Effect of Ambient Pressure and Wire Parameters on Nanoparticle Characteristics during Microsecond Explosion of Aluminum Wire

J. Bai*, Z. Shi*, Z. Wu* and S. Jia*

*State Key Laboratory of Electrical Insulation and Power Equipment, Xi’an Jiaotong University, No. 28
Xianning West Road, Xi’an, Shaanxi Province, China, junbai1207@foxmail.com,
zqshi@mail.xjtu.edu.cn, wuziqian1993@163.com, sljia@mail.xjtu.edu.cn

ABSTRACT

Ambient pressure, wire purity and diameter have great effect on the morphology and size distribution of the nanoparticles during microsecond explosion of Aluminum wire. Experimental investigation is carried out in this paper. Basic characteristics of explosion and nanoparticles are analyzed at different air pressures and a threshold pressure is found for the wire of certain purity. The sputtering net structure of the products is also presented. Then the effect of wire purity and diameter is analyzed. It is found that bigger deposited energy will generate smaller and more centrally-distributed nanoparticles. Finally it is indicated that thinner wire is more easily exploded and generates larger nanoparticles.

Keywords: Aluminum nanoparticles, microsecond wire explosion, morphology, size distribution

1 INTRODUCTION

Al nanoparticles have important applications in various fields, e.g., solid rocket propellant, explosives [1], electronics [2], detection of biomolecules [3], and enhancement of the properties of various nanocomposites [4-6], etc. Among various synthesis methods of Al nanoparticles, microsecond explosion of wires (MSEW) has drawn attention of many researchers due to its abundant physical processes and various applications.

The synthesis of Al nanoparticles in different ambient gas has been investigated by some researchers. However, the medium pressure and wire parameters during MSEW, which may have significant effect on the morphology and size distribution of the Al nanoparticles, still require more research.

In this study, MSEW is carried out in a self-made chamber with different Al wire parameters and air pressures. The contents of this paper are arranged as follows. Firstly the experimental setup is described. Then the basic explosion characteristics along with the morphology and size distribution of Al nanoparticles are obtained. The effect of different experimental conditions is also discussed. Finally some conclusions are drawn.

2 EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in Fig. 1. L_0 and R_0 are the inductance and resistance of the experimental circuit, respectively. *EW* is the Al wire. A coaxial backflow structure is designed to conduct the current and fix the wire inside the chamber. The voltage across the wire and the current through it are measured using the voltage probe (Tektronix, P6015A, USA) and the self-integrating Rogowski coil (Pearson Electronics, Current monitor Model 4997, USA), respectively. The nanoparticles are collected on the surface of the monocrystalline silicon wafers, which are placed between the backflow rods around the Al wire. The morphology of the nanoparticles is acquired through the scanning electron microscope (SEM) (JEOL, 7800F, Japan). The details of the experimental parameters are listed in Table 1.

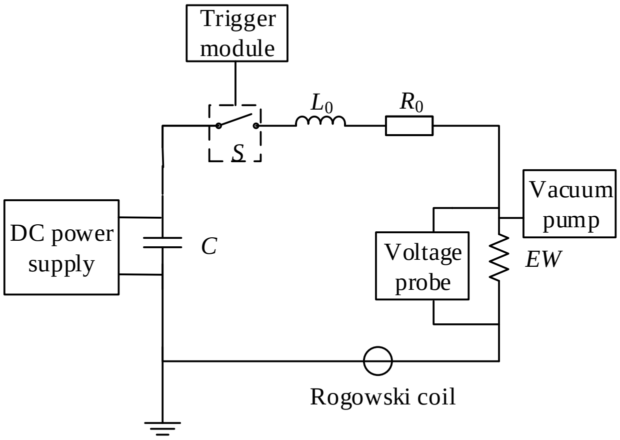


Figure 1: Schematic diagram of the experimental setup.

Wire material	Aluminum
Wire diameter	125, 200, 250 μm
Purity of the wire	99.999%, 99.5%
Length of the wire	1, 2 cm
Capacitance	0.5-2 μF
Charging voltage	10-20 kV
Ambient gas	Air
Pressure of the ambient gas	No more than 1 atm

Table 1: Details of the experimental parameters.

What we are concerned about is the actual resistively deposited energy on the wire. Therefore the inductive part should be removed from the measured voltage. This calls for the determination of the inductance of the coaxial structure, which is done through the short circuit experiment (wire replaced by a copper rod). The measured and fitted results are shown in Fig. 2. Therefore the inductance of the coaxial part is 1.52 μH and the resistance can be ignored as the resistive characteristics is not obvious.

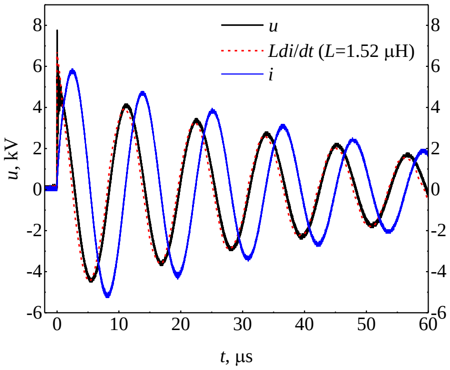


Figure 2: Measured and fitted results of the short circuit experiment.

3 RESULTS AND DISCUSSION

3.1 Typical Expetrimental Results

The typical experimental results mainly consist of the voltage and current waveforms, the calculated resistively deposited energy, the morphology and size distribution of the collected nanoparticles, as shown in Fig. 3 and 4. One can see that at the explosion moment, there appears a significant drop of the voltage due to the formation of Al plasma. The current transforms from the high-resistance Al vapor to the plasma of low-resistance. Therefore it shows an under-damped oscillation after a short-time plateau. The energy deposited into the wire is also terminated at the explosion moment, which is 6.72 eV/atom. From Fig. 4(a) one can see that most nanoparticles are spherical in shape. Some nanoparticles show a hexagonal shape, which should be the aluminum nitride formed by the reaction between the nanoparticles and the nitrogen in air. The size distribution is obtained by analyzing approximately 150 nanoparticles in different SEM images. It presents a normal distribution law.

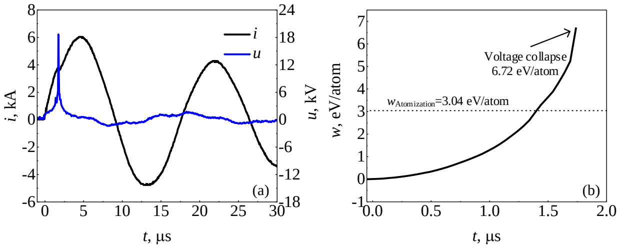


Figure 3: Measured waveforms (a) and calculated resistively deposited energy (b) under the condition 2μF/10kV/1atm/2cm/ϕ125μm.

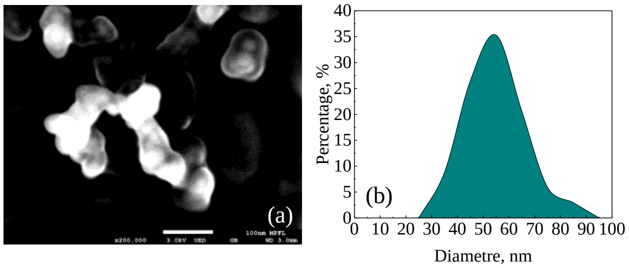


Figure 4: Morphology (a) and size distribution (b) of the collected nanoparticles under the same condition as Fig. 3.

3.2 Effect of Air Pressure

The basic characteristics of the explosion and the nanoparticles may change as the ambient air pressure decreases from the atmosphere pressure. Fig. 5 shows the resistive voltage at different air pressures. It can be seen that the voltage waveforms are nearly the same when the pressure is set more than 1 kPa. When the pressure is set 1 kPa, the feature of voltage breakdown is quite unobvious. It means that the threshold pressure (1 kPa) greatly limits the energy deposited in the wire and the surrounding vapor, which makes the wire unable to fully turn into the high-resistance metal vapor.

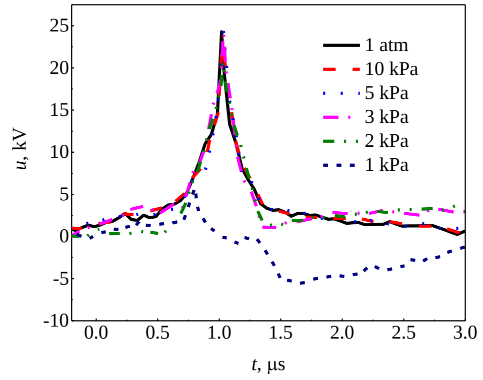


Figure 5: Resistive voltage at different air pressures under the condition 1μF/20kV/2cm/ϕ125μm.

From Fig. 6, one can see a tremendous drop of both peak voltage and deposited energy when the air pressure is set 1 kPa. The deposited energy has been lower than the atomization enthalpy, which means that the wire is not fully turned into gas atoms. The effect of this can be clearly identified in the SEM images of the nanoparticles, as shown in Fig. 7. The nanoparticles under 1 atm and 5 kPa are mostly spherical in shape. The size distributions under these two pressures are also nearly the same. In connection with Fig. 6, the deposited energy of these two conditions has little deviation, which demonstrates that the deposited energy is a key factor in deciding the morphology and size distribution of nanoparticles. When the pressure reaches the demarcation point 1 kPa, the morphology of the collected nanoparticles becomes quite different. Spherical nanoparticles are no more obviously formed. The collected products perform a sputtering net structure on the silicon wafer, as shown in Fig. 7 (e, f). From Fig. 6 one knows that the wire is not fully turned into gas atoms under these two pressures. This means that the fully vaporized wire is the foundation of the formation of the spherical nanoparticles and their centralized distribution, which are, as mentioned above, significant characteristics in the application of Al nanoparticles.

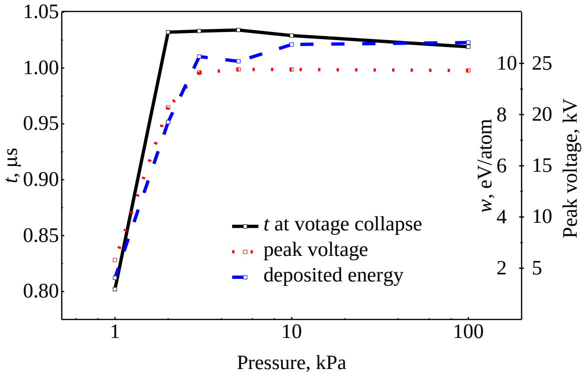


Figure 6: Characteristics at different air pressures under the same condition as Fig. 5.

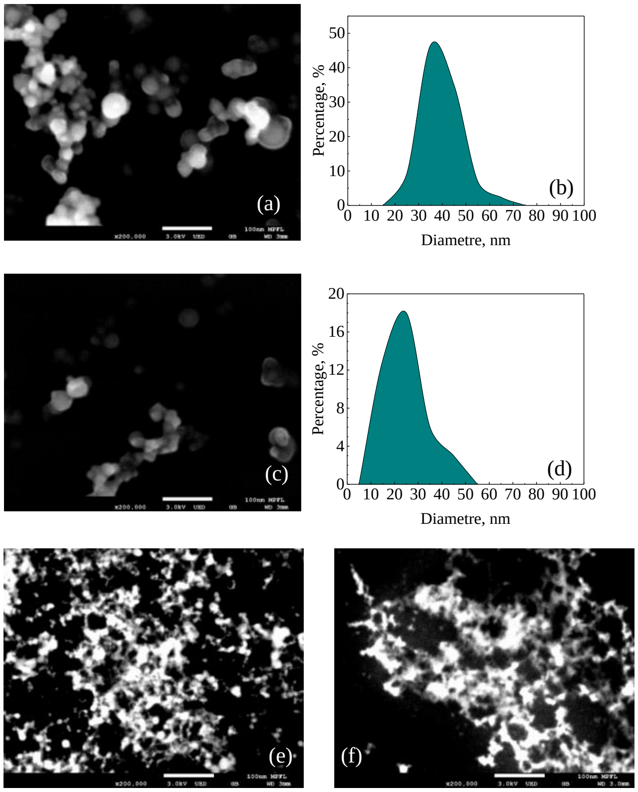


Figure 7: Morphology (a, c, e, f) and size distribution (b, d) of the collected nanoparticles at different air pressures: (a, b) 1 atm; (c, d) 5 kPa; (e) 1 kPa; (f) 0.5 kPa.

3.3 Effect of Wire Parameters

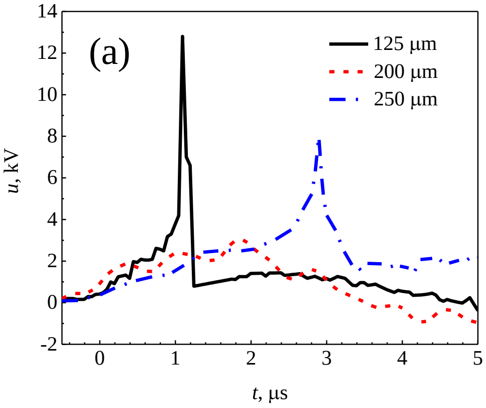
In order to investigate the effect of the wire parameters, the specific energy of the wire under different conditions is kept the same. It means that every single Al atom corresponds to the same capacitive storage. The energy stored by the capacitor bank can be written as

$$W = \frac{1}{2} C U^2 \tag{1}$$

where C is the capacitance and U is the charging voltage. In the experiment, the equal specific energy is achieved by adujsting the capacitance.

The resistive voltage of Al wire with different diameters at 10 kPa and the deposited energy at different pressures is shown in Fig. 8. Unlike the other two diameters, one can see an unobvious explosion feature with the 200 μm-wire. This should be owing to the different purity of the wire we used. The 200 μm-wire with high purity (99.999%) has fewer impurities on the surface and makes it hard to emit the surface electrons. Therefore the explosion features are far less obvious than the other two (99.5%). From Fig. 8(b) one can see that the deposited energy 200 μm-wire is below the atomization enthalpy at 10 kPa.

Although the specific energy is set equal for different diameters, one can see from Fig. 8(a) that the thinner wire is more easily exploded. It has a higher peak voltage and an earlier explosion time. This is due to the more rapid transfer of energy from the surface to the inside in the thinner wire. From Fig. 8(b) it can be seen that the deposited energy of the thicker wire is more than the thinner one due to the longer deposition time.



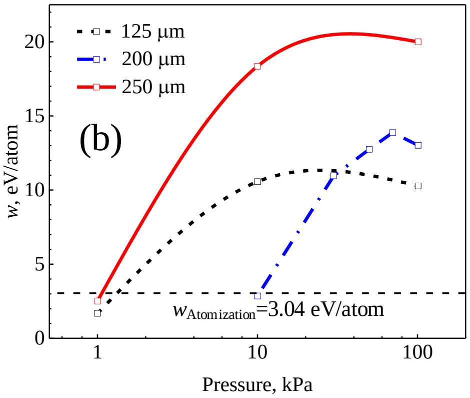
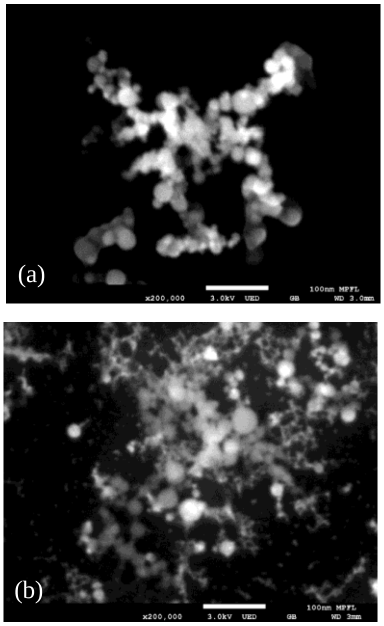


Figure 8: Effect of wire diameter and purity under the condition 20kV/1cm: (a) resistive voltage under 10 kPa; (b) deposited energy under different pressures.

The morphology of the collected nanoparticles at 10 kPa air with different wire diameters is shown in Fig. 9. One can see again the sputtering net structure with the 200 μm-wire due to the insufficient energy deposited therein. Fig. 10 presents the size distribution of 125 μm and 250 μm-wire. One can see that the size distribution of 250 μm-wire is smaller than the other one. It is due to the larger deposited energy of the 250 μm-wire as shown in Fig. 8(b) and it is favorable for the smaller and more centralized size distribution of nanoparticles. The average diameters under these two conditions are 20.95 nm and 23.10 nm, respectively.



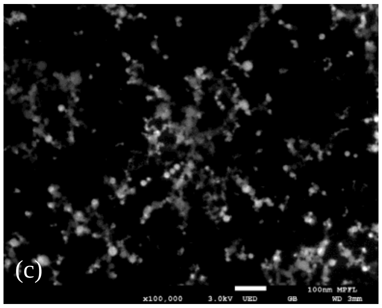


Figure 9: Morphology of the collected nanoparticles in 10 kPa air with different wire diameters: (a) 125 μm; (b) 200 μm; (c) 250 μm.

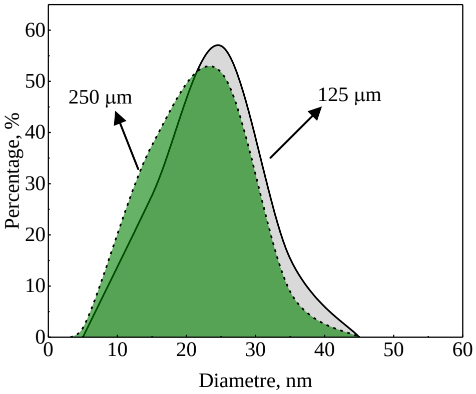


Figure 10: Size distribution of 125 μm and 250 μm-wire

4 CONSLUSIONS

In this paper, the effect of ambient air pressure, wire purity and diameter on the morphology and size distribution of the collected nanoparticles during microsecond explosion of Aluminum wire is investigated experimentally. It is indicated that larger deposited energy is favorable for the smaller size and more centralized distribution of nanoparticles. There exists a threshold pressure of certain wire purity below which the collected nanoparticles will perform a sputtering net structure. Finally, it is found that thinner wire is more easily exploded under equal specific energy and generates bigger nanoparticles.

REFERENCES

[1] M. Kearns, Mater. Sci. Eng. A 375-377, 120, 2004.
[2] V. Reddy, S. Karak, S. Ray and A. Dhar, Org. Electron. 10, 138, 2009.
[3] M. Chowdhury, K. Ray, S. Gray, J. Pond and J. Lakowicz, Anal. Chem. 81, 1397, 2009.
[4] X. Zhong, W. Wong and M. Gupta, Acta. Mater. 55, 6338, 2007.
[5] G. Liang and S. Tjong, Adv. Eng. Mater. 9, 1014, 2007.
[6] B. Mary, C. Dubois, P. Carreau and P. Brousseau, Rheol. Acta. 45, 561, 2006.