Chapter 1

Introduction

1.1 Materials

The discovery and development of various important solid materials are among the important factors for the advancement of human civilizations. With these materials, humans are able to fabricate tools that lead to advancement in technology and thus changing their lifestyle. The evolution of early human history from Stone Age to Bronze Age which then followed by Iron Age has seen the change in human civilizations due to the discovery and development of the use of stone, bronze, copper and iron. Due to the growth of scientific research in modern times, more materials that are previously unknown have been revealed.

From the study of materials science, fundamental solid materials can generally be categorized into five groups which are metals, ceramics, polymers, composites and semiconductors (Callister, 2007). Each of these materials has their own distinguished properties either in terms of electric, thermal, magnetic, mechanical, optical or chemical behavior. Further modification of the fundamental materials might produce smart materials, biomaterials or nanomaterials that will give significant impact to the modern society due to their novel properties and a large variety of potential applications.

1.2 Nanomaterials

Nanomaterial is generally referred to as material which has one or more of its dimensions falling in the range of one nanometer to 100 nanometers (Yokoyama, 2007). Examples are nanoparticles, nanotubes and nanowires. The length scale in the range of 1 to 100 nanometers (nm) is normally known as the nanoscale. The “nano” is a prefix being used in the International System of Units (SI units) where it is equivalent to 10^{-9}. As an illustration, one nanometer is approximately equal to the length of 10 hydrogen atoms or 5 silicon atoms aligned in a line (Cao, 2004). Bulk materials with nanoscale building blocks are also known as nanomaterials.

The nanomaterials will usually exhibit novel properties compared to their bulk counterpart. These properties could be of catalytic, electrical, magnetic, mechanical as well as optical. This is due to the relatively large surface-to-volume ratio and the quantum effects that might take place when the dimension of the materials is in the nanoscale. For example, the melting point of gold particles is found to drop rapidly when the particle size reduced from 20 nm to 10 nm (Yokoyama, 2007). Besides that, the curie point of $PbTiO_3$ has also been observed to decrease rapidly when its particle size is reduced from about 50 nm to 10 nm (Yokoyama, 2007).

Nanomaterials have received growing interest from scientists around the world since last few decades. The main factor has been the increasing research enthusiasm in the field of nanoscience and nanotechnology since nanomaterials are the building blocks of the field. The field of nanoscience and nanotechnology is getting more attention because it is believed that the advancement in this field will revolutionize the world of science and technology (Feynman, 1992). At the same time, the increasing research interest in nanomaterials is also driven by the dissemination of various probing instruments used to probe the low dimensional objects. Examples of such instruments are SEM, TEM, AFM and STM. Without such instruments, the study of nano-sized materials will not be an easy task or in certain sense, it might be impossible.

It has been known that nanomaterials are not something new in human civilization. For example, nanoparticles have been incorporated in the production of a type of glass cup known as the Lycurgus cup across the Roman Empire around the fourth century AD (Freestone, et al., 2007). The cup has been found to show dichroic property due to the addition of the nanoparticles in the glass. Nevertheless, the fabrication of the nanomaterials is continued today with the aid of advanced technology and knowledge in the related field.

1.3 Synthesis of nanoparticles

Nowadays, fabrication of nanoparticles is normally done by two approaches namely the top-down approach and the bottom-up approach. In the top-down approach, bulk materials will be processed to break them into smaller pieces until their dimension achieves that of the nanoscale. Examples of techniques which fall into this category are ball-milling (Guittoum, et al., 2010) and lithography (Muller, et al., 2008). On the other hand, the bottom-up approach synthesizes nanoparticles by assembling atomic or molecular species into the nano-sized particles. This approach can be further divided into two groups which are the thermodynamic approach and the kinetic approach (Cao, 2004). The thermodynamic approach produces nanoparticles from a supersaturated vapour or solution. Nucleation will occur in the supersaturated vapour or solution and nanoparticles will be produced from the subsequent growth of the nuclei. Meanwhile, the kinetic approach is achieved either by limiting the amount of precursors available for particle growth or by confining the particle formation process in a limited space.

Efforts to improve nanoparticle synthesis method are being put in by various researchers in order to find the suitable way to produce nanoparticles with the desired characteristics while at the same time being economical, environmental friendly and capable for mass production. A synthesis technique that is economical and capable of mass production will allow a large quantity of nanoparticles to be produced at a reasonable price and in a short time. Meanwhile, an environmental friendly technique can prevent various types of pollutions such as air or chemical pollution that might arise from the synthesis process. Synthesis method with such advantages will probably promote the use of nanoparticles in various technological applications.

1.4 Synthesis of nanoparticles by the wire explosion technique

From a large number of techniques used to fabricate nanoparticles, the wire explosion technique is one of those that can fulfill the above requirements. This synthesis method makes use of the bottom-up approach to produce the nanoparticles. In this method, a thin metallic wire is disintegrated by passing a high power pulsed current through it to generate a supersaturated vapour. The pulsed current is normally generated by discharging a capacitor bank. When the current is passing through the wire, heat will be deposited to the wire due to the wire resistance according to the Joule heating effect. The solid wire will thus be melted and vaporized if sufficient heat is deposited. After the supersaturation has been formed, the bottom-up approach will take place where nucleation will occur in the supersaturated vapour and it is followed by subsequent growth of the nuclei. Nanoparticles are produced from the growth of the nuclei.

1.5 Outline of the dissertation

In this work, the production of nanoparticles by the wire explosion technique has been studied. The physical and chemical characteristics of the particles produced by the wire explosion technique at different experimental parameters are investigated. In Chapter 2, we will first review some of the research works being done in the field of wire explosion and its application in the synthesis of nanoparticles. The experimental setup and methodology used in this work will be described in Chapter 3. After that, results obtained from the experiments and analyses done on the results will be presented in Chapter 4. Discussion on the results will be presented in Chapter 5. Finally, the conclusion of the study and some future works that can be carried out will be given in Chapter 6. In this dissertation, the words nanoparticles and nanopowder will be used interchangeably to refer to particles with size that falls within the range of 1 nm – 100 nm.

Chapter 2

Literature Review

2.1 A Brief Preview on the Wire Explosion Research

The wire explosion is a physical phenomena which can be observed when a high current passing through a thin solid wire within a short interval of time. Nairne had reported the use of the wire explosion in scientific research as early as 1774 (Nairne, 1774). In his work, Nairne had applied the wire explosion to prove that the current in a series circuit is the same. According to Chace, no major scientific research on the wire explosion has been reported until 1920s when Anderson had carried out various spectroscopic studies on the high temperature plasma generated from the wire explosion (Chace, 1959).

The research interest in the wire explosion had been boosted in 1950s mainly due to the advancement in the pulsed power technology after World War II and various potential applications of the wire explosion. Four major conferences on the wire explosion phenomena had been conducted in 1959, 1961, 1964 and 1967. Proceedings for the conferences contained a large number of literatures on the wire explosion research of the time. Meanwhile, Chace and Watson had prepared a bibliography that included most literatures related to the wire explosion phenomenon published from 1774 to 1966 (Chace & Watson, 1962, 1965, 1967). Other than that, Chace had also written two introductory articles related to the wire explosion phenomenon which was published in New Scientist and Physics Today in year 1963 and 1964 respectively (Chace, 1963, 1964).

On the other hand, Bennett had reported a review on the use of wire explosion to produce matter in the high temperature state in 1968 (Bennett, 1968). In his review, he had discussed the classification and the general theory of the wire explosion process, various phenomena which might be observed during the wire explosion and the conditions necessary to produce different modes of wire explosion. Lebedev and Savvatimskii had published another review on the wire explosion which focused on the change of thermophysical properties of the wire when it was heated by intense pulsed current (Lebedev & Savvatimskii, 1984).

In recent years, the wire explosion phenomenon had received growing research interest due to its potential applications in various fields. For example, its ability to generate matter at different states from solid to plasma has enabled the study of thermophysical properties of certain materials in the different states (Hess, et al., 1999). This might not be possible by using other methods due to the large amount of energy needed to melt, vaporize and ionize the materials. Besides that, the X-pinch plasma generated by exploding two wires arranged in an “X” shape is able to act as an intense pulsed X-ray source (Shelkovenko, et al., 2001). Wire explosion had also been applied in thermonuclear fusion research (Spielman, et al., 1998; Stephanakis, et al., 1972). Meanwhile, research had been carried out to utilize the shockwave generated from the wire explosion to shatter the cockpit canopy of a fighter plane in order to allow the safe ejection of the pilot from the plane (Novac, et al., 2007). Other than that, the wire explosion phenomenon is also used as fuse in electrical circuit (Schoenbach, et al., 1984), detonation of explosives (Chae, et al., 2006) as well as the synthesis of nanopowders (Kotov, 2003).

According to Phalen, the wire explosion technique had been used to produce fine particles by Abrams as early as 1946 to study the aerosols of Al, U and Pu. From the study, it was found that the particles produced from the wire explosion had mean diameter of 200 nm and agglomerated particles had been observed (Phalen, 1972). In 1962, Karioris and Fish had reported the production of various aerosols by exploding Ag, Al, Au, Cu, Fe, Mg, Mo, Ni, Pb, Pt, Sn, Ta, Th, U and W wire in air (Karioris & Fish, 1962). Spherical particles forming chains and agglomerates had been observed. In the following years, more works had been done to investigate the effect of various circuit parameters on the particles being produced. Besides that, attempt had also been made to synthesize fine powders of iodides, sulfides, carbides, oxides and nitrides for a wide variety of elements. Kotov had presented two reviews in year 2003 and 2009 regarding the production of nanopowders by the wire explosion technique (Kotov, 2003, 2009). Circuit parameters and the ambient conditions that affect the particles characteristics had been discussed.

In the following sections, review on the literature related to the study of nanopowder synthesis by the wire explosion technique and the investigation of the wire explosion process in recent years will be presented.

2.2 Review on the literature related to the study of nanopowder synthesis by the wire explosion technique

Review to be presented in this section will focus on the literatures related to the synthesis of nanopowders of various elements and their oxides, nitrides as well as carbides by the wire explosion technique. Literatures related to the synthesis of intermetallic or alloy nanopowders by the wire explosion technique are not included in this review. However, some of the works being done to synthesize these nanopowders by the wire explosion technique will be summarized at the end of this section.

As mentioned in previous section, study on the production of fine particles by the wire explosion technique was started with the work reported by Abrams in 1946. In the following years, most of the related research had been performed researchers in various countries especially the United State of America. Meanwhile, researchers in Russia had put in considerable effort in 1970s and 1980s to study the use of wire explosion technique to synthesize nanopowders (Tepper, et al., 2004). On the other hand, according to Umakoshi *et al.*, the study of wire explosion technique to produce fine powder had been reported as early as 1970 by Kase *et al.* in Japan (Umakoshi, et al., 1995).

In year 1992, Saunders *et al.* reported the synthesis of nano-sized gallium arsenide (GaAs) clusters by exploding GaAs wire in different ambient gas (Saunders, et al., 1992). The wire with a dimension of 0.2 x 0.2 x 10 mm^3 was produced by two methods. The first one was by etching a photolithographically patterned <100> oriented n-doped GaAs wafer. The second one was by cleaving a wafer, which has been lapped to a thickness between 0.1 mm and 0.2 mm. The wire was soldered to the wire holders and exploded in argon, helium or hydrogen ambient at approximately 1 bar. It was observed that size distribution for clusters produced from wire explosion in 1 bar argon with a charging voltage of 6 kV approximate the log-normal with mean diameter of 8.3 nm and geometric standard deviation of 1.4. From HRTEM, it was observed that the clusters had random relative orientations. This suggested that the nucleation of the clusters might occur at a shorter time scale compared to that of agglomeration. Besides that, oxide layer about 1.5 nm in thickness was observed around the particle surface from the HRTEM. Lattice fringes that were not observed on the oxide layer suggested that the layer formed was amorphous.

Kotov *et al.* reported the synthesis of zirconium dioxide or zirconia (ZrO_2) nanopowder by the wire explosion technique in 1995 (Kotov, et al., 1995). The experimental setup was able to produce the powder at a rate of 1 kg/hour with power consumption of 2 kWh/kg. The powder produced from the wire explosion process was going through ultrasonic treatment and centrifuging to remove particles with diameter larger than 100 nm. The powder was heated up in argon-nitrogen admixture for two hours to increase its temperature. It was observed that the BET specific surface of the powder initially increased to 75 m^2/g as the temperature increased from 300 ^oC to 350 ^oC. This was suggested to be due to desorption of gases and water from the powder. When the temperature was further increased to 600 ^oC, the specific surface area was found to drop due to the sintering of the particles. As the temperature of the powder was increased, it was observed that the content of monoclinic phase would increase while the tetragonal phase was reduced.

Jiang and Yatsui had used wire explosion technique to produce nano-sized powder of various metals (Al, Fe, Cu, Mo and Pb), metal oxides (Al_2O_3, TiO_2, Fe_2O_3, NiO, ZrO_2, SnO_2, and PbO) and metal nitrides (TiN, ZrN, Ta_2N) (Jiang & Yatsui, 1998). Metal wires were exploded in three different ambient, namely argon, oxygen and nitrogen at 530 mbar. Particles with an average size in the order of 10 nm were obtained. In the synthesis of titanium nitride nanopowder, it was observed that the average particle size decreased with decreasing pressure. Thus, it was suggested that the average particle size could be controlled by the pressure of ambient gas. The authors had claimed that the powder could be produced at an average rate of 180 g/hour with an electric consumption of 800 W.

Sedoi and Ivanov had investigated the effect of the initial microstructure on the specific surface area and median diameter of particles produced from the wire explosion (Sedoi & Ivanov, 2008). In that work, wires being used were aluminum, indium, copper and titanium wires. Two types of aluminum wires had been used where one of them was the original wire while another wire had been annealed to give a larger crystallite size. Titanium wire being used had the smallest crystallite size that was 25 nm. This was followed by original aluminum wire, copper wire, indium wire and annealed aluminum wire, which had crystallite sizes of 50 nm, 64 nm, 71 nm and 77 nm respectively. In the effort to establish a comparable condition between wire explosions of different materials, the following parameters had been considered: (i) the mode of the wire explosion, (ii) ratio of the energy supplied by the capacitor, w to the sublimation energy of the metal, w_s and (iii) high current density at which instabilities had no time to develop. Match mode wire explosion had been used where the energy from capacitor was fully released into the wire within the first pulse to explode the wire and no discharge had occurred thereafter. It had been observed that the BET average particle size generally increased with increasing crystallite size although copper did not follow the trend accurately. From the results, it was suggested that the resistance was higher at crystallites' boundaries and defects in the metal. This caused the energy deposited at such sites to be higher due to Joule's heating. Thus, material at those spots would experience phase change earlier than that in the grain where this would affect the size of particles being formed after the wire had been disintegrated.

In the synthesis of aluminum nanopowder by the wire explosion technique, several studies had been conducted. These studies included the passivation of the powder, measurement of the powder's excess energy, activation energy of the powder's grain growth, effect of ambient gas and pressure on the particles characteristics and the modeling studies on the formation of nanopowder. Other than that, the emission spectrum of the aluminum wire explosion had also been studied to find possible relation between the plasma temperature and the particle size.

By using differential scanning calorimetry (DSC) technique, Dong *et al.* found that the aluminum nanopowder produced by the wire explosion technique had a high excess stored energy compared to nanopowders produced by other methods (Dong, et al., 2001). It was about 65 % of the fusion enthalpy of the bulk polycrystalline aluminum and it was 13 % higher than the fusion enthalpy of the nanopowder itself. It was suggested that the high excess energy was due to the large amount of non-equilibrium grain boundary and a wide range of internal stresses and strains in the powder. Meanwhile, it was found that the activation energy for grain growth increased to a value higher than that of bulk crystalline aluminum when the powder's temperature was increased. This was suggested to be due to the formation of pores in the powder as small nanoparticles combined together to form larger particles with pores. The occurrence of pores would increase the activation energy of the grain growth, as the contact between the particles in the powder was less.

Lee *et al*. and Gromov *et al.* had studied different types of passivation on the aluminum nanopowder produced by the wire explosion technique. Lee *et al*. had passivated the aluminum nanopowder by a layer of aluminum oxide which was about 2.5 nm in thickness as observed from HRTEM (G. H. Lee, et al., 2003). The oxide layer was suggested to be in the form of amorphous because it was not detected by the XRD. The existence of aluminum oxide was confirmed by XPS. The average particles size was estimated by TEM, SEM, and laser particles' size analyzer to be in the range of 80 nm – 120 nm. On the other hand, BET average particle size was calculated to be 109 nm while the average grain size derived from XRD pattern was 28 nm. This suggested that the particles were polycrystalline formed by several grains.

Meanwhile, Gromov *et al*. studied the passivation of aluminum powder by aluminum oxide, stearic acid, oleic acid and fluoropolymer (Gromov, et al., 2006). The effect of various passivation methods on the properties, morphology and compositions of the passivated particles had been investigated. Comparison between powders passivated by oxide coating and those passivated by organic coating had been carried out.

Sarathi *et al*. had studied the effect of various ambient gas and pressure on the characteristics of aluminum nanopowder being produced. In one of their works, they had studied the effect of pure argon, helium and nitrogen at different pressures on the particle characteristics (Sarathi, et al., 2007a). From XRD analysis, only aluminum peaks had been observed in samples produced in 1 bar argon and helium ambient.

Meanwhile, both aluminum and aluminum nitride peaks had been observed in sample produced in 1 bar nitrogen ambient. From EDX analysis, aluminum and oxygen had been observed in all samples obtained from wire explosion at 500 mbar and 1 bar. The weight percentage of aluminum was higher than that of oxygen. At the same time, nitrogen had been observed in samples produced in 500 mbar and 1 bar nitrogen ambient. The pressure of the ambient gas was found to have no major effect on the composition. The TG-DTA analysis showed that the melting temperature of powder produced at ambient pressure of 1 bar was slightly lower than that for micron-sized aluminum powder. The micron-sized aluminum powder has average size of 10 μm. Besides that, the nanoparticles were observed to react with ambient gas at lower temperature when compared to micron-sized aluminum particles. Spherical particles had been produced in helium and argon ambient while those produced in nitrogen ambient were having hexagonal and irregular shape. It was found that the median diameter of the particles produced in argon ambient increased from 32 nm to 42 nm when the argon pressure was increased from 250 mbar to 1 bar. On the other hand, particles produced in nitrogen ambient had shown the opposite trend where the median diameter decreased from 48 nm to 35 nm when the nitrogen pressure was increased from 250 mbar to 1 bar. Meanwhile, median diameter of particles produced in helium ambient had maintained at about 35 nm when the pressure was changed from 250 mbar to 1 bar. The geometrical standard deviation was in the range of 1.5 – 2.0.

In another work, they had exploded aluminum wire in binary ambient gas which was formed by argon and helium mixture (Sarathi, et al., 2007b). The proportion of argon and helium in the mixture had been varied while keeping the ambient pressure constant. Three conditions being applied were 25% Ar + 75% He, 50% Ar + 50% He and 75% Ar + 25% He. At the same time, pure argon and pure helium ambient had also been applied. From the XRD patterns, only peaks corresponding to pure aluminum had been observed in all samples. However, oxygen had been detected by EDX in all samples. Thus, it was suggested that aluminium oxide in the form of amorphous had also been produced. From TEM, particles were observed to have spherical shape. It was found that the ambient of pure argon produced particles with largest median diameter, which was 41 nm, while the ambient of 75% Ar + 25% He produced particles with smallest median diameter, which was 27.4 nm. It was suggested that the high thermal conductivity of the ambient gas would result in the production of powder with smaller median diameter. The geometrical standard deviation was in the range of 1.6 – 2.4. Pure nitrogen had also been used in the experiment where particles with hexagonal and irregular shape had been produced. Mixture of aluminum, aluminum oxide and aluminum nitride had also been produced in this case. The median diameter for particles produced in nitrogen ambient was 33.7 nm. It was suggested that the median diameter was not too large because of the high thermal conductivity of AlN formed during the wire explosion process. The AlN would reduce the local temperature of the reaction site and thus limit the growth of the particles.

Sindhu *et al*. had later carried out modelling studies on the formation of aluminum nanoparticles and predict the particle size distribution (Sindhu, et al., 2008). This was done by solving the general dynamic equation through nodal approach. The saturation ratio (the ratio of vapour pressure to the saturation vapour pressure) and the nucleation rate had been discussed where it was suggested that these terms would affect the critical size of the nuclei formed by nucleation and thus affecting the particle size. The authors had compared the experimental results with the modelled particle size distribution. The quantity of particles with larger size was observed to be higher in the distribution obtained from experiment results. This might due to the reason that vapour did not nucleate simultaneously in actual situation. Besides that, nucleation and coagulation process that continued to occur up to certain time after the explosion might also cause the formation of larger quantity of larger particles in the experiment. The authors had suggested that the cooling of particles in the inner plasma zone would be slower compared to those at the outer zone that interact directly with the ambient gas. This caused the coagulation of the particles in the inner plasma zone to occur for a longer time compared to those at the outer zone. Thus, more particles with larger size would be formed, as the particles would have longer time to grow larger.

Suzuki *et al.* had investigated the production of γ-Al_2O_3 by exploding aluminum wire in oxygen ambient at different pressure (Suzuki, et al., 2001). From XRD results, it was observed that the crystallization of γ-Al_2O_3 would increase when the ambient pressure increased. Meanwhile, the average diameter was found to decrease with decreasing ambient pressure. Spherical particles had been observed from TEM. By using framing photography, it was observed that the plasma expansion was small but with a high luminescence when the ambient pressure was high. It was suggested that higher collision rate in the case of higher ambient pressure had caused larger average particle size.

On the other hand, Giri *et al.* had carried out a similar work where γ-Al_2O_3 nanopowder was produced by exploding aluminum wire in oxygen (Giri, et al., 2004). From the EDX results, some impurities (Cu, Zn, Mg and Si) had been observed in the powder. TEM results showed that spherical particles with an average size of 30 nm had been produced. The broad peak corresponding to amorphous Al_2O_3 was not observed on the FTIR results and thus it was suggested that the powder was in the crystalline form instead of amorphous.

Lerner *et al*. had studied the effect of ambient gas and pressure on the yield of Al_2O_3 in the powder being produced by the wire explosion technique (Lerner, et al., 2001). The yield of Al_2O_3 had been determined by chemical analysis. It was found that binary gas ambient of 80% Ar + 20% O_2 and 96% N_2 + 4% O_2 at 2 bar yield 100% Al_2O_3. They had also reported the production of pure AlN powder in N_2 at 15 bar. Powders that contained the mixture of metal and its oxide or nitride were observed to react with air, water, acids and alkalis. It was thus suggested that continuous oxide or nitride films were not formed on the particle surface to passivate the particle. The authors assumed that the wire had been fully evaporated during or immediately after the explosion. They suggested the condition of the chemical reaction to form the powder as follow: (i) the reaction between the metal and ambient gas to form the compound would occur in a volume of gas cylinder smaller than that of the chamber, (ii) the temperature would be the same everywhere in the cylinder and it would decrease when the cylinder expand and (iii) the reaction would take place on mutual diffusion of the metal vapour into the ambient. Two possible processes by which the reaction could occur had been suggested. In the first process, the cylindrical metal vapour formed from the wire explosion would expand into the ambient. The chemical reaction to form the compound could occur simultaneously when the vapour mixed with the ambient gas during the expansion. On the other hand, a fast cylindrical vapour expansion was assumed in the second process and the vapour and gas molecules did not have enough time to mix. This fast moving vapour would act as a piston that compressed the ambient gas at its boundary. The chemical reaction to form the compound would occur in a thin layer of the compressed vapour-gas mixture in front the expanding vapour cylinder.

Sangurai *et al.* had studied the production of aluminum nitride (AlN) nanopowder in nitrogen and nitrogen-ammonia mixture at different pressures (Sangurai, et al., 2001). They found that wire explosion in nitrogen ambient had produced a mixture of Al and AlN powder. The content of AlN had been estimated from the XRD results and it was observed to increase from 3% to 14% when the nitrogen pressure was increased from 533 mbar to 1 bar. No aluminum nitride was produced in nitrogen ambient at 133 mbar. The BET average particle size decreased from 67 nm to 30 nm when the ambient pressure was decreased from 1 bar to 133 mbar. On the other hand, the nitrogen-ammonia ambient generally produced powder with higher percentage of aluminum nitride. At a given pressure, the AlN content increased when the ammonia content in the ambient gas increased. Similar to the case of nitrogen, the AlN content increased when the pressure of nitrogen-ammonia mixture increased.

On the other hand, Cho *et al.* had studied the effect of deposited energy on the AlN content in the nanopowder prepared in the ambient of nitrogen-ammonia mixture at 1 bar (Cho, et al., 2003). The ammonia content had been fixed at 20% of the ambient gas. The AlN content was found to increase from 65% to 98% when the energy deposited into the wire increased from 60 J to 360 J. It was suggested that pure AlN could not be obtained because the energy deposited into the wire was not sufficient to vaporize the whole wire. Liquid droplets that were composed of pure aluminum would be formed when the deposited energy was insufficient to vaporize completely the wire. These droplets would then form the micron-sized particles that contributed to the Al content in the powder. It was believed that the reduction of the quantity of such particles by increasing the deposited energy could increase the AlN content. BET average particle size of the powder obtained from the case with 360 J of deposited energy had been determined to be 28 nm.

Antony *et al.* had investigated the emission spectrum from wire explosion in different ambient gases and pressures (Antony, et al., 2010). Temperature and electron density of the plasma formed during the wire explosion process had been estimated. Plasma temperature had been estimated by assuming local thermal equilibrium (LTE) model while electron density was calculated by a modified Saha equation. The emission spectra for aluminum wire explosion in helium, nitrogen and argon at 250 mbar, 100 mbar and 1 bar had been obtained. The plasma temperature was found to have no significant correlation with the median diameter of particles for cases of different ambient gases and pressures.

Murai *et al.* had studied the passivation of copper nanopowder by oleic acid (Murai, et al., 2007). In order to produce the nanopowder, copper wire was exploded in nitrogen ambient at 1 bar. Before the wire was exploded, oleic acid has been evaporated in the chamber and mixed with the ambient gas. From TEM, the thickness of the oleic acid passivation on the nanoparticles was found to be a few nanometers. The median diameter of nanopowder with passivation was 25 nm while that without coating was 35 nm. The nanopowder with passivation had gone through the acetone dispersion treatment to remove the oleic acid before being viewed by TEM. Thus, the particle size being measured did not include the organic passivation. Inter-particle neck growth due to particle collision and coalescence had been observed in powder without passivation. From FTIR analysis, it was observed that the molecular structure of the oleic acid had changed after being applied on the particles. It was suggested that the decomposition of the structure was due to the heat content of the nanoparticles. By using XRD, CuO was found to form after 5 days when the powder was not passivated. With passivation, no oxidation of the powder had been observed after 2 months.

In another work reported in 2008, Murai *et al*. had studied the effect of ambient gas and pressure on the deposited energy and the particles characteristics (Murai, et al., 2008). Similar to most other cases, the median diameter was found to decrease with decreasing ambient pressure. Powder with smallest median diameter had been produced in helium ambient at 13.3 mbar, which is 14 nm. On the other hand, powder with largest median diameter was produced in argon and nitrogen ambient at 1 bar, which was about 36 nm. It was suggested that the pressure would affect the initial volume of metal vapour and thus the density and collision probability of the metal vapour. Higher pressure would promote the particle growth due to Brownian coagulation. Particles growth due to Brownian coagulation would stop when they were cooled down below a certain temperature. Meanwhile, it was observed that the energy deposited into the wire before the formation of plasma decreased with decreasing ambient pressure. Highest energy deposition had been achieved in nitrogen ambient at 1 bar while lowest energy deposition occurred in neon ambient at 13.3 mbar. It was suggested that the low energy deposition would promote the occurrence of coarse particles.

The effect of energy supplied by the capacitor, the capacitance of the capacitor and the ambient pressure on the amount of energy deposited into the copper wire before plasma formation had been studied by Cho *et al*. (Cho, et al., 2004). The increase in the energy supplied by the capacitor was found to increase the deposited energy. It had been observed that the voltage value just before the plasma formation was lower than the estimated value of a Paschen breakdown. Thus, it was suggested that the thermal electrons emitted from the wire surface and the Lorentz force exerted on those electrons might have caused the lowering of the breakdown voltage instead of the Paschen breakdown. When the capacitance of the capacitor was varied while maintaining the same level of supplied energy, it was observed that the current rise time would increase when the capacitance was decreased. The deposited energy was found to be highest when the current rise time was shortest. Meanwhile, the deposited energy would increase when the ambient pressure was increased. It was also reported that the quantity of submicron-sized particles would decrease when the deposited energy was increased.

In 2007, Suematsu *et al.* had designed an apparatus for the mass production of nanopowders by the wire explosion technique (Suematsu, et al., 2007). The system had been tested successfully in exploding copper wires continuously at a rate of 1.4 Hz. Copper nanopowder of 2.0 g had been obtained after the system was operated for 90 s. Energy consumption was calculated to be 362 g/kWh. The powder was found to have a median diameter of 41 nm. It was reported that problems such as wire tangling and electrode melting would arise if the system operated for more than 90 s.

Lee *et al.* had prepared iron nanopowder using a needle-plate wire explosion system (H. M. Lee, et al., 2008). Iron wire was exploded in 4 bar argon ambient in order to produce the powder. The nanopowder was passivated with a thin layer of iron oxide that was 2 – 3 nm thick as determined from TEM observation. From TEM images, the mean particle size was determined to be 50 nm and the particles were observed to have spherical shape. No iron oxide peaks had been observed in the XRD results. Thus, it was suggested that the oxide was in form of amorphous instead of crystalline. Meanwhile, the authors had tried to synthesize iron oxide nanopowder by exploding iron wire in argon-oxygen admixture ambient. The oxygen content in the ambient had been varied to study the effect of the oxygen content on the powder composition. Mössbauer measurement was used to differentiate the crystalline phase of Fe_3O_4 (magnetite) and γ-Fe_2O_3 (maghemite) because the peak positions and lattice parameters for these composites were expected to be very close on the XRD pattern. From XRD, it was found that pure Fe_3O_4 nanopowder had been produced in ambient containing 15% of oxygen. When the oxygen content was lower than 15%, the powder being produced was found to contain both Fe and Fe_3O_4. Meanwhile, iron oxide powder consisted of α-Fe_2O_3 and γ-Fe_2O_3 phase had been obtained when the oxygen content was 30%. Powder produced in ambient containing more than 30% of oxygen was also found to be in the same crystalline phases but with a slightly different relative ratio of the two phases.

Wang *et al.* had produced pure γ-Fe_2O_3 in dry air at 3.5 bar. From TEM, it was found that the powder had an average particle size of 9 nm (Wang, et al., 2001a). It was suggested that Fe_2O_3 was produced instead of iron nitride (FeN) because the binding energy of FeN is higher than that of Fe_2O_3. This had caused the reaction to form Fe_2O_3 to be relatively easier to occur. The saturation of the magnetization and coercivity of the powder had been determined. They were found to be about 30% of that corresponding to the bulk γ-Fe_2O_3. The authors suggested that this was due to the equiaxed γ-Fe_2O_3 particles produced by the wire explosion technique.

On the other hand, Suwa *et al.* had studied the production of FeN in ammonia and nitrogen-ammonia mixture ambient (Suwa, et al., 2005). In the case where pure ammonia was used, the ammonia pressure had been varied to study the effect of ambient pressure on the particle composition and the energy deposited to the wire. It was found that the deposited energy decreased with the decrease in the ammonia pressure. From XRD result, α-Fe, γ-Fe and γ'-Fe_4N phase were observed in all samples. The α-Fe phase was dominant in sample produced at low pressure. At higher pressure, volume fraction of γ-Fe and γ'-Fe_4N would increase while that for α-Fe would decrease. For the case where nitrogen-ammonia mixture at 1 bar was used, it was observed that the deposited energy was approximately the same as the vaporization energy of the wire.

When pure nitrogen was used, pure α-Fe powder had been obtained. Meanwhile, both the α-Fe and γ-Fe phases would occur when the ambient contained 3% of ammonia. As the ammonia content was further increased to 30%, α-Fe, γ-Fe and γ'-Fe_4N phases had been observed. The volume fraction of α-Fe dropped when the other two phases appeared. It was suggested that if the γ-Fe phase produced from the wire explosion was slowly reduced to room temperature, the γ-Fe phase would turn into α-Fe and γ'-Fe_4N phases. On the other hand, if the phase had been cooled rapidly, it would not change into other phases. Meanwhile, it was suggested that since the γ'-Fe_4N phase was only stable at a temperature below 680 ^{o}C, a portion of the powder might be maintained at a temperature below 680 ^{o}C to allow the formation of γ'-Fe_4N phase. The higher volume fraction of α-Fe at lower ambient pressure of ammonia was believed to be due to the lower amount of deposited energy at low pressure. Submicron-sized particles were observed in samples obtained from low-pressure wire explosion. It was believed that these particles were formed by liquid droplet of the wire. Their occurrence was due to incomplete vaporization of the wire at low pressure because of low energy deposition. Thus, it was suggested that they were in the α-Fe phase.

Uhm *et al.* had studied the characteristics of nickel nanopowder produced by the wire explosion technique (Uhm, et al., 2004). The particle size as observed from HRTEM was in the range of 20 – 80 nm. From XRD, the average grain size had been determined to be 40 nm. Thus, it was suggested that the powder being produced had multi-magnetic domains since a single magnetic domain of nickel had a size of 20 nm or less. Only peaks corresponding to nickel were observed in the XRD pattern while NiO was only observed through neutron powder diffraction (NPD) analysis. Hysteresis loop for the powder had been obtained by using a superconducting quantum interference device (SQUID) magnetometer at a temperature of 5 K. The saturation magnetization,

M_s, had been found to be similar to that of a bulk nickel at 5 K. It had been observed that the initial magnetization curve overlapped with the hysteresis loop when the applied field was larger than 750 Oe. It was suggested that this was due to the non-collinear magnetic structure in metastable state that existed on the surface or in the core of the nano-sized particles. It was suggested that the magnetic effect of NiO phase could be ignored because their quantity was very small.

Kotov *et al*. had investigated the effect of overheating (ratio of the supplied energy to the sublimation energy of the wire) and oxygen content in ambient gas on the specific surface area of NiO powder being produced (Kotov, et al., 2005). Particle collecting mechanism consisted of two cyclones, an electric filter and a fabric filter had been used to collect the powder. It was found that wire with a diameter of 300 μm had produced powder with larger specific surface area compared to that produced by 500 μm diameter wire. When overheating was smaller than one, the specific surface area increased with the decrease in overheating. If the oxygen content was increased while keeping the overheating to be constant, the specific surface area was found to increase. In the case where the overheating was equal to or larger than one, the specific surface area was slightly reduced when the oxygen content was increased. It was suggested that this was because of the high supersaturation generated by the higher input energy that created a higher vapour concentration. The higher supersaturation would increase the particle growth rate and thus producing particles with larger size and smaller specific surface area. Hence, as the oxygen content was increased in cases with overheat factor equal to or larger than one, the combustion rate would also increase and contribute to the increase of supersaturation and specific surface area. From TEM images, the particle shape was observed to vary from cubic to spherical while the average geometric diameter was found to be 24.4 nm with the standard geometrical deviation being 2.3.

Particles with diameter larger than 100 nm had also been observed. By using SAED, the crystal structure of the particles had been determined to be rhombohedral NiO. It was suggested that the NiO powder could be having both single-crystal and polycrystalline phases.

Tokoi *et al*. had investigated the effect of the energy supplied by the capacitor bank on the amount of energy deposited into the wire, the particle characteristics and the density of plasma-vapour mixture generated during the wire explosion. Titanium wire was exploded in oxygen ambient to produce the TiO_2 nanopowder. In their work in year 2008, they found that the energy deposited into the titanium wire increased almost linearly when the energy supplied by the capacitor is increased (Tokoi, et al., 2008). They used the term "relative energy" to represent the ratio of the energy supplied by the capacitor to the vaporization energy of the solid wire. From the XRD results, an increase in the relative energy was found to reduce the anatase content of the powder while increasing the rutile content. It was suggested that the wire material would be raised to a higher temperature and the quenching rate of the particles was higher when the relative energy being applied was higher. They suggested that since rutile was the more stable phase when the temperature was higher than 800 ^{o}C, more rutile would be formed when higher temperature was achieved during the wire explosion. Due to the high quenching rate, the rutile phase would remain when the particles were cooled down. Thus, the rutile content increased when the relative energy was higher. From SEM study, the increase in the relative energy would also reduce the median diameter of the powder being produced. Submicron to micron-sized particles had been observed in samples produced from wire explosion with low relative energy. It had been suggested that the decrease in the median diameter for the case of higher relative energy was due to the increase in expansion volume of vapour-plasma mixture. The density of the mixture was lower when the expansion volume was larger. The lower density of the mixture would then limit the particle growth and resulted in production of smaller particles.

In another work in year 2009, Tokoi *et al*. studied the energy deposited into the wire before the plasma was formed when the ambient pressure had changed (Tokoi, et al., 2009). They found that the deposited energy was about the same for the ambient of 1 bar and 500 mbar. However, it was a few joules lower for the case of 100 mbar. After that, they used high-speed photography to observe the expansion of the plasma-vapour mixture when different relative energy and ambient pressure were applied. It was found that the expansion was generally larger at higher relative energy or lower pressure. The density of the mixture had been estimated from the high-speed photograph by assuming it to have spherical volume and mass equal to the initial mass of the wire. It had been observed that the density decreased with increasing relative energy or decreasing pressure. However, there was an exception when relative energy was equal to 4.3 where the density at 100 mbar was slightly higher than that of 500 mbar but lower than the case of 1 bar. From SEM study, median diameter of the powder generally decreased with increasing relative energy and decreasing pressure. One exceptional case was the sample produced at 100 mbar ambient by applying a relative energy of 4.3. That sample had larger median diameter compared to those produced at same relative energy but higher pressures (500 mbar and 1 bar). It was suggested that this was related to the plasma-vapour density. The geometrical standard deviation was in the range of 1.5 – 2.2. The authors had studied the relation of the median diameter and rutile content with the mixture density. It was observed that the median diameter generally decreased with decreasing mixture density at a same ambient pressure. Meanwhile, the rutile content increased with decreasing mixture density at a same ambient pressure. This was suggested to be due to the quenching rate of the particles at different mixture’s density and ambient pressure. The rutile content was expected to be higher when the quenching rate was higher.

Hokamoto *et al*. attempted to produce TiN powder containing micron to nano-sized particles by exploding titanium wire in liquid nitrogen ambient (Hokamoto, et al., 2009). Particles with sizes of a few nanometers to a few microns had been observed from SEM. It was suggested that the micron-sized particles that had a cotton-like shape was formed by aggregation of smaller particles. It was found that powder produced by exploding a single 500 μm diameter wire had similar characteristics as that produced by exploding twenty-five 100 μm diameter wire at the same time. Only peaks corresponding to TiN were observed on the XRD pattern.

In 2009, Sarathi *et al*. had synthesized tungsten nanopowder and study the effect of ambient gas on the powder characteristics (Sarathi, et al., 2009). Powders had been produced in helium, nitrogen and argon ambient. It was found that powder produced in helium ambient had smallest median diameter while that produced in argon ambient had largest median diameter. This was suggested to be due to the high cooling rate of the helium ambient that generated a higher supersaturation compared to the case of nitrogen and argon. XRD results showed that α-W and β-W were present in all samples. From EDX study, small quantity of oxygen (0.5% - 2.6%) had been observed in all samples while over 97% of the samples were tungsten. Meanwhile, 0.4% of nitrogen was found in sample produced in nitrogen ambient.

Debaline *et al*. had studied the effect of ambient gas and pressure on the tungsten carbide powder being synthesized (Debalina, et al., 2010). Besides that, the effect of deposited energy had also been studied. Carbon dioxide (CO_2) and methane

(CH_4) at 1 bar and 500 mbar had been used as the ambient gas. It was found from XRD analysis that α-W, WC_{1-x} (cubic tungsten carbide), WC (hexagonal tungsten monocarbide) occurred in powder produced in 1 bar and 500 mbar CH_4. It was suggested that α-W was formed due to insufficient amount of carbon for complete carburization of the tungsten. The intensity of α-W was reduced while WC_{1-x} became dominant when the ambient pressure was increased to 1 bar. For the case where the ambient gas was CO_2 at 1 bar and 500 mbar, WO_3, WC_{1-x} and WC had been observed on the XRD patterns. From the analysis by TEM, the median diameter of the powder was found to be smaller for the case of CH_4. It was suggested that this was due to the higher thermal conductivity of CH_4 compared to CO_2. Besides that, it was suggested that the oxidation of particles produced in CO_2 ambient would generate particles with larger size. Meanwhile, for the same ambient gas, powder produced at lower pressure was found to have smaller median diameter. The geometrical standard deviation was in the range of 2.1 – 2.7. When the deposited energy was increased, it was found from XRD study that the content of WO_3 would increase when the ambient gas being applied was 1 bar CO_2. It was suggested that the increase in deposited energy resulted in an increase of the local temperature and promoted the oxidation process. Meanwhile, in the case of 1 bar CH_4, the contents of WC and WC_{1-x} would increase when the deposited energy was increased. No WO_3 had been observed in this case. From TEM study, the median diameter had decreased with increasing deposited energy. The geometrical standard deviation was in the range of 2.1 – 2.5.

FTIR analysis had been carried out on samples produced in 250 mbar and 1 bar CO_2. The stretching vibration mode of tungsten oxide (-W=O-) and carbide (-W-C-) had been observed in sample produced in 250 mbar CO_2. Similar mode had also been observed for the case of 1 bar but with higher intensity. On the other hand, only the stretching vibration mode of tungsten carbide had been observed in the case of CH_4 ambient. The intensity of the stretching vibration mode was higher when the pressure was higher. The higher intensity suggested that the rate of carburization and oxidation was higher in the case of higher pressure. Broad peak was observed in FTIR results for samples obtained at lower pressure. It was suggested that this was due to the finer particles present in the samples. Narrower peaks that were observed for samples produced in higher pressure were believed to be due to coarsening of particles.

From high-speed photography, it was observed that the duration of light emission was longer for the case of CO_2. It was suggested that this was due to the lower thermal conductivity of CO_2 that caused a higher local plasma temperature. The higher temperature would provide more chance for the particles to coagulate through collision and thus grow larger. Some localized bright spots had been observed at later time of the wire explosion process in CO_2 ambient. It was suggested that the white spots showed the burning due to the oxidation of the particles. The local white spots had not been observed in the case of CH_4.

Kinemuchi *et al*. had studied the effect of ambient pressure and energy supplied by the capacitor on the tin oxide (SnO_2) powder characteristics (Kinemuchi, et al., 2004). It was observed that the energy deposited into the wire had increased with increasing pressure or energy supplied by the capacitor. From XRD study, pure SnO_2 nanopowder was produced in oxygen at higher pressures, which were 267 mbar and 1 bar. Meanwhile, mixture of Sn and SnO_2 nanopowder had been produced at 67 mbar oxygen. The average grain size as determined from XRD results was in the range of 12 – 36 nm where smaller size had been obtained in the case of lower pressure or higher deposited energy. Similar to the results from XRD, analysis by TEM showed that powder with smaller median diameter was obtained when lower ambient pressure was applied or the deposited energy was higher. The standard geometrical deviation was in the range of 1.4 – 1.8. At lower ambient pressure and higher deposited energy, the plasma was able to have a larger expansion volume that decreased the concentration of the vapour during particle growth. The lower vapour concentration would limit the growth of particles and thus produce particles with smaller size. These authors had tried to compare the experimental results with a reported numerical simulation results. It was found that the results were well correlated when both coagulation rate and chemical reaction rate of particles were taken into account in the simulation.

Other than those materials discussed above, the wire explosion technique had also been applied to the synthesis of a wide variety of intermetallic and alloy nanopowders. Some of these nanopowders were: Al_2O_3-ZrO_2 (P. Lee, et al., 2006), Cu-Al (Kim, et al., 2007), Cu-Ni (Kwon, et al., 2007), Cu-Ni-P (Kim, et al., 2008), Cu-Sn (Kwon, et al., 2008), Cu-Zn (Wang, et al., 2001b), Fe-Al (G. Lee, et al., 2004), Ti-Cr (Kim, et al., 2009), Ti-Ni (Fu & Shearwood, 2004), ZnO-CuO (Fan, et al., 2008), $ZnFe_2O_4$ (P. Y. Lee, et al., 2007), $NiFe_2O_4$ (Kinemuchi, Ishizaka, et al., 2002), NiFeO (Suematsu, et al., 2004) and PZT (Kinemuchi, Ikeuchi, et al., 2002).

2.3 Review on the literature related to the study of the wire explosion process

Wire explosion of millisecond and microsecond time scale had been studied by using various scientific instruments and methods since many decades ago. In recent years, the explosion time scale had moved into the nanosecond regime due to the effort to avoid the plasma instability. Thus, work had also been carried out to study the nanosecond time scale's wire explosion in detail. Through these studies, better understanding on how a wide variety of parameters affecting the way a wire being melted, vaporized, ionized and exploded by an intense current pulse had been obtained. Nevertheless, the understanding on the subject is still far from complete as the process can be influenced by many factors. Current and voltage waveforms are the fundamental results in the study of wire explosion process. Meanwhile, the use of time-resolved imaging system such as Kerr cell photography, laser shadowgraphy, laser interferometry and X-radiography will be the next step in the effort to get a closer view on how a wire is exploded. In the following paragraphs, a review on the study of the wire explosion process either experimentally or theoretically will be presented.

In 1957, Kvartskhava *et al.* reported the study on the effect of circuit inductance on copper wire explosion (Kvartskhava, et al., 1957). Meanwhile, calculation of the deposited energy based on current waveform had also been studied. Two different circuit inductances (0.4 μH and 4.2 μH) had been applied to study the effect of the circuit inductance on the explosion process. It was observed that the current rising rate was faster when the circuit inductance was smaller. Meanwhile, increasing the charging voltage from 10 kV to 40 kV also increased the current rising rate. It was also observed in the case of lower circuit inductance that a current pause would occur after the first pulse when the charging voltage was low. A method of calculating the deposited energy without the need to use the voltage data had been discussed. The current data, charging voltage, circuit inductance and the decrease in capacitor charging voltage after time t were used in the calculation. The change of total deposited energy and the wire resistance at the maximum of the first current pulse at different charging voltages had been studied.

Tucker reported the dependence of wire resistance on the deposited energy and another variable known as action in 1961 (Tucker, 1961). A simple mathematical model showing that dependence at different stages of wire explosion had been discussed. The author had carried out experiment to explode gold wire by using square-wave current pulse with 3 μs duration and 6 ns rise time. The amplitude of the current pulse was adjusted to a maximum of 2 kA while varying the current density in a series of experiments. Current density in the range of 0.25 x 10^8 to 3.26 x 10^8 A cm^{-2} had been applied to explode the wires. The resistance of the wire was calculated from the measured voltage and the calculated current across the wire. The current was calculated from the current density being applied by assuming constant current and wire cross-sectional area. The change of resistance with the deposited energy and action in various wire explosions with different current density being applied had been plotted. From theoretical calculation, the resistance was expected to rise to infinity when the wire had been fully vaporized. This was because the arc breakdown had not been taking into consideration in the mathematical model. In actual case, an arc breakdown during the wire explosion process would terminate the rise of the resistance and cause a drop in the resistance. From the plot of resistance versus deposited energy and action, it was observed that the maximum value of resistance occurred at higher value of deposited energy or action when the current density being applied was increased from 0.25 x 10^8 A cm^{-2} to 3.06 x 10^8 A cm^{-2}. This showed that more energy was deposited into the wire before the occurrence of arc breakdown when the current density was increased. The deposited energy was found to increase up to three times the vaporization energy of the wire when the current density was increased from 0.25 x 10^8 A cm^{-2} to 3.06 x 10^8 A cm^{-2}. On the other hand, it was also observed that the resistance level before the resistance peak was generally lower for wire explosion with higher current density. Kerr cell photographic studies had been carried out on the explosion of wire with a diameter of 50.8 µm and a length of 6.35 mm. For wire explosion using current density of 0.13 x 10^8 A cm^{-2}, it was observed that plasma occurred at random spots along the wire just before the resistance peak was reached. After the resistance peak, while the resistance value was falling, it was observed that the plasma would cover the whole length of wire. It was suggested that the plasma formed was due to the breakdown through the metallic vapour. Kerr cell photographs had also been obtained for wire explosion by current density of 0.24 x 10^8 A cm^{-2} and 1 x 10^8 A cm^{-2}. For these two cases with higher current density, it had been suggested that the plasma was formed due to the breakdown of ambient instead of the metallic vapour.

Vlastos had investigated the relationship between the dwell (current pause) time and the charging voltage of capacitor (Vlastos, 1967). Explosions of copper, constantan and lithium wires with different lengths had been carried out by discharging a capacitor bank of 9.6 µF at different charging voltages through the wires. The wire explosions had been carried out in air at 1 bar. For all wire explosions, it was observed that the dwell time generally decreased with increasing charging voltage. It was found that above a certain critical voltage, the wire explosion might have two possible dwell times. Below that critical voltage, only one dwell time was possible for a given applied voltage. The critical voltage would have a higher value when the wire length (equivalent to the distance between the wire holders) was longer. On the other hand, the relation between the dwell time and the average field strength (ratio of the charging voltage to the distance between wire holders) had been studied as well. For wire explosions of same material, it was observed that two dwell times were possible when the average field gradient was above a critical value. Only one dwell time was possible for wire explosion below the critical value. Two equations that gave the approximate relation between the dwell time and the average field strength had been given. One of the equations was for the case of short dwell time while another was for the case of long dwell time. Streak camera had been used to study the process of wire explosion with different average field gradient. Differences between the wire explosion processes with different applied average field gradient as observed from the streak camera photographs had been discussed.

Meanwhile, in 1969, Vlastos had reported the investigation on the resistance of the restrike channel which occurred after the current pause in the copper and constantan wire explosion in air at 1 bar (Vlastos, 1969). The equation used to calculate the resistance had been derived with a few assumptions being applied. The wire explosion system had a coaxial configuration. From the calculated restrike resistance based on the experimental data, it was observed that the resistance generally decreased with increasing charging voltage. At the same time, the resistance was also found to decrease almost exponentially with time. Meanwhile, the restrike developed at the exterior of the wire was found to have lower resistance compared to that for the restrike developed at the interior of the wire. Besides that, the resistance for the exterior restrike decreased faster compared to the drop of resistance for the interior restrike. When the charging voltage was changed, it was observed that those with higher charging voltage generally had lower restrike resistance. The conductivity of the restrike channel was derived by using the resistance value and channel diameter observed from Kerr cell photographs. The current was assumed to distribute uniformly over the wire cross-section. It was observed that the conductivity was maximum at the voltage ledge occurred at the initial stage of the restrike. The conductivity fell gradually after the maximum.

Payne had studied the nonlinear model of the exploding wire circuit for the initial stage of the wire explosion before the wire is melted (Payne, 1988). Several assumptions had been made to simplify the nonlinear model. Parameters variation method had been used to transform the state equations of the nonlinear model into variational equations. The approximate solutions for these equations were then being derived where the solutions gave the time dependent current and voltage. The approximate solutions had been compared with the exact solutions obtained by numerical integration. It was found that the approximate solutions gave results that were almost same as those obtained by exact solution.

Pikuz *et al.* had carried out the X-radiography time-resolved imaging of nanosecond time scale wire explosion by using the X-ray produced from X-pinch device (Pikuz, et al., 1999). Wires with low conductivity such as tungsten (W), molybdenum (Mo) and nickel-chromium (NiCr) as well as those with high conductivity such as aluminum (Al), copper (Cu), silver (Ag) and gold (Au) had been used. Their diameters were in the range of 7.5 – 25 µm. One to four wires connected in parallel had been exploded at a time by current with average rising rate in the range of 5.7 – 14.3 A/ns per wire. The effect of wire pre-heating on the wire explosion process had been investigated as well by pre-heating the wire to about 2000 K before it was being exploded. The pre-heating step was expected to eliminate the gas adsorbed in the wire. From the radiographs for tungsten wire explosion with heated and unheated wire, it was observed that the wire had been boiled explosively throughout its volume. This had produced an inhomogeneous liquid-vapour mixture over most of the wire length with cylindrical symmetry. Besides that, vapour bubbles were observed to break the surface of the mixture at various spots. The expanded mixture had an irregular boundary that was suggested to be due to surface tension. When the vapour bubbles were further expanded, foam-like structure was observed where bubbles with different sizes were contained in the liquid wire. It was observed that the expansion of preheated wire was larger than that which was unheated. Meanwhile, it was observed that the parts of wire near the electrodes always lag in expansion. It was suggested that plasma had been generated promptly near the electrodes and it had prevented the current from flowing through the parts of wire near the electrodes. Thus, the parts of wire near the electrodes were not fully boiled and expanded as other parts of the wire did. At later stage, it was observed that the foam-like structure had collapsed while thread-like structure with separated micron-sized droplets was formed. Based on the radiographs taken for tungsten wire explosions, the authors had suggested the process by which the wires had been exploded. Molybdenum and nickel-chromium wire explosions were found to have very similar characteristics as that of tungsten wire explosion. On the other hand, explosion of wires with high conductivity showed different properties. In such case, it was observed that foam-like structure either occurred only at the portion of wire near to the electrodes or only briefly during the beginning of the discharge. The wires were completely vaporized after that. From the voltage signals obtained during tungsten wire explosion, it was observed that voltage spike occurred at earlier time for the explosion of unheated wire compared to that of pre-heated wire. If the rapid drop of voltage after the voltage peak indicated the formation of plasma, the argument that pre-heating the wire can eliminate the adsorbed gas, and thus delayed the breakdown of the gas and wire vapour might be correct. From the calculation of deposited energy into the tungsten wire, it was suggested that the wire had been melted just before the voltage peak. However, the deposited energy was not enough to vaporize the whole wire.

In 1999, Sedoi *et al.* had studied the characteristic time of capillary force action, MHD sausage type instabilities and current skinning which would disturb the uniform heating of wire by the pulsed current (Sedoi, et al., 1999). The study was limited to wire explosion by current density in the range of 10^7 A cm^{-2} and 10^9 A cm^{-2}. It was found that the times were mainly affected by the wire radius, current density, specific action to the point of explosion and some physical properties of the wire material. From the experimental data, it was observed that the ratio of deposited energy before explosion to the sublimation energy of the wire increased from 0.3 to about 4 when the heating rate of the wire (just before explosion) was increased from 10^8 J g^{-1} s^{-1} to about 10^{12} J g^{-1} s^{-1}. The heating rate is the power measurement of the heating and it is affected by the current density, wire resistivity and wire density. It was also suggested that the deposited energy would exceed the sublimation energy when the wire was heated uniformly.

Chandler *et al.* had investigated the relation between the wire resistivity and the expansion rate during explosion for Zn, Ag, Au, Cu, Pd, Pt, Ni, W and Ti wires (Chandler, et al., 2002). The wires were exploded in nanosecond time scale in vacuum of 10^{-4} – 10^{-5} mbar. X-ray produced by X-pinch had been used to obtain the X-radiograph of the wire explosions. The expansion rate was then derived from the X-radiograph. It was suggested that it was the resistivity of wire near to the boiling point that had affected the initiation of voltage breakdown and not the resistivity at room temperature. For a given material, a lower resistivity at point near to the boiling temperature will act to delay the voltage breakdown. This will increase the time of energy deposition into wire core and thus increase the amount of deposited energy into the wire. The expansion rate was found to be larger when more energy was deposited into the wire due to the delay in voltage breakdown that was related to the resistivity of the material near boiling point.

On the other hand, Taylor had investigated the fragmentation of wire and the formation of plasma along the wire during the copper wire explosion in air (Taylor, 2002). Inductance between 26 µH and 800 µH had been introduced to the circuit to avoid the occurrence of current pause during the wire explosion. Wire explosion process of a few milliseconds with early breakdown had been obtained where the breakdown was critically damped instead of underdamped. The resistance and the deposited energy at various time of the wire explosion had been derived from the current and voltage signals. Intensified fast framing camera and x-radiography had been used to explore the wire explosion process. From the high-speed photography, it was found that plasma started to occur at random spots after the wire had been melted. These plasma spots had a fast initial expansion which followed by a pause and then a slow expansion. From the spectrum of these plasma spots, it was confirmed that they were copper plasma. For explosion with high discharge power, it was observed that the initial expansion was about 100 times faster than that with low discharge power. The wire had been completely covered by the plasma when the voltage spike reached its peak. The author had tried to relate the resistance of the wire-plasma system with the total length of plasma spots along the wire. It was found that the resistance increased linearly with the increase in the length. From the x-radiography with a resolution of about 100 µm, it was observed that two major fragmentation processes had occurred. The first one was the coarse fragmentation before the voltage peak while the second one was the finer fragmentation after the peak. The finer fragmentation might have happened before the peak but not captured by the x-radiography due to the limitation of the image resolution. The coarse fragmentation was suggested to be due to the kinks caused by the buckling of the wire where the buckling was in turn due to the thermal expansion of the wire. It was suggested that premature vaporization occurred at the kink locations and led to the formation of plasma spots as observed from high-speed photography. It was also suggested that the current would flow through the plasma instead of the condensed wire fragments at those spots where plasma had formed. The way by which the current might have been diverted from the condensed wire fragments into the plasma had been proposed. Besides that, evolution of plasma and vapour from the kink locations to the entire wire had been discussed.

Sarkisov *et al.* had investigated the effect of current rate on the energy deposited into the metal wire in nanosecond wire explosion (Sarkisov, et al., 2004). Different kind of metal wires had been exploded by fast explosion and slow explosion. The fast explosion had a current rising rate of about 150 A/ns while the slow explosion had current rising rate of a bout 20 A/ns. Non-refractory (Ag, Al, Cu and Au) and refractory (W, Mo, Pt, Ti and Ni) metals wire 2 cm long with diameters in the range of 4 – 38 µm had been used. The wires had been exploded in vacuum at a pressure in the range of 10^{-4} – 10^{-5} mbar. Current, voltage and light emission power had been obtained during the experiment. Deposited energy and resistance across the electrodes were derived from the current and voltage signals. The energy deposited into the wire was taken as the total deposited energy up to the point where the resistance between the electrodes dropped to one third of its maximum value. Besides that, radial streak shadowgram, laser shadowgram and open-shuttle visible light charged-coupled device (CCD) images for the wire explosion had also been obtained. It was observed from streak shadowgram that the wire remained at its initial size during the stage of heating and started to expand rapidly when the voltage breakdown occurred. The voltage breakdown is the time where the voltage decreased rapidly after the peak of voltage spike occurred. The expansion velocity and deposited energy was generally higher for the case of high current rising rate compared to that of low current rising rate. The voltage spike occurred earlier in the case of high current rising rate compared to that of low current rising rate. From laser shadowgram, it was observed that the radial expansion of wire near the anode was larger than that near the cathode. It was suggested that this was related to the polarity effect where the energy deposited to the portion of wire near anode was higher. Meanwhile, shock wave had been observed near the electrodes due to the collision of the expanding plasma shell from the wire with the plasma generated near the electrodes. For both fast and slow explosion, it was found that the deposited energy into all refractory metal wires was underheated (the ratio of deposited energy to the atomization enthalpy is less than one). On the other hand, energy deposited into all non-refractory metal wires in the fast explosion mode was overheated (the ratio of deposited energy to the atomization enthalpy is more than one). The actual energy required to vaporize the whole wire was expected to be 20 % - 50 % higher than the atomization enthalpy due to high magnetic field and hydro-pressure in wire. For refractory metal wire exploded in slow explosion mode, the deposited energy was close to the atomization energy except for the case of silver, which was overheated. It was observed that all refractory metal wires had slower expansion velocity compared to refractory metal wires. At the same time, the fast explosion gave a higher expansion velocity compared to the slow explosion. The expansion velocity was suggested to depend on the overheating parameter. For cases of underheated explosion where voltage breakdown occurred before or during melting, it was suggested that the hydrocarbon impurity on the wire had caused an early breakdown before the wire was fully vaporized. This had prevented further deposition of energy into the wire.

Duselis *et al.* had studied the effect of the connection of wire with the wire holder, the polarity effect of the wire holders and the effect of the current rising rate on the energy deposited into the wire before the formation of plasma (Duselis, et al., 2004). Copper and tungsten wires had been exploded in wire explosion of nanosecond time scale. For the investigation of the polarity effect of the wire holder, the capacitor was either charged with positive or negative polarity. It was found that the energy deposition was generally higher for the case of positive polarity. It was suggested that the main reason was related to the emission of stray electron from the cathode (a copper rod) due to the electric field around the cathode when negative polarity was applied. It was found that the polarity effect was absent when a plate was used as the cathode instead of rod. To investigate the effect of wire connection with the wire holders, the wires were soldered to the wire holder or without solder. In some other cases, the wires were only soldered at either anode or cathode. From the results, it was observed that wires soldered at both ends and exploded with positive polarity allowed higher amount of energy deposition. It was suggested that stray electrons would be emitted near to the connection sites if the wire had not been connected properly to the wire holders. These electrons would then cause the plasma formation, which reduced the deposited energy into the wire. Other than the case of copper wire soldered at both ends and exploded with positive polarity, the energy deposition in other wire explosion was generally found to increase with increasing current rising rate. The energy deposition in copper wire soldered at both ends and exploded with positive polarity was found to be independent of the current rising rate. The period of resistive heating was found to decrease with increasing current rising rate. From laser shadowgram for copper wire explosion, it was observed that the copper wire being soldered at both ends expanded uniformly. However, for the case of copper wire without solder, the expansion of the wire was observed to be higher for the portion of wire near to anode and gradually reduced towards wire near to cathode. At the same time, the expansion of the wire in front of the anode was very small compared to other part of the wire. It was suggested that plasma, which was more localized, had been formed in front of the anode while plasma formed near the cathode had propagated along the wire towards anode. It was suggested that the section of wire with less expansion was shrouded by plasma at earlier time and thus had a lower energy deposition.

Tkachenko *et al.* had tried to investigate the transformation of the wire state from a liquid core surrounded by vapour to a weakly conducting system of droplets in vapour which expanding rapidly in the radial direction (Tkachenko, et al., 2004). They had suggested that two situations might lead to the transformation of the wire state. First of them is the transformation which occurred instantaneously when the parameters of the supersaturated vapour reach their spinodal values. This is known as the spinodal mechanism of explosion (SME). The second situation is due to the growth of liquid nucleus into droplets that appear at the earlier stage of vapour supersaturation, which causes a phase imbalance on the wire surface. This will then lead to the early transition of the wire into the dispersed state of liquid droplets in vapour. This second situation is called nucleus mechanism of explosion (NME). The time at which the liquid nucleus would appear in the NME had been calculated. It was shown that the appearance time of nucleus decreased rapidly at some threshold temperature. Thus, liquid nucleus can be expected to form very soon after the temperature has been reached. The temperature at which the time reduced rapidly had been estimated. From simulation, the time at which the estimated temperature would be reached after the current started to flow through the wire had been suggested. From the voltage signal obtained experimentally, it was observed that the time at which the temperature was reached correlated well with the time of the beginning of abrupt increase in voltage signal. This had led the authors to conclude that the explosion of wire in the case being considered had been caused by the nucleation of the supersaturated vapour. Besides that, the supersaturation of vapour was small at any temperature of wire explosion when the deviation from the phase equilibrium was small. On the other hand, for the case of SME, the supersaturation of vapour and pressure at the wire axis had been estimated higher compared to that of NME. Thus, the authors had suggested that NME would occur in most cases of wire explosion while occurrence of SME would require additional effort. In term of maximizing the energy deposited into the wire, it had been suggested that the heating of a wire with initial radius, R_o, should be sufficiently slow to reach a high temperature at the point of explosion but fast enough to prevent the development of MHD instabilities. Based on the theory discussed by the authors, they had proposed that the deposited energy through resistive heating should not exceed the sublimation energy of the wire. In case where the deposited energy was larger than the sublimation energy, they believed that the additional energy had been delivered to the surrounding gas, vapour or plasma. The distribution of particle size produced from the explosion had also been analysed. The particle size was said to depend on the explosion temperature that is related to the amount of deposited energy. The authors had suggested that the particle size distribution should show two peaks. The first peak was due to particles formed through the condensation of vapour while the second peak was caused by the presence of particles generated from the dispersed liquid core.

Sarkisov *et al.* had studied the structure of the nanosecond exploding tungsten wire at different deposited energy by using laser shadowgram and time-integrated images (Sarkisov, Struve, et al., 2005). The wires were exploded in vacuum of about 10^{-4} to 10^{-5} mbar. The deposited energy before the plasma formed was calculated from the current and voltage data. When the energy deposited into the wire was below the solid-state enthalpy, the wire was not exploded. When the energy was between the solid-state and liquid-state enthalpy, the wire only disintegrated into macro-pieces and no significant wire expansion was observed. If the deposited energy was further increased above the liquid-state enthalpy, the wire was exploded after the wire had been fully melted. The expansion of wire core was observed but the expansion was not uniform along the wire axis. The portion of wire near to the anode was having larger expansion compared to the part near to the cathode. This was suggested to be due to the polarity effect. The expansion had better uniformity when the energy was higher. At this range of deposited energy, it was suggested that the expanding wire core consisted of submicron-sized liquid drops. When the deposited energy was about 8 % higher than the atomization enthalpy, the wire was first observed to vaporize at the part of wire near to the anode while other section was still in the form of liquid micro-droplets. It was suggested that due to the high pressure in the wire, deposited energy much higher than the atomization enthalpy would be needed to vaporize the whole wire. From the time-integrated images, it was observed that the vapour-plasma core had lower light emission compared to that of wire core in liquid form. It was suggested that the vapour-plasma core had a fast adiabatic cooling due to rapid expansion and emitting line spectra while the liquid core cooled at slower rate and emitting blackbody-like radiation. This difference enabled the differentiation of vapour-plasma core and liquid core by a simple observation on the time-integrated images. From the time-resolved light emission power obtained by PIN diode, it was observed that the light emission was very low if voltage breakdown occurred before or during melting. If the breakdown occurred when the core was in liquid form, a long time-scale radiation was observed. Meanwhile, in case where the wire was fully vaporized before any plasma was formed, the emission fell quickly after the maximum emission power was reached. It was found that the average expansion velocity of the wire explosion had linear dependence on the deposited energy.

From the linear relationship, the authors had tried to estimate the energy deposited at different part of the wire during explosion by examined the expansion of the wire from laser shadowgram. The possible reason that caused two different types of expansion (homogeneous and inhomogeneous) of wire had been suggested.

Sarkisov *et al.* had exploded aluminum alloy (94.6 % Al, 5.2 % Mg, 0.1 % Mn and 0.1 % Cr) wires in vacuum in the range of 10^{-4} – 10^{-5} mbar (Sarkisov, Rosenthal, et al., 2005). The wire explosions were in nanosecond time scale. Laser shadowgram for the wire explosion had been obtained to study the structure of the wire when different amount of energy was deposited into the wire by applying slow and fast current rising rate. It was observed that stratification occurred when energy deposited into the wire was enough for complete vaporization. When the deposited energy did not achieve the vaporization energy, foam-like or sol structure was observed. Expansion rate was found to be higher for wire section near to the anode. It was suggested that this was due to the deposited energy into the wire which increased from cathode to anode caused by the polarity effect (Sarkisov, et al., 2002). Meanwhile, the overall expansion rate was higher when fast current rising rate was applied. From optical spectroscopy, hydrocarbons impurities had been observed in the plasma formed during the explosion process. It was suggested that this impurities would cause early voltage breakdown before or when the wire was melted. It had been suggested that the impurities could not be removed by simply cleaning of wire surface or preheating the wire before being exploded. From the steak camera images, it was observed that the onset of light emission and the fast expansion of wire were correlated with the onset of voltage collapse. The light emission was due to the ionization of surrounding vapour. It had a maximum during the voltage collapse and it decreased after the maximum due to the rapid expansion of plasma shell. Power and amount of energy deposited into a wire at different time had been derived from the current and voltage waveforms. The relation between various wire explosion parameters (such as resistivity, specific deposited energy, power, total deposited energy, heating time and wire diameter) had been discussed. For the case of fast current rising rate, it was suggested that transition from liquid wire to gas-plasma phase occurred when the wire material had turned into supercritical fluid. The liquid wire had become a supercritical fluid because of the high magnetic pressure and wire temperature. This had caused a homogeneous transition without going through boiling. Meanwhile, for the case of slow current rising rate, the magnetic pressure was not sufficient to raise the pressure on the wire to turn it into supercritical fluid. Therefore, the transition from the liquid wire to the gas-plasma phase occurred by going through boiling. One-dimensional (1-D) MHD simulation had been carried out by using ALEGRA (Arbitrary Lagrangian Eulerian General Research Application) code developed by Sandia National Laboratories. The simulation results were observed to agree with the experimental data.

Tkachenko *et al.* had carried out nanosecond wire explosion of Cu, W and Ni wires in air (Tkachenko, et al., 2007). From the measured voltage across the wire during wire explosion, a voltage pulse with amplitude higher than the initial charging voltage of the capacitor bank was observed. The authors had solved the differential equation of the wire explosion LCR circuit with several approximations being applied. Condition required for overvoltage with significant magnitude to occur had been derived. The condition was related to the wire resistance at the instant where overvoltage pulse begins, the circuit inductance, and the time at which the wire lost its conductivity. Numerical calculation had been carried out to derive the current, voltage and resistance waveforms with respect to time. The effect of the time at which the wire lost its conductivity on the waveforms had been studied. The numerically calculated waveforms had been compared with the experimental results. The results matched each other in some cases but not in others. The possible reasons for the differences between the experimental and numerically calculated results had been discussed.

Rousskikh *et al.* had investigated the formation of strata during the nanosecond time-scale explosion of aluminum wire by a current density of about 10^8 A cm^{-2} (Rousskikh, et al., 2008). The strata are alternating layers of material with increased and decreased density perpendicular with the wire axis. Aluminum wires with different diameters of 20 µm, 35 µm and 50 µm had been exploded in two different modes, namely, explosion with current cutoff and explosion without current cutoff. In explosion with current cutoff, the wire explosion circuit had been modified such that the discharge from capacitor would be terminated when the energy deposited into the wire had reached the required amount. The capacitor bank of 69 nF was charged up to a voltage that would provide a current density of about 1 x 10^8 A cm^{-2} to the wires with different diameters at the time of voltage breakdown. X-radiography had been conducted to obtain the images on the strata formed during the wire explosion. The X-ray flash with energy was produced by an X-pinch device. The energy deposited into the wire for the case of explosion without current cutoff before voltage breakdown had been determined from current and voltage waveform. They were found to be 4.2 – 5.3 kJ/g for explosion of 20 µm diameter wires, 6.3 – 7.7 kJ/g for explosion of 35 µm diameter wires and 6.1 – 8.1 kJ/g for explosion of 50 µm diameter wires. It was suggested that these amount of energy would rise the temperature of the wire material to about 0.3 – 0.45 eV that was higher than the boiling temperature of 0.08 eV but lower than the critical temperature of 0.69 eV. From the X-radiographs, strata had been observed in these wire explosions. On the other hand, explosion with different amount of deposited energy had been realized in the explosion with current cutoff. It was observed from the X-radiograph that strata were not formed when the deposited energy was below a certain range. For explosion of

20 µm diameter wires, strata were not formed for deposited energy below 2 - 3 kJ/g. Meanwhile, it was below 4 - 4.5 kJ/g for explosion of 35 µm diameter wires and below 4 – 4.7 kJ/g for 50 µm diameter wires. It was observed from X-radiography that the expanding velocity of the wire increased with increasing deposited energy. Besides that, the strata wavelength immediately after the voltage breakdown had been estimated. It was 8 µm for wires with diameter of 20 µm, 7.5 µm for wires with diameter of 35 µm and 5 µm for wires with diameter of 50 µm. The strata wavelength was the length between the starting point of an increased (or decreased) density layer and the starting point of the next increased (or decreased) density layer. It was found that the wavelength of strata had increased as the wire expanded. It was observed that, when wires with same diameter were exploded by different explosion mode (with current cutoff and without current cutoff), but with approximately the same deposited energy, the wire cores had about the same expansion velocity. It was believed that this was due to the expansion of the core that was adiabatic where the expansion velocity would be approximated to the thermal velocity of the material's atoms. The thermal velocity was influenced by the deposited energy. Therefore, when the deposited energy was about the same, the expansion velocity would also be close to each other. It had been suggested that sausage-type MHD instabilities were not the cause for the strata formation because the instabilities would only occur at later time, which was longer than the characteristic time of the nanosecond wire explosion. Thus, it was believed that the thermal instability was responsible for the strata formation where the instability formed because of increasing resistivity due to temperature rise. The development of thermal instability in wire explosion had been analysed by the perturbation theory method. It was found that the characteristic wavelengths of the thermal instability at different temperature of wire material were close to the range of strata wavelengths as observed from experiment. At the same time, the occurrence time of the thermal instability was found to be very short

compared to the characteristic time of the wire explosion. This showed that the instability could develop during the wire explosion. These coincidences were believed to support the hypothesis that the strata had been formed due to the thermal instability.

Mao *et al.* had simulated the current and voltage waveforms for copper and titanium wire explosion (Mao, Zou, Wang, Liu, *et al.*, 2009). This was done by solving the nonlinear differential equation describing the wire explosion's LCR circuit. The resistance of the wire that was changing during the wire explosion process was calculated from its resistivity at different stages of wire explosion. For copper wire explosion, equations used to calculate the resistivity at various stages of wire explosion had been derived from a quasi-static theoretical model by Tucker and Toth (Tucker & Toth, 1975). However, these equations could not be applied for the case of titanium wire explosion because the resistivity of titanium does not increase continuously. Instead, its resistivity decreases during the liquid heating phase before it rises again during the vaporization phase. In order to obtain the resistivity of titanium at different stage of the wire explosion, the specific action, g ($g = \int j^2 \, dt$, where j = current density) at various times was first determined. Tucker had plotted the dependence of the titanium resistivity with the specific action where these data had been obtained experimentally. By knowing the specific action at certain times during the wire explosion, the resistivity corresponding to the specific action at that time could be determined. Current and voltage waveform obtained from experiment and simulation had been compared. Differences between the waveforms had been observed and the possible reasons that caused the differences had been discussed. The deposited energy into copper wire had also been calculated by using the simulated current and voltage waveform. In the calculation, it was assumed that energy was deposited into the wire up to the point where the vaporization energy of the wire had been reached. From the results, it was found that the vaporization energy could be achieved at earlier time when higher charging voltage, lower circuit inductance and capacitor with small capacitance were being applied.

Mao *et al.* had used the Mach-Zehnder interferometer to investigate the evolution of an exploded titanium wire (Mao, Zou, Wang, & Jiang, 2009). As observed from the current signal, an explosion with early breakdown had occurred in the wire explosion. By using the current and voltage signals, the deposited energy into the wire before the formation of plasma had been determined to be 57 J. Fourteen images had been obtained at various time of the wire explosion where the first image was captured at about 0.7 µs before the plasma formed. Since the deposited energy was less than the energy required to vaporize completely the solid wire, which was 69 J, it was suggested that both the liquid and vapour phase of the wire existed just before the plasma formed. The plasma was suggested to form around the wire material due to the breakdown of the wire vapour or ambient gas. From the image captured at about 0.8 µs after the formation of plasma, plasma had been observed on the wire material and the air near the plasma had been compressed due to the expanding plasma. The expanding speed had been estimated to be 2.3 km/s. This was done by measuring the radius of the expanding shell in two consecutive images and divided by the time interval at which the images were captured. Burst of wire material and plasma had been observed at about 2.9 µs after the plasma had formed. This showed that the wire was not exploded at the time the plasma formed. As the wire material and plasma further expanded into the surrounding, it was observed that a residual core remained at the initial position of the wire. This was believed to be the portion of the wire that had not been vaporized during the initial heating. From the observation on the images captured at later time, it was suggested that the vaporization of the residual core had continued due to the heating by the plasma. It was observed that the residual core had been completely vaporized later. Thus, the wire was initially heated by the current due to Joule heating and being heated again by the plasma after the explosion occurred until it was fully vaporized.

This section ended the discussion related to the literature review of the wire explosion for the synthesis of nanopowder as well as the wire explosion process. In the next chapter, the experimental setup and methodology to be used in our work will be discussed in detail.