Process parameter optimization of screen printing device for vacuum glazing pillar arrays

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Abstract
Among the key factors that comprise vacuum glazing panels, pillars are an essential element deposited to maintain the internal vacuum gap against external forces. Deposited pillars may cause cone cracks in glass according to the contact area with glass so pillars have a shape to prevent such crack. Method of depositing pillars include the screen printing method, which is widely used in forming high precision micro-patterns in fields of flat display such as LCD, PDP and organic EL. In this paper, we presented a trapezoidal cross section pillar manufacturing model that can prevent cone crack in screen printing. This paper actually examined relations between screen printing process conditions and cross section shape using the Taguchi method and analysis of variance(ANOVA), and presented process conditions through which trapezoidal cross section shape can be manufactured. Also, We finally obtained formula about the relationships based on process parameters to prevent cone crack on contact area glass and pillar, and found the optimal value of the parameters.

Key words : Vacuum glazing, Pillar, Shape, Screen printing, Taguchi method

NOMENCLATURE

\[ \begin{align*}
  v_s &= \text{Squeegee velocity} \\
  \theta_s &= \text{Squeegee angle} \\
  P_s &= \text{Squeegee pressure} \\
  g_{so} &= \text{Snap-off height} \\
  d_p &= \text{Distance between} ~ w_p \text{ of } 80 \mu m \text{ and top of pillar} \\
  w_p &= \text{Contact width of pillar with glass} \\
  u_p &= \text{Uniformity of pillars} \\
  \text{wt} \% &= \text{Weight percent}
\end{align*} \]

1. Introduction

Vacuum glazing panels, which are comprised of two sheets of glass separated by a narrow vacuum space, are a product with minimized heat loss from conduction and convection and refer to high performance glass panels with insulating properties similar to those of building walls. Among the key factors that compose vacuum glazing panels, pillars are an essential element deposited to maintain internal vacuum against external forces such as stress from the pressure difference between the inside and outside. Although the insulating properties of vacuum glazing panels improve as separation between the deposited pillars increases and contact area decreases, cone cracks may occur in the glass in such cases (Collins and Fischer-Cripps, 1991). The shape and separation of pillars must be considered during their design.
and array since cone cracks may lead to self-destruction in vacuum glazing panels.

Collins conducted design and stress analysis based on separation in pillar arrays and according to pillar shape; through this analysis, it was found that the cylindrical shape is appropriate for pillars of vacuum glazing panels (Collins, et al., 1991). Methods of depositing such pillars of cylindrical shape include one method that uses a dispenser. However, using a dispenser leads to problems such as losses due to static electricity and friction forces when depositing pillars on glass in micro units. To compensate for such problems, paste type pillar specimens were printed on glass by making use of the screen printing method. Screen printing is undergoing technological development and changing into a method that allows the printing of high precision micro-patterns outside the traditional printing ranges such as textiles or paper. Based on this technological development, screen printing is often being utilized in the electronic and display fields. Especially, it is widely used in producing high precision micro-patterns in fields of flat display such as LCD, PDP, and organic EL; many studies are being conducted regarding screen printing as a cost reducing method through improved productivity (Yu-Tang Yen, et al., 2011, D.-H. Lee, et al., 2008). However, the printing of desired shapes is rather difficult because screen printing has many varieties of process parameters such as the physical and rheological properties of paste, the hardness and thickness of the squeegee, the applied pressure and velocity of the squeegee, the screen material, and the distance between the screen and the object (Tsung-Nan Tsai, 2011, Babu, et al., 2014, Muthuramalingam and Mohan, 2014).

In the existing PDP processes, by using the screen printing method in order to form the barrier rib and phosphor, printing was made of lines (Mandal, et al., 2011, Lin, et al., 2008) Many studies have been performed that have considered the uniformity and width of the barrier ribs, with result that impact screen printing. When a printing device in an existing print processing condition is applied to pillar arrays for vacuum glazing, the pillars are printed in hemispheric shapes. Point contact occurs between the inside of the glass surface and the pillar and due to the hemispheric shape of the pillar and this present state of things causes stress concentration and self-destruction in the glass.

Although, a cylindrical shape is possible for metal pillar, which is a previous method, a hemisphere shape that may cause cone crack as shown in Figure 1 can occur, if printing process is not properly controlled upon applying the screen printing method. This paper presented a trapezoidal cross section pillar manufacturing model that can prevent cone crack in screen printing. This paper actually examined relations between screen printing process conditions and cross section shape using the Taguchi method and analysis of variance(ANOVA), and presented process conditions through which trapezoidal cross section shape can be manufactured. Also, this paper presented a mathematical model to prevent cone crack with process parameters.

![Fig. 1 Shape of printed pillar by screen printing with not optimized process conditions](image)

2. Materials and methods

The LSP-5040 model of Line System Co. was used as the screen printing device for the array of pillars; the type of material for the screen was stainless steel, which is often used for high precision printing processes. And the pillars printed on the glass were measured by using a 3D laser microscope, model Vk-9710 of Keyence Co as shown in Figure 3.

Based on the results of the initial experiment, as shown in Figure 2, the process parameters of screen printing, which
are squeegee velocity (\(v_s\)), squeegee angle (\(\theta_s\)), squeegee pressure (\(P_s\)), and snap-off height (\(g_{mg}\)), were selected as the process parameters of the screen printing device for printing pillars. And the pattern on the screen was composed of cylindrical holes with diameter of 400 \(\mu m\) and height of 150 \(\mu m\); this was a square pattern with separation of 23 \(mm(s)\) (Kim and Jeon, 2011).

Glass with dimensions 100 \(mm\) \(\times 100\ \text{mm} \times 3t\) was used for printing; in order for the pillar paste to be printed, a mixture based on glass frit (wt. 80~90%), feldspar (wt. 5~10%), and boric acid (wt. 5~10%) was used (Kim and Jeon, 2012). The viscosity of the paste was 4.2Pa•s. As shown in Table 1, the value applied for each factor was selected at a level of 3.

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![Fig. 2 Process parameters of screen printing device and configuration of the array pattern](image)

Table 1 Screen printing parameters and levels used in the experiment

| Group | Parameters | Level I | Level II | Level III | Descriptions                                      |
|-------|------------|--------|----------|-----------|---------------------------------------------------|
| A     | \(P_s\) (kgf) | 10     | 20       | 30        | Amount of air pressure applied on the squeegee    |
| B     | \(g_{mg}\) (mm) | 2      | 3        | 4         | Distance between the glass and the metal mask     |
| C     | \(v_s\) (\(\text{mm/s}\)) | 50     | 100      | 150       | Squeegee traveling speed                          |
| D     | \(\theta_s\) (°) | 49     | 52       | 55        | Amount of angle applied on the squeegee           |

![Fig. 3 Apparatus used to print and measure pillars](image)
Fig. 4 Show the real shape of pillar by screen printing. \( w_p \) is width of pillar which is cross section of contact area between glass and pillar and \( d_p \) is distance from top of pillar when \( w_p \) is measured 80 \( \mu m \), \( u_p \) is uniformity of pillar height.

If less contact area between the Pillar and glass, glass are damaged or occur cracks by concentrated stress. In order to prevent these case, Collins investigated the radius of the pillar that crack on the basis of the research for both spherical indenters (Langitan and Lawn1969) and flat indenters (Mouginot and maugis 1985). The distance (\( d_p \)) is related to the
width of the pillar cross section \( (w_p) \); the width \( (w_p) \) can be defined according to the results of the following equation (1) (Collins and Fischer-Cripps, 1991).

\[
\lambda = 155\alpha^{3/4}
\]

where, \( \lambda \) = Separation of the pillar arrays (unit: mm)
\( \alpha \) = Radius of the pillars (unit: mm)

According to equation (1), the pillar’s radius is limited according to the separation of cylindrical shape’s pillar. Crack can occur, if the radius of pillar is smaller than the allowable radius.

Uniformity of Pillar also must be in uniform order to maintain the vacuum gap from internal and external pressure differential, and other external forces. If the error in the uniformity is increased, it is possible that the deflection of the glass is increased, and damage.

Among the possible designs of the experiment, the Taguchi method provides systematic and efficient methodology for optimizing printing process parameters with less effort required than that of most other optimization techniques (Lee, et al., 2010, SHIH, et al, 2012, Sivasakthivel, et al, 2014). With the Taguchi method, it is possible to objectively and quantitatively evaluate how the difficult-to-control parameters such as environmental conditions, mechanical errors, or noise, which were traditionally perceived to be impossible to control, affect the test results (Tang, et al., 1998). Accordingly in this study, we used the Taguchi method to optimize the screen printing process parameters for arrays of pillars.
Figure 5 shows the printed pillars on the glass by first process parameter condition of design of experiment. A total of 16 pillars are printed. According to the properties of the printing pillars, which are printed in identical patterns, symmetric conditions were applied and resulting values of the average distance ($d_p$) and uniformity ($u_p$) of 6 pillars were used like shown in first figure.

3. Results and discussion

The purpose of the Taguchi method is to find controllable factors with strong influence so that effects of noise are minimized by maximizing the influence of such strong factors. A technique needed for such a robust design is the SN ratio technique (Park, 2008), which is applied differently to the three types of performance variable, which are defined separately for product and objective function and are categorized into smaller-the-better (STB), larger-the-better (LTB), and nominal-the-best (NTB). In this study, STB was applied because it approximates a trapezium shape as distance ($d_p$) becomes smaller and the uniformity ($u_p$) of pillars improve structural stability when printing pillar uniform. SN ratio of STB can be expressed as shown in equations (2) (Park, 2008).

$$SN = -10 \log_{10} \sum_{i=1}^{n} \left( \frac{y_i^2}{n} \right)$$  \hspace{1cm} (2)

Where, $y_i$ = observed data

$n$ = number of observation
The mean value of printed six pillars was calculated after repeating the experiments two, using the same process parameters. Conventionally, data from design of experiments were used to study the main objective function. The signal-to-noise ratios were calculated using the condition been smaller is the better i.e. Eq. (2) for each of the nine experimental combination which are reported in Table 2. Figure 6 shows results with STB applied for distance (d_p); it can be observed that the factors with much influence were, in order, squeegee velocity, snap-off height, squeegee pressure, and squeegee angle. And process parameters indicate that squeegee pressure was large, snap-off height was smaller, squeegee velocity was faster, squeegee angle was smaller than derive maximum SN ratio. Squeegee angle was indicated to be less effect on the shape of the pillar. Table 3 shows the analysis of variance about the contribution of each of the parameters. As discussed earlier for the main effect plots, the same trend can be observed for parameters.

As a result of the analysis of variance, the effect of squeegee angle (θ_s) among four process parameters on distance (d_p) was small. Therefore, according to the analysis of variance after removing the insignificant squeegee angle (θ_s), the significance of other process parameters improved.

| Exp. Run | Control factors | Pillar width dimension(h_u) | Pillar uniformity(u_p) |
|----------|----------------|----------------------------|-----------------------|
|           | P | g_mg | ν_s | θ_s | d_p1 | d_p2 | \( \bar{d}_p \) | \( n_1 \) [dB] | u_p1 | u_p2 | \( \bar{u}_p \) | \( n_2 \) [dB] |
| 1         | 1 | 1    | 1   | 1   | 17.5 | 25.0 | 21.3 | -26.7 | 14.0 | 3.2  | 8.6  | -20.1 |
| 2         | 1 | 2    | 2   | 2   | 16.8 | 26.5 | 21.7 | -26.9 | 49.2 | 8.0  | 28.6 | -30.9 |
| 3         | 1 | 3    | 3   | 3   | 16.7 | 21.8 | 19.3 | -25.8 | 48.8 | 124.8| 86.8 | -39.5 |
| 4         | 2 | 1    | 2   | 3   | 15.7 | 15.5 | 15.6 | -23.9 | 14.2 | 5.3  | 9.8  | -20.6 |
| 5         | 2 | 2    | 3   | 1   | 12.8 | 18.0 | 15.4 | -23.9 | 5.2  | 14.0 | 9.6  | -20.4 |
| 6         | 2 | 3    | 1   | 2   | 17.8 | 26.8 | 22.3 | -27.1 | 14.0 | 14.5 | 15.8 | -23.0 |
| 7         | 3 | 1    | 3   | 2   | 5.2  | 18.0 | 11.6 | -22.4 | 14.2 | 18.7 | 16.4 | -24.4 |
| 8         | 3 | 2    | 1   | 3   | 26.8 | 20.6 | 23.7 | 27.6  | 3.8  | 9.7  | 6.8  | -17.3 |
| 9         | 3 | 3    | 2   | 1   | 13.8 | 21.2 | 17.5 | -25.1 | 9.8  | 14.0 | 11.9 | -21.6 |

Table 2: Experimental results and performance evaluations

![Main Effects Plot for SN ratios](image)

**Fig. 6 Main effects plot for SN ratios (Distance)**

Table 3: Results of ANOVA for distance (d_p)

| Factor     | DF | Seq SS | Adj MS | \( F_0 \) | P  |
|------------|----|--------|--------|-----------|----|
| Pressure   | 1  | 14.570 | 14.570 | 6.04      | 0.091 |
| Height     | 2  | 29.616 | 14.808 | 6.13      | 0.087 |
| Velocity   | 2  | 74.389 | 37.194 | 15.41     | 0.026 |
| Error      | 3  | 72.242 | 2.414  | 0.045     |     |
| Total      | 8  | 125.817|        |           |     |

\[ S = 155374 \]  \[ \text{R-Sq} = 94.24\% \]  \[ \text{R-Sq(adj)} = 84.65\% \]
For results related to pillars uniformity, STB was applied to pillars that have heights of 150 μm, which is the actual mask thickness; accordingly, analysis was conducted to determine the average. Figure 7 shows the results of applying STB for the uniformity ($u_p$); factors with much influence were, in order, squeegee pressure, squeegee velocity, snap-off height and squeegee angle. It is almost same as discussed earlier for the distance ($d_p$) data exclude squeegee velocity.

By using the regression analysis technique based upon the analyzed result about the governed parameter having an effect on the shape of the pillar and uniformity, the polynomial regression equation was drawn. This regression analysis assumes the mathematical model in order to investigate the correlation between variables. It is the statistical analysis method estimating this model from measured data of the variables. When the change of any kind of dependent variable is affected by many independent variables, by using measured data of the independent variables, the regression equation is induced.

In case of distance ($d_p$), the independent variable was the squeegee pressure, snap-off height, and squeegee velocity. After pooling parameter squeegee angle, drew the polynomial regression equation because of less effect.

In the case of the uniformity of the Pillar, the independent variable becomes assumed all parameters. The mathematical model can be expressed as in equation (3), (4) through polynomial regression analysis of pillar distance and uniformity.

$$d_p = 23.51 - 0.15P_s + 1.76g_{mg} - 0.07v_s$$ \hspace{1cm} (3)

Where, $d_p$ = Predicted distance between $w_p$ of 80 μm and top of pillar

$P_s$ = Squeegee pressure

$g_{mg}$ = Snap-off height

$v_s$ = Squeegee velocity

$$u_p = -227.58 - 1.48P_s + 13.28g_{mg} + 0.27v_s + 4.07\theta_s$$ \hspace{1cm} (4)

Where, $u_p$ = Predicted uniformity of pillars

$P_s$ = Squeegee pressure

$g_{mg}$ = Snap-off height

$v_s$ = Squeegee velocity

$\theta_s$ = Squeegee angle

The ANOVA results showed that $p \leq 0.10$ and that the adjusted determination coefficient was each 75.81%, 70.93%; these values confirm the feasibility of the established regression model. Furthermore, the residual plot illustrated in Figure 8 and 9 showed a normal distribution; therefore, it was concluded to satisfy homoscedasticity. Table 4 and 6 presents the regression coefficients and p-values of each term in Equation (3) (4), and Table 5 and 7 presents the ANOVA results.
Table 4 Coefficients of regression equation (3) (distance of pillar)

| Term     | Coeficients | Se coefficients | T    | P   |
|----------|-------------|-----------------|------|-----|
| Constant | 23.51       | 3.34            | 7.02 | 0.017 |
| Pressure | -0.15       | 0.08            | -1.95| 0.108 |
| Height   | 1.76        | 0.79            | 2.21 | 0.077 |
| Velocity | -0.07       | 0.01            | -4.39| 0.007 |
| S = 1.95 | R-Sq = 84.88% |

Table 5 Analysis of variance test for mathematical models (distance of pillar)

| Term     | DF | SS  | MS  | F    | P   |
|----------|----|-----|-----|------|-----|
| Constant | 3  | 106.80 | 35.60 | 9.36 | 0.017 |
| Pressure | 1  | 11.57  | 14.57 | 3.83 | 0.108 |
| Height   | 1  | 18.73  | 18.73 | 4.92 | 0.077 |
| Velocity | 1  | 73.50  | 73.5  | 19.32 | 0.007 |
| Error    | 5  | 19.02  | 3     |      |     |
| Total    | 8  | 125.82 |       |      |     |
Table 6 Coefficients of regression equation (4) (uniformity of pillar)

| Term    | Coef | SE Coef | T   | P   |
|---------|------|---------|-----|-----|
| Constant | -227.58 | 99.36   | -2.29 | 0.084 |
| Pressure | -1.48 | 0.55    | -2.65 | 0.056 |
| Height   | 13.28 | 5.57    | 2.38  | 0.076 |
| Velocity | 0.27  | 0.11    | 2.44  | 0.071 |
| Angle    | 4.07  | 1.85    | 2.19  | 0.093 |

S = 13.64 R-Sq = 85.47%

Table 7 Analysis of variance test for mathematical models (uniformity of pillar)

| Term    | DF | SS   | MS   | F    | P   |
|---------|----|------|------|------|-----|
| Constant | 4  | 4318.1 | 1095.3 | 5.88 | 0.057 |
| Pressure | 1  | 1317.2 | 1317.2 | 7.07 | 0.056 |
| Height   | 1  | 1058.7 | 1058.7 | 5.68 | 0.076 |
| Velocity | 1  | 1109.8 | 1109.8 | 5.96 | 0.071 |
| Angle    | 1  | 895.5  | 895.5  | 4.81 | 0.093 |
| Error    | 4  | 745.0  | 186.2  |      |      |
| Total    | 8  | 5126.1 |      |      |      |

Accordingly, regression equations (3) and (4) can be used to print pillars with shapes as close to trapezium as possible when printing vacuum glazing pillars through screen printing; also, it is considered that the prediction of subsequent pillar height will be possible as well.

Based on equations (3) and (4) and on the results of the Taguchi method, optimal process parameters were found to be a squeegee pressure of level Ⅲ, a snap-off height of level Ⅰ, a squeegee velocity of level Ⅲ, and a squeegee angle of level Ⅰ. It is considered that result of being contrary showed up in case of the squeegee velocity and it has to apply as the optimal value considering the crack because of the stress concentration and structural stability.

The additional experiment was performed with the optimal process condition. Figure 8 show the shape of the six pillars by optimal process condition. We confirmed the top confirm dug one by the inside direction among the shape of the pillar. We assumed that it is not occur cone crack because of supporting on an annular shape of pillar top part. The predicted and mean values of pillar shape are shown in Table 6, where maximum distance is 12.03, uniformity is 5.49. The distance ($d_p$) of pillar by optimal process parameters are better approach almost 54% compare with mean value of all experiments. Also, an optimized value distance ($d_p$) and value of the same by optimal process the same by confirmation experiments using the optimized printing condition comes out.
4. Conclusions

This paper is on the pillar shape manufacturing technology among core processes to develop vacuum glass. In other words, this paper is on the process to manufacture pillar shape in screen printing. Also, presented a trapezoidal cross section pillar manufacturing model that can prevent cone crack in screen printing.

L9 orthogonal array was applied for experiments, S/N ratio was calculated using smaller the better criteria and ANOVA technique was adopted for finding the better printing parameters like squeegee velocity, squeegee pressure, snap-off height. The process parameters optimization was also done with 90% confidence level. The confirmation experiments were also performed to compare predicted and experimented values. Predicted values of distance of pillar \( (d_p) \) using regression analysis were close to the experimental values which suggest that the polynomial regression model.

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