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Study on the Application of Magnetic Force to Mold Decoration Formation

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Abstract

This study proposed an innovative magnetic assisted film-forming process for in-mold decoration (IMD). A peel test was performed on a pre-heated polymer thin film laminated with a piece of plastic using magnetic assisted molding to verify the feasibility of this type of molding in the IMD process. And Taguchi's design of experiments was used to discover the optimal processing parameters such as the pre-heated temperature, holding time, film thickness and magnetized steel ball diameter. This proposed magnetic assisted film-forming technology is believed to improve the bonding strength of thermoplastic IMD process.

Keywords: In-mold decoration; Magnetic assisted film-forming; Peel test

Introduction

Currently, the in-mold decoration (IMD) process can primarily be divided into three categories: in-mold labeling (IML), in-mold forming (IMF), and in-mold roller (IMR). The procedures for each can be summarized into eight steps: punch a hole in a specific position on the polymer thin film, cut, print, allow ink to dry in a fixed position, attach the top layer, pre-heat, laminate together with plastic piece, and trim the edges. The three categories differ in terms of whether the top layer is left on the finished decorative surface as a protective layer. IML and IMF have a top layer after lamination; but in "transfer printing" [1], the top layer is peeled away after the plastic piece and polymer thin film are laminated, the decoration on the color layer surface and the base layer remain, and a layer of hard coating is often applied to protect the decorative surface. IMR pertains to this category of IMD [2,5,7,12].

Due to early limitations on manufacturing characteristics, researchers attempted to avoid dramatic drops in height which might introduce small air bubbles, or thereby decrease the strength of the lamination [4].

Secondly, the design of the mold draft angle cannot be too small, in order to avoid severe residual stresses when the molded part is ejected. This residual stresses could cause the product to crack or break at the lamination point, seriously affecting the mechanical properties of finished products. These effects are especially obvious when the molded thermoplastic is brittle material like PMMA [6]. Furthermore, improper mold temperature, melt temperature, the viscosity and high shear rate of melted plastic and the gate locations may result in washout of the colored ink [3,8]. Methods such as NGF and TOM using hydraulic, barometric, and vacuum pressures have been developed to overcome these defects [9].

Experiment Planning and Procedures

Hydraulic, barometric, and vacuum pressures generally produce uneven pressure distribution. This study proposes using magnetic fields to generate magnetic conduction in magnetized beads and provide more uniform force. Such magnetic force was converted into uniform pressure to laminate the polymer thin film onto the molded thermoplastic. It's believed that this technique can help solve the defects which is currently existed in the IMD process [3,8]. In addition to verifying the feasibility of this concept, this study also carried out the experiments for the optimum parameters in the process.

Before the experiments were conducted, some specific process parameters needed to be defined. When the electricity was on and the beads were magnetized, they produced downward pressure and laminated the polymer thin film to the molded thermoplastic part. The period between the electricity on and off was defined as the holding time. And the pressure generated was referred to as the holding pressure.

Experiment Planning

Platform System Specifications

A vertical double liquid silicone injection molding machine manufactured by Fui Cha Co., Ltd. was used as the molding machine for this experiment.

Pressure Mold Design

The materials used for the pressure mold were required to enhance the magnetic effect and to be able to withstand the pressure generated during the experiment. Magnetically conducive steel molding was selected as the primary material. Additionally, the pressure mold primarily used a magnetic ball bearing with a diameter between 0.43 mm and 1.18 mm. To prevent ball bearings from becoming loose, each part of the mold matched within ±0.02 mm. The designed mold is displayed in Figure 1, and an actual picture of the constructed model is shown in Figure 2.

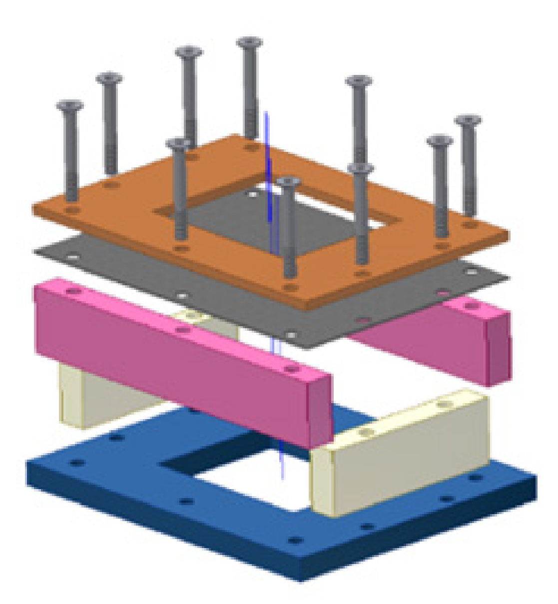

Figure 1: Pressure mold design.

Figure 2: Photo of the pressure mold.

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Magnetic Mold Design

This study generated a magnetic field by passing an electric current through magnetic coils, thereby magnetizing the ball bearings within the pressure mold. Displacement converted magnetic force into pressure, laminating the polymer thin film to the piece of plastic. The designed mold is displayed in Figure 3 and an actual picture of the constructed model is shown in Figure 4.

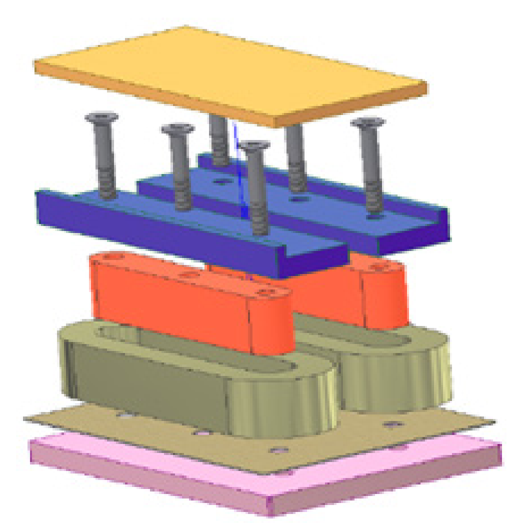

Figure 3: Magnetic mold design.

Figure 4: Photo of the magnetic mold.

Polymer Thin Film Feeding Machine Design

This machine included 1 trolley, which primarily held and transferred the polymer thin film from the preheating machine to the molding machine, and 1 track with a polished surface and a layer of lubricant to allow the trolley to move smoothly along it. The machine that was designed is displayed in Figure 5, and an actual picture of the constructed machine is shown in Figure 6.

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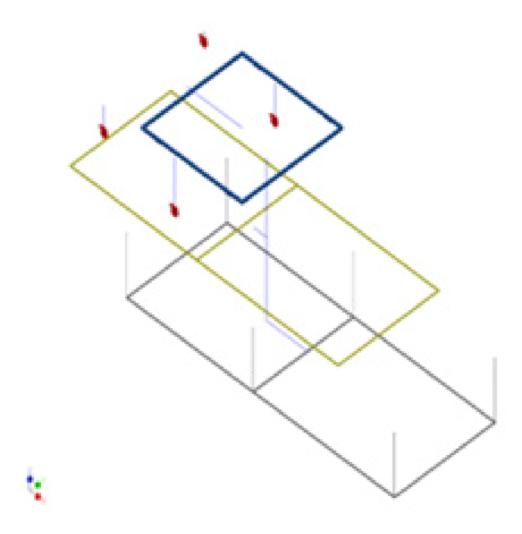

Figure 5: Feed machine design.

Figure 6: Photo of the feed machine.

Plastic Piece

Because this experiment used data obtained from the peel test to determine the feasibility of applying magnetic assisted molding to the IMD process, the piece of plastic was selected for the experiment with the following requirements: (a) The material properties could combine with polymer thin film; and (b) the exterior geometric shape could produce accurate data using the peel test. The plastic piece adopted in this experiment is shown in Figure 7.

Figure 7: Plastic piece.

Polymer Thin Film

The films used in this experiment were Nanya Plastics Corp. HC polymer thin films (2TNHCCA). See Figure 8. Its properties are listed in Table 1.

Table 1: HC film (2TNHCCA) basic characteristics.

Characteristic	Item		Unit	Test Value	Standard
Object	Thickness		µm	100	100 ± 5%
	Transparency		%	92	93± 1%
	Pencil hardness		-	2H-3H	≥ 2H
	Hundred grid test		-	100/100	100/100
	Haziness		%	1.4	≤ 2.0
Mechanical	Tensile strength	MD	kg/mm^2	18	15↑
		TD		19	15↑
	Elongation	MD	%	150	100↑
		TD		134	100↑
Heat	Decrease in heat	MD	%	-0.7	1.0↑
		TD		-37	1.0↑

Source of materials: Nanya Plastics Corp., EMD Supreme Technical Package Co., Ltd.

Figure 8: HC optical thin film.

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Actual Lamination Experiment

According to property tables provided by the relevant literature and vendors, manufacturing parameters such as preheating temperature, ball bearing diameter, and holding time were set in a variety using the Taguchi method to conduct the multiple test piece lamination process.

Peel Test with Clamps Design

For the peel test, a test piece of the product resulting from the lamination of polymer thin film and the piece of plastic was placed in the tensile testing machine with clamps. To ensure that the polymer thin film and plastic piece were perpendicular during the peeling process, the clamps were connected to a linear slide at the bottom. The design is displayed in Figure 9, and an actual picture of the constructed machine is shown in Figure 10.

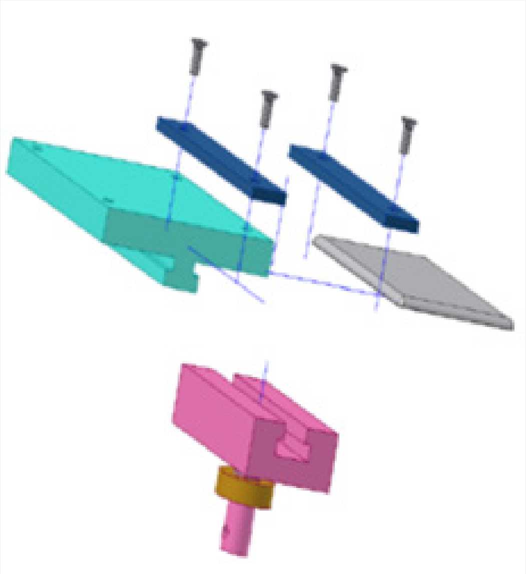

Figure 9: Peel clamp design.

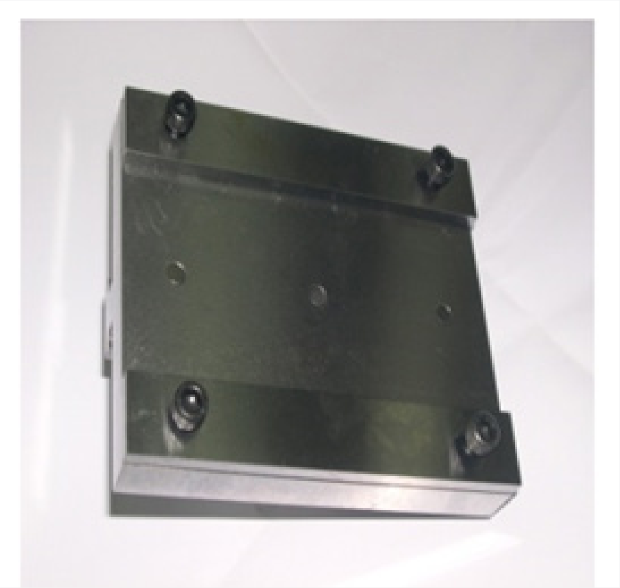

Figure 10: Photo of peel clamp.

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Measurement

This experiment used the SHIMADZU–500G universal testing machine developed by the Sanpany Instruments Co. to conduct the peel test and measure the lamination strength, thereby verifying the concept's feasibility and the optimum parameters provided by the Taguchi method.

Experimental Procedures

The experiment process is outlined below:

i. The ball bearings were inserted into the pressure mold, and the mold was inspected for gaps between pieces to prevent magnetic ball bearing spillover during the experiment.

ii. The pressure mold, magnetic mold, preheating equipment, and feeding machine were installed in the vertical double liquid silicone injection molding machine. See Figure 11.

iii. A 220 V electric source was connected to the rectifier, converting alternating current to direct current to be used in the magnetic mold.

iv. The polymer thin film was trimmed to the required length and width.

v. The plastic piece was placed into the magnetic force testing mold and positioned appropriately.

vi. Different manufacturing parameters were designed using the Taguchi method.

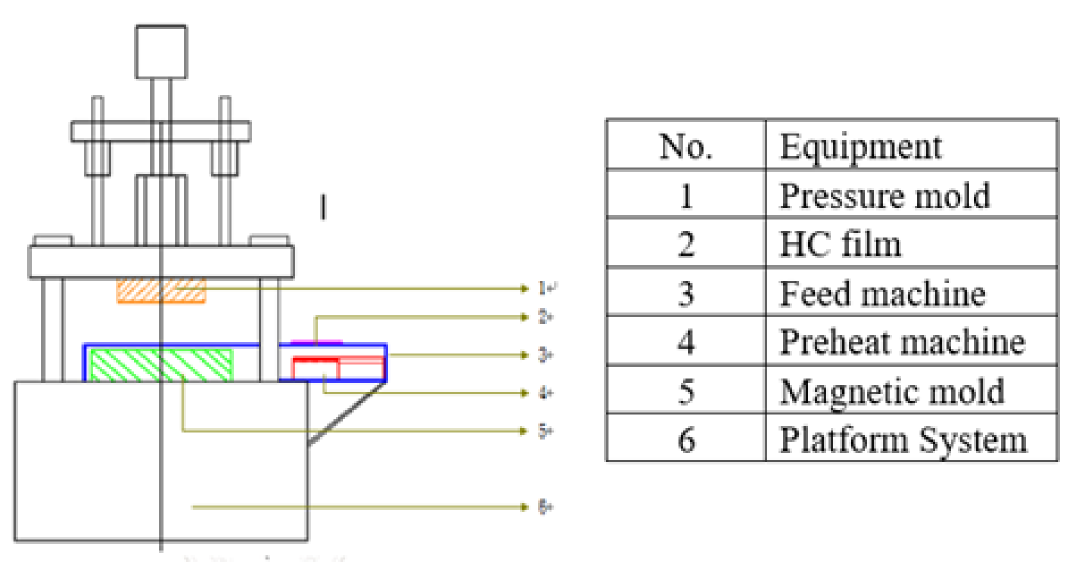
vii. The polymer thin film was preheated to the set temperature and then moved to the set position using the feeding machine.

viii. The pressure mold descended for lamination. See Figure 12.

ix. The magnetic mold electricity was turned on and timing began. At this time, the ball bearings in the pressure mold were pressured downward by the magnetic field, generating downward force and laminating the thin film to the piece of plastic. See Figure 13.

x. At the established time, the electricity was turned off, the magnetic field disappeared, and the ball bearings returned to their original position due to the elastic action of the rubber sheet. See Figure 14.

xi. The pressure mold was lifted and the final product was retrieved. See Figure 15.



No.	Equipment
1	Pressure mold
2	HC film
3	Feed machine
4	Preheat machine
5	Magnetic mold
6	Platform System

Figure 11: Machine schematic diagram.

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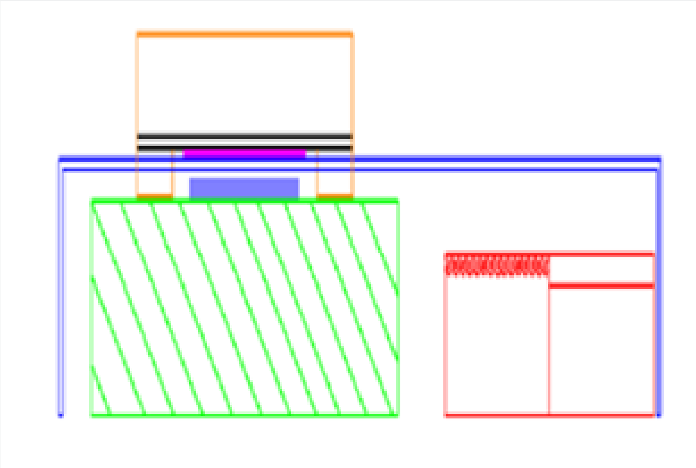

Figure 12: Pressure mold moves downward.

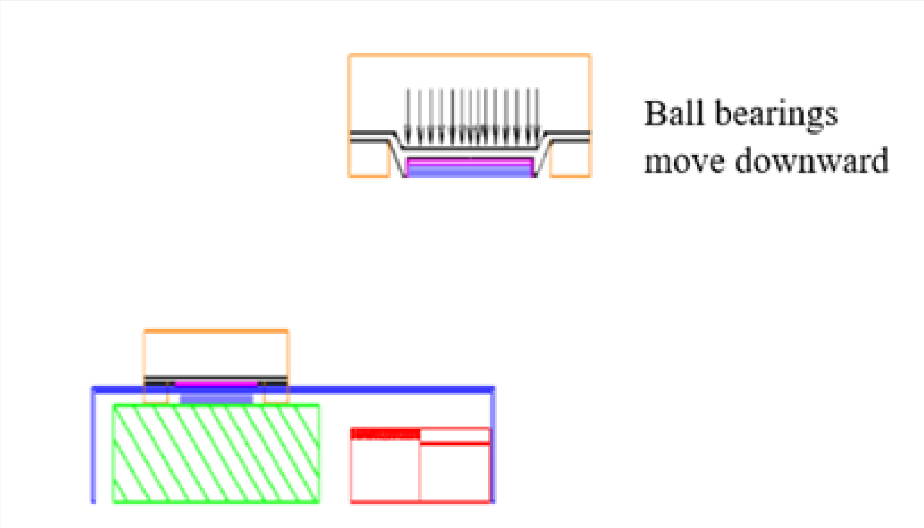

Figure 13: Electricity turn on.

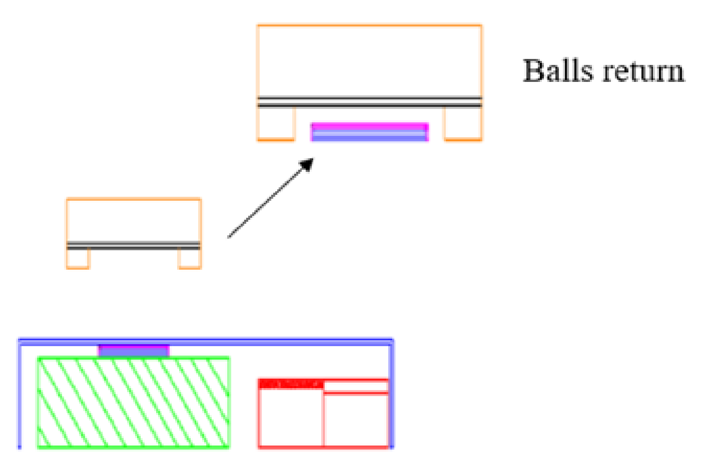

Figure 14: Electricity turned off.

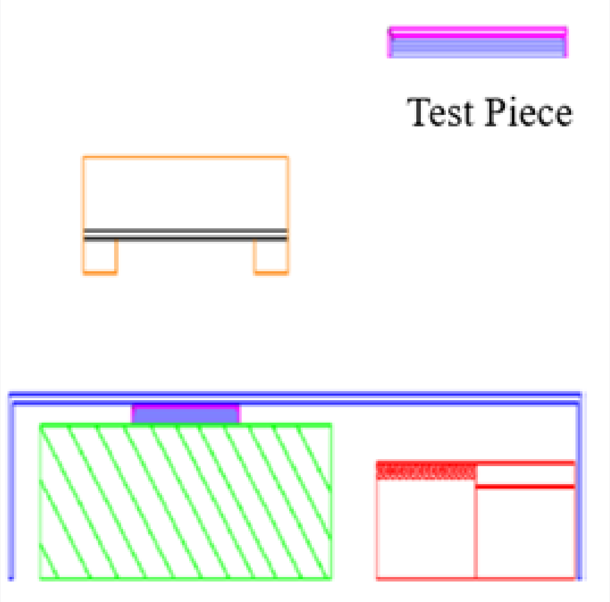

Figure 15: Take out sample piece.

Results and Discussion

Optimal manufacturing parameters were obtained using the Taguchi method [9,10], and a peel test [13] was conducted using the information and property tables provided by related literature and vendors after removal of test pieces that were clearly inadequate.

Manufacturing Test Pieces Using Different Thin Film Preheating Temperatures

The first test piece was manufactured using preheating temperatures as the variable, and ball bearing size and holding time as constants. See Table 2 for manufacturing parameters.

Table 2: Settings for the first group of test pieces manufactured.

Manufacturing conditions	Settings
Film preheat temperature (˚C)	150, 140, 130, 120, 110, 80
Ball bearing size (mm)	SAE S330 ψ 1.18-0.8 5
Holding time (s)	120

Surface Investigation of the First Test Pieces

The results of the first test pieces manufactured by laminating polymer thin film with a plastic piece using electricity and pressure are displayed in Figure 16. The analysis from observing the surface of the test piece is shown in Table 3.

Table 3: Surface analysis for the first test pieces.

No.	Preheat Temp. (°C)	Surface condition
A	150	Film is trimmed, charred, and curled; conditions are poor; product determined to be deficient
B	140	Bubbles formed on the surface cannot be improved even through the use of pressure; product is determined to be deficient
C	130	Uneven surface cannot be improved even with the use of pressure; product is to be determined to be deficient
D	120	Uneven surface, improved after application of pressure
E	110	Entirely smooth surface
F	80	Entirely smooth surface

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Peel Test for the First Test Pieces

The test pieces with better surface conditions D, E, and F were selected from the analysis in Figure 16 and Table 3, and placed in the universal testing machine for peel testing. Relevant settings are displayed in Table 4 & 5, and the process is depicted in Figures 17 & 18.

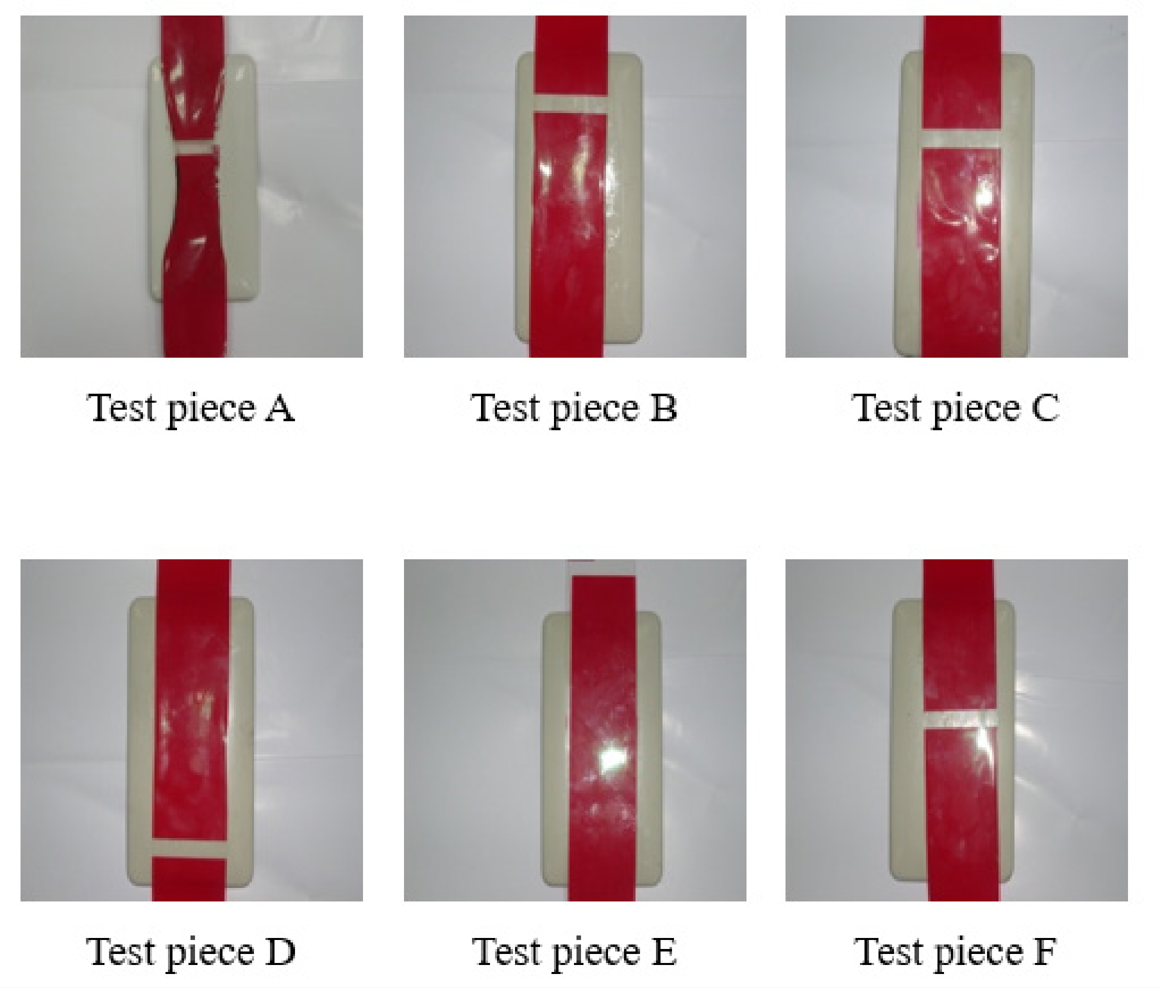

Figure 16: Surface conditions of each test piece manufactured using different preheating temperatures.

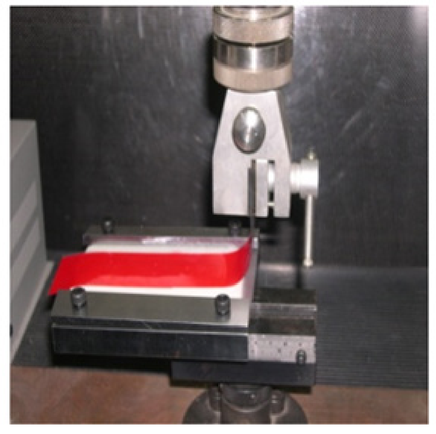

Figure 17: Peel test.

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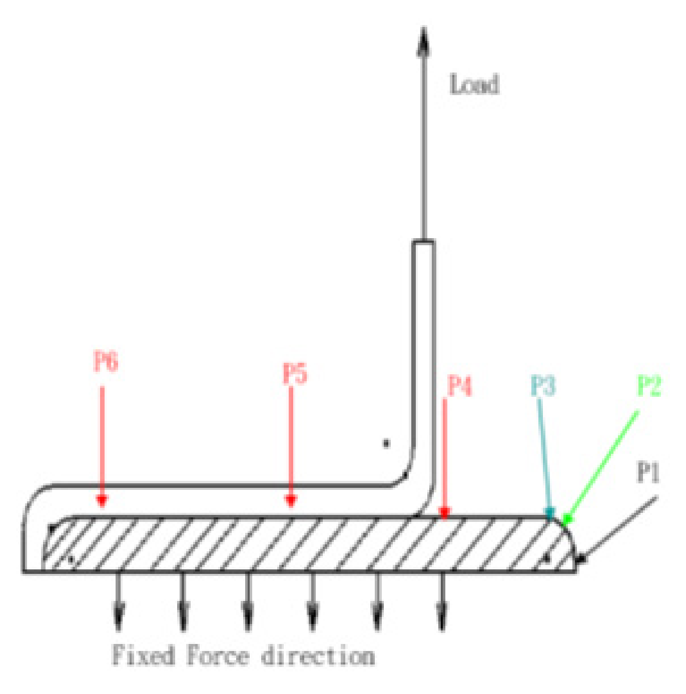

Figure 18: Measurement positions.

Table 4: Universal peel test machine settings.

Primary item	Sub-item	Setting
Mobile measurement clamp head	Type	SBL-50N
System	Max. tension (N)	50
	Displacement (mm/s)	5
Conditions	Display original condition	Load 0 N
	Peel sensitivity	5-50
Test piece	Shape	Long, flat board
	Material	Plastic
	Thickness (mm)	0.175

Table 5: Peel test data for the first test pieces.

Preheat temp. (°C)	Max. peel force (mN)	Avg. peel force (mN)
120	17	14.3
110	15	13.8
80	13.7	12.1

Peel Test Results for the First Test Pieces

A comparison of the peel tests for pieces D and E in Figures 18 & 19 reveals that the peel force suddenly spiked above the average when the film was pulled up from point P1 through point P2, but dropped dramatically when point P3 was reached. The reason for this fluctuation was that the film's plasticity deformation is better when exposed to higher levels of heat, so lamination occurs between the film and the plastic piece at the curve from point P2 to point P3. When the film is pulled upward through point P2, the concentration of stress caused by geometric deformation increases the lamination force between the film and piece of plastic, confirming that the concepts in this study could be applied to the IMD process to work on pieces with significantly changing geometric surfaces.

IMD Process Control Factor Standard Selection Table

The IMD process control factors were selected and the standards were set based on the test results of the first

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manufactured test pieces. See Table 6. The 9 groups of set pieces were manufactured based on the standards established in the orthogonal array designed in the Taguchi method, as shown in Table 7.

Table 6: IMD Process Control Factors.

Factor	Description	Level 1	Level 2	Level 3
A	Film preheat temp. (°C)	120	110	80
B	Ball bearing type	SAES 330	SAES 230	SAES 170
C	Film thickness (mm)	0.2	0.175	0.18
D	Holding time (s)	110	100	60

Table 7: $L_9(3^4)$ Orthogonal array.

Exp.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Peel Test Measurements

Peel tests were conducted on the 9 groups of set pieces described above, and 6 points were selected from each test piece to measure relevant positions. See Figure 18. For recorded data, see Table 8.

Table 8: Measured data for each point.

Exp.	P1	P2	P3	P4	P5	P6
1	13	15.1	13.5	14.5	14.6	14.7
2	13.6	15.9	14.2	14.6	14.6	14.8
3	10.2	13.4	10.3	12.3	12.3	12.5
4	13.2	15	13.6	14.5	14.6	14.7
5	12.9	14.8	13.4	14.2	14.4	14.4
6	13.6	15.9	14.1	14.6	14.6	14.8
7	13	15.1	13.6	14.5	14.6	14.7
8	12.8	13.2	11.4	11.6	11.6	11.8
9	11.1	12	11.1	11.2	11.2	11.4

Quality Characteristics

The average value, square root variance, and signal-to-noise (S/N) comparison for the test piece measurements were calculated using statistical formulae and listed in Table 9. Based on the prospective data in Table 9, the S/N comparison factor response table and figure are depicted in Table 10 and Figure 20, respectively. From the above figures and tables, the optimum combination of factors occurs in A3, C2, and D1. To confirm that these 3 test statistics are independent parameters, an interactive experiment was conducted on A, B, and D, the results of which can be seen in Figures 21, 22 & 23. Each data point for the A2 and A3 curve in the figure was extremely close but still parallel. Therefore, the factor effects for A, C, and D were independent without interacting, creating a resolution of 5.

Variability analysis of Table 11 provides further insight into the proportion contributed by each factor, and confirms whether the selected combination of manufacturing parameters is actually optimal. As the table shows, factor B was insignificant to the entire process, contributing only .20 %; while factors A, C, and D were significant, contributing 28.1 %, 41.2 %, and 25.4 %, respectively. The results in the S/N comparison response in Figure 19 correspond with these results.

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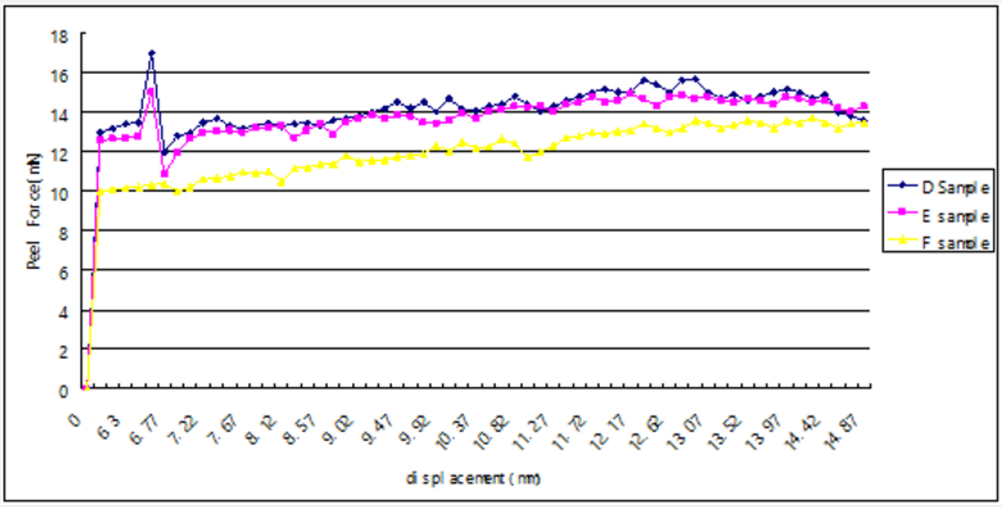

Figure 19: Peel test curve for the first test pieces.

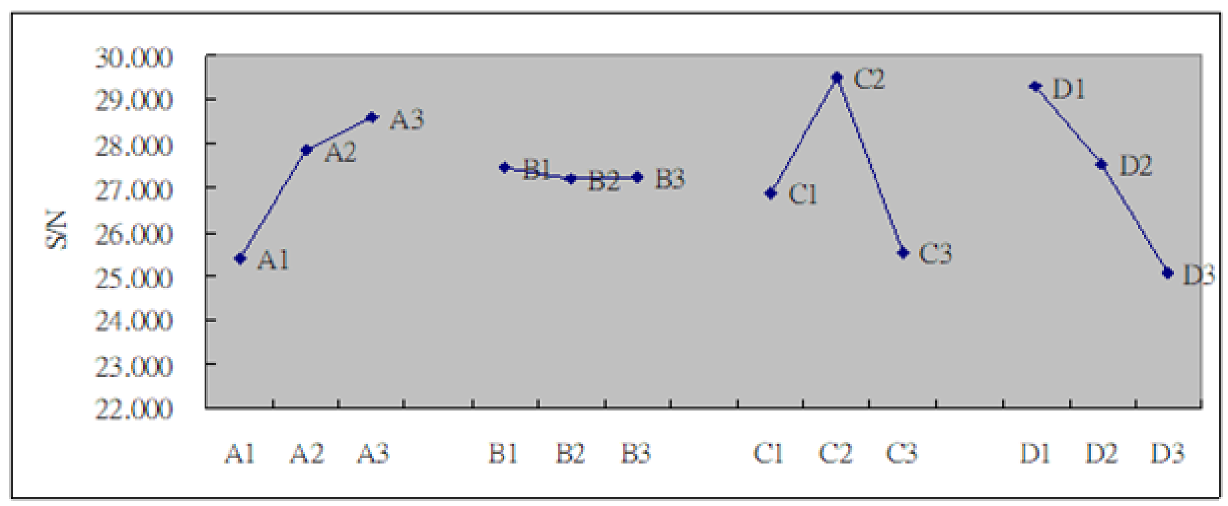

Figure 20: S/N comparison factor response.

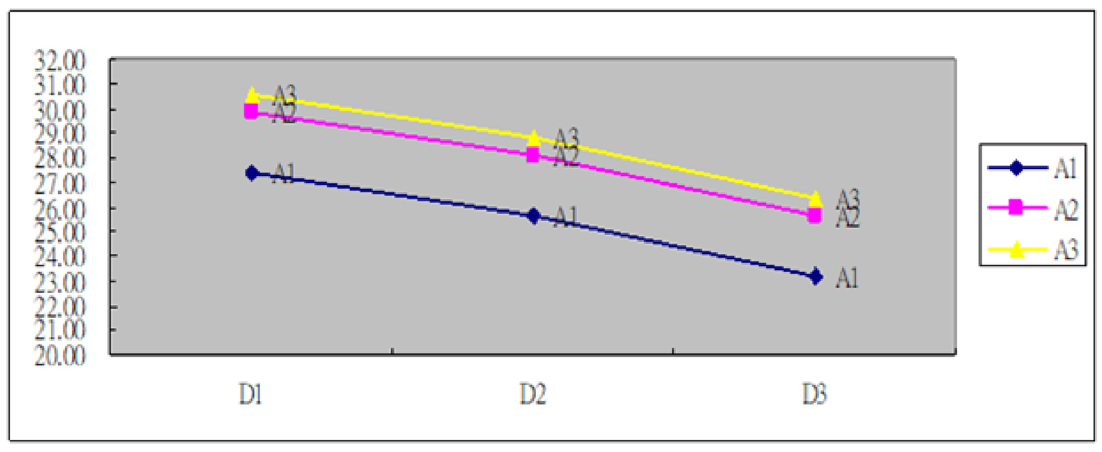

Figure 21: Interaction between A and D.

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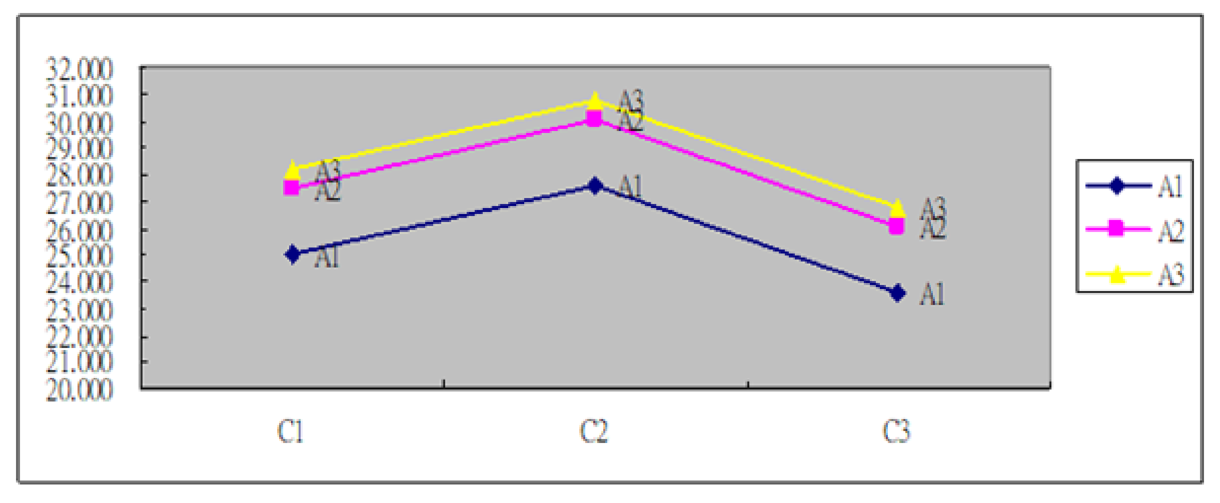

Figure 22: Interaction between A and C.

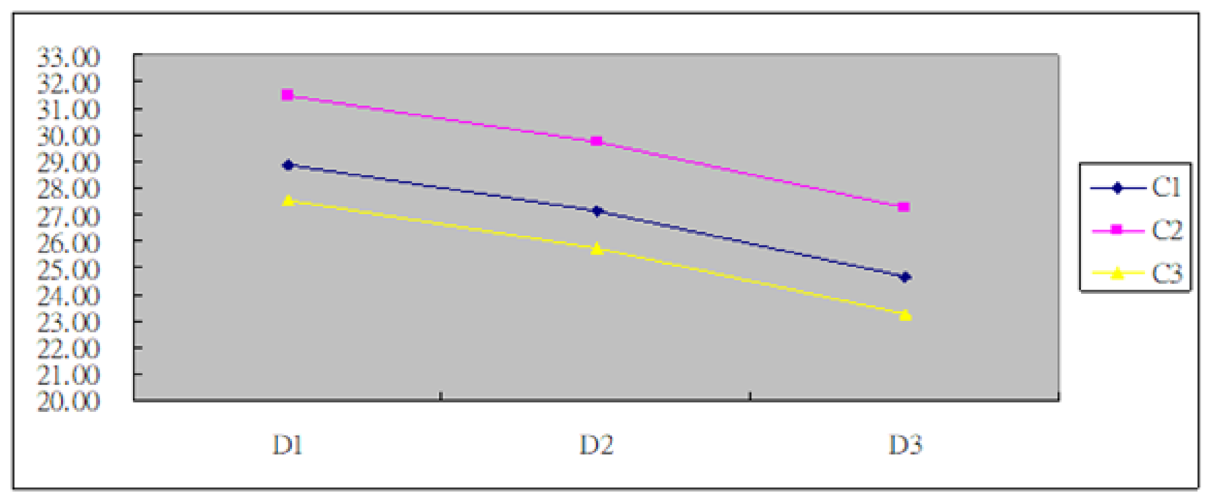

Figure 23: Interaction between C and D.

Table 9: Mean, standard deviation, S/N for each experiment.

Exp.	$\bar{y}$	S	S/N
1	14.2	0.6	27.2
2	14.6	0.6	27.7
3	11.8	1	21.3
4	14.3	0.6	28
5	14	0.6	28
6	14.6	0.6	27.6
7	14.2	0.6	27.2
8	12	0.6	25.9
9	11.3	0.3	32.7
Average	13.5	0.6	27.3

Table 10: S/N comparison factor response.

	A	B	C	D
Level 1	25.4	27.5	26.9	29.3
Level 2	27.9	27.2	29.5	27.5
Level 3	28.6	27.2	25.5	25.1
E^{1-2}	-2.5	0.3	-2.6	1.8
E^{1-2}	-0.7	0	4	2.5
Range	3.2	0.3	4	4.2
Rank	3	4	2	1
significant	yes	no	yes	yes

Table 11: Variance Analysis.

Factor	SS	DOF	Contribution	Var
A	100.39	2	28.10%	
B	0.72	2	0.20%	
C	147.18	2	41.20%	
D	90.94	2	25.45%	
Error	18.04	45	5.05%	0.401
Total	357.27	53	100.00%	

Conclusion

This study has successfully applied an innovative magnetic assisted film-forming process for in-mold decoration (IMD). A peel test was performed on a pre-heated polymer thin film laminated with a piece of plastic using magnetic assisted molding and has verified the feasibility of magnetic assisted film-forming in the IMD process. Factor C, the film thickness is the most significant factor to the bonding strength, contributing 41.2 %, and followed by preheating temperature, 28.1%, and holding time, 25.4 %. Future studies could focus on the applicability of the magnetic assisted molding machine to 3D product manufacturing, and it may help break through current bottleneck in 3D IMD process.

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