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Pyrotechnic Particle Morphologies — Metal Fuels

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ABSTRACT

The morphology (size, shape and surface features) of the constituent particles in a pyrotechnic composition affects its performance. This is particularly true of metal fuel particles in the composition. Particle morphology can also constitute an important part of forensically establishing a match between materials of known origin and evidence. This article catalogs and briefly discusses some characteristic features commonly associated with metal fuels in pyrotechnic compositions.

Keywords: morphology, forensics, metal fuels, pyrotechnics

Introduction

Morphology is a term borrowed from biology for describing the appearance of organisms. In pyrotechnics and forensics the term is often used to denote information about the size, shape and surface features of particles, where knowledge of these attributes is frequently important. In pyrotechnics, particle morphology influences such things as the ease of ignition and burn rate of a composition.[1] While this is true in general, it is especially true for the fuel particles in those compositions. This is because the oxidizer(s) will usually have melted below the ignition temperature of the composition, whereas the fuel particles usually will not have. (See Table 1 for examples.) Large particle size, rounded shape, and smooth surface features all tend to make ignition more difficult and the burn rate slower. Accordingly, knowledge of a composition's particle morphology is important in any attempt to predict (or control) the ignition and propagation properties of a pyrotechnic composition.

Table 1. Examples of Melting Points (in °C) of Some Common Fuels and Oxidizers.

Fuel	T_m	Oxidizer	T_m
Aluminum	660	Ammonium perchlorate	d ~150
Boron	2300	Barium peroxide	450
Iron	1535	Potassium chlorate	356
Magnesium	649	Potassium nitrate	334
Silicon	1410	Potassium perchlorate	d ~400
Titanium	1660	Sodium nitrate	307

Notes:

T_m is melting point in degrees Celsius (°C); values are taken from references 2 and 3.

d is the decomposition temperature and means the oxidizer decomposes before melting.

An important aspect of forensic science is the recognition and identification of materials, often for the purpose of determining the source of the material. Typically this would be accomplished by attempting to physically and chemically compare items of evidence with materials from known sources. In attempting to determine whether two materials match, various attributes of the two are compared and contrasted. The degree of certainty of the match is a function of the number of attributes compared and the degree to which they are identical.[4] For pyrotechnic compositions, one important part of this matching process should be a comparison of the morphologies of the materials. Probably the best

Table 2. Information for Some Common US Sieve Mesh Sizes.

Mesh Number	Opening (in./1000)	Opening (micron)
10	79	2000
20	33	850
40	16	425
60	9.8	250
100	5.9	150
140	4.1	106
200	2.9	75
325	1.7	45
400	1.5	38

Note that particles smaller than about 400 mesh are typically only described in terms of their physical size, usually in microns.

Table 3. Metals Used in Pyrotechnics.

Commonly Used	Occasionally Used(a)
Aluminum	Chromium
Boron(b)]	Copper
Iron	Manganese
Magnesium	Molybdenum
Silicon(b)	Nickel
Titanium	Selenium
	Tellurium
	Tungsten
	Zinc
	Zirconium

(a) Many of these are only used in military items, some of which are being phased out.

(b) A metalloid, not strictly a metal.

known and most complete work on this subject are the writings of McCrone and Delly.[5] This multi-volume treatise provides extensive overall information. However, of necessity, it tends to include only a few of the most common chemicals, and then only in one form. The emphasis is on identification of the nature of the chemical. This is valuable information but it falls short of what is needed to determine whether a firm match exists between materials.

This article presents general information about particle morphology of metal fuel particles used in pyrotechnics. This is augmented with a series of electron micrographs as illustrations.

Particle Size

As a rule, the size of metal fuel particles in a pyrotechnic composition is less than 100 mesh, and they are often less than 400 mesh (see Table 2 for a list of some common mesh sizes and their openings). Metal particles added to a composition for the purpose of producing spark effects are an exception. This often requires that the particles be large enough so as not to be completely consumed during their passage through the reaction zone and flame of a burning pyrotechnic composition.[6] Such particles may be as large as 10 mesh. Table 3 is a list of metals commonly present in pyrotechnic compositions. Some examples of aluminum particle types and sizes used in pyrotechnics and fireworks are presented in Table 4.

All metal powders used in pyrotechnics have a range of individual particle sizes; for some the range is narrow, for others it is quite broad. (Collectively, the figures in this article are examples of the typical range of particle size for metal powders commonly used in pyrotechnics.) Further, in the authors' experience, both the average particle size and the range of particle size can differ somewhat from lot to lot from the same manufacturer. In terms of consistent performance, this can be frustrating for the pyrotechnists. However, for a forensic analyst this can help determine the degree to which a match exists between two materials. (As a word of caution, it must be recognized that even between different points within a single drum, there can be some differences in average particle size and the range of size, although generally these would be rather subtle differences.)

In general, the most expeditious method for determining particle size of bulk powders is by performing a sieve analysis. In this process, a sample of powder is passed through a series of successively finer sieves (typically in a stack that is mechanically agitated). The fraction (by mass) of material that is retained on each sieve is then reported, along with the amount passing the finest sieve. However, for mixed materials such as a pyrotechnic composition, or when only very small amounts of material are avail-

Table 4. Information about Some of the Aluminum Powders Used in Pyrotechnics.[7]

Description — Common Name (Approximate Size Range)	Commonly Used in	Purpose — Effect Produced
Flake — Coarse Flitters (10–28 mesh / 700–2000 μ)	Fireworks comet stars, waterfalls, and fountains	Long duration white sparks
Flake — Fine Flitters (20–80 mesh / 200–850 μ)	Fireworks comet stars, waterfalls, and fountains	Medium duration white sparks
Flake — Bright (≈325 mesh / ≈35 μ)	Fireworks comet stars & fountains	Short duration white sparks
	Large fireworks salutes	Explosive sound or report
Flake — Dark (≈15 μ)	Medium fireworks salutes	Explosive sound or report
	Military simulators	Explosive sound or report
Flake — German Dark (≈5 μ)	Small fireworks salutes	Explosive sound or report
Atomized — Granular Blown (50–150 mesh / 100–350 μ)	Fireworks comet stars and fountains	Long duration white sparks
	Military thermite	Heat and molten iron
Atomized — Spherical (–400 mesh / ≈30 μ)	Fireworks glitter stars / fountains	Delayed trailing flashes
	Composite rocket propellant	Energy production
Atomized — Spheroidal (≈20 μ)	Fireworks color stars	Flame brightening
	Military photo-flash	Intense light production
Atomized — Spherical (≈10 μ)	Fireworks glitter stars / fountains	Delayed trailing flashes
	Military igniters	Thermal energy
Atomized — Spheroidal (≈5 μ)	Large fireworks Salutes	Explosive sound or report
	Fireworks color stars	Flame brightening

able, a sieve analysis to report such "mesh fractions" is often not possible. In that case a microscopic investigation is a common approach, whereby the physical dimensions of a large number of individual particles are measured and reported. For a light microscope this involves the use of a calibrated reticule in the eyepiece or associated with the slide mounting. For an electron microscope, the instrument provides scale information associated with the images produced. These procedures can be performed manually. However, in many cases, computer assisted image analysis can be used.

Particle Shape

A range of particle shapes are used in pyrotechnic compositions, and like particle size, shape also affects ignition and propagation characteristics.[1] Details of particle shape can also provide the basis for forensic comparison of metal powders. Normally it is the manner of production of the material that is the determining factor for particle shape. Atomization (spraying molten metal through an orifice and allowing it to solidify as it falls to a collection area) produces particles that are spheroids. Often, atomization produces nearly perfect spheres, see Figure 1. However, when the metal is quite reactive and when the atmosphere into which the metal is sprayed is not completely inert, much less perfect spheres are often produced.

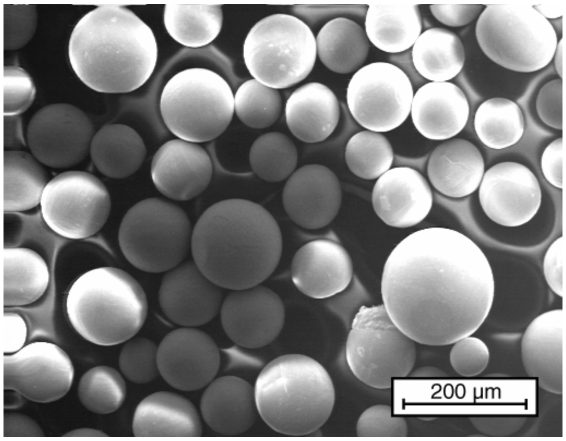

Figure 1. Example of nearly perfect spherical particles of titanium produced by atomization (100 ×).

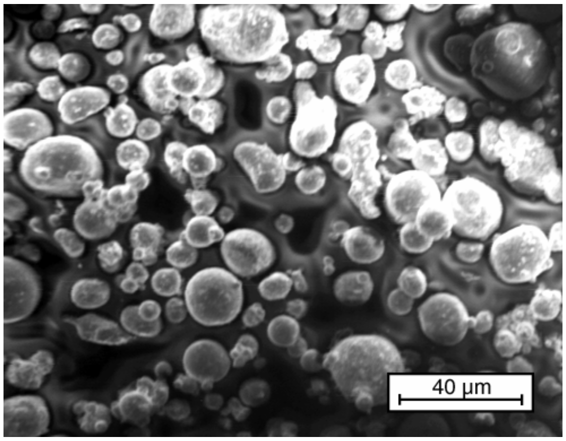

Figure 2. Example of so-called spherical atomized aluminum (500 ×).

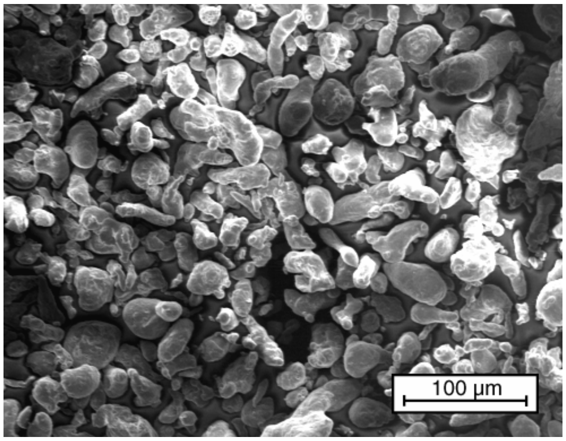

Figure 3. Example of so-called spheroidal atomized aluminum (200 ×).

Aluminum, because of its ability to quickly form a rigid oxide coating, produces a good example of this. Even when using relatively inert atmospheres, the so-called spherical atomized aluminum particles are less than perfect spheres, see Figure 2. Further, when the atmosphere used contains even a modest amount of oxygen, highly distorted spheroids are produced; see Figure 3.

Depending to some extent on the physical properties of the metal, mechanical diminution such as grinding is possible. This produces metal particles that tend to have sharp angular features like the example in Figure 4. While it is somewhat unusual to produce granular aluminum powders, it is common for some aluminum alloys, such as those with iron, titanium and magnesium, to be produced by grinding. Because of their sharp, angular features, particles that have been ground will be more reactive than those of the same size produced by atomization. Also, the sharp, angular features of the ground particles make them fairly easy to differentiate from atomized particles. However, one type of atomized aluminum, so-called "blown" aluminum, has surface features (coarse texturing) that may at first appear somewhat similar to ground particles, see Figure 5. This type of aluminum powder is generally atomized as fairly large particles (20 to 100 mesh / 150 to

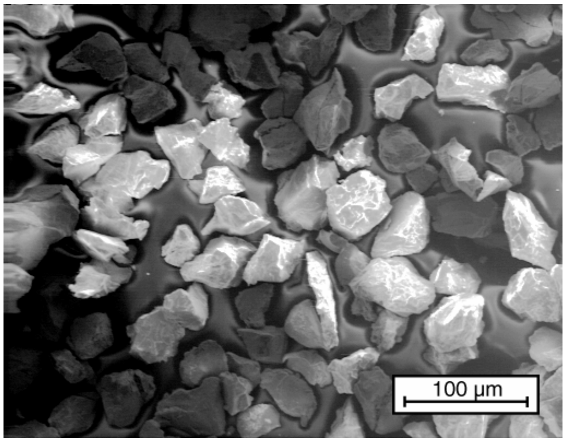

Figure 4. Example of ferro-aluminum alloy particles prepared by grinding (200 ×).

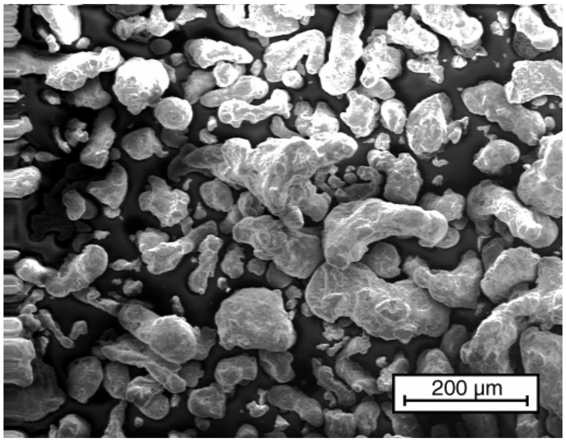

Figure 5. Example of "blown" atomized aluminum particles (100 ×).

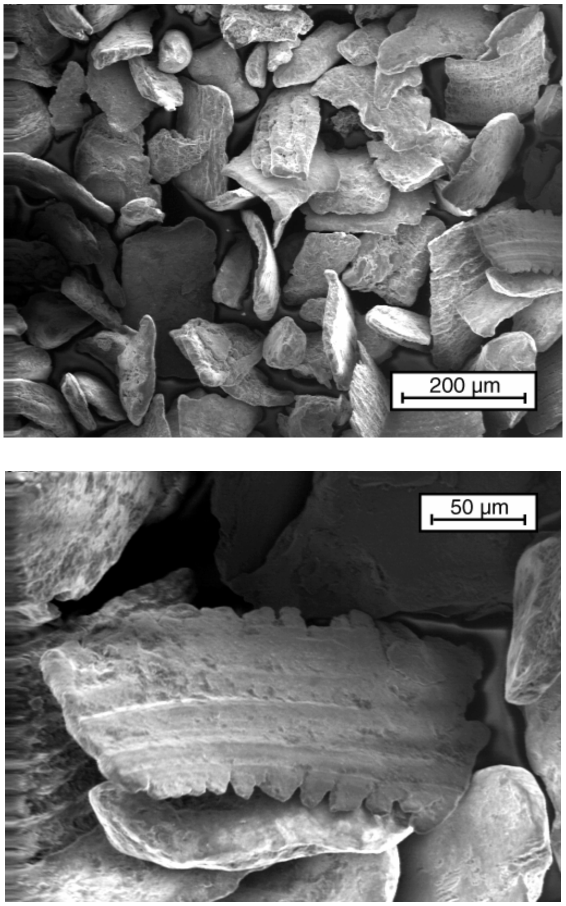

Figure 6. Example of titanium metal turnings at two magnifications (100 and 300 ×).

850 µ) and in an atmosphere that has a relatively large oxygen content. This causes the rapid formation of an aluminum oxide crust, and the resulting particles are far from being spherical. The diagnostic feature differentiating blown atomized aluminum from granular aluminum powders is the nature of their edges and surface features. For blown aluminum these appear rounded and not sharp, as is the case for ground aluminum alloy particles.

Another type of mechanical particle size reduction is by chipping. This may be the primary intent of the operation, or it may be that the material is a byproduct produced when machining metal parts (turning or milling). These particles tend to have two dimensions that are relatively large and a third that is less, either producing large flake-like particles, or long thin strips of material. The large flake-like particles are generally too large for use directly as a pyrotechnic fuel, but may be suitable for producing pyrotechnic spark effects. Chipped material is often further reduced in size by a secondary process such as hammer milling. Figure 6 is an example of titanium metal turnings that have been hammer milled to break the largest particles into smaller ones (hammer milling will not reduce the thin dimension of such particles). That these large flake-like particles were produced from machine turnings, is fairly obvious in the higher magnification micrograph where tool marks are obvious.

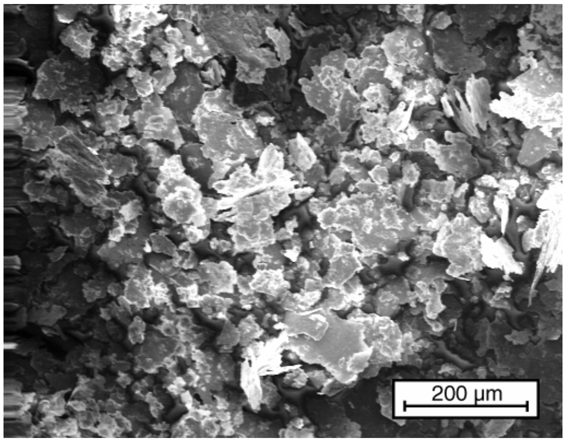

Figure 7. Example of flake aluminum powder (100 ×).

A third type of mechanical particle diminution is the stamping or milling of already tiny particles to produce thin flakes. For malleable metals, this method is quite common, and it is one of the most common methods for the production of aluminum metal powders, especially for those with the greatest surface area to mass ratios. For the same nominal mesh size materials, flakes tend to have the greatest reactivity as compared with the other powder forms. This is because, while one or two flake dimensions may be substantial, the third dimension is generally quite small in comparison. Accordingly flakes can be raised more quickly to their ignition temperature, tending to make pyrotechnic compositions containing them easier to ignite and faster to propagate. Flaked metal powders have a physical appearance that is fairly distinct and identifiable, see Figure 7.

Metal powders can be produced in other, less common ways. For example, flaked mate-

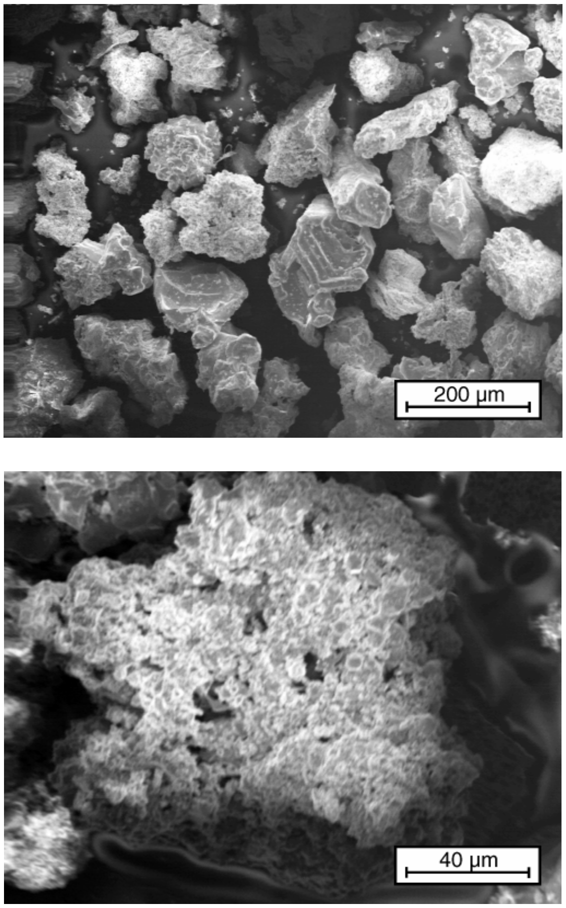

Figure 8. Example of titanium sponge, two magnifications, (100 and 500 ×).

rial can be made by stamping from foil; however, this tends to produce materials that are too large and too thick to be of much use in pyrotechnics.

Surface Features

Particle surface features can significantly affect the reactivity of metal fuel particles. Probably the best-known example of this in pyrotechnics is so-called titanium "sponge". This is the initial product of normal titanium production, wherein titanium tetrachloride is reacted with magnesium metal. Titanium sponge is quite porous, giving it the appearance vaguely like that of the biological organism for which it is named. While this may not be entirely obvious at low magnification, the structure and porosity becomes more apparent at higher magnifications (see Figure 8). These same features are also easily recognizable as a characteristic that is useful in identifying the material. Pyrotechnically, it is because of the pores and fine surface structures that titanium sponge ignites easily and can be propelled at very high velocity through the air without being extinguished.

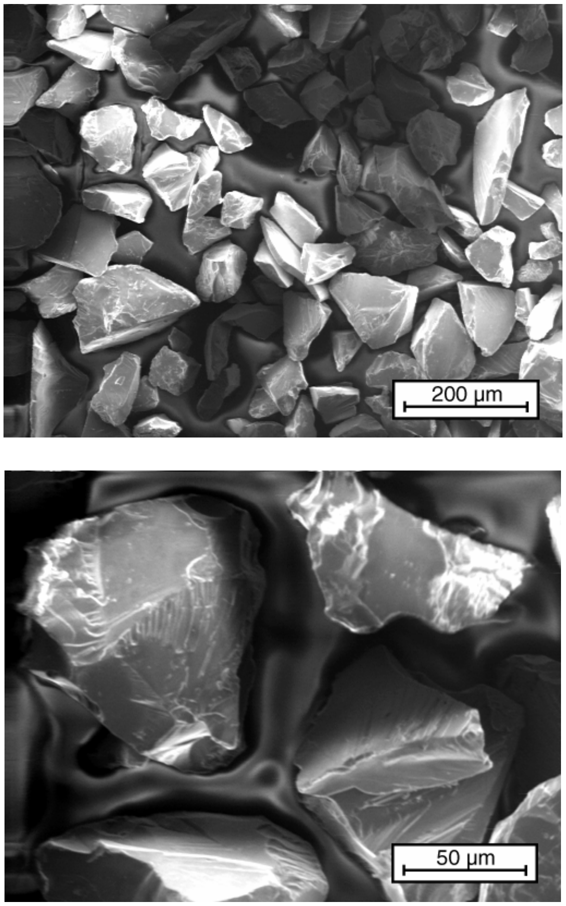

Figure 9. Example of surface features of magnalium, two magnifications (100 and 400 ×).

Particle size reduction of especially brittle metals can produce interesting and characteristic surface features. For example, fracture patterns and "whiskers" are seen in Figure 9 of the 50:50 alloy of aluminum and magnesium (often called "magnalium" in pyrotechnics). While these surface features are not thought to significantly affect pyrotechnic reactivity, they certainly help characterize the particles. Similarly, the two examples of surface features mentioned earlier in this article (coarse surface texturing on blown aluminum and tool marks on titanium turnings) are unlikely to have a noticeable affect on pyrotechnic reactivity, but can be diagnostic in terms of helping to establish a match between materials.

Conclusion

Experience has taught pyrotechnists that particle size, shape and surface features are important controlling factors for ease of ignition (both intentional and accidental) and for burn rate once ignited. Accordingly, knowledge of these attributes is an important first step in designing a pyrotechnic composition or altering the performance of a composition once formulated. From a forensic standard point, these same particle attributes constitute an important part of the basis for establishing a reliable identification of pyrotechnic materials or a match between known and suspect materials. Accordingly, for pyrotechnists it is hoped that this short article provided some information about the physical nature of some of the metal powders being used. For forensic analysts it is hoped that this article has suggested some additional points of comparison that might prove to be useful in their efforts to identify the components of pyrotechnic materials.

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References

1) K. L. and B. J. Kosanke, "Control of Pyrotechnic Burn Rate", *Pro. 2nd Int'l. Symp. Fireworks* (1994). Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 3 (1993 to 1994)*, Journal of Pyrotechnics, 1996.

2) *CRC Handbook of Chemistry and Physics*, 75th ed., CRC Press, 1995.

3) *Engineering Design Handbook*, "Part III–Properties of Materials Used in Pyrotechnic Compositions", Army Materials Command, AMP 706–187, 1963.

4) F. Whitehurst, "Forensic Testimony: *Matches*, An Over-Inference of Data? A Giglio Obligation?", *Journal of Pyrotechnics*, No. 11 (2000).

5) W. C. McCrone and J. G. Delly, *The Particle Atlas, An Encyclopedia of Techniques for Small Particle Identification*, Ann Arbor Science Publishers, 1973.

6) K. L & B. J. Kosanke and C. Jennings-White, "Pyrotechnic Spark Generation", *Proc. 3rd Int'l. Symp. Fireworks* (1996). Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 4 (1995 through 1997)*, Journal of Pyrotechnics, 1999.

7) K. L. and B. J. Kosanke, "Aluminum Metal Powder in Pyrotechnics", *Bulletin of the Pyrotechnics Guild International*, No. 85 (1993). Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 1997.