Exploding Wire Discharge for Synthesis of Nanoparticles

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Abstract

Synthesis of nanoparticles is performed by using the exploding wire technique. Aluminium and copper wires with diameters of 125 µm are used in this project. The exploding wire discharges are performed at atmospheric pressure as well as at low pressure of 10^{-2} mbar and their characteristics are found to be distinctly different at these two pressure regimes. The discharge characteristic is studied by registering the discharge current and the time evolution of plasma emission in the visible to uv region simultaneously. The time-integrated spectra of the emissions are also measured. Nanoparticles produced are collected and their morphology and composition are analyzed by using scanning electron microscope (SEM) and energy dispersive analysis by X-ray (EDAX). The relationship between the size of the particle generated by the exploding wire and the ambient pressure is investigated. The possible mechanisms of nanoparticles formation are suggested.

1. Introduction

Nanoparticles with radii of less than 100 nm are formed from a number of atoms or molecules bonded together. They exhibit distinguished catalytic, electrical, magnetic, mechanical and optical properties. Wire explosion is basically a top-down approach to produce metallic nano-powders. A pulsed discharge system is used to supply a high power pulsed current to a thin metal wire and lead to the wire explosion [1, 2]. Large amount of heat from Joule heating will be dissipated in the wire to melt, evaporate and subsequently ionize it. Plasma formed during the process expands due to its high temperature and high density. This plasma will be rapidly cooled during expansion when it interacts with the surrounding gas and nanoparticles will be formed through nucleation process [3]. In a precisely designed pulsed discharge operation, high energy density can be transferred to the metallic wire in a very short time efficiently while a controlled dosage can be programmed [3-8] and generation of nanoparticles with designed characteristics will be possible .

In the present study, the nanoparticles are produced by wire explosion process in air at atmospheric pressure and at low pressure. Non reactive or inert gases are usually used to fill the explosion chamber thus significantly reduces unwanted products produced from chemical reaction between the metallic particles and the gas particles. The objective is to study the production of nanoparticles by using the wire explosion technique and to characterize them. Effort is also made to investigate the effect of solidification of the super saturated vapour after the wire explosion at different filling pressures. A magnetic probe and a PIN diode are used to measure the discharge current and optical emission from the explosion simultaneously. Physical and chemical properties of the particles formed are characterized by using scanning electron microscope (SEM) and energy dispersive analysis by x-ray (EDAX).

2. Experimental Setup

One of the considerations in this experiment is the energy deposited for the explosion of the metallic wire to form nanoparticles. Considering the sublimation energy of the aluminium wire of about 33 J/mm^3, the ratio of the required energy over the sublimation energy should be more than unity. In the present experimental setup, discharge voltage is set at 7 kV so that the energy ratio k is about 1.4 for aluminium wire explosion.

A pulsed discharge system with energy of around 45 J is used to explode thin metallic wires. Copper and aluminium wires of 125 µm are used in the two series of experiments. The layout of the wire explosion system and the diagnostic tools used in these experiments are shown in Fig. 1.

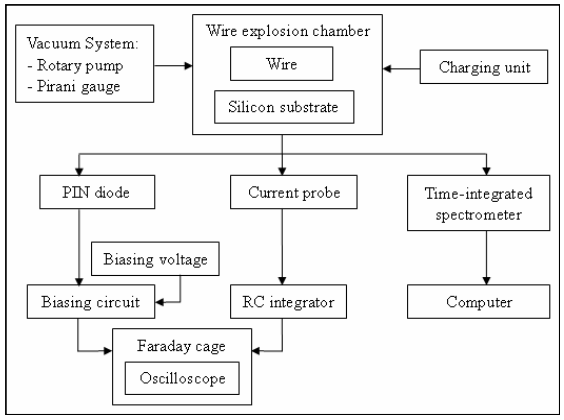


Fig. 1 Schematic of the experimental setup.

The metallic wire is held across a pair of brass electrodes with an exposed length of 15 mm. The schematic of the wire explosion chamber is shown in Fig. 2. The measurement of the discharge current is made by using a magnetic probe installed between the discharge anode and the spark gap switch.

A PIN diode detector is installed over a pinhole collimated to the centre of the wire to measure the plasma emission. The detection range of this detector covers the wavelength from 350 nm - 1100 nm. At the opposite side-on windows, a UV-VIS spectrometer is employed to obtain time integrated signal of the plasma emission. The range of spectrometer is from wavelength of 200 nm to 850 nm.

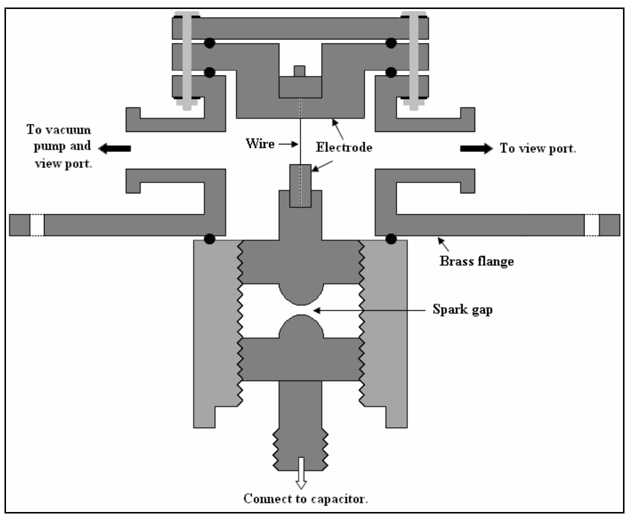


Fig 2. Schematic of explosion chamber and the exploding wire

3. Results and Discussion

At a discharge voltage of 7 kV, the total energy injected into the system is about 45 J. The wire explosion chamber is filled with air. Two pressure regimes are investigated, one at atmospheric pressure (1 bar), and the other at low pressure of 10^{-2} mbar. Typical sets of the current signals and PIN diode signals are shown in Fig. 3 (a) and (b) (for aluminium) and in Fig. 3 (c) and (d) (for copper) for wire explosion under two different pressures.

The current signals obtained at pressure of 10^{-2} mbar for aluminium (Fig. 3 (a)) and copper wire explosion (Fig. 3 (c)) both show a slight drop in current during the explosion at their first quarter cycle. The PIN diode signal obtained shows some emission at the time before and during the wire explosion and a more intense emission after the explosion. This indicates that an ionized column or plasma is formed at the early stage and produces some emission. The current continues to rise and energy deposited is also increased until finally the wire explodes. The plasma expands after the explosion and it cools rapidly.

At pressure of 10^3 mbar (Fig. 3 (b) and (d)), the current is expected to initially flow through the wire until it explodes and the current is observed to drop during the explosion. As plasma is formed after the explosion, the current rises again after the explosion in an underdamped sinusoidal waveform. This emission characteristic is similar to that observed in [9]. Total emission obtained in the wire explosion at 10^3 mbar is much higher compared to that of 10^{-2} mbar.

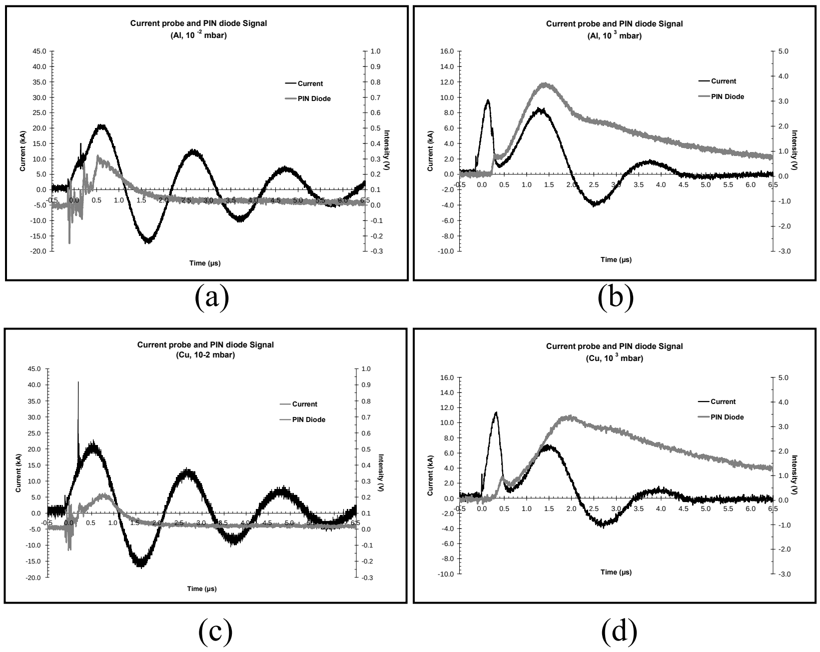


Fig. 3 Typical current signals (black) and PIN diode signals (grey) for wire explosion. (a) Al, 10^{-2} mbar, (b) Al, 10^3 mbar, (c) Cu, 10^{-2} mbar, (d) Cu, 10^3 mbar.

Particles formed from wire explosion are collected and analyzed using SEM and EDAX. For 10^{-2} mbar aluminium wire explosion, most of the particles are found to have the size of a few hundred nanometers. Some micron-sized and nano-sized particles are also observed. For 10^3 mbar aluminium wire explosion, most particles collected are approximately 100 nm. Some agglomerations of particles are observed. SEM image for particles collected at 10^{-2} mbar copper wire explosion is shown in Fig. 4. It is observed that most of the particles sizes are a few hundred nanometers in this case; while some are of micron-sized or nano-sized. For 10^3 mbar copper wire explosion, particles sizes are generally in the range of 100 nm - 200 nm while some nano-sized particles can be observed. Agglomeration of particles is observed. Size of the particles collected at 10^3 mbar are generally more uniform than those collected at 10^{-2} mbar.

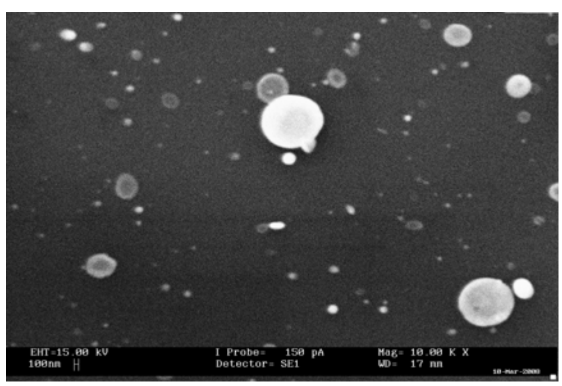
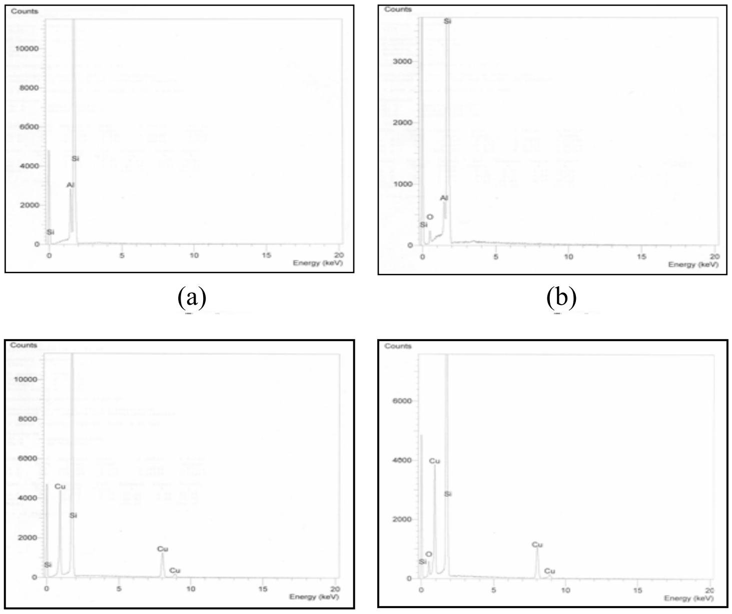


Fig. 4 SEM images for Cu particles collected under 10^{-2} mbar wire explosion. (10000 times magnification)

Particles obtained from aluminium and copper wire explosion under 10^3 mbar are found to compose of the elements and oxygen (Fig. 5 (b) and (d)). At 10^{-2} mbar, explosion of both aluminium and copper wires produced pure particles of the respective elements only (Fig. 5 (a) and (c)).



(a) (b)

(c) (d)

Fig. 5 EDAX results for particles obtained. (a) Al, 10^{-2} mbar, (b) Al, 10^3 mbar, (c) Cu, 10^{-2} mbar, (d) Cu, 10^3 mbar.

Emission spectra obtained for the series of experiments with aluninium and copper wire are analyzed. The major emission lines registered for all the 10^{-2} mbar and 10^3 mbar are very similar. Wavelengths corresponding to the peaks in the emission spectra are determined to identify the possible species occurred in the plasma formed during the wire explosion process. Fig. 6 shows one of the emission spectra obtained for aluminium wire explosion. Table 1 listed the possible species identified in the four cases.

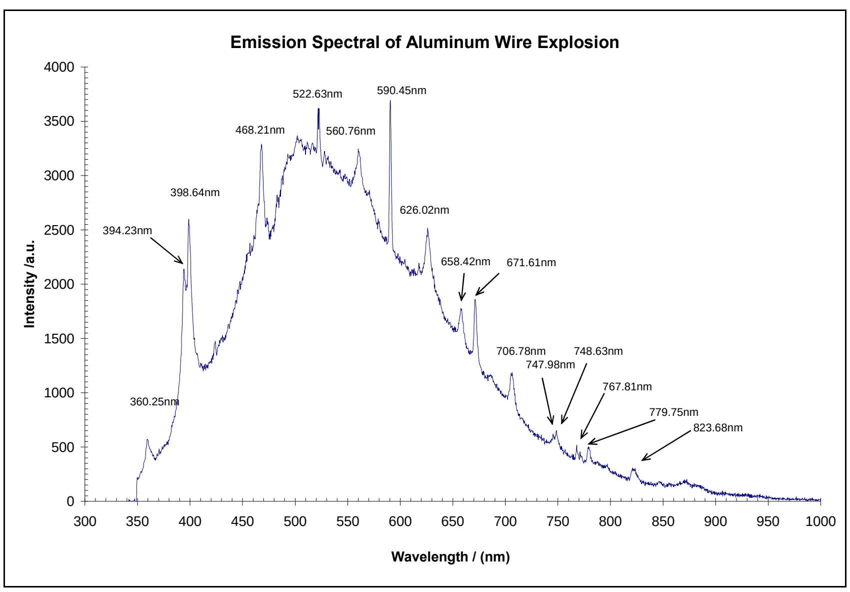


Fig. 6 Emission spectrum of aluminium wire explosion.

Pressure	Wire material	Possible species identified in the plasma
10^{-2} mbar	Aluminium	Al, Al^{+}, Al^{2+}, Al^{3+}
	Copper	Cu, Cu^{+}, Cu^{2+}
10^{3} mbar	Aluminium	Al, Al^{+}, Al^{2+}, Al^{3+}
	Copper	Cu, Cu^{+}, Cu^{2+}

Table 1 Possible species occurred in the wire explosion process.

4. Conclusion

A pulsed discharge system has been developed to facilitate metallic wire explosion for synthesis of nanoparticles. The wire explosion technique has several advantages for the generation of nanoparticles. First, the energy deposition can be controlled precisely, and second, the discharge energy is deposited into the wire with high efficiency and the wire is exploded extremely quickly to form a supersaturated vapor. The plasma formation and expansion process has been investigated from the time profiles of the current and emission of the discharge. Particles of less than 100 nm to several microns have been produced by exploding wire at atmospheric pressure and at low pressure (10^{-2} mbar). It has been observed that low filling pressure allows formation of smaller particles. The production of nanoparticles through wire explosion process is feasible. The effects of medium with different thermal conductivities as well as other operating conditions, including a bigger discharge chamber to accommodate the plasma expansion process are currently being investigated.

Acknowledgments

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References

[1] V. Ivanov, Y. A. Kotov, O. H. Samatov, R. Bohme, H. U. Karow and G. Schumacher, *Synthesis and dynamic compaction of ceramic nano powders by techniques based on electric pulsed power.* Nanostructured Materials, 1995. **6**(1-4): pp. 287-290.

[2] Y. -S. Kwon, Y. -H. Jung, N. A. Yavorovsky, A. P. Illyn, J. -S. Kim, *Ultra-fine powder by wire explosion method.* Scripta Materialia, 2001. **44**(8-9): pp. 2247-2251.

[3] T. K. Sindhu , R. Sarathi, and S. R. Chakravarthy, *Understanding nanoparticle formation by a wire explosion process through experimental and modelling studies.* Nanotechnology, 2008. **19**(2): p. 025703.

[4] A. E. Ter-Oganesyan, S. Tkachenko, V. Romanova, A. Mingaleev, T. Shelkovenko and S. Pikuz, *Nanosecond electric explosion of a tungsten wire in different media.* Plasma Physics Reports, 2005. **31**(11): pp. 919-926.

[5] S. I. Tkachenko, V. S. Vorob'ev and S. P. Malyshenko, *The nucleation mechanism of wire explosion.* Journal of Physics D-Applied Physics, 2004. **37**(3): pp. 495-500.

[6] G. S. Sarkisov, K. W. Struve and D. H. McDaniel, *Effect of deposited energy on the structure of an exploding tungsten wire core in a vacuum.* Physics of Plasmas, 2005. **12**(5): p. -.

[7] C. Cho, Y. W. Choi, C. Kang, and G. W. Lee, *Effects of the medium on synthesis of nanopowders by wire explosion process.* Applied Physics Letters, 2007. **91**(14): p. 141501.

[8] T. W. Hussey, , N.F. Roderick and R.J. Faehl, *Numerical simulation of the nonlinear evolution of an exploded wire plasma.* Applied Physics Letters, 1978. **33**(3): pp. 230-232.

[9] S. I. Tkachenko, S. A. Pikuz, V. M. Romanova, A. E. Ter-Oganesyan, A. R. Mingaleev and T. A. Shelkovenko, *Overvoltage pulse development upon electrical explosion of thin wires*, J. Phys. D: Appl. Phys. **40**(6), pp.1742-1750 (2007)