Innovative in-flight glass melting technology using thermal plasmas

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Abstract: The innovative in-flight glass melting technology with thermal plasmas was developed for the purpose of saving energy and shortening production cycle. Results show that the quenched powders obtained high decomposition and vitrification in the process of in-flight melting by thermal plasmas. The maximum temperature of particles arrived in RF plasma is higher than that of multi-phase arc.

Keywords: Induction thermal plasmas; Glass production; In-flight melting; heat transfer

1. Introduction

Thermal plasmas are well-known to have some distinctive advantages such as high enthalpy, high chemical reactivity, variable properties with required chemical reaction, large plasma volume with low velocity, long residence/reaction time as well as rapid quenching rate [1, 2]. Thermal plasmas, therefore, have been widely applied to many fields such as nanoparticle synthesis, surface modification, plasma spraying, plasma vapor deposition, and chemical synthesis of high purity materials for the material processing [3-5]. Plasma treatment of waste material is an attractive new application, which aims to destruction of toxic wastes and recover higher added value products. Previous studies on the vitrification of mixed medical waste, incineration ashes and radioactive wastes have shown that thermal plasma is a promising technology for the environmental processing [6-9].

The typical system used for glass melting is refractory-lined melting furnace, fired by air or oxygen and natural gas or oil as fuel. It usually costs several days to get the homogeneous molten glass with high viscosity in the traditional fuel-fired melting furnace. Long time is spent on the dissolution of SiO_2 in melting process and the escape of gas bubbles in glass in fining process. According to the U.S. Department of Energy, the 70% energy per ton glass consumes in melting and fining stages used in U.S. flat-glass production. Many improvements have been made in furnace life and energy efficiency, however, the fundamental technology has not been changed [10]. In addition, a mass of emissions such as CO_2, NO_x and SO_x aggravate the environment. As the usage of glass has been rapidly increasing to meet the demands of architecture and automobile industries, thus, it is a crucial issue that how to increase the productivity keeping the energy usage minimum and environment friendly [2]. The high temperatures of thermal plasmas make it possible to develop an energy-saving and environment benign technology for shortening the production cycle and improving the production.

Under the support of New Energy and Industrial Technology Development Organization (NEDO, Japan) project, we are trying to develop an innovative in-flight melting technology for the increasingly urgent energy and environment problems. The schematic of fuel-fired melter and in-flight melter is shown in Fig.1. Compared with the conventional technology, the new technology will make it fast to melt raw material and release the decomposed gas during in-flight melting.

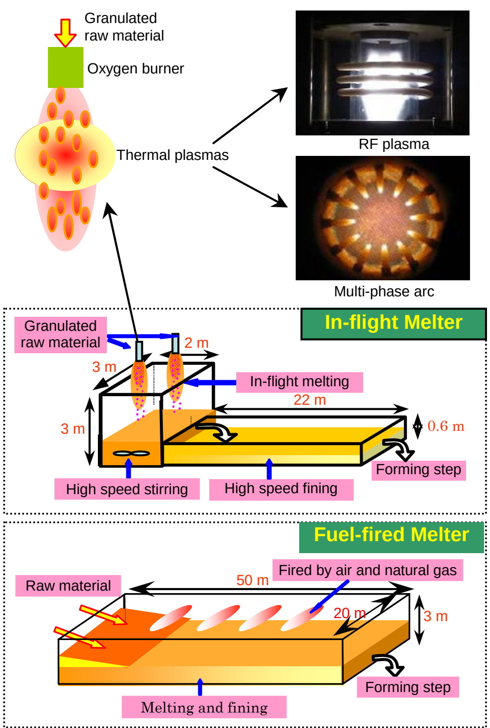

Fig.1 Model of in-flight glass melting

The purpose of this paper is to investigate the possibility of in-flight melting technology using thermal plasmas for glass production, study the melting behavior of particles in thermal plasmas, and compare the melting results with two different plasma sources, thus, provide a guideline for the glass industry.

2. Experimental

The granulated powders of raw material were prepared by the spray drying method from the reagents of Na_2CO_3, $CaCO_3$ for soda-lime glass with the composition of $16Na_2O$-$10CaO$-$74SiO_2$. The average diameter of initial powders was 51 μm and the porosity is 80%.

In the project, we planed to use four kinds of heating sources to compare the in-flight melting results and their respective advantages. The heating sources were induction thermal plasmas, multi-phase arc, oxygen burner as well as the hybrid of multi-phase arc and oxygen burner. All the furnaces are introduced here, but we only presented the finished experiments with thermal plasmas in this paper. The induction thermal plasma apparatus consists of plasma torch, reaction chamber and power supply, as shown in Fig.2. Typical operating conditions were as follows: torch power: 10 kW; total pressure: 101.3 kPa; argon plasma gas: 2.0 l/min; sheath gas: 22 l/min (Ar) + 2 l/min (O_2); carrier gas: 20 l/min (Ar); feed rate: 30 g/min. The powder after melting was quenched and collected on a water-cooled substrate at 340 mm from nozzle to substrate.

The schematic of the hybrid of multi-phase arc and oxygen burner is shown in Fig.3. The furnace can be respectively operated as multi-phase arc, oxygen burner or the combination of arc and burner. The multi-phase arc consists of 12 electrodes, reaction chamber, powder supply and AC power supply. The 12 electrodes are divided into two layers, upper 6 electrodes and lower 6

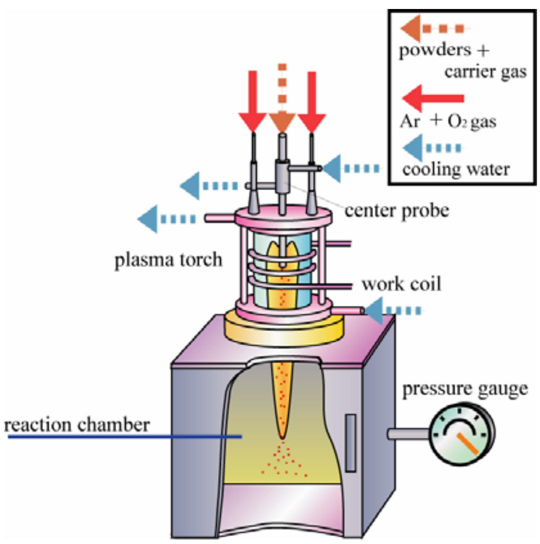

Fig.2. Schematic of RF-plasma apparatus

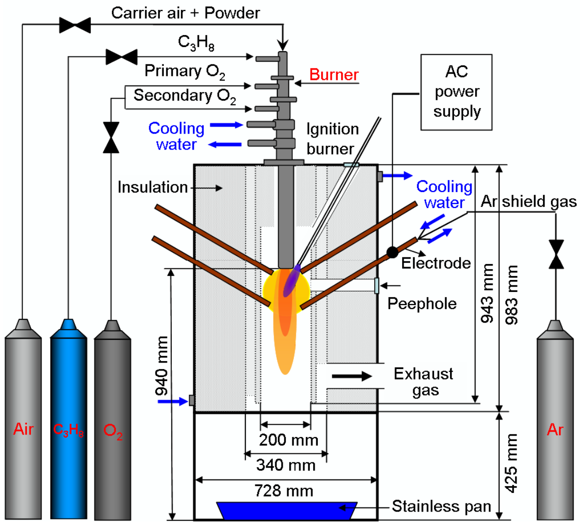

Fig.3 Schematic of combination of multi-phase arc and oxygen-burner apparatus

electrodes. The configuration of 12 electrodes is symmetrically arranged by the angle of 30 deg. The total power of multi-phase arc was 30 kW with 87% efficiency, the input voltage 190 V, the input current 220 A in the experiment. The discharging voltage and its current of each electrode were 25-45 V and 80-100 A. The granulated powders of raw material were injected into chamber at a feed arte of 30 g/min with the flow rate of carrier gas (air) 20 l/min. The glass powders were quenched on the stainless steel pan at a distance of 920 mm. Argon gas was introduced as sheath gas to prevent the electrodes from oxidation. The oxygen-burner is composed of nozzle, fuel and oxygen feeding system, water-cooled tube as well as ignition burner. It is installed on the same furnace as multi-phase arc, fired by oxygen and propane (C_3H_8) as fuel. The experimental conditions and results of oxygen burner and the hybrid of arc and burner will be presented late.

The thermogravimetric (TG) for thermal analysis of samples was performed with thermogravimetry on TG8120 (Rigaku), the measured temperature in the range of 20-1400°C, at the rate of 10°C/min. The micrograph and size distribution of the particles was carried out by scanning electron microscope (SEM) on JSM5310 (JEOL). The structures of the prepared powders were determined by X-ray diffractometry (XRD). XRD was carried out on Miniflex (Rigaku) with CuK_α radiation at 30 kV and 15 mA. The data were collected in the 2θ range 3-90° with a step size of 0.02° and a scan speed of 4°/min. The composition of quenched powders was analyzed by inductively coupled plasma (ICP) spectroscopy on ICP-8100 (SHIMADZU).

3. Results

Fig.4 shows the TG curves of raw material and quenched

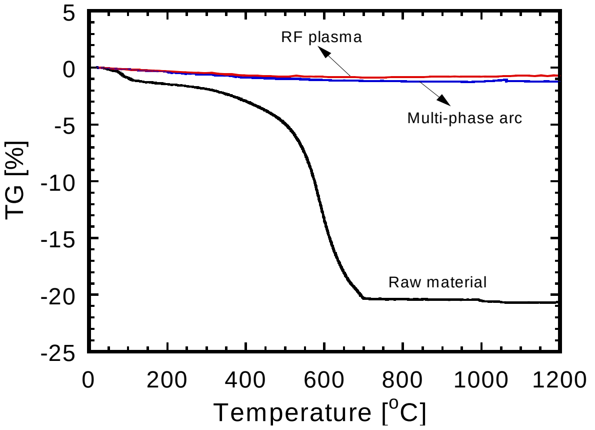

Fig.4. TG curves of raw material and quenched powder

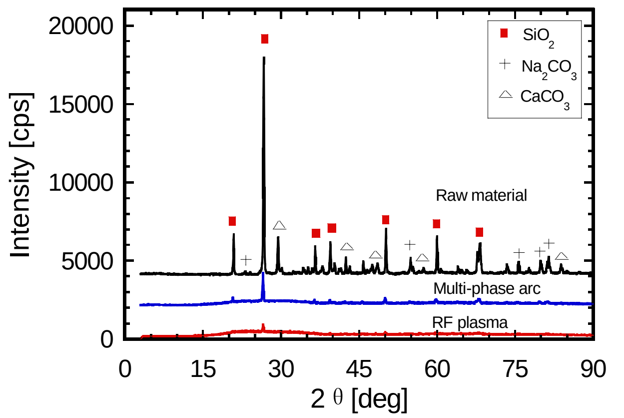

Fig.5. XRD of raw material and quenched powder

powders. The TG curve of raw material indicates two main stages with about 20.5% total weight loss. At the temperature of 50-100°C, the first mass loss is ascribed to the release of physically adsorbed H_2O and CO_2 from the compound. The second large mass loss between 300 and 700°C is due to the decomposition of carbonates (Na_2CO_3 and $CaCO_3$). However, the TG curve of powders heated by RF plasma shows no obvious weight loss during heating to 1200°C, indicating that the raw material decomposed completely in plasmas during in-flight melting. There is a little weight loss in the curves of multi-phase arc. The decomposition rates of carbonates heated by multi-phase arc and RF plasma are 95% and 97%, respectively. It indicates that almost CO_2 gas was released from the compounds during the in-flight melting, and higher decomposition rate shorter glass fining time.

The XRD analysis was performed to demonstrate the structures of powders before and after melting. As seen from the results shown in Fig.5, the peaks of SiO_2, Na_2CO_3 and $CaCO_3$ are clearly identified from XRD pattern before the raw material was heated. It can be found that there are not the peaks of Na_2O and CaO, only SiO_2 peaks in the XRD patterns. In soda-lime glass, sodium (Na^+) and calcium (Ca^{2+}) as the modifier ions are dissolved and inserted into the silicate ion structure such that the tetrahedrons of silicon and oxygen atoms are stretched to random network structure [11]. The random network structure is of amorphous structure with typical glass characteristic. The main peak intensity of SiO_2 of quenched powders decrease in an order of multi-phase arc and RF plasma, which indicates the amount of crystal SiO_2 becomes small after heating. The ratio of reacted SiO_2

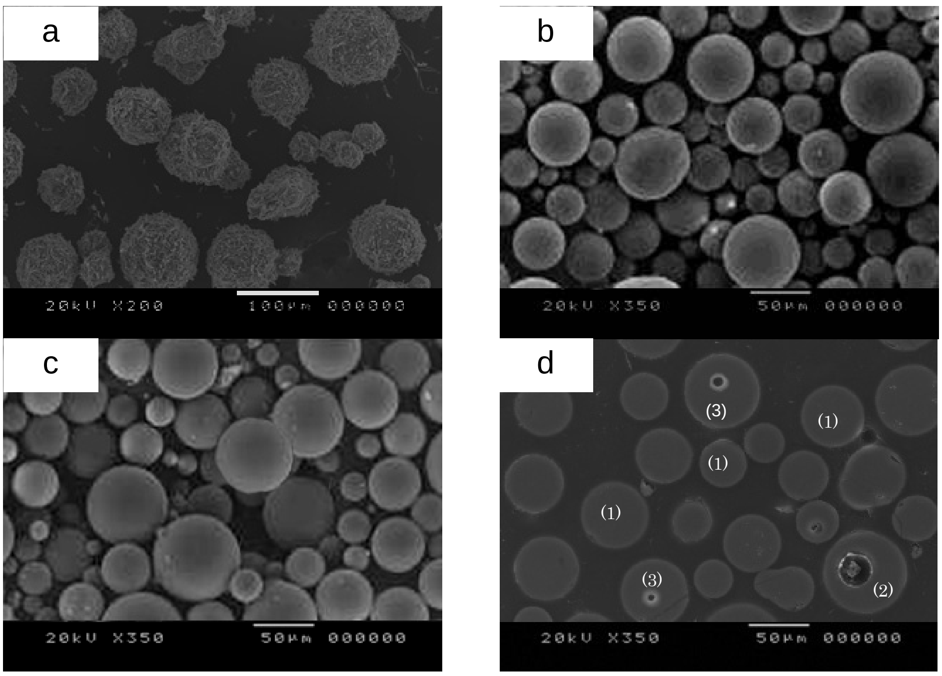

Fig.6 SEM photographs of powders: a. raw material; b. multi-phase arc; c. RF plasma; d. cross-section of RF plasma

from raw material to that in initial material was used to express the vitrification degree of quenched powders. The internal standard method was conducted to analyze the vitrification degree quantitatively, ZnO used as the standard material [12]. The vitrification degree of samples treated by multi-phase arc and RF plasma is 94.4% and 96.5% in the process of in-flight melting, respectively. According to the simulated results [2], it was calculated that the residence time of powders injected in RF plasma is less than 10 ms passing from nozzle exit to water-cooled substrate. It indicates that using thermal plasmas obtains high vitrification of glass raw material in milliseconds.

The SEM photographs of particles before and after melting are shown in Fig.6. The photograph of Fig.6 (a) shows the granulated particles of raw material were of porous structure and rough surface. It can be observed that the quenched particles were also spherical like glass beads from Fig.6 (b) and (c), but the melted particles had smooth surface and compact structure. The average diameter of quenched powders shrank to 25 μm from 51μm, reduced about a half of original after melting. Fig. 6 (d) shows the cross-section of particles melted by RF plasma. It suggests that almost particles completely melted like particles (1) after in-flight melting, but a little unmelted part presents inside particle (2), and some small bubbles with diameters ranging from 3 μm to 15 μm appear in particles (3). The unmelted part inside the particle reveals the reaction first occurs at the outer skin of the particle, then the zone of reaction moves into the inter solid. The bubbles inside particle maybe come from the decomposed gas of raw material and the dissolved gas while powder quenching.

In order to study the maximum temperature of particles arrived during in-flight of melting, a special raw material including 0.5% Fe_2O_3 and no SO_3 was used to investigate the temperature of particles arrived at the melting process by redox potential measurements, the measured temperatures are shown in Fig.7. The results show that the maximum temperature of particles arrived in RF plasma is higher than that of multi-phase arc. The difference in temperature between RF plasma and

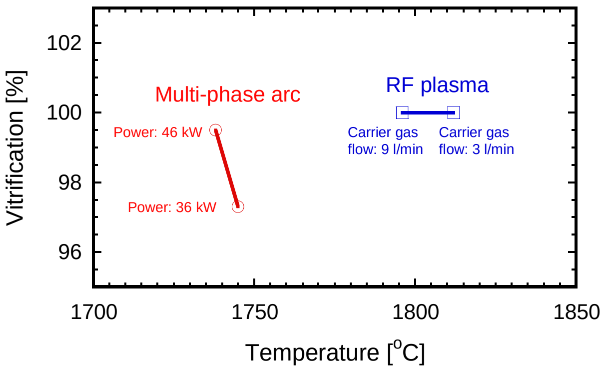

Fig.7 Particle maximum temperature arrived in different heating sources

multi-phase arc is about 60°C, which explains lower vitrification degree and decomposition rate of powders heated by arc. In addition, it was found that the maximum temperature of particles arrived in RF plasma decreases with an increase of flow rate of carrier gas. The effect of input power of multi-phase arc on the maximum temperature of powders is too small to affect the vitrification. The high input power increase the arc intensity and prolong the residence of particles passing, so the vitrification degree is improved. The content of Na_2O of quenched powders treated by RF plasma and arc is 12.9% and 13.6%, respectively. The high temperature of RF plasma leads to more volatilization of Na_2O.

4. Conclusion

The innovative in-flight glass melting technology with thermal plasmas was successfully developed for glass industry. Results show that the decomposition rate of carbonates and the vitrification degree achieved about 95% in the process of in-flight melting by using thermal plasmas, which reveals the new technology can reduce the energy consumption and shorten the production cycle. The maximum temperature of particles arrived in thermal plasmas (>1740°C) was more than the melting point of soda-lime glass (1400°C).

Acknowledgements

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