Polysulfide sparklers revisited: a practical introduction to Carbo Hanabi

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Abstract: *Polysulfide sparklers in the form of Senko Hanabi have been enjoyed for centuries. Research has shown that potassium nitrate can be replaced with non-oxidizing salts providing equally performing compositions that are non-explosive. This article aims to translate this research into practice and presents a detailed construction method for Carbo Hanabi: polysulfide sparklers made with potassium (hydrogen) carbonate. Additionally, it describes the inclusion of magnesium and magnalium in the composition to complement the delicate display of golden sparks with an impressive and bright finale.*

Introduction

Since the Edo period, people in Japan have enjoyed a particularly refined and hypnotic hand-held sparkler. The beautiful display of Senko Hanabi relies on the reaction of a hot polysulfide melt with oxygen from the surrounding air (Figure 1). These fire drops are a micro-laboratory for the pyrotechnist and, by making small changes in the composition and method of construction, the influence of many variables on this unique reaction process can be explored. The manufacture requires only a

Figure 1: A mixed charcoal/soot Carbo Hanabi sparkler ejecting numerous large sparks.

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limited investment in materials and the display-time/construction-time ratio is particularly high compared to most other pyrotechnic devices. These characteristics make polysulfide sparklers an accessible, challenging and rewarding part of pyrotechnics.

In Senko Hanabi, the polysulfide melt is obtained by burning a sulfur-rich Black Powder composition. For an in-depth discussion of the underlying reaction mechanisms and construction of these traditional sparklers, please refer to articles already published [1,2] and an excellent video report by Cusick [3]. In a dedicated article [4], Sturman summarizes the research that led to the discovery that an effective melt can be produced using various non-oxidizing salts to replace potassium nitrate [5]. This finding has important safety implications, as such compositions are no longer explosive. It also means that these devices are not covered by firework legislation and can be freely produced, transported and enjoyed anywhere.

This article aims to be a practical introduction to these still unfamiliar oxidant-free sparklers. Here, the choice was made to work with potassium carbonate - hence the proposed name Carbo Hanabi- because this salt forms a melt that reacts even more impressively than that produced with the traditionally-used potassium nitrate. As is the case for Senko Hanabi, the construction technique is at least as important as the composition used. Compositions containing potassium carbonate have been found to work in sparklers constructed according to the traditional twisted Japanese design. However, because the melt of Carbo Hanabi is created in a different manner than that of Senko Hanabi, one can further optimize the design of the sparkler to suit this new composition. The construction method for a reliable and well-performing sparkler is presented in this article.

Figure 2: A magnesium satori-flash producing a medusa of otherwordly sparks

Materials

Potassium carbonate

The main ingredient is a white, deliquescent powder that has been used for centuries in the manufacture of soap, glass and food. Its hygroscopicity must be considered from the time the composition is made up to the time the sparkler is fired. For correct weighing, especially for research purposes, commercial potassium carbonate can be standardized by dehydrating it in an oven at 250 °C for 2 hours. Once dry, it should be stored tightly sealed, preferably together with some calcium oxide (CaO) which has a lower critical relative humidity and can therefore keep the potassium carbonate dry.

Potassium carbonate is a base and as such irritates the eyes, skin and respiratory tract. Appropriate protection in the form of goggles, gloves and a dust mask is recommended during processing.

Potassium hydrogen carbonate

Only recently, Cusick showed that effective Carbo Hanabi sparklers can be manufactured with this salt as well [6]. Potassium hydrogen carbonate, also called potassium bicarbonate, has numerous applications. Most notable from a pyrotechnic point of view is its application as a fire-suppression agent. Like potassium carbonate it is hygroscopic but has the advantage of not being deliquescent. In addition, it is also non-irritating and even food-safe.

In the ratio proposed by Cusick ($KHCO_3$/sulfur/charcoal 4/2/1), this salt seems to change some properties of the polysulfide melt compared to potassium carbonate. As theoretically expected, one needs to heat the composition a bit longer to compensate for the endothermic release of water and CO_2 to yield potassium carbonate. Interestingly, the droplet then shoots off sparks that reach much further than one would expect from a mere charcoal mixture. These large sparks also have a more 'falling' character to them. Possibly this is caused by a change in viscosity due to the introduction of water into the melt.

The lower hygroscopicity and harmlessness of potassium hydrogen carbonate are important advantages over the carbonate salt. Exploratory experiments did, however, identify some challenges that require further investigation.

Indeed, although not deliquescent, the undried salt is prone to clumping and caking. This is also the case during the processing of the composition in a ball mill, even if the slurry method as discussed further below is used. Drying the salt can possibly provide relief here, although this is again complicated by the decomposition into potassium carbonate that already occurs below 100 °C. This makes standardization more difficult, although this mixture seems to have a very wide margin of effectiveness. Another property that needs attention is that the metal present reacts faster, as was already observed when adding sodium hydrogen carbonate to regular Senko Hanabi mixtures [1].

Sulfur

Readily available sulfur powder is used, optionally kept over a desiccant.

Charcoal

The charcoal type determines the size, number and appearance of the sparks. Carbonized resinous pine wood performs extremely well. This is easily prepared by heating the wood in a loosely sealed can inside a wood or coal fire until no more wood gas is formed. The finer the charcoal is subsequently ground, the more reactive the resultant composition. This grinding is preferably done with a small ball mill, either with or without the other components. A usable grain size can also be produced with a mortar and pestle, with some diligence. And although charcoal produced above 450 °C typically absorbs less than 5% water [7], it can advantageously be stored over a desiccant so as not to introduce water into the composition.

Soot

Adding soot to polysulfide sparklers makes for larger sparks that are shot out over longer distances. On the other hand, it makes the composition less reactive. As with the charcoal used, it appears that the origin of the soot is critical. Traditionally, soot is used derived from the combustion of resinous pinewood. An effective and practical alternative can be obtained by burning turpentine outdoors under an inverted metal pot [1,8]. Soot is a confirmed carcinogen and although the degree of exposure during sparkler making is negligible, it is best to wear respiratory protection and gloves during the processing of the soot itself.

Paper

Again, good choice of paper is important for the proper functioning of the sparkler. After all, the paper is not only a construction material, but is also consumed by the fire drop and as such becomes a reagent as well. The paper must be thin, but at the same time strong enough to withstand winding and compressing. Some Japanese papers are suitable, but some readily available cigarette papers are equally useful. ‘Smoking Thinnest (10 g/m²)’ for instance performs excellently and does not require any cutting in advance. The paper can be colored in advance and numerous variations are possible, from rainbow colors like those in traditional Senko Hanabi to completely black. Alcohol or fluorescent markers can be used without noticeable influence on the sparkler's performance. This paper works very well in the size sold in packs (108x44 mm), but the paper is also available in rolls, which offers more freedom for further experimentation.

Magnalium/Magnesium

The addition of these metals causes the 'satori' effect during the 'old age' phase of the sparkler. This addition was recently discovered and adds an impressive and complementary effect to polysulfide sparklers [2]. In nitrate-based Senko Hanabi, the metal can only be added in a pure soot composition (optionally as a separate second or ‘rebirth’ phase [2]), since it would otherwise react immediately in the fierce charcoal burn. In Carbo Hanabi, on the other hand, the metal can even be added to a pure charcoal composition, possibly because in this case the metal is surrounded by a protective melt from the beginning. Unlike in larger pyrotechnic glitter effects, pure magnesium can be used, which produces a vigorous and bright satori effect (Figure 2). Magnesium also produces individual sparks that exhibit an intriguing corkscrew pattern (Figure 3).

Experiments have shown that the reaction of magnalium (an alloy of magnesium and aluminium) is somewhat less violent, which is safer because the sparks have less tendency to project upwards. Also, the effect is more complementary with the other phases. Often the fragmenting sparks look like a miniature multibreak shell (Figure 4). Magnalium 50/50 with a grain size of 200 mesh gives excellent results. If the sparklers are to be stored for some time, it is advisable to passivate the metal powders with linseed oil.

Collodion

Optionally, one can finish the sparklers with a layer of collodion. This is a solution of cellulose nitrate in a mixture of diethyl ether and alcohol. Although only a few milligrams are left after drying, it does introduce a flammable material in the finished product that detracts from its otherwise perfect safety profile.

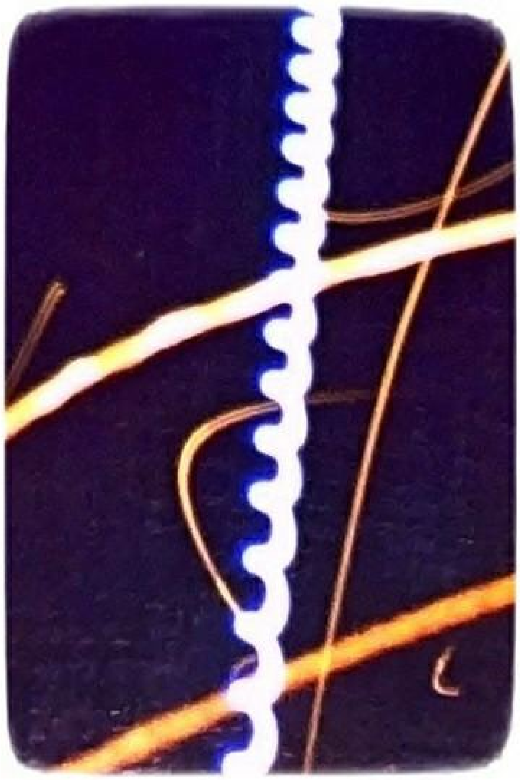

Figure 3: Detail of a ‘corkscrew’-spark

Collodion can be used as a combustible adhesive in the construction of polysulfide sparklers and its application offers some advantages discussed below. An alternative lacquer may be cellulose nitrate dissolved in acetone.

Hexamethylenetetramine

Hexamine has a high energy density and is therefore used in solid fuel tablets. It burns with a hot, smokeless flame and leaves no ash. These properties lend themselves well to its application in Carbo Hanabi, as its incorporation into a sparkler can make the use of a torch lighter unnecessary.

Methods

Following is the illustrated construction method for Carbo Hanabi sparklers, based on a design that guarantees a rich and reliable effect. At the same time, it serves as a starting point for further experiments to obtain an even more effective sparkler. In the latter case, it is important that each step in the process can be performed reproducibly, so that the effect of changing one parameter can be observed. Therefore, in the description below, attention is paid to the standardization of each step of the construction. However, this should not deter the interested novice, because both the composition and the construction method allow for some margin of error. Thus, one will usually end up with a nicely-performing sparkler, albeit not always equally reliable.

An example of this controlled way of working is the 'dry chain' that, due to the hygroscopicity of the salts, is set up from the processing of the reagents to the storage of the finished sparklers. The way used here to reduce the relative humidity is to locally heat the working

Figure 4: A multibreak magnalium satori-flash.

zone. This can be done very efficiently with a 200 W ceramic heat lamp (Figure 5). Optionally, one can additionally work on a large heating mat. Application of both can reduce the relative humidity from 60% to less than 30%, which is more than sufficient, considering the critical relative humidity of potassium carbonate is 40%. In addition, this radiant heat makes the fingers flexible for the construction. However, a dry chain is certainly not essential to produce these sparklers, although without it the duration of exposure of the composition to ambient air should be minimized.

Preparing the composition

For this purpose, the raw materials are ground in the correct weight ratio in a small stainless steel ball mill with Viton O-ring. To prevent caking of the composition during grinding, a slurry is created with hexane (Coleman Fuel). The formula is as follows:

Potassium carbonate (anhydrous): 57
Sulfur: 28
Pine charcoal: 12
Turpentine soot: 3
+45 ml Hexane for every 20 g of composition

In this study, 20 g of composition was processed in a 120 ml ball mill with 60 ml lead balls of 4,5 mm diameter. To vary and experiment, two separate compositions can be prepared. One with pine charcoal and one with turpentine soot. In this case, the simplified ratio of 4/2/1 can be used for each one. Increasing the proportion of soot provides longer and larger sparks but makes the composition less reactive. Nevertheless, in Carbo Hanabi sparklers, using a pure soot composition is possible because one can heat it sufficiently to compensate for the less fierce reaction. This is more difficult with Senko Hanabi, where the sparkler relies on the composition to produce the necessary heat.

When using potassium hydrogen carbonate, Cusick suggests the same ratio of 4/2/1. Clearly, this makes the molecular ratios of potassium and sulfur very different from the above formula. This shows that there is a wide margin for composing the mixture, and a lot of scope for optimizing the proportions.

The mixture can also be processed with mortar and pestle, but in that case both the particle size and homogeneity are more variable. The proposed duration of grinding in a ball mill is at least 1 hour. Longer processing increases the

Figure 5: Supplies for construction: a. ceramic heat lamp 200 W; b. paper on roll (Smoking Thinnest); c. collodion; d. scales with Teflon foil; e. cardboard strip 10x1,5cm; f. magnalium 50/50 200 mesh; g. separate charcoal and soot compositions; h. scalpel

reactivity of the mixture and also affects the size and shape of the sparks.

After grinding, the slurry is poured out and evaporated in a stainless steel oven dish heated on a sealed steam bath. This should be done either outside or under a fume hood. The dry powder is then granulated by shaking it through a 25 mesh sieve with a few lead balls. This step and mesh size ensures that the composition has good flow properties during weighing and makes it easy to compact under slight pressure. A mesh size that is too high (100 mesh) produces a low-density composition that is more difficult to compact. Also, if one chooses to work volumetrically, a homogeneously-granulated powder will provide more reproducible measurements.

The finished composition is stored in a paper bag, which in turn is placed in a hermetically sealed container in which CaO is present as a drying agent. The paper allows diffusion of water vapor so that the composition is kept anhydrous by the desiccant. A portion of the composition is then placed in a small test tube with a stopper, for use during construction.

Figure 6: Measuring the correct length.

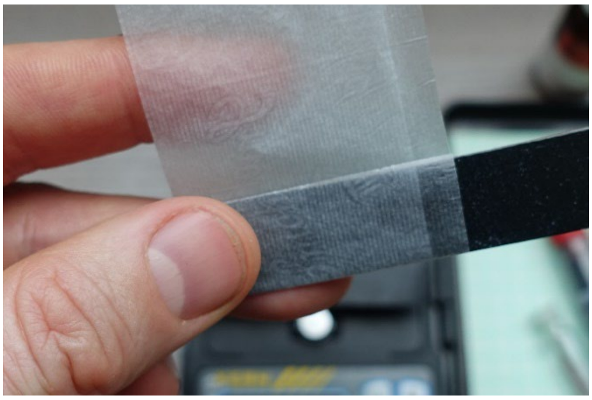

Figure 7: Folding the paper over the correct distance

Construction of the sparkler

Applying the composition on the paper

The paper is rolled out and torn off to size. A 10x1,5 cm cardboard strip is used for this purpose (Figure 6).

The 4,4x10 cm strip of paper is then folded in half lengthwise and folded over 1,5 cm at one end. The cardboard tool is also used for this purpose (Figure 7).

The functioning of the sparkler can be further optimized by cutting the paper at an angle towards the back as in the traditional Senko Hanabi design [3]. One can also choose to fold less of the paper back to reduce the amount of paper. One can experiment with these techniques once one has built up some skill with a larger sheet of paper.

The paper is then unfolded again and placed on the scales. At the intersection of the two folding lines, 125-135 mg of composition is

Figure 8: Applying the composition and metal powder.

Figure 9: Detail showing the granules of the charcoal composition (grey) on top of a soot composition (black). Scattered on the composition lies the metal powder

applied. This can be a single composition, or a combination of charcoal and soot compositions. The powder can be conveniently applied by tapping it from a tube with stopper. If one applies too much, one can easily withdraw some powder with a scalpel.

However, the use of the scales to achieve the maximum effect each time is not essential to create a properly functioning sparkler. Considering the density of the granulated compositions, one can use small measuring scoops (e.g., closed pieces of a drinking straw) to measure out an amount of composition that approximates the above weight.

Subsequently one taps lightly against the paper to spread the powder a little. A very small amount (2 mg) of magnesium or magnalium is now applied on top of it (Figure 8). This has to be done in a scattered manner to avoid all the metal reacting at once. To avoid the metal being burnt up by the gas flame during the heating process, the metal powder should also be surrounded by sufficient composition so that the melt can envelope and protect the metal fragments. If the metal is applied as shown in Figure 9, this will happen automatically during the rolling phase.

Rolling up the sparkler

As with traditional Senko Hanabi, the way the sparkler is rolled up determines its reliability and performance. Several ways are possible, and the reader is invited to further refine the design below. The descriptions assume a right-handed pyrotechnist.

To start, the paper is grasped at the folds between both thumbs and middle fingers as shown in Figure 10.

Then the middle flap (b) and right flap (c) are successively placed on the left flap (a). This leads to the situation of Figure 11.

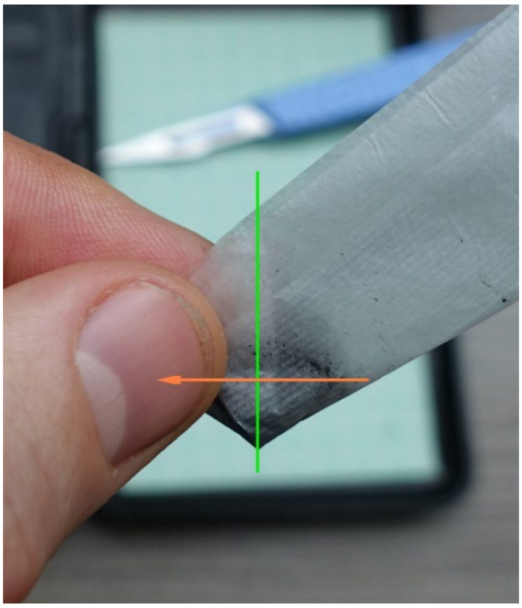

Figure 11: The composition is collected at the bottom and folded over itself

Figure 12: The fingers of the right hand encircle the composition at the start of the winding process.

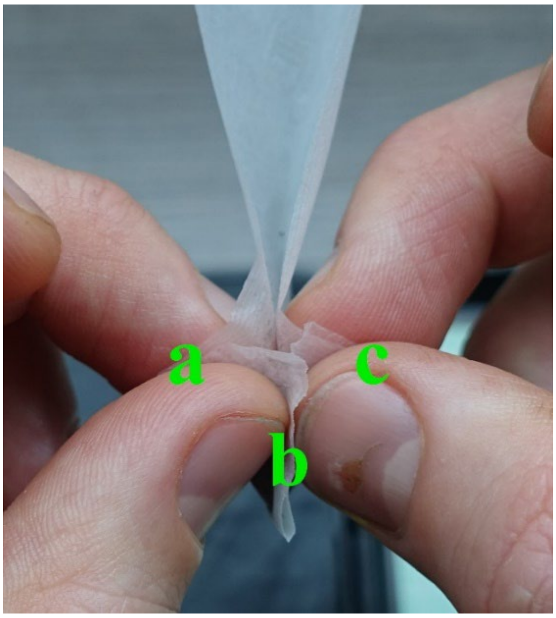

Figure 10: The starting position.

If necessary, one now taps the upright edge of the paper to collect the composition at the bottom. Then one folds the composition onto itself in the direction of the orange arrow over the indicated green fold line as shown in Figure 11. From this position one now grasps the sparkler with the first three fingers of the right hand pinching off the composition and turns the sparkler over so that the rest of the paper is now on the left side (Figure 12).

With the fingers of the right hand on the composition, turn 3-4 half turns, taking care to place the windings on the transition between the composition and the paper. To do this, point the remaining strip of paper at a right angle upwards as in Figure 13. These windings form the neck of the sparkler. This is a crucial area because it will have to carry the ball of molten dross when it is at its largest and heaviest. After these windings, pull the

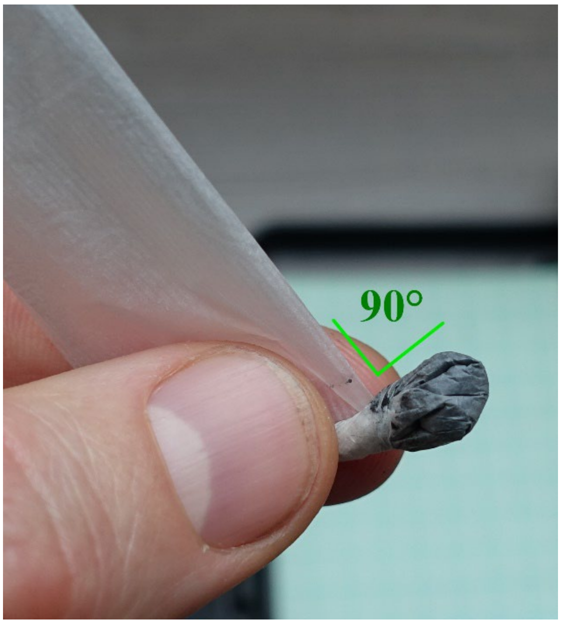

Figure 13: around the neck comes a little more paper

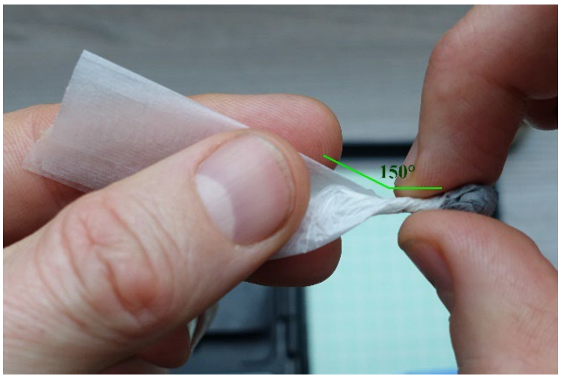

Figure 14: Further rolling up of the sparkler

remaining paper strip more horizontally (to about 150 °) and continue winding the sparkler to the end without applying maximum force right away (Figure 14).

Once at the end, the function of both hands changes and now it is the left hand that tightens and the right hand that holds the paper string. Now we strive for maximum tightening without tearing (Figure 15).

At the level of the neck, one now pays attention to 2 things. The first is to make sure this short, thickened zone of about 3 millimeters is tight enough. This is important to allow the dross ball to achieve its maximum effect. Loose paper causes the ball to consume the paper more quickly and thus to climb up and process paper instead of staying there and producing a hotter and more vigorous reaction. However, if one desires a long ascending sparkler with a longer satori phase, one can deliberately keep the neck looser.

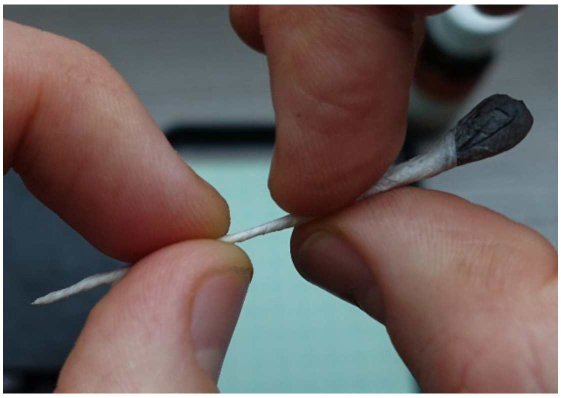

Figure 15: The sparkler is now tightened

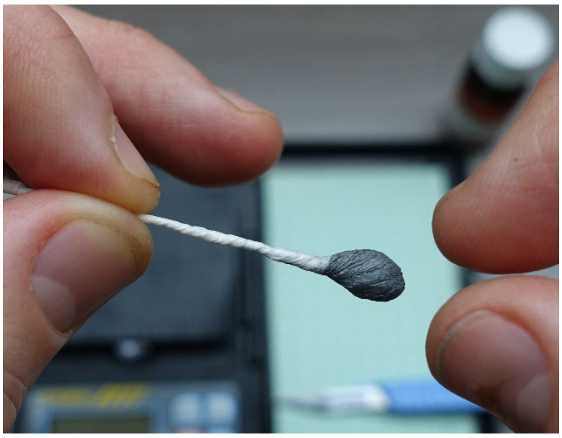

Figure 16: the composition is given a teardrop shape

A second thing to watch out for when tightening the composition is to strive for a teardrop shape rather than a spherical shape (Figure 16). This teardrop shape provides a larger contact surface with the flame and oxygen, and makes it less easy to burn the neck with the gas flame. The best way to compress the composition is with the thumb and forefinger of both hands in a crossed manner.

Finishing the sparkler

At this point, the sparkler is ready for use. Optionally, it can now be coated with cellulose nitrate lacquer by applying collodion with a brush (Figure 17).

This layer, which weighs an average of 6 mg after drying, contracts and provides the sparkler with strength, gloss and protection against moisture. After application, let the sparkler dry in the heated work field until the solvent has evaporated (Figure 18).

Finally, one can finish the sparkler in different ways. With a craft punch and collodion one can easily and quickly add various handles and decorations to the basic shape.

For illustration purposes, the finish to 'Dragon Tear' (Figure 19) is shown here as well as that to 'Fireflower' (Figure 20).

In addition to this teardrop-shaped basic design, other functioning construction methods are possible. For example, one can also roll up the sparkler according to the traditional Senko Hanabi design, after which the part holding the composition is folded back over itself and the end is rolled along in the neck of the sparkler. Thus one obtains a loop

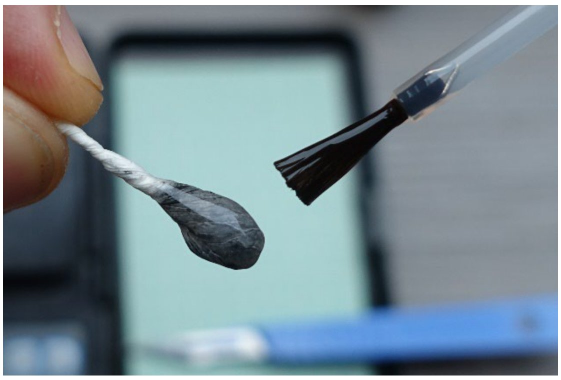

Figure 17: optional lacquer coating of the entire sparkler.

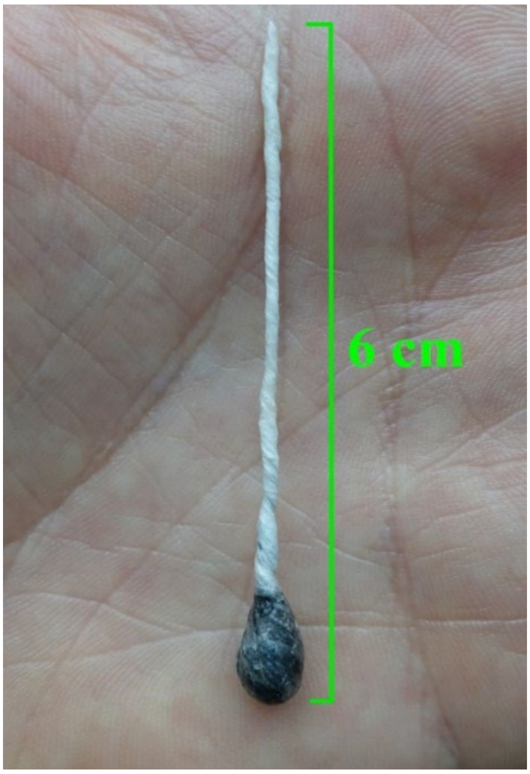

Figure 18: finished sparkler with lacquer coating

Figure 19: finish as 'Dragon Tear'

Figure 20: finish as 'Fireflower'

design that allows a larger contact area with flame and ambient air and also performs beautifully (Figure 21).

One can also incorporate an alternative form of ignition in this loop design. After applying the composition, one splits it into two equal parts and applies 30 mg of hexamine in between. During rolling and folding, one then ensures that this portion is at the end of the loop (Figure 21). The ignition of such a sparkler now can happen remarkably easily through the paper, after which the hexamine produces a hot flame that surrounds the loop. After the hexamine is burnt, both arms of the sparkler are sufficiently heated to fuse together and start the display.

Figure 21: finish according to the loop design. The green ellipse indicates the position of the (optional) hexamine.

Figure 22: The hot hexamine flame envelops the sparkler.

Figure 23: *Finished sparklers can be presented festively and offer amusement and quiet wonder to young and old. The photo shows a crackling magnalium satori-effect of a 'Dragon Tear' sparkler.*

Finished sparklers are best stored in an hermetically sealed container. Because of their safety, small size and beauty, they can be conveniently stored and transported in glass jars.

Instructions for use

Polysulfide sparklers possess a unique beauty due to their delicate sparks. These are best appreciated when the eyes have had some time to adapt to a dark environment. The use of a blue gas flame to ignite the sparkler ensures that the eyes remain sensitive. This is in contrast to Senko Hanabi, where both the luminous ignition source and the bright deflagration can cause the eyes to adjust inappropriately.

To ignite the sparkler, one holds the sparkler with its tear-shaped end downwards and aims the flame of a small torch lighter at it for about 10 to 15 seconds, trying to envelop most of it but being careful not to burn the neck. In the 'Fireflower' design described above, one can gently rotate the sparkler while heating to heat all sides of the composition evenly. This is not essential, however, and sparklers with flat holders such as 'Dragon Tears' also perform well. Through heating, the composition liquefies and begins to boil and glow. When the first sparks are emitted, continue heating for a few seconds and, in windless conditions, gently blow on the molten drop. Now follows a phase of 10 to 15 seconds similar to the "youth phase" of a classic Senko Hanabi sparkler, where a few large sparks (20-40 cm) are fired at short intervals, followed shortly after by a phase lasting about 15 seconds in which the frequency of the sparks increases sharply, forming a sphere of sparks about the size of an orange around the drop.

The appearance of the sparks is bushy and strongly branched. At this point, the first satori flashes may already occur, especially in windy weather (Figure 23). This phase transitions into a phase of around 30 seconds duration in which the sparks no longer branch but are emitted as long luminous streaks. In between, crackling satori flashes occur. This phase provides an impressive finale to the sparkler that nevertheless remains nicely balanced with

Figure 24: The author shoots a Carbo Hanabi droplet with a finger nail.

the subtle splendor of the previous phases. Finally, the shrunken fire drop makes more of a sizzling sound while ejecting very long, barely luminous streaky sparks. Just as the appearance of the sparks changes according to the carbon source used, so does the sound they make. Sparks from briefly ground charcoal sound like 't', from thoroughly ground charcoal more like 'p', and soot sparks sound like 'f'.

Polysulfide sparklers each burn in their own unique way because their effect depends on the conditions in which they are fired. The melt of Carbo Hanabi is stickier than that of Senko Hanabi which makes the fire drop less prone to falling under the influence of gravity or wind. On the contrary, the best performance is obtained in light winds, which make the fire drop burn hotter. The use of a torch lighter guarantees flawless ignition even in these conditions. In calm weather, one can blow on the dross ball to stimulate the reaction. The targeted use of this blowing allows one to optimize the effect and thus create a real interaction between sparkler and user.

These sparklers are very safe to use, although one must always consider the possible falling of the burning drop. Therefore, the sparklers should always be ignited outside above a fireproof surface. Also, one should not hold the sparklers higher than the chest height of the smallest spectator to avoid sparks landing in the face and eyes. This is the reason why, for safety reasons, one should choose magnalium as the satori metal instead of pure magnesium, the sparks of which can be more powerful and projected upwards.

An alternative way to use these sparklers is to flick the dross ball away with a fingernail once it starts ejecting sparks. It goes without saying that this should always be done away from people and flammable materials. The effect is short but impressive, with countless sparking fire drops shooting through the air, like a snapshot of a spur-fire fountain (Figure 24).

The future

This article is intended not only for the novice who wants to be introduced to the art of fireworks in a safe, simple yet challenging way, but equally for the advanced pyrotechnist. After all, there are still many avenues of research that remain open. A first and rewarding step could be to use triangle diagrams [9] to examine the relationship between the different components and thus define an optimal formula for each desired effect. One can do this for charcoal-based, soot-based as well as mixed compositions, using both potassium carbonate and potassium hydrogen carbonate. The latter salt offers relevant advantages over potassium carbonate and deserves further research. Other salts also deserve further study such as sodium (hydrogen) carbonate, potassium thiosulfate, cesium carbonate, rubidium carbonate, antimony sulfide and others. Endless variations in composition and design are possible and the interaction with the environment and user means that no two sparklers are ever the same and the next one may be the most beautiful one has ever seen. The author wishes the reader much success and joy in the construction of these fascinating sparklers and welcomes all feedback.

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