

Article

Synthesis of Multiscale Ultrafine Copper Powder via Radio Frequency Induction Coupled Plasma Treatment

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Abstract: Nano-sized spherical copper powder has important applications in the fields of micro-electronic devices, highly efficient catalysts and lubricant additives. In this study, nano-sized and micron-sized spherical copper powders were simultaneously prepared by radio frequency (RF) induction coupled plasma technology. The effects of processing parameters on the powder properties were studied. The results show that by inputting copper powder with $D_{50} = 34.6 \mu\text{m}$, nano-sized spherical powder with a particle size of 10–220 nm and micron-sized spherical powder with a particle size of 4.0–144.0 μm were obtained. The ratio of the nano-sized powder reached 86.4 wt.%. The optimal processing parameters are as follows: powder feed rate is 5.5 g/min, carrier gas flow rate is 5–6 L/min and reaction chamber pressure is 15 Psia. When the carrier gas flow rate is 6 L/min, in the plasma zone ($>10,000 \text{ K}$), the powder with particle size $<42.0 \mu\text{m}$ is completely vaporized, which forms nano-sized powder during cooling, while the powder with particle size $>42.0 \mu\text{m}$ is melted and partially vaporized, forming a micron-sized powder. The research results provide a new way for engineering the production of copper nano-powder and some other nano-powders with low melting points, such as silver powder, tin powder and so on.



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Keywords: copper nano-powder; RF induction plasma; spheroidization; vaporization

1. Introduction

Copper nano-powder has been widely applied in the fields of microelectronic devices [1–3], highly efficient catalysts [4,5] and lubricant additives [6,7]. For example, Yuan et al. [8] prepared self-reducing nano-paste with 75 wt.% copper nano-powder ($\sim 110 \text{ nm}$), which could form Cu-Cu bonding joints with an average bond strength of up to 52.01 MPa at 523 K, and it is widely used in integrated circuits and semiconductor devices. Copper nano-powder is also used in low-cost metal-based nanocatalysts due to its high catalytic activity, large specific surface area and good degradation resistance. For instance, the catalytic reduction time of Thioflavine-T cationic dye was shortened by 10 times by the addition of 2 wt.% copper nano-powder ($\sim 6.9 \text{ nm}$) in the sulfonated reduction of graphene oxide. Moreover, its catalytic activity remained at 68% after the fifth repetition [9]. Mixing copper nano-powder with lubricating oil can improve friction performance and have a self-repairing effect on bearings and other parts. For example, Chen et al. [10] added 0.2 wt.% copper nano-powder ($\sim 20 \text{ nm}$) into 50 CC lubricating oil, which could reduce the friction coefficient by 20% and the average diameter of wear scar by 25% at 413 K, greatly improving its lubrication effect.

To date, the mainstream technologies for the preparation of copper nano-powder include chemical reduction [11,12], electrolytic deposition and microemulsion [13,14], etc. As for the chemical reduction method, copper nano-powder is prepared through reducing the soluble copper salt precursor, and the prepared copper nano-powder is prone to agglomeration and oxidation during the reaction. For example, Vaseem et al. [15] prepared copper nano-powder with a particle size of 80 nm by reducing copper nitrate with hydrazine

and found that the nano-powder was agglomerated and oxide (or hydroxide) layers with a thickness of 5–10 nm were formed on the powder surface. As for the electrolytic deposition method, copper nano-powder is deposited in the electrolyte of the cathode. This method has low energy-use efficiency and the prepared copper nano-powder is mostly irregular in shape. Nekouei et al. [16] synthesized copper nano-powder with a particle size of 50–100 nm using the electrolysis method in a nitrate solution and found that the shape of the prepared nano-powder was irregular, and the energy-use efficiency was only 30%. As for the microemulsion method, an emulsion is first formed with two immiscible solvents under the catalyzing effect of surfactants, and then the copper nano-powder is formed through nucleation and agglomeration in the emulsion. This preparation process also usually has a long cycle and high cost and is prone to causing agglomeration [17].

Plasma has an extremely high energy density and the temperature in the central area can reach 10^4 – 10^5 K [18], which makes the metal melt and evaporate instantaneously. The steam collides with the inert gas violently and is quenched into nano-powder. Fu et al. [19] prepared TiN nano-powder by arc plasma method and found that TiN nano-powder with a particle size of 10–15 nm was obtained with a quenching gas velocity of 40 m/s. Ghodke et al. [20] prepared nickel nano-powder by arc plasma method and found that under the Ar and N₂ atmosphere (air pressure was 666 mpar, power was 6 kW), nickel nano-powder with a particle size of 30–50 nm was successfully prepared, but there existed electrode contamination in the produced powder. Compared with the arc plasma, induction plasma has a longer reaction time and a higher reaction activity. At the same time, there is no electrode contamination. Therefore, it is expected to produce spherical nano-powder with higher purity and more controllable particle size. For example, Ko et al. [21] successfully prepared SiC nano-powder (30–100 nm) by treating organic precursors with induction plasma, but the influence of experimental parameters on nano-powder was not systematically discussed. Karthik et al. [22] synthesized ultrafine aluminum powder with a particle size of 220–400 nm using induction plasma but neglected to discuss and calculate the relationship between particle size and heat absorption. Kobayashi et al. [23] prepared copper powder with a particle size of 139–250 nm using the induction plasma system. However, they did not study the micron-sized spherical copper powder collected in the collection canister, nor did they characterize the surface morphology and study the mechanism of the copper powder after plasma treatment. Many studies have not fully characterized the surface morphology and properties of plasma-treated powders and have neglected to discuss in detail the reasons why process parameters affect experimental results.

In this paper, nano-sized and micron-sized spherical copper powders were simultaneously prepared by RF induction coupled plasma technology, in which the particle sizes of nano-sized copper powder are in the range of 10–220 nm and the ratio can reach 86.39%. The effects of plasma treatment parameters (powder feed rate, carrier gas flow rate, reaction chamber pressure, etc.) on the morphology, particle size and the ratio of copper nano-powder were systematically studied. The formation mechanism of multiscale ultrafine copper powder was also discussed.

2. Materials and Methods

In the paper, electrolytic copper powder was used as the raw material. Figure 1 shows the SEM morphology and particle size distribution of the raw copper powder. It has a dendritic morphology with a rough surface, and the particle sizes are in the range of 4.6–272.0 μm ($D_{50} = 34.6 \mu\text{m}$). The oxygen content is about 654 ppm, and the purity is higher than 99.99%.

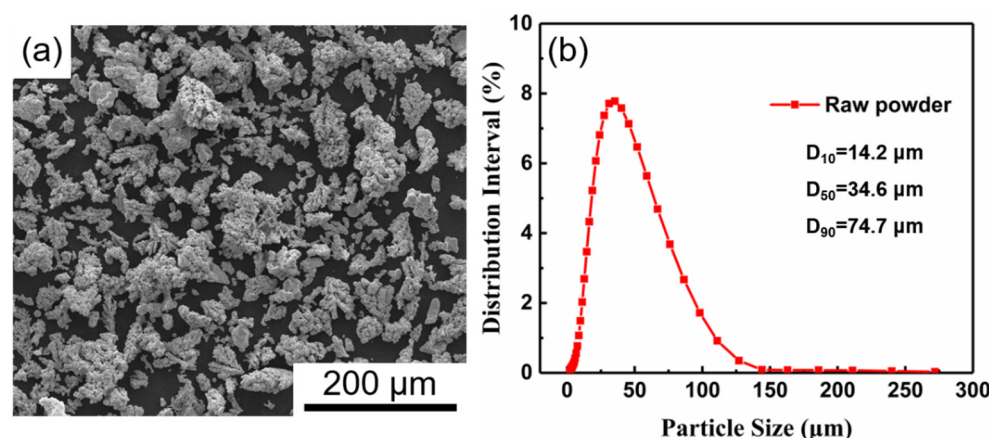


Figure 1. Raw copper powder: (a) morphology, (b) particle size distribution.

The ultrafine copper powder was prepared using RF induction coupled plasma technology (TEKNA Plasma System Inc., Quebec, Canada). The plasma system used high purity argon (Ar) as a carrier gas. The central gas (10 L/min Ar) was injected into the device to excite the plasma and the sheath gas (Mixed gas of 30 L/min Ar and 2.5 L/min H₂) played a role in protecting the quartz tube. The coarse spherical powder (referred to as CS-powder) was collected directly from the collection canister, the nano-powder (referred to as NP-powder) was attached to the chamber wall and blown away by inert gas before falling into the collection canister for collection. In order to study the influence of process parameters (powder feed rate, carrier gas flow rate and reaction chamber pressure, etc.) on powder characteristics (particle size distribution, nano-powder ratio, etc.), ten experiments were designed. The specific experimental parameters are shown in Table 1.

Table 1. The parameters of RF induction plasma in the experiment.

No.	F1	F2	F3	F4	C1	C2	C3	P1	P2	P3
Powder feed rate (g/min)	1.5	3.5	5.5	7.5	5.5	5.5	5.5	5.5	5.5	5.5
Carrier gas (L/min)	6 (Ar)	6 (Ar)	6 (Ar)	6 (Ar)	4 (Ar)	5 (Ar)	7 (Ar)	6 (Ar)	6 (Ar)	6 (Ar)
Reactor pressure (Psia)	15	15	15	15	15	15	15	6	9	12

The microstructure of the powder was observed by field emission scanning electron microscopy (SEM, Quanta FEG 250, FEI Technologies Inc., Hillsboro, OR, USA) and transmission electron microscopy (TEM, Tecnai G2 20S-Twin, FEI Technologies Inc., Hillsboro, OR, USA). The particle size distribution of the CS-powder was measured on a laser diffraction particle size analyzer (Micro-Plus, Malvern Instruments Ltd., Malvern, UK), while the particle size distribution of the NP-powder was measured from TEM images and high-resolution SEM images. The phase composition of the copper powder before and after plasma treatment was analyzed by X-ray diffraction (XRD, D/Max 2550, Rigaku Corporation, Tokyo, Japan), and the data were collected at a scanning rate of 4 deg/min between 30 and 100 deg (2 θ). An oxygen analyzer (TCH-600, LECO Inc., St. Joseph, MI, USA) was used to measure the oxygen content of the powder.

3. Results

3.1. Effect of Powder Feed Rate on Powder Properties

Figure 2 shows the morphology of the NP-powder and CS-powder prepared with different powder feed rates (1.5–7.5 g/min) under the reaction chamber pressure of 15 Psia and the carrier gas flow of 6 L/min. Figure 3a–c shows the particle size distribution of the NP-powder and CS-powder prepared at different powder feed rates. It can be seen that two kinds of copper powders are obtained after plasma treatment. They are the NP-powder with a particle size ranging from 20 nm to 1070 nm and the CS-powder with a particle

size ranging from 5.9 μm to 98.1 μm , respectively. With the increase in powder feed rate from 1.5 g/min to 7.5 g/min, the average diameter of the NP-powder and CS-powder both increases, while both powders show good sphericity and high spheroidization rate. When the powder feed rate reaches 7.5 g/min, micron-sized powder appears (Figure 2g), and some powders with irregular shape appear in the CS-powder (Figure 2h). Figure 3d shows the ratio of the NP-powder obtained at different powder feed rates; it is shown that when the powder feed rate is 1.5 g/min, the ratio of the NP-powder reaches 91.1%, but decreases to 89.0% as the powder feed rate increases to 7.5 g/min.

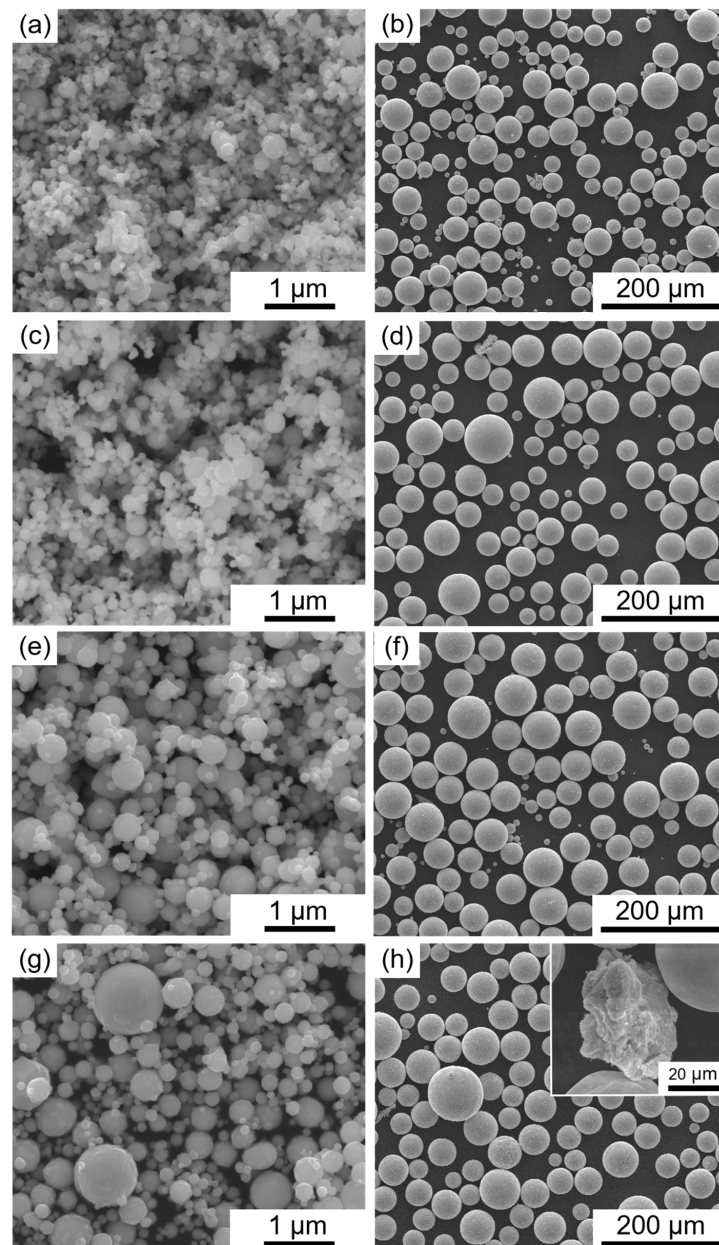


Figure 2. SEM images of the NP-powder and CS-powder with different powder feed rates: (a,b) 1.5 g/min, (c,d) 3.5 g/min, (e,f) 5.5 g/min, (g,h) 7.5 g/min.

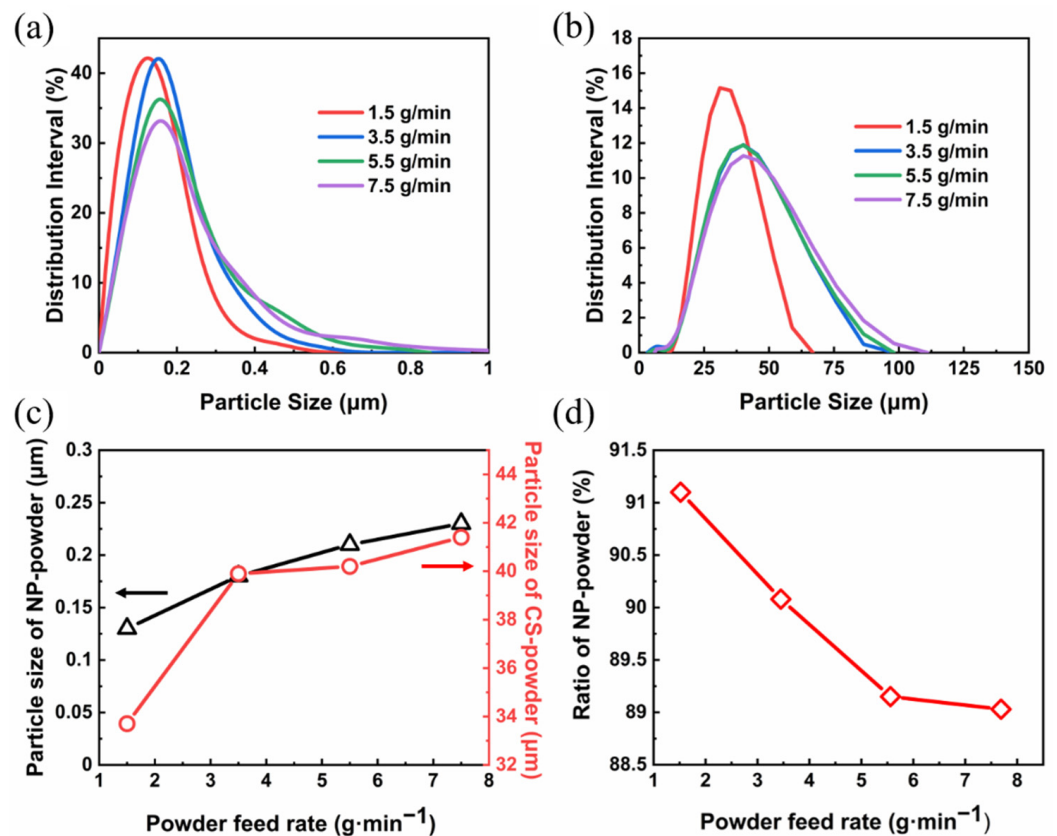


Figure 3. Particle size distribution of the (a) NP-powder and (b) CS-powder; (c) average particle size (D_{50}) of the NP-powder and CS-powder, (d) ratio of the NP-powder at different powder feed rates.

3.2. Effect of Carrier Gas Flow Rate on Powder Properties

Figure 4 shows the SEM images of the NP-powder and CS-powder obtained at different carrier gas flows (4–7 L/min) with the powder feed rate of 5.5 g/min and the reaction chamber pressure of 15 Psia. Figure 5a–c shows the powder particle size distribution after plasma treatment with different carrier gas flow rates. Obviously, after plasma treatment, two kinds of copper powders are obtained. They are the NP-powder with particle size ranging from 30 nm to 890 nm and the CS-powder with particle size ranging from 4.6 μm to 98.1 μm , respectively, which both show good sphericity and high spheroidization rate. With the increase in carrier gas flow rate from 4 L/min to 7 L/min, the particle size of the NP-powder has no obvious change, however, the average diameter of the CS-powder increases significantly. In addition, when the carrier gas flow rate is 4 L/min, a small number of nanoscale satellite powders appear and adhere to the surface of the CS-powder (Figure 4b). When the carrier gas flow rate increases to 7 L/min, some unmelted CS-powders and powders with residual pores exist (Figure 4h). Figure 5d shows the ratio of the NP-powder obtained at different carrier gas flow rates. It can be seen that when the carrier gas flow rate is 4 L/min, the ratio of the NP-powder is 90.6%. As the carrier gas flow rate increases to 7 L/min, the ratio decreases to 88.8%.

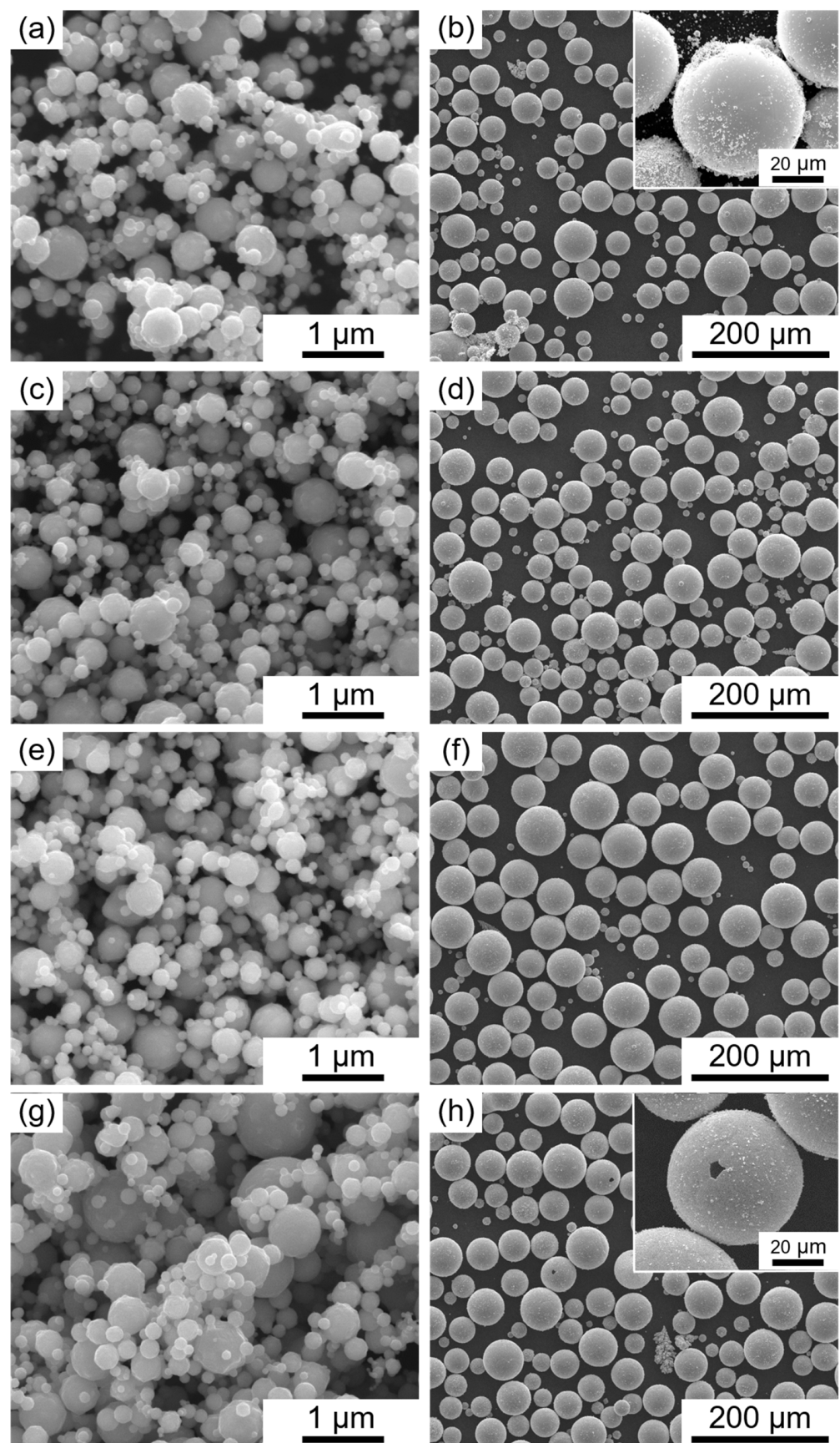


Figure 4. SEM images of the NP-powder and CS-powder with different carrier gas flow rates: (a,b) 4 L/min, (c,d) 5 L/min, (e,f) 6 L/min, (g,h) 7 L/min.

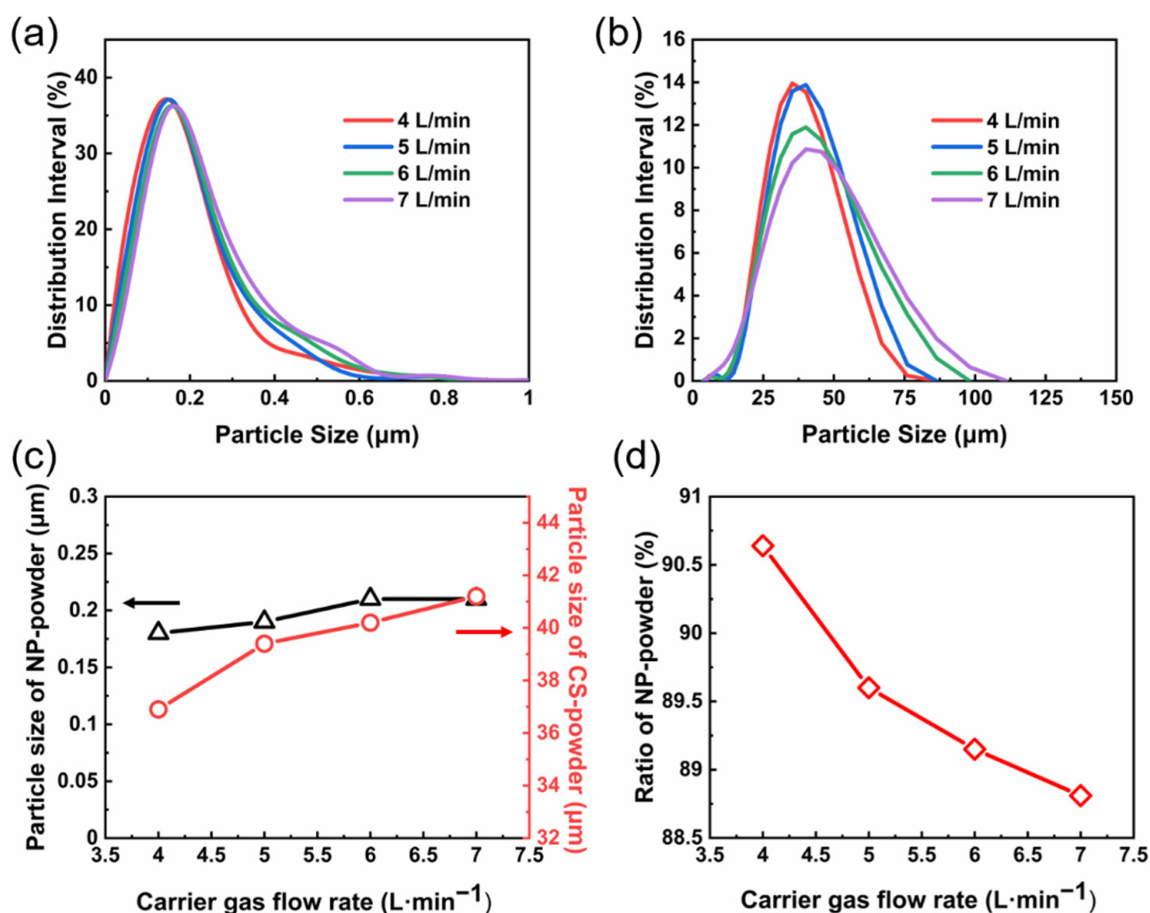


Figure 5. Particle size distribution of the (a) NP-powder and (b) CS-powder; (c) average particle size (D_{50}) of the NP-powder and CS-powder, (d) ratio of the NP-powder at different carrier gas flow rates.

3.3. Effect of Reaction Chamber Pressure on Powder Properties

Figure 6 shows the SEM images of the NP-powder and CS-powder obtained under different reaction chamber pressures (6–15 Psia) at the powder feed rate of 5.5 g/min and the carrier gas flow rate of 6 L/min. Figure 7a–c shows the powder particle size distribution after plasma treatment under different reaction chamber pressures. The NP-powder with particle size ranging from 10 nm to 220 nm and the CS-powder with particle size ranging from 4.0 μm to 144.0 μm can be obtained after plasma treatment. As can be seen from the figure, when the pressure of the reaction chamber is 6 Psia, the spheroidization rate of the NP-powder and CS-powder is not high (Figure 6a,b). With the increase in pressure, the sphericity of both powders increases. Meantime, the average diameter of the NP-powder first increases and then decreases as the pressure increases. By contrast, as the pressure increases, the average diameter of the CS-powder first decreases and then increases. Figure 7d shows the ratio of the NP-powder under different reaction chamber pressures. It can be seen that when the pressure is 6 Psia, the ratio of the NP-powder is 86.4%, which increases to 93.8% when the pressure is 12 Psia and decreases to 89.2% when the pressure increases to 15 Psia.

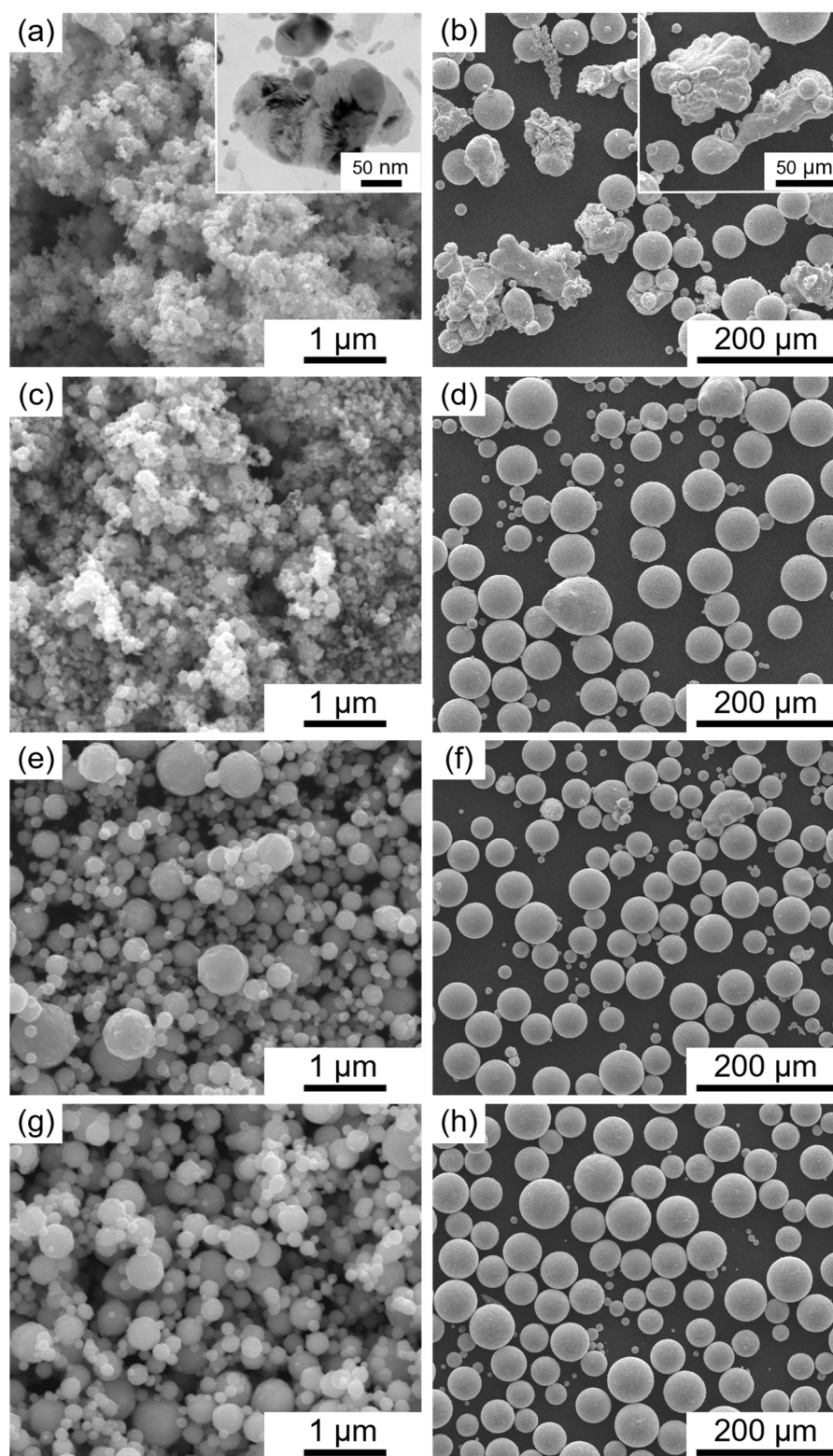


Figure 6. SEM images of the NP-powder and CS-powder at different reaction pressures: (a,b) 6 Psia, (c,d) 9 Psia, (e,f) 12 Psia, (g,h) 15 Psia.

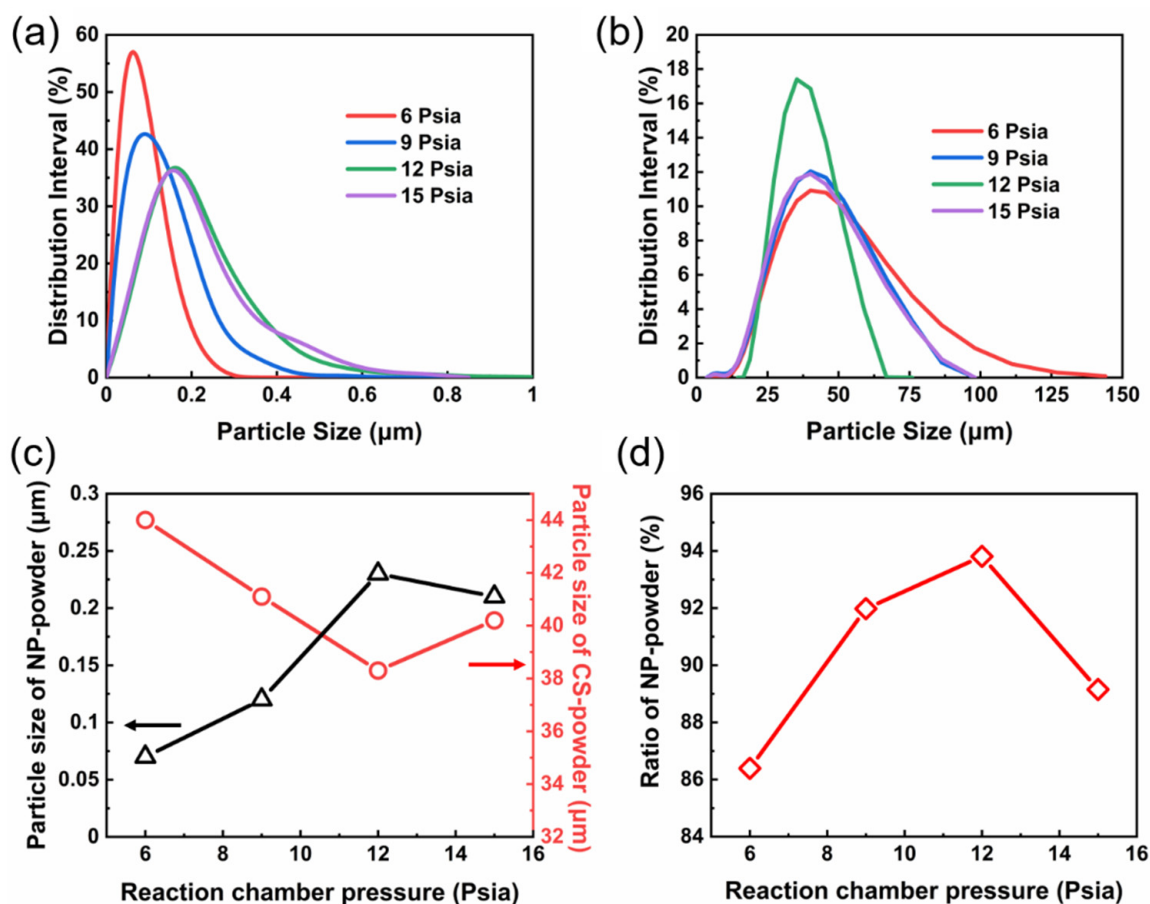


Figure 7. Particle size distribution of the (a) NP-powder and (b) CS-powder; (c) average particle size (D_{50}) of the NP-powder and CS-powder, (d) ratio of the NP-powder at different reaction pressures.

3.4. Characterization of Copper Powder after Plasma Treatment

As revealed from the above results, when the powder feed rate is 5.5 g/min, the carrier gas flow rate is 5–6 L/min and the reaction chamber pressure is 15 Psia, the obtained NP-powder and CS-powder both have perfect sphericity, high spheroidization rate and smooth surface. Therefore, in the following section, the powder prepared by these parameters is used for subsequent characterization. Figure 8 shows the XRD patterns of the copper powder before and after plasma treatment. It can be seen that the diffraction peaks of the NP-powder and CS-powder after plasma treatment are similar to the raw copper powder, indicating that there is no obvious phase structure change during plasma treatment. Figure 9 shows the SEM and TEM morphologies of the NP-powder after plasma treatment. It can be seen that the NP-powder is nano-sized (18.6–169.1 nm) with good sphericity and no obvious agglomeration. Figure 10 shows the morphology and element distribution of the CS-powder after plasma treatment. It can be seen that the CS-powder is dense and spherical, with a smooth surface and almost no satellite powder. In addition, the distribution of Cu and O elements are homogeneous, indicating that no obvious oxidation occurs during plasma treatment. The oxygen contents of the CS-powder and NP-powder measured are 178 ppm and 562 ppm, both obviously lower than that of the raw powder (654 ppm).

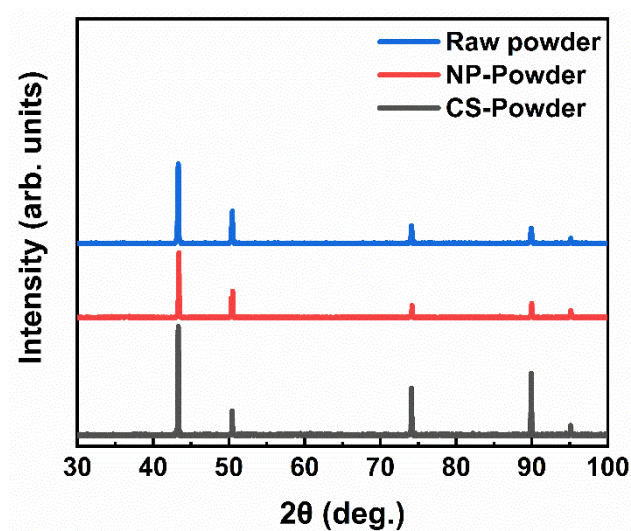


Figure 8. XRD patterns of the raw powder, NP-powder and CS-powder.

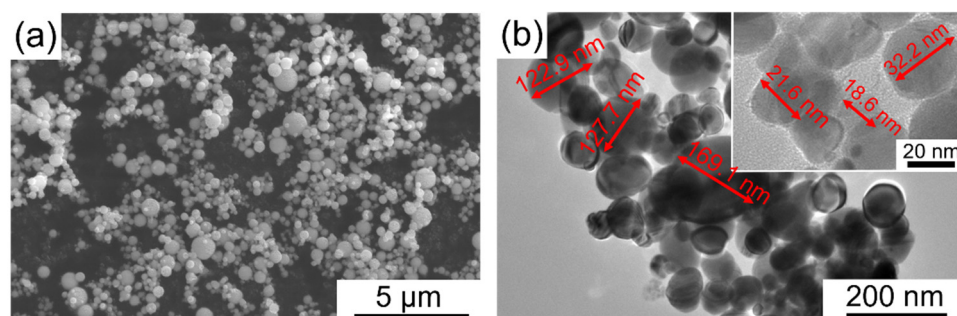


Figure 9. Morphology of the NP-powder: (a) SEM image, (b) high magnification TEM image.

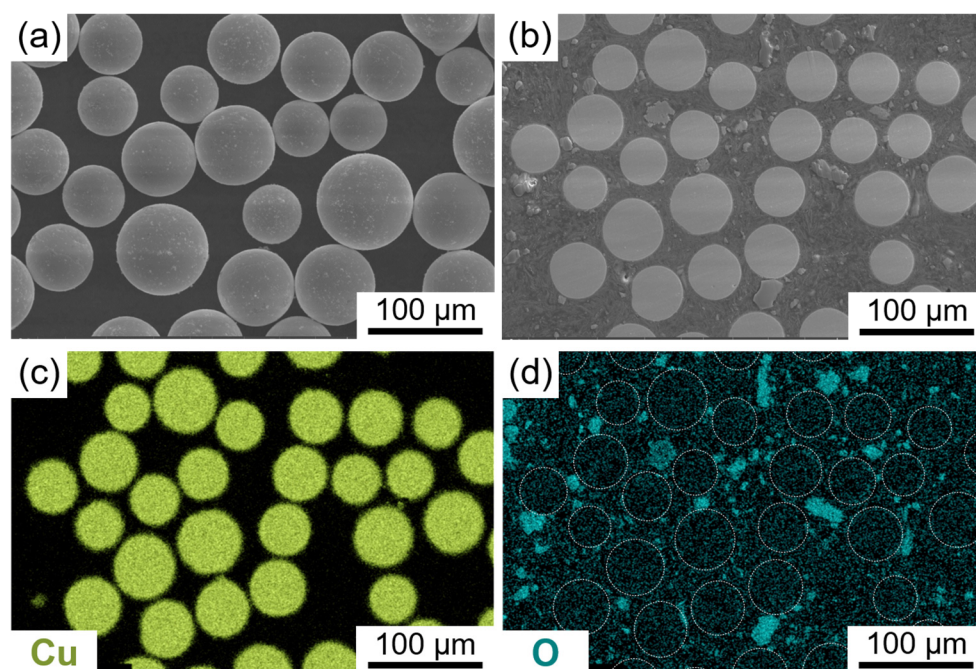


Figure 10. Morphology of the CS-powder: (a) SEM image, (b) SEM image of the cross-section; (c) Cu distribution and (d) O distribution.

4. Discussion

4.1. The formation Mechanism of Multiscale Ultrafine Copper Powder

Based on the above analysis, after the copper powder is treated with high temperature plasma up to 10,000 K, two kinds of powders can be obtained, namely the NP-powder with a particle size of 10–220 nm attached to the chamber wall and the CS-powder with a particle size of 4.0–144.0 μm in the collection canister. The formation mechanism of the above powders can be explained in Figure 11. The reason for the formation of the NP-powder is that when the raw copper powder passes through the plasma zone, it will vaporize at the high temperature, and the supersaturation of the copper vapor continues to increase, leading to the formation of copper nano-powder through homogeneous nucleation, which is eventually attached to the chamber wall (Figure 11b). The reason for the formation of the CS-powder is that when the raw copper powder passes through the plasma zone, it will undergo rapid melting and partial vaporization. The melted droplets become spherical in shape under the action of surface tension, which cool and solidify to coarser micron-sized spherical powder (Figure 11c).

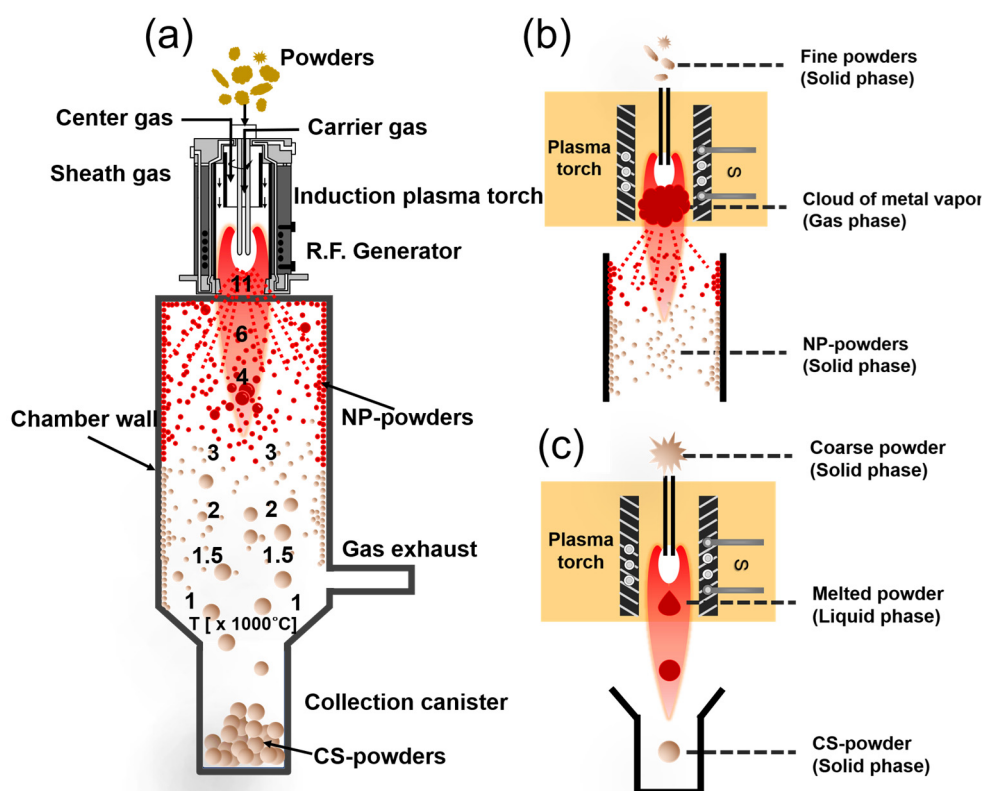


Figure 11. Formation mechanism of multiscale copper powders: (a) RF plasma system, (b) formation of the NP-powder and (c) CS-powder.

The vaporization or melting is directly related to the particle size of the powder and the carrier gas flow rate, while the particle size of the powder and the carrier gas flow rate determine the flight time of the powder at the high temperature plasma zone. The flight time (t_f) of copper powder in the high-temperature plasma zone can be expressed by Equation (1) [24]:

$$t_f = \sqrt{\frac{2Sr_p^2\rho}{4.5V_g\eta_g}} \quad (1)$$

where S is the high temperature zone length of the gas jet (~ 200 mm), ρ is the theoretical density of copper (8.96 g/cm³), η_g is the dynamic viscosity of gas (2.78×10^{-4} kg/m·s), r_p is the radius of the copper powder, and V_g is the velocity of the gas jet (carrier gas flow). In

the high temperature environment, the time required for the complete vaporization (t_v) of copper powder can be calculated by Equation (2) [25]:

$$t_v = r_p^2 / K \quad (2)$$

where K is the evaporation constant ($3.5 \times 10^{-8} \text{ m}^2/\text{s}$), r_p is the radius of the copper powder. Furthermore, the time required for completely melting (t_m) of the copper powder can be expressed by Equation (3) [26]:

$$t_m = \frac{r_p^2}{6} \left(1 + \frac{2}{Bi} \right) \cdot \frac{\rho L_m}{k_1 (T_f - T_m)} \quad (3)$$

where Bi is the Biot number ($Bi = h \cdot r_p / k_1$), h is the convective heat transfer coefficient ($2000 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$) [25], k_1 is the thermal conductivity ($401 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), T_f is the average temperature of the plasma [27], r_p is the radius of the copper powder, ρ is the theoretical density of copper, L_m is the latent heat of melting ($203.44 \text{ J} \cdot \text{g}^{-1}$), and T_m is the melting point (1356.6 K). When $t_f > t_v$, the powder is completely vaporized, while when $t_m < t_f < t_v$, the powder is completely melted and partially vaporized, while when $t_f < t_m$, the powder cannot be completely melted. Taking the carrier gas flow rate as 6 L/min , it can be calculated from the above equations that the critical maximum particle size for complete vaporization is $42.0 \text{ }\mu\text{m}$, and the critical maximum particle size for complete melting is $253.5 \text{ }\mu\text{m}$. In other words, when the particle size is less than $42.0 \text{ }\mu\text{m}$, the powder is completely vaporized, when the particle size is within the range of $42.0\text{--}253.5 \text{ }\mu\text{m}$, the powder is melted and partially vaporized, and when the particle size is higher than $253.5 \text{ }\mu\text{m}$, the powder cannot be completely melted and there may exist a small number of unmelted powders. Therefore, when inputting copper powders with a particle size of $4.6\text{--}272.0 \text{ }\mu\text{m}$ ($D_{50} = 34.6 \text{ }\mu\text{m}$), the powders of different particle sizes have undergone various phenomena such as vaporization, partial vaporization, complete melting and partial melting, resulting in a nano-sized spherical powder, micro-sized spherical powder and a small amount of special shaped powder.

Furthermore, in this paper, the sheath gas (Mixed gas of 30 L/min Ar and 2.5 L/min H_2) contains about 10% hydrogen (H_2). On the one hand, the presence of H_2 can capture the oxygen in the raw copper powder, so that the oxygen contents of the NP-powder and CS-powder prepared are reduced. The oxygen contents of the CS-powder and NP-powder are only 178 ppm and 562 ppm, both lower than the oxygen content of raw copper powder (654 ppm), so as to obtain ultrafine spherical copper powder with high purity. On the other hand, the introduction of H_2 may also promote the formation of copper nano-powder. Studies have shown that under the high temperature plasma, hydrogen is decomposed into hydrogen atoms or ions, which causes its solubility in molten metal to be $10^5\text{--}10^8$ times that of gas [28]. However, as the temperature drops rapidly to about 1773 K , the concentration of hydrogen atoms reaches saturation and further forms hydrogen molecule bubbles. A large number of copper atoms will evaporate in the hydrogen molecular bubbles and then be carried out by the bubbles to form the nano-powders.

4.2. The Influence of Plasma Parameters on the Properties of Copper Powder

The parameters of plasma treatment (powder feed rate, carrier gas flow rate and reaction chamber pressure, etc.) have a significant impact on the powder properties. As shown in Figure 3, as the powder feed rate (v) increases, the average diameters of the NP-powder and CS-powder both increase, and the ratio of the NP-powder decreases. In the plasma process, the particles obtain energy from the plasma through convective heat transfer, while at the same time, they lose energy through thermal radiation to the environment. In a certain period,

the energy required for the complete vaporization and melting of copper powder can be calculated by the following equations, respectively [29–31].

$$Q_v = mC_p(T_v - T_0) + m(L_m + L_v) \quad (4)$$

$$Q_m = 1/6\pi [C_p(T_m - T_0) + L_m] \times vt \times 100\% \quad (5)$$

where m is the powder mass, C_p is the specific heat, T_v is the boiling point, T_0 is the room temperature, L_m is the latent heat of melting, L_v is the latent heat of vaporization, T_m is the melting point and v is the powder feed rate. From Equations (1) and (2), as the powder feed rate (v) increases, the mass (m) of copper powder processed per unit time also increases. Because the total energy provided by the plasma is constant under the same process parameters, as the powder feed rate (v) increases, the energy obtained per unit volume of copper powder will decrease, and the melting and vaporization ratios will decrease. As a result, the average diameter of the CS-powder increases, and the ratio of the NP-powder decreases. Meanwhile, the increase in the powder feed rate (v) increases the amount of powder that undergoes vaporization reaction, and the total amount of copper vapor in the reaction chamber also increases. When the copper vapor is condensed, the probability of collision and fusion of copper droplets increases, which increases the average diameter of the NP-powder. Consequently, as the powder feed rate (v) increases, the average diameter of the NP-powder and CS-powder both increases, and the ratio of the NP-powder decreases.

In Figure 5, with the increase in carrier gas flow rate, the average diameter of the CS-powder increases, while the ratio of the NP-powder decreases. The carrier gas flow rate determines the time for the powder to fly over the plasma, that is, the heating time of the powder. When the carrier gas flow is in the range of 4–7 L/min, the flight time of copper powder can be calculated as 12.71–9.61 ms by Equation (1). The bigger the carrier gas flow rate, the shorter the flight time of the powder in the plasma zone, and the smaller the vaporization ratio of the powder. As a consequence, with the increase in carrier gas flow rate, the average diameter of the CS-powder increases, and the ratio of the NP-powder decreases accordingly.

As the pressure of the reaction chamber increases, the average diameter of the CS-powder first decreases and then increases, while the average diameter of the NP-powder and its ratio first increases and then decreases (Figure 7). The pressure in the reaction chamber affects the powder flow rate and plasma density. On the one hand, with the increase in the pressure, the flow rate of the powder will decrease and the residence time of the powder in the high temperature zone will be prolonged, leading to a decrease in the particle size of the CS-powder and an increase in the ratio of the NP-powder. On the other hand, the increase in pressure will cause the plasma density to increase and the plasma temperature to decrease [32], so the particle size of the CS-powder increases but the ratio of the NP-powder decreases. At low pressures, the powder flow rate plays a leading role, while at higher pressures, the plasma density plays a leading role. The combined effect of the two aspects makes the average diameter of the CS-powder first decrease and then increase, together with the average diameter and the ratio of the NP-powder first increase and then decrease with the pressure increases.

5. Conclusions

In summary, the multiscale ultrafine spherical copper powder was prepared by the RF induction plasma technique. The effects of processing parameters on the powder properties were studied. The following conclusions were drawn:

(1) By inputting electrolytic copper powder with $D_{50} = 34.6 \mu\text{m}$, nano-sized spherical powder with a particle size of 10–220 nm and micron-sized spherical powder with a particle size 4.0–144.0 μm could be obtained. The ratio of the nano-sized powder reached 86.4 wt.%. The optimal process parameters for plasma treatment are as follows: powder feed rate is 5.5 g/min, carrier gas flow rate is 5–6 L/min and the reaction chamber pressure is 15 Psia.

(2) When the carrier gas flow rate is 6 L/min, in the plasma zone ($>10,000$ K), the powder with particle size < 42.0 μm is completely vaporized, which forms nano-sized powder during cooling, while the powder with particle size > 42.0 μm is melted and partially vaporized, forming micron-sized powder.

(3) The obtained multiscale ultrafine powder has a lower oxygen content. The oxygen contents of the CS-powder and NP-powder are only 178 ppm and 562 ppm, respectively, which are significantly lower than that of the raw powder. The reason is that hydrogen in the sheath gas can capture oxygen in the raw copper powder.

The results shown in this study provide an efficient method for the one-step preparation of ultrafine nano-copper powder. The excellent sphericity and dispersibility demonstrate that the nano-sized powder under optimal parameters has considerable application potential in the fields of lubrication and nano-conductive paste.

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