts as ignition source is dependent from many other parameters as well, especially from the type of material pairing for the impact, from the kinetic impact energy and the impact velocity [5][8][9][10].

In EN ISO 80079-36 [3] threshold values are given for the impact velocity and the single impact energy in dependence from the explosion group. If the kinetic impact energy is lower than given in the tables, it is not necessarily considered to be an effective ignition source in the course of the ignition hazard assessment. In the tables a distinction is made between non-sparking metals and other materials excluding some special material pairings like aluminium and iron oxide, which is very reactive. But overall, there is hardly any information for the evaluation of mechanical impacts with heterogeneous material pairings, especially if non-metallic materials, like concrete are involved.

There is no standard procedure for evaluating the effectiveness of mechanical impacts as ignition source in dependence from the material pairing and from the kinetic impact energy or impact velocity. In individual scientific works the ignition effectiveness of impacts was studied experimentally by targeting metallic plates with solid bodies, causing impacts of solid bodies in free fall or with targeted grazing impacts of pins on impact plates in impact spark apparatuses. In some of these works it was observed that for hydrogen-air mixtures the ignition probability is maximized if the hydrogen fraction was at about 10 mol% and not at the stoichiometric fraction of 29 mol% [9][11][12]. It was concluded that with increasing hydrogen contents, the oxygen content decreases and thus the possible oxidation of separated particles is inhibited through which even more heat can be transferred from the particles to the mixture [9][11]. It was also attributed to molecular diffusion processes that have a strong influence on the ignition process [5].

Proust et al [5] investigated the ignition effectiveness of mechanical impacts by means of experiments in which an angled metal plate was targeted with cylindrical metal projectiles of different lengths and made of different materials. The mechanical impacts were not carried out in explosive atmospheres. But based on measurements of the surface temperature near the point of impact, it was found that the impact velocity and especially the material of the projectiles are critical parameters for the temperature rise at the surface and thus for the ignition effectiveness at the hot contact area of impact. The authors assume that ignition occurs in most cases at the hot impact point.

Averill et al [12] investigated the ignition effectiveness of mechanical impacts by free fall of masses up to 50 kg in hydrogen-containing atmospheres. In these investigations, the surfaces were coated with magnesium oxide or rust. Ignition could only be observed when falling onto angled plates, whereas no ignition was observed when falling onto horizontal metal plates. It was found that the impact angle and the shape of the projectile have a greater influence on the ignition probability than the mass of the weights.

In many other works, the ignition probability of mechanical impacts was studied with grazing impacts [4][8][9][10][11][13][14]. In some of these studies, the mechanical impacts were realised by rotating circular discs that were either notched [11] or equipped with impact pins [8] so that the corners of the sawn disc or the fitted impact pins hit a static impact plate during rotation. By varying the material pairing, it was generally found in these works that the ignition probability for many different fuel gases is particularly high with the material pairing of aluminium and rust, which can be attributed to a strong temperature increase of the separated particles due to strong exothermic reactions when iron oxide (rust) comes into contact with aluminium (thermite reaction) [4]. In these works, the ignition of hydrogen atmospheres by mechanical impacts of homogeneous and inhomogeneous material pairings of high-alloy and low-alloy steels was also observed. The kinetic impact energy was not determined in these investigations. Therefore, comparability with similar investigations from other work is difficult.

For the experimental investigation of the ignition effectiveness of mechanical impacts in a grazing impact with defined kinetic impact energy, tests were carried out in impact spark apparatuses in various works [4][9][13][14]. In these test set-ups defined individual impacts of pins on impact plates can be realised at a certain angle. The impact energy is varied by springs of different strengths, through which the lever with the attached pin is moved. From the experiments, it can be concluded that ignition of hydrogen-containing atmospheres by mechanical impacts with unalloyed steel is already possible at impact energies of 10 J, and the ignition probability generally increases significantly with increasing kinetic impact energy [9]. Various homogeneous metal pairings were considered in these works. At higher kinetic impact energies, the ignition probability for steels highly alloyed with chromium is significantly lower than for low-alloy steels. Furthermore, it was observed from high-speed thermal imaging camera recordings that in the case of hydrogen, ignition occurs largely at the hot contact point and not at separated particles for impacts of high-alloy steels, in contrast to unalloyed steels [4]. Impacts with inhomogeneous material pairings, with non-ferrous metal alloys that are difficult to oxidise and, which are used to produce so-called low-spark tools, or with non-metallic materials were not investigated in this works. Fuel gas mixtures were also not considered.

The goal of the experimental studies in the present work was to address exactly these issues. As a result, evaluation of the effectivity of so-called low-sparking tools made of non-ferrous metals to avoid ignition by mechanical impacts in hazardous areas with hydrogen containing atmospheres is possible considering different scenarios. In the experiments of this work low-alloy steel and high-alloy stainless steels as well as non-ferrous metals that are difficult to oxidise were considered as impact partners. Besides, tests with screed concrete with corundum particles as a typical floor covering were carried out. Based on the results, an adaptation of existing regulations might be possible.

Furthermore, the effectiveness of mechanical impacts as an ignition source for atmospheres containing hydrogen-methane-air-mixtures was investigated in this work in dependence of the hydrogen fraction. Hydrogen/natural gas mixtures occur primarily when so-called green hydrogen is fed into the natural gas grid and will probably be increasingly relevant in practical applications in the future due to the ramp-up of hydrogen technologies in the chemical and energy industries. In an earlier project [15], the effects of hydrogen addition to natural gas on the measures for explosion protection was studied in general. For this purpose, standardized safety characteristics of hydrogen-natural gas mixtures were measured according to the standards applicable in Europe. In the present work it was additionally investigated under which conditions and at which hydrogen contents mechanical impacts must be considered as effective ignition sources.

2.0 EXPERIMENTAL METHODS

2.1 Materials

For the tests in this work hydrogen 5.0 (purity ≥ 99.999 %), methane 4.5 (purity ≥ 99.995 %) and pressurized air free of oil and humidity were used. In the following tables, the compositions and the physical properties of the materials used for the impact tests in this work are shown.

Table 1. Compositions of the steel grades as a percentage by mass.

Steel grade	C	Si	Mn	P	S	Cr	Ni	Mo	Ti	Cu
1.0579 1.0577	≤0.22	≤0.55	≤1.6	≤0.03	≤0.03	-	-	-	-	≤0,55
1.4541	≤0.08	≤1.0	≤2.0	≤0.045	≤0.03	17.0-19.0	9.0-12.0	-	≤0.7	-
1.4571	≤0.08	≤1.0	≤2.0	≤0.045	≤0.03	16.5-18.5	10.5-13.5	2.0-3.0	≤0.7	-

Table 2. Composition of the non-ferritic-metal alloy CuBe as a percentage by mass.

	Cu	Be	Co+Ni+Fe	other
CuBe	≥95.5	1.5-2.3	≤1.2	≤1

Table 3. Composition of the non-ferritic-metal alloy AlBr as a percentage by mass.

	Cu	Al	Ni	Fe+Mn	other
AlBr	≥75	10-12	4-6	≤6	≤1

Table 4. Composition of screed concrete as a percentage by mass.

aggregate	cement	water	fluxing agent
81 (containing 5% corundum EKF 10 and 95% quartz sand)	12	6.8	0.2

Table 5. Physical properties of the materials. [16][17][18]

	1.0579 1.0577	1.4541	1.4571	2.1247 (CuBe)	2.0966 (AlBr)	screed concrete
Thermal conductivity [W/(m*K)]	42 -54	15	15	120-170	50	ca. 1.4
Spec. heat capacity [J/(kg*K)]	461	500	500	420	-	1000
Density [kg/dm3]	7.85	7.9	8.0	8.3	7.6	ca. 2.0-2.2
Elastic modulus [kN/mm2]	210 - 212	200	200	135	120	ca. 10-15

2.2 Test Set-Up

The gas mixtures were prepared in a cylindrical mixing vessel made of stainless steel with an inner volume of 78 l. It is equipped with pc-fans for homogenizing the gas mixtures. It has connections for filling the gases, purging, venting, and filling the impact spark apparatus. The impact spark apparatus used in this work is described in detail in [9][13]. In this apparatus mechanical impacts with any material pairing can be triggered in a closed confinement with an inner volume of 29 l. It is sealed at the front with a bursting foil and can be flushed and filled with any explosive gas mixture. The bursting foil is made of polyacetate. If the gas mixture ignites as a result of the mechanical impact, the foil tears and must be replaced before the next test. A pin attached to a lever hits a horizontal impact plate to realize the grazing impact within the volume. The deflected lever is preloaded with a spring before each test. It is relaxed to release the lever. The kinetic impact energy is adjusted by using different springs. It can be adjusted gradually between 31 J and 277 J. A picture and a schematic diagram are shown in the following figure.

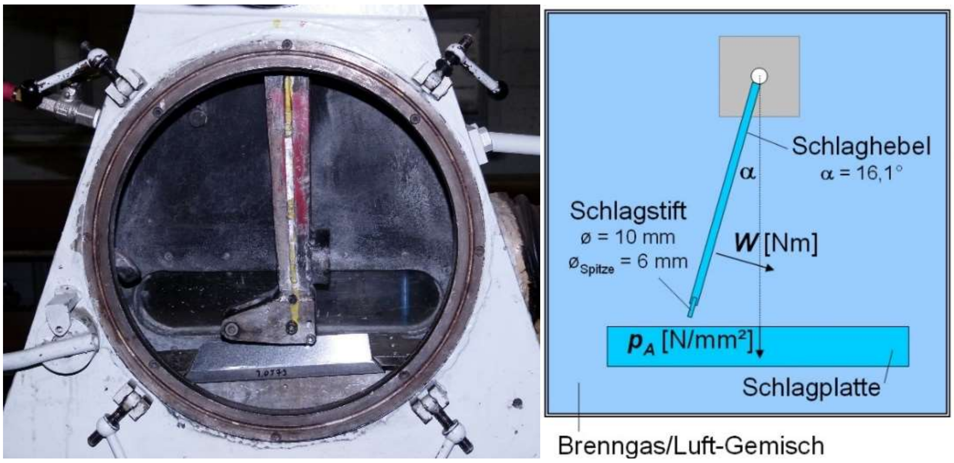

Figure 1. Left: Picture of the impact spark apparatus. Right: Schematic diagram of the impact spark apparatus

2.3 Mixture Preparation

The gas mixtures were prepared in the 78L-mixing-vessel according to the partial pressure method. First the mixture vessel was evacuated to less than 1 mbar, then the components methane, hydrogen and air were added one by one according to their partial pressure in the final mixture. The final pressure for the mixture preparation was constantly 8 bar abs. Ideal gas behaviour was assumed, i.e., it was assumed that the partial pressure fractions of the gas components are equal to their molar fractions. The pc-fans inside the mixing vessel were running during the whole procedure for mixture preparation. After adding the last component, the mixture was homogenized for at least five minutes before starting with the impact tests. For measuring the partial pressures during mixture preparation calibrated manometers (Fa. WIKA, accuracy class 0.6) with measuring ranges up to 4 bar and 10 bar were used.

2.4 Procedure for Impact Tests

For preparing the impact tests the impact plate to be tested was installed at the bottom of the impact spark apparatus and the impact pin to be tested was installed at the top of the lever. Then the lever was aligned, and the apparatus was closed at the open front side with a burst foil. Before each impact test the closed chamber was purged with test gas mixture from the mixing vessel. The fuel gas fraction in air was fixed to 10 mol% in nearly all test series since this composition was identified as most easy to ignite for hydrogen air mixtures [9][11][12]. In certain test series with higher amounts of methane the total fuel gas fraction was also reduced. The amount of gas for purging the chamber was at least 116 l and thus at least four times the internal volume of the chamber. After purging the inner chamber, all valves were closed, and the impact was triggered by relaxing the spring holding the lever. In case of an ignition the bursting foil opens with a loud noise.

Depending on the wear of the material, the pins are changed after five, ten or twenty impact tests and a new impact track is used on the impact plate, or the impact plate is exchanged completely. The relative frequency of ignition was determined in each test series for a certain material pairing and kinetic impact energy by carrying out 100 single impact tests respectively. In most test series the kinetic impact energy was 61 J. But in certain test series the kinetic impact energy was changed by changing the spring preloading the lever.

2.5 Measuring Uncertainty

The kinetic impact energy as a function of different springs was determined for this apparatus in earlier works [4][9][13]. For this purpose, the kinetic impact energy for the rotational movement of the impact lever was determined according to equation 1:

$$E_{kin} = \frac{1}{2} * I * \omega^2 \qquad \text{with I= mass moment of inertia and } \omega = \text{angular velocity} \qquad [1]$$

The average angular velocity as a function of the spring preload was determined experimentally by measurements with light barriers. The mass moment of inertia of the impact lever was determined from the mass, the centre of mass and the simple oscillation period of the impact lever. Overall, this results in a relative deviation of ±8.2%, which was calculated from the respective measurement tolerances of the individual measurement methods (weighing, response time of the oscilloscope and the light barriers, etc.) and their summation. Further parameters, such as the impact lever velocity and the surface pressures as a function of the preload were also determined by calculation and are given in [13].

The accuracy of the gas mixtures is mainly dependent from the accuracy of the pressure measurement. From the accuracy of the pressure measuring devices used a maximum range of deviation of 0.5 mol% was determined. For validation pre-tests were carried out preparing mixtures of 10 mol% oxygen in nitrogen, purging the impact spark apparatus with this gas mixture with an amount of four times the inner volume of the chamber and measuring the oxygen content with a gas analyser (type: Servomex 570 A, accuracy: ±0.1 Mol-% oxygen, linearity: better than 0.1 % according to the manufacturer). The gas samples were taken at the venting line and near the position of the impact in the tests using a pump. A maximum deviation from the target composition of 0.3 mol% was measured.

3.0 RESULTS AND DISCUSSION

3.1 Pre-Tests with homogeneous material pairings

The pre-tests were all carried out with mixtures of 10% hydrogen in air. First of all, four test series were carried out with a homogeneous material pairing for the impacts using the stainless-steel grade 1.4541. In three of these test series the kinetic impact energy was adjusted to 80 J in the other test series the kinetic impact energy was 61 J. These test series were carried out in order to validate the reproducibility of the tests comparing the test results with test results from previous works. Since the number of tests for determining the ignition frequency deviated in different works the dependency of the relative frequency from the number of impact tests is shown for two test series in figure 2. At a number of 20 to 100 impact tests the maximum deviation of the relative frequency of ignition is less than 10% absolute. It was concluded that a minimum of 20 tests must be carried out to determine reproducible relative frequencies of ignition.

The reproducibility of the results within the present work is high. In the three test series under the same conditions (homogeneous material pairing with steel grade 1.4541, kinetic energy: 80 J) the relative frequency of ignition varies only between 60% and 68 % (test series 1-3). But, comparing these results with the results of the previous work [4] a larger discrepancy was observed. In figure 3 the results of the pre-tests compared to the results from a previous work [4] are shown. The cause for this deviation could not be conclusively clarified. However, reducing the kinetic impact energy to 61 J, the results in this work comply very well with the results in the previous work, as shown in figure 3.

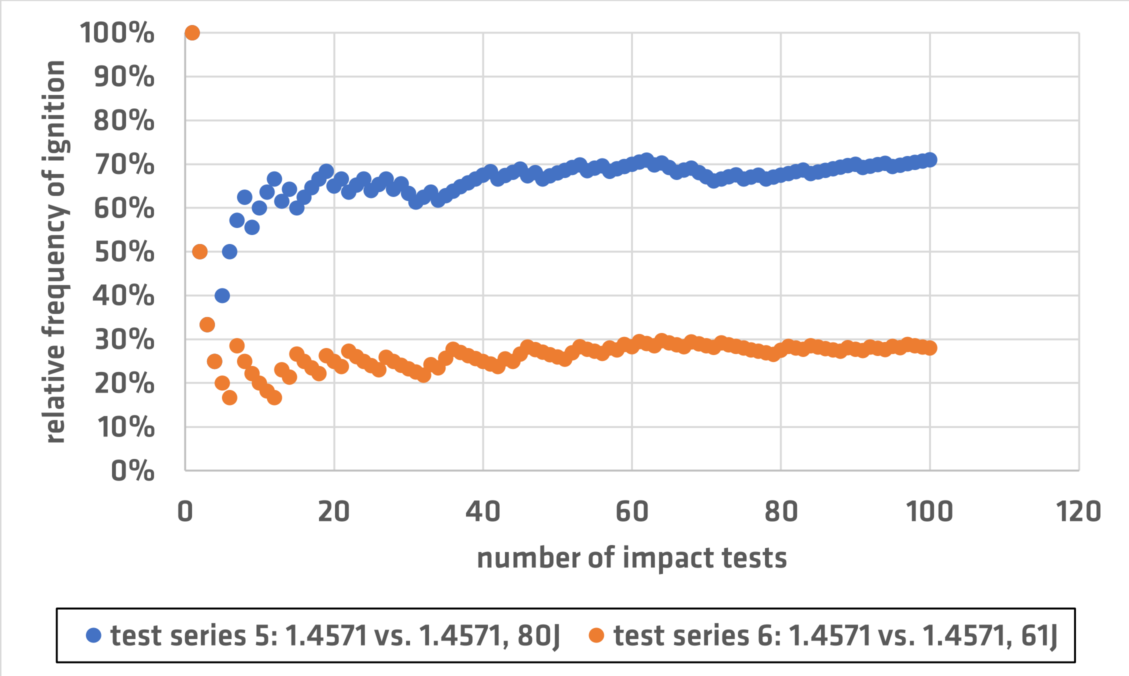

Figure 2. relative frequency of ignitions in dependence from the number of impact tests in different test series

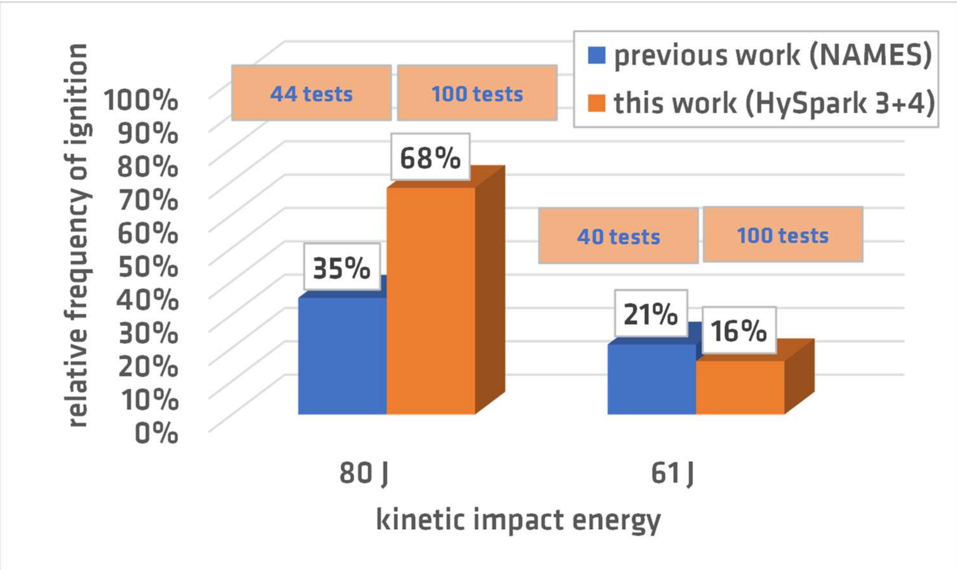

Figure 3. relative frequency of ignitions with homogeneous material pairing (1.4541 vs. 1.4541) and different kinetic impact energies determined in this work (test series 3-4) and in a previous work [4]

Two other test series (5-6) with homogeneous material pairing were carried out as pre-tests comparing the results with stainless steel of steel grade 1.4541 and stainless steel of steel grade 1.4571. The composition of these steel grades is very similar (see table 1) and both steel grades are frequently used in practice. These tests were carried out to evaluate the comparability of tests results using the two steel grades. At a kinetic impact energy of 80 J the relative frequency of ignition was slightly increased from 68% to 71 %, when steel grade 1.4571 was used. At a kinetic impact energy of 61 J the relative frequency of ignition was increased from 16% to 28 %. It was concluded that there is just a slight influence on the test results when the material of steel grade 1.4541 is replaced by material of steel grade 1.4571.

3.2 Impact Tests with Hydrogen

Several impact test series were carried out with different material pairings. Impact pins made of high-alloy stainless steel (steel grade 1.4571) and of the non-ferritic metal-alloys copper-beryllium (CuBe) and aluminium-bronze (AlBr) which are difficult to oxidise were used. Plates made of high alloy stainless steel (steel grade 1.4571), low alloy steel (1.0579) and concrete were used as impact partner. The detailed compositions and physical properties of all materials used are shown in tables 1 -5. The impact tests were all carried out in atmospheres containing 10 mol% hydrogen in air. The kinetic impact energy was fixed to 61 J first. The results are summarized in figure 4. Generally, the ignition probability is clearly increased in impacts against concrete compared to the impacts against the metallic materials, which is attributed to the very low thermal conductivity of concrete and the high brittleness.

Using the non-ferritic metals, the relative frequency of ignition is 0% for impacts against metallic materials compared to 28% or 33% for the impacts of high-alloy stainless steel against the metallic materials. Thus, the general effectivity of using tools made of non-sparking materials like these to prevent ignitions by mechanical impacts in hydrogen-containing atmospheres was first of all proven. Probably, this is not only attributed to the non-sparking properties, but also to the high thermal conductivity of the material since, it was observed in a previous work [4] that ignition occurs not only at the generated sparks, but also at the hot impact area, especially in case of impacts with stainless steel in hydrogen containing atmospheres.

However, figure 4 also shows that ignition cannot be prevented if impacts of the non-ferritic materials against concrete occur at the same kinetic impact energy of 61 J. With impact pins made of ferritic and non-ferritic materials the relative frequency of ignition was in the same range in the impacts tests with impact plates made of concrete and with kinetic impact energy of 61 J.

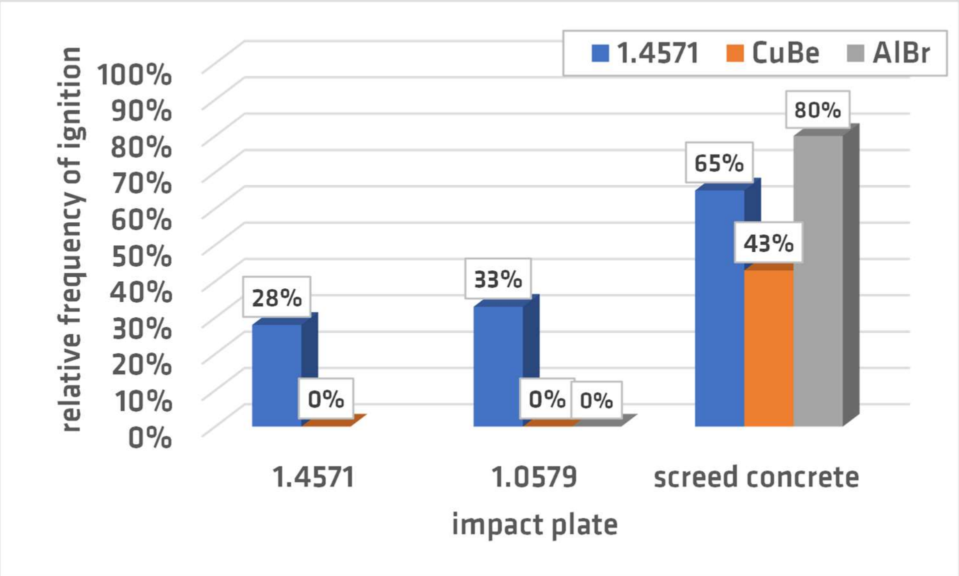

Figure 4. relative frequency of ignitions with heterogeneous material pairings and kinetic impact energy of 61 J (test series 6-10, 15, 21, 23)

Further test series using impact plates made of screed concrete were carried out decreasing the kinetic impact energy to 31 J. Reducing the kinetic impact energy to 31 J, ignition could be prevented completely if pins made of the non-ferritic material CuBe were used (test series 22). However, with pins made of the high-alloy stainless steel 1.4571 the relative frequency of ignition was still at 10% all other conditions being equal (test series 19). Thus, the effectivity of using non-sparking tools made of non-sparking materials like this to prevent ignitions by mechanical impacts in hydrogen-containing atmospheres was also proven generally considering impacts against concrete. However, it was found that using tools made of non-sparking material, the kinetic impact energy must be limited depending on the impact partner to be considered in order to prevent ignitions as a result of mechanical impacts.

3.3 Impact Tests with Methane-Hydrogen-Mixtures

Test series with fuel gas mixtures of 25 mol-%, 50 mol% and 75 mol% hydrogen with methane were carried out. The aim of these tests was to evaluate the ignition sensitivity of these mixtures in dependence from the hydrogen fraction. Impacts of pins made of high alloy stainless-steel (steel grade 1.4571) against impact plates made of low alloy steel (steel grade 1.0579) and against screed concrete were carried out. The kinetic impact energy was fixed to 61 J at first. The results of these tests are shown in figure 5.

In some previous works investigating the ignition of methane-air-mixtures by mechanical impacts the composition most easy to ignite was identified not at the stoichiometric fraction of 9.5 mol%, but at about 7 mol% [11]. Therefore, the impact tests with the fuel gas mixture of 25 mol% hydrogen in methane were also carried out in atmospheres containing 7.5 mol% fuel gas in total. All other impact tests were only carried out in atmospheres containing a total fuel gas fraction of 10 mol%.

Ignitions could only be observed at all if the hydrogen fraction in the fuel gas mixture was increased to 75 mol-% in these test series. And even for this fuel gas mixture one ignition was observed in altogether 200 impact tests. Generally, this result corresponds with the result from a previous work [15], where it was found that mixtures of methane and hydrogen only have to be allocated to the most critical explosion group IIC, if the hydrogen fraction exceeds about 75 mol%. This confirms that explosive atmospheres with fuel gases of explosion group IIC with a low ignition energy are particularly prone to ignition by mechanical impacts.

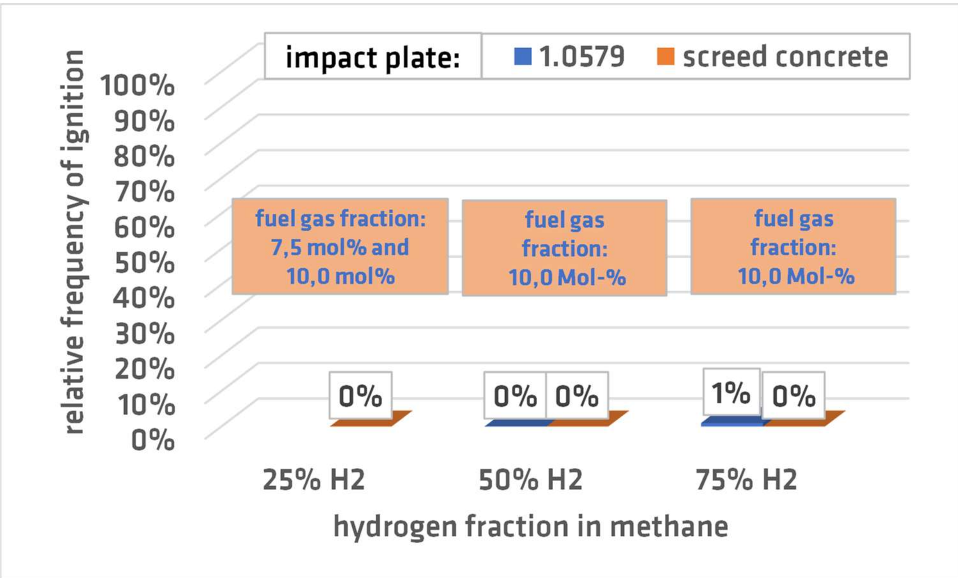

Figure 5. relative frequency of ignitions by mechanical impact with kinetic impact energy of 61 J in atmospheres containing fuel gas mixtures of methane and hydrogen with impact pins made of steel grade 1.4571 and different impact plates and (test series 11-14, 16-17)

Since fuel gas mixtures of methane and hydrogen containing up to 25 mol% hydrogen are of high practical relevance in the context of addition of so called “green hydrogen” to existing natural gas grids, this mixture was further investigated concerning the ignition effectiveness by mechanical impacts. Test series with gradually increasing kinetic impact energy were carried out in order to compare the results with similar tests using methane as fuel gas without adding hydrogen. The total fuel gas fraction in air was fixed to 10 mol% in these tests. The number of tests was reduced to 50 for the tests with kinetic impact energy of 190 J, because of the high effort for the tests with higher kinetic impact energy. The results are shown in figure 6. Even with a kinetic impact energy as high as 190 J, no ignition could be observed at all. The test series with a kinetic impact energy of 190 J was also repeated with the material pairing high-alloy steel (1.4571) vs low-allow steel (1.0579). Again, no ignition was observed in 100 single impact tests (test series 20). Altogether, it was concluded that the ignition effectiveness by mechanical impacts is not increased significantly if hydrogen is added to methane up to fractions of 25 mol%. Again, the results correspond with the results of the previous work [15], where it was found that mixtures of hydrogen and methane are allocated to explosion group IIA if the hydrogen fraction does not exceed 25%.

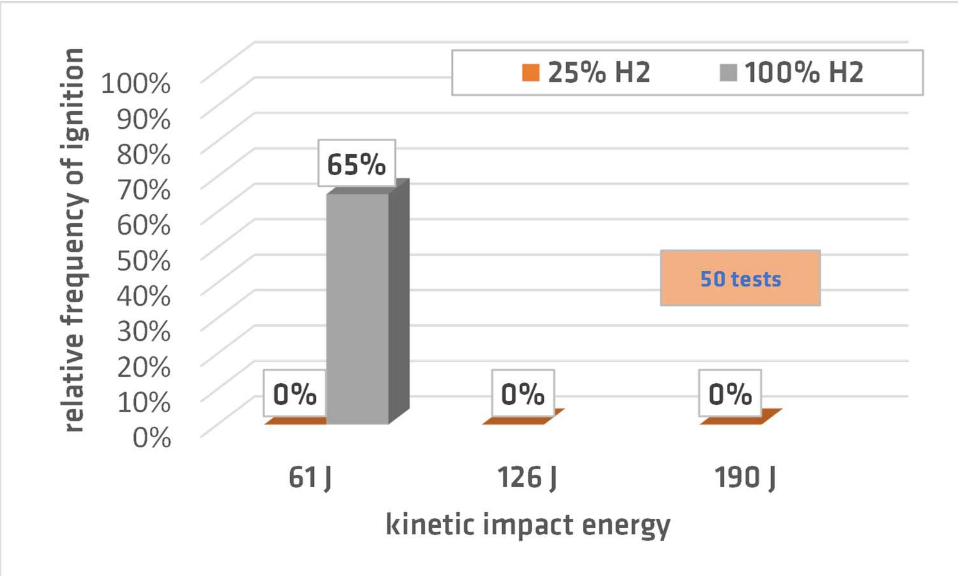

Figure 6. relative frequency of ignitions by mechanical impact (1.4571 vs. screed concrete) in atmospheres containing fuel gas mixtures of 75 mol% methane and 25 mol% hydrogen with different kinetic impact energies (test series 8, 13, 16a, 27)

4.0 CONCLUSIONS

The results of this work show that the effectivity of using tools made of non-ferritic metal alloys to avoid ignition by mechanical impacts in hazardous areas where the occurrence of atmospheres containing hydrogen cannot be excluded is strongly dependent from the impact partner to be considered. In the international regulation ISO 80079-36 [3] maximum values for the kinetic impact energy and the impact velocity are given for non-sparking metals and for other materials. But, for the evaluation of the ignition effectiveness of mechanical impacts the impact partner in heterogeneous material pairings must be considered. Information on impacts with non-metallic materials is hardly available neither in the regulations nor in scientific literature. According to the results of this work, using tools made of non-ferritic metals, the maximum kinetic impact energy to avoid ignition by mechanical impacts is lower if impacts against materials like concrete with low thermal conductivity and high brittleness are considered compared to considering only impacts against metals. However, it seems that the maximum kinetic impact energy is still higher than with commonly used tools made of stainless steel, even if impacts against concrete are considered. Thus, even in this case the use of tools made of non-ferritic metal alloys can still be an effective measure to avoid ignition by mechanical impacts in hazardous areas where the occurrence of explosive gas mixtures containing hydrogen cannot be excluded. Supplementing the regulations with this knowledge is recommended since it is of practical relevance. In industrial or commercial operation especially, impacts involving screed concrete, which is often used as soil material, might be necessary to be considered.

Generally, the results of this work prove that the Minimum Ignition Energy (MIE) is very well suitable to evaluate the ignition sensitivity of fuel gases concerning mechanical impacts. However, it seems that the MIE alone still does not fully cover the ignition sensitivity concerning mechanical impacts. In a previous work it was observed that the ignition probability is higher in acetylene-air mixtures [13] than in hydrogen-air mixtures, in case of impacts of low-alloy steels. In another previous work [14] where impacts of high alloy steels were studied, the relative frequency of ignition was higher in hydrogen-air mixtures compared to acetylene-air-mixtures. Both gases are assigned to explosion group IIC and have a similar ignition energy that is very low compared to other fuel gases [19]. Comparing the results of the present work with the results from [20] where similar tests were carried out in atmospheres containing acetylene, it is striking that the ignition sensitivity in hydrogen containing atmospheres is much higher for the material pairing metal against concrete. Possibly, the different behaviour is due to the fact, that in case of low alloy steels separation of oxidisable particles occurs in a greater extent, which is not the case for impacts with high alloy steels, where ignition mainly occurs at the hot impact area and probably also not for impacts of high alloy steels against concrete. But it cannot be clarified conclusively with the results of this work.

Concerning blends of hydrogen and methane it can be concluded that the ignition sensitivity of methane-air mixtures is only increased substantially if higher amounts of hydrogen are added. No evidence could be found that the ignition sensitivity of methane is increased at all if hydrogen is added up to fractions of 25 mol%. In a previous work [15] standardized safety characteristics of these blends were determined leading to conclusion that no major adjustment to explosion protection concepts is necessary if the hydrogen fraction is limited to 25 mol%. At higher amounts the mixtures must be allocated to another explosion group and thus it might be necessary to exchange explosion-proof equipment designed for natural gas without hydrogen admixture for example. There are no standardized safety characteristics to fully evaluate the ignition sensitivity of fuel gases concerning mechanical impacts, although the MIE and the MESG are a god basis for an estimation. The results in this work verify that the addition of up to 25 mol% hydrogen does not influence the evaluation of mechanical impacts as ignition sources in explosive atmospheres containing natural gas.

Overall mechanical impacts are complex processes. The ignition effectiveness in explosive atmospheres is dependent from many parameters. There is no comprehensive simulation model to predict the ignition effectiveness reliably in dependence from the different influencing parameters. The experimental data obtained in this work can be used to estimate the ignition effectiveness of mechanical impacts more accurately, especially in case of impacts with heterogeneous material pairings and also with non-metallic materials. However, there are many more material pairings that are less well studied, but might be relevant in practice, e.g. light metals and light metal alloys.

5.0 CONCLUSIONS

[1] Directive 2014/34/EU (ATEX 114 “equipment” Directive - - Equipment and protective systems intended for use in potentially explosive atmospheres)

[2] EN 1127-1:2019: „Explosive atmospheres - Explosion prevention and protection - Part 1: Basic concepts and methodology”

[3] ISO 80079-36:2016: “Explosive atmospheres - Part 36: Non-electrical equipment for explosive atmospheres - Basic method and requirements”

[4] Holländer, L., Grunewald, T., Grätz, R., „Entwicklung normativer Anforderungen an explosionsgeschützte nichtelektrische Geräte resultierend aus der Zündfähigkeit mechanisch erzeugter Schlagfunken (NAMES)“, BAM Final Report, Joint Research Project Vh2104, BMBF Funding Number 01FS12042, 2015

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atmospheres by mechanical friction and impacts (MECHEX), *Journal of Loss Prevention in the Process Industries,* **20**, 2007, pp. 349–365

[6] IEC 60079-0:2019: „Explosive atmospheres - Part 0: Equipment - General requirements“

[7] ISO/IEC 80079-20-1:2020: „Explosive atmospheres - Part 20-1: Material characteristics for gas and vapour classification - Test methods and data“

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