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# Direct surface forming: New polymer processing technology for large light guide of TFT-LCD module

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## Abstract

The backlight unit (BLU) is used as a light source of TFT liquid-crystalline-display (TFT-LCD) module. In this backlight unit, one of important components is the light guide, which is usually made of transparent polymers. Currently, the screen-printing method is mainly used for the light guide as a manufacturing process. However, it has limitation to the flexibility of three-dimensional optical design. In the present paper a new alternative manufacturing method for the light guide with low-cost is proposed. This manufacturing method is named as direct surface forming (DSF), which is very similar to the well-known hot embossing except for partial contact between mold and substrate. The results of this new manufacturing method are presented in terms of processing condition, dimensional accuracy, productivity, etc.

***Keywords*** : backlight unit (BLU), thin-film-transistor liquid-crystalline-display (TFT-LCD), direct surface forming (DSF), light guide

## 1. Introduction

Recently, the market share of the thin-film-transistor liquid-crystalline-display (TFT-LCD) is growing rapidly in display device market. In order to lead market share many LCD makers have been making their efforts to develop the TFT-LCD module, which consists of TFT-LCD panel, backlight unit and housing, not only with thinner and wider panel but also at lower cost. In considering these factors, the backlight unit is being focused on as one of target components. The backlight unit is used in TFT-LCD module as a light source. As shown in Fig. 1 the backlight unit consists of light source, light guide, housing and several optical films such as reflective film, prism film, and diffusive film. The function of backlight unit is to make the light from light source, which is usually a fluorescent lamp or light-emitting diode (LED), transferred into the screen of TFT-LCD module and to make the intensity of the transferred light as high and uniform as possible. In order to achieve this goal, the light guide is a very important component in backlight unit, which is usually made of polymethyl methacrylate (PMMA). The light guide should have the micro-optical pattern which is based on optics in order to change the direction in which the light travels. The order of this micro-optical pattern is about 10~100 μm. An example for 3-dimensional micro-optical pattern of light guide designed by reflective method is shown in Fig. 2. The angle, depth and pitch of pattern may not be uniform to achieve the maximum performance.

Currently, screen-printing method is usually adopted for the mass production of making the micro-optical pattern in light guide of most TFT-LCD modules. The printed ink makes the light scattered in order to obtain the uniform intensity of the light in the screen of the TFT-LCD module.

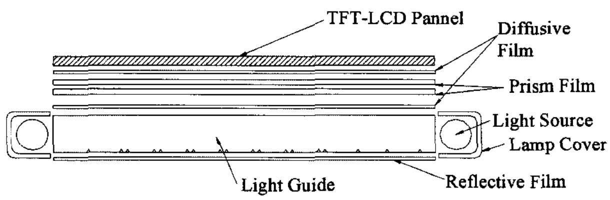


**Fig. 1.** Structure of backlight unit.

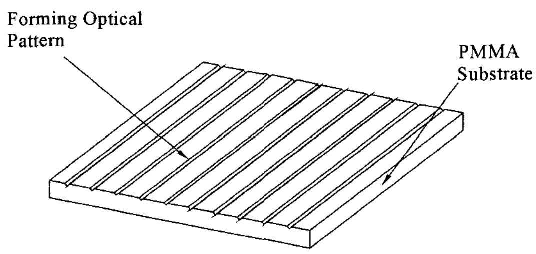


**Fig. 2.** An example of 3-D optical pattern designed by reflective method on light guide.

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Although this manufacturing method seems to be very simple, it has several weak points such as the limitation of optical pattern design, absorption of small amount of light by printed ink, productivity, manufacturing cost, and so on. The other manufacturing technologies for making micro-optical pattern include V-cutting, injection molding, hot embossing, etc., which have also their own advantages and disadvantages (Wimberger-Friedl, 1999). However, these technologies are not proper for large-sized TFT-LCD module (18" or larger).

In this paper a new alternative manufacturing method to the screen-printing method is proposed for large-sized TFT-LCD module, which is called the direct surface forming (DSF). The DSF is similar to the well-known hot embossing(Becker and Klotzbücher, 1999; Becker and Heim, 1999; Becker and Gärtner, 2000; Juang *et al.*, 2002; Kopp *et al.*, 1997) except for partial contact between mold and substrate. The DSF is to make micro-optical pattern directly on the flat rectangular substrate of PMMA by using mold with locally heated micro-optical pattern. The light guide can be deigned not by using scattering of light but by using the refraction and reflection of the light through this manufacturing technology. This manufacturing technology can allow flexibility for optical system design and accurate transcription of micro-optical pattern with low cost, which should be advantages of manufacturing technology.

## 2. DSF technology

This concept of partial contact between mold and substrate is different from that of hot embossing technology as shown in Fig. 3.

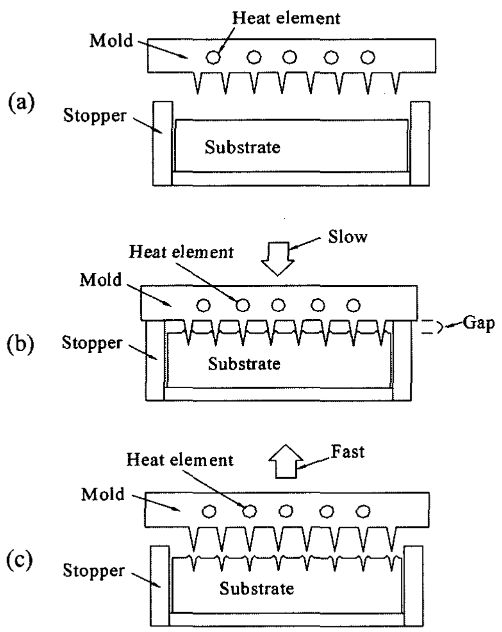


**Fig. 3.** Schematic diagram for DSF technology; (a) initial heating of a mold, (b) partial contact and (c) retraction of a mold.

DSF molding machine consists of press, heating element, cooling channel, mold and stopper. At the first step for DSF molding, the mold is heated by heating elements up to specified temperature. Then the press makes mold move down to the specified position on PMMA substrate. The contact between mold and substrate makes PMMA substrate heated locally up to temperature high enough to make PMMA flow locally for making micro-optical pattern. Only very low pressure is required for making transcription of the micro-optical pattern onto the substrate of PMMA compared with hot embossing, which results from melting locally only the surface of PMMA substrate and decreasing the viscosity of PMMA very fast while hot mold surface starts to touch PMMA substrate.

The advantages for this new manufacturing technology are as follows:

- Increasing the intensity of light on the screen of TFT-LCD module because DSF does not use ink material that can absorb light.
- Increasing the productivity because of low level of energy consumption during the manufacturing due to local heating.
- Decreasing the manufacturing cost because molding machine and mold for DSF can be made at relatively low price in comparing with those for other technologies due to very low pressure required for molding.

## 3. Experiment results

For the first feasibility study of DSF, a mold for the light guide of 70 mm × 70 mm × 3 mm has been made as shown in Fig. 4 (press-type mold). An initial DSF molding machine equipped with the mold is in Fig. 5. Commercial PMMA plate (Mitsubishi) is used as a substrate(Yu *et al.*,

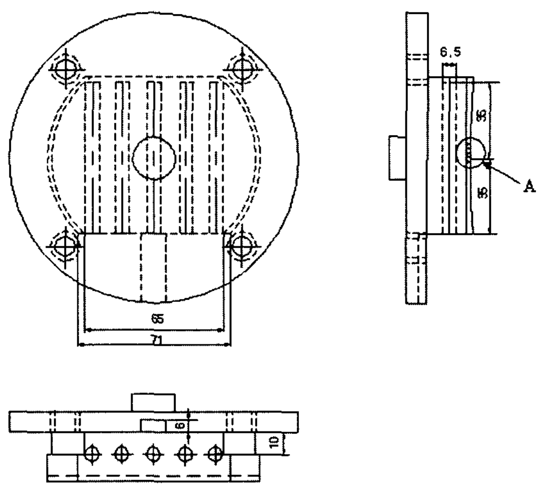


**Fig. 4.** Molding machine and press-type mold for DSF; press-type mold for DSF.

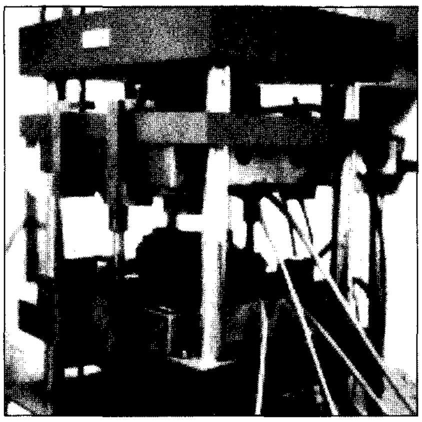

Fig. 5. Picture of DSF molding machine.

Table 1. Processing conditions for experiments with press mold

| Case | Pressure (MPa) | Upper Mold Temp. (°C) | Depth (mm) |
|---|---|---|---|
| 1 | 0.17 | 135 | 0.840 |
| 2 | 0.07 | 135 | 0.460 |
| 3 | 0.05 | 130 | 0.425 |
| 4 | 0.03 | 130 | 0.340 |
| 5 | 0.01 | 130 | 0.050 |
| 6 | 0.02 | 151 | 0.383 |
| 7 | 0.02 | 167 | 0.272 |
| 8 | 0.02 | 170 | 0.520 |
| 9 | 0.02 | 188 | 0.242 |

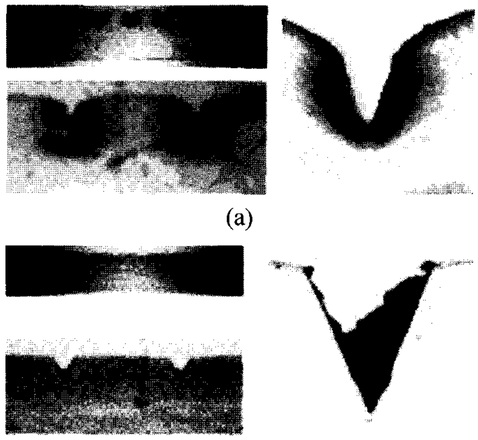


Fig. 6. The cross sectional view of manufactured micro-optical pattern by press-type mold; (a) Case 4 (bad groove) and (b) Case 8 (good grove).

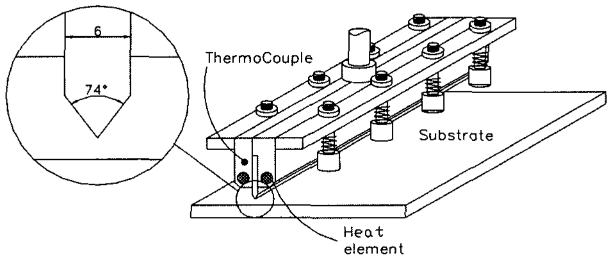


Fig. 7. A knife-type mold used in the feasibility study of DSF.

2000). The micro-optical pattern used in this experiment is V-groove with depth of 50~300 μm, angle of 30° and pitch of 0.5~ 2 mm.

Table 1 shows the list of processing conditions with various pressure and temperature in order to find feasible and optimal processing condition. Fig. 6 shows two experimental results for cross-sectional views of transcribed bad V-groove and good V-groove. As shown in Fig. 6(a), large deformation occurs on the surface of V-groove because of low processing temperature. On the other hand, the deformation can be negligible near the micro-optical pattern at the elevated temperature ($T \geq T_g + 70$°C), as shown in Fig. 6(b). In addition, pressure has been proven to be not a critical factor for DSF technology from these results of preliminary experiments. In this experiment, the applied pressure is only 0.2 atm. This means that the pressure due to gravity is high enough to transcribe V-groove perfectly on the substrate at the elevated temperature

From this experiment, the following results have been found:

- Mold temperature ($T \geq T_g + 70$°C) should be much higher than the recommended temperature of the mold for hot embossing. Note that the processing temperature of hot embossing is slightly higher than the glass transition temperature of PMMA substrate.
- There exists a warpage of light guide after ejection because of local and differential heating and cooling, which results from viscoelastic behavior of PMMA.

For the second feasibility study, several experiments have been performed with a knife-type mold, as shown in Fig. 7. The angle of knife-type mold is changed from 30° to 74° for applying to light guide with more realistic micro-optical pattern. In this study, our goal is to determine optimal processing temperature and pressing time.

The first effort is focused on finding an optimal processing temperature with given pressure of 0.2 atm, pressing time of 20 seconds and depth of 200 μm. In the second feasibility study, the obtained optimal temperature of a knife is 215°C. Fig. 8 shows experimental results for cross-sectional view of transcribed V-grooves at various temperature.

The second effort is focused on determination of the pressing time according to depth with given pressure of 0.2 atm and optimal temperature of 215°C. The pressing time depends on the depth of V-groove because the deeper groove needs more amount of heat. Table 2 shows the results of relationship between the depth of V-groove and the pressing time for desirable shape of V-groove.

Fig. 9 shows the cross-sectional view of transcribed V-

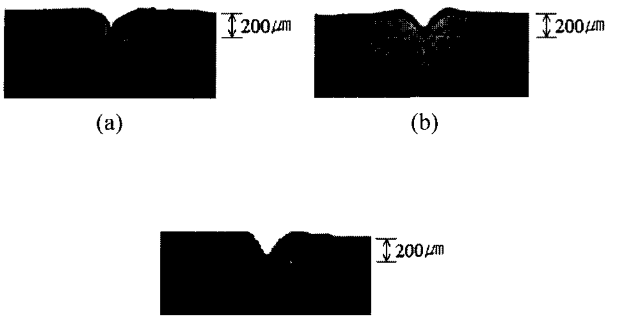


**Fig. 8.** 3-different micro-optical patterns formed by knife-type mold; (a) low temperature condition (180°C), (b) optimal temperature condition (215°C) and (c) high temperature condition (230°C).

**Table 2.** Optimal pressing time according to the depth of V-groove with knife-type mold (temperature at the knife tip: 215°C)

| Case | Depth (µm) | Pressing Time (s) |
|---|---|---|
| 1 | 130 | 10 |
| 2 | 160 | 15 |
| 3 | 200 | 25 |
| 4 | 240 | 35 |

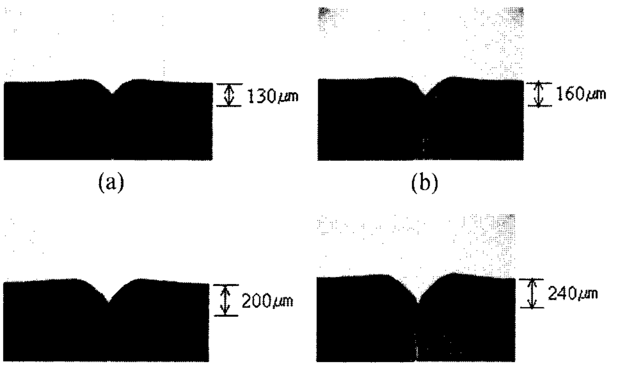


**Fig. 9.** Molded pattern for different nominal depths (D: depth and T: pressing time); (a) D = 130 µm, T = 10 s, (b) D = 160 µm, T = 15 s, (c) D = 200 µm, T = 25 s and (d) D = 240 µm, T = 35 s.

grooves for different nominal depth and pressing time to achieve desired shape.

For a final stage of feasibility study, the complete light guide of 15.1 inches has been made. In this study, the knife-type mold with variable depth, constant pitch and constant angle of 74° is used for DSF technology. After this process, significant warpage, shown in Fig. 10, occurs in the PMMA substrate because of local and differential heating and cooling. This local and differential heating and

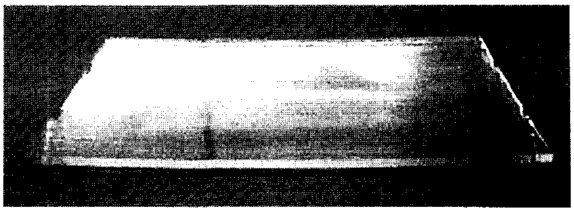

**Fig. 10.** A picture of warped PMMA substrate.

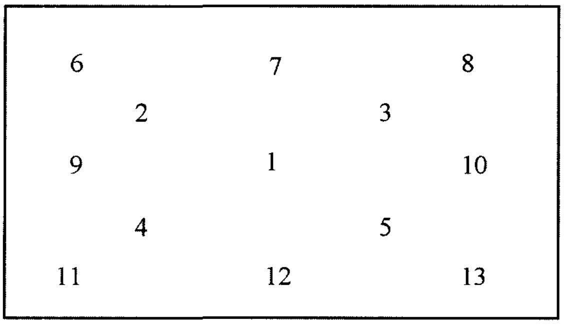


**Fig. 11.** Points for measuring brightness of backlight unit.

cooling induces thermally induced-stress, which results in deformation of PMMA substrate.

Therefore, this thermally induced stress should be considered and minimized. To get rid of warpage an annealing process must be adopted as a post-process. In this feasibility study, the annealing process is performed in the oven with temperature of 130°C for 20 minutes. After the annealing process shrinkage of about 5% in planar direction is found. In order to avoid the reduction of size of light guide the PMMA substrate of 5% larger size can be used. Furthermore, DSF molding machine may need vacuum device to grip the substrate firmly for reduction of warpage during pressing.

To evaluate the quality of final light guide made by DSF technology, local brightness is measured at several positions, shown in Fig. 11, to calculate average brightness and uniformity. Table 3 shows comparison for the brightness of final light guides made by DSF technology and screen-printing technology, respectively.

The uniformity used in Table 3 is defined as follows:
- Uniformity (5 Points) = Max./Min.
- Uniformity (13 Points) = (Max. – Min.)/Avg. × 100

The average brightness of light guide made by DSF is 100 nits higher than that by screen-printing method, while the uniformity of light guide by screen-printing method is much better than that by DSF. From the optical simulation result by ASAP, however, the brightness of light guide by DSF is 30% higher than that by screen-printing method with the almost same uniformity. If the more accurate mold is used in the DSF technology, the quality of light guide made by DSF will be much better than that made by screen-printing method.

**Table 3.** Measured brightness of light guides both by DSF and by screen-printing (1 [nit] = 1 [cd/m$^2$])

| Points | Brightness by DSF | Brightness by ScreenPrinting |
|---|---|---|
| 1 | 1101.52 | 1211.05 |
| 2 | 1402.86 | 1226.94 |
| 3 | 1444.86 | 1211.05 |
| 4 | 1567.44 | 1189.48 |
| 5 | 1483.45 | 1211.05 |
| 6 | 984.95 | 1329.09 |
| 7 | 1320.01 | 1172.46 |
| 8 | 1121.83 | 1335.90 |
| 9 | 1418.75 | 1117.18 |
| 10 | 1512.96 | 1161.11 |
| 11 | 1230.34 | 1272.34 |
| 12 | 1581.06 | 1156.57 |
| 13 | 914.70 | 1267.80 |
| Avg. (5 points) | 1400.02 | 1209.91 |
| Avg. (13 points) | 1314.21 | 1220.15 |
| Uniformity (5 points)[%] | 50.70 | 17.93 |
| Uniformity (13 points) | 1.42 | 1.03 |

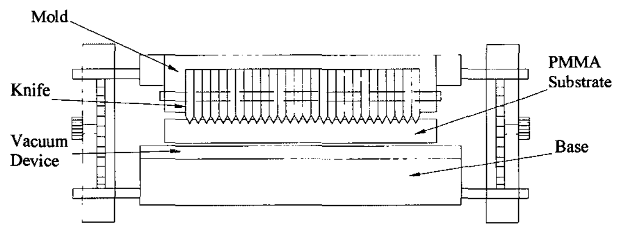


**Fig. 12.** Diagram for union mold of DSF.

Further work is undergoing to apply the DSF process for mass production. Fig. 12 shows the diagram of a union mold for a mass production. This mold is an assembly of series of knife-type molds. The angle, depth and pitch of each pattern may not be uniform.

## 4. Conclusions

The DSF has been proposed and demonstrated successfully as new manufacturing technology for a large-sized light guide in TFT-LCD module, which is a substrate of PMMA with micro-optical pattern. The advantages for this new manufacturing technology are as follows:

- Increasing the intensity of light on the screen of TFT-LCD module because DSF does not use ink material that can absorb light. In this study, increment of the intensity is up to 10~20%.
- Increasing the productivity because of low level of energy consumption during the manufacturing due to local heating. In this study, we can determine the optimal mold temperature of 215°C for PMMA material.
- Decreasing the manufacturing cost because molding machine and mold for DSF can be made with relatively low price in comparing with those for other technologies.

The disadvantage of this new manufacturing technology is the need of a secondary process, An annealing stage is needed to avoid thermally induced warpage due to differential heating and cooling after processing by DSF.

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