Dynamical aspects of nanoparticle formation by wire explosion process

P Ranjan, D H Nguyen, L Chen, I Cotton, H Suematsu, S R Chakravarthy, R Jayaganthan and R Sarathi

1 Department of Electrical and Electronic Engineering, The University of Manchester, Manchester, M13 9PL, United Kingdom
2 Extreme Energy-Density Research Institute, Nagaoka University of Technology, Nagaoka 940-2188, Japan
3 Indian Institute of Technology Madras, Chennai, 600036, India

E-mail: prem.ranjan@manchester.ac.uk

Keywords: nanoparticles, wire explosion, Fick’s diffusion, copper, critical size

Abstract
Copper nanoparticles (NPs) were produced by wire explosion process (WEP) and it was noted that the amount of energy (E) deposited on the wire and the ambient pressure play a major role on the size of particles formed. Dynamic diffusion and condensation processes of NPs formation by WEP were modelled. Calculations of critical size of embryo, activation energy and nucleation rate of the formation of NPs in WEP were made considering classical homogeneous nucleation theory. Decrease in critical size of nuclei and activation energy, increase in nucleation rate with high E (540 J) and low operating pressure (10 kPa) confirm the formation of small size NPs (26 nm). Different cooling rates due to unsymmetrical shape of the vapour cloud has been identified as the cause for generating mixed particle sizes. The qualitative analysis conducted in this work validates the obtained experimental results and can be used as a design tool for industrial apparatus to produce NPs in bulk.

1. Introduction

Nanotechnology provides a systematic control on the morphology of functional nanomaterials and its unique characteristics have potential applications in catalysis, nano-manufacturing, photonics, sensor technology, environmental remediation etc (Rogers et al 2015). The desired properties of nanomaterials could be achieved by specifying its shape, size, phase and its composition (Aliofkhazraei 2016). Precious metal nanoparticles of different sizes and colours were produced by exploiting the property of quantum confinement (Fatti et al 2000).

Various techniques were employed worldwide to synthesize NPs of controlled morphology and phase. Solid state top down methods including ball milling need a long processing time (Koch 1997). Many chemical methods like sol-gel, hydrothermal etc require a number of steps and precursors to obtain pure NPs (Yu et al 2000). Gas/vapour phase methods which were based on the condensation of vapour of materials to get its NPs, e.g. thermal plasma torch, pulsed laser deposition, arc plasma synthesis etc (Kruis et al 1998) has low energy conversion. The principle of wire explosion process (WEP) is based on the pulsed current injection through the conducting wire (mostly metal) to vapourise it after the joule heating (Kotov 2003). It utilizes the wide difference in temperature and density of the vapour and that of the ambient fluid which acts as the cooling medium. The process of solidification of supersaturated vapour in proper inert atmosphere form the metallic nanoparticles (Sindhu et al 2007).

Tokoi et al 2013 used high speed photography to calculate the density ($D_{vap}$) of the vapour/plasma of Copper (Cu) produced after the explosion and found that for a wire with constant mass ($M_{wire}$), its volume of vapour cloud, $V_{vap}$ increases with an increase in deposited energy and/or a decrease in pressure, P; which leads to decrease in $D_{vap}$. Shikoda et al 2009 calculated the expanding diameter, $d_{vap}$ and the temperature (T) profile of Cu vapour for different P and found that $d_{vap}$ and the cooling speed of the vapour increase with decrease in P. Thermodynamic calculation of nucleation rate and the activation energy using the classical
homogeneous nucleation theory for the formation of embryo in WEP also leads to the same conclusion correlating it with high temperature and supersaturated vapour (Ranjan et al. 2017).

In the preparation methods of NPs from vapour/plasma of metal, one of the possible steps before the condensation is the diffusion/effusion of the metal vapour into ambience. Bora et al. 2014 used ICCD (intensiﬁed charge coupled device) images to see the diffusion of Cu vapour during the heating process in WEP and explained the partial reheating of the vapour/plasma during arc discharge. Recently, Zhao et al. 2017 described the WEP using the diffusion of generated Aluminium plasma into Argon ambience. Latest work published by Han et al. 2020 describes the quenching of Cu vapour in WEP as diffusion of discharge channel and the ambient. These works talk about the basic physics of WEP but the discussion on the diffusion for dynamics of particle formation is missing. The speed of diffusion depends on the concentration/DenVap, temperature gradient and pressure difference of the two gases (vapour/plasma of metal and the ambient). The kinetics would lead to the different morphology of formed NPs as shown by Simchi et al. 2007 for Silver and Cu-Tin alloy in vapour phase condensation process. Hence, it is necessary to have a qualitative evaluation of the manufacturing process to design the apparatus for large scale industrial production of NPs. However, theoretical computation for the kinetics of NPs formation in WEP has not been investigated.

Based on the known facts, the present study aims to calculate through Fick’s diffusion, the kinetics and concentration proﬁle of the vapour/plasma generated in WEP as a function of time with the radial distance of the wire vapour. The process of NPs formation in WEP with different energy and P are discussed. Deposited energy to the wire was calculated and expansion of vapour was observed with high speed camera. SEM was used to see the morphology. The critical embryo size and its activation energy were calculated as a function of temperature and saturation ratio. The variation in nucleation rate considering the homogeneous nucleation in vapour phase is elaborated in the present work.

2. Experimental details

Figure 1 shows the schematic of WEP experimental setup. In the present study, nano Cu powder is produced in Ar ambience. The speciﬁcations of Cu conductor used in the present study is provided in table 1. Charging circuit consists of a high voltage DC supply which charges the capacitor bank of total capacitance, Cap to the required voltage, Vc. Energy stored in Cap (Ecap = 0.5CapVc²), is discharged through the wire using gap switch and its controller leading to joule heating of the wire. Ecap is always greater than the vaporisation energy, Evap, which vapourises the wire. Ratio of Ecap and Evap is deﬁned as the relative energy, or reheating factor or energy ratio/factor, K. Formed NPs were collected on the membrane filter (Millipore, 0.1 μm pore size) placed between the chamber and the vacuum pump.

The voltages at each electrode, V1 and V2; and current, I during the explosion were measured using two voltage probes (Tektronix P6015A) and a current transformer (C.T., Pearson 101) respectively as shown in ﬁgure 1. Voltage outside the chamber, V as shown in ﬁgure 2, V = V1 − V2. The deposited energy on the wire during WEP, EWire is the time integral of instantaneous power (VWire * I) and is expressed as equation (1),

![Figure 1. Schematic representation of wire explosion process setup.](image-url)
where,

\[ V_{\text{Wire}} = V - (V_R + V_L) = V - \left( R_C \cdot I + L \cdot \frac{dI}{dt} \right) \]  

and \( V_R (R_C \cdot I) \) and \( V_L (L \cdot dI/dt) \) are voltage drops across the circuit resistance (sum of resistance of electrodes and the wire), \( R_C \) and inductance \( L \) respectively. The values of \( R_C \) and \( L \) were measured experimentally to be 1 m\( \Omega \) and 250 nH respectively.

The explosion of wire followed by formation of Cu vapour cloud and its interaction with ambient gas during WEP were observed using a high speed camera (Photron Fastcam SA4) seeing through the quartz window of the chamber. In the present study, the explosion process was captured at 150,000 frames per second. A scanning electron microscope (SEM; FEI Quanta FEG 200) was used to observe the morphology of WEP synthesized NPs. Sizes (Heywood diameter, diameter of circle with area equal of 2D projection of 3D object) of about 500 NPs were measured using ImageJ software which follows log normal distribution as per equations (3)–(5),

\[ f(d) = \frac{1}{\sqrt{2\pi} \sigma_g} \exp \left( -\frac{(\log d - \log D_{50})^2}{2(\log \sigma_g)^2} \right) \]  

\[ \sigma_g = \sqrt{\frac{\sum n_i (\log d - \log D_{50})^2}{\sum n_i}} \]  

\[ \log D_{50} = \frac{\sum n_i \log d_i}{\sum n_i} \]  

where, \( f(d) \) represents the log-normal distribution, \( d \) and \( D_{50} \) are the particle and geometric mean diameter, respectively, \( n_i \) and \( d \) are the number of particles and its diameter respectively, and \( \sigma_g \) is the geometrical standard deviation.

### 3. Results and analysis

In this section, we will go through the energy deposition to the wire and effect of different pressure and energy on the vapour cloud expansion and particle size. Calculation of vapour concentration profile will be carried out considering its effusion in the ambience. Finally, calculated activation energy and nucleation rate will be correlated qualitatively with vapour concentration and different size NPs produced.
3.1. Energy deposition in WEP

Energy deposited to the wire during WEP was calculated using equation (1), and plotted in figure 3 along with corresponding voltages and currents. First jump in voltage is due to sudden application of voltage across the wire, which causes the wire to melt and the point of evaporation happens at the peak of the voltage curve. Oscillations in current and voltage waveforms are due to inductance being present in the circuit (Ranjan et al 2019). There is no dwell time observed in the present work. Amplitude of the voltage peak increases and instant of its occurrence decreases with increase in K because of the high energy deposition. Total and rate of deposition of energy to the wire also increases with an increase in K. Rate of deposition increases due to fast melting of the wire. There are two parts of energy deposition: (a) wire heating occurs before evaporation and (b) arc discharge takes place after evaporation. Most of the energy is deposited in the process of arc discharge as evident from the literature (Ranjan et al 2019). The formation and morphology of vapour cloud from the wire depends on the energy deposited during arc discharge.

3.2. High speed imaging

Figure 4 shows the high-speed photographs of vapour cloud during WEP. The area of the light emission (volume of the Cu vapour cloud) increases with increase in K and/or decrease in P. For increasing K, the area increase is attributed to higher energy deposition, whilst the change in area due to decreasing P is because of the fact that, vapour cloud expands more and expansion rate will be faster if the pressure gradient is higher. Luminescence time decreases with decreasing P for K3 due to fast expansion i.e. volume is more which leads to less dense vapour/plasma cloud subsequently resulting in faster cooling of vapour and yielding smaller dimensioned NPs.
Vapour cloud expands (figure 4) even after the instant of voltage peak (less than 7 μs) and current peak (less than 10 μs) as shown in figure 3.

3.3. SEM and particle size distribution studies
Figure 5 shows the SEM micrographs of NPs produced at different K (1, 3) and P values (10, 100 kPa). Shape of the NPs is spherical in all cases in the present work. Size distribution follows log normal distribution as per equations (3)–(5). Figure 6 shows the particle size distribution of NPs produced by WEP and table 2 tabulates the mean size and standard deviation of the NPs. Standard deviation for all the case is approximately 1.6–1.7. Size of NPs decreases with increase in K and/or decrease in P similar to findings of previous work (Kotov 2003, Ranjan et al 2019).
is due to less dense vapour cloud and fast cooling when wire is subjected to high K in low pressure ambient as discussed in section 4.2.

3.4. Kinetic modelling of vapour/plasma cloud

3.4.1. Concentration profile of vapour/plasma

Cu metal was chosen for all the calculations as there has been extensive research work carried out to describe the physics and NPs formation in WEP using Cu vapour for the modelling (Han et al 2020, Bora et al 2014, Shikoda et al 2009, Yin et al 2019, Tokoi et al 2013). Fick’s second law (Crank 1975) was used to describe the kinetics and profile of effusion of metal vapour into inert ambience.

In WEP, on deposition of energy to the conductor, joule heating occurs followed with formation of highly conductive plasma/vapour. High speed photographs measuring the expansion diameter of the vapour cloud was reported by Tokoi et al 2013. The first instant of the maximum expansion (formation of the metal vapour cloud) is the first step of interest (time, \( t = 0 \)) for our problem. After this, effusion takes place due to high difference in the density of metal vapour, which is transient and varies with radial distance. Fick’s second law is chosen to model the transport of the metal vapour. Figure 7 shows the schematic representation of expanded vapour/plasma, which is considered as sphere of radius R and r denotes the radial distance from the centre of the sphere.

For spherical geometry, Fick’s law can be written as (Crank 1975) as equation (6),

\[
\frac{\partial C}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 D \frac{\partial C}{\partial r} \right)
\]

where, \( r \) is the radial distance from the centre/core of the vapour cloud, \( C \) is the concentration of vapour cloud and \( D \) is the diffusion coefficient, which is defined using equation (7) as follows for binary gases A and B (Hirschfelder et al 1964);

\[
D_{AB} = D_{BA} = \frac{3}{16n} \left[ \frac{2 k_B T (M_A + M_B)}{\pi M_A M_B} \right]^{\frac{1}{2}} \frac{1}{\Omega_{AB}}
\]

where, \( M \) is molar mass of gas in kg/mol, \( n \) is the number density, \( T \) is the temperature in K, \( k_B \) is Boltzmann’s constant \((1.3807 \times 10^{-23} \text{ J K}^{-1})\), \( \Omega_{AB} \) is a collision integral for the interaction between species A and B.

| Sample      | Mean diameter (nm) | Standard deviation (nm) |
|-------------|--------------------|-------------------------|
| K1, P = 10 kPa | 34.2               | 1.69                    |
| K1, P = 100 kPa | 39.1               | 1.64                    |
| K3, P = 10 kPa | 26.7               | 1.68                    |
| K3, P = 100 kPa | 34.5               | 1.73                    |

Figure 6. Particle size distribution of NPs synthesized by WEP at different K (1, 3) and P values (10, 100 kPa).

Table 2. Mean particle size and standard deviation of nanoparticles produced at different K and P values.
Formation of nanoparticles depends on the diffusion of vapour into ambient which in turn is a function of concentration of the metal vapour generated. Hence, it is quite imperative to have the concentration profile of the vapour as function of \( t \) and \( T \). The solutions of equation (6) with \( D = 0.008 \text{ m}^2 \text{s}^{-1} \) (Murphy 1996), initial and boundary conditions as given by equations (8) and (9) respectively, were obtained numerically. Initial conditions are the concentration, \( C(r, t = 0) \) defined from equation (8) for different value of capacitor energy and ambient pressure as provided in table 3 (calculated through equations (11) and (12)).

Initial condition, \( C(r, t = 0) \)
\[ = \text{constant value from Table 3} \quad (8) \]

Boundary conditions: \( C(r = 0, t) \)
\[ = \text{constant value from Table 3 and } C(r > \pm R, \ t) = 0 \quad (9) \]

The diameter of the vapour cloud was calculated using equation (12) for different values of \( P \) and \( E_C \), keeping \( M_{\text{Wire}} \) constant. From table 3, it is observed that as \( E_C \) increases and/or \( P \) decreases, \( C \) decreases. All calculations were done for Cu vapour.

The concentration of the vapour can be defined using mass density of the vapour \( \text{Den}_{\text{m,Vap-Exp}} \) experimentally as the ratio of the mass of wire and the volume of expansion of vapour, \( \text{Vol}_{\text{Vap-Exp}} \):

\[ \text{Den}_{\text{m,Vap-Exp}} = \frac{M_{\text{Wire}}}{\text{Vol}_{\text{Vap-Exp}}} \text{ where, } \text{Vol}_{\text{Vap-Exp}} = 4\pi R^3 / 3 \text{ and } R = 0.5d_{\text{Vap}}. \]

As reported in previous literature (Kotov 2003, Shikoda et al 2009, Tokoi et al 2013, Han et al 2017) on WEP, the expansion of vapour depends on \( P \) and \( K \). \( K \) plays the role of increasing the temperature as the heating of the wire in WEP is so fast and energy efficient that it gets converted completely to thermal energy if we neglect other losses of energy.

Expansion of the vapour/plasma is volumetric (Tokoi et al 2013) and it increases as \( P \) decreases, so with ideal gas law, we can define the relationship of theoretical volume of vapour cloud, \( \text{Vol}_{\text{Vap,Ther}} \):

\[ \text{Vol}_{\text{Vap,Ther}} \propto E_C P^{-1} \quad (10) \]

where \( E_C = 0.5\text{Cap} V_C^2 \). \( \text{Cap} \) and \( V_C \) are the capacitance and the charging voltage of the capacitor, respectively. The number of particles in vapour cloud is not constant due to simultaneous nucleation and NPs formation. In the present work, ideal gas law was adopted to provide qualitative understanding on the impact of different parameters like cooling rate, ambient pressure and energy on NPs formation dynamics.

We can define theoretical vapour density as, \( \text{Den}_{\text{Vap,Ther}} = \frac{m}{V_{\text{m,Exp}}} = \frac{mE_C^3}{P} \). Tokoi et al 2013 exploded Cu wire in Argon gas and formulated an equation to predict the \( \text{Den}_{\text{Vap,Exp}} \) from \( \text{Den}_{\text{Vap,Ther}} \) and consequently calculated the \( d_{\text{Vap}} \) as follows:

![Figure 7. Schematic view of spherical vapour/plasma of exploded wire.](image)

| Table 3. Value of \( C(r, t = 0) \) in g m\(^{-3}\) and diameter of vapour cloud for different \( E_C \) and \( P \). |
|---|---|---|---|---|---|---|---|---|---|
| \( P \) (kPa) | 10 | 50 | 100 |
| \( E_C \) (J) | \( C(r, t = 0) \) (g m\(^{-3}\)) | \( C(r, t = 0) \) (g m\(^{-3}\)) | \( C(r, t = 0) \) (g m\(^{-3}\)) |
| \( C(r, t = 0) \) (cm) | \( C(r, t = 0) \) (cm) | \( C(r, t = 0) \) (cm) |
| 180 (K1) | 98.15 | 6.75 | 257.79 | 4.89 | 390.74 | 4.26 |
| 360 (K2) | 64.75 | 7.76 | 170.08 | 5.62 | 257.79 | 4.89 |
| 540 (K3) | 50.77 | 8.41 | 133.35 | 6.10 | 202.12 | 5.31 |

...
\[
\text{Den}_{\text{Vap, Expt}} = 106 (\text{Den}_{\text{Vap, Ther}})^{0.6}
\]
\[
= 106 (\frac{M_{\text{Wire}} P_{E_{C}}}{106\pi})^{1.6}
\]

Figure 8 shows variation in C with time (the variation for total time period of \( t = 10 \) ms) and radial distance (maximum expansion depends on the value of \( E_{C} \) and \( P \)). It is observed that \( C \) gets reduced with increase in \( K \) and/or decrease in \( P \). Cooling rate of the vapour relies on magnitude of diffusion coefficient. The concentration profile of vapour/plasma also depends on the value of diffusion coefficient \( D \) between the metal vapour produced and the ambience gas. In addition, the diffusion coefficient is a function of temperature and it varies much in the range of 7–8 kiloKelvin, the ionisation of the vapour/gas starts which has their own collision integral value (Murphy 1996). In WEP, the local T is as high as 10 kiloKelvin and increases with increase in \( E_{C} \) (Tokoi et al 2013). With increase in \( D \), the diffusion is faster and the vapour/plasma gets depleted faster with time and for all the radial distances as observed from figures 8(c), (d). It is due to the more penetration of ambience in the metal vapour/plasma produced due to faster cooling.
3.4.2. Nucleation and condensation of the vapour for NPs formation

Wide difference in T and C of metal vapour/plasma and ambience leads to diffusion and consequently to the formation of stable nuclei (embryo). Embryo of equal to or more than the critical size (stable) nuclei will lead to the growth otherwise it gets dissolved again to vapour. The C at which the nucleation starts is C at time, \( t_m \) at which temperature of the vapour/plasma reaches its boiling point, which was experimentally calculated as about 0.1–0.2 ms for a particular energy and different P (Shikoda et al 2009). Cooling rate is higher in case of lower P. C is calculated at \( t_m \) through equation (6). Vapour pressure of metal increases tremendously if heated to high temperature. CRC databook (Haynes 2014) provides the vapour pressure of metals as a function of temperature, \( T \). Equation (13) shows the corresponding equation for pressure of Cu (\( P_{Cu} \)). The vapour pressure of Cu is plotted in figure 9 which increases with increase in T.

\[
\log_{10}(P_{Cu}) = 5.006 + 9.123 - 11748T^{-1} \\
+ 0.7317 \log_{10}(T)(298K < T < m. p) \\
\log_{10}(P_{Cu}) = 5.006 + 5.849 \\
- 16415T^{-1} (m. p. \leq T \leq 1850 K)
\] (13)

Increase in partial pressure of the vapour leads to the super-saturation which drives the vapour for the phase change. The phase transformation from vapour to solid takes place through the formation of stable nuclei. Critical size of the nucleus, \( r_C \), on which growth occurs is given as equation (14) as (Wyslouzil and Wolk 2016),

\[
r_C = \frac{2\sigma_{\text{Metal}} V_{\text{Metal}}}{\Delta \mu} = \frac{2\sigma_{\text{Metal}} V_{\text{Metal}}}{RT \ln(S)}
\] (14)

where, \( \sigma_{\text{Metal}} \) is the surface tension of solid vapour interface, \( V_{\text{Metal}} \) is the molar volume of the molten metal, \( \Delta \mu \) is chemical potential given by \(-RT\ln(S)\), \( T \) is temperature and \( S \) is saturation ratio. Activation energy (\( \Delta G_{rc} \)) for the formation of \( r_C \) in classical homogeneous nucleation is given as (Wyslouzil and Wolk 2016),

\[
\Delta G_{rc} = \frac{16\pi\sigma_{\text{Metal}}^3}{3\Delta \mu^2} V_{\text{Metal}}
\] (15)

Variation of critical size embryo and corresponding activation energy for Cu vapour (for calculations, all the values were taken from Haynes 2014) is shown in figure 10 as a function of S and T. With the increase in S and/or T, there is a decrease in the size of \( r_C \) and the corresponding activation energy. Increase in saturation ratio for WEP is not easily conceivable. It can be visualised through the high speed photographs taken during WEP illustrated in figure 4, where it takes more time to quench the vapour cloud in the case of higher P. For \( P = 10 \text{ kPa and } K = 51.9 \) (Tokoi et al 2008), the gradient has increased two folds than that of the 100 kPa case. Similarly, for \( P = 10 \text{ kPa and } K = 1 \text{ and } 3 \) as illustrated in the present work. Higher temperature gradient can be correlated to higher saturation ratio achieved in WEP. Even as the S value is doubled, it will leads to lower \( r_C \) and consequently results in low-dimension NPs.

Homogeneous nucleation is considered in WEP and is assumed that the formation of the NPs occurs from the gas phase. The expression for the nucleation rate is given by equation (16),

\[
J_0 = \left( \frac{P_{\text{Total}}}{k_B T} \right)^{\frac{2}{3}} \sqrt{\frac{2\sigma_{\text{Metal}}}{\pi M}} V_{\text{Metal},\exp} \left\{ \frac{16\pi\sigma_{\text{Metal}}^3}{3(k_B T)^2 \ln(S)} \right\}
\] (16)
where, $k_B$ is Boltzmann constant and $P_{Total}$ is the sum of pressure in the ambience/explosion chamber and vapour pressure of metal (given by equation (13)). Figure 11 shows the nucleation rate for Cu embryo varying with $S$ and $T$. It is observed that nucleation rate is always high for all values of $S$ at higher temperatures. With increase in $S$ also, it leads to higher nucleation rate for any temperature.

The nucleation and growth of the embryo after the diffusion of the vapour/cloud of the metal in ambience will lead to the formation of NPs. Particle size distribution studies clearly indicate that the particles formed by WEP are of mixed size and it follows log normal distribution. The formation of mixed size NPs is due to the generation of different size embryos, as the temperature and/or saturation ratio of the vapour/plasma generated is not the same in the reaction chamber due to non-uniform heating of the wire and non-uniform energy deposition during arc discharge in the experimental conditions. As the cooling rate is not the same on the boundary of the vapour cloud, the WEP yields mixed size NPs under different experimental conditions. However, smaller sized NPs are obtained for high $K$ and/or low $P$ scenario due to the different diffusion and cooling rate, faster nucleation and slower growth of the small-sized embryos.

### 4. Conclusions

A detailed study on the formation mechanism of metallic nanoparticles in wire explosion process was made. Diffusion of metal vapour/plasma of spherical geometry formed after the explosion was calculated by Fick’s second law. The following conclusions can be drawn based on the present study:

![Figure 10. Critical size embryo and activation energy as a function of temperature and saturation ratio (arrows indicate the corresponding axes).](image1)

![Figure 11. Nucleation rate of Cu embryo as a function of temperature and saturation ratio.](image2)
• Higher the value of deposited energy and/or lower the value of ambient pressure (P), concentration of vapour will be low due to more vapour expansion which leads to formation of small sized NPs. It also shows that diffusion is faster for higher cooling rate which can be achieved with ambient of appropriate thermal conductivity.

• Critical sizes and activation energy of embryo were lower and the nucleation rate was higher for high S and T values.

• In WEP, higher T and S values were achieved by increasing energy ratio, K and/or decreasing P. So, low concentrated vapour/plasma, higher cooling rate, high T and S for high K and low P leads to small stable embryo, low activation energy and fast nucleation rate; forming smaller nanoparticles.

• Difference in cooling rate due to non-symmetrical geometry of the metal vapour/plasma, different concentration gradient in experimental conditions of WEP leads to mixed size nanoparticle (narrow size distribution, skewed to low dimension NPs) in WEP as observed in the present work.

ORCID iDs

P Ranjan @ https://orcid.org/0000-0001-7840-9904
R Jayaganthan @ https://orcid.org/0000-0002-3039-8385

References

Aliofkhazraei M 2016 Handbook of Nanoparticles (Switzerland: Springer, Cham) (https://doi.org/10.1007/978-3-319-15338-4)
Bora B et al 2014 Observation of the partial reheating of the metallic vapor during the wire explosion process for nanoparticle synthesis Appl. Phys. Lett. 104 1–5
Crank J 1975 The Mathematics of Diffusion 2nd edn (Oxford: Clarendon)
Fatti D N, Valleé F, Flytzanis C, Hamanaka Y and Nakamura A 2000 Electron dynamics and surface plasmon resonance nonlinearities in metal nanoparticles Chemical Physics 251 215–26
Han R et al 2017 Characteristics of exploding metal wires in water with three discharge types J. Appl. Phys. 122 033302
Han R et al 2020 Optical emission and quenching process of a Cu wire explosion: a spectroscopy study J. Phys. D Appl. Phys. 53 225202
Haynes W M 2014 CRC Handbook of Chemistry and Physics 95th edn (Boca Raton: CRC Press)
Hirschfelder J O, Curtiss C F and Bird R B 1964 Molecular Theory of Gases and Liquids 2nd edn (New York: Wiley)
Koch C C 1997 Synthesis of nanostructured materials by mechanical milling: problems and opportunities Nanostructured Mater. 9 13–22
Kotov Y 2003 Electric explosion of wires as a method for preparation of nanopowders J. Nanoparticle Res. 5 539–50
Kruis F E, Fissan H and Peled A 1998 Synthesis of nanoparticles in the gas phase for electronic, optical and magnetic applications—a review J. Aerosol. Sci. 29 511–35
Murphy A B 1996 A comparison of treatments of diffusion in thermal plasmas J. Phys. D Appl. Phys. 29 1922–32
Ranjan P et al 2017 Thermodynamic analysis of ZnO nanoparticle formation by wire explosion process and characterisation Ceram. Int. 43 6709–20
Ranjan P et al 2019 Synthesis, characterisation and formation mechanism of Sn-0.75 Cu solder nanoparticles by pulsed wire discharge Appl. Nanosci. 9 341–3520
Rogers B, Adams J and Pennathur S 2015 Nanotechnology—Understanding Small Things 3rd edn (Boca Raton: CRC press)
Shikoda Y et al 2009 Measurement of metal vapor cooling speed during nanoparticle formation by pulsed wire discharge Trans Nonferrous Met. Soc. China (English Ed) 19 183–8
Simchi A, Ahmadi R, Rehmani S M S and Mahdavi A 2007 Kinetics and mechanisms of nanoparticle formation and growth in vapor phase condensation process Mater. Des. 28 850–6
Sindhu T K, Sarathi R and Chakravarthy S R 2007 Understanding nanoparticle formation by a wire explosion process through experimental and modelling studies Nanotechnology 19 025703
Tokoi Y et al 2008 Synthesis of TiO2 nanosized powder by pulsed wire discharge Jpn J. Appl. Phys. 47 760–3
Tokoi Y et al 2013 Particle size determining equation in metallic nanopowder preparation by pulsed wire discharge Jpn J. Appl. Phys. 52 55001
Wyslouzil B E and Wolk J 2016 Overview: homogeneous nucleation from the vapor phase—the experimental science J. Chem. Phys. 145 211702
Yin G et al 2019 Numerical investigation of shock wave characteristics at microsecond underwater electrical explosion of Cu wires J. Phys. D Appl. Phys. 52 374002
Yu C H, Tam K and Tsang S C 2008 Handbook of Metal Physics, Chapter 5 Chemical Methods for Preparation of Nanoparticles in Solution vol 5 ed John A. Blackman (Amsterdam: Elsevier)
Zhaos J et al 2017 Characteristics and diffusion of electrical explosion plasma of aluminum wire in argon gas IEEE Transactions on Plasma Science 45 185–92