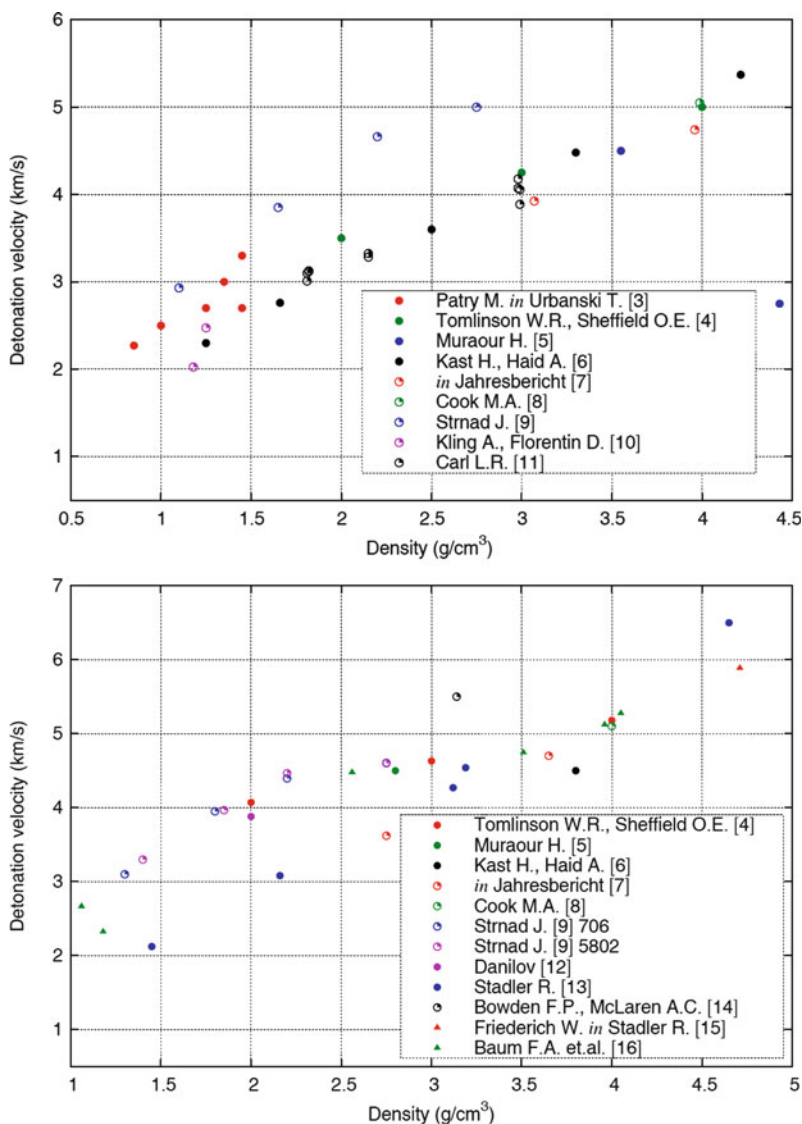# Chapter 2
Explosive Properties of Primary Explosives

The main requirements for primary explosives are sensitivity within useful limits, high initiating efficiency, reasonable fluidity, resistance to dead-pressing, and long-term stability. Useful limits mean that the substance must be sensitive enough to be initiated by an SII but not too sensitive as to be unsafe for handling or transportation. The initiating efficiency, perhaps the most important parameter, determines the ability of a primary explosive to initiate secondary explosives. The reasonable free flowing properties are important for manufacturing where the primary explosives are often loaded volumetrically. Primary explosives must not undergo desensitization when pressed thereby yielding a dead-pressed product. The long-term stability and compatibility with other components, even at elevated temperatures, are essential because primary explosives are often embedded inside more complex ammunition and are not expected to be replaced during their service life. They must also be insensitive to moisture and atmospheric carbon dioxide. Parameters important for secondary explosives such as brisance, strength, detonation velocity, or pressure are of lesser importance to primary explosives although they are of course related to the above properties.

2.1 Influence of Density on Detonation Parameters

Primary explosives are generally prepared in the form of crystalline or powdery material with low bulk densities and large specific surface. This form is hardly ever suitable for direct application and therefore it has to be further processed. For use in detonators they must be compacted by pressing to the detonator caps in a way that assures the best initiation properties.

When higher pressures are used to achieve higher densities, a phenomenon called "dead-pressing" may occur, leading to a material which is hard to ignite and which, if ignited, only burns without detonation [1]. Pressing a primary explosive to a point where it loses its capability to detonate is therefore not desirable.

The phenomenon of dead pressing is not common to all primary explosives. Many azides, including lead azide, cannot be easily dead-pressed. On the other

Fig. 2.1 Influence of density on detonation velocity: *top*: mercury fulminate [3–11] and *bottom*: lead azide [4–9, 12–16]. Two samples with specific surface 706 cm^2 g^{-1} and 5,802 cm^2 g^{-1} were listed in [9]

hand MF, DDNP and peroxides can be dead-pressed very easily. The pressure needed for dead-pressing MF is highly dependent on its crystal size [2].

The compaction process reflects in the density, which influences practically all of the other explosive properties. On the following two charts (Fig. 2.1), the relationship between detonation velocity and density for MF and LA is presented.

The values have been compiled from various literature sources and hence obtained under a variety of conditions. Rigorous conclusions based on such data are not possible but they provide a surprisingly good idea of the shape of the relationship.

The values in Fig. 2.1 show that the detonation velocity of both MF and LA increases with increasing density, as expected. In general, one would further expect that it is desirable to press explosives to densities as close to the theoretical maximum density (TMD) as possible. This is, however, not exactly the case for primary explosives in a detonator where it is more important to have good initiation efficiency rather than high detonation velocity.
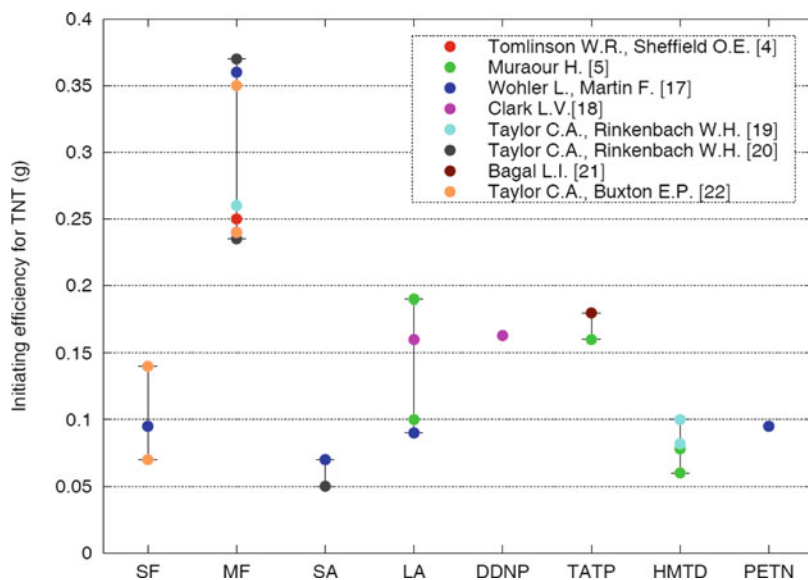
2.2   Initiating Efficiency

Initiating efficiency, sometimes referred to as initiating power, strength, or priming force, is the ability of a primary explosive to initiate detonation in a secondary explosive adjacent to it. It is usually reported as a minimum amount of primary explosive necessary to cause detonation of the adjacent high explosive with 100% probability.

The initiating efficiency is not a material constant for a particular primary explosive. It depends on many factors including: pressure used for compression, type of ignition, type of confinement, presence of reinforcing cap and its material, type of the secondary explosive, size of the contact surface between primary and secondary explosive, etc. The values of initiation efficiency reported in the literature are therefore difficult to compare due to a variation in these conditions. We have collected initiation efficiencies of some primary explosives with respect to TNT and summarized them in Fig. 2.2.
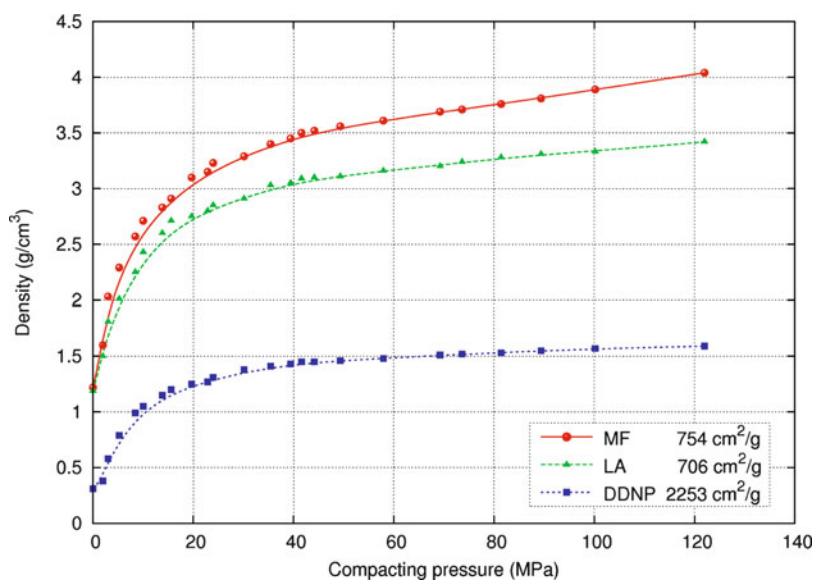
These values show variations in the minimal amount based on a combination of these factors which are generally not provided in the references. This makes comparison of various results quite a troublesome task. It is important to understand that a single number reported without further specification (as shown in Fig. 2.2) has very low information value. The effects of the most important factors are therefore addressed in the following sections.

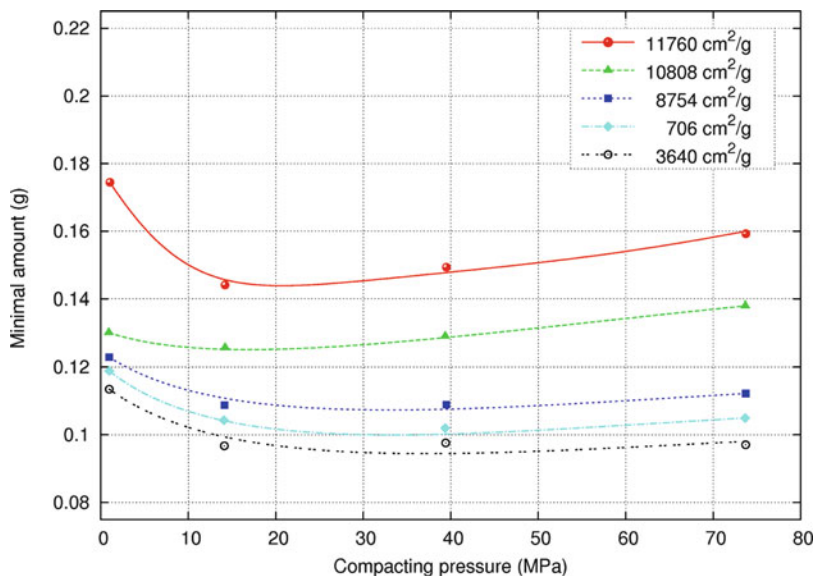### 2.2.1   Influence of Density and Compacting Pressure

The influence of compacting pressure cannot really be separated from the influence of density as these two parameters are related. Higher compacting pressure leads to material of higher density. This is shown in Fig. 2.3 for MF, LA, and DDNP. The reason why we address both of these factors here is purely practical—the lack of data. Primary charges (for testing of initiating efficiency) are prepared in the form of powder compressed either (a) directly onto an already compressed secondary explosive in a metal cap or (b) into a reinforcing cap which is then pressed onto the secondary charge.

Fig. 2.2 Initiation efficiencies of some primary explosives for TNT (previously unused acronyms: *SF* silver fulminate, *SA* silver azide, *TATP* triacetone triperoxide) [4, 5, 17–22]

Fig. 2.3 Density of MF, LA, and DDNP as a function of compacting pressure, by kind permission of Dr. Strnad [9]
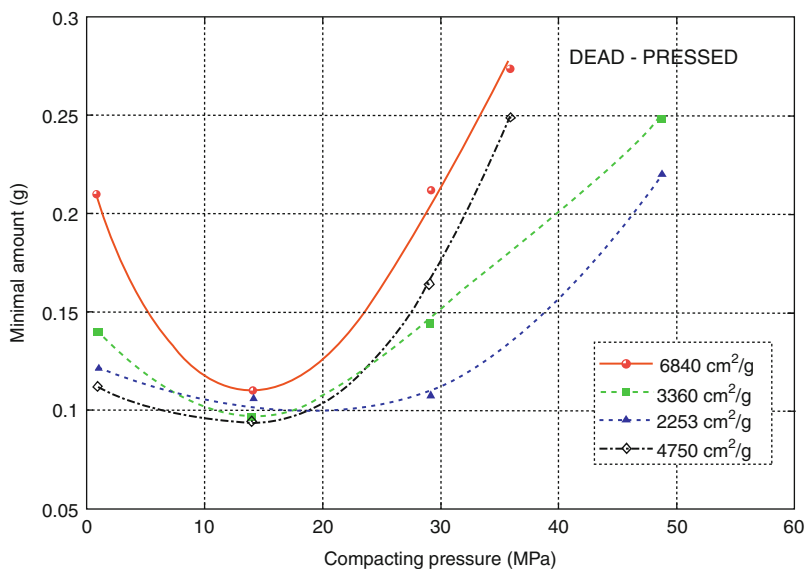
Fig. 2.4 The influence of compacting pressure and specific surface on initiation efficiency of dextrinated LA (acceptor 0.35 g of TNT compressed by 76.5 MPa without reinforcing cap) by kind permission of Dr. Strnad [9]

In both cases it is difficult to determine the exact density before the experiment. The only known (or reported) parameter is therefore compacting pressure.
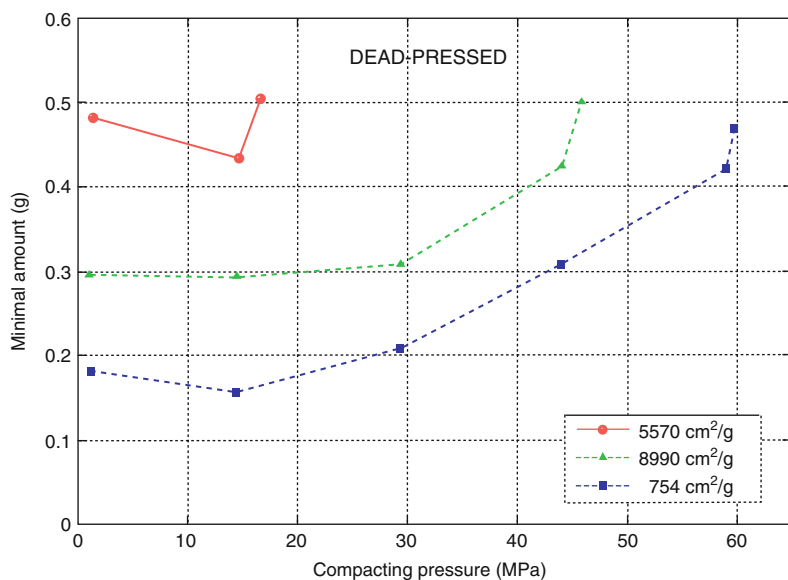
Very rare results have been obtained by Strnad [9] who used MF, LA, and DDNP of various specific surfaces, compressed them with defined pressures, and experimentally measured the resulting densities (Fig. 2.3). This allowed him to study the influence of the resulting density on the initiation efficiency. More on this issue will be addressed in detail later in this chapter but, to summarize, it can be stated that, in the case of MF, LA, and DDNP, an increase in density first leads to a decrease in the minimal necessary amount of explosive—and what happens subsequently is material specific. Some substances (e.g., DDNP, MF) start to lose their ability to initiate secondary explosives, which is reflected in higher amounts needed for successful initiation, while other substances work in the same way, no matter how hard they are pressed (pure LA).

One important and, unfortunately, not so frequently considered parameter is specific surface. Fine powder of the same primary explosive will behave differently from coarse crystals. Figures 2.4, 2.5, 2.6, 2.7, 2.8, and 2.9 demonstrate that very fine powders show worse initiating efficiency compared to their coarser form. Nevertheless, it can be seen that gently compressing any primary explosive of any specific surface leads to an increase of initiating efficiency.
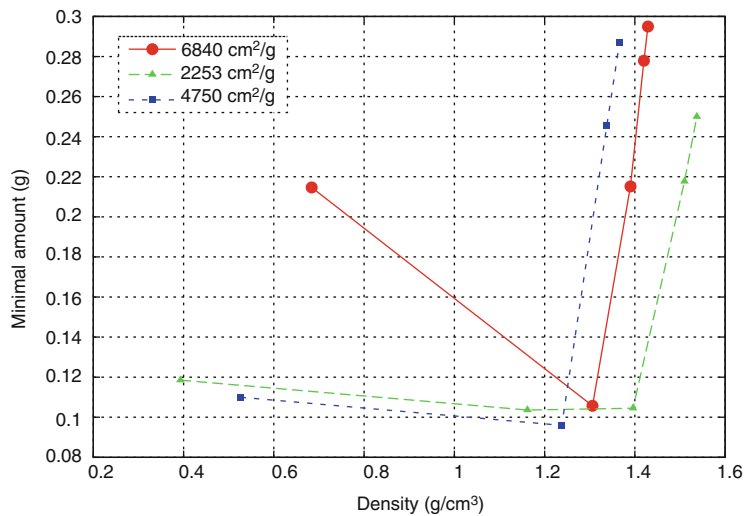
The influence of compacting pressure on the mean minimal amount is shown in Fig. 2.4 for LA, Fig. 2.5 for DDNP, and Fig. 2.6 for MF. All three exhibit a decrease in the minimal amount by slight compression (9.8 MPa). Further increase of pressure

Fig. 2.5 The influence of compacting pressure and specific surface on initiation efficiency of DDNP (acceptor 0.35 g of TNT compressed by 76.5 MPa with reinforcing cap), by kind permission of Dr. Strnad [9]
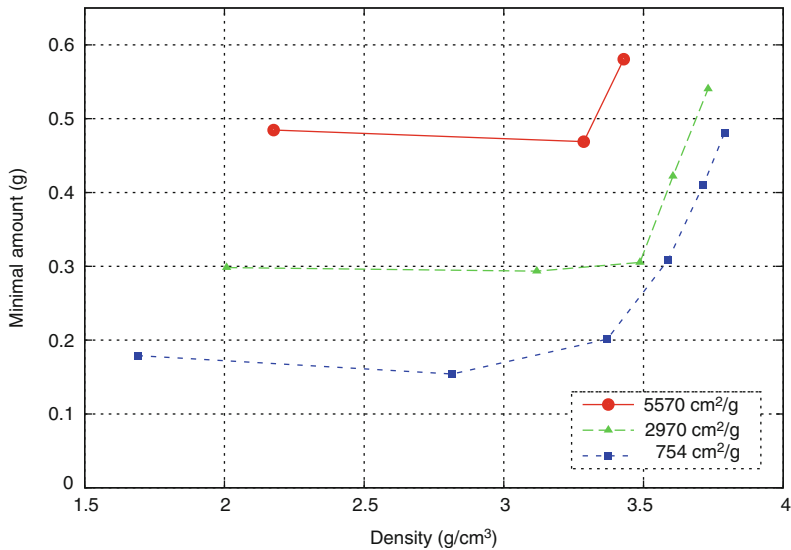

Fig. 2.6 The influence of compacting pressure and specific surface on initiation efficiency of MF (acceptor 0.35 g of TNT compressed by 76.5 MPa with reinforcing cap), by kind permission of Dr. Strnad [9]

Fig. 2.7 Initiation efficiency of DDNP as a function of density and specific surface (acceptor 0.35 g of TNT compressed by 76.5 MPa with reinforcing cap), by kind permission of Dr. Strnad [9]

Fig. 2.8 Initiation efficiency of MF as a function of density and specific surface (acceptor 0.35 g of TNT compressed by 76.5 MPa with reinforcing cap) by kind permission of Dr. Strnad [9]

has a negligible effect on LA but significant effects on both MF and DDNP. The decrease of the initiation efficiency for these two depends on their specific surface. Dead pressing occurs earlier for material with higher specific surface [9].
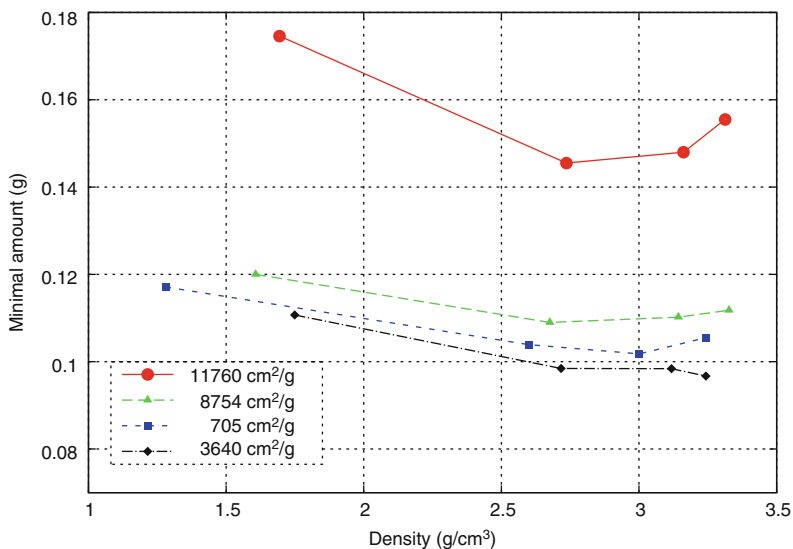
Fig. 2.9 Initiation efficiency of LA as a function of density and specific surface (acceptor 0.35 g of TNT compressed by 76.5 MPa without reinforcing cap) by kind permission of Dr. Strnad [9]

The compacting pressure in Figs. 2.4, 2.5, and 2.6 can be converted to densities of the compacted material and the relationships then plotted as initiation efficiency as a function of density (Fig. 2.7, 2.8, and 2.9). The highest initiation efficiency is obtained for MF at 3.2 g cm^{-3} (72% of TMD) and for DDNP at 1.2–1.3 g cm^{-3} (73.6–80.2 TMD). Using higher pressures leads to an increase in the minimal necessary amount of the explosive, and at density 3.6 g cm^{-3} MF and at 1.3–1.4 g cm^{-3} DDNP became dead-pressed. The density at which dead pressing takes place is lower for material with higher specific surface.

LA shows minimal necessary amount at density 2.7 g cm^{-3} (58% of TMD). Further increase in the compacting pressure does not have any significant effect on the initiation efficiency. The only exception is LA with a very large specific surface (~10,000 cm^2 g^{-1}) which has high minimal amounts that, after exceeding optimal density, increase yet further (Fig. 2.9).

The graphs presented above clearly show that, in the case of primary explosives, optimal rather than high density should be used. All the more so as unnecessarily high pressures used for obtaining material of higher density are also more susceptible to detonations during compression.

The compacting pressure is an important parameter not only for the primary but also for the secondary explosive as it influences the densities of both. The values tabulated in Table 2.1 refer to the amount of primary explosive causing detonation of PETN in 10 out of 10 trials [23]. It can be clearly seen that the uncompressed PETN requires much lower amounts of practically all primary explosives than compressed PETN. The compression of the secondary charge may lead to such a

Table 2.1 Influence of processing pressure on the minimal amount of primary explosive needed to detonate PETN in 10 out of 10 trials (copper detonator cap with internal diameter 6.2 mm without reinforcing cap) [23]

Pressure on PETN (MPa)	0	196			
Pressure on initiator (MPa)	0	0	49	98	147
Primary explosive	Minimum initiating charge (g)				
Tetrazene	0.16	0.25	Dead pressed		
Mercury fulminate (white)	0.30	0.34	Dead pressed		
Lead styphnate	0.55	Without detonation with 1 g			
Lead azide	0.015	0.1	0.01	0.01	0.01
Silver azide	0.005	0.110	0.005	0.005	0.005

Table 2.2 Influence of the amount of unpressed lead azide on the probability of detonation of a PETN charge pressed by 0 or 196 MPa [23]
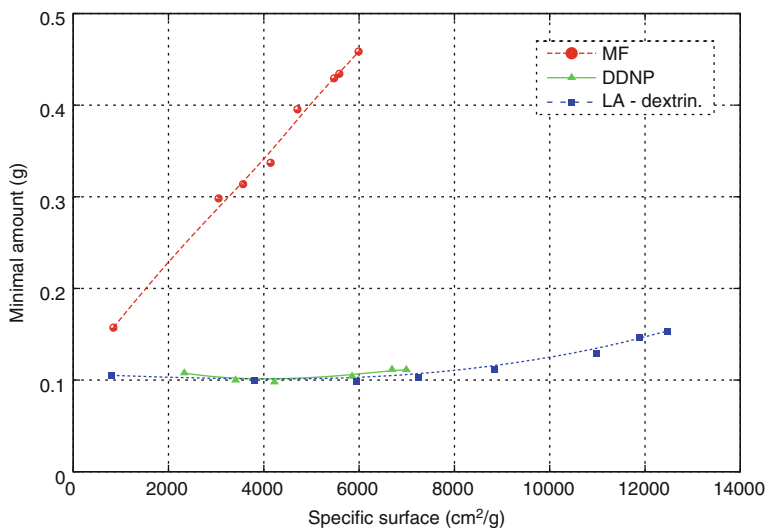
PETN pressed by (MPa)	Weight of LA (g)	Result (+ detonation, − failure)
0	0.01	+ + + + −
0	0.015	+ + + + + + + + +
0	0.02	+ + + + +
0	0.03	+ + + + +
196	0.03	− − − − −
196	0.05	+ + + − −
196	0.09	+ + + − −
196	0.10	+ + + + + + + + +

desensitization of the secondary charge that it is impossible to initiate it by primary explosives with lower initiation efficiency.

The amounts in Table 2.1 are the minimal amounts causing initiation in 10 out of 10 trials. This does not necessarily mean that lower amounts of primary explosives do not initiate the secondary charge. In fact they do, but the probability of failure is higher. This behavior is demonstrated by results for LA in Table 2.2.

2.2.2   Influence of Specific Surface

The influence of the specific surface of the primary explosives on their initiation efficiency has already been included in the graphs above as reflected by their compaction behavior. It was further studied in a standard detonator number 3 cap with 0.35 g of TNT compressed by 76.5 MPa as a secondary charge [9]. LA was compressed by 13.8 MPa without any reinforcing cap while MF and DDNP were compressed by the same pressure with a reinforcing cap. The results are shown in Fig. 2.10. Both DDNP and LA show a performance relatively independent of specific surface with the best performance around 4,000 cm^2 g^{-1}. The behavior of MF is however quite different, as its minimal necessary amount continually increases with increasing specific surface (decreasing crystal size).

Fig. 2.10 Initiation efficiency as a function of specific surface, LA without reinforcing cap, DDNP and MF with reinforcing cap, compacting pressure 13.8 MPa, acceptor: 0.35 g of TNT compressed by 76.5 MPa, by kind permission of Dr. Strnad [9]
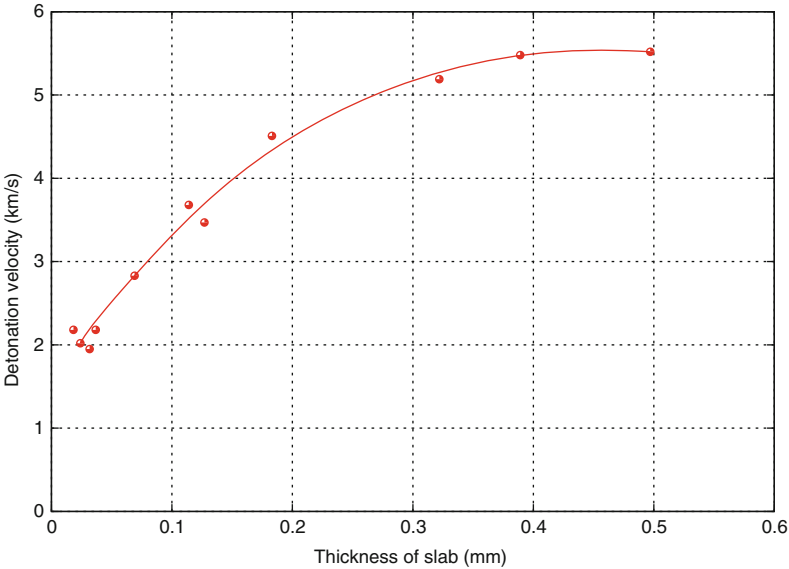
2.2.3 Influence of the Charge Diameter

The detonation velocity is not influenced only by its density but, just as in secondary explosives, also by the diameter of the charge. The fact that LA detonates practically immediately without a predetonation zone does not mean that it always detonates with the same detonation velocity irrespective of the charge size, as can be seen from Fig. 2.11. In these experiments, the LA was measured in layers of varying thickness [14].
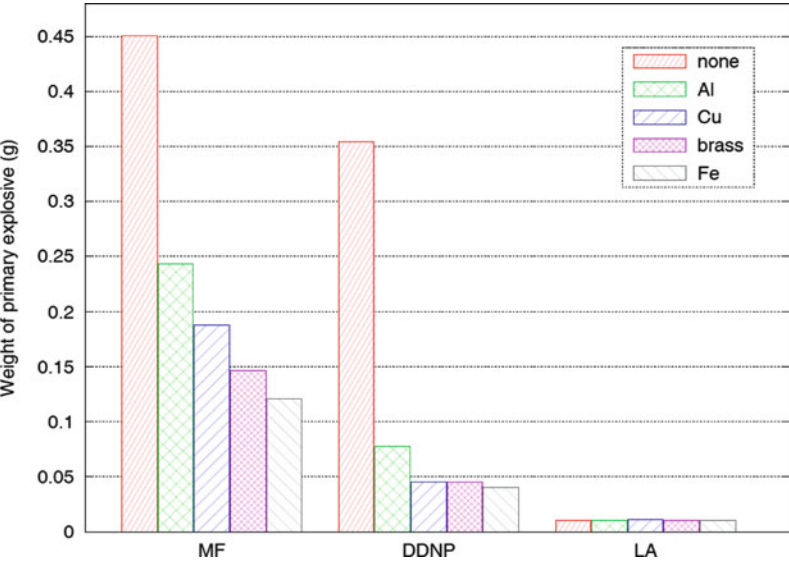
2.2.4 Influence of Confinement

The initiating efficiency represented by the minimal initiating charge is further influenced by the overall design of the detonator, especially by the material of the detonator cap and the material of the reinforcing cap. This influence is more significant in the case of primary explosives with a long predetonation zone (DDNP, MF) but has only limited significance in the case of immediately detonating substances (LA). In the cases where it plays a role (DDNP, MF), a larger amount of primary explosive is required with aluminum detonator caps than is required when copper is used.

The influence of the material of the reinforcing cap is shown in Fig. 2.12. The initiation efficiency is in this case represented as a minimum amount of primary

Fig. 2.11 Detonation velocity as a function of thickness of lead azide sheet (mean density 3.14 g cm^{-3}) [14]

Fig. 2.12 Influence of reinforcing cap material on the minimal amount of primary explosive necessary to detonate PETN with 50% probability [24]

explosive necessary for 50% initiation [24]. It can be seen that tougher confinement significantly decreases the weight of the primary explosive required in the case of MF, to a lesser extent in the case of DDNP, and has practically no effect on LA. This is

Fig. 2.13 Initiating efficiency of various primary explosives (*lines* are included just to help understanding the chart) [17]
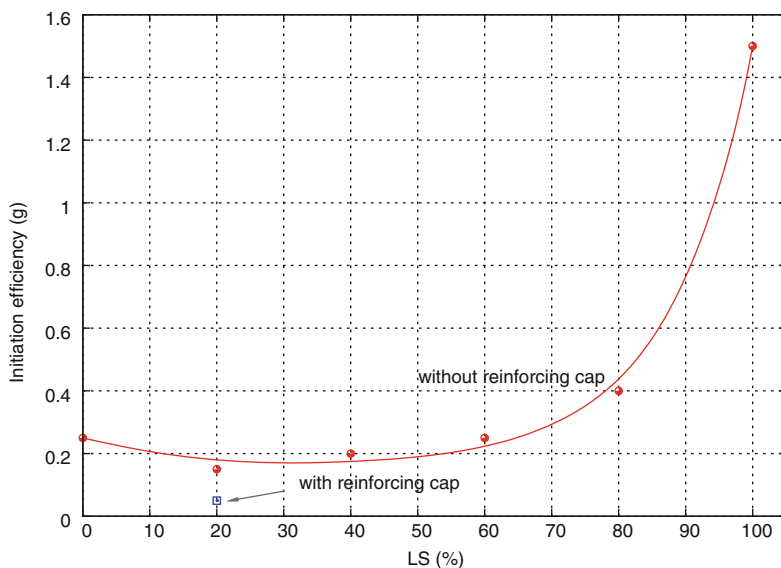
caused by the fact that LA detonates practically instantaneously after ignition while both MF and DDNP detonate via DDT process. A careful optimization of the detonator design with respect to the thickness of the reinforcing cap and the size of the hole can further decrease the minimal necessary amount of some types of primary explosives.

2.2.5   Influence of Secondary Charge Type

For initiation of various secondary explosives different minimum amounts of the same primary explosive are needed. Using a secondary explosive less sensitive to detonation results in the need for an increased amount of the same primary explosive. An amount that works well for tetryl (relatively sensitive substance) is completely insufficient for initiation of TNT (relatively insensitive substance). It is interesting to note that MF, with its long predetonation zone, does not show a steep increase in the necessary minimum amount when going from sensitive to insensitive secondary acceptors (Fig. 2.13). The order of various primary explosives with respect to their initiating efficiency varies with varying type of secondary explosive considered, as can be seen from Fig. 2.13. Substances such as those in Fig. 2.13 are not used in detonators today. They were replaced by PETN, RDX, and for applications requiring high thermal stability by HNS.

Fig. 2.14 Influence of amount of LS in LS/LA mixture on the initiating charge (values are for detonators with tetryl as secondary charge) [25]

2.2.6 Mixtures

The initiating efficiency of mixtures of primary explosives does not necessarily have to be between the values typical of its components. The classical mixture of LA and LS in which LS serves as a substance sensitive to flame is a typical example. Initiating efficiency of an LS and LA mixture is highly dependent on the ratio of the two substances and the highest values are obtained for mixtures with ratios around LS/LA 20/80 (Fig. 2.14). It is interesting to note that the initiation efficiency of the mixture is higher than that of pure LA up to a 60/40 ratio [25].

2.3 Sensitivity

The usefulness of energetic materials is in their ability to explode when desired. The energy of the stimulus that starts the explosion may range from a simple touch of a feather (nitrogen triiodide) to the impact of a shock wave (in NONEL detonators). Sensitivity of an energetic material can therefore be seen as an amount of energy that the material needs to absorb to attain a certain probability of developing an explosive reaction.

A distinction is sometimes made between the term *sensitiveness* and the term *sensitivity*. The first is related to accidental initiation and the determination of probabilities of initiation by various unwanted stimuli, while the second is related

to the reliability of the function. With this approach, impact and friction tests are sensitiveness tests while the gap test is a sensitivity test [26]. In many sources, these two concepts are, however, both referred to using the term sensitivity, and for the sake of simplicity we decided to use this majority approach.

From the perspective of sensitivity, the most sensitive energetic materials are primary explosives, less sensitive are secondary explosives, and very insensitive are tertiary explosives. Rigorous limits between these groups do not exist and new explosives are therefore related to the existing ones through a series of comparative experiments. Some authors define primary explosives as substances being more sensitive than PETN.

The problem of sensitivity is further complicated by the fact that it is influenced by many factors. The most important are the type of initiation, the experimental conditions, the state of the sample tested (crystallography, shape, size), and the method of evaluating the results.

The presence of other materials in primary explosives (additives) also influences the resulting sensitivity values. In some cases, hard particles (e.g., glass dust) are added to increase the sensitivity of a primary explosive which would otherwise be too insensitive for the desired method of initiation. A typical example is addition of glass dust to the LA which increases the sensitivity of the mixture to a level desired for application in stab and friction detonators. The opposite effect is observed after addition of waxes or oils which lubricate the resulting mixture. This desensitizing effect is often utilized when it would be too risky to transport the substance in its pure form.

The tests used for determinating sensitivity of explosives have developed from the historical ones to those that we use today. The progress in development was, however, mainly on a national level and many different tests measuring generally the same thing evolved. The results as absolute values are therefore highly dependent on the country, or even the laboratory, carrying out the tests. Some testing methodologies became standardized (STANAG, MIL-STD, GOST, ADR, BAM) and provide to a certain degree the possibility of comparing results—absolute values—of various researchers. However, the most reliable are still relative results which compare newly referred substances to some well-defined standard. This problem with reported values is not just typical of primary explosives but relates to sensitivity testing of energetic materials in general.

One of the additional complications when trying to compare sensitivity data from various sources is the unspecified methodology of the test. Not only the testing instruments differ but in many cases it is not clear what method was used for the acquisition and evaluation of the results. The most typical ones include 50% or 100% probability of initiation, minimal initiation energy as one positive out of 6 or 10 trials at the same level, at our institute the recently implemented probit analysis [27], etc. Detailed specification of the variety of test methodologies is outside the scope of this work and may be found in the literature [28, 29].

From an application perspective those materials that are easily initiated by relatively small amounts of energy from a nonexplosive event (impact, spark, stab, friction, flame, etc.) are used as the first members of an initiating sequence.
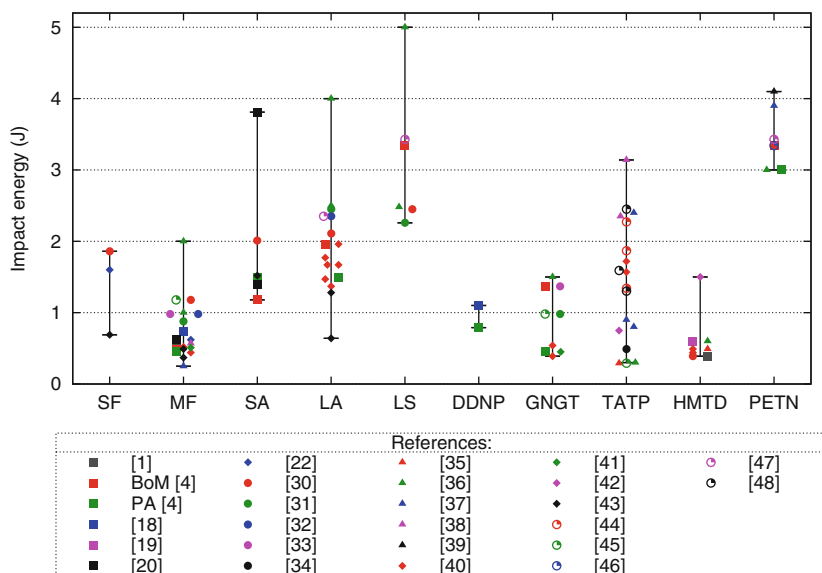
The outcome of their reaction–flame or shock wave–then initiates less sensitive substances which require more energy and are not as easily initiated by nonexplosive stimuli. This leads to an initiation series in which the most sensitive substances initiate the less sensitive ones which then initiate even less sensitive ones, etc. This sequence is called the initiation train or, more specifically, the detonation or ignition train, depending on the desired output. The reason for a sequence of initiation is purely practical. The sensitive substances such as primary explosives are very vulnerable to accidental initiation and do not have the desired performance properties. They are therefore used only in small quantities enclosed in some type of initiating device that prevents as much as possible an unwanted initiation. They may further be stored and transported apart from the main secondary explosives to ensure that an accidental explosion would not initiate the main charges. The secondary explosives, on the other hand, are designed to fulfill specific performance parameters and are used in much larger quantities than primary explosives. Their sensitivity is much lower and they need to be initiated by primary explosives. The even less sensitive tertiary explosives must be initiated by a charge of secondary explosive (so-called booster) that amplifies the output effect of the detonator.

Let us look at a typical example of an explosion train, for example, in a surface mining blasting application. How does it work practically? A hole is first drilled into a rock; some booster with a detonator is inserted and filled with some explosive of low sensitivity—for example, an emulsion explosive. Let us further assume that the detonator is electric. What happens when the electric impulse is discharged into the wires leading to the detonator? First the bridgewire heats up and ignites the pyrotechnic mixture of the fusehead. Flame from the fusehead ignites the delay composition if it is present, flame from the delay composition ignites the primary explosive which undergoes deflagration to detonation transition, and the outgoing detonation wave initiates the adjacent secondary explosive inside the detonator which amplifies the shock wave. As the detonator is placed inside the booster (charge made from secondary explosive) the shock wave, in combination with the kinetic energy of the fragments of the metal cap, initiates it. The detonating booster initiates the detonation reaction of the main explosive (the above-mentioned emulsion).

2.3.1   Impact Sensitivity

Impact sensitivity is probably the most common sensitivity test and, just like other tests of explosive properties, it gives very different results depending on the methodology used and the testing apparatus. Figure 2.15 shows data obtained by various authors for the same substances. Although the idea behind this test is very simple—hitting an explosive by a falling object—ball or hammer—the results obtained show considerable scatter. It can be clearly seen that the values of impact energy cannot easily be compared without exact specification of the test conditions.

An excellent summary of a large number of impact and friction tests of LA and to a lesser extent of some other common explosives has been published by Avrami
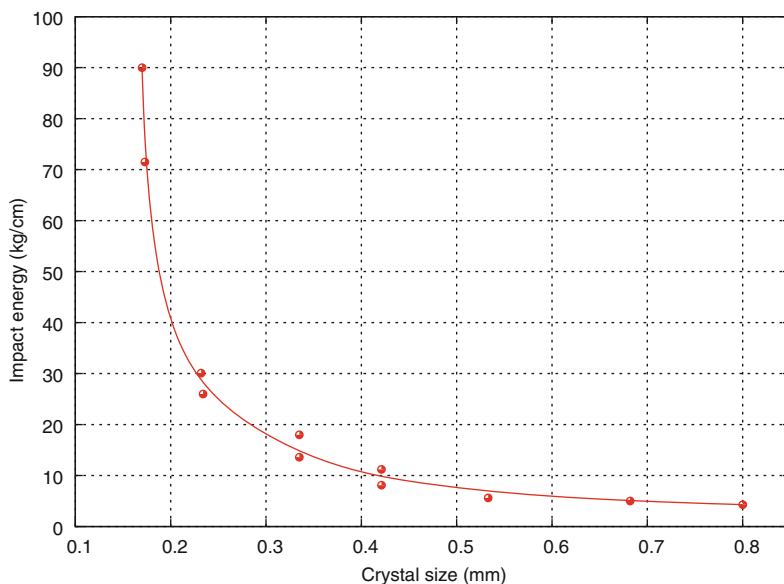
Fig. 2.15 Impact sensitivity of individual primary explosives [1, 4, 18–20, 22, 32–50] (*BoM* Bureau of mines, *PA* Picatinny Arsenal)

and Hutchinson [49]. The importance of methodology, additives, impurities, methods of evaluation, temperature, and many other issues is discussed in great detail especially for lead and copper azides, and will not be repeated here.

Despite the above-mentioned problems, most common primary explosives have been compared and the order of their impact sensitivity has been evaluated by various authors. The sensitivity of LA and SA is lower than that of MF and comparable to that of PETN. The sensitivity of DDNP is mentioned as lower than for MF [4, 18, 50]. 1-Amino-1-(tetrazol-5-yldiazenyl)guanidin (GNGT, tetrazene) is sometimes reported as slightly more sensitive than MF [41] but slightly less sensitive than MF by [33]. SF, often mentioned as a very sensitive substance, has an impact sensitivity comparable to that of LA. Its high sensitivity to friction is sometimes misleadingly attributed to impact. TATP is often reported as extremely sensitive but, as indicated by the figures in Fig. 2.15, the results are relatively evenly spread from about 0.2 to over 3 J. Of the usual primary explosives, LS shows the lowest sensitivity to impact.

Impact sensitivity significantly depends on many aspects. Let us look at some of these properties starting with crystal size of the material under test. Colloidal silver azide prepared from concentrated solutions exhibits significantly lower sensitivity (0.5 kg from 77.7 cm) than coarser crystals prepared from diluted solutions, which required less than half the energy (0.5 kg from 28.5 cm). MF measured under the same conditions for comparison required 12.7 cm with the 0.5 kg hammer [20]. It is interesting to note that the impact sensitivity of SA (in fine powdery form), which is considered very sensitive, is lower than that of MF. Similar investigations have

Fig. 2.16 Influence of crystal size on the impact sensitivity of lead azide (50% probability) [51]

been carried out with lead azide and the results are shown in Fig. 2.16 [51]. It can be clearly seen that the fine particles are again much less sensitive.

Impact sensitivity is most often reported as 50% probability which gives a good comparative value but it does not say anything about the steepness of the dependency. An example of results covering the whole range from 10 to 100% probability of initiation for cuprous azide is shown in Fig. 2.17. Results of this type are not very common because it is a very time-consuming process to obtain them. Each point in Fig. 2.17 represents probability calculated out of 15 trials, at various heights, totaling 300 shots. It can be clearly seen that the finer particles are less sensitive and that the drop height more than doubles when going from 10 to 100% probability. In this particular case, the probability curves exhibit roughly the same slope, and the order of sensitivity is the same for all percentages. It will be shown later, in the part on friction sensitivity, that the probability curves may even cross each other. One substance may then appear more sensitive when looking at 10% probability of initiation and less sensitive when evaluating 50% probability. It is therefore desirable to obtain the entire sensitivity curve. Methods such as the probit analysis significantly reduce the number of trials necessary. The steepness of the probability curves depends on the particular explosive [52].

A good comparison of impact sensitivity for various explosives is presented in Fig. 2.18. It shows probability of initiation at specific drop heights expressed as a number of positive trials out of 5.

Impact sensitivity is further influenced to a very large extent by the thickness of the layer of explosive tested. The sensitivity of the azides of silver, lead, and mercury increases with the layer thickness, that of cadmium is almost constant,
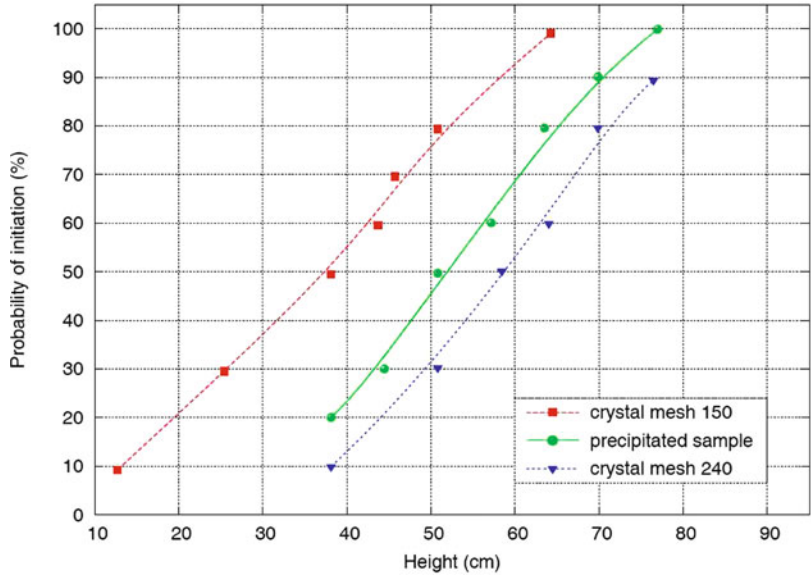
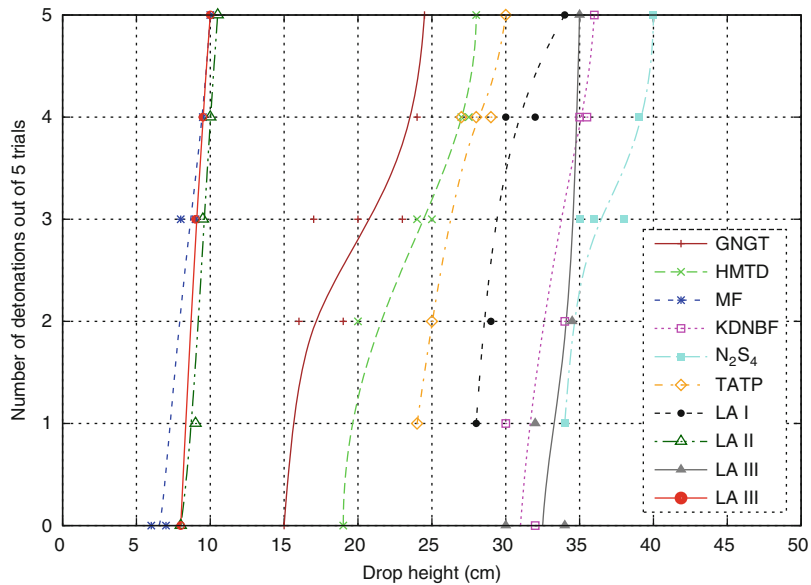**Fig. 2.17** Impact sensitivity of cuprous azide [52]

Fig. 2.18 Impact sensitivity of various primary explosives determined as number of positive trials out of five at specific drop heights (KDNBF-potassium salt of 4,6-dinitrobenzofuroxan, for other abbreviations see previous text) [40]

those of copper, manganese, zinc, and thallium decreased in sensitivity with increasing thickness, and those of nickel, cobalt, calcium, barium, and strontium increased to a maximum value with 0.02 g and then the sensitivity decreased [53].

Increasing the temperature significantly increases the impact sensitivity of LS. It is therefore crucial to carefully control temperature and time of drying during manufacture to prevent an unnecessary increase in manipulation risk.
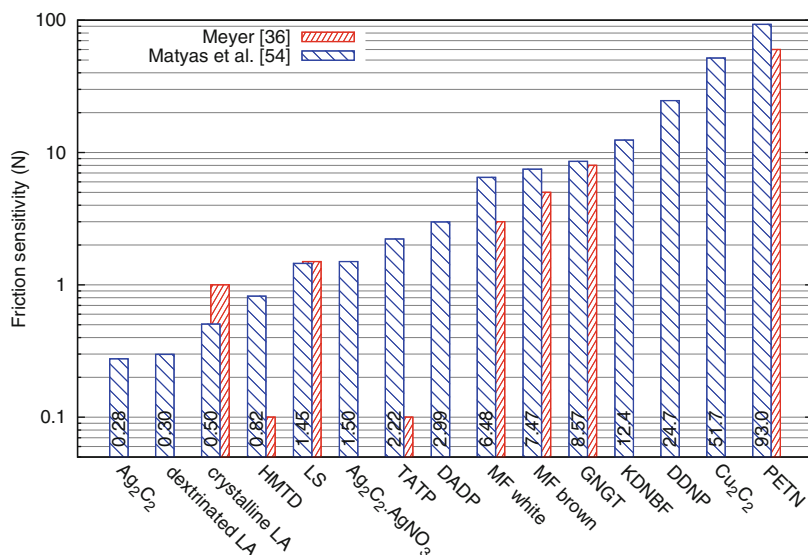
2.3.2 Friction Sensitivity

Despite decades of friction testing, the phenomenon is still relatively poorly understood. The quantitative interpretation of the results is problematic due to numerous factors affecting the mechanism of "friction initiation." In practice, the test is done by placing the tested explosive between two inert surfaces, applying a defined load on the sample and then sliding one or both of the surfaces in a direction normal to the direction of the applied force. Ceramic plates are often the material of choice.

Only a small number of investigations comparing friction sensitivity of primary explosives have been published to date. The most common approach is to synthesize a new compound and compare it to one or two standards, commonly LA, MF, PETN or, more recently, also LS. Comparison of sensitivity of various substances is therefore difficult and mostly based on results gathered from various sources. One of the oldest comparative works was done by Wallbaum [31] who found the following order of decreasing sensitivity of primary explosives: SA > LA > LS > GNGT ~ MF. This is practically identical with the order reported by Meyer [36] for at least one initiation out of 6 trials. The order is consistent with our data of 50% probability of initiation (from probit analysis) [54] which is shown in Fig. 2.19. Sensitivity of organic peroxides (TATP and HMTD) is, however, reported to be very high by Meyer. Measurements of Matyáš [37] indicate that TATP and HMTD are slightly more sensitive to friction than MF. According to our recent results both peroxides, as well as DADP, are less friction sensitive than LA. The results shown in Fig. 2.19 were obtained at our institute under the same conditions and by the same operator.

Some primary explosives are reported to have extreme sensitivity. SF and SA are two such substances. Extreme sensitivity of SF is reported in [33], very high sensitivity (approximately 2–3 times higher than that of LA depending on the testing surface) is reported for SA [55]. Such statements must be carefully considered and evaluation based on solid data. Extreme sensitivity of SA is, for example, commonly found in older sources and could be the result of the method of preparation. In the early days, SA was prepared by direct precipitation of aqueous solutions of sodium azide and the silver salt and such a method of preparation could have led to a more sensitive product. Today's industrial SA (product of BAE Systems) is reported to have sensitivity lower than that of LA (determined by emery friction test) [56].

Comparing friction sensitivity of LA and MF based on published results can be quite complicated. Some authors report LA to be more sensitive [23, 33, 36] than MF while others refer to it being less sensitive [45, 57]. The reason for such
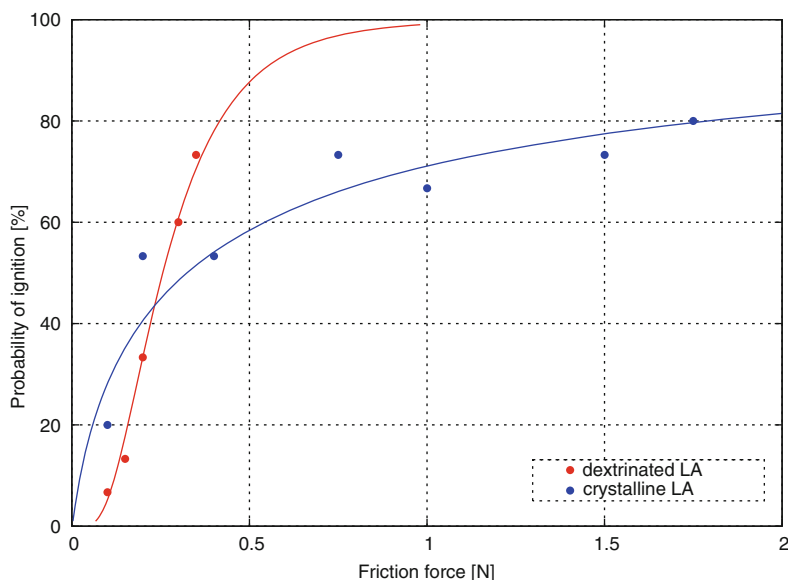
Fig. 2.19 Friction sensitivity of primary explosives—comparison of our data (50% probability of initiation from probit analysis) [54] and data from Meyer (min. one positive out of six trials) [36]

different results could be caused by many factors, e.g., different forms of LA. We have measured dextrinated and crystalline α-LA and both white and brown MF under the same conditions and found MF to be much less sensitive than LA, as can be seen from Fig. 2.19.

A large batch-to-batch variation in surface roughness of porcelain plates used in a BAM testing machine is a well-known problem. The relationship of the plate surface roughness and the resulting friction sensitivity has been studied by Roux [55]. He recommends using sandpaper with a well-defined roughness to obtain better reproducibility and lower the measurement cost. The obtained order of sensitivity of classical primary explosives is the same as the one obtained under standard conditions which are mentioned above. Temperature has also been reported to play an important role in the case of LS whereas in the case of LA, SA, and GNGT it did not [31].

Sensitivity to friction is highly dependent on the method of measurement. The most important factors influencing the final results include the material of the plate surface and the peg, speed of the peg sliding, and humidity. These factors are very difficult if not impossible to compare making results of various authors hardly ever directly comparable.

Figure 2.20 demonstrates another issue regarding sensitivity of primary explosives. Each point on the graph represents the probability of initiation from 15 trials at particular friction force. The curves were obtained by probit analysis [27] for two samples—pure crystalline LA and dextrinated LA. The *x*-axis shows the used friction force and the *y*-axis the probability of initiation. Interestingly, the
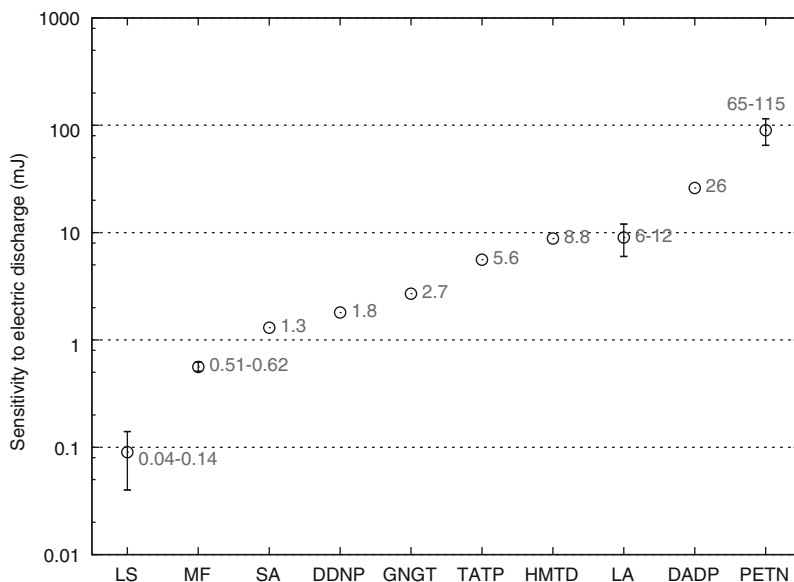
Fig. 2.20 Friction sensitivity of dextrinated and crystalline α-LA [58]

sensitivity curves for crystalline LA cross with those for dextrinated LA showing it to be more sensitive at higher friction forces and less sensitive at lower ones [58].

2.3.3   Sensitivity to Electrostatic Discharge

With sensitivity to electrostatic discharge the situation is even more complicated than in the case of impact and friction sensitivities. The main problem is the variety of testing instruments and testing modes of the discharge circuit (oscillating vs. damped mode) [59]. Due to this variability, it is practically impossible to compare values obtained by different authors. It should always be seen in relation to other substances measured under the exact same conditions. We have therefore included results of measurements of electrostatic discharge sensitivity of some primary explosives measured at our institute, where we can be sure that they have been obtained under the same conditions, and summarized them in Fig. 2.21 (Majzlik J and Strnad J, unpublished work). We are aware of the fact that some published results (e.g., [60]) may be as much as an order of magnitude different from ours due to the variation in methodologies but the order of the individual substances should remain the same. The complete methodology with the description of the measuring device and conditions may be found in [59, 61, 62].

The electrostatic discharge sensitivity of LS is significantly higher than such sensitivity in other primary explosives. This creates problems for the technology used in its production and processing.
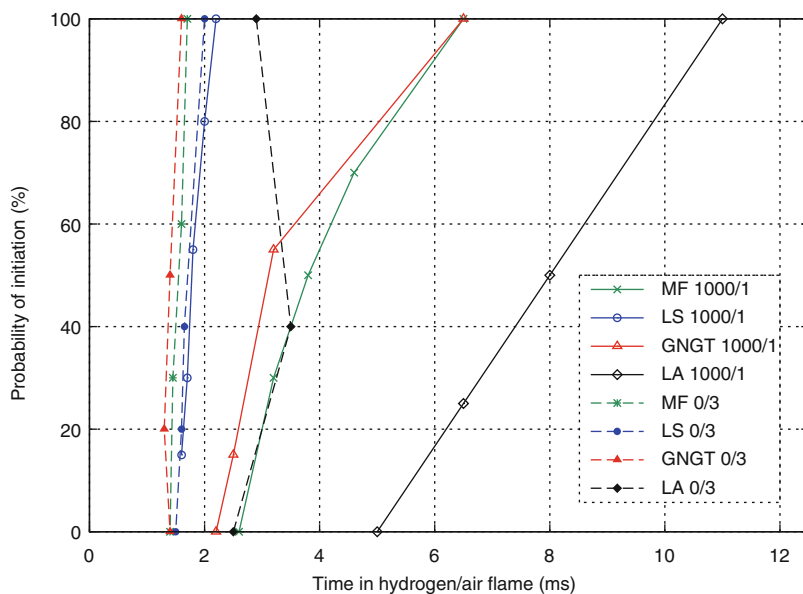
Fig. 2.21 Electrostatic sensitivity of some primary explosives (Majzlik J and Strnad J, unpublished work)

2.3.4 Sensitivity to Flame

Primary explosives differ in the way they respond when subjected to flame and, based on this type of response, may be divided into two groups. The explosives in the first group burn when initiated by flame and may, but do not have to, undergo transition to detonation. The detonation then propagates further with stable detonation velocity if such transition occurs. The typical substances in this group are MF, HMTD, TATP, and DDNP. This group is sometimes called a "mercury fulminate group."

The second group, the so-called lead azide group, does not exhibit a predetonation zone under normal conditions. Initiation by flame results in practically instantaneous detonation. The typical members of this group include, besides lead azide, also silver fulminate and silver azide. Explosives of both groups—MF group as well as LA group—detonate when initiated by shock wave [24].

The sensitivity of primary explosives to flame varies based on their chemical composition and manufacturing process. The pressure by which the material is prepared again plays an important role. Of the classical primary explosives, the most sensitive are LS and GNGT and the least sensitive is LA. The data comparing flame sensitivity of primary explosives are relatively rare. The most compact comparison of flame sensitivity of primary explosives is given by Bagal who used a specially designed pendulum for investigating their ignition behavior (Fig. 2.22) [21]. This pendulum test is, however, not widely used and sensitivity to flame is more often determined by the "ease of ignition" (Bickford fuse) test

Fig. 2.22 Sensitivity of primary explosives to flame [21]—the first number refers to the compacting pressure (MPa) and the second to the orifice diameter (mm)

where observations are made of the ease of ignition and type of response after the action of a flame from a safety fuse. Such results, although they are easier to achieve, do not provide a quantitative measure of the sensitivity.

It can be clearly seen from Fig. 2.22 that the sensitivity of LA to flame is lower compared to other primary explosives. This is the reason why it is in some applications mixed with other primary explosives with high flame sensitivity, such as LS.

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