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Influence of Material Properties of Stainless Steel on the Ignition Probability of Flammable Gas Mixtures due to Mechanical Impacts

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Grazing impact experiments of various types of stainless steels were performed in explosive atmospheres of hydrogen, acetylene, ethylene or propane with air. Depending on the gas mixture, kinetic energy of the impact, and applied stainless steel, the dominant ignition sources are either separated particles or hot friction surfaces. An influence of chromium content on the ignition probability was not found, although an increase in chromium content results in a reduction of the oxidizability of separated particles. Additionally, the influence of the material properties thermal conductivity, specific heat, density and hardness on the ignition probability of the hydrogen–air mixture was investigated. With increasing thermal conductivity a decreasing rate of ignitions was observed. In contrast, an influence of the physical properties specific heat, density and hardness on the ignitability was not found.

1. Introduction

For non-electrical equipment intended for use in potentially explosive atmospheres, an ignition hazard assessment must be carried out in accordance with standard EN 13463-1:2009 (BSI, 2009). This includes a consideration of all potential ignition sources. One of these is the ignition source “mechanically generated sparks“ generated by single impacts. During the impact, kinetic energy is converted. This causes a rise in the temperature of the contact surfaces and possibly a separation of hot particles. Both the hot surfaces as well as the hot particles may be able to ignite an explosive gas mixture. Since the necessary temperature for ignition increases with decreasing size of the hotspot (Cutler, 1974), small particles must have a higher temperature than the larger contact surfaces to act as an effective source of ignition. The required temperature for ignition also increases with increasing relative movement between particle and gas (Laurendeau and Caron, 1982). The required rise in temperature can be effected by exothermic reactions such as a thermite reaction (Gibson et al., 1967) or an oxidization of iron with the oxygen of the gas mixture.

Energy limits for single impacts are given in the standard EN 13463-1:2009 (BSI, 2009). Below these energy limits an occurrence of an effective ignition source is assumed to be unlikely. Here, a differentiation is made between impacts of non-sparking metals such as copper and impacts of so-called other materials. The energy limits of the other materials follow from results of experiments with mild steel. At such impacts, it is assumed that the ignition of the gas mixture is caused by oxidized particles. However, in industrial applications mild steel is often replaced by stainless steel. Stainless steel is supposed to be less problematic than carbon steel as a possible ignition source because of the decreasing oxidizability of stainless steel particles with increasing content of alloying elements such as chromium. Due to the reduced oxidizability, Voigtsberger (1955) concluded that stainless steel with chromium content over 18.11 % does not oxidize. However, experimental investigations of impacts with various stainless steels did not demonstrate a reduced ignition probability with increasing chromium content (Holländer et al., 2014).

Besides the oxidizability, the temperature increase and thus the ignitability is affected by other material properties. Investigations of friction processes showed an increasing maximum temperature of the contact area with decreasing thermal conductivity of the grinding material (Meyer et al., 2015). The hardness of the materials is supposed to influence the ignition probability as well. However, Gibson et al. (1967) and Jones et

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al. (2006) observed an increasing ignition probability with increasing hardness, whereas experimental studies of Averill et al. (2014) showed a reduced ignition probability when using a harder material. Averill et al. (2013) presented with

$$\theta_{\max} - \theta_b = 1.6\mu \left(\frac{{p_f}^3 F_N v^2}{\pi k^2 \rho^2 {c_p}^2} \right)^{1/4} \tag{1}$$

a relation for the estimation of the maximum rise in temperature of the contact surfaces due to friction processes. According to this relationship, the difference between maximum temperature θ_{max} and bulk temperature θ_b depends on the experimental parameters normal force F_N and velocity v as well as on various material parameters. A decreasing thermal conductivity k, specific heat capacity c_p or density ρ causes an increased temperature whereas a decreasing friction coefficient μ or material flow stress in pure shear p_f, which is assumed to be proportional to the hardness, lowers the temperature. However, due to the non-static friction process equation (1) is not applicable for grazing strikes.

In this paper, we present the results of grazing impact experiments using various types of stainless steel in gaseous mixtures of acetylene, hydrogen, ethylene and propane with air. Here, the ignition probability and the influence of the chromium content on the oxidizability were determined. In addition, the influence of the physical properties thermal conductivity, specific heat capacity, density and hardness on the ignition probability of the hydrogen–air mixture was investigated.

2. Experimental Details

The grazing impact experiments were performed in a massive steel chamber (Cylinder section) with a gas volume of 20 L. This chamber included a pivot-mounted hammer with a pin made of stainless steel with defined measures mounted on the lower side. A steel plate that always consisted of the same type of stainless steel as the pin was placed below the hammer. The hammer was connected at the pivotal point with a torsion spring. Energy of the spring was stored by its distortion. Abrupt release of the hammer results in a conversion of this energy to kinetic energy. Near the initial position the pin hit the plate and performed the grazing impact. A big circular opening on one side of the chamber was covered with a transparent polymer film that would burst in case of an explosion of the gas mixture, leading only to a small build-up of the pressure inside the setup.

The use of different torsion springs with different torques led to a variation of the maximum kinetic energy. Thus, it was possible to adjust energy values of 189 J, 126 J, 80 J, 61 J and 30 J with the appropriate maximum velocities of 14,2 m/s, 11,6 m/s, 9,3 m/s, 8,1 m/s und 5,7 m/s. The tests were always started with the highest amount of impact energy and subsequently decreased stepwise until the minimum value of 30 J was reached. If no ignition could be detected in at least 200 impacts of the same energy, no further experiments with lower kinetic energies were performed. The chamber was filled with gaseous mixtures of dried air and one of the gases hydrogen (10.0 vol-%), acetylene (8.0 vol-%), ethylene (6.5 vol-%) or propane (4.0 vol-%) during the experiments. The experiments were performed at room temperature and atmospheric pressure of the gaseous mixture. Each experiment was recorded by means of a high-speed infrared camera (ThermoVision SC4000, FLIR), which was located at a distance of one meter from the setup. These recordings allowed the localisation of the initial points of ignitions.

Four different types of stainless steels with material numbers 1.4307, 1.4313, 1.4462 or 1.4541 were used for the investigations. From these steels, the material properties thermal conductivity, specific heat capacity, density and hardness were determined. Each of these parameters depends on the temperature. However, parameters which are easy to determine are preferred for industrial applications. Therefore, the measurements of the parameters were carried out only at room temperature.

From each type of stainless steel one rectangular cuboid was made. The density of the stainless steels was determined by measurements of the mass (SX4002S DeltaRange, Mettler Toledo) and the volume of the rectangular cuboids (calliper gauge). The thermal conductivity and thermal diffusivity were measured using the transient plane source method (TPS 1500, Hot Disk AB). For this purpose, a thin coil was positioned between two plates of the same material, with which the material was slightly heated by short current pulses. The thermal conductivity and specific heat capacity were determined from measurements of the temperature-dependent resistance of the heating coil.

The hardness of the pin and the plate were determined by at least five independent measurements with the Brinell method (M4C 025 G3, EMCO-TEST). The results of the measurements are given in Table 1.

Table 1: Overview of selected physical properties and the chromium content of the four types of stainless steels used.

Material number	Thermal conductivity in W/(mK)	Specific heat capacity in J/(kgK)	Density in kg/m^3	Hardness of the plate	Hardness of the pin	Chromium content in %
1.4307	15.24	514.8	7926	166	219	18.2
1.4313	18.45	509.2	7787	272	298	12.6
1.4462	14.04	501.2	7796	245	319	22.5
1.4541	14.69	489.0	7932	163	230	17.7

3. Results and Discussion

3.1 Hydrogen–air Mixture

The results of the experimental investigations showed that the hydrogen–air atmosphere used can be ignited by stainless steel impacts with maximum kinetic energy of 30 J. At this energy, the rate of ignition was between 1.7 % for material 1.4313 and 6.7 % for material 1.4462 (cf. Figure 1). With increasing kinetic energy the ignition probability likewise increased. At each energy level, except 80 J, the impacts of material 1.4462 were the most incendive ones. For the other materials, a distinct order could not be observed. At kinetic energies between 189 J and 80 J, the ignition probability due to impacts of stainless steel was lower compared to impacts of mild steel. In contrast, at energies of 61 J and 30 J the ignition probability of some types of stainless steel was even higher than for mild steel.

The impact events caused a rise in temperature at the surfaces of pin and plate. In addition, brightly glowing particles were observed, particularly at high power levels, which were separated from the pin or plate and then flew through the gas mixture. Despite these particles, the ignitions were initiated by the hot surfaces of the pin or plate in most cases.

3.2 Acetylene–air Mixture

In addition to previously reported results of stainless steel impacts in acetylene–air (Holländer et al., 2014), 40 single impacts of the material 1.4307 were carried out at an energy value of 189 J. For these experiments, the rate of ignition was 42.5 %. Thus, the gas mixture was ignited more frequently than for impacts of the materials 1.4313, 1.4462 or 1.4541 (cf. Figure 2). Almost all of these ignitions were initiated by separated particles, as already observed in the experiments with the materials 1.4313 and 1.4541.

3.3 Ethylene–air Mixture

There was no ignition of the ethylene-air atmosphere within 200 individual experiments of the material 1.4313 with a maximum energy value of 189 J. In contrast, ignitions could be observed due to impacts of the materials 1.4462 and 1.4541 in the former study (Holländer et al., 2014). Impacts of 1.4462 with 189 J ignited the gas mixture with a probability of 1.7 %. With a kinetic energy of 126 J no ignition was detected. In contrast, even with a kinetic energy of 61 J an ignition probability of 0.8 % could be observed when using 1.4462 (cf. Figure 3).

3.4 Propane–air Mixture

Experiments with propane-air mixture were performed with the stainless steel 1.4541 only. Within 200 experiments with a maximum kinetic energy of 189 J an ignition could not be observed.

3.5 Influence of Chromium Content on the Ignition Source

The experiments in hydrogen–air with the used types of stainless steel showed mainly ignitions by the hot surfaces of the pin or the plate. Differences between the various materials were not observed. At kinetic energies of 126 J and 189 J, the ignition source of acetylene–air depends on the type of stainless steel. While mainly the hot surfaces of pin or plate initiated the ignitions when using 1.4462, particles acted as ignition source in most cases when the experiments were performed with 1.4313 or 1.4541 (Holländer et al., 2014). The difference of the ignition source was explained by the decreasing oxidizability with increasing chromium content. Voigtsberger (1955) claimed that a chromium content of 18.11 % is sufficient to prevent the oxidation of the particles.

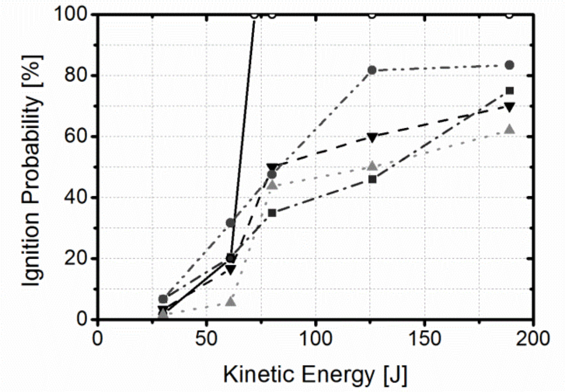

Figure 1: Ignition probability of a hydrogen-air mixture (10 vol-% hydrogen) due to impacts of stainless steel type 1.4307 (▼), 1.4313 (▲), 1.4462 (●) or 1.4541 (■) with different kinetic energies. For comparison, the results of impact experiments using mild steel 1.0570 (○) are added (Grunewald et al., 2010).

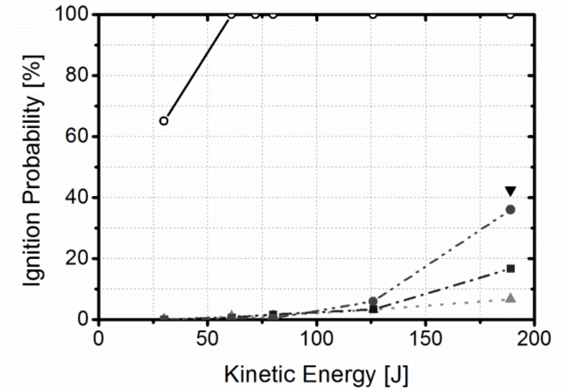

Figure 2: Ignition probability of an acetylene-air mixture (8 vol-% acetylene) due to impacts of stainless steel type 1.4307 (▼), 1.4313 (▲), 1.4462 (●) or 1.4541 (■) with different kinetic energies. For comparison, the results of impact experiments using mild steel 1.0570 (○) are also shown (Grunewald et al., 2010).

Additional tests with the stainless steel 1.4307, having a chromium content of 18.2 %, also showed ignitions by particles in most cases. Due to the small size of the particles, the temperature must be higher than the temperature of the bigger surfaces of pin and plate to act as an ignition source. Thus, an oxidization process of the particles is assumed. In consequence, the assumption of Voigtsberger could not be verified. But the results indicate that with increasing chromium content an increased kinetic energy is necessary for oxidation.

3.6 Influence of Physical Parameter on the Ignition Probability of the Hydrogen–air Mixture

The hydrogen–air mixture was mainly ignited by hot surfaces. Thus, only the increase in temperature generated by friction was essential for ignition. For identical test conditions, the temperature increase was mainly influenced by the material properties of the used stainless steel. Potential oxidation processes occurring on the surfaces could be neglected.

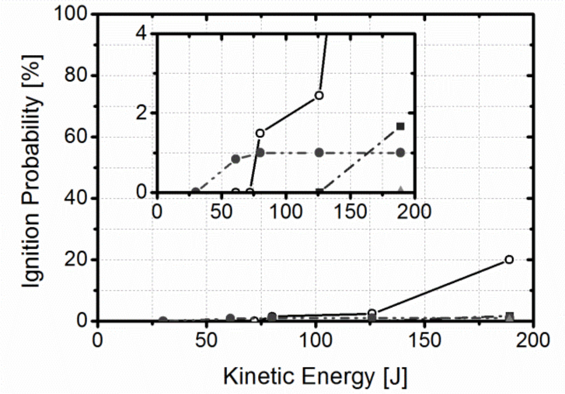

Figure 3: Ignition probability of a ethylene-air mixture (6.5 vol-% ethylene) due to impacts of stainless steel type 1.4313 (▲), 1.4462 (●) or 1.4541 (■) with different kinetic energies. For comparison, the results of impact experiments using mild steel 1.0570 (○) are also shown (Grunewald et al., 2010). The inset shows an enlargement of the same data.

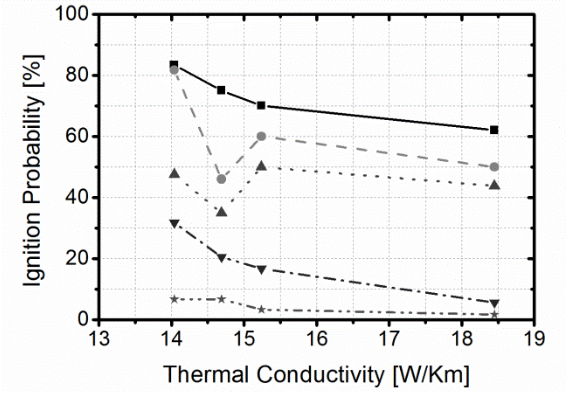

Figure 4: Influence of the thermal conductivity on the ignition probability of a hydrogen-air mixture (10 vol-% hydrogen) at impacts with energies of 189 J (■), 126 J (●), 80 J (▲), 61 J (▼) and 30 J (★).

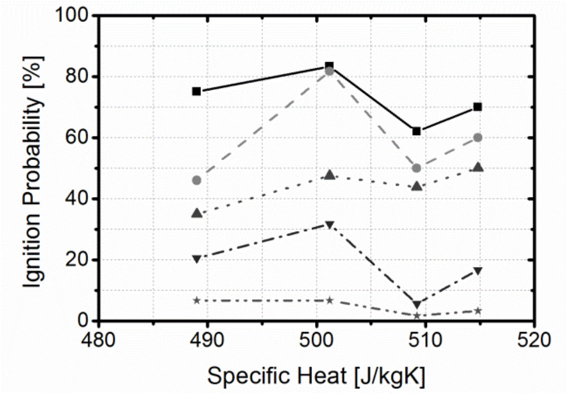

Figure 7: Influence of the hardness of the specific heat on the ignition probability of a hydrogen-air mixture (10 vol-% hydrogen) at impacts with energies of 189 J (■), 126 J (●), 80 J (▲), 61 J (▼) and 30 J (★).

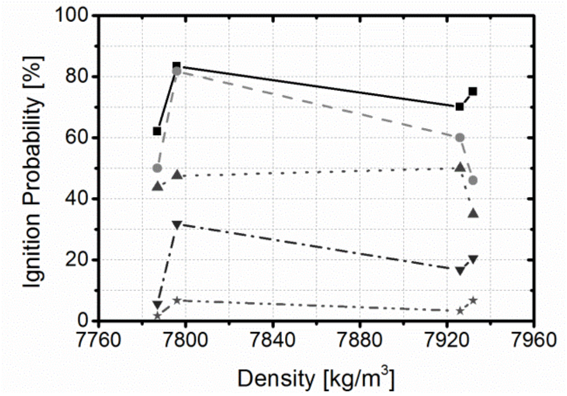

Figure 8: Influence of the density on the ignition probability of a hydrogen-air mixture (10 vol-% hydrogen) at impacts with energies of 189 J (■), 126 J (●), 80 J (▲), 61 J (▼) and 30 J (★).

In contrast, for ignition by particles as in acetylene–air the oxidizability played a role too. Therefore, only the results of the experiments with hydrogen and air were used for investigations of the influence of material properties on the ignitability.

Considering the results of the experiments, it is noticeable that the ignition probability decreases with increasing thermal conductivity of the stainless steel (cf. Figure 4). Especially for energies of 189 J and 61 J this correlation can be seen clearly. For energies of 126 J and 80 J, the correlation is not as pronounced. This could be a consequence of the limited number of experiments. The increasing probability of ignition with decreasing thermal conductivity indicates a lower temperature increase for stainless steels with higher thermal conductivity. This result is in accordance with temperature measurements during grinding experiments (Meyer et al., 2015).

A correlation of the ignition probability with the material properties specific heat, density or hardness could not be found (cf. Figures 5, 6, 7, and 8). However, this does not necessarily imply that the ignition probability is completely independent of these parameters. An influence of several parameters is still possible. However, the dependence on a single parameter is too low, as could be seen in the small number of different steels. Due to the lack of theoretical descriptions of the temperature development in impact processes, only the influence of each parameter could be examined.

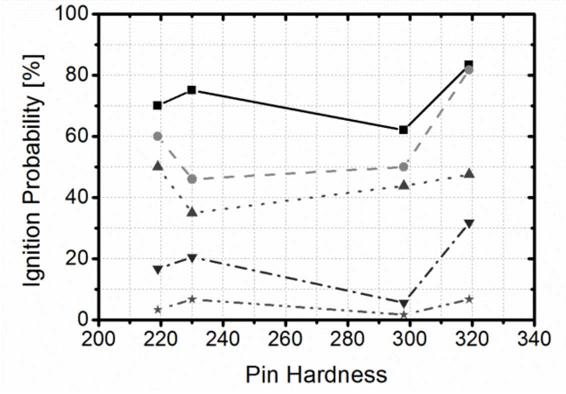

Figure 7: Influence of the hardness of the stainless steel pin on the ignition probability of a hydrogen-air mixture (10 vol-% hydrogen) at impacts with energies of 189 J (■), 126 J (●), 80 J (▲), 61 J (▼) and 30 J (★).

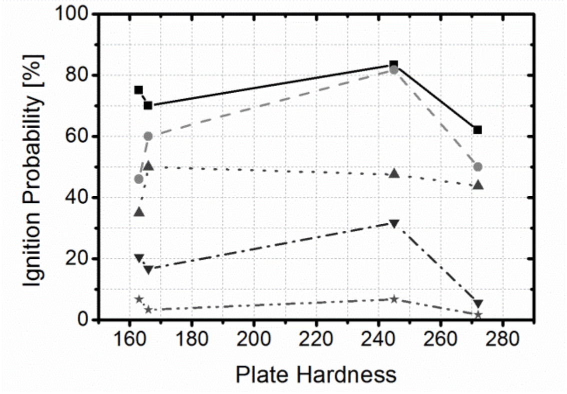

Figure 8: Influence of the hardness of the stainless steel plate on the ignition probability of a hydrogen-air mixture (10 vol-% hydrogen) at impacts with energies of 189 J (■), 126 J (●), 80 J (▲), 61 J (▼) and 30 J (★).

4. Conclusions

Flammable gas mixtures can be ignited by grazing impacts between stainless steel components. The probability of ignition increases with increasing kinetic energy. The investigations showed that ignitions of the used hydrogen–air mixture were more probable than for the mixtures acetylene–air or ethylene–air. The propane–air mixture could not be ignited by grazing impacts of stainless steel 1.4541.

The ignitions can be initiated both by separated particles as well as by the hot contact surfaces. The occurrence of the ignition source “separated particles” depends on the type of stainless steel and the kinetic energy. This observation is attributed to the reduced oxidizability of the stainless steel particles with increasing chromium content. However, a correlation between chromium content and ignition probability was not found. In contrast, for ignitions of hydrogen–air in result of hot surfaces, an influence of the thermal conductivity of stainless steel on the ignition probability was observed. The rate of ignitions decreased with increasing thermal conductivity which indicates a smaller temperature rise for stainless steels with a higher thermal conductivity.

As a result, stainless steel used in potentially explosive atmospheres should possess a high thermal conductivity as well as a low oxidizability. Additionally, a dependence on a combination of several parameters is presumed. However, for investigations of such an influence a theoretical description of the temperature development at the surfaces has to be developed. But in order to investigate such a relationship, the temperature development on the surfaces has to be described theoretically first.

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