Preparation Technology of Ultra-Fine Tungsten Carbide Powders: An Overview

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Ultrafine tungsten carbide (WC) powder refers to WC powders with a particle size between 100 and 500 nm. Researchers have improved the comprehensive properties of WC-based cemented carbides by preparing ultra-fine WC powders. Because of the preparation and application of nanoscale WC powders, ultrafine-grain cemented carbides with excellent hardness and wear resistance have been successfully produced. In this paper, the preparation methods of ultra-fine WC powder are divided into solid-phase, liquid-phase, and vapor-phase methods according to the state of the raw materials (i.e., the W or C source). The liquid-phase methods could realize the preparation of WC at the temperature between 500 and 800°C. The purity of WC prepared by vapor-phase method is the highest. The solid-phase reduction carbonization method has potential industrial application.

Keywords: ultra-fine tungsten carbide, preparation method, solid-phase method, liquid-phase method, vapor-phase method

INTRODUCTION

Cemented carbides using tungsten carbide (WC) as main raw materials with high hardness and excellent wear resistance are widely used in drill, mold, needle, cutting tool, and other special processing industries. Due to the high bonding strength and fine microstructure between ultrafine WC particles and metal binder phase, ultrafine-grain cemented carbide combines the characteristics of ceramics and metal at the same time, which has high toughness, good strength and excellent hardness. Thus, a large number of studies on the optimal preparation of composite powders, the most suitable proportions of bonding phases, the effects of doping with other elements, and the best size and morphology of WC grains, among others, have been conducted to improve the hardness and toughness of cemented carbides (Zheng et al., 2015; Wang et al., 2017). Among many factors, the size of WC particles generates the greatest impact on the mechanical properties of cemented carbides. As shown in Figure 1, the hardness and bending strength of cemented carbides increase as the proportion of fine WC particles increases (Akhtar et al., 2007). The conventional and ultrafine WC particles’ size is 4, 0.2 µm, respectively. The samples were prepared by mixing two kinds of WC powders with different mass ratio between conventional and ultrafine powders. The particle size of WC powders directly determines the size of WC grain.
in cemented carbide during the sintering process. And the grain size of WC is related to the mechanical properties of sintered cemented carbides. Hardness of cemented carbide increased with the mass fraction of ultrafine WC particles. The bending strength presented the same trend as the hardness.

Ultrafine WC powders improve sintering performance and enhance the mechanical properties of the cemented carbide (Liu et al., 2010; Emani et al., 2015). As shown in Figure 2; Liu et al. (2010) carried out studies on the displacement rate curve of WC–10 wt% Co powder samples by taking WC powders of different particle sizes and Co powder of equal particle sizes as sintering materials and found that smaller WC particle sizes result in higher displacement rates and degrees of densification of powder sintering.

Maheshwari et al. (2007) carried out a comprehensive study by sintering WC–10Co powders with different initial particle sizes. Figure 3 shows the relationship between the sintering densification and sintering temperature of WC powders of different initial particle sizes. The entire sintering temperature range decreased gradually as the initial average particle size decreased from 30 μm to 10 nm. When the initial particle size was 10 nm, the densification of the alloy was up to 90% approximately.

Some researchers have proved that ultrafine WC powders have better activation in plating binder-phase mental coat on the WC particles. Such as, Luo et al. (2011) have studied the activation
technique of ultra-fine powders and prepared a uniform Ni-coated WC composite powder, taking less than 1 µm WC as a matrix. As shown in Figure 4B, ultrafine WC powders after ultrasonic-assisted electroless plating appear step-like defects on the surface of WC particles. These defects make nucleation and growth of Ni cell generate on the activated WC particle surface more effectively. Further studies showed that the thinner the WC powder, the better the Ni coating (Luo et al., 2011; Chen H. Y. et al., 2017).

Some scholars have carried out further theoretical studies to figure out how ultra-fine WC powders can improve the comprehensive performance of cemented carbides (Chuvil’deev et al., 2015; Postek and Sadowski, 2018). The most consistent view at present is that the use of ultra-fine WC powders decreases the average thickness of the bonding phase, which increases the dispersion of the former through the latter and, thus, improves the strength and toughness of the resulting alloy (Zhang et al., 2012). Several studies have focused on the preparation method and industrial production of ultra-fine WC (Xu et al., 2018; Luo et al., 2019). A number of methods to prepare ultrafine WC powder, such as mechanical alloying (Li et al., 2019), in situ carburizing reduction (Li et al., 2019), direct reduction of carbonization (Chen L. J. et al., 2018), gas-phase reaction synthesis (Zhang et al., 2018), and spray conversion (Guo et al., 2015), have been proposed. These methods can generally be summarized into three synthesis categories, namely, solid-phase methods, vapor-phase methods, and liquid-phase methods, based on the initial state of the reactants.

**SOLID-PHASE METHOD**

When preparing tungsten carbide by the solid-phase method, WO$_3$ is usually taken as the W source. Carbonization of WO$_3$ can be divided into reduction carbonization and direct carbonation according to the generation of elemental W; it can also be divided into mechanical alloying and high temperature carbonization according to the temperature of carbonization.

**Reduction Carbonization**

Reduction carbonization is a traditional WC preparation process that is commonly used for the high-volume industrial production of WC (Borchardt et al., 2012). A typical synthesis route is: W source [Ammonium paratrungstate (APT) or ammonium metatungstate (AMT)] calcination $\rightarrow$ WO$_3$ $\rightarrow$ hydrogen reduction $\rightarrow$ ultrafine W powders $\rightarrow$ carbonization $\rightarrow$ ultrafine WC powders.

Ma and Zhu, 2010 calcined a mechanically activated WO$_3$ and graphite mixture at 1215°C under vacuum conditions and achieved the solid C thermal reduction of WO$_3$ to nano-WC particles. The specific preparation process was as follows: WO$_3$ (purity 99.9%) and graphite (purity 99%) powders as raw materials were mixed at a molecular weight of 1:4 and then ball milled under an Ar atmosphere for 10 h. The composite powder was placed in a ceramic vessel, first heated to 741°C and then heated to 1215°C in a vacuum tube furnace at a rate of 10°C/min, finally kept in the temperature for 1 h.

Ma and Zhu (2010) analyzed ultrafine WC particles’ generation based on homogeneity increase and associated decrease during the diffusion period of mechanical milling. Besides, formation of some intermediates, such as WO$_2$ and WO$_2$ are also responsible for the successful production of ultrafine WC powders. Thermodynamic calculations for reactions that may occur during the calcination process have accurately detected the reaction process and generation phase, and the results are shown in Figure 5. As the calcination temperature increases, WO$_3$ is reduced to other lower-valence WO$_3$ types, such as WO$_2$ and WO$_2$. These low valence WO$_3$ forms are called Magneli-phase WO$_3$ (meta-stable phase WO$_3$) (Ma and Zhu, 2010; Lee et al., 2019). When the temperature is higher than 273, 346, or 489°C, the solid-phase carbothermal Frontiers in Materials | www.frontiersin.org 3 May 2020 | Volume 7 | Article 94
reaction of WO₃ generates these Magnéli phases. Magnéli-phase WO₃ is reduced to elemental W by graphite when the temperature is 599–794°C. X-ray diffractometry (XRD) of the samples was carried out at 741°C, and only the diffraction peaks of mesophase WO₂₋₂, WO₂, and W were found; no diffraction peaks of WO₃ were observed, likely due to the initial reaction temperature of 599–644°C, which fully reduces the metal oxide to WO₂₋₂, WO₂, and W (Ma and Zhu, 2010). The peaks of WO₂₋₂ and WO₂ were still present at 741°C because the initial reaction temperatures of WO₂₋₂ and WO₂ are 726–754°C and 747–794°C, respectively, or slightly higher than 741°C. As the temperature continues to increase, W reacts with graphite to generate WC. The reaction route can be summarized as WO₂₋₂ + C → W + WO₂ + WO₂₋₂ + C → WC (Ma and Zhu, 2010).

Using ammonium paratungstate (APT) as a raw material, Ryu et al. (2009) prepared nano-WC powders by using the thermal plasma method. The preparation process was divided into three stages:

Stage 1: Thermal decomposition of ammonium paratungstate (APT):

\[(NH_4)_{10}W_{12}O_{41} \cdot xH_2O \rightarrow 12WO_3 + 10NH_3(g) + (5 + x)H_2O(g)\]  

Stage 2: Hydrogen reduction:

\[WO_3 + 3H_2(g) → W + 3H_2O(g)\]  

Stage 3: CH₄ carbonization:

\[WO_3 + H_2(g) + CH_4(g) → W_2C, WC_{1−x}, WC + H_2O(g)\]  

In the thermal plasma reaction system, APT generates a nano-WC₁₋ₓ powder which the powders sometimes contain a small amount of the W₂C phase after the period of thermal decomposition, reduction, and carburization. By using this way to prepare WC, the particle size of the prepared WC₁₋ₓ powder is less than 20 nm. The synthetic powder is heated by hydrogen to fully carburize the WC₁₋ₓ and W₂C phases to WC. After removing excess C, we could obtain WC powders whose particle size is less than 100 nm, as shown in Figure 6.

**Direct Carbonization**

Direct carbonization to prepare WC is known as a one-step method. Researchers have developed different techniques for the one-step preparation of WC powder. For example, Won et al. (2010) prepared WC powders with particle size of 50–100 nm through carbonization at a high temperature by using WO₃ and C powder as raw materials and NaN₃ as a combustion agent (Won et al., 2010; Lin et al., 2013). Lee et al. (2003) converted WO₃ into WC by heating WO₃ to 300–700°C in He atmosphere; here, −HX, −NaX, and −KX were added to WO₃ powder as catalysts, and CO gas was used as the C source. He and Tang (2011) had prepared ultra-fine WC powders with particle size of 0.3 µm through direct reduction and carbonization of AMT by
using carbon-black as the C source in N$_2$ atmosphere. The direct carbonization method utilizes the reducibility of C to conduct direct reduction of WO$_3$ and generate WC. During the reduction process, only Magneli phases W is generated, and eventually WC powder particles are difficult to gather. In the traditional method, W powder is prepared and then carbonized to generate WC via hydrogen reduction of WO$_3$. During the reduction process, hydrates of WO$_3$, such as WO$_3$(OH)$_2$ and WO$_x$H$_2$O, are generated, and these compounds cause W powder particles to grow. Thus, the carbonized WC powder yields large particles that must be ground to obtain a fine WC powder (Venables and Brown, 1996; Gu et al., 2002).

Wang et al. (2006) invented a supercritical CO$_2$ heat treatment method to prepare WC based on the direct carbonation method. The reaction route of this method is shown in Figure 7, and the reaction could divide into two stages. In Stage 1, dense CO$_2$ is reduced to graphite sheets by Na, and metal W is oxidized into WO$_3$. During the reduction process, hydrates of WO$_3$, such as WO$_3$(OH)$_2$ and WO$_x$H$_2$O, are generated, and these compounds cause W powder particles to grow. Thus, the carbonized WC powder yields large particles that must be ground to obtain a fine WC powder (Venables and Brown, 1996; Gu et al., 2002).

Finally, the solid product was washed with distilled water and dried at 80°C for 2 h. The resultant WC powder is shown in Figure 8; Wang et al. (2006).

**Mechanical Alloying**

Mechanical alloying involves the high-speed and long-running transmission of mechanical energy to the powder through a high-energy ball mill to improve the powder activity. During the ball milling process, the ball in the milling jar repeatedly collides with the powder, thus subjecting it to various forces, such as impact, compression, friction, and shearing. The powder is further refined, crushed, and cold welded into dispersed ultra-fine particles and then alloyed at room temperature. The basic principle behind powder alloying at room temperature is the repeated mixing, crushing, and cooling of weld powder particles through high-energy ball milling. The mixed powder in the ball mill can form high-density dislocations, and the particles are gradually refined to the nanoscale level. Increases in powder activity accelerate the mutual diffusion of atoms. Under certain conditions, alloy phase nuclei are formed through ball milling and gradually grow into an alloy phase until all elemental powders are consumed (Dai et al., 2013; Maat et al., 2018; Sadeghi et al., 2018).

By using the ball-milling method, Wu et al. (2009) mixed pure WO$_3$, graphite, and Mg powder according to a certain atomic ratio at room temperature and characterized the resulting powder through SEM, XRD and TEM. As shown in Figure 9, the XRD peaks of MgO and WC could be clearly detected after 4.5 h of ball milling. These results show that a redox reaction occurs between
the WO₃ powder, Mg, and graphite during ball milling to form MgO and WC via the following reaction:

\[ \text{WO}_3 + 3\text{Mg} + C \rightarrow \text{WC} + 3\text{MgO} \]

The powder was further refined with ball milling going on. As shown in Figure 10, after 80 h ball-milling, nanocrystalline WC particles (25 nm) were embedded in the fine MgO matrix, thus forming a nanoscale MgO–WC composite powder with diameters close to 100 nm. This process could overcome the shortcomings of the high-cost preparation of WC by using MgO instead of Co, Ni, and Fe which are the conventional binder. Besides, the newly developed binder could be used for other carbide substrates.

**High-Temperature Carbonization**

The high-temperature carbonization of solid metal W essentially involves the diffusion reaction of C in W. When the temperature is above 1000°C, C atoms can be soluble into W particles to form WC phase which the process called C diffusion reaction, which is also the basic principle in high-temperature carbonization. C diffusion is based on the formation of a thin polycrystalline WC layer around W particles; this layer gradually develops toward the core, thus enabling the growth of polycrystalline WC by extending toward the center of the W particles and moving to the grain boundary of WC (Yang et al., 2015). Although the principle of high-temperature carbonization of metal W is similar, researchers have developed different methods to prepare ultra-fine WC. For instance, Li (2013) used AMT and violet tungsten as raw materials to prepare W powders with a minimum particle size of about 30 nm through hydrogen reduction; thereafter, the scholar prepared a nano-WC powder with a minimum particle size of 60 nm after carbonization at 1200°C and microwave heating (Li, 2013). Chen Z. et al. (2017) combined C with W, Co, Cr₂C₂, and VC as raw materials and then placed this mixture into a combustion reaction chamber for carbonization with burning; finally, WC powders with a grain size of 30–100 nm were obtained.

Wang et al. (2018) studied the effects of As on the growth of WC powders by adding As element into the high-temperature carbonization process of nano-W. The experimental process is as follows: First, the W–As composite powder was mixed with C black at 100 rpm for 1 h by a planetary mill. Next, the mixed powder of W, As, and C was placed in a graphite boat and placed into a tube furnace for high-temperature carbonization.
at 1300, 1400, 1500, and 1600°C with a controlled heating rate of 5°C/min.

**Figure 11** shows the XRD patterns of the samples obtained by carbonization of W powder and W–As powder at 1300 and 1400°C. The diffraction peak shown in [Figure 11A](#) reveals the presence of a W₂C phase in the WC powder after carbonization of the W powder at 1300°C. As shown in [Figure 11C](#), W₂C phase was not observed in the diffraction peak after the carbonization at 1400°C, contrasting to [Figure 11A](#) which indicates that pure W powder was not fully carbonized at 1300°C but was totally carbonized at 1400°C. According to the diffraction peaks in [Figures 11B, D](#), only WC could be detected, and no W₂C phase was found. Comparison of the peaks of the two composite powders after carbonization at high temperature reveals that addition of As have decreased the temperature of complete carbonization (Wang et al., 2018).

As shown in **Figure 12**, the average particle size of the WC–As powder is less than that of WC at the same temperature, which indicates that addition of arsenic has decreased the concentration of WC during the carbonization process. Wang provided the following explanation for this phenomenon: during carbonization, W and As generate a WAs₂ mesophase, which attaches to the grain boundaries of WC and hinder the growth of WC grains through migration of these boundaries. Therefore, uniform WC composite powders could be obtained even at high carbonization temperatures.

**LIQUID-PHASE METHOD**

The traditional liquid-phase method refers to the coprecipitation of tungstate and cobaltate in the liquid phase, and then makes the sediment completely decomposed at a low temperature. The precursor of the highly dispersed and highly active W–Co compound is prepared to generate ultra-fine WC–Co composite powders through reduction and carbonization in a fixed or fluidized bed. This method is also called chemical precipitation (Yang et al., 2018). Compared with other methods, chemical precipitation presents the advantages of simple equipment and easy process control; moreover, the prepared nano-WC–Co powders have small particle size, uniform distribution, and high reaction activity. However, chemical precipitation method also have a number of issues need to be overcome, such as introduction of impurities during the preparation process, physical statement change of the generated sediment, high difficulty in filtering and washing the product, high preparation cost, and poor scaling to batch production. All advantages mentioned above have limited the technique's applications (Fan et al., 2013).

Several researchers have developed a solvothermal method to prepare WC powder. Solvothermal method is a synthetic method that uses organic or non-aqueous solvents as solvents to react the original mixture with the solution at a certain temperature under the spontaneous pressure in a closed system (Hosokawa, 2016).

Preparation of WC powder via the solvothermal method generally takes WO₃ as the W source and C-based organic solvents as the C source. The raw materials are mixed proportionally and then react by heating to 500–800°C after addition of a reducing agent to the reactor. This method can be used to generate WC at low temperatures, but the subsequent processing of reaction products is often complex. Indeed, high-purity WC can only be obtained after several cycles of removal of the reducing agent, distillation drying, immersion, and filtration with ethanol (Kumar et al., 2010).

Zeng et al. (2008) took Mg as a reducing agent, anhydrous ethanol and WO₃ as C and W sources, respectively. He synthesized WC nanocrystals using a simple solvothermal method. The effect of reaction temperature on the synthesis of WC was discussed. [Figure 13](#) shows the XRD patterns of products obtained at different reaction temperatures. There are WO₃ and MgWO₄ existing at different temperature. The peaks of WO₃ disappear at 550°C and the peaks of MgWO₄ disappear at 650°C. With the increase of temperature, the peaks of WO₃ and MgWO₄ disappeared gradually, while the peak intensity of WC increased obviously. The activity of C and W atoms increased with the increase of reaction temperature which made the reaction more completely and WC crystallization more completely. The pressure produced in the high pressure reactor greatly reduces the synthesis temperature of WC. When the temperature was 500°C, hexagonal WC phases with particle sizes of about 40–70 nm could be synthesized.

Singla et al. (2015) prepared WC nanoparticles with a particle size between 30–80 nm by using Mg, acetone (C₃H₆O), and WO₃ as raw materials. During the reaction, acetone was used as a hot solvent and C source, Mg acted as the catalyst, and the mixed raw material was placed in an electric furnace to heat to 600°C and kept warm for different periods of time. Then, it was cooled to room temperature using an autoclave. The product was washed with dilute HCl to remove MgO, leached, and washed...

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**FIGURE 11** | XRD patterns of: (a) W powder at 1300°C; (b) W–As powder at 1300°C; (c) W powder at 1400°C; (d) W–As powder at 1400°C (Wang et al., 2018) [Figure 3 of Wang et al. (2018), Copyright Elsevier B.V. and The Society of Powder Technology Japan].
with distilled water several times to remove the acid. Finally, the product was washed with acetone and then dried under vacuum at 100°C. The synthesized WC powder had plate- or sphere-shaped grains that dispersed without aggregation, and ultra-fine WC powders could be obtained without pulverization. However, because the oxygen content of the powders increased with increasing insulation time, control of the insulation time is the key to prepare high-quality WC via this method.

VAPOR-PHASE METHOD

The chemical vapor-phase synthesis (CVS) of WC powder refers to the preparation of WC powders via hydrogen and hydrocarbon vapor reduction precursors (Dushik et al., 2018). If WCl₆ is used as a precursor, CH₄ and hydrogen are taken as the C source and reducing agent, respectively, and the reaction temperature is set to 1200°C, the following reaction takes place (Anela and Srikanth, 2018):

$$\text{WCl}_6(g) + \text{H}_2(g) + \text{CH}_4(g) \rightarrow \text{WC}(s) + 6\text{HCl}(g)$$

WCl₆, WF₆, and W(CO)₆ are preferred W sources for preparing WC because these raw materials have a low volatilization temperature and are easy to reduce or thermally dissociate by hydrogen; hydrocarbon gases often used as C sources such as methane, ethylene and propane (Wu et al., 2018). The preparation of WC powders via the vapor-phase method can result in uniform and controllable particle sizes; moreover, because no other solid products are generated, the WC purity is usually higher than that obtained from other methods. However, this kind of method requires raw materials and substrates with high initial purity, and the use of flammable gases presents significant risk during mass production.

The plasma chemical vapor deposition method is a widely used to prepare nano-WC. The raw material is quickly heated to above 1500°C using plasma as the heat source, and the raw materials decompose, react, and synthesize the product. The raw materials are generally W or WO₃, and the C source is usually CH₄ or acetylene. The plasma chemical vapor deposition method can also be used to produce other nano-powders, such as TiC, TiN, and Si₃N₄ (Morimitsu et al., 2013; Chen L. et al., 2018).

Using WCl₆ as raw materials, Sohn et al. prepared nano-WC by plasma heating to ultra-high temperature. In this experiment, H₂ and CH₄ were used as reducing and carburizing agents,
respectively. WC\textsubscript{1-x} with a particle size of less than 30 nm was obtained. The particle size of this product increased with increasing plasma transmitter power and decreasing plasma flow rate. Hydrogen was used for the heat treatment of the WC\textsubscript{1-x} powder. The C content was reduced to stoichiometric levels and the WC\textsubscript{1-x} phase was fully carburized to generate the WC phase. However, the particle size of the powder increased from 30 nm to approximately 100 nm after hydrogen heat treatment, as shown in Figure 14; Sohn et al. (2007).

Ryu et al. (2008) taking WCl\textsubscript{6} as a precursor, reduced and carbonized it by using CH\textsubscript{4}-H\textsubscript{2} mixed gas, and then prepared nano-WC powder by the thermal plasma method. His team also studied the effects of other factors on the product composition and particle size, such as molar ratio of the reaction gas, plasma torch power, plasma gas flow rate and addition of a secondary plasma gas. Results showed that nano-WC\textsubscript{1-x} powder containing WC and W\textsubscript{2}C phases could be synthesized by using the thermal plasma method with WCl\textsubscript{6} and CH\textsubscript{4} as the W and C sources, respectively. The content of W\textsubscript{2}C in the product decreased with increasing plasma torch power and plasma gas flow rate. In addition, the particle size of WC\textsubscript{1-x} was affected by the plasma torch power, plasma gas flow rate, and addition of a secondary plasma gas (H\textsubscript{2}) but is not subject to the CH\textsubscript{4} concentration within the range tested. The generated WC\textsubscript{1-x} and W\textsubscript{2}C phases were carburized into the fully carbidized WC phase, and excess C in the product was removed completely by hydrogen heat treatment at 900°C. The particle size of WC\textsubscript{1-x} obtained by the thermal plasma process was less than 20 nm, and the particle size of the WC powder obtained after hydrogen heat treatment was between 40 and 100 nm. Since the plasma process can operate continuously, it is also suitable for the mass production of nano-WC powders.

Table 1 lists different WC preparation methods in the literature. Compared with the liquid-phase and vapor-phase method, the solid-phase method on preparing WC powders have a more wider range of particle size which means that the accuracy of WC particle size is not easy to control in the period of carbonization by the solid-phase method. Except for mechanical alloying, the intermediate products of other solid-phase methods are all related to tungsten compounds which could be carburize completely by promoting the temperature of carbonization.

**CONCLUSION AND EXPECTATIONS**

In general, high-quality ultra-fine WC powders are often evaluated with some characteristic like these: (a) Tungsten needs to be completely carbonized. The amount of material that is not completely carbonized, such as W\textsubscript{2}O\textsubscript{3} and W\textsubscript{2}C, should be as small as possible; (b) The content of impurities should be as low as possible; (c) The particle size distribution

**TABLE 1** | Comparison of characteristics of WC prepared by different methods.

| Preparation method | Raw materials | Particle size of WC powders | Intermediate product |
|--------------------|---------------|-----------------------------|----------------------|
| Solid-phase method | Reduction carbonization | WO\textsubscript{3}, graphite (Ma and Zhu, 2010) | 100–200 nm | WO\textsubscript{2}, WO\textsubscript{2.72}, W |
| Direct carbonization | APT, H\textsubscript{2}, CH\textsubscript{4} (Ryu et al., 2009) | 20–100 nm | W\textsubscript{2}C, WC\textsubscript{1-x}, W |
| Mechanical alloying | CO\textsubscript{2}, Na, W (Wang et al., 2006) | Less than 150 nm | W\textsubscript{x}O\textsubscript{y}, W\textsubscript{2}C |
| High-temperature carbonization | WO\textsubscript{3}, Mg, C (Wu et al., 2009) | 25–100 nm | MgO |
| Liquid-phase method | WO\textsubscript{3}, Mg, anhydrous ethanol (Zeng et al., 2008) | 40–70 nm | MgWO\textsubscript{4}, MgO, MgCO\textsubscript{3} |
| Mechanical alloying | WO\textsubscript{3}, Mg, acetone (Singla et al., 2015) | 30–80 nm | MgO |
| Vapor-phase method | WCl\textsubscript{6}, H\textsubscript{2}, CH\textsubscript{4} (Sohn et al., 2007; Ryu et al., 2008) | 30–100 nm | HCl |

**FIGURE 14** | TEM micrographs of (A) WC\textsubscript{1-x} powder synthesized by plasma-assisted CVS from WCl\textsubscript{6} and (B) WC powders obtained after 5 h of hydrogen heat treatment of WC\textsubscript{1-x} powders at 900°C (Sohn et al., 2007) [Figure 1 of Sohn et al. (2007), Copyright Elsevier Ltd].
should be as uniform as possible. The precipitation methods which have mentioned in the literature are able to make the WC powders meet these characteristics, but some of them have some problems in the period of preparation.

Using reduction carbonization to prepare ultra-fine WC powders needs to generate simple-substance W, and then make W powders carbonize to WC powders. The particle size of WC depends on the W powder. If size of W particle during preparation of WC was not as small as possible, WC nanoparticles may be failed to produce. The other methods in the Solid-phase methods, which have taken Na, Mg, and, As as catalyst or inhibitor, WC can be prepared directly, but the effect of additions on crystallization of tungsten carbide during the sintering period need to be made further research. Besides, using solid-phase methods to prepare WC often proceed in the high temperature environment and need to keep the high temperature for a long time in order to completely carbonize. However, the liquid-phase method could prepare WC powders at low temperatures. Zeng et al. (2008), researchers achieved preparation of WC at 500°C which had greatly decreased the temperature of carbonization. But the liquid-phase method in preparing WC powders often generates other by-products. In order to remove these intermediates, it is necessary to add other solvents to dissolve them which may increase the difficulty of WC preparation. The vapor-phase method could get high-purity ultrafine WC powders. But the cost of large-scale preparation of WC by vapor-phase method is higher than others which limit its application and development. Compared with the vapor-phase method, the solid-phase reduction carbonization method has potential industrial application. Because it is much closer to current commercial production mode of tungsten carbide, which just replaces graphite to CH₄ as the C source comparing to the traditional method to produce WC.

Throughout all methods mentioned above, useful studies have been made on the option of W and C sources around the refinement of WC particles, which has laid a foundation for the industrial production of ultrafine WC powders. The preparation technology of ultra-fine WC powders is an interesting branch of nanotechnology that shows the importance of this field in the research and development of new materials. Although different methods have been developed to prepare nano-WC powder, the approaches proposed are often limited to laboratory-scale production. Thus, the large-scale industrial production of ultra-fine WC powders remains a very important direction for future research.

**AUTHOR CONTRIBUTIONS**

Y-CW, YY, and LL drafted the manuscript. Y-CW and LL supervised the experiments. X-YT, LL, XZ, X-YZ, QX, and J-GC were involved in the data analysis and discussions.

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