EVALUATING EXTRUSION COMPRESSION MOLDING FOR IMPARTING BETTER SURFACE FINISH IN LONG FIBER THERMOPLASTICS USING IN-MOLD FILM TECHNOLOGY

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Abstract

Automotive applications of compression molded products with a thermoplastic matrix have been growing rapidly within the last few years, as demonstrated by increased use in applications including front-ends, bumper beams, dashboards, and under body shields. Long fiber thermoplastics (LFTs) have received much attention due to their processability by conventional technologies. However, applications of LFT materials have been limited in external body parts that require a good surface finish. Painting LFT parts is rare and requires considerable equipment investment. Further, painting is often associated with environmental concerns such as Volatile Organic Compounds (VOCs) and high energy consumption.

This paper innovates the process of extrusion compression molding for long fiber thermoplastic parts by placing a film (with a thermoplastic olefin backing) in-mold that melt bonds to the LFT material. This results in a compression molded LFT part that has the nice surface finish required for exterior applications.

In order to evaluate the process, variables potentially contributing to the surface quality are identified and analyzed. A Design of Experiments is carried out to investigate thoroughly yet economically the effect of four process variables. Gloss, chip resistance, and adhesion of film to substrate are tested according to ASTM standards. These test results are used to evaluate the effect of the processing variables considered and to establish optimum operating parameters.

KEYWORDS: Long Fiber Thermoplastics (LFTs), Design of Experiment (DOE), Surface Film/Sheets, Class A Surface Finish, Composites

Introduction

Long fiber thermoplastic (LFT) materials are a family of compounds that incorporate fibrous fillers as reinforcement into a wide variety of crystalline and amorphous thermoplastic matrices.

The fibrous fillers in the LFT material are often glass fiber. Depending upon the end application, LFT materials can also include carbon, aramid, and stainless steel fibers as filler. Thermoplastic matrices in the LFT material range from the polyolefin and polyamide families to other high-performance engineering thermoplastic polymers. The length of the fiber is between 1 to 40 mm and is often determined by the process that is used to mold the final part [1, 2]. The position of LFT materials in the field of fiber reinforced plastics is shown in Figure 1.

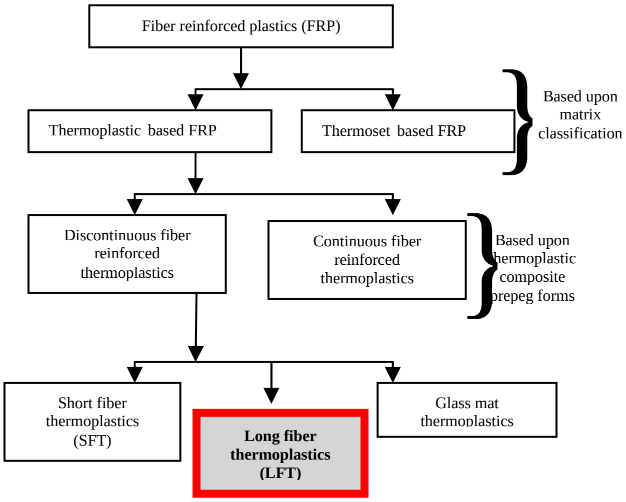


Figure 1: Position of LFT Materials in the Field of Fiber Reinforced Plastics

Compared to short fiber thermoplastics, for which the fiber length is less than 2 mm, LFT materials offer advantages including superior mechanical properties, reduced tendency to creep, improved toughness at low and high temperature and improved flexural modulus. Compared to metals, LFT materials are lighter in weight, more resistant to corrosion and chemicals, and are able to fill complex geometries. Further, LFT materials have higher toughness, lower resin prices, better damping resistance, intrinsic recyclability, high volume processability, shorter manufacturing cycle times and longer shelf life than thermoset composites. As a result of the above benefits, LFT materials are getting more consideration for structural applications [3].

However, polypropylene-based LFT materials have not yet been used to their full potential. Das et al have reported paintability of polypropylene-based LFT materials, but the ability to paint LFT materials economically at production scale remains a challenge [3, 4]. Painting is complex, costly and highly polluting. A paint line for an automotive plant can require an investment of up to $500 million [5].

Due to the fact that structural applications often have cosmetic requirements, use of LFT materials has been limited. Recently, original equipment manufacturers are showing desire to explore alternatives to current paint and coating technology to allow the incorporation of advanced materials to meet property enhancement needs. This market pull has led to many advances [6] in the field of process technology to color thermoplastic / thermoplastic composite materials. However, most of the processes still have limitations. Recently investigated techniques include co-extrusion (limited to continuous profiles), co-injection (limited to non-structural applications), in-mold process using dry film/sheets (limited to simple geometry), insert molding using dry film/sheets (capital intensive), insert molding of co-extruded film/sheets (limited to non/semi-structural applications), thermoformed co-extruded sheets (limited in achieving class A finish) and mold in color with clearcoat (still uses coatings) [6]. Arthur Delusky et al have also reported on the Valyi surface finishing/compression molding process for short fiber and long fiber thermoplastic composite materials [7, 8, 9].

This paper explores the extrusion compression molding of paintless film/sheet inserts, also sometimes referred to as paintless film molding (PFM) in the automotive industry [10]. This process is compatible with polypropylene-based long fiber thermoplastic materials with available paintless film technology in the market. The process is applicable to structural or semi-structural parts, gives a surface finish that is close to class A, is environmentally friendly (materials have no volatile organic components and are recyclable) and tooling costs are minimal.

To investigate the feasibility of extrusion compression molding of film inserts, polypropylene-based flat LFT panels with films are molded using an extrusion compression molding process. Process variables potentially influencing film behavior during the extrusion compression molding process are identified as temperature of film prior to processing, residence time in compression mold, glass content of LFT material and film source. Design of Experiments with three levels is used to evaluate the effect of each of these variables within a practical number of processing runs. The panel properties tested include film gloss, chip resistance and adhesion of film to polypropylene-based LFT substrate.

Material and Process Identification

25 mm polypropylene-glass based LFT pellets were supplied by Ticona for use in the study. Length of LFT material was chosen to be 25 mm rather than the 12.5 mm alternative (both available commercially) as the former has better or similar mechanical properties. Polypropylene matrix is chosen because of its wide use in the automotive market (low cost and low weight). Fiberglass is selected as it is one of the most commonly used reinforcements in LFT materials for many applications. Further, glass sizing is well developed for the polypropylene matrix.

TPO-based backbone films supplied by Solvay and A. Schulman were selected to allow melt bonding with the polypropylene-based LFT material. Also, the material properties are compatible with the requirements of most automotive exterior car part applications.

Extrusion compression molding process was selected to maintain fiber length during processing in comparison to other available LFT processing technologies. The increased fiber length in the final product yields greater mechanical properties. Other criteria include low tooling cost and the ability to make structural and semi-structural parts.

Process of Extrusion Compression Molding Process and Tooling

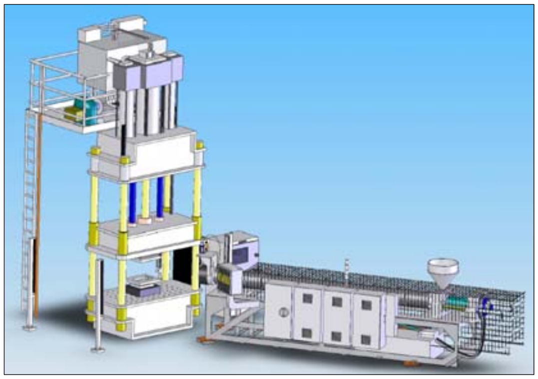


Figure 2: 150 mm Barrel Size Plasticator

LFT pellets (glass-polypropylene combination) are introduced into a 150 mm barrel diameter Lawton Plasticator (Figure 2). The low shear screw of the plasticator melts the LFT pellets with heat action and shear force of the screw without degrading the glass fiber, therefore maintaining fiber length. The melted LFT pellets are discharged from the plasticator in the form of a slug. The slug is manually transferred to the flat panel compression mold. The film is then placed on top of the slug and the material combination is immediately compression molded (Figure 3). The slug is converted to a flat panel under pressure with a film adhered to it.

The hydraulically heated flat panel compression mold (Figure 3) can produce 9.5 inch by 23.5 inch flat panels (Figure 4). The thickness of the flat panels can be varied from 0.15 inches to 0.50 inches. The mold features hydraulic ejectors at six different points to reduce local stresses.

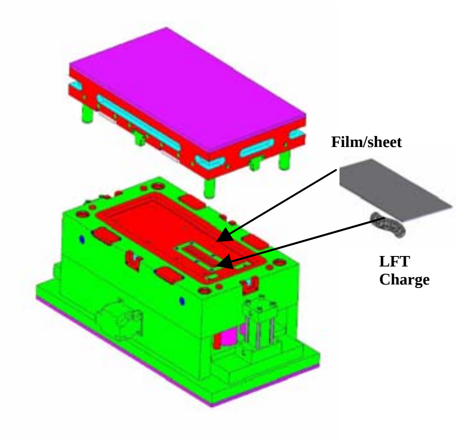
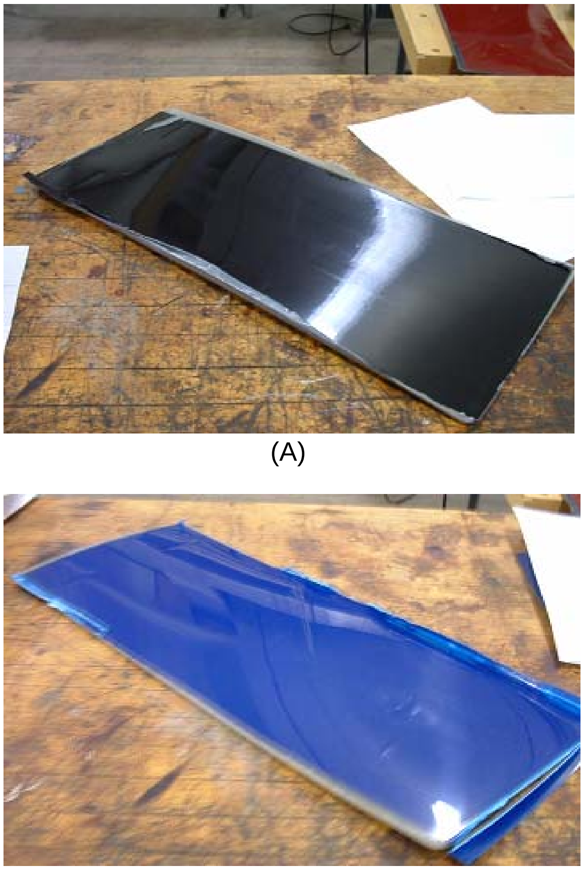


Figure 3: Flat Panel Processing of LFT Pellets with Films



(A)

(B)

Figure 4: Extrusion Compression Molded Flat LFT Panels with Paintless Films (A: Black, B: Blue)

Extrusion Compression Molding Process Variables

Process variables potentially affecting the film behavior during the extrusion compression molding process are identified as film temperature, thickness of film, residence time in compression mold, glass content of LFT material and film supplier.

Design of Experiment

Design of experiments was used to thoroughly evaluate the affect of each process variable while efficiently utilizing available resources. Being an independent project, commercially available films were selected from two film suppliers currently available in the market. Two design of experiments were completed separately for the two film suppliers. Reasons for having two independent design of experiments is explained as follows.

Films from Supplier I (Solvay) was available in only 1 thickness and therefore there were three process variables (temperature, residence time, film temperature) that required investigation. The two level full factorial matrix DOE is chosen for supplier I as it is efficient for evaluating the three process variable conditions.

Films from supplier II (A Schulman) were available in three different thicknesses. So there were four process variables (temperature, residence time, film temperature, film thickness) that required investigation. And for that three level Box and Behnken DOE style was determined to be efficient and therefore used.

Three levels were chosen for each of the three variables to enable identification of quadratic effects for films from supplier I (Table 1). Three levels were also chosen for each of the four variables for films from supplier II (Table 2).

Table 1: Factors and Levels for Film from Supplier I

Factors	Level 1 (-1)	Level 2 (0)	Level 3 (1)
Residence time in mold (seconds): A	60	180	300
Glass Content (% weight) : B	10	30	50
Film Preheat Temperature (ºC) : C	0	25	50

Table 2: Factors and Levels for Film from Supplier II

Factors	Level 1 (-1)	Level 2 (0)	Level 3 (1)
Residence time in mold (seconds): A	60	180	300
Glass Content (% weight) : B	10	30	50
Film Preheat Temperature (ºC) : C	0	25	50
Film Thickness (mm) : D	0.43	0.76	1.52

A full factorial approach considering all levels for each variable would require a total of 108 experimental runs for the two design of experiments. This number of runs was not feasible due to the limited amount of material, time and money; therefore, a more efficient method was required.

For films from supplier I, a three variable, two level full factorial matrix was established to minimize runs. Three center point runs were added to incorporate the intermediate levels of each variable while maintaining a practical number of runs. This allows main effects (three degrees of freedom (DOF)), two variable interactions (three DOF), three variable interactions (one DOF), curvature (one DOF) and experimental error (two DOF) to be captured. Eleven experimental runs allowed the mean effect and ten other variables to be discriminated. Table 3 on the next page outlines the design of experiment matrix for film supplier I.

For films from supplier II, a four variable, three level Box and Behnken style design was used. This type of design of experiment allows main effects (four DOF), two factor interactions (six DOF), quadratic effects (four DOF) and experimental error (four DOF) to be estimated using only 29 runs. The design of experiment matrix for film supplier II is illustrated in Table 4.

Table 4: Variables and Levels for Films from Supplier II

Film II: Box-Behnken				
Std Run Order	A	B	C	D
B1	0	0	0	0
B2	-1	-1	0	0
B3	1	-1	0	0
B4	-1	1	0	0
B5	1	1	0	0
B6	0	0	-1	-1
B7	0	0	1	-1
B8	0	0	-1	1
B9	0	0	1	1
B10	-1	0	-1	0
B11	1	0	-1	0
B12	0	0	0	0
B13	0	0	0	0
B14	0	0	0	0
B15	-1	0	1	0
B16	1	0	1	0
B17	0	-1	0	-1
B18	0	1	0	-1
B19	0	-1	0	1
B20	0	1	0	1
B21	-1	0	0	-1
B22	1	0	0	-1
B23	-1	0	0	1
B24	1	0	0	1
B25	0	-1	-1	0
B26	0	1	-1	0
B27	0	-1	1	0
B28	0	1	1	0
B29	0	0	0	0

Table 3: Variables and Levels for Films from Supplier I

Film I: A three variable, two level full factorial matrix with center point consideration			
Std Run Order	A	B	C
A1	-1	-1	-1
A2	-1	-1	1
A3	0	0	0
A4	1	-1	-1
A5	0	0	0
A6	-1	1	-1
A7	-1	1	1
A8	0	0	0
A9	1	1	1
A10	1	-1	1
A11	1	1	-1

Standard Test Methods

The panel properties tested include film gloss, chip resistance and adhesion of films to polypropylene-based LFT substrate.

Adhesion testing was performed in accordance with ASTM D4541: Standard Test Method for Pull-off Strength of Coatings using portable adhesion testers. The surface is lightly abraded with sandpaper and a ring is milled through the coating down to the substrate, with the inside diameter of the ring being equal to the outside diameter of the pull-off stud.

The chip resistance of the film surface of each molded panel was measured using a Q-panel model MTG gravelometer in accordance with ASTM D3170: Standard Test Method for Chipping Resistance of Coatings.

The specular gloss was determined using a BYK Gardner model 4528 micro-TRI-gloss meter in accordance with ASTM D523: Standard Test Method for Specular Gloss.

Results

Smaller test specimens as defined by ASTM standards were cut from each of the molded flat plaques using a diamond coated band saw.

Adhesion testing was performed on 200 test specimens. The adhesion test results showed that the film from supplier II pulled off at an average of 700 to 800 psi with the predominant failure occurring at an intermittent layer (Figure 5). For film supplier I, the adhesive used to secure the studs to the samples failed before the film or substrate.

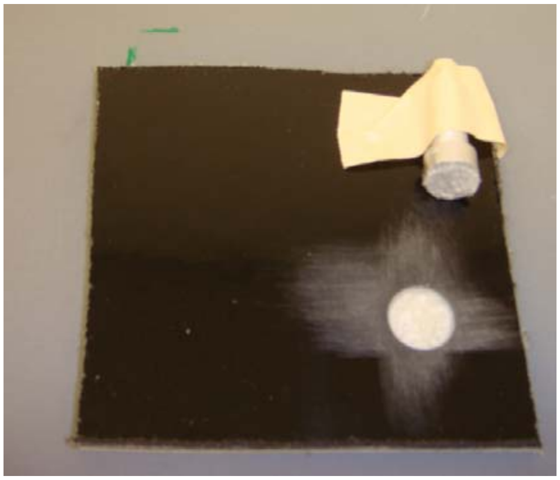


Figure 5: Adhesion Test Predominant Failure occurring at an Intermittent Gray Layer

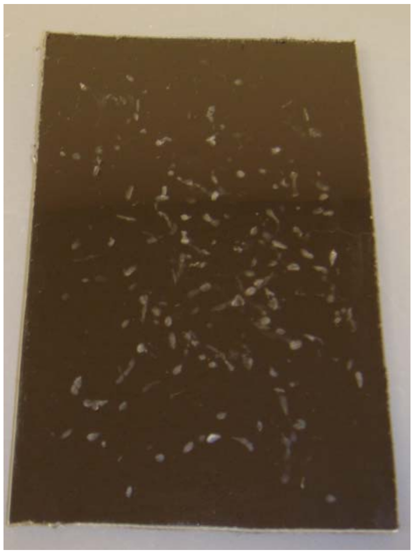


Figure 6: Heavy Marring on Test Specimens

The chipping resistance tests were performed on 120 specimens. None of the films produced any chipping during the test; however, heavy marring was observed on all test specimens as well as some instances of tearing/rupturing in the impact areas (Figure 6).

Specular gloss was measured on 320 specimens. Gloss measurement data is measured on a scale of 0 to 100 with 100 being a surface with 100% gloss and 0 being a gloss free surface. Each specimen was measured for gloss by taking four measurements with a 90° rotation of the gloss meter after each measurement, and then averaging the four measurements. The gloss of each system was calculated as the average gloss of the eight specimens comprising the system. The 60˚ gloss readings averaged in the mid to high 80's. Lower readings were attributed to scratching/marring present on the test surfaces prior to measurement.

Analysis

Analysis of films from Supplier I

The gloss data from the three variable design of experiment for films from supplier I was considered in an analysis of variance (ANOVA) which included main effects, two and three variable interactions as well as a curvature term. Using a 95% level of significance, only film preheat temperature (variable C) was statistically significant. Figure 7 illustrates the effect of variables (factors). Variable A and B had negligible effect.

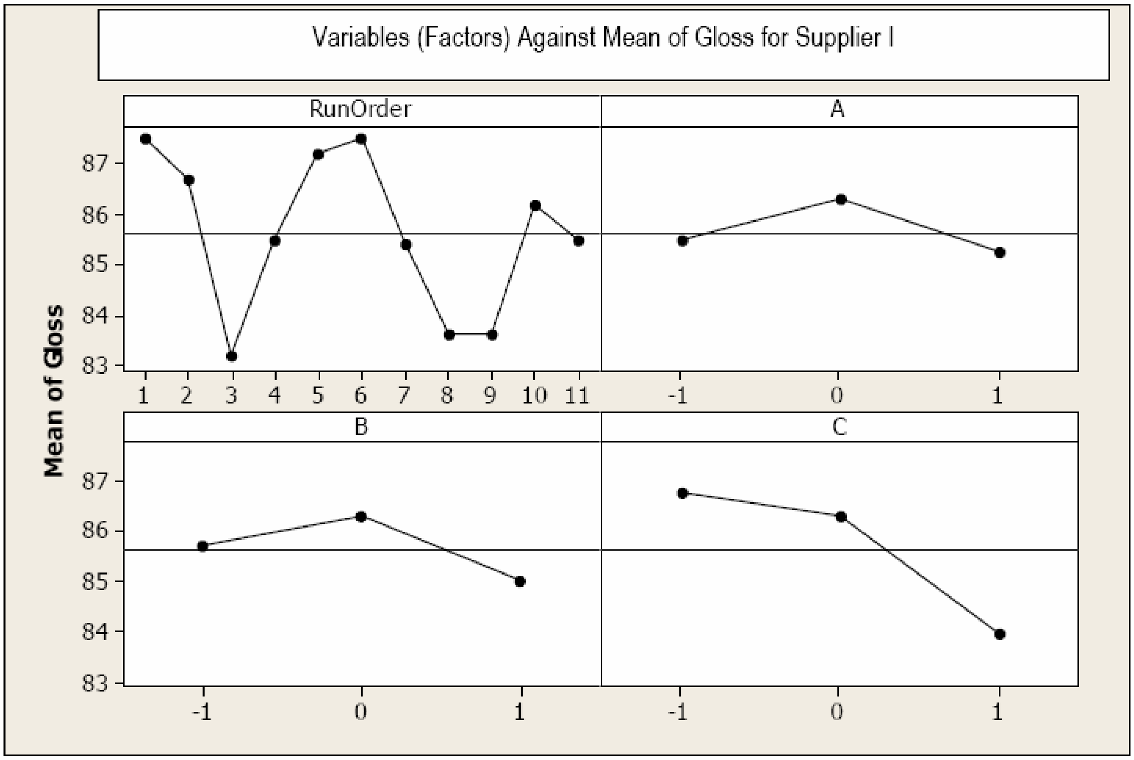


Figure 7: Variables (Factors) Against Mean of Gloss for Supplier I

Chipping did not occur in films from supplier I. Although marring was observed on all of the panels, the size and amount of damage was consistent for all panels independent of changes in process parameters.

Design of experiment for the adhesion testing for the films from supplier I indicated that the adhesive used for the test fixture was not sufficient to fail the film or the film to substrate bond. A maximum of 614 psi and minimum of 483 psi were obtained for the samples. The observed failure mode for these specimens invalidates the test procedure and results were not statistically analyzed.

Analysis of films from Supplier II

An ANOVA which included main effects, two variable interactions and quadratic effects was performed for the four variable design of experiment for film supplier II. A 95% level of significance was used for discriminating variables. Film preheat temperature (variable C), film thickness (variable D) and their interaction CD were significant. Using a least squares fit for these coded variables, the gloss level as a function of film preheat temperature and film thickness is defined in Equation 1.

$$\text{Gloss Level} = 77.24 + 9.72C + 8.33D - 11.8CD \qquad (1)$$

The significant main effects and interactions for the four variable design of experiment for film supplier II are plotted in Figures 8 and 9, respectively.

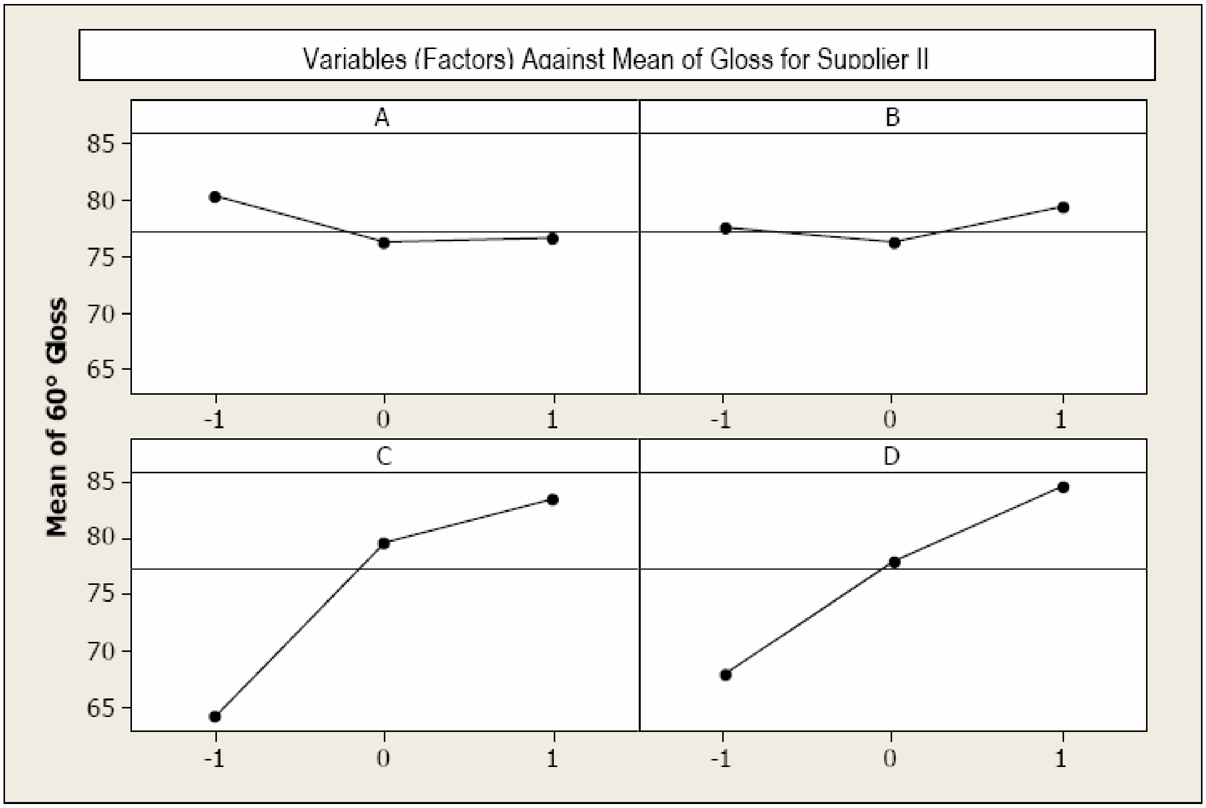


Figure 8: Variables (Factors) Against Mean of Gloss for Supplier II

Chipping did not occur in any of the samples from either film supplier. Although marring was observed on all of the panels, the size and amount of damage was consistent for all panels independent of changes in process parameters.

ANOVA results for the film supplier II adhesion data indicate again that film preheat temperature (variable C) and film thickness (variable D) are significant. Figure 10 is a plot of these mean effects. Two of the data points referred to specimens having unacceptable failure modes; if these two points are replaced by an average value for all of the data points (714 psi), the effect of film thickness (variable D) shown in Figure 11 changes considerably.

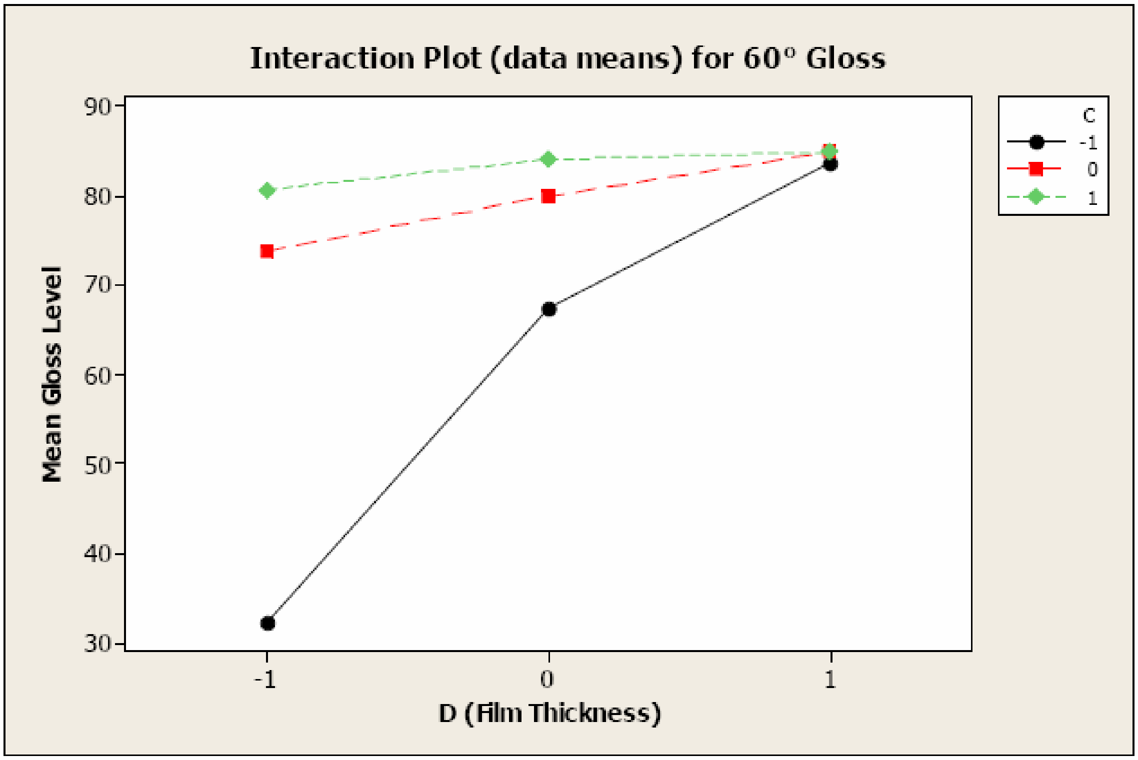


Figure 9: Two Factor Interaction versus Gloss Levels

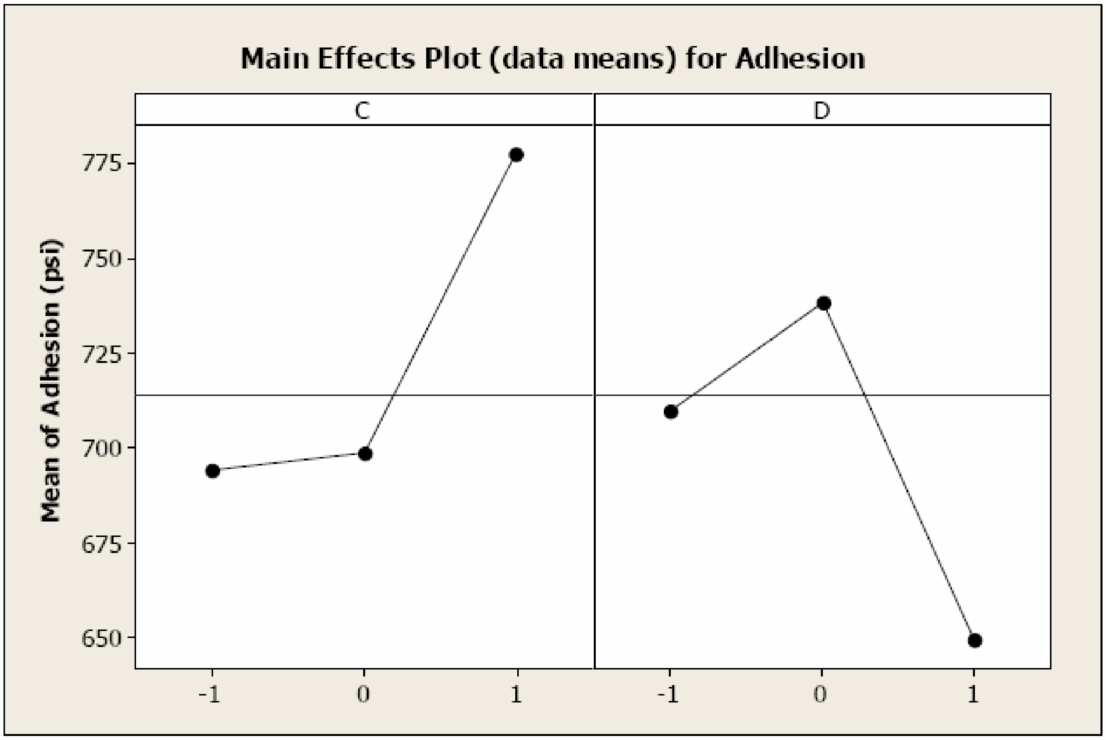


Figure 10: Preheat Temperature and Film Thickness versus Adhesion

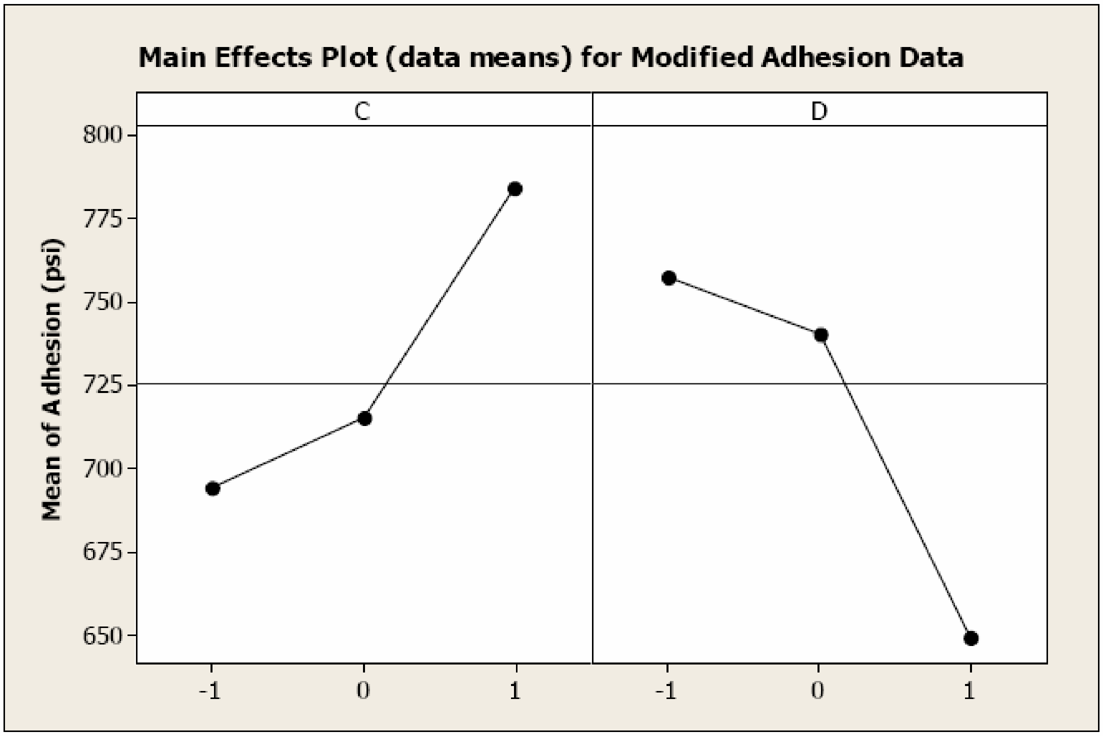


Figure 11: Preheat Temperature and Film Thickness versus Modified Adhesion Data

Application development of the film and LFT material combination

In order to check the practicality of using films for an end application, a LFT compression molded battery bus door part (508mm X 956mm) is chosen to apply the in-mold film-extrusion compression molding technology. Figure 12 shows the comparison. The white door is an extrusion compression molded door that is painted later, and the red door is an extrusion compression molded door that has the in-mold film technology. The film conformed to the battery bus door tool readily. Film surface maintained its properties. However sink marks on the surface of the film were seen along the rib structure of the battery bus door.

Figure 12: Comparison of paint and in-mold film battery box door

Summary

Extrusion compression molding can be easily adopted for in-mold paintless film molding. The process suits both structural and semi-structural parts. This process is also capable of producing good surface finish without significant tooling investment. Further, it has negligible VOC emissions. The adhesion of the films is encouraging, and chipping is proven not to be a concern.

Residence time in mold (Variable A) and glass content in LFT material (Variable B) did not have a statistically significant effect on any of the three responses with the levels investigated. Therefore, materials with different glass contents can be run without changing processing parameters or film properties. However, orange peel might be an issue with the increase in high glass content which was not investigated but was observed with naked eye.

For film supplier I, the only significant effect was the film preheat temperature (Variable C). The data indicated that using the lowest level (0°C) was best for the gloss rating. This tells us that the top layer of the film (supplier I) is made out a material that would reduce its gloss value with the increase in the film temperature.

For film supplier II, gloss readings indicated that choosing level 1 for both variables C and D (50°C film preheat temperature and 1.52 mm film thickness) will give the best gloss readings. Better gloss reading is related to higher thickness of the film because higher thickness insulates the glossy surface of the film from the hot LFT charge that is placed at the top of the film.

Adhesion main effects results support using level 1 for variable C (50°C film preheat temperature) and level -1 for variable D (0.43 mm film thickness). The difference in the recommended film preheat temperatures for the two suppliers is attributed to the interaction between film thickness and preheat temperature for supplier II. Fortunately, due to this strong variable interaction for the gloss response, if the level for 0.43 mm film thickness is used the gloss level is only negatively affected by 4 points. Therefore, for film supplier II, preheating the thinnest film (0.43 mm) to 50°C is recommended to maximize both gloss and adhesion of film to the LFT substrate. Another possibility for the difference in the recommended film preheat temperatures might be attributed to the difference in the chemistry of the two films.

Future work will be necessary to address the extensive marring resulting from the chipping resistance test. In addition, applying the process to complex geometries will require further optimization. However, the present work identifies in-mold paintless film extrusion compression molding as a promising technology for enhancing the surface finish of long fiber thermoplastic materials for automotive applications.

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