High Energy Density Physics 17 (2015) 270–276

Contents lists available at ScienceDirect

High Energy Density Physics

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

Effect of energy deposition rate on plasma expansion characteristics and nanoparticle generation by electrical explosion of conductors

Somanand Sahoo, Alok K. Saxena, Trilok C. Kaushik *, Satish C. Gupta

Applied Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India

ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form 6 October 2015
Accepted 20 October 2015
Available online 2 November 2015

Keywords:
Nanoparticles
Electrically exploded foil
Exploding wire
Pulse discharge
Overheat factor
Plasma expansion rate

ABSTRACT

The process of electrical explosion of metal conductors has been used to produce nano particles under normal atmospheric conditions. The impact of average rate of energy deposition, overheat factor on size distribution of particles and expansion characteristics of plasma generated from exploding conductors have been experimentally investigated. The particle size was characterized by TEM and XRD while expansion rate was measured using streak photography.The geometric mean diameter of size distribution was found to be influenced by rate of energy deposition in the conductors. It is observed that higher the rate of energy deposition, higher will be the expansion velocity, and smaller will be the size of particles formed.

1. Introduction

When a high current pulse, which is usually produced by the discharge of a capacitor bank, passes through a thin metal conductor, the energy deposited may exceed the vaporization energy of the material. As a result, the material rapidly boils up and finally results in a burst, accompanied by a bright flash light. A mixture of superheated vapour and droplets of exploded material is scattered into the surrounding medium. The energy density in the exploding metal conductor is of the order of 10^{11} J/m^3 which is many times more than that in chemical explosive, generally known as a very high energy density source. In capacitor based pulse power systems, current is decided by the electrical circuit parameters such as capacitance C of capacitor, inductance L of the discharge circuit, charging voltage of the capacitors, and dimensions of exploding conductor [1]. The exploding conductor technique has a number of applications such as shock wave generation in solids [2], x-ray generation [3], and opening switches [4]. Exploding conductor technique is also used as an ion source for intense pulsed beam accelerators [5].

Recently, this technique has gained the research interest in the synthesis of nanoparticles with controlled particle size. Conventionally solid nanoparticles have been prepared in gas phase or liquid phase. But lowering energy consumption, increasing production rate and reducing equipment cost are challenging issues in these processes. Most of the energy used in gas-phase synthesis is consumed in raising the energy state of atoms to high temperature. The energy conversion efficiency can be increased by decreasing heat dissipation from the materials [6]. Exploding conductor method helps to achieve that by supplying an intense pulsed current to the material directly. Some of the initial work in the field of exploding wires have been carried out by Nairne as early as in 1774 as reported in Reference [7]. The experimental set up is relatively simple to realize in a high voltage, high energy density laboratory due to ease of availability of necessary infrastructure.

Recently, new technologies of industrial metal nanopowders production have been developed with increased interest in use of nanopowders as main components of energetic materials [8]. The results of research works have indicated prospective use of nano aluminium as a component of high energy material not only to enhance the energy characteristics of the propellant, but also to reduce the agglomeration rate and increase the combustion rate [8]. Other applications of aluminium nanopowders include as a support to high surface area catalyst; as anti-microbial, anti-biotic, antifungal agents in plastics and textiles; in super strong metals and alloys; as nano-crystalline aluminium alloys for space applications as a substitute for titanium. Further research is being carried out for their potential electrical, dielectric, optical, imaging, bio medical properties [9].

Characterization of the plasma generated from an exploding conductor is necessary for not only its understanding, but also helpful in explaining the physical processes and to construct theoretical models for this phenomenon. Models have been reported [10] that incorporate MHD instabilities, both thermal and non-thermal, and

* Corresponding author. Applied Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India.
E-mail addresses: tckk@barc.gov.in; kaushiktin@yahoo.com (T.C. Kaushik).

http://dx.doi.org/10.1016/j.hedp.2015.10.002
1574-1818/

their effect on process of metal dispersion, condensation process and thereby the size distribution. Understanding the dynamics of explosion and generated plasma is also relevant to its other applications such as opening switch and wire array z-pinch schemes [11]. Theoretical models on exploding aluminium foils suggest that appearance of plasma is related to ejection of metal vapour during metal boiling. Images of exploding aluminium foils by the fast framing camera show the evolution of discharge radiation [12]. It is worthwhile to mention that apart from direct streak photography carried out in this work, self emission spectroscopy [13], Kerr cell photography, X-ray shadow photography, and laser interferometry are some other common techniques which have also been reported to measure plasma expansion rate from exploding conductors.

Average size and size distribution of nanoparticles generated by this method depends on the energy deposited in the conductor, as well as on surrounding gas and its pressure [1,6,14]. Therefore, it is imperative to choose appropriate experimental parameters in order to obtain nanopowders with desired size characteristics. This paper reports experimental investigations on explosion characteristics, design of conductor parameters, and effect of rate of energy deposited into aluminium conductor on size distribution of generated nanoparticles. Since size characteristics of the nanoparticles could also depend on the volume and rate of expansion of plasma generated from electrical explosion of metal conductors, present work experimentally also looks at possible relationship of plasma expansion velocity with the specific energy deposited in the conductor and further to the nanoparticle characteristics. The influence of overheat factor on size distribution of nanoparticles as reported in papers [1,6,14] has also been verified.

2. Experimental description

2.1. Design of operational parameters

Action integral is an important quantity utilized to study the phenomenon of exploding conductors which could be in form of a wire or a foil. For a metallic conductor of length "ℓ" and area of cross section "A", power P(t) dissipated into the conductor due to flow of current I(t) at time "t" is given by

$$P(t)=R(t)\cdot I(t)^2, \tag{1}$$

$$P(t)=\frac{\eta(t)\cdot\ell}{A}\cdot I(t)^2, \tag{2}$$

where $\eta(t)$ and R(t) are the resistivity of the material and resistance of the conductor respectively at time "t", assuming there is no change in ℓ and A until the time of burst. If E is internal energy per unit mass of the material, then at any point of time power dissipated in the conductor due to Joule's heating can be written as

$$P(t)=m\cdot\frac{dE}{dt}. \tag{3}$$

Eqs. (2) and (3) give

$$\frac{\eta(t)\cdot\ell}{A}\cdot I(t)^2=m\cdot\frac{dE}{dt}, \tag{4}$$

where m is the mass of the conductor. Resistivity $\eta(t)$ changes as specific internal energy of the conductor changes and hence can be expressed as $\eta(E)$. Considering ρ as density of the material, Equation (4) can be rearranged as following

$$\frac{\ell}{A\cdot m}\cdot I(t)^2\,dt=\frac{1}{\eta(E)}dE, \tag{5}$$

$$\frac{I(t)^2}{\rho\cdot A^2}dt=\frac{1}{\eta(E)}dE. \tag{6}$$

Up to the time of burst t_b, the above equation can be written as

$$\frac{1}{A^2}\int_0^{t_b} I(t)^2\,dt=\rho\int_{E_0}^{E_V}\frac{1}{\eta(E)}dE=a, \tag{7}$$

where "a" is termed as the action integral of the material and has dimension of A^2s/mm^4. Action integral is mainly dependent on the material properties and hence considered constant for a given material. E_O and E_V are the total internal energy of the conductor at room temperature and point of vaporization respectively. Action integral represents the pre explosion thermal toughness of the material. An empirical relation for energy W deposited in the conductor has been reported [1] as:

$$W=\left(aW_oA^2Z\right)^{1/2}. \tag{8}$$

Here, W_o is the total stored energy in the capacitor and $Z=\sqrt{L/C}+R_c$ is the characteristic impedance of an RLC circuit. However, R_c, the resistance of the circuit in our experiments can be neglected as it is much smaller than the passive resistance $\sqrt{L/C}$. The conductor parameters have to be designed so as to cause the burst to occur around quarter cycle of damped oscillation to utilize most of the energy stored in capacitor.

The vaporized metal conductor after burst forms a dense gaseous/plasma column which expands subsequently. There are now two possibilities, one is surface breakdown and the other is current dwell or pause. If the conductor is not long enough, breakdown takes place in the surrounding medium, thus shunting the current on the surface. So the current re-strikes after a non-zero minimum. But in case of a conductor longer than a particular length, current falls nearly to zero and this time persists for certain duration called dwell time. A re-strike takes place as the vapour column slowly expands out, reducing the pressure and the breakdown voltage. The transition between these two regions takes place at *critical length* of the conductor. Critical length (l_c) was reported to be predicted by the following relation [1]

$$l_c[mm]=B(W_0dLZ)^{0.36}, \tag{9}$$

where B is a material dependent parameter equal to 27.7 for Al, 18.5 for Cu as reported in Reference [1] while d is diameter of conductor in mm, L is expressed in μH and W_0 is the stored energy in capacitor expressed in "Joules". The current at burst (I_b) could also be predicted by the empirical relation [1]

$$I_b=0.75I_0\left(aA^2Z/W_0\right)^{0.25}, \tag{10}$$

where I_o is the amplitude of short circuit current in the same RLC circuit.

Experiments with copper wires have been conducted by us to validate these parameters with their predicted values based on relations reported in Reference 1 and mentioned in Eqs. (8)–(10). Based on these experiments, it has been confirmed that burst current, critical length, and the energy deposited in the conductor could be designed as per the requirements of the experiment to an accuracy of 70–80% of their predicted values for further experiments on aluminium foils. Subsequently, experiments have been carried out to study the variation of average size of nanoparticles with respect to rate of energy deposition, overheat factor and possible relationship with expansion velocity of plasma generated from exploding conductor. Overheat factor K is defined as the ratio of energy deposited in the conductor to the characteristic energy of the conductor