Innovative Thermal Plasma Processing from Fundamental Research

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Abstract: Development of thermal plasma generation systems and fundamental researches of electrode phenomena determining thermal plasma characteristics are introduced in this paper. These efforts lead to the development of innovative industrial applications of material processing and waste treatment using thermal plasmas.

Keywords: Thermal plasma: Electrode Phenomena: Nanoparticle Synthesis: Waste Treatment

1. Introduction

Thermal plasmas have attracted extensive attention due to their unique advantages, and it is expected to be utilized for a number of innovative industrial applications such as decomposition of harmful materials, recovery of useful materials from wastes, and synthesis of high-quality and high-performance nanoparticles as shown in **Fig. 1**. The advantages of thermal plasmas including high enthalpy to enhance reaction kinetics, high chemical reactivity, and oxidation or reduction atmospheres in accordance with required chemical reactions are beneficial for innovative processing.

Recently, an innovative in-flight glass melting technology with thermal plasmas was developed. The granulated raw material with small diameter is injected into thermal plasmas and the powders contact fully with the plasma. The high heat-transfer and temperatures of the plasma melt the raw materials quickly. In addition, the decomposed gases of carbonates are removed during the in-flight treatment to reduce the refining time considerably.

In spite of these experimental efforts for industrial applications, thermal plasma generation and its characteristics remain to be explored. In particular, the electrode phenomena are one of the most considerable issues for the practical use of industrial applications, because it determines the electrode lifetime and the performance of materials in thermal plasmas. Combination of the two-color pyrometry and the high-speed camera observation provides a powerful tool to reveal the electrode phenomena.

Another important fundamental work is the development of thermal plasma generation system. Among various thermal plasma reactors, arc plasma as an energy source with high energy-efficiency has been applied in many applications. Most power sources for generating arc plasma are accomplished by direct current (DC) power supply, however it takes more cost in the apparatus for converting alternating current (AC) to DC. The single-phase or three-phase AC power supplies have a characteristic of intermittent discharge which limits the application of arc plasma systems generated by AC power supply. Therefore, a multi-phase AC power supply was developed to obtain a more effective arc plasma reactor.

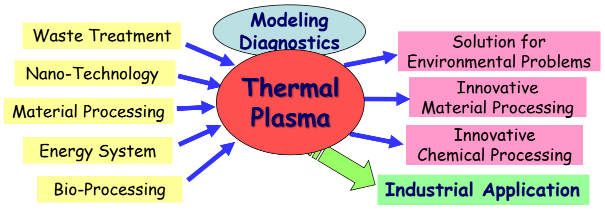

Fig.1 Industrial application of thermal plasmas with a help of fundamental work.

In this paper, new systems for thermal plasma generation are introduced. Moreover, fundamental researches for electrode phenomena determining thermal plasma characteristics are introduced to develop innovative industrial applications of material processing and waste treatment.

2. Thermal Plasma Generation

The glass industry is a large global industry that annually produces more than 100 million tons of glass products such as sheet glass, container glass, fiber glass, optical glass, and so on. Most glass has been produced by typical Siemens-type melter fired in air with heavy oil or natural gas as the fuel. This type of melter has been used for more than 140 years because of its good large-scale performance and continuous melting system. In the air-fuel fired furnace, the heat transfer from above burner flame to glass melt is so low that the conventional melting technology is energy intensive and time consuming, especially in the melting and the refining processes. With the rapid growth of glass usage and the increased energy and environment issues, it is crucial to develop a new glass melting technology to solve these problems.

An innovative in-flight glass melting technology with thermal plasmas was developed from the above point of view [1,2]. The granulated raw material with small diameter is dispersed in thermal plasma and the powders contact fully with the high temperature plasma. The high heat-transfer and temperatures of the plasma will melt the raw material quickly. At the same time, the decomposed

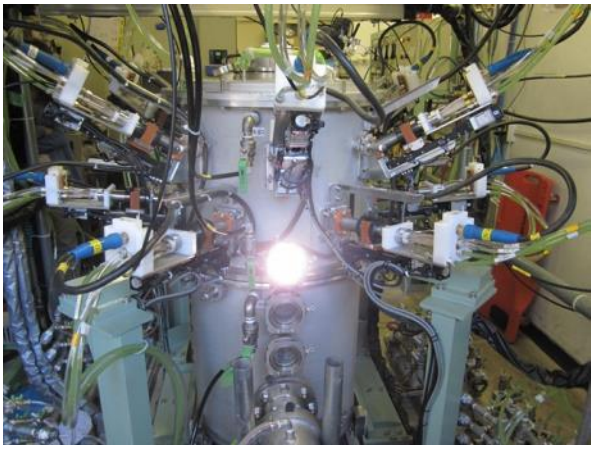

Fig.2 Multi-phase AC arc for glass in-flight melting.

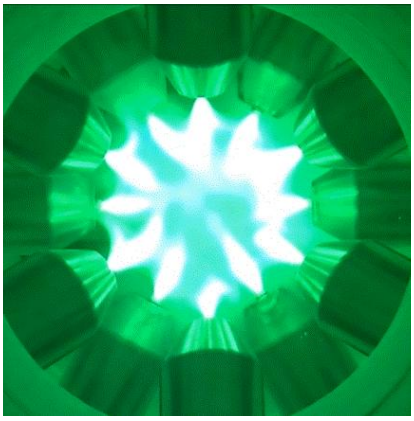

Fig.3 Multi-phase AC arc generation.

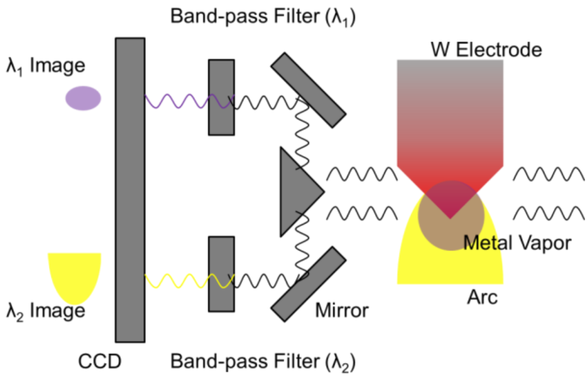

Fig.4 Schematic diagram of the combination of high-speed video camera and the band-pass filters.

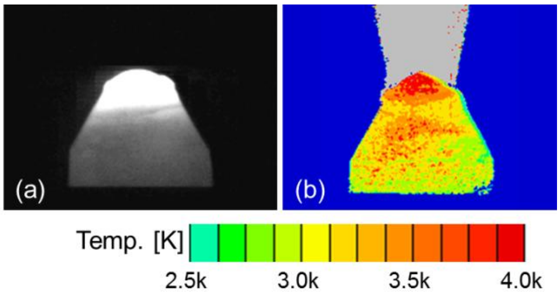

Fig.5 Snapshot of the electrode taken by the high-speed camera (a) and representative electrode temperature distribution in 12-phase AC arc (b).

gas of carbonates is removed during the in-flight treatment to reduce the refining time considerably. Compared with the traditional glass production which costs several days, the total vitrification time is evaluated as only 2-3 h at the same productivity as the fuel-fired melter.

The multi-phase AC arc is suitable heat source for the in-flight glass melting because it possesses many advantages such as high energy efficiency, large plasma volume, and long residence time of the treated materials. The multi-phase AC arc shown in **Fig. 2** has twelve electrodes divided into two layers, upper six electrodes and lower six electrodes. The upper electrodes were positioned at an angle of 30 degree with regard to the horizontal plane, while the lower electrodes were at an angle of 5 degree to control the plasma volume. The electrodes were symmetrically arranged by the angle of 30 degree. The electrodes of 6 mm diameter were made of tungsten with 2wt% thoria. **Figure 3** shows the stable discharge with the arc diameter of 100 mm. The arc discharge takes 20 ms for a periodic cycle while the frequency of power source used for 12-phase AC arc is 50 Hz.

3. Electrode Phenomena

Electrode erosion phenomena in the arc torches for welding and cutting processes were found as a significant problem because it determined the lifetime of the electrode during the processes. High-speed video camera with the band-pass filter system was used to measure the radiation intensities as shown in **Fig. 4**. Electrode temperature was then evaluated from the radiation intensities at 785 nm and 880 nm. **Figure 5** shows the snapshot of the electrode obtained by the high-speed camera and the representative temperature distribution of the electrode for the 12-phase arc [3]. The grey image indicates the arc. The temperature around the electrode tip was higher than the melting point of tungsten (3,695 K).

This system can be applied to observe the dynamic behavior of the vapors in the arc on the millisecond time scale [3]. Emissions from argon and tungsten vapors were observed at the wavelength of 738 nm and 393 nm, respectively. The representative high-speed images of the 12-phase arc for tungsten and argon vapors during one AC cycle are shown in **Fig. 6**. The contour maps indicate the distributions of the relative emission intensity of tungsten to argon. The relative intensity was calculated to estimate the number density of the tungsten vapor qualitatively. The electrode was at the anodic period in the first half period, while at the cathodic period in the other half. The snapshots represents that the tungsten electrode started to evaporate just after the peak top of the arc current at 5 ms in the anodic period. Moreover, the tungsten metal vapor becomes the main species in the arc during the anodic period when it started to evaporate. In contrast, a small amount of tungsten evaporation was observed during the cathodic period. These experimental studies enable us to understand the electrode erosion mechanism of the multi-phase AC arc.

4. Functional Nanoparticle Synthesis

Efficient production of high-purity nanoparticles is necessary for myriad applications in industrial, biomedical, and environmental purification processes because nanoparticles exhibit unique capabilities such as electronic, optical, and catalytic properties, in addition to better hardness and ductility than those of larger particles of micrometer size or bulk materials. Although several methods have been developed to produce nanoparticles, neither the precise control of the particle size nor mass production has been successful in practice.

The above-mentioned multi-phase AC arc as well as conventional induction thermal plasma has been anticipated as a powerful tool for efficient production of nanoparticles within a single process. A raw material, even that with a high melting/boiling point, is vaporized completely. Subsequently, the vapor is transported to the plasma tail flame with a high cooling rate, 10^5 K s^{-1}, and the vapor falls into a highly supersaturated state, which achieves effective formation of nanoparticles by nucleation and condensation. Consequently, the multi-phase AC arc can be regarded as an innovative tool that automatically creates nanoparticles with a high production rate.

Thermal plasma technology has been proven capable for production of functional nanoparticles by many scientific papers addressing the synthesis of intermetllics, silicides, and borides, yet the industrial application for nanoparticle production is behind the scientific researches. Therefore, the understanding of nanoparticle formation for precise control of composition and size is indispensible for industrial application of high quality nanoparticles.

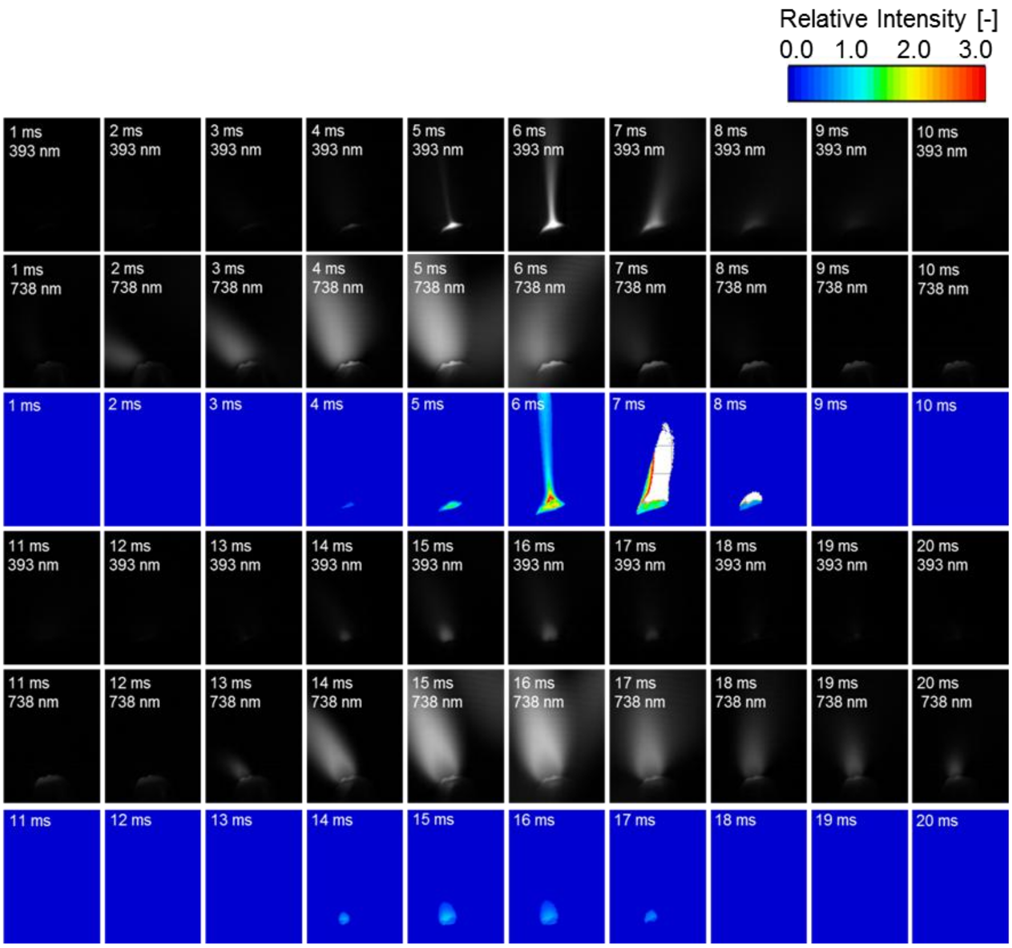

Fig.6 High-speed snapshots with relative intensity distribution of tungsten to argon emissions.

Transition metal borides are an important class of advanced structural ceramics due to their special properties of high melting points, hardness, high thermal and electric conductivities, and great thermal stability. However, synthesis of boride nanoparticles with high-purity is difficult by conventional methods due to the high melting and boiling points of raw materials. Even combustion process is impossible to be applied on the fabrication of such nanoparticles in spite of its high temperature, because oxidation atmosphere in combustion process leads to the production of contaminants of oxides. Therefore, thermal plasma which can provide high temperature without oxygen is a promising alternative to conventional methods in boride nanoparticles synthesis.

Formation mechanism of boride nanoparticle is attributed to the nucleation temperature of the constituent components of boride [4]. The formation mechanism of metal borides nanoparticles is presented in **Fig. 7**. After the precursors are injected into the plasma, they instantaneously start to evaporate. The evaporated vapors are transported with the plasma flow to the reaction chamber where the temperature decreases rapidly. The saturation vapor pressure of the vapor decreases drastically along with the temperature decrease and will fall below their partial pressures to reach their supersaturated state. This supersaturated state consequently leads to the production of nuclei by homogeneous nucleation. In the upstream region of plasma flow, boron vapor with lower saturation vapor pressure becomes supersaturated first, then the nucleation process of boron takes place homogeneously. The heterogeneous co-condensation of metal and boron dominantly occurs on the surface of boron nuclei during their molten conditions. Therefore, the boron cores are synthesized homogeneously, but boride particles grow on these cores by heterogeneous co-condensation of boron and transition metal. Boridation is believed to take place after the co-condensation process with boron diffusion in the transition metal.

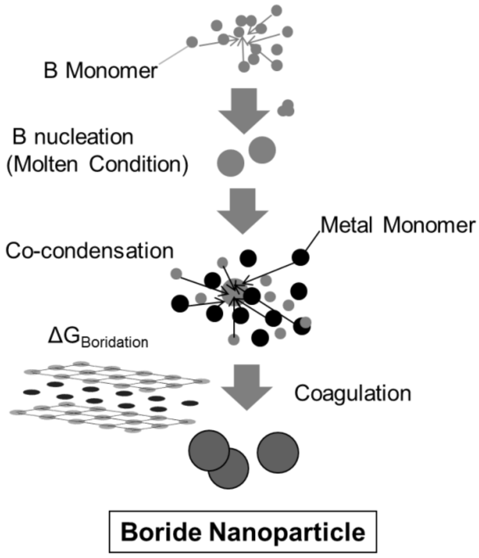

Fig.7 Formation mechanism of metal boride nanoparticle in RF thermal plasma.

For nanoparticle formation in thermal plasmas, nuclei are considered to be produced by homogeneous nucleation in higher supersaturation ratio of nucleated particles at high temperature. Following homogeneous nucleation, heterogeneous condensation dominantly occurs on the surface of the nucleated particles when the supersaturation ratio is relatively low. A new model was developed for numerical analysis of the entire growth process of binary alloy nanoparticles in thermal plasma synthesis [5]. The model effectively simulates the combined process of binary homogeneous nucleation, binary heterogeneous co-condensation, and coagulation among nanoparticles.

5. Conclusion

Thermal plasmas have been simply used as high temperature source for conventional processing. For innovative material processing and waste treatments, thermal plasmas would be utilized effectively as chemically reactive gas with more capability. More intensive research on the plasma generation, electrode phenomena, and sophisticated numerical analysis of reactive plasmas are important for the development of innovative processing.

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