Chapter 5

Discussion

5.1 Discussion on different modes of explosion generated in different ambient condition

After going through the analysis of results obtained from different ambient conditions, we can see that different ambient condition might give rise to different modes of wire explosion. The effect of the ambient gas and ambient pressure on several characteristics of the wire explosion process has been summarized in previous chapter. In this section, we will discuss the wire explosion process for different modes of explosion. In the later sections, we will discuss the correlation between the powder characteristics and the condition of wire explosion.

As mentioned in chapter 3, we have tried to trace the wire explosion process from the current and voltage signals. From chapter 4, we can see that three modes of wire explosion process have actually been observed from the experiments carried out in different ambient conditions. These wire explosions are being categorized according to the characteristics observed from their current signals. These include wire explosion with current pause, wire explosion with current dip and wire explosion with immediate discharge.

It can be seen that the occurrence of different modes of explosion is highly affected by the ambient condition. In case where the dielectric strength of the ambient is high, breakdown or ionization will not occur at the early stage. This will normally lead

to the wire explosion with current pause as observed in the case of 500 mbar nitrogen-argon mixtures, 1 bar nitrogen, 1 bar air, 500 mbar nitrogen and 500 mbar air.

On the other hand, an ambient gas with low dielectric strength will give rise to wire explosion with current dip or immediate discharge as shown in the case of 500 mbar argon, 100 mbar air, 50 mbar air, 100 mbar nitrogen and 50 mbar nitrogen. Wire explosion with current dip and that with immediate discharge are almost the same and the only difference is the time at which the discharge occurs. This can be seen by comparing the signals shown in Figures 4.6(c) and (d).

5.1.1 Wire explosion with current pause

Wire explosion with current pause has been observed in the case of 500 mbar nitrogen-argon mixtures, 1 bar nitrogen, 1 bar air, 500 mbar nitrogen and 500 mbar air. From the calculation of energy deposited into the wire, it is found that the wire has been completely melted around the time where the peak of current spike occurred. After the wire has completely melted, the current flowing across the wire starts to drop rapidly. It has been suggested by Vlastos that instability has occurred along the wire and caused the disintegration of wire during the melting stage (Vlastos, 1973). From the rotating mirror camera's photograph, Korneff *et al.* have shown that the wire has started to expand into the ambient at time where the peak of current spike occurred (Korneff, *et al.*, 1959). No discharge has been observed along the wire during this stage but discharge has been observed in front of the wire holder in some cases. During the current pause, the wire has further expanded and discharge has been observed to occur at random location along the wire. The duration of the current pause presented by the authors is about 6 μs, which is very close to that of our case.

From the calculation of deposited energy, it is also found that the boiling point has been reached before the current pause occurred. Thus, it is suggested that a liquid-vapour mixture has been formed at the end of the current spike and just before the start of the current pause. Chace *et al.* have found that the current flowing across the wire material might have a value of a few hundred to about 2000 amperes instead of zero (Chace & Morgan, 1959). They have suggested that the current has been carried mainly by thermionic electrons produced from explosion fragments.

In another study, Vlastos has observed that a long current pause is normally followed by a restrike (formation of plasma) started at the interior of the wire material (Vlastos, 1968). Meanwhile, a short current pause is normally followed by a restrike that starts at the exterior of the wire. It is suggested that the restrike starts at the interior of the wire when intense vaporization has occurred on the surface of the wire and prevented the ionization to occur on the wire surface. This will delay the occurrence of restrike until the wire material has expanded to a density that allows an avalanche breakdown to occur in the region of the wire material. On the other hand, restrike will start at the exterior of the wire when ionization can occur near the surface of the wire.

As reported in chapter 4, the duration of the current pause in our experiment has been observed to be about 7 to 8 μs for all explosion with current pause except for the case of 25% nitrogen + 75% argon. It is about 1.2 μs for the case of 25% nitrogen + 75% argon. Based on the study carried out by Vlastos, it is suggested that the restrike occurred in the case of 25% nitrogen + 75% argon ambient is due to the ionization started near the wire surface. This is because the short current pause has been observed most of the time for wire explosion in that ambient. It is also suggested that the restrike in that case is caused by the ionization of the ambient gas instead of the wire material.

The pure argon ambient has been observed to breakdown more easily compared to pure nitrogen ambient. Thus, it is suggested that the increase of argon content to about 75% has caused the nitrogen-argon mixture to breakdown more easily. This can be seen by comparing this case with that of 50% nitrogen + 50% argon as well as 100% argon ambient.

Mao *et al.* have studied the wire explosion process by using Mach-Zehnder interferometer (Mao, Zou, Wang, & Jiang, 2009). They have suggested that the plasma formed during the wire explosion has contributed to the heating of the wire material. Thus, it is suggested that the plasma formed after the current pause in our case has also contributed to the heating of the wire material at the later stage of the wire explosion. However, the degree to which the wire material has been heated by the plasma in our case is unclear and this required further investigation.

We can summarize the observed wire explosion process for an explosion with current pause as follows:

(1) The solid wire has been heated into liquid form by the Joule heating effect due to the intense current flowing through the wire.

(2) Electromagnetic instability has developed along the wire when the wire has turned into liquid form. This has caused the wire to break into smaller pieces and lead to the rapid drop of current.

(3) While the current is falling, the wire material has been heated to its boiling point and it is suggested that a small amount of the wire material has been vaporized and expanded into the ambient.

(4) The vaporization of the wire material has further increased the resistance of the wire and causing the occurrence of the voltage spike in the voltage waveform.

(5) It is suggested that some sort of minor ionization that does not lead to avalanche breakdown has occurred around the time where the peak of voltage spike occurred. The minor ionization could be due to thermionic electrons as suggested by Chace. This ionization will reduce the resistance along the wire material and thus reduced the voltage across the wire.

(6) The resistance of the wire material continues to increase causing the current flowing across it to become very low. This is represented by the end of the current spike and the beginning of the current pause. At this moment, it is suggested that the wire is formed by liquid core broken into small pieces. The liquid core is surrounded by vapour that is expanding into the ambient. At the same time, thermionic electrons have taken over the main role to conduct the current across the wire holders.

(7) During the current pause stage, the flow of current through the wire material is very small and the current is mainly carried by the thermionic electrons. Thus, only a very low level of current has been observed at this stage.

(8) As the vapour further expanded, a point will be reached where avalanche breakdown will occur at either the interior or exterior of the wire material to generate a restrike.

(9) The plasma formed from the restrike will further heat the remaining liquid and vaporize it until the energy supply from the capacitor stopped.

5.1.2 Wire explosion with current dip

Wire explosion with current dip has only been observed in the case of 100 mbar air and 100 mbar nitrogen ambient. The characteristics of the initial process for both of these cases are almost the same. From the calculation of deposited energy, it is found that the wire has been completely melted at the peak of the current spike. Similar to the case of explosion with current pause, it is suggested that the wire has been broken into smaller pieces due to electromagnetic instability when the wire has melted.

Meanwhile, the boiling point has been reached very soon after the peak. Voltage peak that represents the formation of plasma has been observed to occur at about 0.08 μs after the boiling point has been reached in both cases (100 mbar air and 100 mbar nitrogen). Thus, it is suggested that the wire material has been transformed into liquid and vapour at the point when the plasma is formed.

From the study carried out by Mao *et al.*, it has been observed that the vapour will expand rapidly into the ambient even after the plasma is formed (Mao, Zou, Wang, & Jiang, 2009). After the plasma is formed, it is suggested that the wire material will be heated by the plasma.

5.1.3 Wire explosion with immediate discharge

Wire explosion with immediate discharge has been observed in the case of 500 mbar argon, 50 mbar air and 50 mbar nitrogen ambient. For the case of 500 mbar argon, the solid wire has not even reached its melting point when the plasma has formed. This has been shown in Table 4.3. Since the wire is still in solid form, current still can

conduct through the wire after the plasma formed. Therefore, the wire will be heated by both the current and the plasma while it is still conducting current on its own. However, it is not possible to know the amount of current that flow through the solid wire from the current signal directly, as part of the current will be diverted to flow through the plasma. After the wire lost its conductivity, it will be heated purely by the plasma. As no obvious characteristics on the current signal that, allow us to determine the evolution of the wire after the plasma has been formed, other diagnostic technique will be required to study the process.

On the other hand, the solid wire has reached its melting point just before the plasma formation in the case of 50 mbar air and 50 mbar nitrogen as shown in Table 4.7. It is suggested that either one of the following two reasons might have caused the formation of plasma. One of the reasons suggested is attributed to the occurrence of electromagnetic instability along the wire when the wire has melted. Meanwhile, another reason is purely due to the breakdown of the ambient gas. Based on the study conducted by Mao *et al.*, it is suggested that the wire material will be further heated and thus vaporized by the plasma (Mao, Zou, Wang, & Jiang, 2009).

5.2 Discussion on FESEM observation

The FESEM has been used to observe the powder produced from wire explosion in nitrogen and air. The main purpose is to observe the existence of micron-sized structures that might be produced from the wire explosion in different ambient condition. At the same time, the condition of the as-produced powders can also be observed as the samples being viewed by FESEM did not go through any treatment as those for TEM viewing.

From the observation through FESEM, it has been confirmed that the web-like structure is formed by agglomerated nanoparticles. Web-like structure has been observed in all cases. This shows that agglomerated nanoparticles has been produced. A small amount of non-agglomerated nano-sized particles has also been observed in the samples obtained from wire explosion in nitrogen and air. Besides that, micron-sized spherical particles have also been observed in all cases. It is suggested that the micron-sized particles are formed from the molten wire material that has not been vaporized.

5.3 Discussion on the characteristics of powders produced by different modes of explosion

It is suggested that the main factors which will affect the powder characteristics in our work is the ambient pressure, ambient gas species, mode of explosion as well as the amount of deposited energy at various stages of the explosion. There are some inter-relations between these factors. The mode of explosion will be influenced by the ambient pressure and gas species. Meanwhile, different modes of explosion will affect the amount of deposited energy into the wire.

Other than that, the ambient pressure will affect the expansion of the wire material and thus the density of the vapour produced from the wire. High density of vapour is preferable during the early stage of particle formation in order to generate a supersaturation. A supersaturation with higher concentration can generate more nuclei and produce nuclei with smaller size. However, a dense vapour is not preferred during the growth stage of the nuclei, as this will promote the growth of nuclei and thus producing particles with larger size.

On the other hand, the thermal conductivity of the ambient gas species is the property that might affect the particles size. It has been suggested that ambient gas with high thermal conductivity will be able to reduce the temperature of the particles and thus the growth of the particles.

The deposited energy will affect the heating of the wire material and thus the temperature and the amount of vapour available for nanoparticles formation through supersaturation at the later stage. Besides that, the amount of deposited energy will also affect the expansion of the wire material against the pressure of the ambient gas.

In the following sub-sections, we will examine the characteristics of powder, i.e.: median diameter and chemical composition, and compared the characteristics between powders produced from different ambient conditions. The possible factors that have caused the differences in the powder characteristics will be discussed. We will categorize the discussion according to the mode of explosion.

5.3.1 Powders produced by wire explosion with current pause

As mentioned previously, wire explosion with current pause has been observed in the case of 500 mbar nitrogen-argon mixtures, 1 bar nitrogen, 1 bar air, 500 mbar nitrogen and 500 mbar air. It has been observed from FESEM that the powders produced generally consist of nano to micron-sized particles having elliptical, spherical or irregular shape. Most of the nanoparticles are observed to agglomerate and form web-like structures. Pure Cu powders have been produced in pure nitrogen and nitrogen-argon ambient while copper oxides have been observed in the case of air. It is suggested that the occurrence of copper oxides is due to the presence of oxygen in air.

In the following sub-sections, we will examine the possible factors that have affected the powder characteristics. This is done through the comparison between characteristics of powders produced in various ambient conditions.

5.3.1.1 Difference in the median diameter of nanopowders produced from wire explosion in 500 mbar nitrogen

Before we carry out the comparison between powders produced in different ambient condition, it can be noted that the median diameter given for the case of 500 mbar nitrogen is different in the previous section. This is shown in Table 4.5 and 4.8. It is suggested that the variation in median diameter between the two sets of nanopowder is mainly due to the different procedure being applied in preparing the TEM samples. In the case where smaller median diameter has been obtained, the collected powder has been treated by ultrasonic wave for about 2 hours. However, no such treatment has been carried for the set of powder with larger median diameter. Meanwhile, the resolution of the TEM being used might also have effect on the measured particle size as the two samples have been viewed by TEM of different model.

5.3.1.2 Comparison between powders produced in 1 bar and 500 mbar air and nitrogen

For the case of 1 bar and 500 mbar air and nitrogen, no obvious difference in the amount of energy deposited at the time of peak of current spike, peak of voltage spike, as well as the end of current spike. The energy deposited at peak of current spike, peak of voltage spike and the end of current spike is about 5 J, 17 J and 25 J respectively.

The energy deposited at the end of the current pause is about 41 J for the case of 1 bar air, 1 bar nitrogen and 500 mbar air. For the case of 500 mbar nitrogen, it is slightly lower at 37 J. This amount of deposited energy does not seem to match with the trend of the median diameter of nanopowders. As we can see, the median diameter is smallest when the deposited energy is 37 J, which is lowest compared to other cases. On the other hand, those cases with higher deposited energy have larger median diameter. Thus, it is suggested that the ambient pressure has larger effect on the median diameter especially in the case of nitrogen ambient.

5.3.1.2.1 Comparison between powders produced in 1 bar and 500 mbar air

For the case of air at 1 bar and 500 mbar, the median diameter is found to be about the same for nanopowder produced at both pressures (31 nm). It has been observed that the powder produced in 1 bar air consists of Cu_2O only while that in 500 mbar air consists of both Cu_2O and CuO. According to Korshunov *et al.*, the CuO is a product of Cu_2O oxidation from the reaction: $Cu_2O + \frac{1}{2}O_2 \leftrightarrow 2CuO$ (Korshunov & Il'in, 2009) .

It is suggested that the Cu_2O particles are initially produced in the 500 mbar air and their sizes are smaller than that produced in 1 bar air (Due to the ambient pressure effect, particles with smaller average size are suggested to be produced at lower pressure). However, as CuO is formed by the oxidation of Cu_2O, the particles sizes will be slightly increased. The molar volumes of Cu_2O and CuO are 23.6 cm^3 mol^{-1} and 12.3 cm^3 mol^{-1} respectively. If Cu_2O is oxidized in the way shown in the reaction above, 1 mole of Cu_2O will produce 2 moles of CuO. This will cause an increase in the volume from 23.6 cm^3 to 24.6 cm^3 where 23.6 cm^3 is the volume of original 1 mole of Cu_2O while 24.6 cm^3 is the volume of the 2 moles of newly formed CuO. This is suggested to be the reason for the increase in the median diameter of the nanopowder produced in 500 mbar air, which has caused the median diameter to be closed to that of the case of 1 bar air.

5.3.1.2.2 Comparison between powders produced in 1 bar air and 1 bar nitrogen

From Table 4.10 and 4.11, it has been shown that pure Cu_2O powder has been produced in the ambient of 1 bar air while pure Cu powder has been produced in the ambient of 1 bar nitrogen. It is found that median diameter of nanopowder produced in 1 bar air is smaller than that produced in 1 bar nitrogen although the molar volume of Cu_2O is larger than that of Cu. The main difference between the two cases is the ambient gas species. The ambient pressure and the amount of deposited energy at the peak of current spike, peak of voltage spike, the end of current spike and the end of current pause are approximately the same. It is suggested that the Cu_2O particles produced in air have been efficiently cooled to terminate their growth and thus producing nanopowder with smaller median diameter.

5.3.1.3 Comparison between powders produced in 500 mbar nitrogen-argon mixtures at various compositions

In the case of binary gas ambient, the amount of energy deposited at the peak of current spike, peak of voltage spike and the end of current spike is about 3 J, 16 J and 21 J respectively. Meanwhile, the amount of energy deposited at the end of current pause is different in each case. It is highest in the case of 50% nitrogen + 50% argon (66 J) and lowest for the case of 25% nitrogen + 75% argon (34 J). It is 42 J for the case of 75% nitrogen + 25% argon. The difference in the deposited energy does not seem to bring any significant effect on the median diameters as they are about the same at 33 nm for the three cases. It is suggested that the median diameters are almost the same because the property of the three binary gas ambient, especially the thermal conductivity of the gas, does not vary significantly.

5.3.1.4 Comparison between powders produced in 500 mbar nitrogen and 500 mbar nitrogen-argon mixtures

It has been observed that the amount of deposited energy at the peak of current spike, peak of voltage spike and the end of current spike is slightly higher in the case of 500 mbar nitrogen. The energy deposited at the end of current pause in the case of 500 mbar nitrogen is about the same as that of 75% nitrogen + 25% argon which is approximately 42 J. It is suggested that the main reason for the lower median diameter obtained in the case of 500 mbar nitrogen is the higher thermal conductivity of nitrogen compared to the nitrogen-argon mixtures. At the same time, the slightly higher deposited energy at the initial stage of the wire explosion is suggested to be an added advantage. In both cases, pure Cu powders have been obtained.

5.3.2 Powders produced by wire explosion with current dip

Wire explosion with current dip has been obtained for the case of 100 mbar air and 100 mbar nitrogen. It is observed that energy deposited at peak of current spike and peak of voltage spike are about the same for both cases, which are approximately 5 J and 20 J respectively. The amount of energy deposited at current dip is slightly higher in the case of 100 mbar nitrogen. Although the deposited energy is higher, the median diameter is found to be larger for the case of 100 mbar nitrogen compared to that of 100 mbar air. The deposited energy at current dip does not seem to correlate well with the median diameter where higher amount of deposited energy is expected to give smaller median diameter but this is not the case here. Meanwhile, the effect of pressure and the mode of explosion can be excluded here as both cases have same pressure and mode of explosion.

Thus, it is suggested that the main factor that has affected the size of the particles is the ambient gas species in each case. This is very similar to the comparison between the case of 1 bar air and 1 bar nitrogen. However, the composition of powder is slightly different here. Mixture of Cu and Cu_2O has been produced in the case of 100 mbar air while pure Cu has been produced in the case of 100 mbar nitrogen. It is suggested that the occurrence of Cu in the case of 100 mbar air is due to the lack of oxygen in the low pressure ambient. As most peaks in the XRD pattern are corresponding to Cu_2O, it is suggested that the overall Cu_2O content in the powder is higher than the Cu content. Individual particles might be formed by pure Cu_2O, pure Cu or a mixture of Cu_2O and Cu. The quantity of particles composed of pure Cu_2O is suggested to be higher as the overall content of Cu_2O is higher.

5.3.3 Powders produced by explosion with immediate discharge

Explosion with immediate discharge has been observed in the case of 500 mbar argon, 50 mbar nitrogen and 50 mbar air. No current spike has been observed on the current signals and the first voltage peak is taken as the estimated point where the plasma has formed.

In the case of 500 mbar argon, it is observed that only 1 J of energy has been deposited into the wire before the plasma is formed. This amount of energy is not enough to bring the wire to its melting point before the plasma formed. Therefore, it is suggested that the wire is still in solid state after the plasma has formed. This might explain why the median diameter of nanopowder produced in 500 mbar argon is large (37 nm).

Since the wire is still in solid state that is conductive, current from the capacitor will flow across the wire holders through the wire and the plasma at the same time. In addition, since a part of the current has been diverted into the plasma, current flowing through the wire will be reduced. Nevertheless, a smaller amount of direct heating of the wire by the current is still in progress until the wire lost its conductivity. It is suggested that heating of the wire will be contributed by the current flowing through it as well as the plasma around the wire.

On the other hand, the amount of energy deposited at the voltage peak for the case of 50 mbar nitrogen and 50 mbar air is found to be about the same. The deposited energy has brought the wire to its melting point just before the plasma is formed. This is higher than the case of 500 mbar argon. Although the deposited energy is about the

same, the difference in the median diameter of the nanopowder varied as much as 7 nm. It is about 24 nm for the case of 50 mbar air and about 31 nm for the case of 50 mbar nitrogen.

Again, median diameter for nanopowder produced in 50 mbar air is smaller than that produced in 50 mbar nitrogen. This is similar to the cases in previous section where nanopowder produced in 100 mbar air has smaller median diameter (26 nm) compared to that produced in 100 mbar nitrogen (34 nm). Since the pressure, the amount of deposited energy at voltage peak and the mode of explosion in the case of 50 mbar air and 50 mbar nitrogen are the same, it is suggested that the main factor which has caused the difference in the median diameter is the ambient gas species.

The powder produced in 50 mbar air is composed of both Cu and Cu_2O. As most peaks in the XRD pattern are corresponding to Cu, it is suggested that the overall Cu content in the powder is higher than the Cu_2O content. The reduction in the quantity of Cu_2O as compared to the case of 100 mbar air is due mainly to the decrease of the oxygen content in the air at low pressure. On the other hand, pure Cu powder has been obtained in the case of 50 mbar nitrogen.

5.4 Summary of the characteristics of powders produced at different ambient conditions

In the previous sections, we have discussed about the powders produced at different ambient conditions according to the mode of explosion by which the powders have been produced. In this section, we will summarize the effect of different ambient conditions on the powders characteristics. First, we will compare the median diameter and composition of powders produced in air and nitrogen when the ambient pressure is changed. After that, we will look at the change of the median diameter when the ambient gas is changed from pure nitrogen to nitrogen-argon mixture and then the pure argon while the ambient pressure is kept constant at 500 mbar.

5.4.1 Powders produced in air and nitrogen

It has been observed that the median diameter of nanopowders produced in air and nitrogen decreased with decreasing ambient pressure with a special case of 500 mbar nitrogen. Meanwhile, at the same pressure, nanopowders produced in air has smaller median diameter compared to that produced in nitrogen.

Median diameter of the nanopowders produced in nitrogen has been observed to decrease sharply from 34 nm to 27 nm when the pressure is decreased from 1 bar to 500 mbar. When the pressure is further decreased to 100 mbar, the median diameter increases again to 34 nm. It is suggested that the inconsistency in the change of median diameter is due to the change of the mode of explosion as the pressure is decreased from 500 mbar to 100 mbar. When the mode of explosion is the same, the decrease in nitrogen pressure has caused the median diameter to reduce. When the nitrogen pressure

is decreased from 500 mbar to 100 mbar, the mode of explosion changes from that with current pause to that with current dip. It is suggested that the main factor, which has caused the increase of median diameter when the pressure is decreased from 500 mbar to 100 mbar, is the formation of plasma that has occurred at an earlier time in the case of 100 mbar.

As the nitrogen pressure is decreased from 100 mbar to 50 mbar, the median diameter has decreased from 34 nm to 31 nm. As mentioned in section 5.1, the explosion with current dip and explosion with immediate discharge are almost the same. Therefore, it is suggested that the slight variation in the mode of explosion does not give significant effect on the median diameter. Instead, it is suggested that the median diameter has been reduced due to the decrease in ambient pressure.

On the other hand, no sharp drop has been observed in the case of air when the pressure is decreased from 1 bar to 500 mbar. Besides that, the median diameter also does not increase when the ambient pressure is further decreased from 500 mbar to 100 mbar. As discussed in previous sections, for the same ambient pressure, the mode of explosion and the amount of deposited energy at various stages are approximately the same. Other than the ambient gas species being used, the main difference between the case of air and nitrogen is suggested to be the composition of the powders.

Pure Cu_2O powder is produced in 1 bar air while a mixture of Cu_2O and CuO is obtained in the case of 500 mbar air. Meanwhile, mixtures of Cu and Cu_2O have been produced in 100 mbar and 50 mbar air. On the other hand, pure copper powders have been produced by wire explosion in nitrogen ambient at different pressures. It is

suggested that the formation of the oxide particles has caused the difference in the way the median diameter changed when compared to the case of nitrogen.

5.4.2 Powders produced in 500 mbar nitrogen, argon and nitrogen-argon mixtures

Comparison between powders produced in 500 mbar nitrogen and 500 mbar nitrogen-argon mixtures has been discussed in Section 5.3.1.4. In this section, the discussion will be focused on the comparison between the nitrogen containing ambient with that of pure argon ambient. It has been observed that nanopowder produced in 500 mbar nitrogen has smallest median diameter compared to those produced in 500 mbar argon and 500 mbar nitrogen-argon mixtures. On the other hand, nanopowder produced in 500 mbar argon ambient has largest median diameter. As suggested in Section 5.3.3, the larger median diameter in the case of 500 mbar argon is mainly because the amount of deposited energy before the plasma formation is too low. The low amount of deposited energy is caused by the early breakdown of the ambient gas. The early breakdown of the ambient gas has given rise to wire explosion with immediate discharge. The difference in the mode of explosion is the main factor that has caused the difference in median diameter between the nanopowders produced in argon and nitrogen containing ambient. Meanwhile, as suggested in section 5.3.1.4, nanopowder produced in pure nitrogen has smaller median diameter than those produced in nitrogen-argon mixtures because the pure nitrogen has better thermal conductivity.

Chapter 6

Conclusion and Suggestions for Future Work

6.1 Conclusion

A wire explosion system with coaxial configuration had been built to study the synthesis of metallic nanopowders by the wire explosion technique. Copper wires 125 μm in diameter and 6.1 cm long had been exploded in air and nitrogen at 1 bar, 500 mbar, 100 mbar and 50 mbar. Besides that, same type of wires had been exploded in three different 500 mbar nitrogen-argon mixtures (25% nitrogen + 75% argon, 50% nitrogen + 50% argon and 75% nitrogen + 25% argon) and 500 mbar argon.

The TEM, FESEM and XRD had been used to characterize the nanopowders produced from the wire explosion. Meanwhile, energy deposited into the wire at various stages of the wire explosion had been calculated based on the current and voltage data.

Three modes of explosion had been observed from the wire explosion at different ambient conditions, namely, explosion with current pause, explosion with current dip and explosion with immediate discharge. The main difference between the three modes of explosion was the time of plasma formation. The possible reasons for each of these explosions to occur had been discussed. Other than that, effect of the ambient condition on the characteristics of the nanopowders produced by the wire explosion technique had been discussed.

6.2 Future works

Suggested future works are grouped into three categories, namely, investigation related to the wire explosion process, investigation related to the particles formation process and investigation related to the synthesis of nanopowders by the wire explosion technique. With a better understanding of the wire explosion process, it is suggested that the properties of the supersaturation following the wire explosion can be estimated. Knowledge on the properties of the supersaturation will allow us to estimate the process of the nucleation and growth. By studying the particles formation process, we can understand the way by which the particles will be formed and estimate the effect of the initial nucleation and growth on the particles characteristics. Thus, it is suggested that the understanding in the wire explosion process and the particles formation process will allow us to bridge the parameters of the wire explosion with that of the particles formation. Following the investigation related to the synthesis of nanopowders, we may suggest several improvements that can be carried out to improve the quantity and quality of the nanopowders being produced and thus making the wire explosion technique an effective method for nanopowders production.

6.2.1 Investigation related to the wire explosion process

It is suggested that the following aspects of the wire explosion should be studied in order to have a better understanding of the wire explosion process:

(1) The thermodynamic properties of the wire at various stages of the wire explosion. For example, the temperature, pressure, volume and phase of the wire material.

(2) The electrical behavior of the wire at various stages of wire explosion. For example, the current, voltage and resistance of the wire explosion.

(3) The instabilities that might occur during the wire explosion.

(4) The properties of plasma formed during the wire explosion. For example, the temperature, density, resistance and inductance of the plasma.

(5) The formation of shock wave and the expansion of wire material.

The above suggestions can be carried out experimentally, theoretically or by numerical modelling. In terms of experiment, other than the study of current, voltage and light emission as shown in our work, time-resolved imaging, spectroscopy or high speed infra-red thermometer may be used to achieve the studies suggested above.

6.2.2 Investigation related to the particle formation process

Studies related to the particle formation process may be carried out mainly by numerical modeling or simulation. The following studies are suggested:

(1) Effect of various parameters of the supersaturation on the nucleation and growth of particles. For example, the temperature and concentration of the supersaturation.
(2) Effect of cooling rate of particles on the particle size distribution.
(3) Effect of wire explosion parameters on the wire explosion process and thus the parameters of supersaturation and the cooling rate.

6.2.3 Investigation related to the formation of nanopowders by the wire explosion technique

The following steps or studies are suggested to improve the quantity and quality of the nanopowders being produced:

(1) More advanced powder characterization technique should be used in order to obtain more information on the characteristics of the nanopowders produced. For examples, we can determine the specific surface area of the powders by using BET method, study the surface structure of particles by using AFM, study the crystal structure by using HRTEM, Raman spectroscopy or small angle X-ray scattering (SAXS) and determine the chemical composition by using energy dispersive X-ray spectroscopy (EDS) and electron energy-loss spectroscopy (EELS).

(2) Increase the efficiency of the production system such that more powder can be produced. It is suggested that this can be done by using load of multiple wires that can be exploded before the chamber is opened. At the same time, the particles collecting mechanism should be improved to enhance the efficiency of the powder collector.

(3) Improve the dispersivity of the nanoparticles being produced such that agglomeration will not occur. It is suggested that this can be achieved by introducing surfactant that will passivate the particles after the particles are formed. Another advantage of such passivation is the reduction of the particles size, as the growth will also be reduced when the particles have been passivated (Murai, *et al.*, 2007). Well-dispersed particles will also allow the particle size measurement to be performed by computer software automatically. This is because the computer software cannot recognize individual particle if they are agglomerated. Thus, the particle size can only be measured manually.

(4) In order to produce nanopowders with smaller size, it is suggested that the ambient gas being applied should have good cooling effect and energy supply by the capacitor should be hundreds of times higher than the vaporization energy of the wire (Tokoi, *et al.*, 2010).

(5) Production of nanopowder by match mode explosion which gives an explosion without formation of plasma as suggested by Kotov (Kotov, 2003) should be studied to verify whether such explosion can significantly reduce the particles size.

APPENDIX A

Calculation of vaporization energy of a copper wire

Some physical properties of copper are shown below:

Melting point (^{o}C)	1083	
Boiling point (^{o}C)	2567	
Specific heat (J K^{-1} kg^{-1})	385	(At 25 ^{o}C)
Latent heat of fusion (J g^{-1})	205	
Latent heat of evaporation (J g^{-1})	4796	
Density (g cm^{-3})	8.96	(At 20 ^{o}C)

The copper wire being used in the experiment is 125 μm in diameter and 6.1 cm long. The volume of this wire is about 7.5 x 10^{-4} cm^{3}. The density of copper is 8.96 g cm^{-3} at 20 ^{o}C. So, the mass of the copper wire being used is about 6.7 mg.

First, we need to determine the energy required to bring the wire from room temperature (25 ^{o}C) to its melting point. The amount of energy has been determined by equation (A-1) to be 2.73 J.

Energy required to heat the wire from room temperature to melting point = *Temperature difference between melting point and room temperature* x *Specific heat of copper* x *Mass of wire* (A-1)

After the wire has reached its melting point, additional energy will be required to turn it into liquid state. The amount of energy required to turn the solid wire at melting point into its liquid state is given by equation (A-2) to be 1.38 J.

Energy required to turn the solid wire at melting point into liquid state = *Latent heat of Fusion* x *Mass of wire* (A-2)

Thus, the total energy required to turn a solid wire at room temperature into liquid state is approximately 4.1 J.

During the stage where the wire is melted, its temperature will be approximately same as its melting temperature. When the wire is completely melted, its temperature will start to rise again if the energy supply to the wire material is continued. The energy required to heat the liquid wire to its boiling point is given by equation (A-3) to be 3.83 J. This equation is same as (A-1).

Energy required to heat the liquid wire from melting point to boiling point = *Temperature difference between boiling point and melting point* x *Specific heat of copper* x *Mass of wire* (A-3)

Additional energy requires to turn the liquid wire at boiling point into gaseous state is given by equation (A-4) to be 32.17 J. Equation (A-4) is similar to (A-2).

Energy required to turn the liquid wire at boiling point into gaseous state = *Latent heat of Fusion* x *Mass of wire* (A-4)

Thus, the total energy required to turn a solid copper wire 125 μm in diameter and 6.1 cm long into its gaseous state is approximately 40.1 J.