The effect of heating sources on temperature profiles on a cross section of glass

Hoikwan LEE, Seoyeong CHO, Kyungmin YOON, Yoonyoung KWON, Kyungwook PARK, Jinsu NAM, Jaeyoung CHOI and Sangecheol JUNG

Energy Materials Lab, Samsung Corning Precision Materials, Chungnam 336-725, Korea

In this study, the effect of heating sources on the temperature profiles of soda-lime silicate glass was investigated. Conventional heating created an extreme thermal gradient (the surface temperature > the interior temperature) when glass which is a poor thermal conductor was heated. As a result, an adequate soaking time depended on the thickness was required for the interior of the glass to become as hot as those surface. On the other hands, microwave heating which was employed to rapidly and homogeneously heat the glass, showed an inverted temperature gradient that the surface temperature is cooler than the interior temperature of the glass. When using microwave energy, critical temperature ($T_{c}$) at which the glass can self-heat, was observed to be at 370°C. At this temperature, the heating rate which is the interior temperature of glass increased from 8 to 16°C/min. On a cross section of glass, the thermal gradient ($\Delta T_{\text{heating}}$ the interior–the surface) and the heating rate of glass were successfully manipulated by introducing a hybrid heating method which combined microwave heating with conventional heating. The results were $0^\circ \text{C} \leq \Delta T_{\text{heating}} \leq 180^\circ \text{C}$ and $\sim 3^\circ \text{C/s}$, respectively.

Key-words : Microwave heating, Conventional heating, Temperature profile, Homogeneous heating, Glass

1. Introduction

Microwave heating of ceramic materials was first recognized in the 1950’s. In recent years, many researchers have studied this type of heating for high-temperature processing of ceramics such as in sintering, joining, and crystallization. They have reported on the “microwave effect” which has an unpredictable result observed only in the microwave heating process. This effect cannot easily be duplicated using conventional heating methods.

In microwave processing, the microwave energy can be directly coupled with the materials at the molecular dipoles or with ionic motion. This coupling (including interaction) results in the conversion of electromagnetic energy into heat in the materials due to intermolecular friction. This process is being studied for rapid and uniform heating of poor thermal conductive materials such as ceramics and glasses.

The micro-wave frequency of 2.45 GHz which is designed primarily to process foods and has good interaction with hydroxyl group in water is commonly used in industry. Therefore, most ceramic materials do not absorb 2.45 GHz microwave energy well at room temperature, and heating aid materials called susceptors (Silicon Carbide, Carbon, Organic Binders) are required for the initial heating of a ceramic material up to its critical temperature ($T_{c}$). This is the temperature at which the materials themselves can be heated using microwave energy.

Contrary to a wide range of studies for ceramic materials using microwave processing, due to its low dielectric loss, many studies focused on glass have not been carried out yet in depth. Only a few papers describing the application of microwave heating on glass have been published and have only emphasized “the microwave effect” on crystallization, glass melting and sintering of glass frits. Some engineers were trying to uncover a new microwave effect for glass. In some studies, they investigated the feasibility that microwave heating as a heating source could be used in tempering machine. As a result of these feasibility studies, it is necessary to carry out systematic studies of microwave heating on glass in order to apply the process to the glass industry.

In this study, the effect of microwave heating and conventional heating on glass was defined by analyzing the temperature profile between the surface and the interior of glass during heating. The technical limitations on both heating sources were discussed in detail. This study also showed that the thermal gradient from across section of glass could be controlled by using a hybrid heating method.

2. Experimental procedure

In order to analyze the microwave energy absorption of soda-lime silicate glass, a hybrid heating furnace with an inner cavity size of $120 \times 120 \times 60 \text{mm}$ was designed. Figure 1 shows the schematic diagram of the hybrid heating cavity. A Kitchen microwave oven (MWO-20E6, Tong Yang inc.) with a power of 800 W at 2.45 GHz in the multimode was equipped with a programmable sheath heater shielded with metal pipe to prevent the microwave field from interfering with the EMF (electromotive force) signal. The temperature of the sample was monitored with shielded K-type thermal couples (WHP503041, Wisetherm) which had a negligible temperature difference. The temperatures produced from the glass surface and the mid plane of the glass were measured continuously, and simultaneously with the gauge (GT309, Giltron) connected to its computer system. A thermal insulation package made of lightweight and porous Fiberfrax board (Cerakwool, KCC corp.) was inserted to prevent heat loss.

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To measure interior glass temperatures, glass samples with a hole in the middle were prepared by using the slumping method where two glass plates were bonded by applying heat treatment at 780–800°C for 30–60 min. A low iron soda-lime silicate glass made by Pilkington was employed, and the size and thickness of the samples prepared were 100 mm x 100 mm and 2.2–4 mm, respectively. In the experiment, a conventional electrical furnace with 4-side heating wire (Wisetherm FHP-03, DAIHAN Scientific) and a hybrid furnace combined microwave heating and conventional heating (as shown in Fig. 1) were employed. The electrical furnace was used to evaluate the effect of conventional heating on temperature and to calibrate the temperature detected by hybrid furnace. In hybrid heating, the samples were placed as shown in Fig. 1, and the factors such as position of the glass in the cavity, glass size and shape, initial cavity temperature were carefully controlled to minimize experimental error.

Conventional heating, radiation and convection, which heats the glass surface only was carried out in order to observe the effect of the heating source on the temperature profile. Temperature differences between the interior and the surface of each sample were calculated as a function of the heating rate (10–30°C/min) and the glass thickness (2.2–4 mm). In addition, the soaking time required for thermal homogenization was measured. In hybrid heating, the glass was heated up to a target temperature (500–600°C) with conventional heater and it was soaked at each target temperature till the interior temperature of glass became as hot as its surface temperature. After that microwave energy was supplied with conventional heating to heat the glass further. The temperatures when the microwave energy is applied and the microwave powers were manipulated in order to create better control over the temperature profile.

3. Results and discussion

3.1 Temperature profile of glass during conventional heating

Figure 2(a) shows the temperature profiles on a cross section of 3.2 mm thick glass measured as a function of heating rate (10–30°C/min). As seen in Fig. 2(a), the surface of the glass is hotter than the interior when heating to 700°C. The range of temperature difference between the glass interior and the surface at 700°C is 25–40°C. The difference widens as the heating rate increases. In Fig. 2(b), the temperature differences were plotted against the soaking time. Here, the glass was heated up to 650 and 700°C, respectively and then soaked at those temperatures to measure the temperature profiles on the surface of the glass and the interior as a function of the soaking time. After heat soaking at each temperature for 3 min, the results show that there is still a temperature difference of about 22–23°C. The temperature difference finally reached uniformity, which is within 3°C after soaking time for 20 min.

As was previously mentioned, conventional heating heats only the material surface through radiation and convection. Heat is conducted from the surface to the interior until a uniform temperature is reached. Thus, adequate soaking time is necessary to improve glass temperature homogeneity. In view of the above, it can be assumed that thermal conductivity is the dominant mechanism for homogeneous thermal distribution in glass.

3.2 Temperature profile of glass during microwave heating

In order to characterize the effect of microwave heating on glass, Fig. 3 shows the temperature profiles of the glass surface and the interior measured as a function of heating time. Here, no heating aid was used to evaluate the self-heating ability of the glass itself. As shown in Fig. 3, during microwave heating it is observed that the interior temperature of the glass was higher than the surface temperature at about 180°C. From Fig. 3, we found two interesting points. The first point to note is that the surface temperature of glass should not be the same as the interior temperature. According to microwave heating principles based on volumetric heating, the surface and interior temperatures should be the same. However, the result was
that the glass surface has a relatively lower temperature range than the interior. It was assumed that these thermal gradients originated from heat loss at the surface through convection and radiation. The second point to note is that we observed the slope change at around 370°C. This indicates that heating rate of glass has increased due to increasing microwave energy absorption. Simply put, the microwave energy absorbed of glass is proportional to its dielectric loss ($\varepsilon''_{\text{eff}}$) and its operating frequency ($\omega$) of glass. This process is described by the following equation:

$$P_a = \varepsilon''_{\text{eff}}\varepsilon_0 E_{\text{rms}}^2 \text{ (watts/m}^2)$$  

(1)

Based on this equation, where $\omega$ and $\varepsilon_0$ are the angular frequency ($\pi f$, $f$ = operating frequency in hertz) and permittivity of free space ($8.85 \times 10^{-12}$ farads/m); $E_{\text{rms}}$ and $\varepsilon''_{\text{eff}}$ are the root mean square of the internal electric field (volts/m) and the effective relative dielectric loss (dissipation) factor (unitless), respectively.

The rate of temperature rise ($\Delta T/\Delta t$) in glass when microwave energy is absorbed is given by the equation.

$$\left(\Delta T/\Delta t\right) = (Pa/\rho C_p) \text{ (C/sec)}$$  

(2)

Where $\rho$ is the density of the glass (kg/m$^3$) and $C_p$ is the specific heat (kJ/kg-°C), respectively.

In Eqs. (1) and (2), it should therefore be noted that temperature rise indicates that glass absorbs more microwave energy. From the view of this, it can be said the microwave energy absorption of soda-lime silicate glass improved at around 370°C and this resulted in an increase in the heating rate from 8 to 16°C/min. This behavior corresponds with that in Dr. Mahmood’s research.$^{1}$ He reported that the critical temperature of lithium disilicate glass was at around 400–500°C as an estimate of dielectric loss ($\tan \delta$) measurement as a function of temperature. Based on glass structure, it was assumed that the ionic mobility of glass elements especially alkali cations (i.e. Na$^+$, K$^+$) became an activated process. This means that the glass is ready to be heated up itself. These results also suggest that a special heating aid system is needed to activate glass at below critical temperature in order to apply microwave heating process for glass.

### 3.3 Design of temperature profile on a cross section of glass using the hybrid heating method

In order to make uniform heating, we used a hybrid heating method which combined conventional heating with microwave energy. During conventional heating up to 700°C by increment of
surface and interior temperature control difficult was not observed. This result proves that hybrid heating is a very effective heating method for maximizing uniform heating in poor thermal conductors such as in ceramics and in glass.

Figure 5 shows that hybrid heating can also be used to control non-uniform heating of glass. In order to design the temperature gradient and the heating rate on glass while heating, the ambient temperature and the magnetron power were suggested as key factors. Based on Fig. 5(a), the interesting point is that the surface temperature increase slightly within 10°C in comparison to the ambient temperature made by conventional heating in spite of the interior temperature of the glass rise rapidly. It is noted that the ambient temperature (500, 550, 600°C) is a very important factor to create an artificial temperature gradient on glass. Figure 5(b) shows the heating rate of the glass interior increases from 1 to 2.9°C/s when increasing the magnetron power from 30 to 100%.

The most important point is that the temperature gradient on a cross section of glass can be designed and controlled using this hybrid heating process which is that microwave heating dominates the interior temperature and that conventional heating decides the surface temperature.

4. Summary

In this study, the effect of heating sources on temperature profiling on a cross section of glass was successfully investigated. Both methods currently used, conventional heating and microwave heating, each carried its own disadvantage when trying to lead uniform heating. The former needed adequate soaking time and the latter suffered from self-heating at room temperature. We found that the adequate soaking time for uniform heating is around 20 min and the temperature which self heating is available is above 370°C on soda-lime silicate glass.

Hybrid heating was suggested as another method to make both the rapid and the uniform heating possible on the surface and the interior of glass. In addition, this method built the temperature gradient on glass as well. We expect that this result will broaden the application of microwave technology in the glass industry.

References