Chapter

Ultrasonic Vibration-Assisted Hot Glass Embossing Process

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Abstract

This chapter is intended to provide the reader with background information about the assistance of ultrasonic vibration in hot glass embossing process. For this purpose, the description of the conventional hot glass embossing process and the ultrasonic vibration-assisted hot glass embossing process will be defined first. Based on the comparison between these two processes, components of the ultrasonic vibration device which produces ultrasonic vibration will be discussed in principle. Among these components, ultrasonic horn will be especially analyzed. After that, each interesting effect of ultrasonic vibration on hot glass embossing process will be explained in detail. With the development and application of simulation tools on forming process, this chapter will finally describe some results of finite element analysis (FEA) of ultrasonic vibration-assisted hot glass embossing process.

Keywords: ultrasonic vibration, hot glass embossing, ultrasonic vibration device, microstructures, friction, finite element analysis

1. Introduction

1.1 Conventional hot glass embossing process

Hot embossing process is one of the common replication technologies for the replication of microstructures in micro optic systems, such as micro-lens array, micro-prism array, photoresist columns on a glass substrate, etc. The micro-replication process is known as a process replicated from a microstructured master. With the development of microsystem technology, low cost is one of the important requirements for manufacturing optical components in a micro range. Besides injection molding process, hot embossing has been favored because of its operation as well as the convenience in producing mold tools. Especially, it is the best choice to create micro components with complex geometry and high aspect ratio. In addition, hot embossing is also suitable for mass volume fabrication with high quality.

Material is the main component in molding process, also hot embossing process. Most applicable materials for hot embossing are thermoplastic polymers. Nevertheless, alternative molding materials like glass, metals, or ceramics will also be used [1]. Glass is a material commonly used in optical microsystem. Compared to optical polymers, optical glass has higher transparency, higher scratch, and humid resistance. Another advantage of the optical glass is that its thermal expansion coefficient is smaller than that of the optical polymers. This reduces significantly the deviation between the design and the final optical components. Moreover, the refractive index of the optical glass is much higher than that of optical polymers (a range from 1.5 to over 2.0 compared to a range from 1.3 to 1.7). With the higher refractive index, optical glass could bend the light rays to focus in a smaller range, which is suitable to optical lenses. With the above advantages, optical glass has been favored for high-precision applications.

The hot glass embossing process is divided into four major steps (**Figure 1**). The process starts with heating the sample to the molding temperature, which is usually above transition temperature T_g or the annealing temperature A_t of the material, followed by an isothermal molding by embossing with speed- and/or force-controlled, the cooling of the molded part to the de-molding temperature, and finally de-molding of the component. Heating and embossing stages are usually performed in vacuum environment to protect molds from oxidation, while the cooling stage is usually supported by high-pressure nitrogen. Compared to injection molding, hot embossing process has more advantages, such as shorter flow distances and lower velocity, which decreases shear stress of material significantly. As a result, the decrease of shear stress of material as filling into micro cavities should reduce the residual stress of the embossed parts. In addition, hot embossing process could be the best choice for manufacturing microstructures, which are hardly performed by injection molding. Since the molding temperature is set constantly, the conventional hot glass embossing process is isothermal. The temperature setting of this process is shown in **Figure 2**.

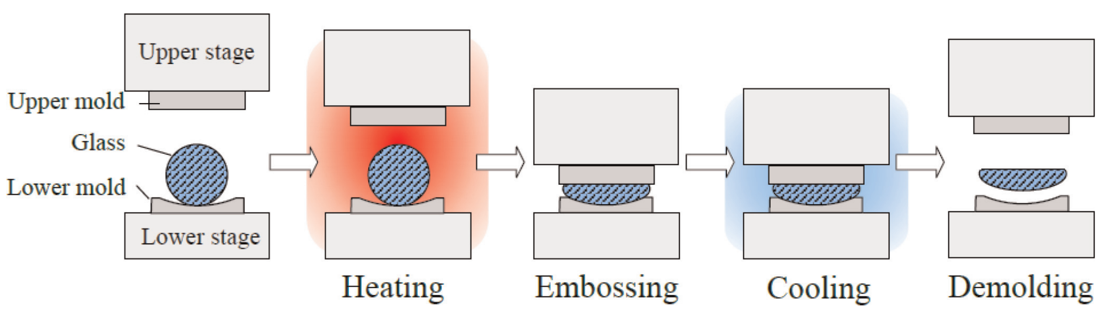

Figure 1.
Steps for the conventional hot glass embossing process [2].

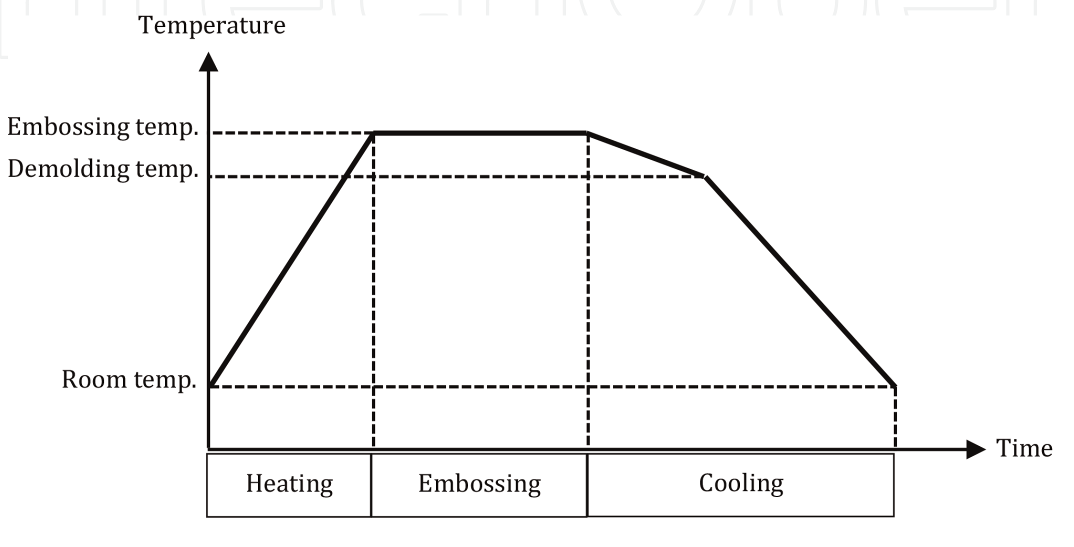

Figure 2.
Temperature setting for the conventional glass hot embossing process.

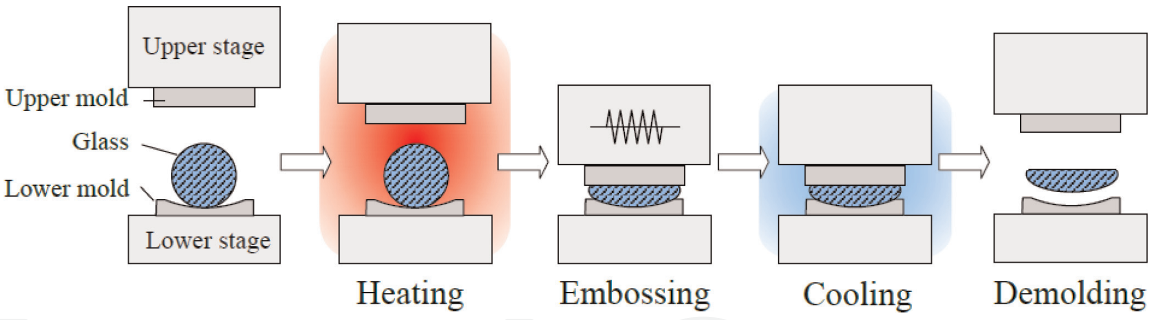

Figure 3.
Steps for the ultrasonic vibration-assisted hot glass embossing process [2].

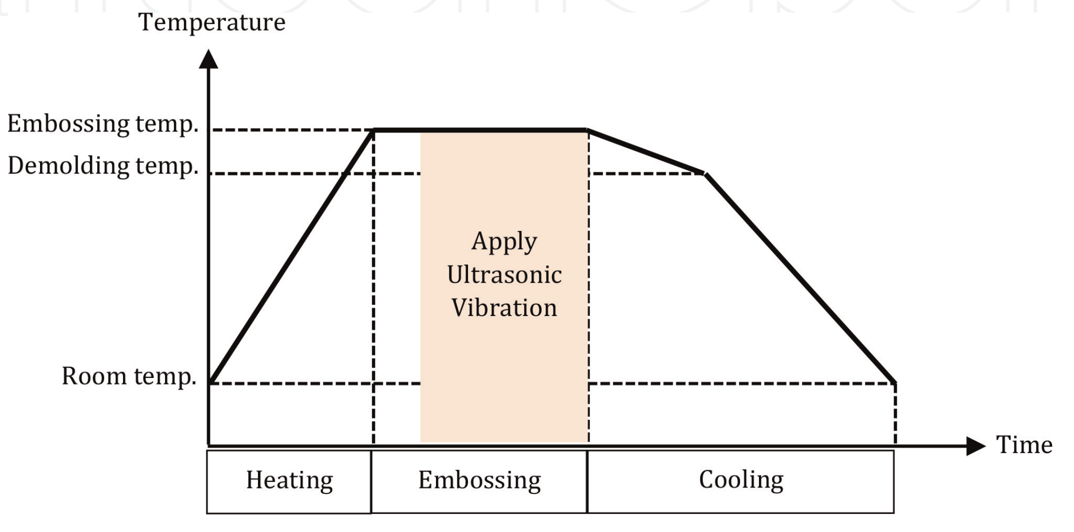

Figure 4.
Temperature setting for the ultrasonic vibration-assisted glass hot embossing process.

1.2 Ultrasonic vibration-assisted hot glass embossing process

Ultrasonic vibration technology has been widely applied in various industrial processes, such as machining, welding, and forming. Recently, this technology has been also utilized for processes working at high temperature like hot upsetting and hot embossing. The steps of an ultrasonic hot glass embossing process are like those of the traditional one, except the embossing stage. During the embossing stage, an ultrasonic source is located on the top of the mold to generate high-frequency vibrations (**Figure 3**). The high energy of ultrasonic vibration rapidly increases the temperature at the contact area between the glass and the mold. Because of this principle, the temperature distribution between the traditional process and the ultrasonic process is different. In the conventional process, the temperature distribution inside the glass during the embossing stage is identical, whereas in the ultrasonic process the localized heat-affected zones are concentrated on the contact area of the mold and the glass. Therefore, this ultrasonic embossing method is not an isothermal process. Temperature setting of this process is shown in **Figure 4**.

2. Components for ultrasonic vibration-assisted hot glass embossing process

In general, an ultrasonic vibration-assisted hot glass embossing process has three main components: heating furnace, compression tester, and ultrasonic vibration device. The role of heating furnace is to heat the glass and the mold to the embossing temperature. Vacuum environment is usually remained within the heating furnace to prevent the heat loss. The ultrasonic vibration device is usually compiled with one of the molds, which transfers ultrasonic vibration to the mold directly. Both the heating furnace and the ultrasonic vibration are attached to the compression tester, as shown in **Figure 5**. The role of compression tester is to control the embossing load after receiving feedback signals from the load cell.

2.1 The heating furnace

A cross-sectional diagram of a heating furnace is shown in **Figure 6**. The heating furnace is integrated by a quartz tube. Because the heating furnace is fixed to the wall, the lower die is controlled by the compression tester to move up and down, so that it can emboss the glass inside the chamber and de-mold the product. Some infrared heaters are distributed around the quartz tube. Energy from the infrared light penetrates through the quartz to heat the molds and the specimen inside.

During the embossing stage, temperature is very high. To protect the load cell, which is located inside the lower die, from damage under high temperature, a cooling system is set up. Besides that, the load cell is also working in the vacuum environment. This condition helps the load cell detect external forces precisely. Although vacuum environment is useful for the load cell, it is useless for the infrared heaters. Therefore, the infrared heaters are placed outside the vacuum chamber to increase their lifetimes.

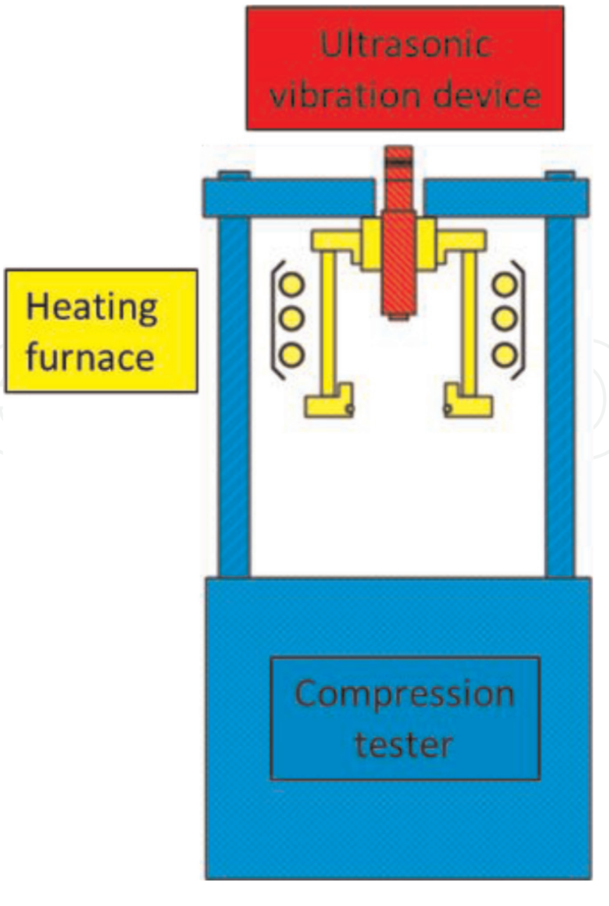

Figure 5.
Schematic of apparatus design [2].

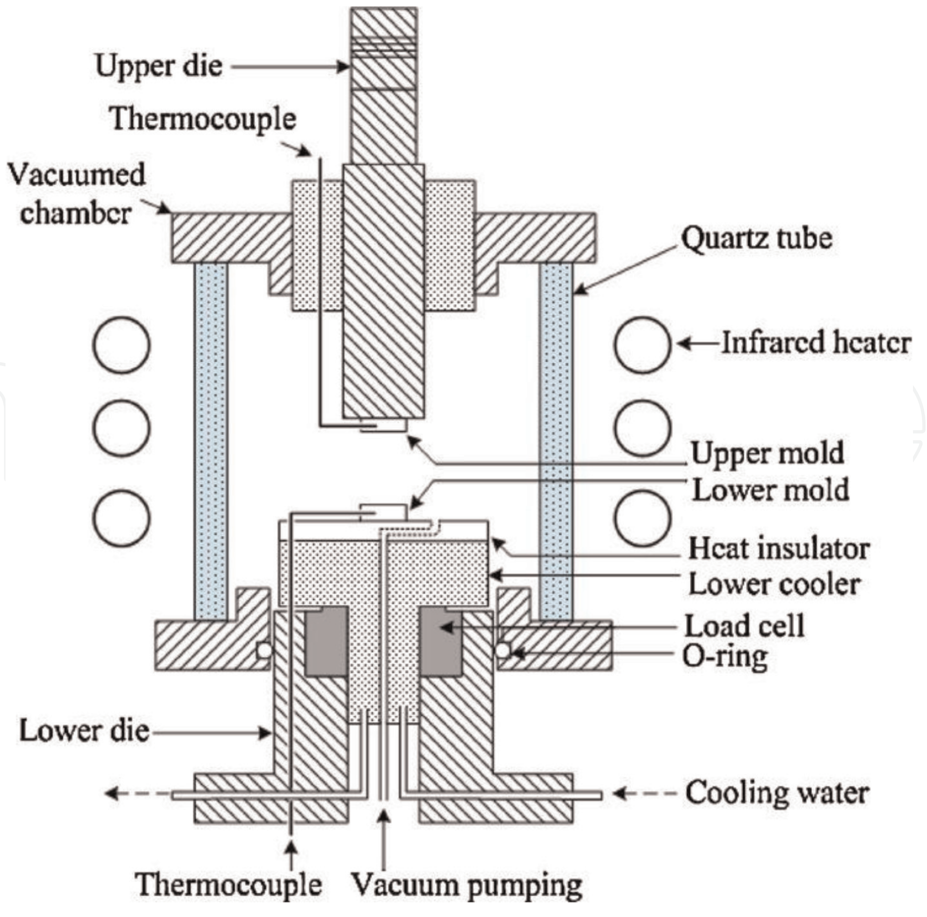

Figure 6.
Cross-sectional diagram of a heating furnace [3].

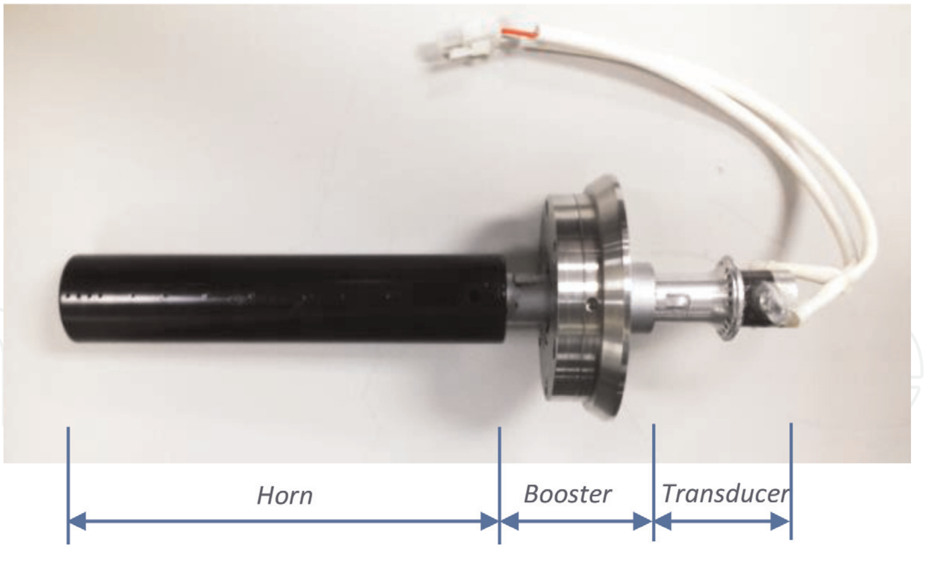

Figure 7.
An ultrasonic vibration device.

2.2 Ultrasonic vibration device

As shown in **Figure 7**, an ultrasonic vibration device consists of a piezoelectric transducer, a booster, and a horn. The vibration is generated from the transducer by inputting an electrical signal through a frequency generator. Resonance phenomenon is usually adopted in ultrasonic vibration devices and then harmonized with the frequency of electrical signals. The ultrasonic vibrating device is designed to work properly at a constant frequency. For thermal protection, a horn cooler is mounted outside the ultrasonic horn. O-rings placed between the ultrasonic horn and the horn cooler to form a water seal do not significantly affect the ability of the ultrasonic device to vibrate.

Since the material properties of the horn would change in elevated temperature, its resonant frequency is shifted, and a mismatch with the frequency generator occurs. Hence, the ultrasonic device must be modified to ensure that it can operate correctly at high temperature. By simplifying theoretical equations, the speed of a wave traveling along a one-dimensional medium is described by

$$c_L = \sqrt{\frac{E}{\rho}} \tag{1}$$

where E and ρ are Young's modulus and density, respectively. The wavelength is

$$\lambda = \frac{c_L}{f} = \frac{\sqrt{E/\rho}}{f} \tag{2}$$

where f is the resonance frequency of the ultrasonic vibration device. In longitudinal vibration mode, multiples of $(\lambda/2)$ can be used as reference for the design of the device length.

As the temperature of a device whose geometry is fixed rises, its resonant frequency falls due to the decrease in Young's modulus [4], so such frequency will shift beyond the tracking range of the frequency generator. To increase the resonant frequency of the device at high temperature, its length must be reduced. With theoretical perspective, reducing the device length could increase the resonant frequency in longitudinal vibration mode. It means that the length reduction could compensate the frequency decrease caused by the increase in temperature. This trend has been verified by both finite element analysis and experiments as shown in **Figure 8**.

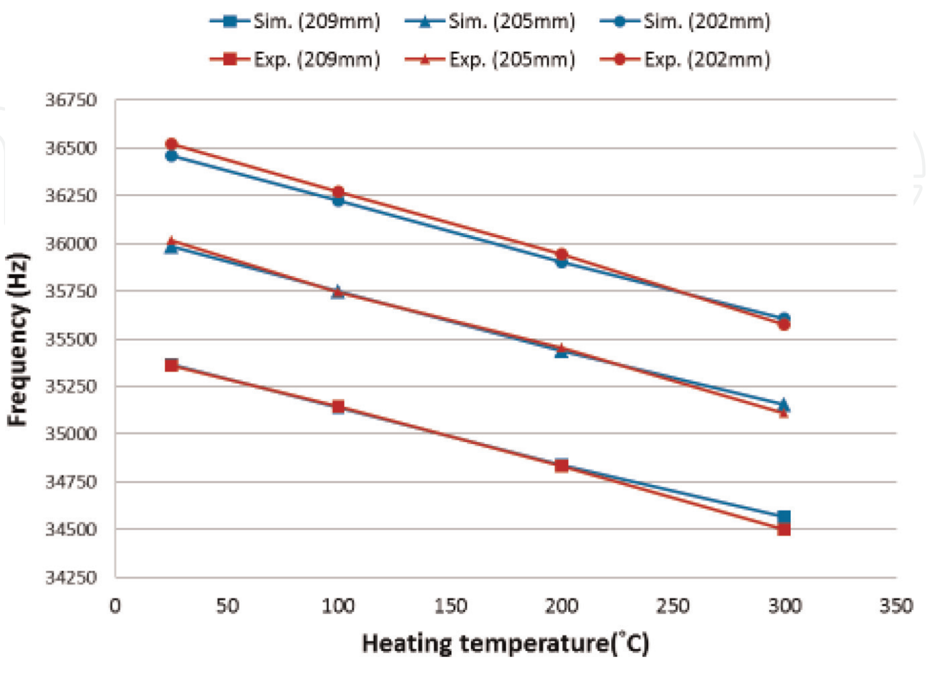

Figure 8.
Resonant frequency of the ultrasonic vibration device with different horns and heating temperatures at 25°C [5].

3. Effects of ultrasonic vibration on hot glass embossing process

3.1 Glass behavior under the application of ultrasonic vibration

In a dynamic experiment, if a sinusoidal strain with angular frequency ω and amplitude ε_0 is applied into a viscoelastic solid

$$\varepsilon = \varepsilon_0 \sin(\omega t) \tag{3}$$

the resulting stress would be also sinusoidal with the same frequency which is lagging with a phase angle δ (**Figure 9**):

$$\sigma = \sigma_0 \sin(\omega t + \delta) \tag{4}$$

Using complex notation

$$\varepsilon^* = \varepsilon_0 \exp[i(\omega t)]; \sigma^* = \sigma_0 \exp[i(\omega t + \delta)] \tag{5}$$

the complex modulus G^* is then defined by the relation

$$G^* = \frac{\sigma^*}{\varepsilon^*} = \frac{\sigma_0}{\varepsilon_0} \exp(i \cdot \delta) = \frac{\sigma_0}{\varepsilon_0}[\cos\delta + i \cdot \sin\delta] = (G' + i \cdot G'') \tag{6}$$

The first term on the right-hand side of Eq. (6) is in phase with the strain and is the real part of the complex modulus, often called the storage modulus:

$$G' = \frac{\sigma_0}{\varepsilon_0} \cos\delta \tag{7}$$

The second term of Eq. (6) represents the imaginary part of the complex modulus, often called loss modulus:

$$G'' = \frac{\sigma_0}{\varepsilon_0} \sin\delta \tag{8}$$

The ratio $G''/G' = \tan\delta$, so-called loss factor, is widely used as a measure of the damping capacity of viscoelastic materials.

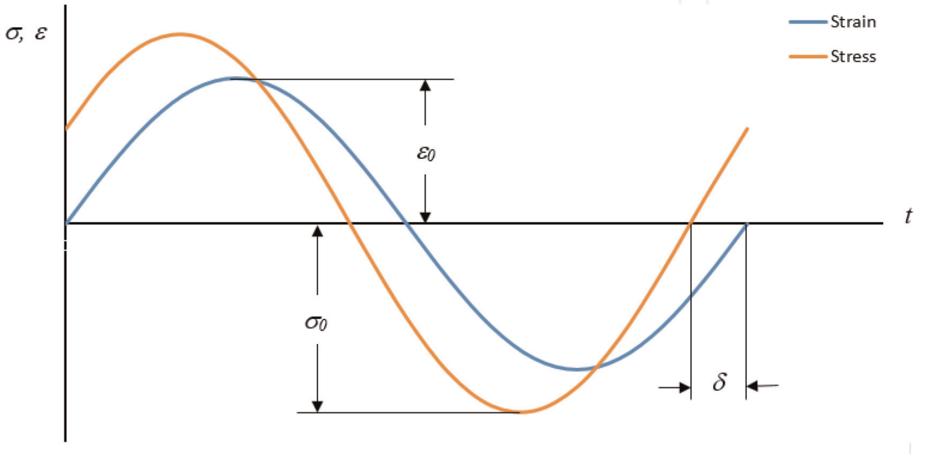

Figure 9.
Oscillating strain ε, stress σ, and phase lag δ.

3.2 Viscoelastic dissipation during the embossing stage of ultrasonic hot glass embossing process

During the embossing stage of the ultrasonic hot glass embossing process, besides embossing load (force or displacement input), high-frequency longitudinal waves are applied to the mold; thus, using this kind of load is similar to applying an oscillating load to the glass material. As propagating through the glass material, the energy of ultrasonic vibration is absorbed and converted into other kinds of energy. Since glass is an amorphous material, energy of ultrasonic vibration should be mostly converted into heat. The amount of heat will cause the temperature rise of both glass and molds, which should be the explanation for experimental observations, including the reduction of embossing force and the improvement of the micro-replication of the glass. In order to model the glass behavior during the

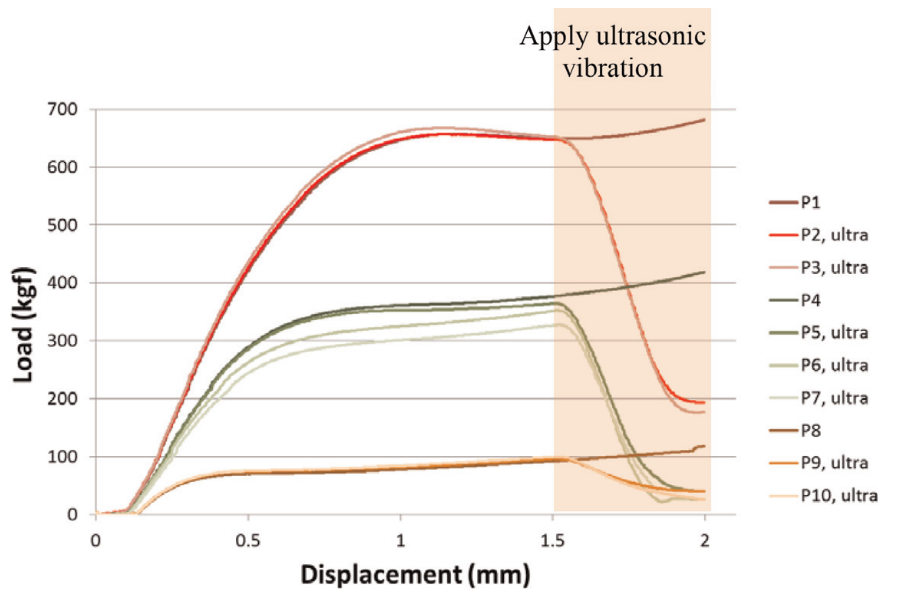

Figure 10.
Force-displacement results for the flat hot embossing experiments [7].

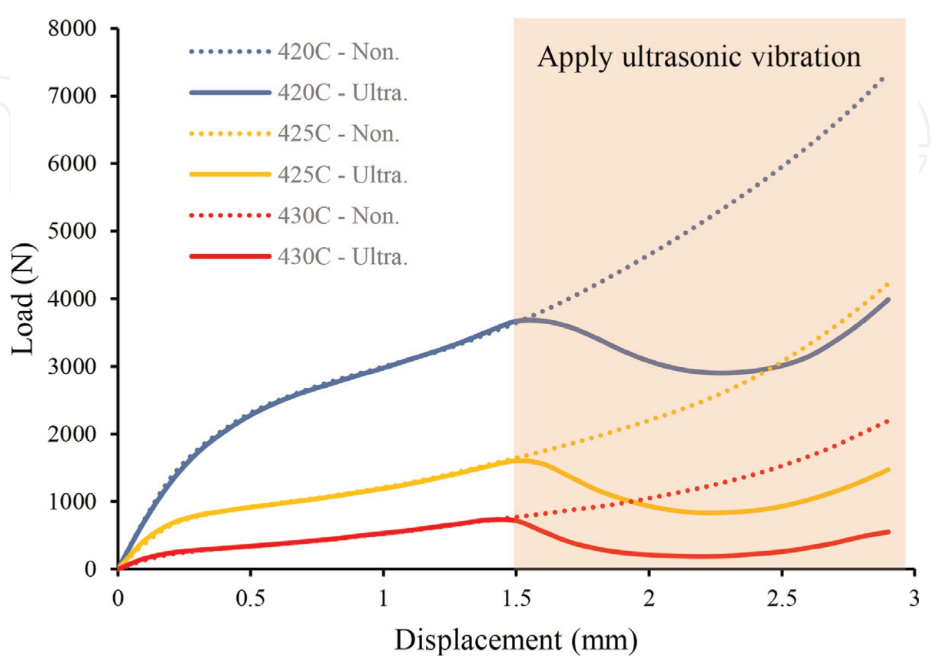

Figure 11.
Reduction of embossing load with different embossing temperatures [8].

embossing stage with the assistance of ultrasound, it must determine the amount of heat which is the conversion of energy of ultrasound absorbed by the glass.

In the previous section, we introduced the loss modulus G" which represents the energy dissipated by the material. The significance of G" is made apparent by calculating the energy absorbed by the specimen. If dissipated energy is converted to heat completely, then the heat generation rate which would be inputted into the finite element simulations is [6]

$$\dot{q} = f \cdot \pi \cdot G'' \cdot \varepsilon_0^2 \tag{9}$$

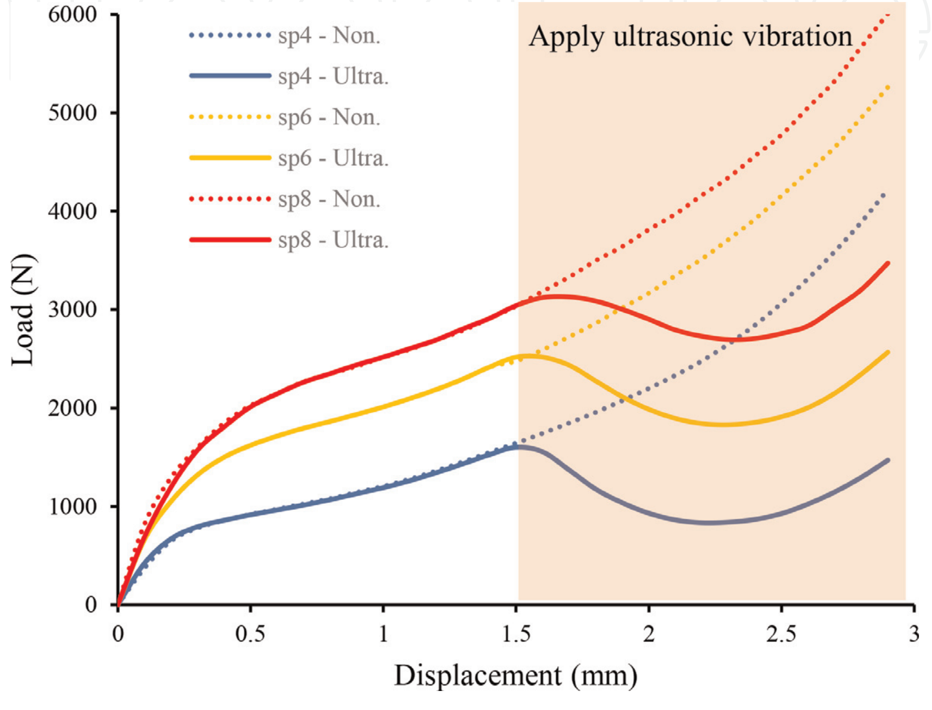

Figure 12.
Embossing load at initial temperature of 425°C and at different speeds [8].

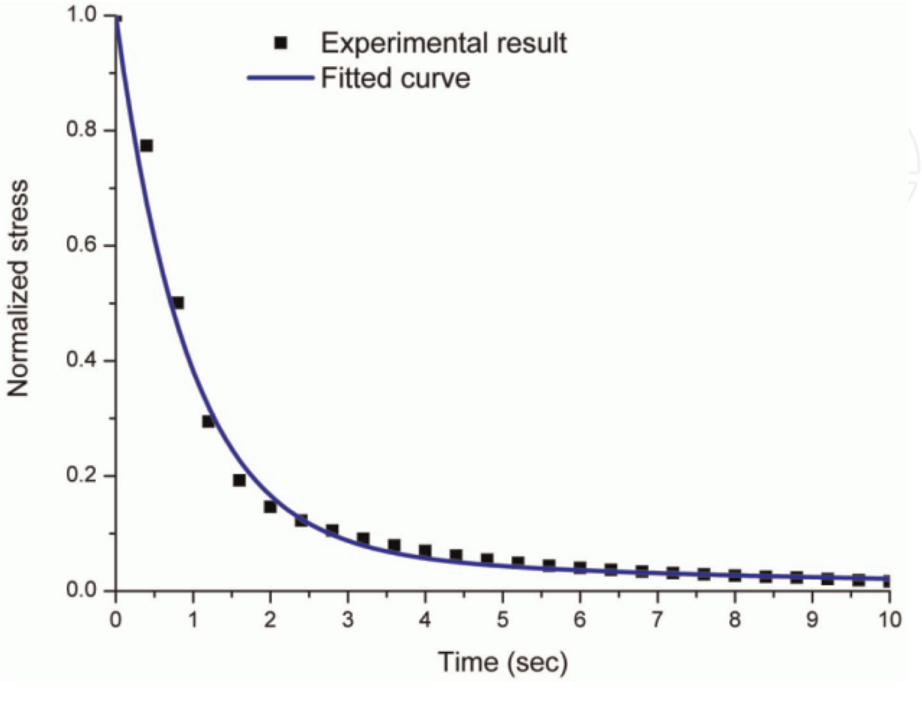

Figure 13.
Experimental result of stress relaxation at 556°C (Tg + 50°C) and the fitted curve [9].

3.3 Effect of ultrasonic vibration on reducing embossing load

During the embossing stage, the mold is controlled by force or by displacement to emboss the glass. In general, at a higher molding temperature, the force required to emboss the glass is lower. As ultrasonic vibration is applied, the forces dropped rapidly, while the displacement continues to increase (**Figure 10**). However, this force reduction could not remain to the end of the embossing stage. After reducing to a finite value, the force increases again (**Figure 11**). This interesting effect was not only verified experimentally with different initial molding temperatures but also with different embossing speeds (**Figure 12**). This phenomenon could be explained by the heating effect of ultrasonic vibration. The high energy of ultrasonic vibration was mainly converted to heat, causing the temperature of the glass specimen to rise.

The force reduction under the effect of ultrasonic vibration is not only a safe solution for the mold but also decreases the molding time of the whole process. The stage which wastes most of the time is the cooling stage. In this stage, the glass needs quite a lot of time for stress relaxation and structural relaxation. The larger

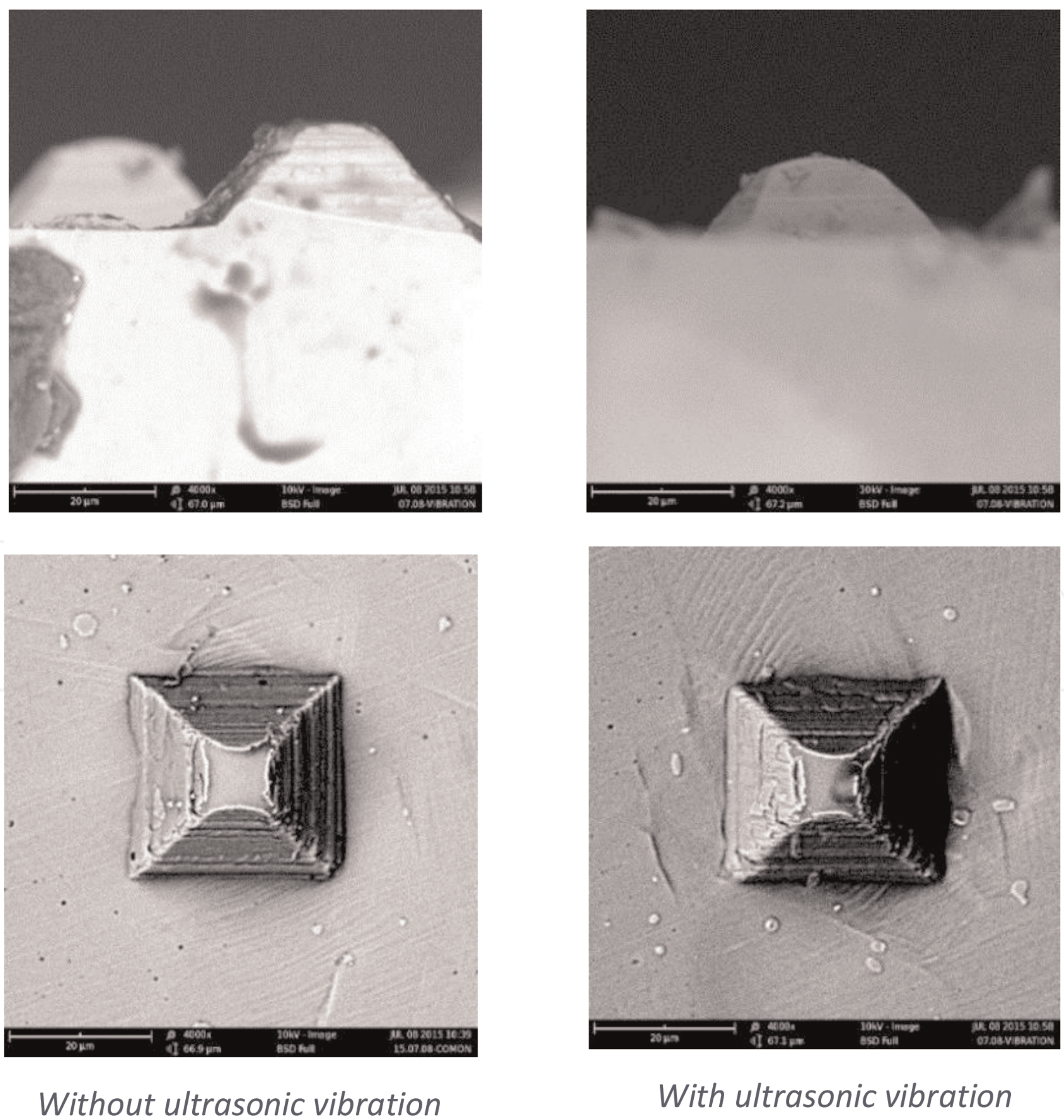

Figure 14.
Scanning electron microscope (SEM) of pyramid structures [10].

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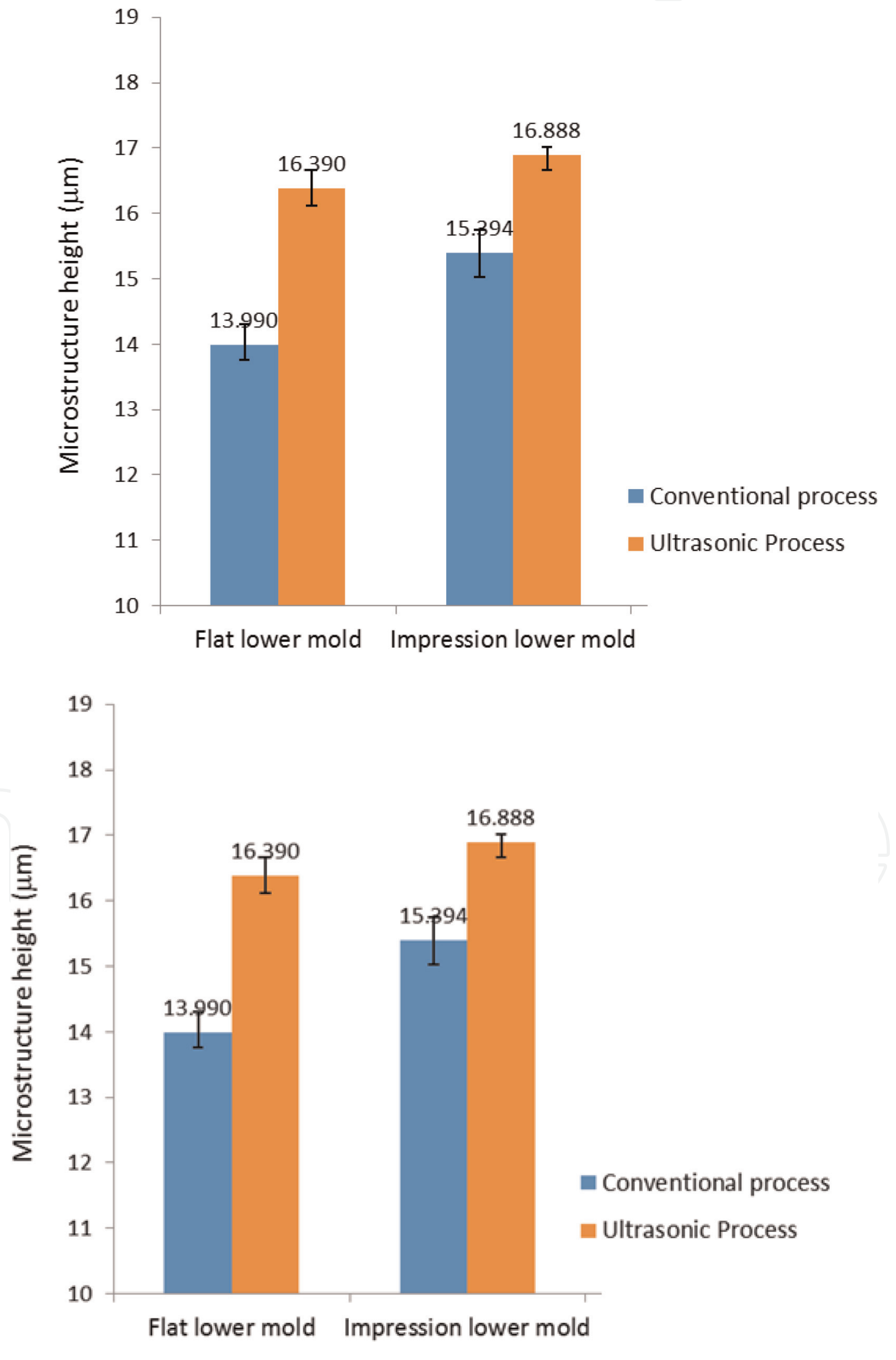
the value of embossing load at the end of the embossing stage, the longer the required cooling time (**Figure 13**). Therefore, with the significant reduction force as applying ultrasonic vibration, the productivity of hot glass embossing process could be improved.

3.4 Effect of ultrasonic vibration on improving glass formability

As mentioned above, hot glass embossing is a novel process to produce microstructures on glass substrate. Although the fabrication of microstructure should be performed by conventional process, the accuracy of the final shape of products is hard to achieve due to the surface defect or the adhesion between the glass and the mold as glass is filling into the micro cavities. These disadvantages especially appear



Microstructure height (µm)
16.390
16.888
15.394
13.990
Conventional process
Ultrasonic Process
Flat lower mold
Impression lower mold

Figure 15.
Comparison of the final height of microstructure between conventional process and ultrasonic process [11].

with three-dimensional microstructures such as micro-grooves, micro-pyramids, micro-prisms, and micro-lenses which are increasingly needed in optical, optoelectronic, and biomedical industries. These difficulties could be resolved with the effect of ultrasonic vibration. **Figure 14** shows the experimental data results which illustrate that applying ultrasonic vibration to hot embossing process can increase the filling ability of glass material significantly (up to 17%). Under the effect of ultrasonic vibration, the glass formability would even improve better than the case of using compression mold, which is usually a solution to help the glass fill more into the microwave (**Figure 15**). Similarly, ultrasonic vibration could also increase

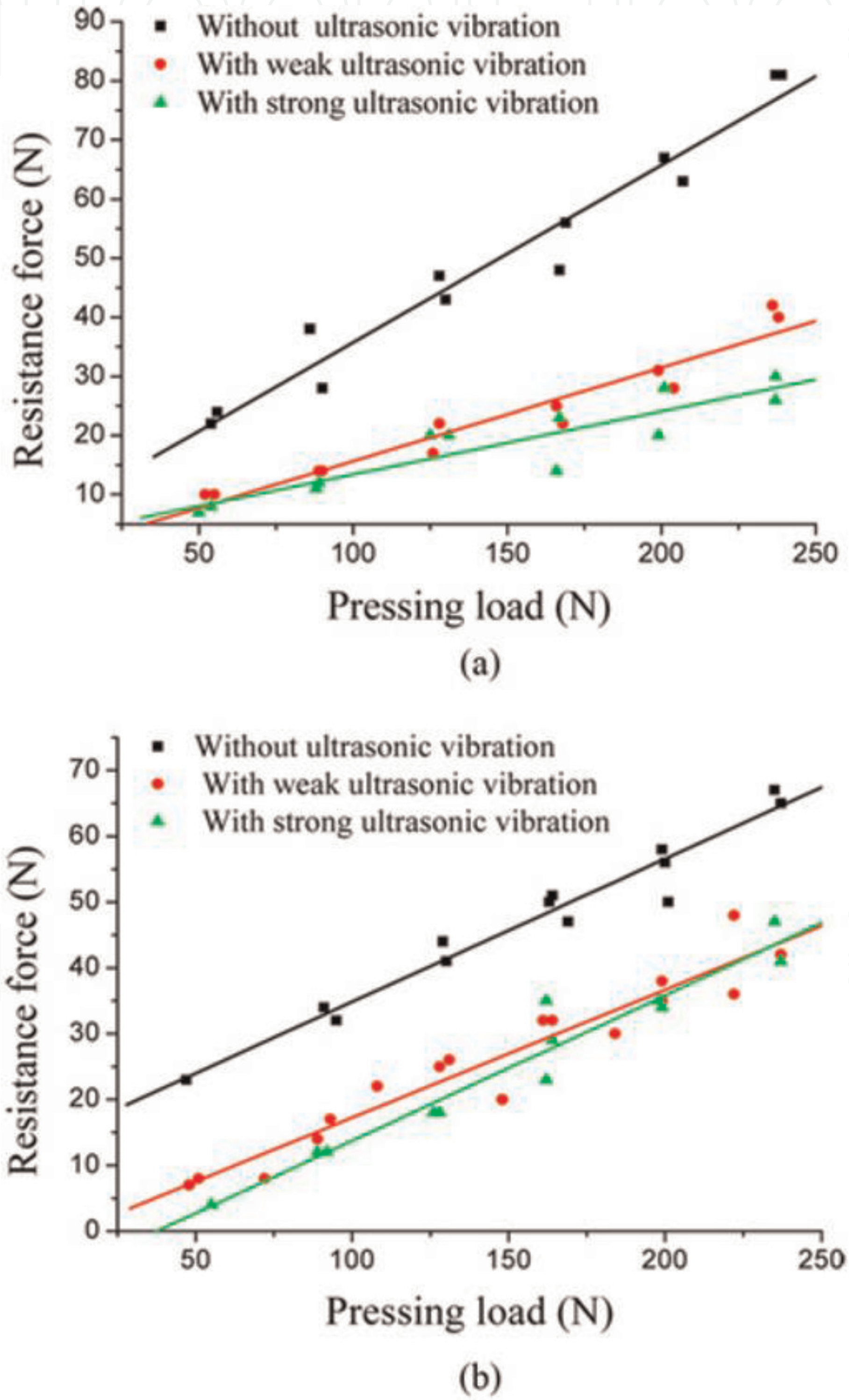


Figure 16.
Resistance force decrease by ultrasonic vibration with smooth end surface (a) and rough end surface (b) glass [14].

the embossing speed. Experiments show that the amount of glass filled into the micro cavities at high speed during the ultrasonic process was even more than that at lower speed during conventional process [12, 13]. Similar to the above discussion, these phenomena could be explained by the heat generation when glass absorbed the energy from ultrasonic vibration.

3.5 Effect of ultrasonic vibration on decreasing friction force

Glass pressing experiments with the assistance of ultrasonic vibration at room temperature and at elevated temperature have been performed to show effect of ultrasonic vibration on friction force [14]. Some hot embossing experiments were first performed at room temperature. Since ultrasonic vibration is applied to the glass as a sinusoidal displacement, the time that the glass contacts to the mold would be much shorter than that without ultrasonic vibration. Another finding was that the contacting time could be decreased more as increasing the amplitude of ultrasonic vibration. Those findings should be considered as the reasons for the friction reduction during the hot embossing process assisted by ultrasonic vibration [15]. **Figure 16** shows the results from the above experiments. Two kinds of glass with different surface qualities were used as specimens for both conventional and ultrasonic experiments. Although the resistance force grew linearly with the increase of pressing load, the resistance force in case of ultrasonic experiment was much lower than that in case of conventional case. Further, the reduction of resistance force was also more with better quality of glass surface (60% with smooth surface compared to 50% with rough surface in average). As the resistance force is smaller, the life of the mold should be prolonged [16].

4. Finite element analysis of ultrasonic vibration-assisted hot glass embossing process

Glass molding, also hot embossing, is a replicative process that allows the production of high-precision optical components from glass without grinding and polishing. Many researchers have been studying the glass molding process using finite element analysis. However, very few studies have focused on the hot glass embossing process assisted by ultrasonic vibration. Since the only difference between the conventional process and the ultrasonic vibration-assisted process is in the embossing stage, the glass model for the embossing stage should be created. This model could not only describe the glass behavior under embossing force but also express the effect of ultrasonic vibration. Standard linear solid (SLS) model, one kind of viscoelastic models, which combines a Maxwell model and a spring in series, was proposed for the glass deformation behavior during the embossing stage [8] (as shown in **Figure 17**). Substituting complex strain and complex stress from Eq. (5) into constitutive equation [8]:

$$\boldsymbol{\sigma} = \left[\frac{E_0\eta_1}{E_1} - \frac{v}{L}\frac{(E_0+E_1)}{\left(\frac{E_1}{\eta_1}-1\right)}\right] exp\left(-\frac{E_1}{\eta_1}\varepsilon\right) + \frac{v}{L}\frac{(E_0+E_1)}{\left(\frac{E_1}{\eta_1}-1\right)} exp(-\varepsilon) + E_0\varepsilon - \frac{E_0\eta_1}{E_1} \tag{10}$$

where E_0, E_1, and η_1 are constants, determined by fitting experimental data; v is the embossing speed; and L is the initial height of glass sample. Storage and loss moduli can be calculated as

$$G' = E_1\left[\frac{(\omega\eta_1{}^2)}{E_1^2 + (\omega\eta_1)^2}\right]; G'' = E_1^2\left[\frac{\omega\eta_1}{E_1^2 + (\omega\eta_1)^2}\right] \tag{11}$$

where ω is the angular frequency of ultrasonic vibration. Substituting G'' in Eq. (11) into Eq. (9), the amount of heat created by ultrasonic vibration could be determined.

Another viscoelastic model, which has been proposed for the glass deformation behavior during the hot embossing stage, is the Generalized Maxwell model, as shown in **Figure 18** [14]. Basically, Generalized Maxwell model is similar to SLS model, except having more the elements of Maxwell model.

The time-dependent response is characterized by the deviatoric terms as

$$\sigma = \int_0^t 2G(t-\tau)\frac{de}{d\tau}d\tau \tag{12}$$

The above integral is evaluated for current time t on the basis of past time τ. G(t − τ) is not a constant value, but it is represented by a Prony series, as described by

$$G(t-\tau) = G_0\left[\sigma_\infty + \sum_{i=1}^{n_G}\alpha_i\, exp\left(-\frac{t}{\tau_i}\right)\right] \tag{13}$$

where τ_i is the relaxation time, α_i the weight factor, n_G the number of Generalized Maxwell model units, and G_0 the initial modulus. The dynamic viscosity η^* can be calculated correspondingly, as demonstrated by

$$\eta^* = \sum_{i=1}^{n_G} G_i\frac{\eta_i}{1+\omega_i^2\tau_i^2} \tag{14}$$

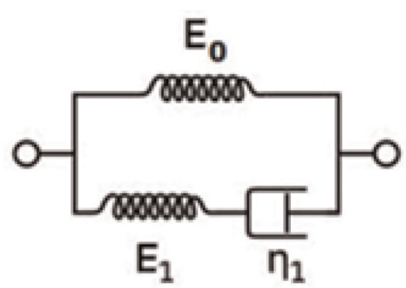


Figure 17.
Standard linear solid model.

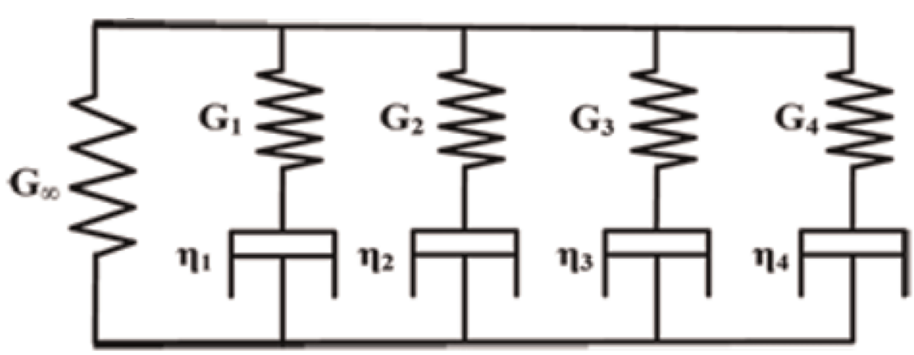


Figure 18.
Generalized Maxwell model.

As an alternating stress is applied to the material specimen, it is similar to an elastic solid which its elastic properties are exhibited, and the dynamic viscosity decreases significantly. The above reason shows that ultrasonic vibration could be assumed to improve the forming process [15].

After inputting the above models to simulation, simulated results could be used to verify the value of proposed models. As shown in **Figures 19** and **20**, the agreement between simulated results and experimental data proved that finite element analysis would have an important role in analyzing and predicting the effect of

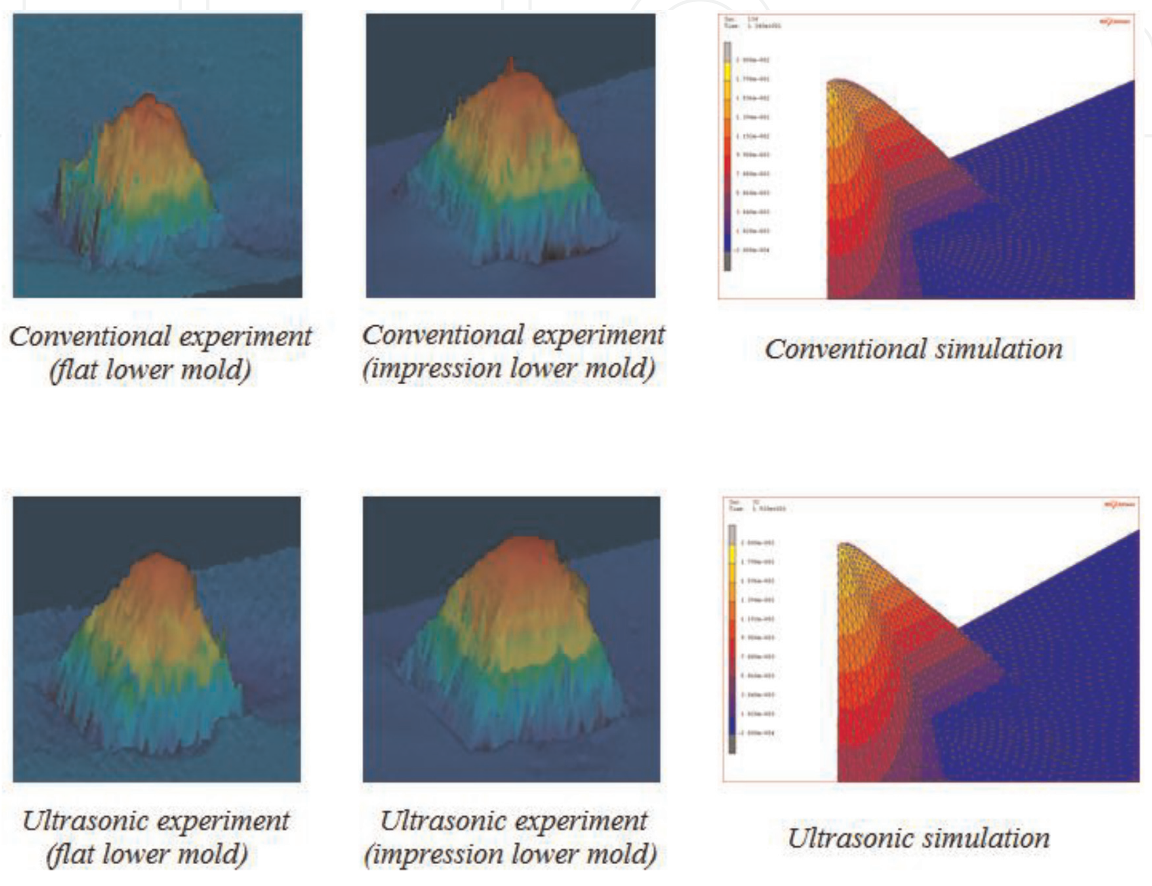


Figure 19.
3D profile of pyramid microstructures after hot embossing process [10].

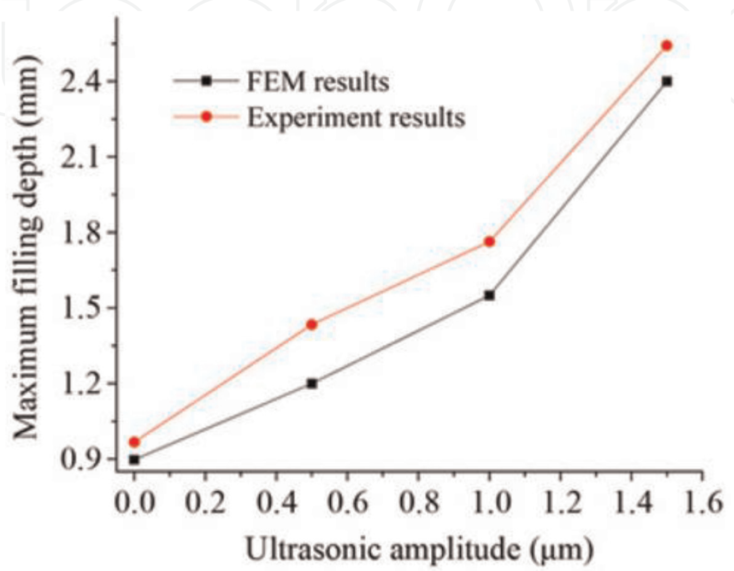


Figure 20.
Plot of glass maximum filling depth against amplitude [14].

process factors, such as temperature, speed, amplitude, frequency, etc. in improving the quality of the final glass products.

5. Conclusion

Ultrasonic vibration technology has been utilized in hot glass embossing process. Under the effect of ultrasonic vibration, glass formability could be improved significantly. Moreover, productivity of the whole process also increases, and life time of molds could be expanded. Finite element analysis has become an effective tool for analyzing and predicting so that the quality of the final glass products would be achieved.

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Conflict of interest

The author declares that there are no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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