SURFACE APPEARANCE CATEGORIZATION OF SHEET MOLDED COMPOSITES

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ABSTRACT

Composites are often used in applications where surface appearance is an important attribute to the final product, such as a painted Class A body panel on an automobile or the gel-coated hull of a composite boat. Composite manufacturers are faced with the challenge of optimizing the surface appearance of the part while maintaining the other product requirements such as strength or weight. Changes to the composition of the formulation or process conditions often lead to changes in surface appearance. Appearance has typically been evaluated by visual inspections which are inherently subjective to the individual inspecting. Because of this, manufacturers struggle with determining if proposed changes have a significant effect on the surface appearance of their product. This paper will provide examples of the use of a deflectometry measurement instrument combined with a statistical choice modelling method to provide definitive rankings of parts with varying degrees of surface appearance. It will also be shown how this technique can be used in design of experiments to evaluate the effects of process and formulation changes on the appearance of the final part.

1. INTRODUCTION

Composites have been used in automotive body panels since 1945 and most notably with GM's introduction of the Corvette in 1953. As the demand for vehicle electrification increases, manufacturers continue looking toward lighter weight options such as composites to replace steel. Painted steel sets the standard for surface appearance of an automotive body panel. The goal when using alternative materials, such as sheet molding compound (SMC), to produce a body panel is to achieve the same flatness, smoothness, and reflection of a painted stamped metal part. An acceptable surface is termed a Class A surface. An advantage of using composites is the ability to formulate with different resins, additives, fillers, and reinforcement materials to optimize desired properties such as strength or material density. Surface appearance is often adversely affected as other properties are improved. The goal of the formulator is to maintain a Class A surface while optimizing for the other performance properties.

Several challenges exist when evaluating surface quality. First, currently utilized testing methods and devices are focused primarily on painted surfaces. Secondly, accepted methods such as surface roughness of an unpainted surface have limited usefulness due to testing area and impact to the tested surface. Additionally, most outer body panel specifications generally include a human observation aspect and require the creation of boundary samples for future reference. The existing analytical methods are limited in scope and focused primarily on painted surfaces. The visual techniques and methods can be taught and ultimately rely on an expert and boundary samples. Industry desires specificity and accuracy. A set of devices and methods to evaluate painted and unpainted surface areas, able to assign numerical representations of quality, and can be utilized by novice and expert users with identical results, would be an ideal improvement.

One of the challenges is the evaluation of the surface quality. There is not an industry recognized standard test method. In addition, there are several different technologies that measure different aspects of the surface. These measurements don't often correlate with human visual inspection, and visual inspection is not consistent between people. Final surface grades and rankings are typically based on the consensus of a group of judges. This method of rating is not conducive to product development. A formulator will use design of experiments (DOE) to evaluate the effects of material changes on the final molded part properties. A single DOE can generate a significant number of panels. For example, a standard two-level full factorial design used to evaluate three group of judges provide a consensus ranking of the panels each time a DOE is completed. In addition, the output from this method of evaluation is a categorical value or ranking. There is a loss in statistical power when analyzing categorical data, making it difficult to discriminate between results and determining if a material change has a significant effect on the surface appearance.

Core Molding Technologies and INEOS Composites jointly developed an SMC for a 1.2 specific gravity, 2 mm thickness, Class A body panel. This paper will present the steps taken to determine the effectiveness of deflectometry as a tool to accurately quantify the surface appearance of Class A surfaces. First, a gage study was completed with Class A SMC panels to understand the variation in the deflectometer. Second, several choice model studies were completed to determine if the output of the deflectometer aligned with the consensus of a panel of judges. The choice model technique will be described in this paper along with the results of several such studies. Finally, an example study will be presented demonstrating the use of a DOE to optimize the surface appearance of the final product based on the output of the deflectometer.

2. EXPERIMENTATION

2.1.Deflectometry

2.1.1.Equipment

A QualiSensor Test Plaque System was used to measure the surface appearance of the test parts. The QualiSensor consists of 12 MP fixed focus camera, 55” LCD screen, a mirror, and a desktop PC. The equipment is shown in Figure 1. The LCD screen, camera, and mirror are located in the top portion of the booth and are shown in Figure 2.

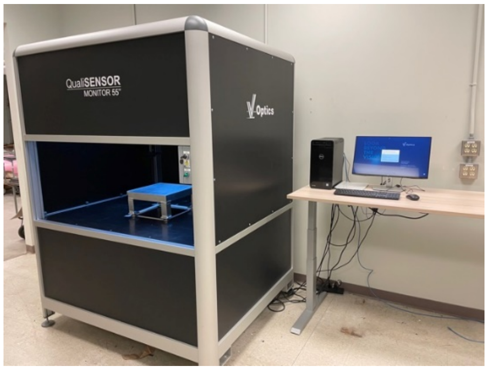


Figure 1. QualiSensor equipment.

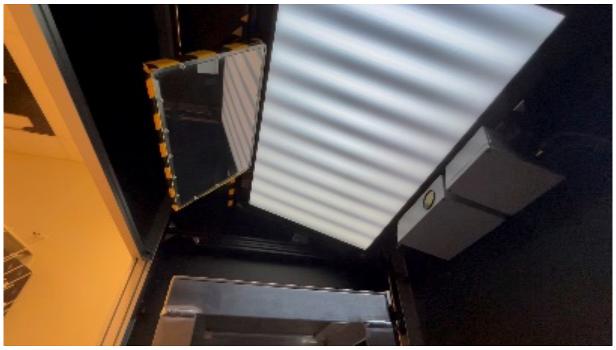


Figure 2. LCD screen, camera, mirror.

2.1.2.Principle of Deflectometry[1]

The surface analysis is based on a non-contact white light optical technique referred to as phase stepped deflectometry. A periodic sinusoidal waveform is projected by the LCD screen on the part to be measured. This image is reflected off the part to the mirror and captured by the camera. The pattern is projected in both the horizontal and vertical directions to calculate the elevation and curvature at all points on the surface. The reflection of light rays follows the Snell-Descartes law. The law stipulates that the angle of incidence and the angle of reflection are equal. On a perfect surface, the paths of the light rays are known. A distorted surface will cause the reflected rays to follow a different path and therefore have a different slope than the expected path. The software loaded on the PC generates the slope data based on the images captured by the camera during the pattern projections. The derivative of the slopes (dz/dx) of the surface is the curvature of the surface (d^2z/dx^2). The curvature maps of different samples can then be analyzed and compared to each other. To aid in the evaluation, the curvature maps are filtered into different wavelengths to characterize the roughness, waviness, and shape of the surface. The software is configured to provide summary statistics of the profiles filtered at five different wavelengths:

- A wavelength: 0.1 – 0.3 mm
- B wavelength: 0.3 – 1.0 mm
- C wavelength: 1.0 – 3.0 mm
- D wavelength: 3.0 – 10.0 mm
- E wavelength: 10.0 – 30.0 mm

The lower wavelengths characterize the roughness and orange peel of the surface and the larger wavelengths characterize the waviness and shape. The standard deviation of the curvature profiles is used to provide a quantitative value of the surface quality. A perfect surface would have a standard deviation of zero at all wavelengths.

2.2.Gage Study Class A panels

A gage study was conducted to understand the variability due to the measurement system. Three compression molded SMC plaques with different levels of agreed and known surface quality were measured using the deflectometer. Each plaque was measured ten times in random order by a single operator on two different days for a total of sixty readings. The standard deviation at each of the wavelengths A-E were recorded.

2.3.Choice Model Study[2]

Choice modeling is a powerful analytic method used to estimate the probability of individuals making a particular choice from presented alternatives. Choice modeling is also called conjoint choice modeling, discrete choice analysis, and conditional logistic regression. The specific study conducted is referred to as a MaxDiff study. Several judges were presented multiple sets of three samples called a choice set and asked to identify the best and worst sample in terms of surface appearance from each set. MaxDiff analysis uses the framework of random utility theory. A choice is assumed to have an underlying value, or utility, to respondents. The MaxDiff analysis estimates these utilities as well as the probabilities that one choice is preferred over other choices. Several MaxDiff studies were conducted to determine if this technique could be used to develop a consensus rank order of molded parts by visual inspection and develop a correlation between visual inspection and the deflectometer curvature values, at the various wavelengths.

2.3.1.MaxDiff analysis of flat plaques

The surface appearance of eight 30.5 cm x 30.5 cm flat plaques was measured using the QualiSensor. The standard deviation of the curvature profiles was recorded at each wavelength, A through E. These same panels were incorporated into a MaxDiff study. A total of eighteen judges from three companies completed the MaxDiff survey. The individuals possessed experience ranging from novice to expert and were employees of either the resin manufacturer, molder, or final customer. The survey consisted of a blind study including twelve different choice sets of three panels. The only markings on the plaques were handwritten letters. Each judge was asked to assign a value of one for the panel with the highest quality surface appearance of the set and a three for the panel with the worst surface. The remaining panel was assigned a rating of two. A sampling of the survey is shown in Table 1. Everyone recorded their results on a prepared test selection form which included the choice set number, the three panels for the choice set, and space to record the ranking of the three plaques. JMP 15.1, statistical software, was used to analyze the MaxDiff study and generate the utility factors for each panel. The resulting utility factors from the MaxDiff study were analyzed to fit models to the QualiSensor readings. The goal was to determine if the output of the instrument could be used as a replacement for visual inspection.

Table 1. Sampling of MaxDiff Study.

Judge	Choice Set	Panel 1-2-3	Panel 1 rating	Panel 2 Rating	Panel 3 rating
1	1	B-D-G	3	1	2
1	2	F-A-B	2	1	3
1	3	A-D-E	2	3	1
…	…	…	…	…	…
18	12	B-C-D	2	3	1

2.3.2.MaxDiff analysis of molded parts

A MaxDiff study was completed with actual molded, unpainted, component panels. The standard deviation of the curvature profiles was measured and recorded at each wavelength, A-E. The component panels were then used in a MaxDiff study where sixteen judges completed a twelve-choice survey. This study included a component panel with significant geometry and surface area, five different materials from Core Molding Technologies used in Class A applications, and alternate supplier's low-density Class A material. Additionally, the samples included two items of the proposed Core Molding Technologies material, and two items of the alternate supplier's low-density Class A material; all other material selections were single samples. In total, eight molded component panels were evaluated and ranked. As with the plaque study, this was blind, with the component panels marked only with letters as designation. Material type, molding condition, and manufacture information was not available to the evaluators. Of special note, this evaluation was carried out during the early stages of the Covid-19 lock down. The component panels were staged in an outside area, participants wore gloves, and social distancing was observed. The utility factors from the study were analyzed versus the deflectometer output to determine if the deflectometer could be used as a replacement for the visual inspection of parts and determine which of the filtered wavelengths were significant factors that correlate to visual inspection.

2.4.Surface Optimization DOE

A three-factor custom DOE was performed to determine the process molding conditions that optimize the surface appearance of the molded parts. The three factors evaluated were number of days after compounding the SMC prior to molding, part thickness, and charge placement. The levels of the DOE were as follows:

- Days after compounding: 1 day, 4 days, 8 days
- Part thickness: 2mm, 3mm
- Charge Placement: Center of mold, upper right corner of mold

Molding was performed using a 75-ton press with the following fixed molding parameters:

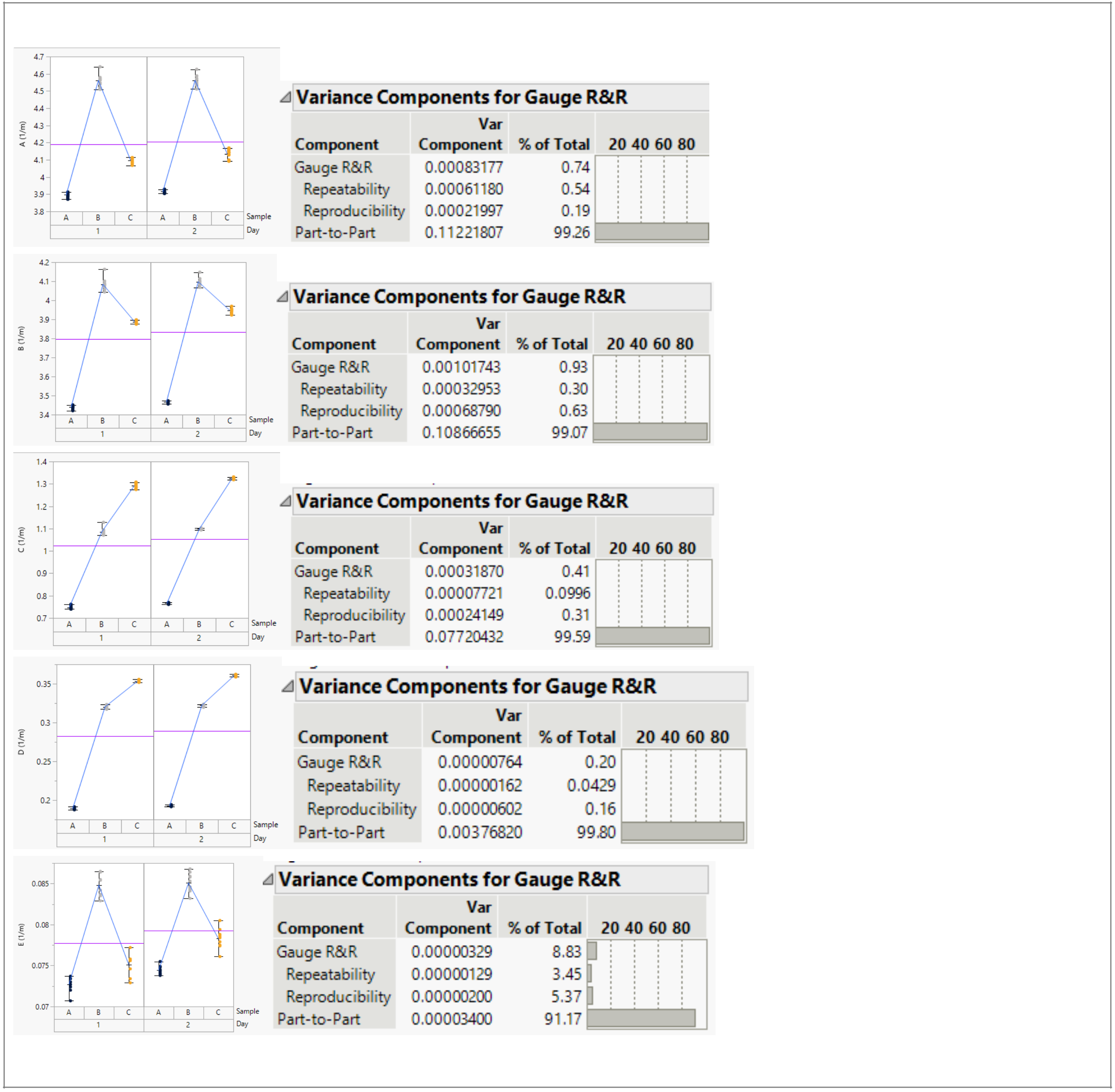
- Cavity temperature = 152 °C
- Core temperature = 149 °C
- Pressure = 35 US tons
- Time = 120 seconds
- Charge:
    - 3mm: 5 ply 6x6, 380g
    - 2mm: 3 ply 6x6, 230g

Thirty plaque samples were generated. Deflectometer readings were measured of all thirty samples and the standard deviations of the curvature profiles were recorded for wavelengths A-E. A model was fit for each of the wavelengths to determine which factors were significant factors toward improving surface appearance.

3. RESULTS

3.1.Gage Study Results

The gage study results of the curvature standard deviation values (1/m) from the deflectometer are given in the below figures. Results are presented for each of the filtered wavelengths A through E in Figure 3. In summary, the measurement test variation was less than 1% for all wavelengths except for the E wavelength which was 8.8% of the total. The increased total gage variation in the E wavelength can be further studied to evaluate theories for the difference.



Variance Components for Gauge R&R

Component	Var Component	% of Total	20 40 60 80
Gauge R&R	0.00083177	0.74	
Repeatability	0.00061180	0.54	
Reproducibility	0.00021997	0.19	
Part-to-Part	0.11221807	99.26	

Variance Components for Gauge R&R

Component	Var Component	% of Total	20 40 60 80
Gauge R&R	0.00101743	0.93	
Repeatability	0.00032953	0.30	
Reproducibility	0.00068790	0.63	
Part-to-Part	0.10866655	99.07	

Variance Components for Gauge R&R

Component	Var Component	% of Total	20 40 60 80
Gauge R&R	0.00031870	0.41	
Repeatability	0.00007721	0.0996	
Reproducibility	0.00024149	0.31	
Part-to-Part	0.07720432	99.59	

Variance Components for Gauge R&R

Component	Var Component	% of Total	20 40 60 80
Gauge R&R	0.00000764	0.20	
Repeatability	0.00000162	0.0429	
Reproducibility	0.00000602	0.16	
Part-to-Part	0.00376820	99.80	

Variance Components for Gauge R&R

Component	Var Component	% of Total	20 40 60 80
Gauge R&R	0.00000329	8.83	
Repeatability	0.00000129	3.45	
Reproducibility	0.00000200	5.37	
Part-to-Part	0.00003400	91.17	

Figure 3. Deflectometer test variation.

3.2.Choice Model Studies

3.2.1.Flat Panel Choice Model Study

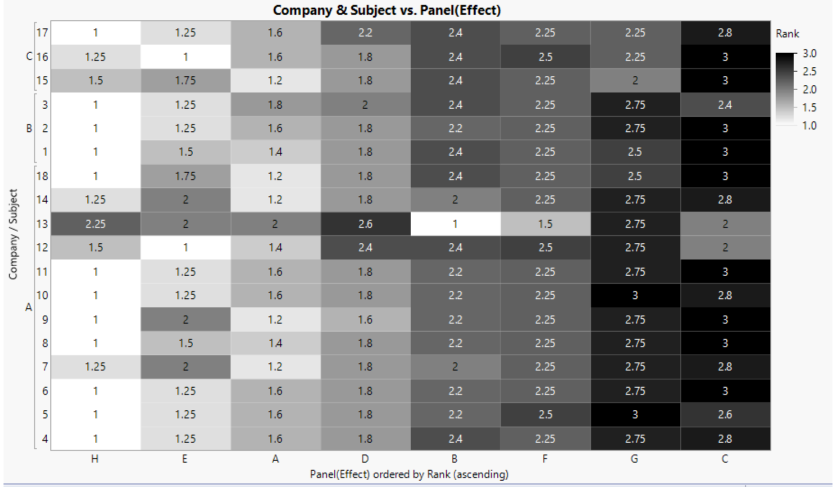
During development, SMC formulations are evaluated with SMC produced on a small-scale lab line. Flat panel plaques 30.5 cm x 30.5 cm square are molded on a lab press. Various tests such as mechanical properties, specific gravity, and surface appearance are performed on these flat panels. Larger quantities of SMC are then compounded and molded on a production tool once a formulation passes these screening tests. This first study was used to demonstrate that deflectometry could be used as a tool to evaluate surface appearance rather than relying on visual inspection.

The curvature readings for wavelengths A through E are given in Table 2 for the eight plaques under investigation.

Table 2. Standard deviations of curvature profiles of flat plaques, (1/m).

	Wavelengths				
Panel	A (1/m)	B (1/m)	C (1/m)	D (1/m)	E (1/m)
A	4.506	3.995	0.9749	0.2818	0.0758
B	3.156	3.218	1.068	0.3892	0.1805
C	2.204	2.643	1.138	0.3909	0.2279
D	4.349	4.111	1.482	0.413	0.0726
E	2.874	2.625	0.6681	0.2056	0.085
F	2.391	2.789	1.288	0.347	0.1157
G	2.98	3.781	1.934	0.5261	0.1579
H	3.872	3.404	0.7513	0.1967	0.0755

The same eight plaques were evaluated by a panel of eighteen judges. A summary of the ratings is presented in the heat map shown in Figure 4. The heat map includes the mean value rank of each panel by judge. The mean values were calculated by taking the average rank value (1=best appearance, 3=worst appearance) for each of the twelve choice sets for each judge. As shown in the graph, there is good agreement between the judges, except for judge thirteen from Company A.

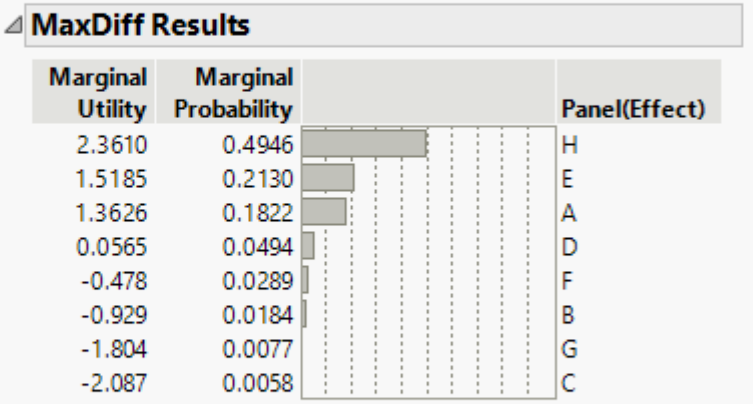


Company & Subject vs. Panel(Effect)

Company / Subject		H	E	A	D	B	F	G	C
C	17	1	1.25	1.6	2.2	2.4	2.25	2.25	2.8
	16	1.25	1	1.6	1.8	2.4	2.5	2.25	3
	15	1.5	1.75	1.2	1.8	2.4	2.25	2	3
B	3	1	1.25	1.8	2	2.4	2.25	2.75	2.4
	2	1	1.25	1.6	1.8	2.2	2.25	2.75	3
	1	1	1.5	1.4	1.8	2.4	2.25	2.5	3
A	18	1	1.75	1.2	1.8	2.4	2.25	2.5	3
	14	1.25	2	1.2	1.8	2	2.25	2.75	2.8
	13	2.25	2	2	2.6	1	1.5	2.75	2
	12	1.5	1	1.4	2.4	2.4	2.5	2.75	2
	11	1	1.25	1.6	1.8	2.2	2.25	2.75	3
	10	1	1.25	1.6	1.8	2.2	2.25	3	2.8
	9	1	2	1.2	1.6	2.2	2.25	2.75	3
	8	1	1.5	1.4	1.8	2.2	2.25	2.75	3
	7	1.25	2	1.2	1.8	2	2.25	2.75	2.8
	6	1	1.25	1.6	1.8	2.2	2.25	2.75	3
	5	1	1.25	1.6	1.8	2.2	2.5	3	2.6
	4	1	1.25	1.6	1.8	2.4	2.25	2.75	2.8

Figure 4. Heatmap of MaxDiff panel ratings by judge and company.

The results of the MaxDiff analysis are shown in Figure 5. Both the marginal utility values and the marginal probability values are given for each panel. The marginal utility is an indicator of the perceived value of the corresponding panel. Larger numbers indicate a better appearance. The marginal probability is the estimated probability that a judge will select that panel as having the best appearance over the other panels. Panel H had the highest marginal utility at 2.361 and a marginal probability of 49.46% while panel C had the lowest marginal utility and marginal probability at -2.087 and 0.58%, respectively.



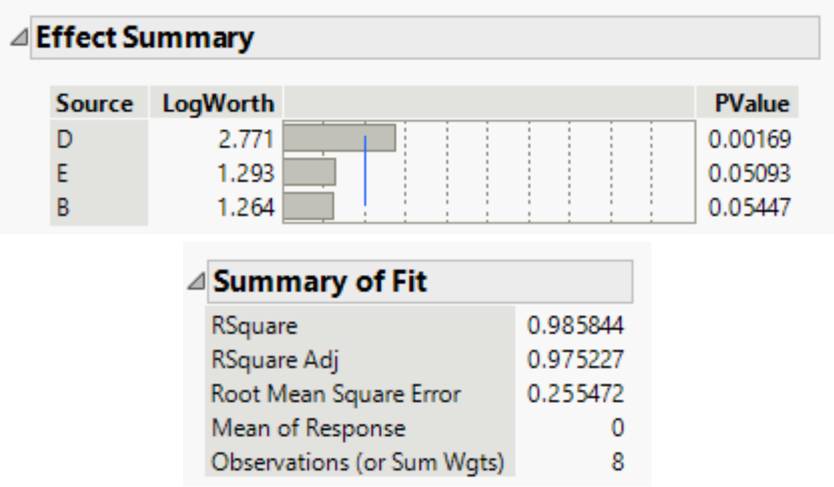
MaxDiff Results

Marginal Utility	Marginal Probability	Panel(Effect)
2.3610	0.4946	H
1.5185	0.2130	E
1.3626	0.1822	A
0.0565	0.0494	D
-0.478	0.0289	F
-0.929	0.0184	B
-1.804	0.0077	G
-2.087	0.0058	C

Figure 5. MaxDiff results.

A predictive model was fit using linear regression for the marginal utility value obtained from the MaxDiff analysis in terms of the curvature readings obtained from the deflectometer (Table 2).

The results from the analysis are presented in Figure 6. As shown in the effect summary table, curvature readings from wavelengths B, D, and E were significant with a P-value ≤ 0.05. The R-Square for this model is 0.986. The prediction profiler is shown in Figure 7. In summary, higher B, lower D and lower E curvature values will result in higher marginal utility values, (better surface appearance as perceived by visual inspection) for the flat panel plaques.



Effect Summary

Source	LogWorth	PValue
D	2.771	0.00169
E	1.293	0.05093
B	1.264	0.05447

Summary of Fit

RSquare	0.985844
RSquare Adj	0.975227
Root Mean Square Error	0.255472
Mean of Response	0
Observations (or Sum Wgts)	8

Figure 6. Model fit analysis of flat plaques, MaxDiff marginal utility in terms of curvature.

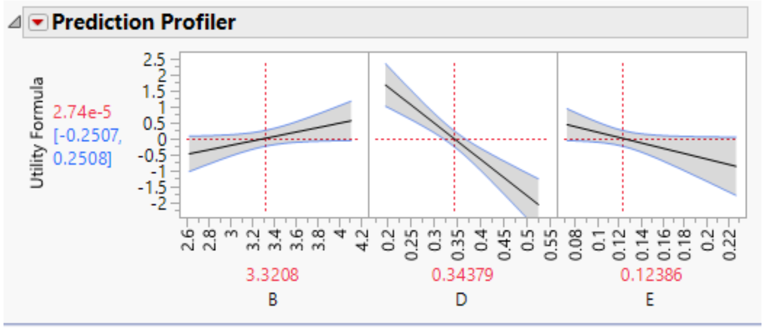


Figure 7. Prediction profiler of the MaxDiff utility formula.

3.2.2. Unpainted Part Choice Model Study

The following study was completed on actual production components molded on a finished chromed SMC tool. This study was completed to confirm that the same surface evaluation methodology used for the lab produced flat panels could be applied to production parts. Eight different formulas were compression molded into automobile component panels and the curvature readings at each of the wavelengths was measured and recorded. This study included six materials, two material manufacturers, and three different densities. Materials representing 1.2 to 1.3 specific gravity are panels A, C, E, F, G, and H, Panel B is a 1.9 specific gravity material, and Panel D is a 1.5 specific gravity material. The results are presented in Table 3.

Table 3. Curvature readings for molded parts.

	Wavelengths				
Panel	A (1/m)	B (1/m)	C (1/m)	D (1/m)	E (1/m)
A	17.32	15.56	3.607	0.7582	0.2518
B	21.57	18.7	3.426	0.6868	0.2729
C	19.95	17.63	3.778	0.8692	0.2805
D	12.16	11.43	3.179	0.6879	0.2158
E	14.58	13.25	3.209	0.6874	0.2263
F	13.41	12.28	3.065	0.6785	0.2163
G	17.4	15.51	3.574	0.7844	0.244
H	19.76	17.32	3.506	0.7837	0.2815

The same eight parts were evaluated by a panel of sixteen judges. A summary of the ratings is presented in the heat map shown in Figure 8. The heat map includes the mean value rank of each panel by judge. The mean values were calculated by taking the average rank value (1=best appearance, 3=worst appearance) for each of the twelve choice sets for each judge. As shown in the graph, there is general agreement between the judges.

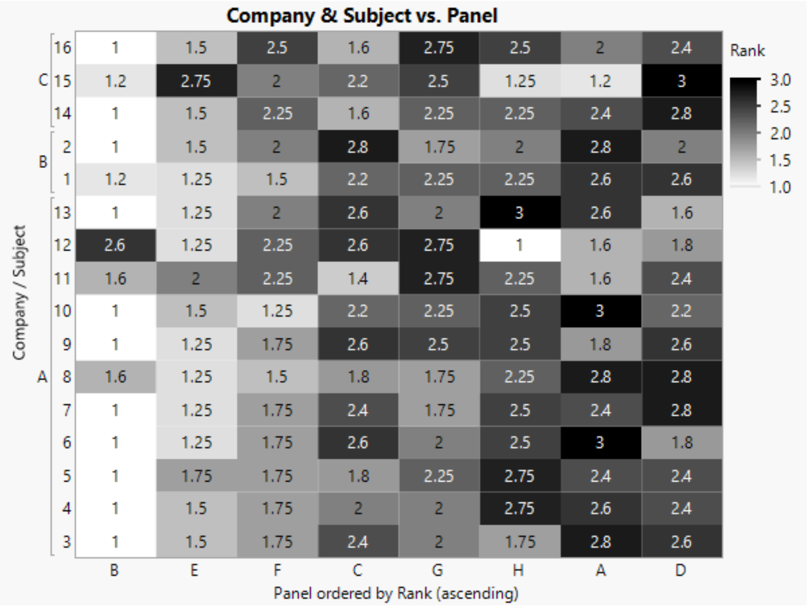
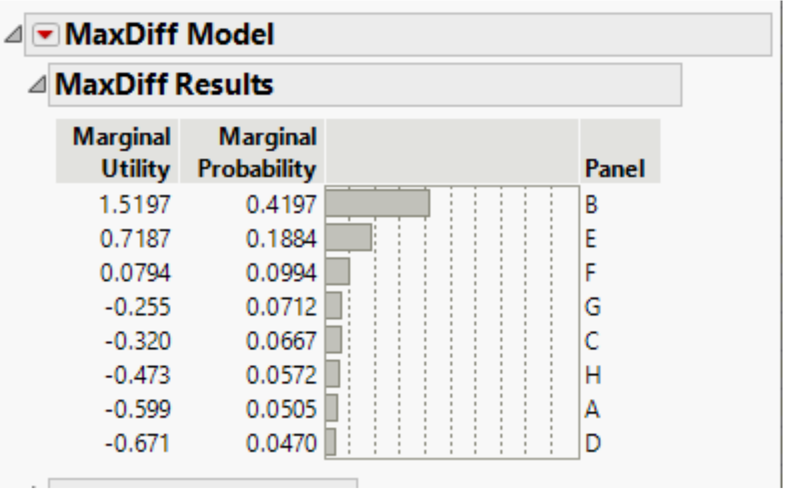


Figure 8. Heatmap of MaxDiff automobile part ratings by judge and company.

The results of the MaxDiff analysis are shown in Figure 9. Both the marginal utility values and the marginal probability values are given for each part. Part B had the highest marginal utility at

1.5197 and a marginal probability of 41.97% while part D had the lowest marginal utility and marginal probability at -0.671 and 4.7%, respectively.

A predictive model using linear regression was fit for the marginal utility value obtained from the MaxDiff analysis in terms of the curvature readings obtained from the deflectometer (Table 3). The results from the analysis are presented in Figure 10. As shown in the effect summary table, curvature readings from wavelengths B and C were significant with a P-value ≤ 0.05. The R-Square for this model is 0.638. The prediction profiler is shown in Figure 11. In summary, higher B, and lower C curvature values will result in higher marginal utility values, (better surface appearance as perceived by visual inspection) for the molded automobile parts. Panel B is the only high-density material in the study, specific gravity of 1.9, and was included as a control sample. All other materials were below a specific gravity of 1.5. All component panels were molded to the same thickness of 2.3 mm +/- 0.2 mm and material optimized molding conditions.

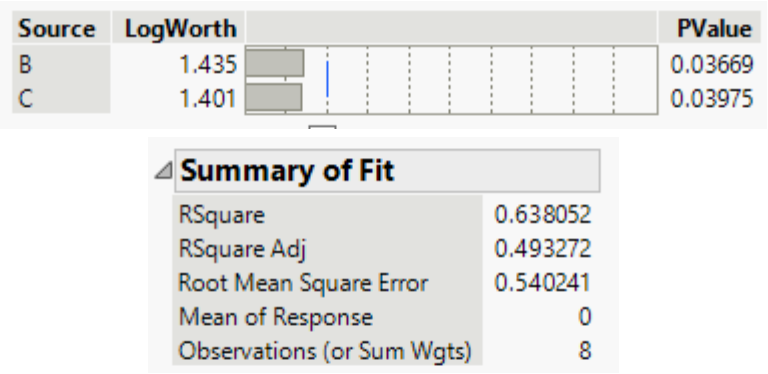


MaxDiff Model

MaxDiff Results

Marginal Utility	Marginal Probability	Panel
1.5197	0.4197	B
0.7187	0.1884	E
0.0794	0.0994	F
-0.255	0.0712	G
-0.320	0.0667	C
-0.473	0.0572	H
-0.599	0.0505	A
-0.671	0.0470	D

Figure 9. MaxDiff Results of automobile parts



Source	LogWorth	PValue
B	1.435	0.03669
C	1.401	0.03975

Summary of Fit

RSquare	0.638052
RSquare Adj	0.493272
Root Mean Square Error	0.540241
Mean of Response	0
Observations (or Sum Wgts)	8

Figure 10. Model fit analysis of automobile parts, MaxDiff marginal utility (curvature).

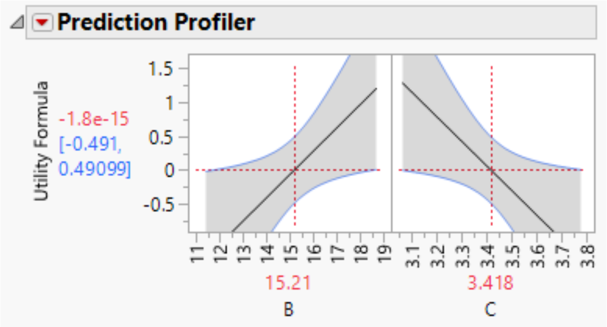


Figure 11. Prediction profiler of the MaxDiff utility formula of automobile painted parts.

Reviewing the resluts in Figure *8*, Judge 12 had the least amount of agreement with the other judges confirming that ranking and evaluation is highly individualistic. The MaxDiff analysis and model fit were re-analyzed after removing the results of Judge 12. The model fit improves with an r square of 0.86 and now the B, C and E curvature values are significant. The profiler from this model is shown in Figure 12. From the profiler, higher B curvature values, lower C values and lower E values will result in a better surface appearance as perceived by most inspectors.

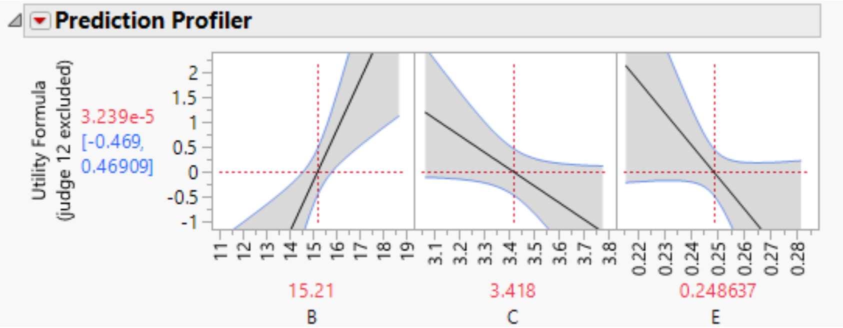


Figure 12. Prediction of model fit with Judge 12 eliminated.

3.3.Surface Appearance Comparison of Unpainted and Painted Parts

Four of the eight component panels were painted, one of the four, Panel B, is a 1.9 specific gravity material. Post paint, the componenet panels were again evaluated using the QualiSensor deflectometer as well as a BYK Wavescan device. The same areas were scanned with both devices and with a visual MaxDiff analysis. It must be noted, the painting method was manual and not the production intent process, only production intent materials. The resultant orange peel and paint quality impacted evaluation by all devices and inspectors. An unanticipated benefit, however, was the ability to visualize the deflectometer results leading to an improved understanding of the impact from painting.

Figure 13 provides the results of a regression analysis from the four painted panels, comparing the curvature results before paint with the readings of the same samples after paint using the QualiSensor deflectometer. The curvature readings before paint are on the x-axis and the readings after paint are on the y-axis.

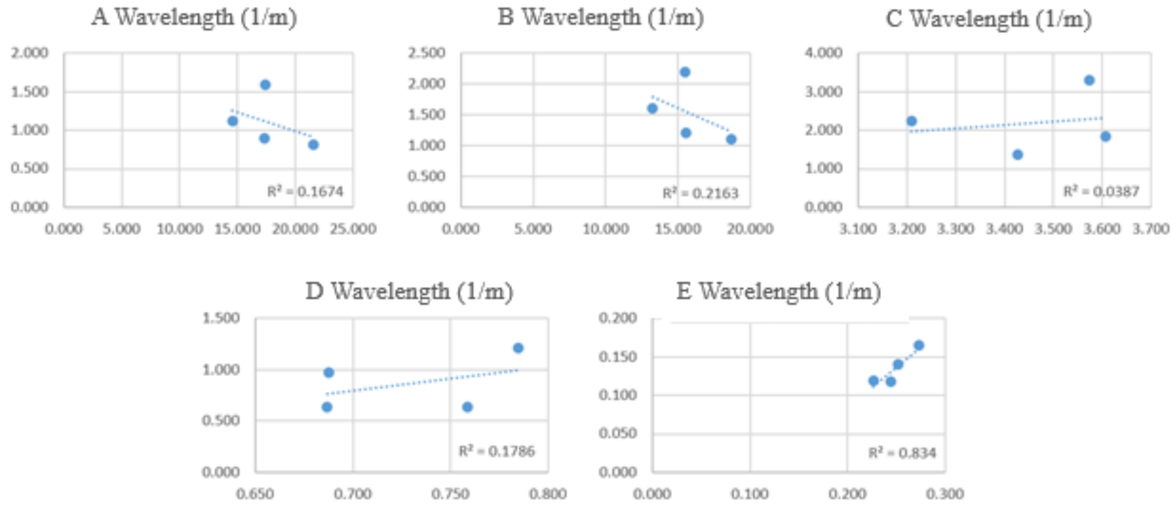


Figure 13. Surface appearance comparison of before and after paint using QualiSensor.

The results of a regression analysis of the before and after paint readings from the BYK Wavescan are shown in Figure 14. The before paint results are on the x-axis and the results from the painted parts are on the y-axis.

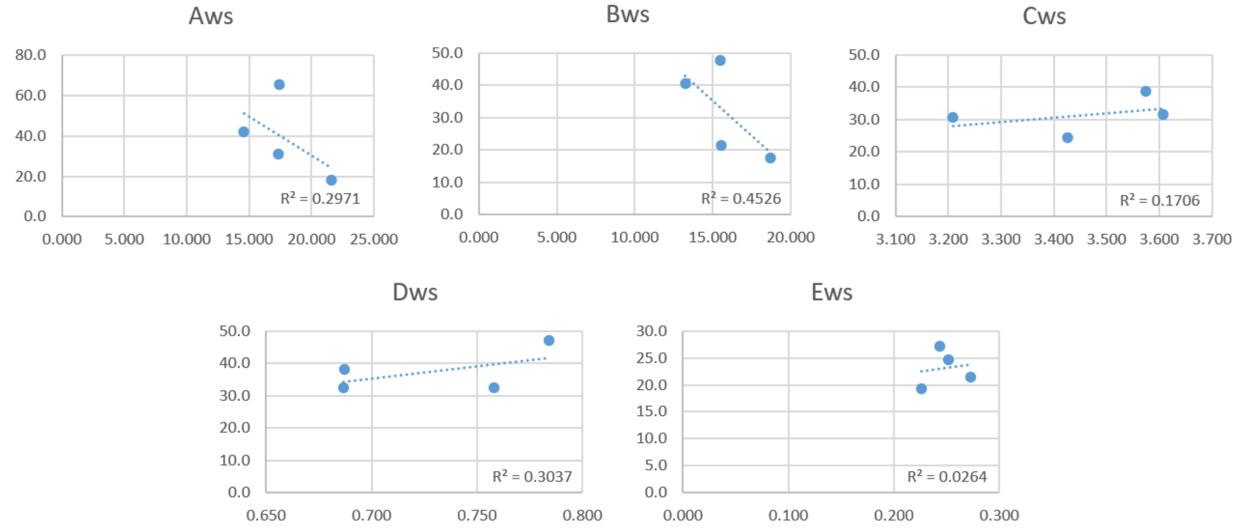


Figure 14. Surface appearance comparison of before and after paint using the BYK Wavescan.

Lastly, in Figure 15, the results from the BYK Wavescan are compared to the results of the QualiSensor for the painted panels.

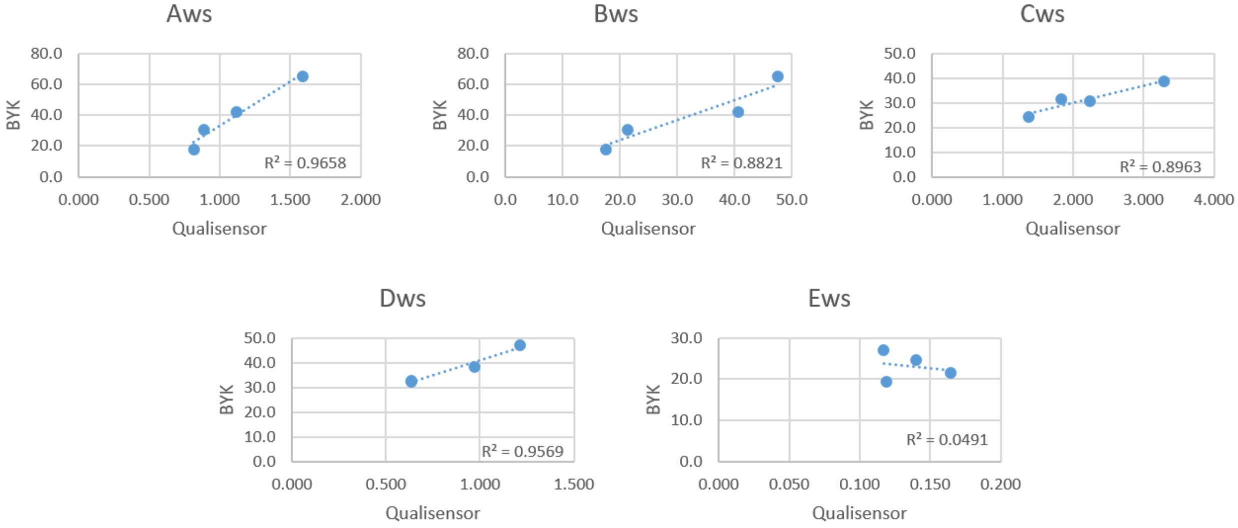


Figure 15. Painted part surface analysis: BYK Wavescan vs QualiSensor.

With only a single exception, there was no correlation in any wavelengths when comparing before-paint to after-paint results when measuring with either the QualiSensor or the BYK Wavescan. The only exception was in the E wavelength when using the QualiSensor exclusively. The lack of correlation is speculated to be causal effect of the paint masking the subtle features of the bare substrate. When comparing after-paint results from the QualiSensor to the results of the BYK Wavescan, the results are very acceptable with correlation coefficients generally near or above 90%. Again, there is a single exception with the E wavelength. This is not unexpected as the E wavelength is primarily shape related, the QualiSensor is an area scan and the BYK is a line scan.

3.4.Optimization of Surface Appearance

Having an instrument that can provide quantitative results of surface appearance that directly correlate to results of a visual inspection facilitates the ease of evaluating numerous experimental samples without human judgement. Design of experiments (DOEs) are often conducted to evaluate the effects of multiple factors on product performance outputs. Conducting a DOE to understand which factors have an effect on surface appearance would be a challenge if the evaluation method was only by visual inspection. Visual inspection can only provide categorical data and may be heavily influenced by a dominant personality or an inexperienced inspector as observed in this paper. A DOE is most effective when the output data is continuous, such as the curvature readings from the deflectometer. The following is an example DOE demonstrating the use of the deflectometer readings to understand the effects of molding conditions on the surface appearance of the molded part.

A 30-sample, custom DOE was conducted. The input factors studied were 1) days of SMC maturation, 2) molded thickness, and 3) charge location. Parts were molded 1 day, 4 days, and 8 days after compounding. Parts were molded at either 2 mm or 3 mm in thickness. The SMC charge was either placed in the center or the edge of the tool. The responses analyzed were the curvature readings at each of the filtered wavelengths, A through E.

The results are summarized in the boxplots in Figure 16. In general, molding at 3 mm thickness results in lower curvature values than parts molded at 2 mm. There is also less variation in the curvature readings with the 3 mm molded parts. At 3 mm thickness, the length of maturation has no effect on the surface appearance. Alternatively, for the 2 mm thickness part the waviness increases as the maturation time increases.

Models were fit for all wavelengths in terms of maturation time, molded thickness, and charge location. The results of the C-wavelength are presented in Figure 17. All 3 factors were significant with p-values <0.05. In addition, there is a significant interaction between day and thickness. This was shown earlier in the boxplots. The profilers for this model are shown in Figure 18 and Figure 19. The lowest curvature, best surface appearance, is achieved by placing the charge at the edge of the tool, and molded at 3 mm. If molded at 3 mm, maturation time does not influence the surface appearance.

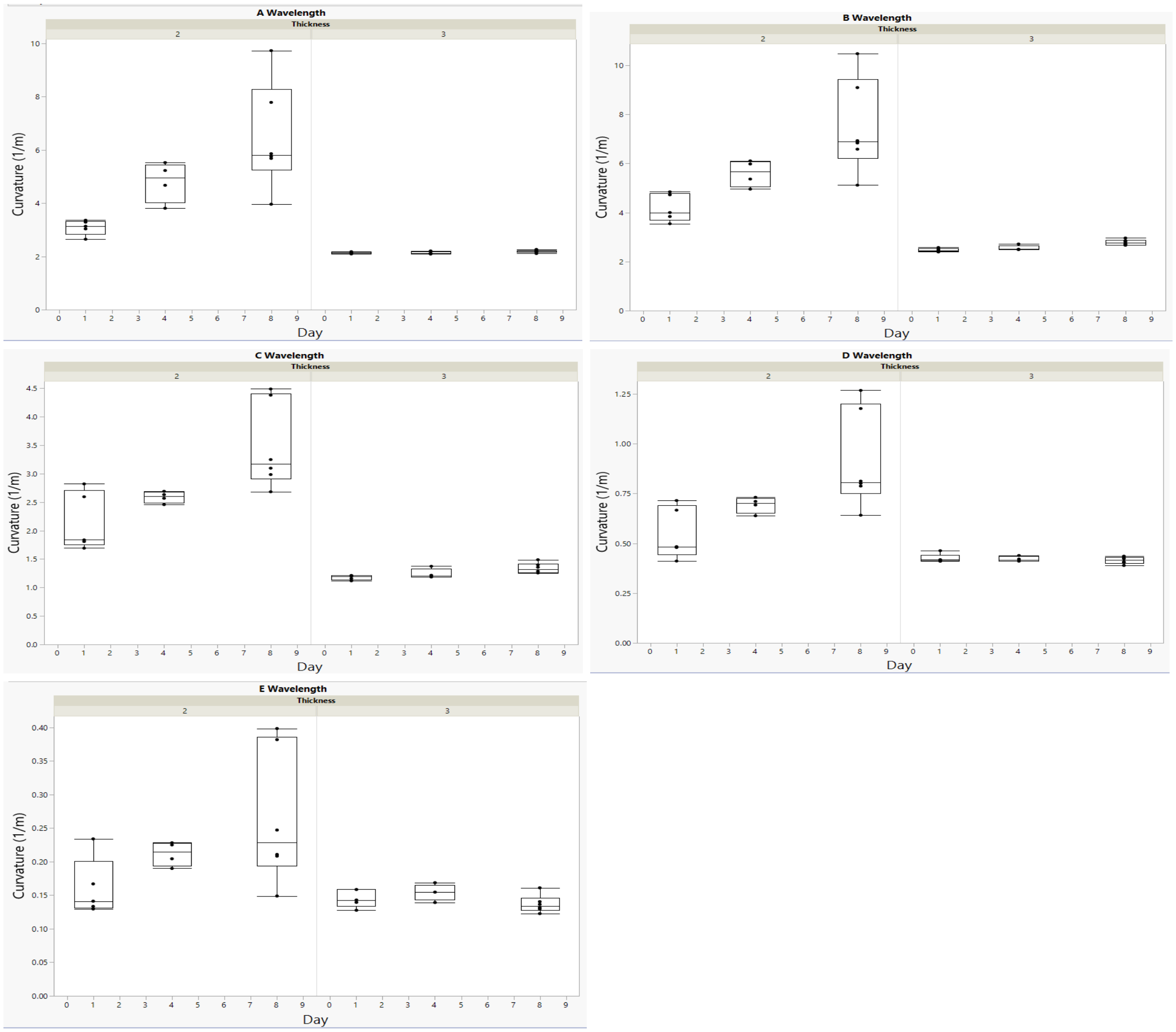
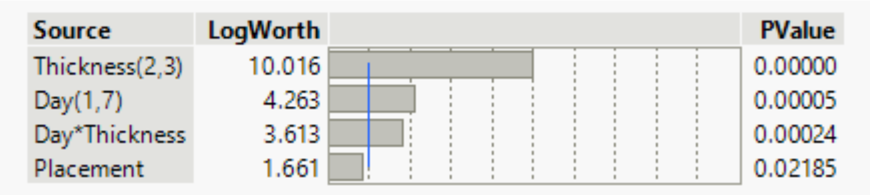


Figure 16. DOE curvature vs maturation day and part thickness.



Source	LogWorth		PValue
Thickness(2,3)	10.016		0.00000
Day(1,7)	4.263		0.00005
Day*Thickness	3.613		0.00024
Placement	1.661		0.02185

Figure 17. Effect summary for C-wavelength curvature

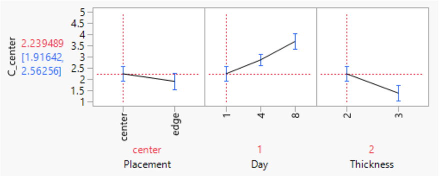


Figure 18. C-wavelength model profiler at 2 mm thickness.

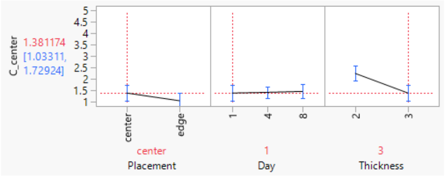


Figure 19. C-wavelength model profiler at 3 mm thickness

4. CONCLUSIONS

Deflectometry can be successfully used to evaluate the surface quality of Class A composite molded parts. The deflectometer can accurately measure the different aspects of the surface such as roughness, orange peel, waviness, and shape. It was demonstrated that there is very little variation due to the instrument and the test method, permitting the detection of small differences in surface quality of molded samples. Differences that may not be detected by visual inspection. It was also demonstrated that there is a strong correlation between the deflectometry curvature readings and visual inspection. Results from the deflectometer can be used to predict acceptance or rejection from visual inspection. There are several advantages to using an instrument to measure surface appearance over visual inspections. The results are repeatable, non-biased, and measured under the same controlled lighting and orientation conditions. These benefits lend themselves to the development of an industry standard for measuring surface quality of a Class A parts.

5. REFERENCES

[1] https://www.v-optics.fr/en/phase-shifting-deflectometry-technology/
[2] SAS Institute Inc. 2019. *JMP® 15 Documentation Library*. Cary, NC: SAS Institute Inc.