ULTRASONIC MECHANISM OF MICRO PATTERN REPLICATION ON GLASSY POLYMER FILMS

Junsheng Xu, Jin Li, Enlei Chen

East China University of Science and Technology, Shanghai, China

Changjun Liu

East China University of Science and Technology, Shanghai, China
email: jsxu1507@163.com

Ultrasonic embossing is a potential forming method of polymer microstructure. As the heating on polymer is generated by high frequency vibrations, ultrasonic embossing has some advantages such as high replication quality, low cost and easy fabrication. Due to uncertain mechanism, practical accuracy of ultrasonic embossing is far from its theoretical limit. In this paper, the pressure profile during the embossing process was measured to study the ultrasonic mechanism. According to different working principles, the embossing process was divided into heating and filling by high frequency vibrations. The relationship between process condition (vibration amplitude, embossing pressure, embossing time and holding pressure) and replication quality has been systematically investigated. The replicated microstructure was observed by LSCM and result was analyzed by ANOM and ANOVA. The most significant factor and the optimal process parameters were obtained and the experiment showed a good replication quality.
Keywords: ultrasonic embossing, pressure profile, forming uniformity

1. Introduction

Micro electro mechanical system has been widely applied in life science and automotive electronics system to monitor environment in real time. As significant substrate materials of MEMS, thermoplastic polymers have many advantages such as low cost, easy fabrication and wide choices for different environments.

Many methods have been developed in the past decades to replicate microstructure on polymeric substrates including hot embossing, photofabrication, ultrasonic embossing, microinjection molding[1,2], silver halide sensitized gelatin method, casting[3,4] and laser welding. Li et al. (2005)[5] proposed a low-temperature hot embossing method for PMMA microfluidic chips. Zhang et al (2009)[6] studied Thermal assisted ultrasonic bonding method for PMMA microfluidic devices. Ussing et al. (2007)[7] studied micro laser welding of polymer microstructures. Yussuf et al. (2005)[8] employed microwave welding in polymeric microfluidic devices. However, most methods cannot meet typical requirements of high replication accuracy, low cost and short fabrication cycle for mass production simultaneously.

Among them, ultrasonic embossing is considered to be a promising forming method with higher replication accuracy for thermoplastic polymer. During ultrasonic embossing, the heat generated at the contact surface of polymer and mold is caused by hysteresis heating which is a result of the mechanical vibrations generated by the ultrasonic horn. When contact surface's temperature is over glass transition temperature, local polymer at specific regions becomes viscous and conforms exactly to the mold by filling the cavities of the surface relief. Owing to this local heating mechanism, the replicated microstructure has higher replication accuracy with small shrinkage. Ultrasonic embossing process consists of preloading, ultrasonic loading, pressure-holding and demolding. Lin et. al.[9] found that ultrasonic embossing could significantly reduce the process cycle time and energy consumptions.

Ultrasonic embossing, as a potential method for polymeric substrates mass production in MEMS, is attracted more attention in recent studies. To soften polymer and control temperature, thermal assisted ultrasonic embossing has been investigated by many researches. Harutaka Mekaru et al.[10] found that the effect of ultrasonic vibration was well pronounced at low contact force. Parameter optimizing for great imprint quality is also a hot issue. Luo et al.[11-12] compared the imprint quality of ultrasonic embossing in energy control mode and time control mode and found that under the similar embossing parameters, energy control mode has lower peak temperature and wider processing window. However, most of ultrasonic embossing study focused on combining with hot embossing. Due to heating method, hot embossing has lower replication accuracy than pure ultrasonic embossing. The effect of embossing conditions on the replication accuracy of ultrasonic embossing has not yet been fully investigated systematically.

In this work, a novel ultrasonic embossing system with high imprint quality is proposed. Orthogonal experiment with four parameters and three levels was used to parameter study of ultrasonic embossing. The replicated microstructure was observed by LSCM and forming uniformity has been observed for the first time. Ultrasonic mechanism during embossing was explained by pressure profile, which can be divided into two parts: melting and filling. Result was also analyzed by using ANOM and ANOVA. The optimal parameters which can control ultrasonic energy precisely are determined.

2. Analytical heating model of ultrasonic embossing

As shown in Fig.1, in ultrasonic embossing process, ultrasonic energy is applied to the polymer substrates and can be seen as mechanical vibration. The polymer unit under the mold was crushed and deformed. There are two types of deformation: horizontal deformation of the interface polymer unit and vertical deformation of under-mold polymer. They correspond to two heating mechanism: friction heating mechanism and viscoelastic heating mechanism.

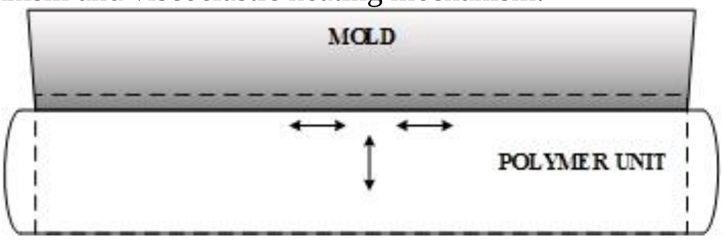


Figure 1: The ultrasound mechanism during ultrasonic embossing.

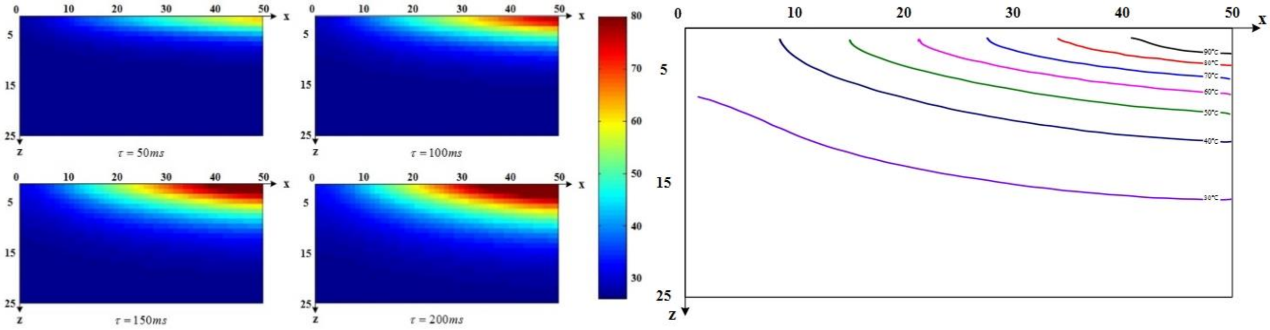
2.1 Friction heating mechanism

Friction heating is considered as the beginning mechanism of ultrasonic embossing. At this time polymer is in a glassy state and will be elastically deformed when squeezed. Due to the volume conservation law, horizontal deformation occurred on the upper surface polymer contacted with the mold. There is a relative displacement between the upper surface polymer and the mold, which causes a sliding friction. Ultrasonic energy is converted into heat by friction and friction heating power on a polymer unit is given by:

$$P_f(\gamma) = F\mu \cdot v(\gamma) \tag{1}$$

where is the distance between the polymer unit and mold center position, $P_f(\gamma)$ and $v(\gamma)$ correspond respectively to friction heating production and speed of the polymer unit.

Fig.2(a) shows the two-dimensional axisymmetric simulation result of the $50\mu m \times 25\mu m$ polymer temperature field during friction heating process. The maximum friction heating power is on the edge of contact interface between the mold and the polymer The polymer on the edge is melted first. The shape of isotherm in friction heating process is similar to oval as Fig.2(b) shown.



(a) temperature field (b)isotherm

Figure 2: The simulation result of friction heating process.

2.2 Viscoelastic heating mechanism

When polymer temperature rises near the glass transition temperature, dynamic loss modulus of polymer will rise sharply and the strain of the polymer can't keep up with the stress change, which leads to viscoelastic heating and makes ultrasonic energy turn into heat. In ultrasonic embossing process, the viscoelastic heating is caused by the vertical strain. The viscoelastic power of polymer unit is given by:

$$P_v = \pi \varepsilon^2 E f \quad (2)$$

where is the strain of polymer, is the ultrasonic frequency and is the dynamic loss modulus of polymer, which is a function of temperature and frequency.

Fig.3 shows the temperature field of polymer during viscoelastic heating process simulated by MATLAB. Due to the friction heating, the polymers on the edge of contact interface reach glass transition temperature first and trigger viscoelastic heating. Thus viscoelastic heating is dominant, whose power is much larger than friction heating power. Through the heat conduction, viscoelastic heat makes more polymers trigger viscoelastic heating and the polymer in the middle is melted finally. In addition, the viscoelastic power is a function of polymer thickness so that the difference of temperature between the middle polymer and outside polymer will gradually shrink.

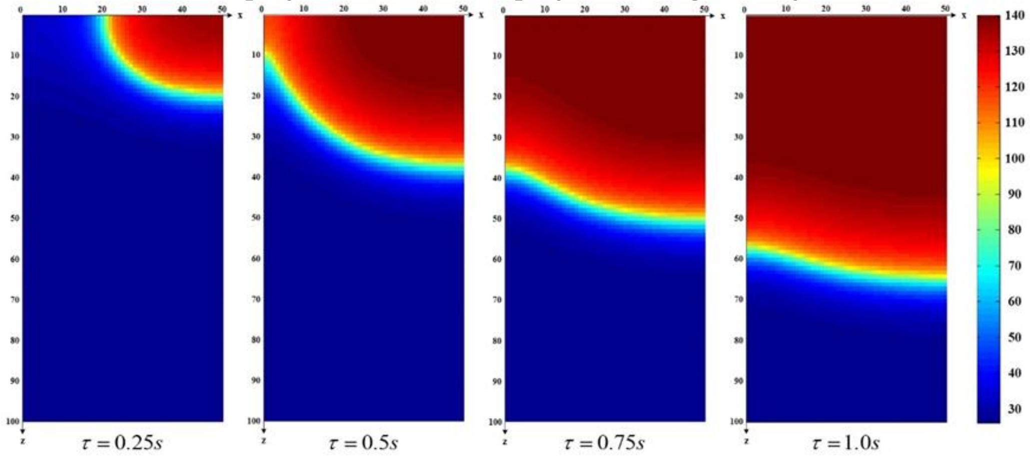


Figure 3: The simulation result of viscoelastic heating process.

3. Experimental section

3.1 Substrate material

In this study, PVC was used as substrates. It is glassy polymer at room temperature, with glass transition temperature of 79℃. Fig.4 shows the dynamic storage modulus(DSM) and dynamic loss modulus(DLM) of PVC varies with temperature carried out with dynamic mechanical analyser(DMA-Q800). Each substrate with a thickness of 0.3mm was cut to 40mm×30mm in size.

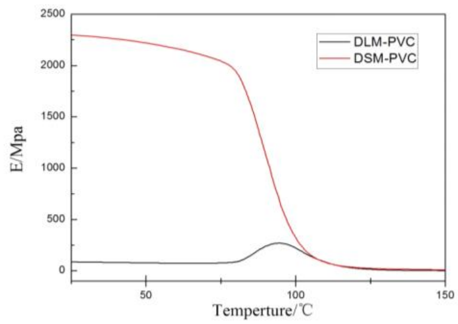
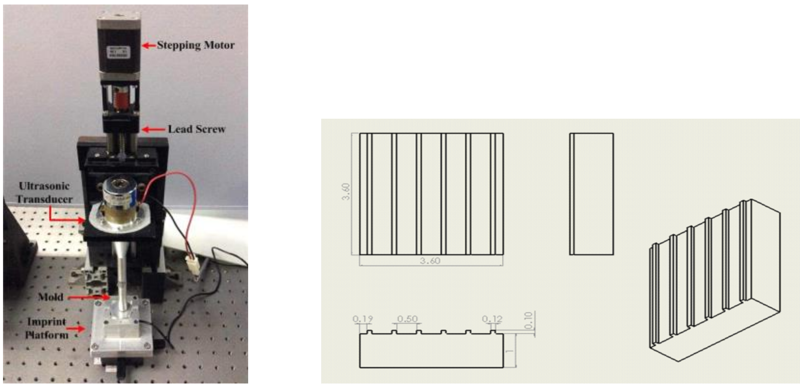


Figure 4: DSM and DLM-Temperature for PVC.

3.2 Experimental equipment

Fig.5(a) shows the picture of ultrasonic embossing apparatus, composed of stepping motor, lead screw, ultrasonic transducer with mold, imprint platform with pressure sensor and control system (not shown in Fig. 2). The stepping motor is placed on the top of the ultrasonic embossing apparatus to provides constant compression force by controlling the vertical position of ultrasonic transducer. The pressure, acting on imprint platform, is recorded synchronously by pressure sensor during ultrasonic embossing.



(a) (b)

Figure 5: (a)the apparatus for ultrasonic embossing and (b)the schematics of microstructure on the mold.

As shown in Fig.5(b), there is the schematics of microstructure on the mold fabricated by matching. It can produce grooves in the polymer substrates. The groove is 100 in depth,120 in width and the distance between neighboring grooves is 500. Limited by fabricating method, the size of microstructure on the mold cannot be reduced further and its rough face has a passive influence on replicating.

3.3 Experiment parameter design

Embossing pressure, embossing time, amplitude and holding pressure are significant parameters in ultrasonic embossing process. Among them, amplitude during process is hard to obtain directly. In this study, amplitude was obtained indirectly by measuring voltage on the ultrasonic transducer. As is shown in Table.1, there are four parameters with three levels in orthogonal experiment.

Before ultrasonic embossing, imprint platform should be adjusted horizontal and parallel to the mold face with microstructures so that the microstructures will be replicated integrally.

Table 1: The parameters of orthogonal experiment.

Parameters	Level 1	Level 2	Level 3
Embossing Pressure(kgf)	4	8	12
Embossing Time(s)	0.3	0.6	0.9
Voltage(V)	180	200	220
Holding Pressure(kgf)	8	10	12

In order to evaluate the replication accuracy accurately, the effective filling ratio and forming uniformity are selected. Filling ratio can be calculated as volume of formed pattern divided by the cubage of the corresponding [9]. In this study, filling ratio was calculated by the depth of the cavity(D) over the height of microstructure(H). As is shown in Fig.6, there is the difference between each side's depth and H shows greater depth between them. Forming uniformity was calculated by the difference between D and d over the height of microstructure(H).

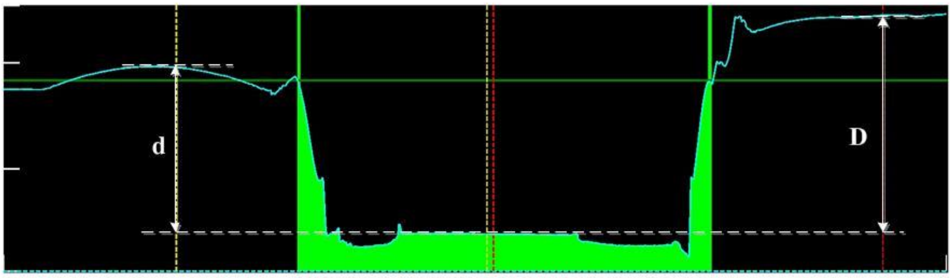
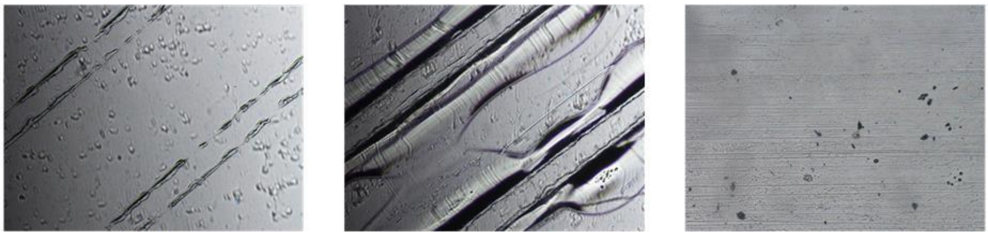


Figure 6: The surface shape appearance profile of replicated groove.

4. Results and discussion

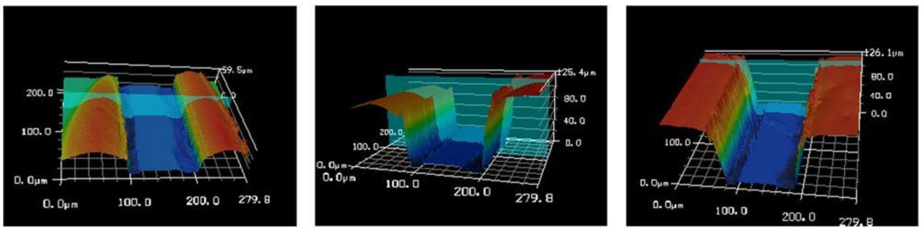
Repeatable experiments were carried out by the new ultrasonic embossing method. Fig.5 shows three different kinds of results on replicated microstructure: incomplete embossing and complete embossing, which correspond to different amount of ultrasonic energy. Fig. 7(a), there are scratches on the replica due to the rough surface of mold. If ultrasonic energy applied onto polymer substrates is too little, the edge of microstructures will be replicated first due to most of heat produced on the edge of microstructures and the rest cannot be replicated. In As is shown in Fig.7(b), there are whole grooves with lateral squeezing polymer on the replica. The replicated microstructures of over embossing are the same as the complete embossing ones, but there are some dark spots on the polymer as Fig.7(c) shown, which are the result of excessive temperature caused by excessive ultrasonic energy.



(a)incomplete embossing (b)complete embossing (c)over embossing

Figure 7: Three different kinds of results on replicated microstructure.

The microstructure on the PVC substrate were observed by laser scanning confocal microscopy(LSCM) and the groove profile was measured to calculate the effect filling ratio and filling uniformity of ultrasonic embossing as the response of various parameters. The three-dimensional of replicated microstructure on different ultrasonic energy level is shown in Fig. 8.



(a)lower energy level (b)medium energy level (c)higher energy level

Figure 8: The three-dimensional of replicated microstructure on different ultrasonic energy level.

4.1 Pressure profile

During ultrasonic embossing, pressure on the polymer substrate is collected by pressure sensor in the imprint platform and pressure profile is obtained. According the pressure profile in Fig.9, the mechanism of ultrasonic embossing is easier to understand. The whole ultrasonic embossing process can be divided into 6 stages: pre-loading, friction heating, viscoelastic heating, ultrasonic filling, solidification and unloading.

For the pressure profile, we refer 1 as the loading stage below embossing pressure,2 as the short friction heating stage, 3 as the viscoelastic heating stage with pressure dramatically decreasing, 4 as filling stage with constant pressure, 5 as holding stage with lower constant pressure and 6 as deloading stage. Thus there are three terraces of stage 2,4 and 5 in complete embossing cycle pressure. When friction heating is dominated, the temperature of polymer is below and polymer is glassy state with constant pressure in stage 2. When the variation of melt and solidified polymer is equal in stage 4, pressure balance is reached under ultrasonic vibration. In stage 5, all polymer is glassy state again and pressure is stable.

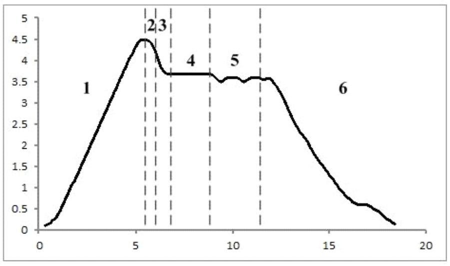


Figure 9: The pressure profile for complete embossing cycles.

At the beginning of process, friction heating is dominant due to ultrasonic vibration and the interface of mold and polymer is heated. After temperature is over glass transition temperature, the local polymer at interface becomes viscous. Then as a result of the mechanical vibrations, hysteresis heating is employed to replace friction heating and pressure is released with polymer filling the cavities of the microstructure in stage 4. In this stage, polymer melting rate is equal to solidification rate and ultrasonic energy helps melted polymer to squeeze and fill the cavities. After that, vibration is stopped and polymer is solidified gradually during holding time. The microstructure is finally replicated. We think ultrasonic energy plays two roles during embossing:

1. Heating and melting polymer in stage 2 and 3;
2. Assisting melted polymer to fill the microstructure in stage 4;

In incomplete embossing process, stage 3 is shorter than the complete one and pressure decrease in stage 3 is smaller and stage 4 is vanished. Owing to its limited ultrasonic energy, fewer polymer is melt by viscoelastic heating and replication can't be complete.

4.2 Filling uniformity

During orthogonal experiment, it was found that filling uniformity is not always great with parameters changing. It followed the rules shown in Fig.10.When ultrasonic energy is small, filling uniformity is great due to limited squeezing polymer. With ultrasonic energy increasing, filling uniformity raised at first, then decreased. More importantly, the directivity of the difference between each side was found. We believe that when ultrasonic applying, there has the constant phase angle of radial and vertical vibration, which makes this directivity.

(a)lower ultrasonic energy (b)medium ultrasonic energy (c)higher ultrasonic energy

Figure 10: The filling uniformity on different ultrasonic energy level.

4.3 Analysis of ranges(ANOR)

From these data of orthogonal experiment, the average effects of parameters in each level are calculated, which is shown in Table.2. The range, in the last column of Table.2, means the range for the whole range of parameter and can be calculated by the difference between maximum and minimum of the same row.

Table 2: Analysis of ranges (average effects of parameters).

Parameters	Effective filling ratio(%)				Filling uniformity(%)			
	Level 1	Level 2	Level 3	Range	Level 1	Level 2	Level 3	Range
Embossing Pressure(kgf)	38.02	101.72	102.43	64.41	12.37	25.31	2.21	23.10
Embossing Time(s)	79.15	81.34	81.68	2.53	14.94	9.39	15.56	6.18
Voltage(V)	79.16	81.65	81.61	2.49	19.88	10.82	9.20	10.68
Holding Pressure(kgf)	79.30	80.93	81.94	2.64	14.72	14.80	10.37	4.43

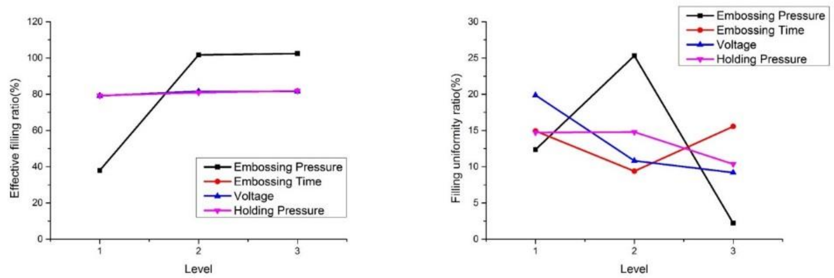


Figure 11: Variation of the response with different levels for each parameter.

Based on the data in Table.2, the effective filling ratio and filling uniformity with different levels are plotted in Fig.11 for each parameters. The bigger mean value of effective filling ratio and the smaller mean value of filling uniformity represent the higher replication accuracy. Therefore, within the given levels, the optimal conditions for higher replication accuracy can be chosen as A at level 3, B at level 2, C at level 2 and D at level 3.

4.4 Analysis of variances(ANOVA)

The main object of ANOVA is to determine whether there is any significant difference between the effects of different parameters. In another words, it is to investigate which parameter significantly affects the filling ratio and filling uniformity. The calculations of ANOVA are listed in Table.4.

Table 3: Analysis of variances.

Parameters	Effective filling ratio			Filling uniformity		
	DOF(f)	Sum of square of deviations(Q)	F-ratio(F)	DOF(f)	Sum of square of deviations(Q)	F-ratio(F)
Embossing Pressure(kfg)	2	24619.22	6412.16	2	2411.73	106.23
Embossing Time(s)	2	33.94	8.84	2	208.33	9.18
Voltage(V)	2	44.13	11.49	2	596.76	26.29
Holding Pressure(kgf)	2	31.80	8.28	2	115.55	5.09
Error	18	34.56		18	204.33	
F(0.05)=3.55						

Among them, embossing pressure has the most significant influence to the filling ratio and filling uniformity. The impacts of other three parameters on the filling ratio and filling uniformity are limited.

5. Conclusions

Experimental study on thermoplastic polymer ultrasonic embossing has been carried out. The microstructure on the mold was successfully replicated into polymer PVC. To investigate three major parameter affecting replication accuracy during ultrasonic embossing, A novel ultrasonic embossing system with high imprint quality is proposed. Based on LSCM, the pressure profile can explain the mechanism of ultrasonic embossing clearly. Forming uniformity due to the constant phase angle has been observed for the first time and used to judge the replication accuracy of ultrasonic embossing. Embossing pressure is found to be the most significant parameter to filling ratio and filling uniformity. The impacts of other three parameters on the filling ratio and filling uniformity are limited.

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