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Enhancing the Surface Finish of LFT Compression Molded Parts via Application of Surface Film

by

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Abstract

Long Fiber Thermoplastics (LFTs) has been one of the fastest growing material technologies for automotive applications over the past few years. However, its use in structural and semi-structural applications requiring a close to Class A surface finish has been limited due to the fact that painting LFT material is complex, costly and harmful to the environment. This paper considers the current film/sheet technology for imparting a desirable surface finish to LFT materials. Polypropylene-based flat LFT panels with surface film/sheets are molded using an extrusion compression molding process. Process variables potentially affecting the film behavior during the extrusion compression molding process are identified as film temperature, residence time in compression mold, glass content of LFT material, and film source. Design of Experiments (Box-Behnken and Full Factorial) with three levels is used to evaluate the effect of each of these variables in an efficient manner. The panel properties tested include film gloss, chip resistance and adhesion of films to polypropylene-based LFT substrate. This report identifies the relationship of the processing variables with these end properties seen in the LFT panels having a near to "Class A" finish.

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

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 most often glass fiber. Depending on 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.

Compared to short fiber thermoplastics, 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 weight, more resistant to corrosion and chemicals, and are better 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 more frequently being considered 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. Setting up of a paint line for an automotive plant can cost up to $500 million [5].

Due to the fact that structural applications often also have cosmetic requirements, use of LFT materials in this field has been limited. Also, original equipment manufacturers have started showing desire to explore alternatives to current paint and coating technology. Although many advances [6] in the field of process technology have been reported, each process still has limitations. Recently investigated techniques include co-extrusion (limited to continuous profiles), co-injection (limited to 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 can be easily used for 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 Selection

25 mm polypropylene-glass based LFT pellets were supplied by Ticona for use in the study. Polypropylene matrix is chosen because of its wide use in the automotive market (low cost and low weight). Fiberglass is chosen 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.

Films supplied by Solvay and A. Schulman were selected on the basis of a TPO-based backbone so that it melt bonds 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 is selected as it helps to maintain fiber length during processing to a greater extent than 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.

Description of Extrusion Compression Molding Process and Tooling

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 placed atop 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 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.

Process Variables in Extrusion Compression Molding

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 is used to thoroughly evaluate the affect of each variable while efficiently utilizing the resources for this study. Two design of experiments are completed separately, one for each of the two film suppliers. The design of experiments investigates three process variables for film supplier A (Solvay) and four processing variables for film supplier B (A. Schulman). The three variables common to both design of experiments are residence time in mold, glass content and film preheat temperature. The second supplier had several film thicknesses available; therefore, film thickness is the additional variable considered in the design of experiments for the second supplier.

Three levels were chosen for each variable to enable identification of quadratic effects. Table 1 lists the variables and levels for film supplier A. Table 2 outlines the variables and levels for film supplier B.

A full factorial approach considering all levels for each variable would require 34 and 81 experimental runs for the two design of experiments. This number of runs was not feasible due to the limited amount of time and material; therefore, a more efficient method was required.

For Supplier A, a three variable, two level full factorial with the addition of three center points was completed. 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 experiments allowed the mean effect and ten other variables to be discriminated.

For Material B, a four variable Box and Behnken style design was used. This type of design of experiments 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.

Test Methods

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

Adhesion testing is 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 is measured using a Q-panel model MTG gravelometer in accordance with ASTM D3170: Standard Test Method for Chipping Resistance of Coatings.

The specular gloss is 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 is performed on 200 test specimens. The adhesion test results showed that the A. Schulman films pulled off at an average of 700-800 psi with the predominant failure occurring at an intermittent layer (Figure 5). The films containing Solvay material will have to be reconsidered because the adhesive used for the pull off test failed around 400 psi, leaving the film still attached to the specimen.

Chipping resistance testing is performed on 120 specimens. None of the films exhibited 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 is measured on 320 specimens. The 60 degree gloss readings averaged in the mid to high 80's. Lower readings are attributed to scratching/marring present on the test surfaces prior to measurement.

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 and a curvature term. Using a 95% level of significance, only film preheat temperature (variable C) was statistically significant. Figure 7 illustrates the main effects of the variables (factors). Variables A and B had negligible effect.

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.

For supplier I films, the adhesive used for the test fixture was not sufficient to fail the film or the film to substrate bond. A maximum pull-off strength of 614 psi and minimum of 483 psi are observed; however, failure mode for these specimens invalidates the test procedure and results are not statistically analyzed.

Analysis of Films from Supplier II

An ANOVA which included main effects, two variable interactions and quadratic effects is 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.

Chipping does not occur in any of the samples from either film supplier. Although marring is observed on all of the panels, the size and amount of damage is 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 refer 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.

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 the need of 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 of the LFT material (variable B) do 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 is not investigated but is observed.

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

For film supplier II, gloss readings indicate that choosing level 1 for both variables C and D (50°C film preheat temperature and 1.52 mm film thickness) will yield the best gloss results. Better gloss reading is related to increased thickness of the film because increased 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 four 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 LFT substrate. The difference in the recommended film preheat temperatures may also 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 testing. 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.

Authors

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Uday Vaidya, PhD is a Professor of Materials Science & Engineering. He serves as the Principal Investigator on the bus program at UAB School of Engineering sponsored by the Department of Transportation. UAB and the NCC often collaborate on long fiber thermoplastic technology programs.

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Table 1: Variables and Levels for Film Supplier I

Film/Sheet I: Full Factorial			
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

Table 2: Variables and Levels for Film Supplier II

Film/Sheet 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

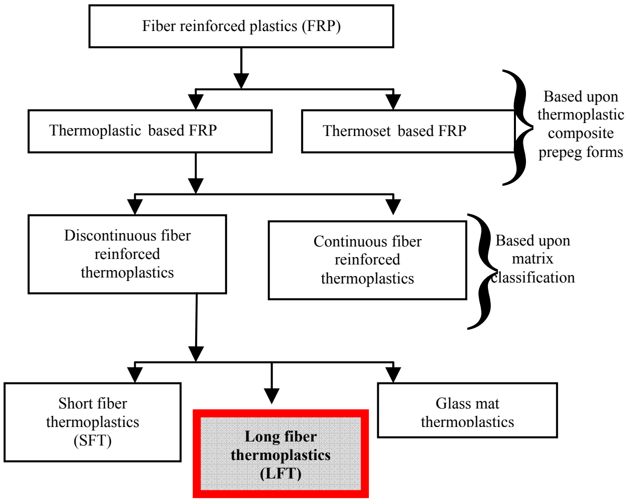

Figure 1: Position of LFT Materials in the Field of Fiber Reinforced Plastics

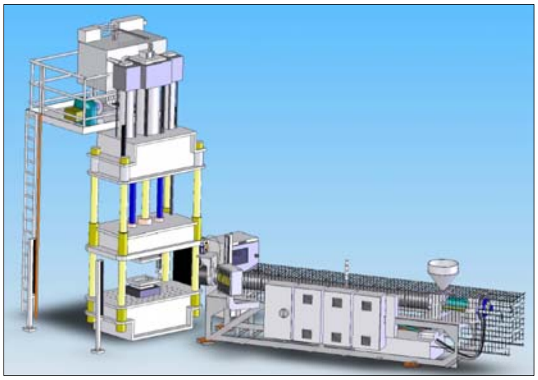

Figure 2: 150 mm Barrel Size Plasticator

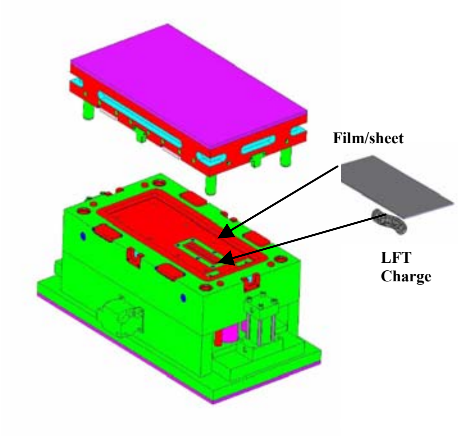

Figure 3: Flat Panel Processing of LFT Pellets with Film/Sheets

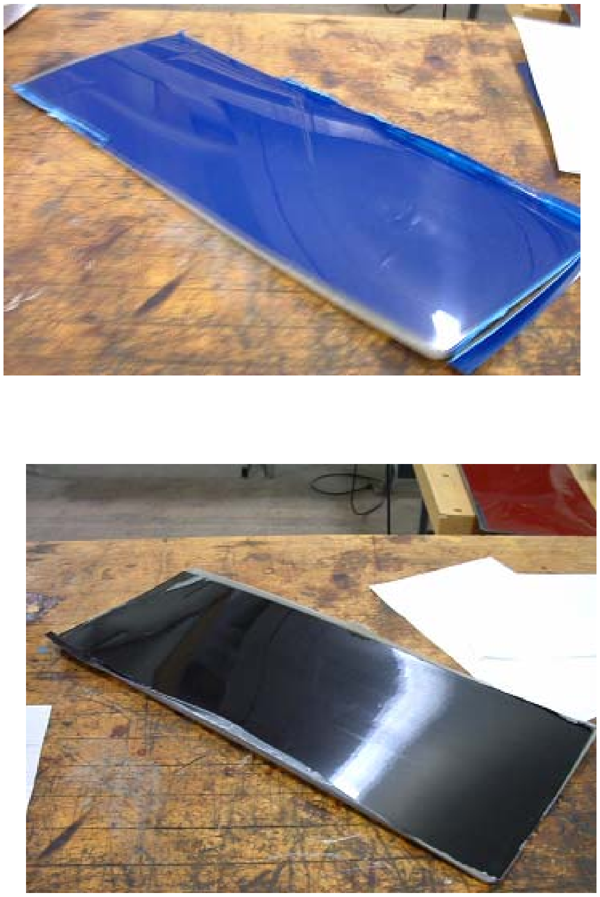

Figure 4: Extrusion Compression Molded Flat LFT Panels with Paintless Films (A: Blue, B: Black)

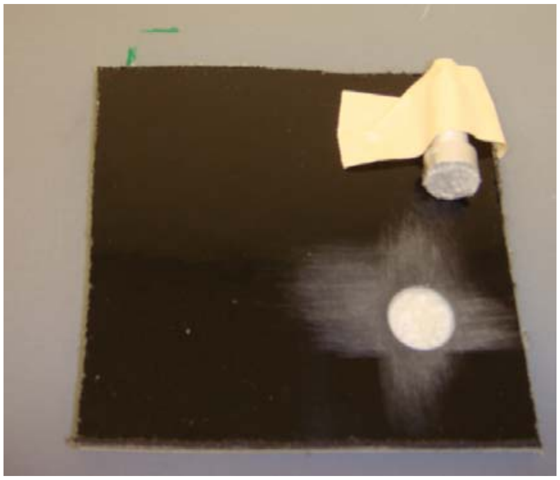

Figure 5: Supplier I Film Pulled Off at an Average of 700-800 psi with the Predominant Failure occurring at an Intermittent Gray Layer

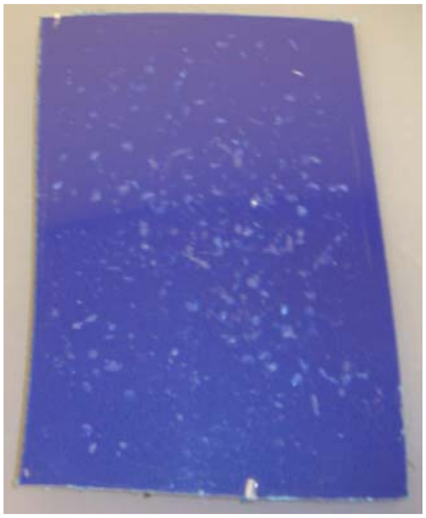

Figure 6: Heavy Marring on Chipping Resistance Test Specimens

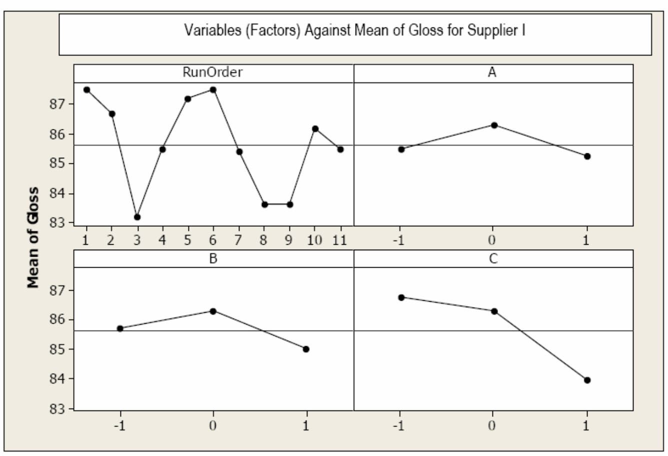

Figure 7: Variables (Factors) Against Mean of Gloss for Supplier I

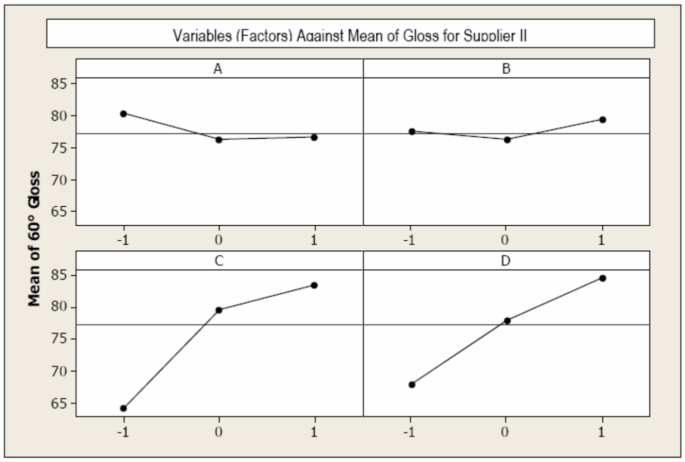

Figure 8: Variables (Factors) Against Mean of Gloss for Supplier II

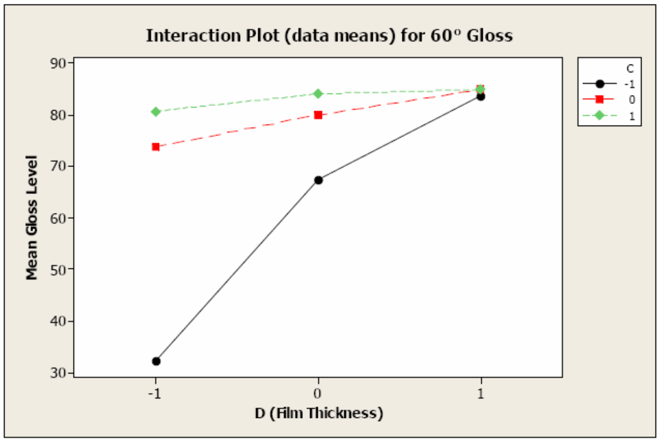

Figure 9: Two Factor Interaction versus Gloss Levels

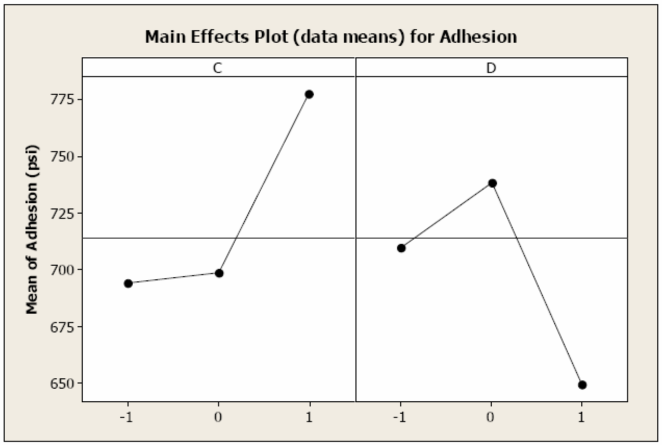

Figure 10: Preheat Temperature and Film Thickness versus Adhesion

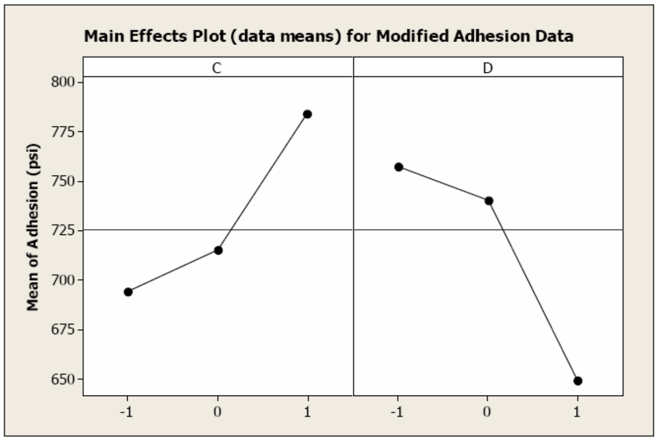

Figure 11: Preheat Temperature and Film Thickness versus Modified Adhesion Data