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Effect of Pressure Thermoforming Conditions on PC Sheet integrating Electric Wiring for 3D Electronics Technology

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ABSTRACT

As a new method for "3D Electronics", we have investigated the effect of pressure thermoforming conditions on PC sheet integrating Electric Wiring. By evaluating sheet deformation and disconnection behavior of electric wiring, we found that long-pressing time and early pressing timing were especially significant parameters of process conditions.

1 INTRODUCTION

3D Electronics: a functional 3D product embedded electric wiring onto or into a product, has been expected for use in various fields such as automotive, home appliances, robotics, and medical health care, due to its advantages of simplicity and designability. As for methods of integrating electric wiring into 3D objects, laser direct structuring [1] and the method of drawing conductive paste line directly onto surface of 3D objects by inkjet printing [2] or soft blanket gravure printing[3] have been developed. However, since productivity of these methods is poor, we have been focusing on another method called 3D conformable electronics, which is produced with 3 steps – first: printing electric circuit using conductive paste on a flat plastic sheet, second: forming the plastic sheet into 3D shape, third: finishing 3D formed sheet into 3D objects by injection moldings or bonding. Since the conventional printing method such as screen printing can be used for this method, it has an advantage of mass production. Additionally, with this method, the electric wiring can be inserted between the interfaces of a 3D formed sheet and a 3D object. Therefore, the products with this structure is called in-mold electronics and have high durability and designability. As for means of thermoforming: forming sheets into 3D shape, although vacuum thermoforming, deep drawing, and pressure thermoforming have been generally used [4][5], we have focused on the TOM (Three-dimension Overlay Method) forming. TOM forming is the new type of pressure thermoforming and has been attracting attention due to its decoration technology, which is the technology decorating a 3D object by a designed sheet while pressure thermoforming process. With this technology, not only forming a plastic sheet with electric wiring into a 3D shape, but also bonding it with a 3D object are possible at once while TOM forming[6].

Fig.1 shows the process flow of TOM forming;

(1) Set 3D object or mold on a table and then set a plastic sheet between the upper and lower boxes.

(2) Upper and lower boxes are divided by the sheet made vacuum and then the sheet is heated.

(3) When the sheet is heated enough, the table moves up towards the sheet.

(4) The sheet is formed in a mold shape by either atmospheric pressure, compressed air, or both of them in the upper box while the lower box is under vacuum.

(5) Remove 3D object covered by the sheet from the mold.

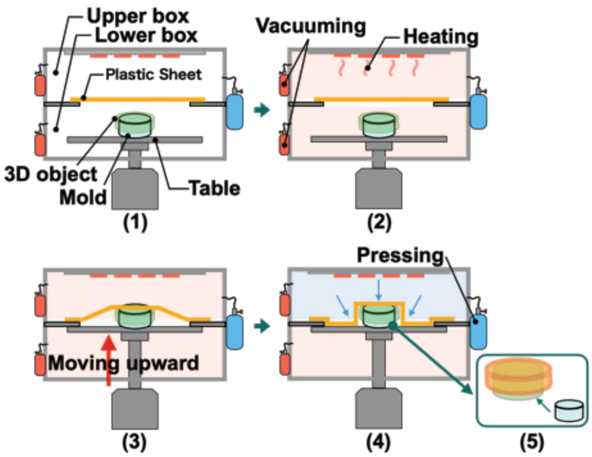


Fig. 1 Process flow of TOM forming

Despite vacuum thermoforming has frequently used for forming a plastic sheet with an electric circuit into 3D shape, there has been no report using TOM forming for the method.

In this study, we investigated the effect of TOM forming conditions on a PC (Polycarbonate) sheet integrating electric wiring. To evaluate it, a thermoformable conductive paste line was printed on a PC sheet, then formed into a 3D shaped sheet under different process conditions, especially original conditions of TOM forming such as pressure strength, pressing time, and pressing timing. After that, the sheet deformation, and disconnection behavior of the printed paste lines under different process conditions were observed. The effect of process conditions of TOM forming on PC sheet integrating electric wiring was revealed.

2 EXPERIMENT

2.1 Materials and Machines

2.1.1 Substrate and Paste

Polycarbonate sheet “Panlite® Sheet PC-2151” (manufactured by Teijin Limited) with 0.4 mm thickness, 335 mm width, 450 mm length, and thermoformable conductive paste “DOTITE XA-3737” (manufactured by Fujikura Kasei Co., Ltd.) were used, respectively.

2.1.2 3D Thermoforming Machine

TOM forming machine “NGT-T-0203” (manufactured by Fuse Vacuum Forming Co. Ltd.) was used. The used mold shape was a cylinder, which was made of iron, 80 mm diameter, and 40 mm height.

2.2 Evaluation Method

2.2.1 Sheet Deformation

To evaluate sheet deformation by TOM forming, the gridline using a thermoformable conductive paste, which 260 μm width and 5 mm pitch between lines, was printed on PC sheets (See Fig.2).

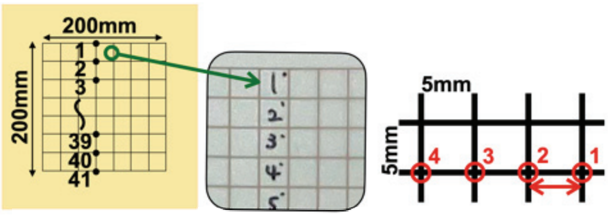


Fig. 2 Printed grid pattern

The distances of lines from top to bottom were measured before and after deformation by using a digital measurement tool. The formed sheet was divided into 3 parts. Bottom area: marking points from 1 to 9 and 33 to 41, sidewall area: the marking points from 10 to 13 and 29 to 32, top area: the marking points from 14 to 28. (See Fig.3) The percentage of dimensional elongation of PC sheets can be described by,

$$\Delta L=(L_j-L_i)/L_i \times 100\%$$

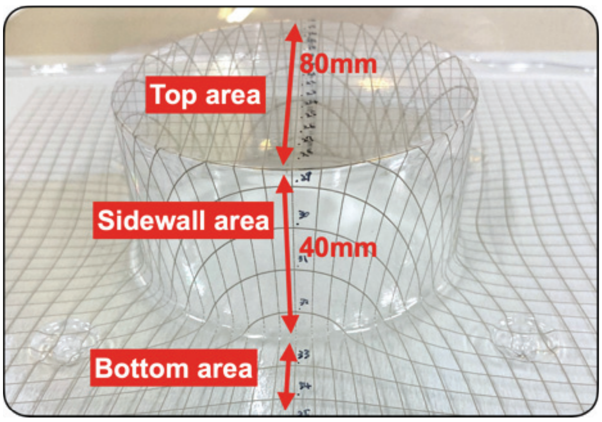


Fig. 3 Figure of formed sheet

where ΔL is the percentage of dimensional elongation, Li is the measured distance before deformation, and Lj is the measured distance after deformation, respectively.

2.2.2 Shape Change of Printed Conductive Paste Line and Its Volume Resistivity

To investigate the shape change of the paste line and its disconnection behavior occurred by TOM forming process, its shapes were observed by using a confocal microscope at different points. Volume resistivity was also calculated by ρv [Ω・cm] = V/I × S/L.

2.3 Sample Preparation

2.3.1 Preparing a PC Sheet Integrating Electric Wiring

A grid was printed on a PC sheet by screen printing using thermoformable conductive paste at a Squeegee speed of 100mm/s with an 1mm lift-off. The specifications of screen mesh were as follows: mesh material; stainless steel, line frequency; 325 line/inch, screen opening area percent; 41 %, wire diameter; 28 μm, emulsion thickness of mesh; 10 μm. The grid was square, with dimensions of 200 mm by 200 mm. (See. Fig.2) Then, the printed sheet was baked at a temperature of 140℃ for 30 minutes in a clean oven.

2.3.2 3D Thermoforming of a PC Sheet Integrating Electric Wiring

PC sheets integrating electric wiring were formed by TOM forming machine under different conditions including, mold speed: the speed of the table moving upwards (80 mm/s and 110 mm/s), pressure strength (200 kPa and 400 kPa), pressing time (10s and 60 s), and pressing timing (0.2, 0.7 s, and 1.7 s) (See Table.1).

Table. 1 Parameters of TOM forming

Sample No.	Sheet temperature [℃]	Mold speed [mm/s]	Pressure [kPa]	Pressing time [s]	Pressing timing [s]
1	140	80	200	10	0.7
2	140	80	200	10	1.7
3	140	80	200	10	0.2
4	140	110	200	10	0.7
5	140	80	200	60	0.7
6	140	80	400	10	0.7

3 RESULT AND DISCUSSION

3.1 Correlation between Sheet Deformation and Volume Resistibility of Paste Line

ΔL and volume resistivity of the printed paste line of sample 1 were observed (See Fig.4).

In the top area, both ΔL and volume resistivity was kept the lowest number. On the other hand, in the sidewall area, ΔL was the highest, and volume resistivity was unmeasurable as the paste line was disconnected. In the bottom area, both ΔL and volume resistivity was steadily increased toward sidewall.

Based on these results, there was a certain relation between sheet deformation and volume resistivity.

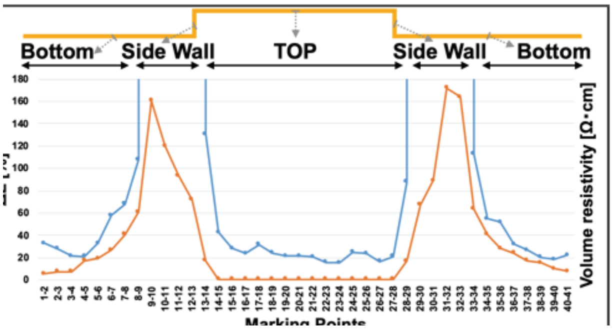
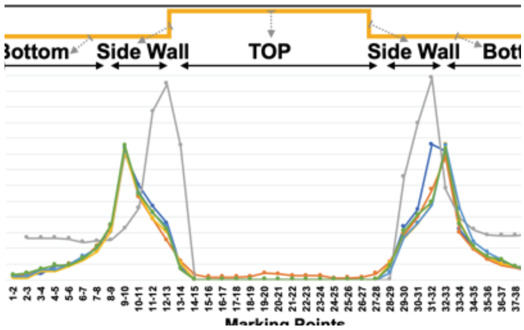


Fig. 4 Correlation of dimensional elongatio with volume resistivity of sample 1



5 Sheet elongation rate under different condi

3.2 Effect of Different Conditions of TOM Forming on Sheet Deformation

Fig. 5 shows ΔL under different conditions at various measurement points.

Only the result of sample 3 showed an extremely different number of ΔL, especially in the sidewall area. The reason why only sample 3 deformed far more than other samples is because when the pressing timing was too early, the sheet was pressed before the mold reached to the top (See Fig. 6), which did not happen with other conditions as compressed air is to be pressed after table re

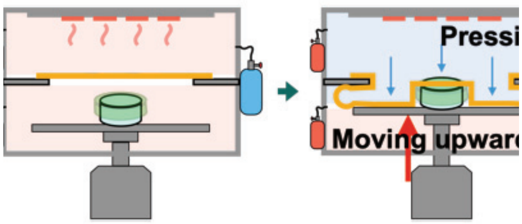
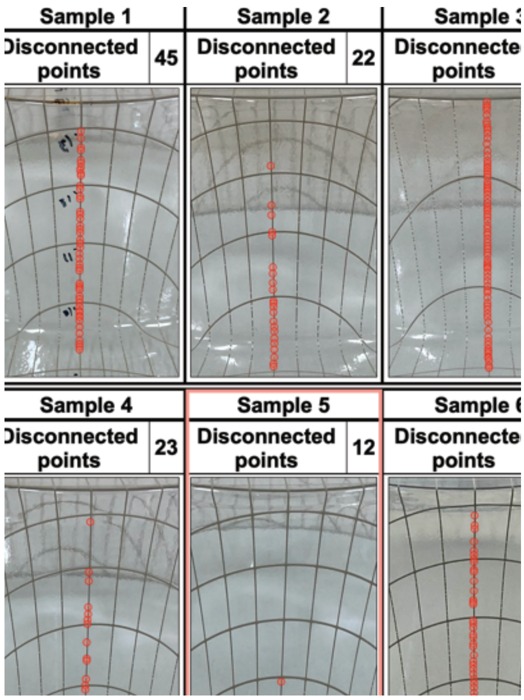


Fig. 7 shows each picture of the sidewall area of 3D formed sheet, where most deformation occurred, under different conditions. There were some disconnections of the paste lines at sidewall area, and they increased towards bottom area. Although almost every ΔL was quite similar except sample 3, only sample 5 seemed to suppress its disconnected paste line area and number dramatically. In other words, the process condition "longer pressing time" was able to contribute to suppressing the disconnection of the paste line even though it did not change the result of ultimate sheet deformation. We believe the reason why longer pressing time suppressed disconnection of the paste line can be explained by strain rate dependency. In TOM forming process, longer pressing time means that longer pressure was gradually applied by the maximum. Therefore, it is assumed that longer pressing time provided smaller strain ration on both sheets and paste lines. Additionally, it is a well-known fact th lus of elongation[7]; therefore, it might have happened that the paste lines were elongated with a smaller modulus of elongation. As a result, suppressing disconnections of paste lines might have caused by avoiding forceful elongation with a high modulus.



under different conditions with red circles

3.3 Shape Observation of Printed Conductive Paste Line

The surface condition of the printed paste line and its shape were observed after TOM forming. Fig. 8 shows the surface of the printed line after printing paste line.

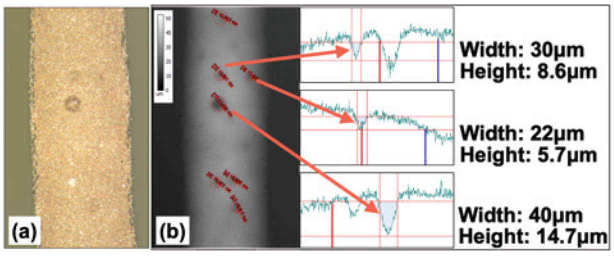


Fig. 8 (a) Picture of paste line (b) and its surface conditions with halls' size

Because of the printing condition and the screen mask we used for printing the paste line, the air contained in a paste appeared randomly as depressions, which sizes were 20 ~ 40µm diameter and a few to 15µm depth, on the surface of paste lines a lot.

The printed paste line after TOM forming process was also observed at different elongation points (See Fig.9).

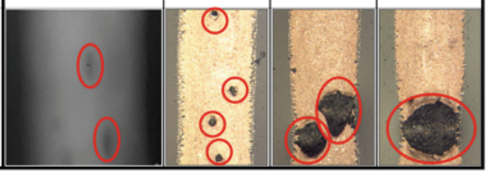
Marking point	8-9	12-13	10-11	9-10
Sheet elongation rate [%]	61.0	71.0	120.0	160.0
Line height [µm]	21.3	20.6	21.0	23.2
Line width [µm]	222.8	250.9	219.4	220.5
Line cross section	2977.0	2994.9	2960.2	3248.6
Surface photos				

Fig. 9 Shape change of paste line at different elongation points after TOM forming and its picture

According to Fig. 9, despite the shape of paste line itself was similar regardless of different point and different ΔL, the depressions found after printing was changed its form from round to oblong at marking point 8-9 where the sheet was 61% elongated. Furthermore, with increasing the ΔL, oblong depressions seemed to have become into small halls and then bigger and bigger, which resulted in disconnections of paste lines (See Fig.9). According to the results, the increasing of volume resistivity with increasing ΔL, and disconnection of the paste line might have occurred as the paste line was locally stacked by depression or halls rather than changing the shape of paste lines. Therefore, we believe when the condition of screen printing is adjusted and decrease depressions, the paste line will be able to be more elongated and increase its electric conductivity.

3.4 Effect of Printed Paste Line on Sheet Deformation

To investigate the effect of printed paste line on sheet deformation, the dots were written within lattices by oiled pen before 3D forming and then formed (Fig.10).

A bigger gap between the paste line and dots, than the gap of dots, was observed and it is assumed that conductive paste line might change sheet deformation.

4 CONCLUSIONS

PC sheet with printed thermoformable conductive paste line was formed into 3D shape by TOM forming method and it was observed that there was a certain relation between the sheet deformation and volume resistivity of electric wiring. Most importantly, this was revealed that: "Pressing timing" affect a lot on a sheet deformation; otherwise, the result of sheet elongation rate was quite similar regardless of process conditions of TOM forming. "Longer pressing time" was another remarkable condition, which suppressed disconnections of printed paste lines. Additionally, it was observed that the printed paste line might disturb the PC sheet deformation.

For our future work, we will produce 3D conformal electronics by either injection molding, or bonding while TOM forming.

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