

专 论

## 脉冲放电高能转化制备纳米粉体

末松久幸, 村井啓一, 床井良徳, 鈴木常生, 中山忠親, 江偉華, 新原皓一

(長岡技術科学大学 極限エネルギー密度工学研究所, 新潟 長岡 940-2188, 日本)

**摘 要:** 综合介绍了脉冲电流通过细金属丝放电(pulsed wire discharge, PWD)制备纳米粉体的方法。讨论了影响纳米粉体, 特别是晶粒尺寸的因素, 以防止形成亚微米颗粒。因为达到电压峰值的丝的沉积能相当于丝的汽化能, 因此, 能够计算出沉积能。随着所施加的能量增加, 气体压力降低, 介质气体的热扩散率增大, 晶粒尺寸变小。在惰性气氛中, 采用 PWD 工艺, 由金属蒸气急冷可制备金属粉体。如果介质气体变为氧气或者氮气, 就能制备氧化物、氮化物纳米粒子。要制备双金属合金、双氧化物或氮化物纳米粒子就必需采用双金属丝和不同的介质气体。采用 PWD 工艺, 在有机气体或烟气中, 能制备电磁屏蔽和导电浆料和其它用途的钝化纳米粒子。采用丝输送器而实现大量生产纳米粉体的 PWD 工艺一个实例证明了 PWD 工艺生产纳米粉体的可行性。

**关键词:** 金属丝脉冲放电; 脉冲能量; 钝化金属纳米粉体; 导电膏

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## NANOSIZED POWDER PREPARATION WITH HIGH ENERGY CONVERSION EFFICIENCY BY PULSED WIRE DISCHARGE

SUEMATSU H, MURAI K, TOKOI Y, SUZUKI T, NAKAYAMA T, JIANG W, NIIHARA K

(Extreme Energy-Density Research Institute, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka 940-2188, Japan)

**Abstract:** A method for preparing nanosized powders by the pulsed wire discharge (PWD) method utilizing a pulsed electric current going through a thin metal wire is described. Factors that affect the properties of the nanosized powders, in particular the grain sizes of nanosized powders, are discussed to prevent submicrometer grain formation. Since the energy deposited on a wire up to the voltage peak coincides with the energy for the evaporation of the wire, the wire was almost completely evaporated by the peak. With the increase of the charged energy, and the decrease of the gas pressure or increase of the thermal diffusivity of the ambient gas, the grain size decreases. The metal powder can be prepared by the cooling of metal vapor in the PWD process in inert gas. If the ambient gas is changed to oxygen or ammonia, oxide or nitride nanoparticles can be synthesized. For the preparation of binary alloys, double oxides or nitrides, it is necessary to use two different metals and different gases. By using the PWD method in the organic vapor/fume, passivated nanoparticles for electromagnetic shields, conductive pastes and other applications can be prepared. The example of pulling a wire feeder for a large-scale production of nanosized powders by PWD shows the effectiveness of PWD for the preparation of passivated metal nanosized powders.

**Key words:** pulsed wire discharge; pulsed power; passivated metal nanosized powders; conducting paste

### 1 History of wire explosion experiments

In the 1850's, Faraday, who introduced the law of electromagnetic induction, was interested in the optical properties of metal aerosols. He tried to fabricate gold particles in air by various methods. In one of these methods, he "deflagrated" a thin gold wire by connecting

it to Leyden jars to form gold particles in the air.<sup>[1]</sup> These particles were collected on glass, rocks or cardboard placed near the wire. He confessed that the particles were "too small to be recognized by the highest powers of the microscope". As far as the authors know, this was the first reported experiment of particle formation by electric current using metal wires.

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第一作者: 末松久幸(1963~), 男, 博士, 副教授。

通讯作者: 新原皓一(1941~), 男, 博士, 教授。

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First author: SUEMATSU Hisayuki (1963—), male, doctor, associate professor.

E-mail: suematsu@nagaokaut.ac.jp

Correspondent author: NIIHARA Koichi (1941—), male, doctor, professor.

E-mail: niihara@nagaokaut.ac.jp

The basic idea of the experiment is shown in Fig.1.<sup>[1]</sup> A thin metal wire was connected to a current source. The whole wire was heated by the pulsed current driven through the wire. In a short period of time, the wire was melted and then it quickly evaporated into the air. This phenomenon is known as electric wire explosion<sup>[2]</sup> and it has been studied in pulsed intense X-ray source research.<sup>[3]</sup> After the electric wire explosion, the formed metal vapor was cooled in ambient gas to form solid metal particles. This method is currently termed as electric wire explosion, or pulsed wire discharge (PWD).

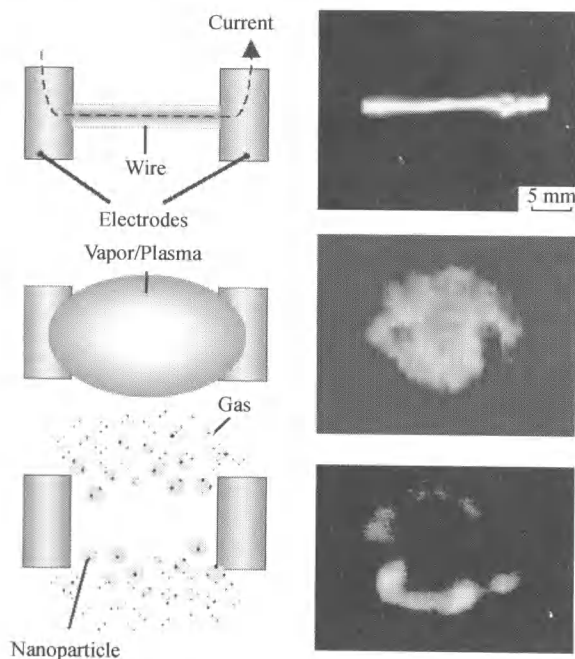


Fig.1 Schematic of nanosized powder preparation by pulsed wire discharge<sup>[1]</sup>

Since the transmission of electrical energy began in 1882 by Edison, it was suspected that Leyden jars and batteries were the only electricity sources available in 1857. Their energy and power were limited. If gold was heated by the DC current method on a separate heater connected to a battery, most of the energy was dissipated through the heater. Thus, the amount of gold vapor and produced gold particles must have been limited. On the other hand, a pulsed current in the metal wire itself can suppress the heat dissipation and effectively evaporate the metal. This is still the biggest merit of PWD as compared with other gaseous methods.

Over the years, PWD was forgotten. Instead, high energy and power current sources were developed. In 1947, a particle preparation method using constant DC and AC currents in a separate heater was reported.<sup>[4]</sup> Much basic research was carried out, and the mechanisms of particle formation in gaseous media were revealed.<sup>[5-6]</sup>

In 1962, PWD was rediscovered, and  $U_3O_8$  and other metal nanosized powders were synthesized.<sup>[7]</sup> Then, nanosized powders of nitrides,<sup>[8]</sup> carbides,<sup>[9]</sup> arsenides,<sup>[10]</sup> iodides and sulfides were synthesized.

However, the mechanism of the PWD process prevailed, the application of PWD is limited because there are uncertain mechanisms in the PWD process and there are also clear disadvantages in nanosized powders prepared by the PWD method. In this review, we first try to reveal the factors used to control chemical reactions and the grain size distribution of synthesized nanosized powders from recent experimental results. Then, we describe our attempt to overcome the barriers to the mass production of nanosized powders by PWD.

## 2 Pulsed wire discharge

### 2.1 Deposited energy to wire and prevention of incomplete wire evaporation

The schematic of the simplest PWD apparatus is shown in Fig.2. A thin metallic wire is clamped with two electrodes, which are connected by cables to a capacitor through a switch. The capacitor is charged with an external power supply. The charged energy must be higher than the evaporation energy of the wire. Gap switches have been widely used in the PWD apparatus because of the high voltage and large current provided, although a static induction thyristor was applied. Then the switch is closed so that a large current goes through the wire. This large current heats, melts and evaporates the wire in a short period of time. The vapor is condensed in ambient gas to form solid nanosized powders. Typical metal nanosized powders observed by transmission electron microscopy (TEM) are shown in Fig.3. If the ambient gas was inert gas or nitrogen, the obtained nanosized powders were metallic. If the ambient gas was oxygen, ammonia or methane, the synthesized powders were oxides,<sup>[1]</sup> nitrides,<sup>[8]</sup> carbides<sup>[9]</sup> or other compounds.<sup>[10]</sup>

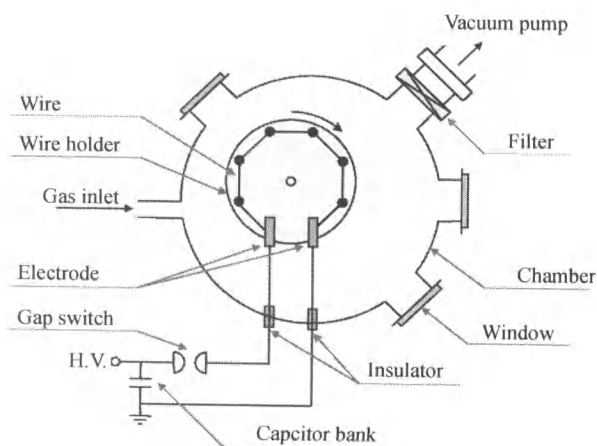


Fig.2 Schematic of PWD apparatus

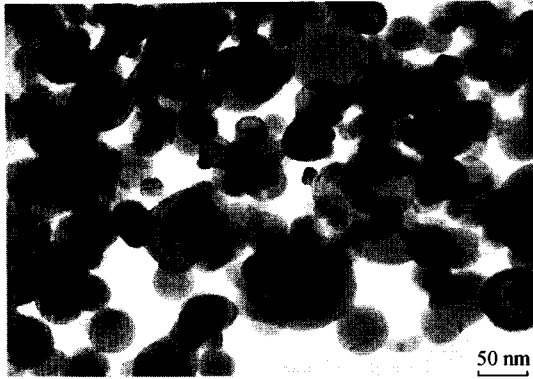
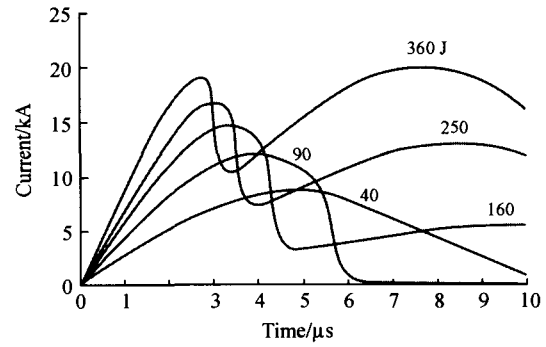


Fig.3 Bright field TEM micrograph of Cu nanosized powders prepared by PWD

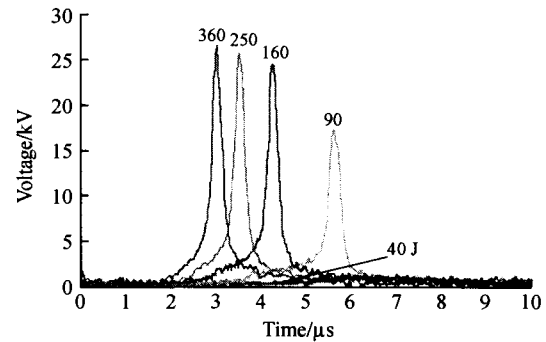
Again, the short duration of the large current is a characteristic of the PWD method. The wire works as not only a source of the powder, but also as a heater. The heater is disconnected upon the evaporation, and the heat dissipation to the electrodes did not take place after the evaporation, except for the radiation and conduction in the ambient gas. This is the reason for the high energy conversion efficiency of PWD. In a previous experiment, an efficiency of 360 g/(kW·h) was reported for the preparation of Cu nanosized powders.<sup>[11]</sup>

Current and voltage waveforms have been collected<sup>[3]</sup> in many experiments and the PWD process has been partly understood.<sup>[12]</sup> Typical current and voltage waveforms are shown in Fig.4. With a charged energy of 90 J in approximately the first five microseconds, the voltage is low and the current is high. This indicates that the wire is of solid metal. At 5.7 microseconds, a sharp peak in voltage and an abrupt drop in current are observed. Since the resistivity of most metals in a gaseous state is higher than that found in a solid state, this voltage peak was explained as the evaporation of a wire of low-boiling-point metals.<sup>[3,13]</sup> From the power obtained by multiplying the voltage and current, the deposited energy to the wire can be calculated. Since the deposited energy to the wire, up to the voltage peak, coincided with the energy of evaporation of the wire (67 J), the above explanation was verified. After the peak, the voltage rapidly decreased and the current began to oscillate.<sup>[3]</sup> This was thought to be the resistivity decrease caused by the ionization of the vapor. The residual energy in the capacitor can be released as the current to the ionized vapor. The current waveform shows a damped oscillation curve resulting from the resonance of the capacitor and a parasitic inductance in the cables.

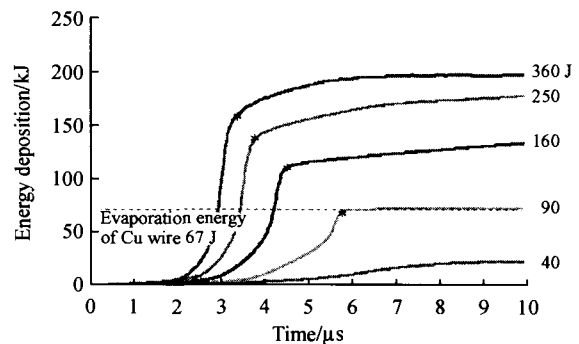
This is the typical current and voltage waveforms of the PWD process. In Fig.4, the deposited energy to the wire and the evaporation energy of the wire were close, but did not match exactly. This is more prominent in the



(a) Current



(b) Voltage



(c) Deposited energy

Fig.4 Current, voltage and deposited energy to wire waveforms of PWD of Cu wires with different charged energy crosses indicate the deposited energy to the voltage peaks

PWD method with a lower charged energy than that of the evaporation energy. The difference was thought to be the incomplete vaporization of the wire,<sup>[12-13]</sup> which was caused by the unevenness of the wire. In high-speed photographs, some bright spots were seen prior to the whole evaporation.<sup>[14]</sup> Furthermore, in PWDs using a kinked wire, the kinked area emitted light earlier than the rest of the wire.<sup>[15]</sup> These results imply that an uneven dislocation density or diameter caused by the wiring is the reason for the incomplete evaporation of the wire.

The unevaporated portion of wire must still be solid or liquid at the voltage peak. The solid or liquid portion

should have different shapes than that in the evaporated wire<sup>[16]</sup>. Cu nanosized powders prepared with the incomplete evaporation condition are shown in Fig.5. Submicrometer particles are seen along with nanosized powders. These submicrometer particles must be a result of the unevaporated portion of the wire.<sup>[12,17]</sup> Since these particles are spherical, it is likely that the particles are formed by condensation from a liquid.

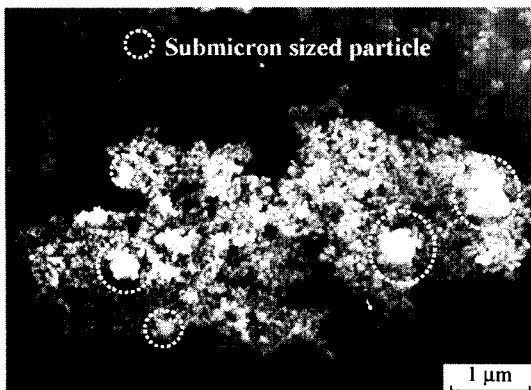


Fig.5 Scanning electron micrograph of Cu nanosized powder and a submicrometer particle prepared with incomplete evaporation condition

Since the submicrometer particles were formed from the nonuniformity of the wire, it is likely that the volume of the unevaporated portion must be statistically increased with the size of the wire. The volume fraction of the submicrometer particles, which is the difference between the specific surface area, as measured by the Brunauer–Emmett–Teller (BET) method, and the grain size distribution, as measured by scanning electron microscopy (SEM), with different wire lengths, is shown in Fig.6. It is clear that the amount of submicrometer particles increases with the increase in the wire length and diameter. This result confirms the above hypothesis.

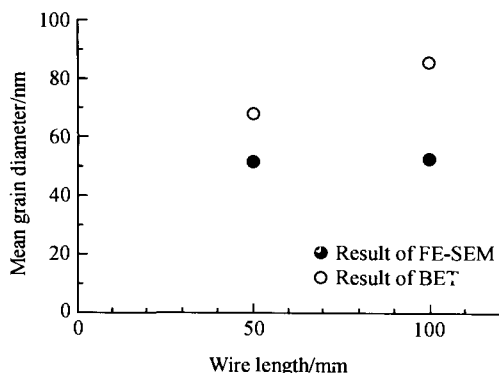


Fig.6 Grain size of Cu nanosized powders prepared from different wire length

## 2.2 Dependence of grain size on input energy

In the previous section, the liquid droplets formed from the unevaporated wire and the submicrometer particles are described. It is natural to think that the quick heating of the wire can prevent the incomplete evaporation of the wire. Since the pulse width was defined by the capacity and the inductance of the cable, the increase in current and charged energy can be a solution for the above-mentioned problem. The dependence of the grain size on the charged energy in the Cu nanosized powders is shown in Fig.7. With the charged energy increase, the grain size decreases to 9 nm. An example of Cu nanoparticles with a median diameter of 13 nm is shown in Fig.8.

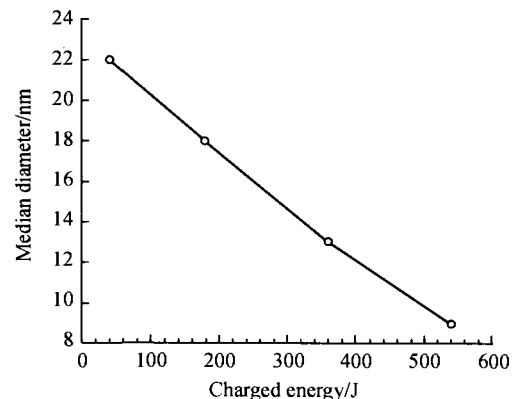


Fig.7 The dependence of on grain size charging energy in Cu powders prepared by PWD

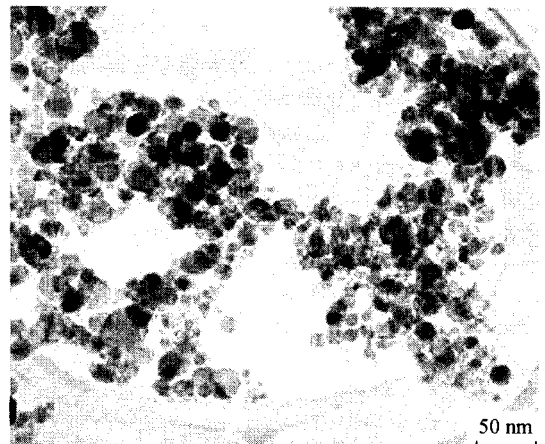


Fig.8 Bright field TEM micrograph for Cu nanoparticles prepared at a charged energy 33 times that of the evaporation energy of the wire

There is a report showing that the grain size increases with the increase of charging energy.<sup>[18]</sup> Further research must be conducted.

## 2.3 Dependence of grain size on ambient gas pressure

In the nanosized powder prepared by evaporation in

a gaseous media, it is well known that the grain size decreases with a decrease in the gas pressure.<sup>[5-6]</sup> This is explained by the decrease in the probability of atoms coagulating under a low vapor pressure. In the PWD process, a similar phenomenon was observed.<sup>[19]</sup> The pressure dependence of particle size in Cu powder, as prepared by the PWD method, is shown in Fig.9. With a decrease in the pressure, the Cu particle size decreases to 16 nm.

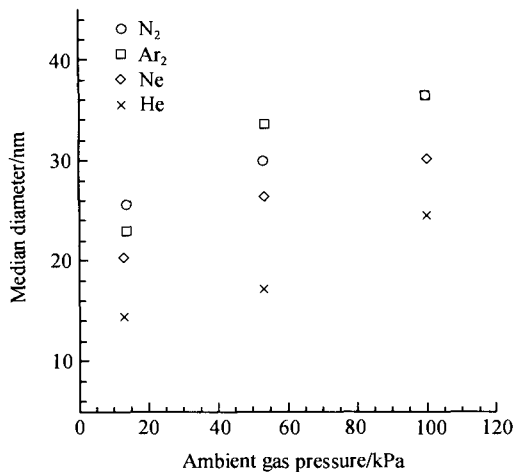


Fig.9 The pressure dependence of grain size on ambient gas of Cu nanosized powders

A report which is contrary to the above results exists.<sup>[20]</sup> However, their results are also different from the dependence of pressure in other methods of evaporation in gas.<sup>[5-6]</sup> The authors think that these results were obtained in exceptional experimental conditions.

By changing the ambient gas species, the grain size can be changed, which is also shown in Fig.9. Please note that the grain size decreases with an increase in the thermal diffusivity of the ambient gas. This phenomenon can be explained in that the quick cooling of the metallic vapor by an ambient gas reduces the chance of metal atoms coagulating and growing nanoparticles.

If we decrease the pressure to below 1.33 kPa in this apparatus, the dielectric discharge takes place between the electrodes in the gas. From Paschen's law, above a certain pressure, the dielectric breakdown of the electric field is proportional to the pressure, and this depends on the gas species. Below this pressure, a current goes through not the wire, but the gas, and it does not contribute to the evaporation of the wire.

Thus, in order to obtain small nanoparticles, it is ideal to increase the gas pressure during heating, and to decrease gas pressure after evaporation. A gas puff apparatus can be used in the PWD system.<sup>[21-22]</sup> The schematic of the gas puff apparatus is shown in Fig.10. An external current source produces a pulsed magnetic field

around a coil, which is also used to produce an Eddie current in a disk. From the magnetic field and the Eddie current, the Lorentz force pushes the rod to open the valve to generate a gas puff in the PWD chamber. The grain sizes and specific surface areas of the Cu nanosized powders as prepared by the PWD method, with and without the gas puff apparatus, are shown in Fig.11.<sup>[21]</sup> Using the gas puff apparatus, a dielectric breakdown was effectively suppressed at 130 Pa, which is more than one order of magnitude lower than the lowest ambient gas pressure for PWD without the gas puff apparatus, and thus Cu nanoparticles with a grain size of 9 nm were obtained.<sup>[21]</sup>

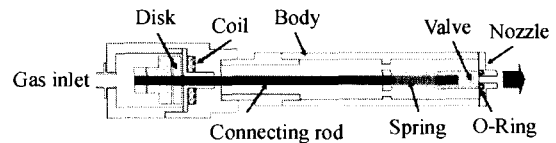


Fig.10 Schematic of gas puff apparatus<sup>[21-22]</sup>

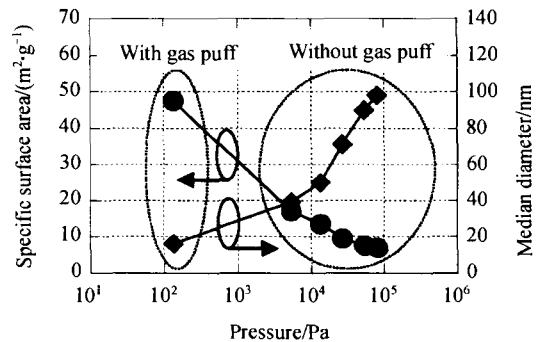


Fig.11 Grain size of Cu nanosized powders prepared with and without the gas puff apparatus<sup>[21]</sup>

### 3 Synthesis of alloys and compounds nanosized powders by PWD

In the former section, it is described that the metal vapor formed in the PWD process was cooled in inert gas. If the ambient gas was changed to oxygen or ammonia, oxide<sup>[7]</sup> or nitride<sup>[8]</sup> nanoparticles can be synthesized. Powder X-ray diffraction (XRD) patterns of nanoparticles synthesized by the evaporation of Al wire in ammonia gas are shown in Fig.12. From this pattern, it is obvious that AlN nanoparticles were obtained. The volume fraction of AlN can increase to 99% by increasing ammonia partial pressure and optimizing the electrodes.<sup>[13]</sup>

For preparation of binary alloys, double oxides or nitrides, it is required to evaporate two different metals. If alloy wires were not obtained, we can use wound wires consisting of two or more metals for PWD apparatus.

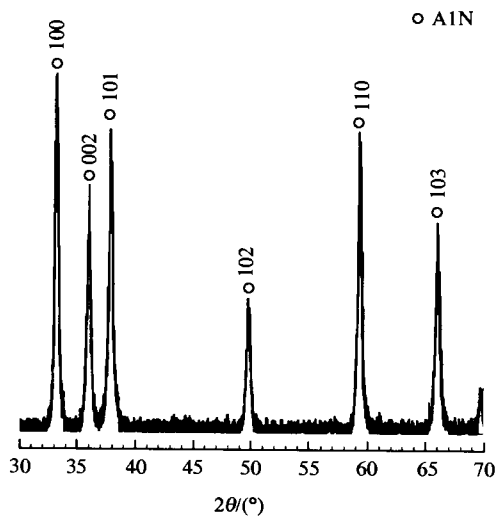


Fig.12 Powder XRD patterns of AlN nanosized powders synthesized by PWD<sup>[8]</sup>

PWD using a Ni-Fe wound wire in oxygen gas was carried out and the XRD pattern of the synthesized nanosized powders are shown in Fig.13.<sup>[23]</sup> All peaks correspond to those of NiFe<sub>2</sub>O<sub>4</sub> phase. This result indicates that Ni and Fe wires with different resistivity were evaporated at the same time and the Ni and Fe vapors were mixed in oxygen gas to synthesize NiFe<sub>2</sub>O<sub>4</sub> nanoparticles.<sup>[23]</sup> By sintering this NiFe<sub>2</sub>O<sub>4</sub> nanosized powders, porous Ni-Fe-O bulks were formed. These bulks exhibit a sharp resistivity change above 200 °C by absorption and desorption of organic molecules.<sup>[24]</sup> These bulks are candidates for high temperature organic molecule sensors.<sup>[25]</sup>

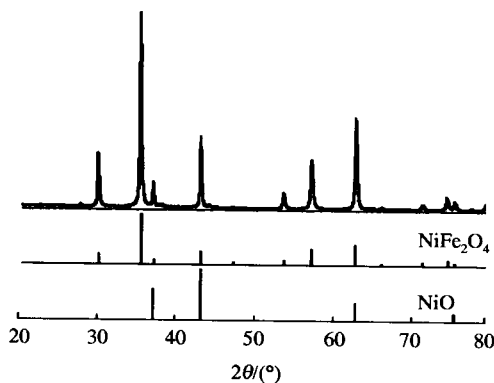


Fig.13 XRD patterns of NiFe<sub>2</sub>O<sub>4</sub> nanosized powders using a Fe-Ni wound wire<sup>[23]</sup>

#### 4 Preparation of metal nanosized powders by PWD and their passivation coatings

In the former section, it is described that the some

examples of metal vapors cooled in the ambient gas to condense and form nanosized powders. It is expected that addition of overcooled organic molecules vapors in the ambient gas to condense the organic molecules on the metal nanosized powders. An example of PWD of Cu wire in mineral oil vapor/fume is shown in Fig.14. At the center of the bright field image, there is a particle with diameter of 50 nm. This particle is surrounded by a layer with thickness of 10 nm. Characteristic XRD patterns from these two portions indicate that the particle is mainly of Cu and the surrounding layer is of C. Infrared absorption spectrum obtained on Cu particles prepared in oleic acid vapor/fume is shown in Fig.15. This spectrum was recorded using an attenuated total reflection prism and indicated absorption in a surface layer of the sample. All peaks correspond to those of Cu oleate. The XRD patterns for the Cu particles are shown in Fig.16. Only Cu peaks are found and no oxide peaks are seen after 2 months of exposure in air at room temperature.<sup>[26]</sup> These results show that all Cu particles are evenly coated by Cu oleate to prevent oxidation.

This method can be applied to other metal nanoparticles and organic layers. Furthermore, by changing metal wire and organic vapor fume to introduce in PWD chamber, various combinations of passivated nanoparticles can be easily obtained. This is the advantage of PWD comparing to those thorough chemical condensation methods, which require reaction process optimization in each organic molecule and metal system. By using PWD in organic vapor/fume, we can prepare passivated nanoparticles for electromagnetic shields, conductive pastes and other applications.

#### 5 Development of high reproduction-rate PWD apparatus

For mass production of nanosized powders, the biggest barrier is to feed wires between electrodes after a discharge.<sup>[27]</sup> Two wire supply methods are attempted to overcome this barrier. One is to push wire through a hole in an electrode until contacting the other electrode. The other is to pull wire to contact electrodes. The pushing wire feeder was developed by Tomsk group<sup>[18]</sup> and have been used and modified in many research facilities in the world.<sup>[28-30]</sup> With pushing the wire feeder, the gap between the wire and the latter electrode works as a gap switch. The voltage between the electrodes can be constant and, by pushing the wire and shortening the gap distance, PWD automatically takes place at a certain distance.

As mentioned before, the volume fraction of submicrometer grains can be reduced by using a small diameter wire. It is difficult to push the small diameter wire through airtight seal in the PWD chamber. Thus, we have been developing a pulling wire feeder for PWD apparatus.<sup>[11,31]</sup>

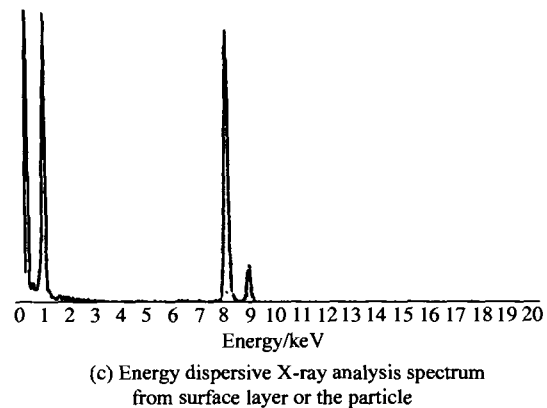
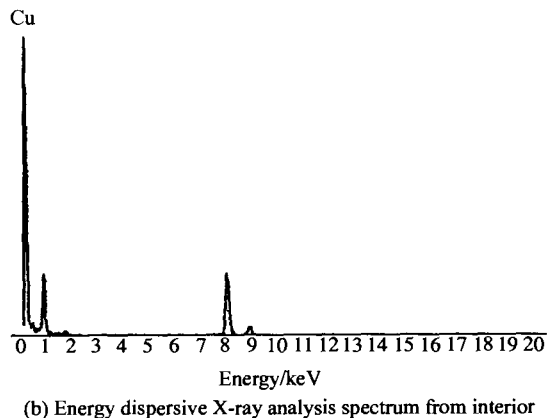
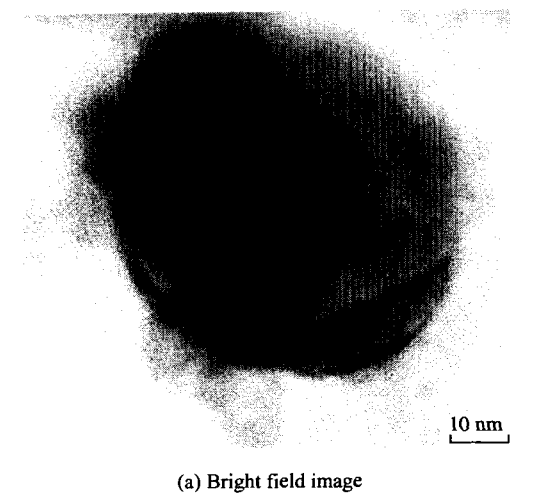


Fig.14 Bright field image and energy dispersive X-ray analysis spectra of passivated Cu particle<sup>[26]</sup>

The demonstration apparatus with a pulling wire feeder is shown in Fig.17. This apparatus can operate at a repetition rate of 1.4 Hz. In test operations, we obtained passivated Cu nanosized powders of 2 g in 90 s. The energy conversion efficiency was 360 g/(kW·h).<sup>[11]</sup>

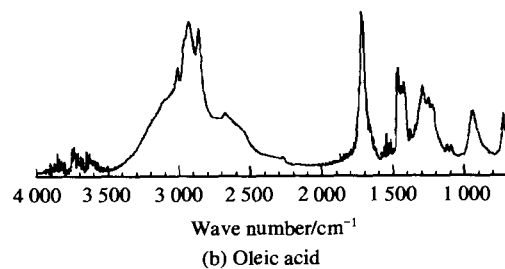
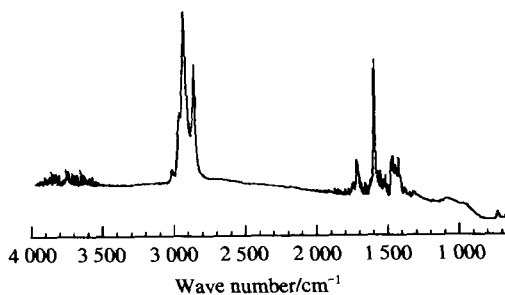


Fig.15 Infrared absorption spectra from passivated Cu nanosized powders<sup>[26]</sup>

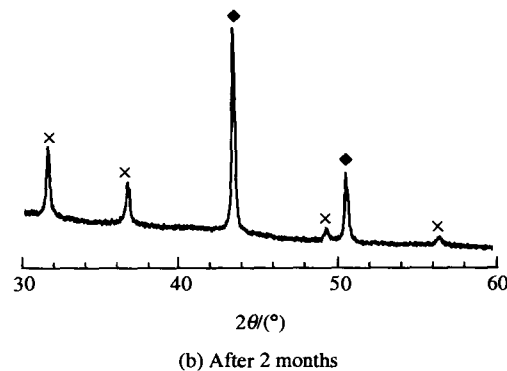
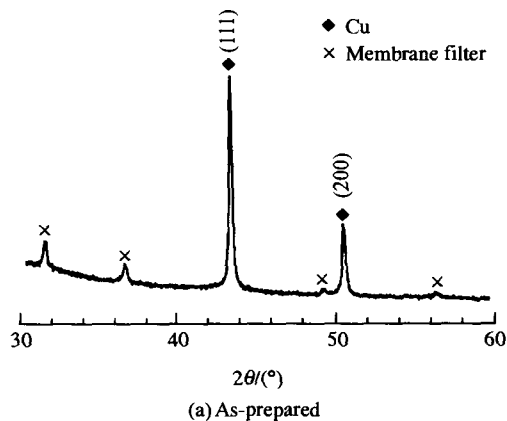


Fig.16 XRD patterns of passivated Cu nanosized powders in as-prepared and after exposure<sup>[26]</sup>

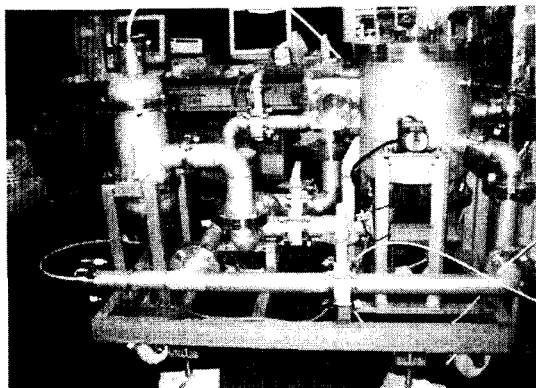


Fig. 17 PWD apparatus with a pulling wire feeder capable of supplying wire at 1.4 Hz<sup>[11,31]</sup>

## 6 Summary

In this review, history of development of PWD was briefly listed. From the experimental results, mechanism in the PWD process is drawn to reduce grain size and to minimize volume fraction of submicrometer grains. Finally, an example of pulling wire feeder for large scale production of nanosized powders by PWD is presented to show effectiveness of PWD for preparation of passivated metal nanosized powders.

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### References:

- [1] FARADAY M. Experimental Researches in Chemistry and Physics [M]. London: Taylor and Francis, 1857. 145–181.
- [2] NAIRNE E. Electrical experiments by Mr. Edward Nairne of London, mathematical instrument-maker, made with a machine of his own workmanship, a description of which is prefixed [J]. *Phil Trans*, 1774, 64: 79–89.
- [3] WEBB J F H, HILTON H H, LEVINE P H, *et al.* The electric and optical properties of rapidly exploded wires [A]. In: CHACE W G, MOORE H K eds. *Exploding Wire* [M]. New York: Plenum Press, 1962, 2: 37–75.
- [4] UYEDA R, KIMOTO K. Research on zinc powders by electron diffraction (in Japanese) [J]. *Oyo Buturi*, 1948, 18: 28–30.
- [5] WADA N. Preparation of fine metal particles by means of evaporation in helium gas [J]. *Jpn J Appl Phys*, 1967, 6: 553–556.
- [6] WADA N. Preparation of fine metal particles by means of evaporation in xenon gas [J]. *Jpn J Appl Phys*, 1968, 7: 1 287–1 293.
- [7] KARIORIS F G, FISH B R. An exploding wire aerosol generator [J]. *J Colloid Sci*, 1962, 17: 155–161.
- [8] JONCICH M J, VAUGHN J W and KNUTSEN B F. Preparation of metal nitrides by the exploding wire technique [J]. *Can J Chem*, 1966, 44: 137–142.
- [9] COOK E, SIEGEL B. Carbide synthesis by metal explosions in acetylene [J]. *J Inorg Nucl Chem*, 1968, 30: 1 699–1 706.
- [10] SAUNDERS W A, SERCEL P C, ATWATER H A, *et al.* Vapor phase synthesis of crystalline nanometer-scale GaAs clusters [J]. *Appl Phys Lett*, 1992, 60: 950–952.
- [11] SUEMATSU H, NISHIMURA S, MURAI K, *et al.* Pulsed wire discharge apparatus for mass production of copper nanopowders [J]. *Rev Sci Inst*, 2007: in press.
- [12] CHO C, MURAI K, SUZUKI T, *et al.* Enhancement of energy deposition in pulsed wire discharge for synthesis of nanosized powders [J]. *IEEE Trans Plasma Sci*, 2004, 32: 2 062–2 067.
- [13] CHO C, KINEMUCHI Y, SUEMATSU H, *et al.* Enhancement of nitridation in synthesis of aluminum nitride nanosize powders by pulsed wire discharge [J]. *Jpn J Appl Phys*, 2003, 42: 1 763–1 765.
- [14] SUHARA T, FUKUDA S. Wire explosion spraying and its applications (in Japanese) [J]. *Zairyo*, 1975, 24: 1 003–1 012.
- [15] EDELSON H D, KORNEFF T. Conducting mechanisms for exploding wires [A]. In: CHACE W G, MOORE H K eds. *Exploding Wire* [M]. New York: Plenum Press, 1964, 3: 267–284.
- [16] KINEMUCHI Y, SUZUKI T, JIANG W, *et al.* Ceramic membrane filters using ultrafine powders [J]. *J Am Ceram Soc*, 2001, 84: 2 144–2 146.
- [17] KINEMUCHI Y, MURAI K, SANGURAI C, *et al.* Nanosize powders of aluminum nitride synthesized by pulsed wire discharge [J]. *J Am Ceram Soc*, 2003, 86: 420–424.
- [18] KOTOV Y A, AZAARKEVICH E I, BEKETOV I V, *et al.* Producing Al and Al<sub>2</sub>O<sub>3</sub> nanopowders by electrical explosion of wire [J]. *Key Eng Mater*, 1997, 132–136: 173–176.
- [19] JIANG W, YATSUI K. Pulsed wire discharge for nanosize powder synthesis [J]. *IEEE Trans Plasma Sci*, 1998, 26: 1 498–1 501.
- [20] KOTOV Y A, SAMATOV O M. Production of nanometer-sized AlN powders by the exploding wire method [J]. *Nano Struct Mater*, 1999, 12: 119–122.
- [21] TOKOI Y, IKEUCHI T, SUEMATSU H, *et al.* Nanosized powder synthesis by pulsed wire discharge in high-speed gas flow [J]. *IEEE Trans Fund Mater*, 2005, 125: 727–732.
- [22] TOKOI Y, NAKAYAMA T, SUEMATSU H, *et al.* Clarification of wire heating process in pulsed wire discharge with high-speed gas puff [J]. *Mater Sci Forum*, 2006, 510–511: 1 010–1 013.
- [23] KINEMUCHI Y, ISHIZAKA K, SUEMATSU H, *et al.* Magnetic properties of nanosize NiFe<sub>2</sub>O<sub>4</sub> particles synthesized by pulsed wire discharge [J]. *Thin Solid Films*, 2002, 407: 109–113.
- [24] SUEMATSU H, KINEMUCHI K I, SUZUKI T, *et al.* Novel critical temperature resistor of sintered Ni–Fe–O nanosized powders [J]. *J Mater Res*, 2004, 19: 1 011–1 014.
- [25] SUZUKI S, SUZUKI T, NAKAYAMA T, *et al.* Abrupt slope change in temperature dependence of resistivity in Ni–Fe–O sintered body [J]. *J Jpn Soc Powder Powder Metal*, 2007, 54: 209–212.
- [26] MURAI K, WATANABE Y, SAITO Y, *et al.* Preparation of copper nanoparticles with an organic coating by a pulsed wire discharge method [J]. *J Ceram Proc Res*, 2007, 8: 114–118.
- [27] KRUIS F E, FISSAN H, PELED A. Synthesis of nanoparticles in the

- gas phase for electronic, optical and magnetic applications—a review [J]. *J Aerosol Sci*, 1998, 29: 511–535.
- [28] CHO C. Private Communication, 2004.
- [29] KWON Y S, AN V V, ILYIN A P, *et al.* Properties of powders produced by electrical explosions of copper–nickel alloy wires [J]. *Mater Lett*, 2006: in press.
- [30] UHM Y R, KIM W W, KIM S J, *et al.* Magnetic nanoparticles of  $\text{Fe}_2\text{O}_3$  synthesized by the pulsed wire evaporation method [J]. *J Appl Phys*, 2003, 93: 7196–7198.
- [31] KINEMUCHI Y, IKEUCHI T, AKIMOTO H, *et al.* Mass production of nanosize powders by pulsed wire discharge [A]. *Proc 2nd Int'l Symp Pulsed Power and Plasma Applications [C]*, [s. l.], 2001. 143–148.

### [First author introduction]



**Hisayuki Suematsu**

Hisayuki SUEMATSU was born in Kawasaki, Japan, in 1963. He received the M.S. and Ph.D. degrees in nuclear engineering from Tokyo Institute of Technology, Ookayama, Meguro, Japan, in 1988 and 1991, respectively. He was a Research Fellow with Los Alamos National Laboratory, Los Alamos, NM, from 1992 to 1994. He is currently an Associate Professor with the Extreme Energy-Density Research Institute, Nagaoka University of Technology, Nagaoka, Japan. His research interests include synthesis of novel functional materials by using pulsed power apparatus.

### [Correspondent author introduction]



**Koichi Niihara**

Koichi NIIHARA received the BS, MS and PhD degrees in nuclear science and engineering from Osaka University, Osaka, Japan. He is a Professor at Nagaoka University of Technology, Nagaoka, Japan, and General Director of the Extreme Energy-Density Research Center, Nagaoka, after he retired in March 2005 from The Institute of Scientific and Industrial Research (ISIR) at Osaka University. His academic career included an Associate Professor position with the Materials Research Institute, Tohoku University, and a Professor position with the Physics Department, National Defense Academy, prior to joining ISIR in 1989. He is the author or coauthor of more than 700 publications and is a holder of over 220 patents. Based on his basic research on nano and nanocomposite ceramics, he is currently involved strongly in development and industrialization of various multifunctional materials not only in ceramics but also in metals and polymers, and also in the development of lattice and molecular-level composites with new structure and functions. Dr. Niihara, who is known as the pioneer of strong nanocomposite ceramics, has received 18 awards, including the Richard M. Fulrath Award in 1983, the Ministry Award in 1988, and the Distinguished Patent Award in 1996. He is Member of the International Editorial Advisory Committee of Journal of the Chinese Ceramic Society.