Powder Technology 295 (2016) 307–314

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Synthesis of *Al* nanoparticles and *Al*/AlN composite nanoparticles by electrical explosion of aluminum wires in argon and nitrogen

Marat I. Lerner [a], Elena A. Glazkova [a,b], Aleksandr S. Lozhkomoev [a], Natalia V. Svarovskaya [b], Olga V. Bakina [a,*], Aleksandr V. Pervikov [b], Sergey G. Psakhie [a,b]

[a] National Research Tomsk Polytechnic University, 30 Lenin Prospekt, Tomsk 634050, Russia
[b] Institute of Strength Physics and Materials Sciences of the Siberian Branch of the Russian Academy of Sciences, 2/4, pr. Akademicheskii, Tomsk 634021, Russia

ARTICLE INFO

Article history:
Received 14 September 2015
Received in revised form 3 March 2016
Accepted 4 April 2016
Available online 7 April 2016

Keywords:
Electrical explosion of wire
Nanoparticles
Powders
Aluminum
Aluminum nitride
Coagulation

ABSTRACT

During the electrical explosion of aluminum wires in argon and nitrogen, *Al* nanoparticles and *Al*/AlN composite nanoparticles were synthesized. The as-prepared samples were characterized by transmission electron microscopy, energy dispersive X-ray microanalysis, X-ray diffraction and Brunauer–Emmett–Teller specific surface area measurements. The parameters of the electrical explosion of wires and the gas medium influenced the average size of the nanoparticles and the content of aluminum nitride in the powder. A nanoparticle formation mechanism caused by the coagulation of the primary particles generated in the early stages of the electrical explosion of the wires has been proposed.

1. Introduction

Aluminum nanoparticles are interesting nanomaterials due to their numerous potential applications. The high reactivity of aluminum nanoparticles makes them promising for use in high-energy compositions [1] and hydrogen production in reactions with water [2] as well as the synthesis of alumina 2D and 3D structures [3].

The unique properties of aluminum nitride (AlN), e.g., high thermal conductivity [4], thermal expansion coefficient, low dielectric constant and mechanical strength [5], are of considerable importance for electron, refractory and ceramic materials. AlN nanoparticles have a wide range of applications in various high-technology industries. *Al*/AlN nanoparticles as precursors are used for the creation low-dimensional structures with different morphology and phase compositions [6].

Generally, there are various methods to synthesize *Al* and AlN nanoparticles. Aluminum nanoparticles are prepared chemically [7], with mechanochemical process [8], sonoelectrochemical process [9], laser ablation in solution [10], by arc plasma in gas [11]. To obtain aluminum nitride nanoparticles such methods are used as evaporation of micro-sized *Al* powders non-transferred arc plasma in ammonia [12], laser ablation [13], thermochemical pathway [14], electrochemical low-temperature nitridation of the metallic aluminum [15], the use of organometallic precursors and solid state reaction by plasma assisted high energy ball milling [16].

A promising method for producing nanoparticles with metal and chemical compositions (e.g., oxides, nitrides and carbides) involves the electric explosion of wires (EEW) [17]. The EEW allows preparing high purity nanoparticles, to control the nanoparticle size, the method being ecologically safe and providing a sufficiently high production rate [18]. The EEW is a process with high rates of variation in the thermodynamic parameters of the system, which is achieved when current with a density of 10^6–10^9 A/cm^2 passes through a metal wire.

During the EEW the expanding electrical explosion products for some time keep the cylindrical symmetry and do not mix with the ambient gas. The density of the substance in the cylinder is significantly greater than the gas density [18,19]. According to the data [20–23] the explosion products represent a system of submicron particles dispersed in a metal vapor (liquid metal — gas/plasma). The EEW products are expanded to gases at rates of several 1000 m/s, which results in a cooling rate of 10^{10} K/s [24] and the formation of nanoparticles. During the EEW, the heating of the wire occurs by two current pulses. In the course of the first current pulse, the wire is heated, melted and continues to heat up in a liquid state. The resistance of the wire begins to grow due to its heating and the explosive expansion of wire. The wire loses metallic conductivity and the current in the circuit is cut off. The material of the wire extends to the ambient gas. When the EEW products are expanding, their resistance is decreased, and if there is sufficient energy

* Corresponding author.
E-mail address: ovbakina@ispms.tsc.ru (O.V. Bakina).

http://dx.doi.org/10.1016/j.powtec.2016.04.005
0032-5910/

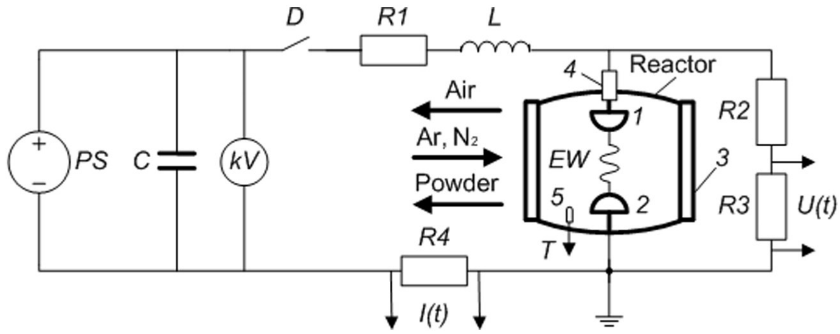

Fig. 1. Circuit diagram of the facility employed for the production of aluminum and aluminum nitride nanoparticles.

in the capacitor, the second current pulse (arc discharge plasma) through the explosion products is developed.

The authors [18,25] have shown that the particle size depends not on the injected energy, but on the overheat *K* of the wire material, i.e., the ratio between the energy transferred to the wire during the first current pulse *W* and the specific energy of sublimation W_s (J/mm^3). The nanoparticle size was shown to be inversely proportional to magnitude *K*. The effect of energy transferred into arc discharge plasma on nanoparticle size was not considered. Effects of arc plasma and ambient gas species on the characteristics of the nanoparticles produced by wire explosion technique have been investigated in [26–29].

Based on the fact that the energy transferred to the wire during the first current pulse is higher than that required to melt the metal, the authors [28] suppose the wire material to be before the formation of arc plasma a mixture of liquid and vapor. During the formation of arc plasma, the liquid–vapor mixtures may be heated additionally [30]. As the pressure decreases, the formation of the arc plasma occurs at an earlier time for N_2 and He, hence the heating of the liquid vapor mixture is higher. Due to this increase in heating of the wire material, the particle size increases with decreasing pressure in N_2 and He [29].

Accordingly, two probable sources of heating the wire are reported in papers, which can affect the nanoparticle sizes. These are: a) energy E_1 released during the first current pulse at heating and evaporation of wire metal [18,26], b) energy E_2 released during the second current pulse in the arc discharge plasma formed in the electrical explosion products [27–30]. In papers [18,26–30] the concerted effect of E_1 and E_2 on the nanoparticles was not considered.

Also, the mechanism nanoparticle formation in the EEW is not clear. According to [18,25–30], the expansion of the wire material is due to the liquid–vapor mixture. Respectively, the explosion products must contain primary the particles of condensed phase formed at wire explosion. Moreover, the primary particles, as well as the ions, can be centers for the metal vapor condensation to allow the nanoparticle growth. In the above papers, the role of the primary particles during the formation of nanoparticles was not considered.

A direct study of the process of nanoparticle formation is difficult due to the small space and time scale of the EEW. However, some information regarding the nanoparticle formation process can be obtained by studying their characteristics in relation to the synthesis conditions.

The aim of this research was to reveal the influence of E_1 and E_2, the gas pressure and the diameter of the wire at the electric explosion of aluminum wires in argon and nitrogen on the characteristics of the *Al* and *Al*/AlN nanoparticles. Based on the conditions of production and the characteristics of the nanoparticles, a possible mechanism for their formation during the combining of primary particles is proposed.

2. Materials and methods

Aluminum and aluminum nitride nanoparticles were synthesized using the circuit diagram shown in Fig. 1. *Al* and *Al*/AlN nanoparticles were produced using the following method. A high-voltage source (*PS*) charged the capacity storage (*C*) to the required voltage and was controlled by a kilovoltmeter mounted to the *SP*.

The energy storage system (*C*) consists of a pulse capacitor bank IK-100-0.4 (100 kV, 0.4 μF) connected in parallel. After switching on the discharger (*D*), the energy stored in *C* is transferred to the aluminum wire (*EW*), which is located between high-voltage electrode 1 and grounded electrode 2. The high-voltage electrode 1 is introduced in the Reactor through the bushing isolator 4. The discharge current ($I(t)$) and voltage ($U(t)$) are recorded using a current sensor (*R*3), voltage sensor (*R*1–*R*2) and TDS2022B oscillograph. *R*1 and *L* are the intrinsic resistance and self-inductance, respectively, of the electric circuit of the facility.

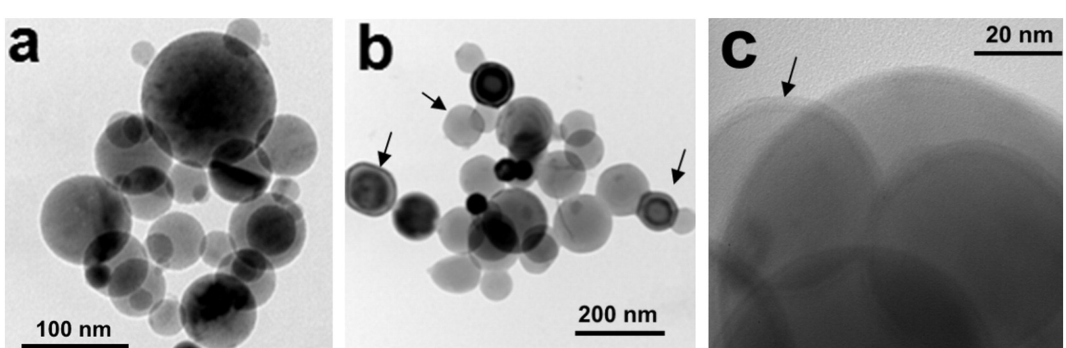

Fig. 2. Typical TEM images of the aluminum nanoparticles produced at $W_m = 1.6$ (a), $W_m = 2.5$ (b) and a fragment of nanoparticles coated with an alumina layer which is marked with an arrow in Fig.(c) and nanoparticles synthesized at a pressure of argon $P_{Ar} = 0.5$ MPa, $d_0 = 0.38$ mm.