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Influence of thermal process on particle size distribution of ultrafine magnesium powder prepared by inert gas condensation method

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ABSTRACT

Ultrafine magnesium powder has become a research hotspot for the last few years because of its high-activity and low-density. Inert gas condensation method is a better method compared to mechanical pulverization method to produce magnesium ultrafine powder with high-purity, narrow particle size distribution and short production cycle. As particle size distribution is a vital factor when it comes to determine the application area, it is necessary to investigate particle size distribution of ultrafine magnesium powder prepared by inert gas condensation method. The purpose of this research is to determine particle size distribution of ultrafine powder produced by inert gas condensation method under different thermal conditions, then to provide a reliable method for optimum thermal parameter selection. Thermal mechanisms of ultrafine magnesium powder preparation using inert gas condensation method are proposed. Dynamic equations for the nucleation, evaporation/condensation, coagulation and deposition processes are established. This paper develops a convenient way for the prediction of the particle size distribution by deriving a modified Monte Carlo method, which is able to calculate the particle size distribution giving only a relative error less than 3%, compared with the experiments. An attempt to discover the relation between particle size and absolute pressure is conducted in the discussion part. The particle size increases exponentially with the condensation pressure increases. The method derived here may offer a mathematical method to predict particle size distribution of other ultrafine metal powder prepared by inert gas condensation method, then to choose appropriate thermal conditions for different applications.

1. Introduction

Ultrafine metal powders are valuable materials in both manufacture and laboratory; and they are of great importance in numerous applications including chemical engineering, electronic engineering, and aeronautics and astronautics technology [1–7]. One way to produce ultrafine metal powder is the inert gas condensation (IGC) method. It is a popular method in laboratory because of the purity of the product and the simplexes of the process. Ultrafine metal powder prepared with IGC method has the advantages of narrow particle size distribution and controllable particle size [8–10]. Of all the ultrafine metal powders, ultrafine magnesium powder has received much attention due to its properties such as low-density, high-activity and high adsorption capacity and so forth. Ultrafine magnesium powder can be used as efficient active agent and combustion stabilizer [11–14]. Nano magnesium particle is also a promising material for cancer therapeutics in biomedical science. While any changes to the particle size distribution (PSD) can affect the size-determined nano-properties or potential nano-properties to a great extent, this leads to the fact that the application fields vary with each PSD [15–19]. Hence, the master of each PSD formation conditions is of prime importance.

Formation process of individual zinc particles was studied in our previous work, and also the formation temperature and pressure influence on particle size is analyzed with both numerical computation and experimental methods [20]. Nevertheless, the particle size studied with the numerical method is the average particle size grown under the certain conditions; it cannot provide the PSD under the same conditions. Herein, PSD of ultrafine magnesium powder prepared with IGC method is studied by treating the dynamic grown process as the research object. The dynamic evolution of the PSD in particulate processes is commonly obtained through the solution of the general dynamic equation (GDE) [21–25]. A volume of work has been carried out on the solution of GDE, and it shows that numerical methods have a more flexible application range and reliable veracity [26–29]. Several experiments have been conducted on PSD of nanoparticles. However, little attention has been dedicated to the employment of numerical methods to study the PSD of ultrafine magnesium powder prepared with IGC method, and, more important, to discover the relation between the PSD and the preparation conditions.

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The purpose of the present study is to obtain the PSD of ultrafine magnesium powder produced with IGC method in an efficient and veracious way, and further investigate how the thermal process influences the PSD. The results of this study may help to predict the PSD of ultrafine magnesium when certain manufacturing conditions are proposed. Also, the methods reported here could benefit to predict PSD for other nanoparticles prepared with IGC method.

2. Preparation of ultrafine magnesium powder

The objective of the experiment was to obtain the PSD of ultrafine magnesium powder prepared by inert gas condensation under different pressure, and thus provided fundamental information for the accuracy of the PSD prediction calculated in this paper.

Ultrafine magnesium powder was prepared by induction heating evaporation and inert gas condensation. The experimental apparatus schematic diagram is shown in Fig. 1. Magnesium ingot (purity > 99.98) was put into crucible, and the device was vacuumed. The condensation room is a cylinder with a diameter of 100 mm and height of 1000 mm. Then magnesium ingot was heated according to the setting parameters. After magnesium ingot evaporating a certain time, argon gas was filled in the device to force magnesium vapor to condense. Ultimately, the condensed magnesium deposited on the deposition plate.

3. Thermal process

The process of condensation nuclei growth in ultrafine zinc powder preparation has been described in the previous paper [20]. Evaporation, condensation, coagulation and deposition are also studied by establishing event probability equations respectively. Nucleation, coagulation and deposition processes are shown in Fig. 2.

4. Determination of particle size distribution

The purpose of the present paper is to accomplish the PSD prediction of ultrafine magnesium powder prepared with inert gas condensation

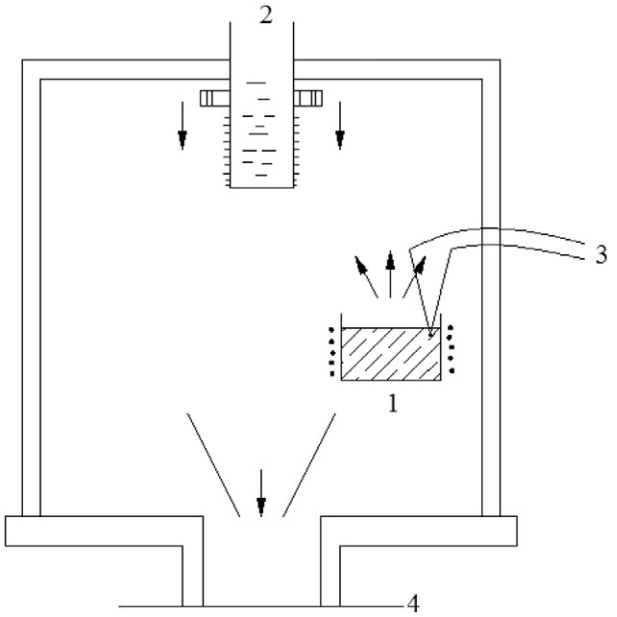

Fig. 1. Experiment schematic diagram.

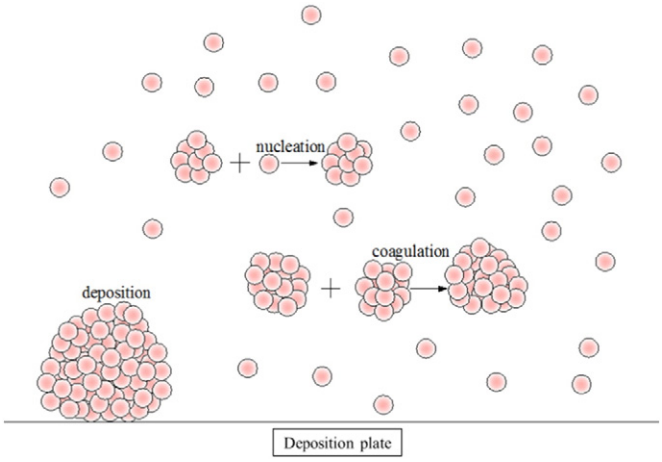

Fig. 2. Nucleation, coagulation and deposition process.

by developing the process model and the homologous arithmetic. The principles in the preparing process include evaporation of metal, nucleation mechanisms, condensation, coagulation and deposition. With these study proofs, we hold the opinion that the most important thermodynamic parameter here is the absolute pressure in the condensation room since the volume of the room is invariant and the temperature in the room is controllable. The variation of molecule density is determined by the evaporation of metal, so this parameter can be simplified, and no need to consider an evaporation model, to be that of computing the change of molecule density. In this paper, the evaporation process is considered in another way, which is to ponder the gas pressure p because of its direct relevancy with the molecule density. Coalescence and breakup process are neglected, since in such low absolute pressure, they unlikely occur. Therefore, the general dynamic equation [21,25] for PSD of ultrafine magnesium powder prepared by inert gas condensation is simplified as follows.

$$\frac{\partial n(v,t)}{\partial t} = \left\{ \begin{array}{l} \frac{1}{2}\int_{v_{\min}}^{v} \beta(v-u,u,t)n(v-u,t)n(u,t)du \\ -n(v,t)\int_{v_{\min}}^{v_{\max}} \beta(v,u,t)n(u,t)du \end{array} \right\}_{coagulation} - \left\{ \frac{\partial (I(v,t)n(v,t))}{\partial v} \right\}_{condensation/evaporation} + \{J(v,t)\delta(v_{nucl},v)\}_{nucleation} - \{E(v,t)n(v,t)\}_{deposition} \quad (1)$$

where $n(v,t)$ is PSD at time t, that is, $n(v,t)$ is the amount of particles whose size range from v to $v+dv$ per volume unite at time t. $\beta(v,u,t)$ is coagulation probability for two particles of volume v and volume u at time t. $I(v,t)$ is condensation/evaporation probability for the particle of volume v at time t. $J(v,t)$ is nucleation probability for the particle of volume v at time t, $\delta(v_{nucl}, v)$ is the volume change for the nucleation particle. $E(v,t)$ is deposition probability for the particle of volume v at time t.

For nucleation,

$$J = B\exp\left(-\frac{\Delta G_c}{k_B T}\right). \quad (2)$$

For evaporation/condensation,

$$I_i = \frac{2\pi d_p M_i D_i}{\rho_i RT}\left(P_i^{\infty} - P_i^{eq}\right). \quad (3)$$