ACHIEVING CLASS A APPEARANCE

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ON FIBER-REINFORCED SUBSTRATES

solutions and the evolving measurements used to characterize topcoated surface appearance.

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Achieving Class A appearance over fiber-reinforced substrates can be challenging. We discuss the evolving measurements used to characterize topcoated surface appearance.

The influence of carbon fiber on the surface appearance of a thermoplastic resin-transfer-molding (RTM) substrate is related to differences in thermal expansion within the substrate.

The mechanism identified here is then extended to several chopped-fiber-filled thermoplastic substrates where the fiber-mapping effect is manifested in a different manner. We then investigate the influence of thick-film applications to the Class A surface on appearance. Our analysis finds that both the depth and the width or wavelength of the substrate affect the ability of the thick films to cover fiber mapping.

INTRODUCTION

Fiber-reinforced exterior automotive body panels are receiving increased interest due to light-weighting activities in the automotive industry. In addition to meeting their requirements for stiffness, weight, and cost, exterior automotive body panels must also be capable of providing excellent appearance as a painted part. This is often referred to as "Class A appearance" within the industry, and it is a requirement that proves to be a challenge.

CLASS A APPEARANCE DEFINED AND MEASURED

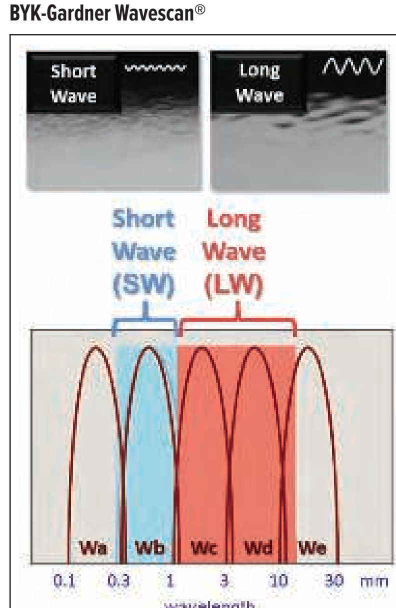
Class A appearance is a visible test that requires that the surface of the panel after painting be smooth and free from defects. The smoothness is now measured instrumentally to define the smoothness more precisely. The requirement to be free of defects is still evaluated visually.

A good example where the fiber-reinforced substrate has influenced paint defects is sheet-molding compound (SMC). Fiber protrusion and porosity in SMC panels have long been known to cause solvent and air release during the baking of the topcoat, which results in small boiling defects. Such parts could not be sold, and SMC coating processes frequently had rejection rates of 20-40% due to this defect alone.[1] Another common defect is de-wetting or cratering due to mold-release agents[2]. These defects and their solutions are better understood, so this article will not address these further.

The smoothness requirement is always assessed via the light reflected from the surface after the topcoating. Visually, the observer will judge the quality of the images reflected from the surface. These reflected images are distorted by any waviness or diffuse reflection from the surface. Many factors can influence surface waviness, including both the quality of the substrate and the coating itself. Due to this complexity, the waviness itself is usually composed of many wavelengths superimposed upon one another. Fortunately, we now have instruments such as the BYK Wavescan® that can measure the complex reflected-wave pattern and deconvolute this into its constituent wave packets of varying amplitudes.

Although the Wavescan uses visible light reflection from the surface, the wavelengths reported refer to those of the coating surface structure and not to those of the electromagnetic radiation that is reflected. This concept is represented in *Figure 1* where the individual wave packets Wa-We are shown along with their corresponding wavelengths.

FIGURE 1—Constituent Wave Packets from BYK-Gardner Wavescan®



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It is convenient to summarize these as longwave (LW) and shortwave (SW). The Wavescan also reports a Du, or dullness value, that represents diffuse reflectance. The Wavescan then reports the amount or amplitude for each wave packet in arbitrary units.

In addition to the longwave and shortwave summary values, most every automotive OEM manufacturer has their own individual appearance metric(s) that weigh these various wave packets differently. In most cases, lower-amplitude values are better for any wave packets included in the metric since lower amplitude corresponds to a smoother surface.

However, some more sophisticated metric algorithms include the ability of shortwave structure to visually obscure the viewer's perception of longwave structure. For our purposes, we will focus on the LW and SW as summary values and use the individual Wa-We values when more precision is justified. Study of these individual wavelengths is helpful to understand the factors causing the waviness and those factors that can reduce the waviness.

The SW and LW values will vary depending upon the colored pigments that are in the formula and depending on whether the panel orientation is horizontal or vertical during the application and bake cycle. For horizontal panels, values less than 5 LW and 10 SW are desired and for vertical panels values less than 10 LW and 20 SW. Some OEM customers have more demanding requirements than these, and some OEM customers have less-demanding requirements.

FIGURE 2—Cross Section of RTM Substrate

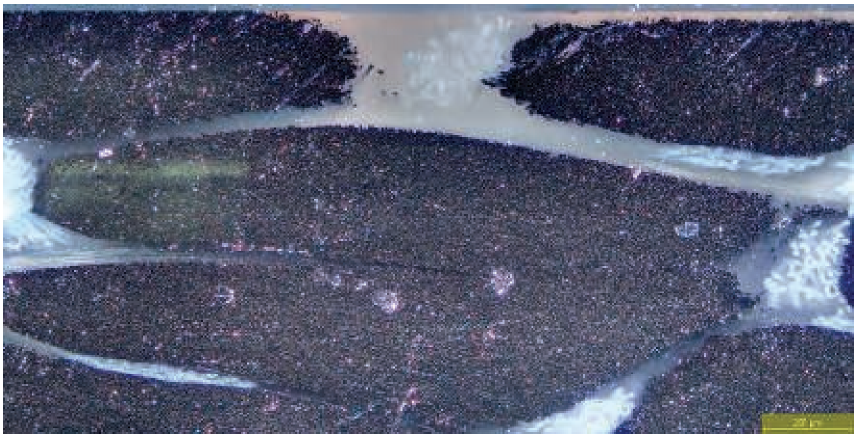
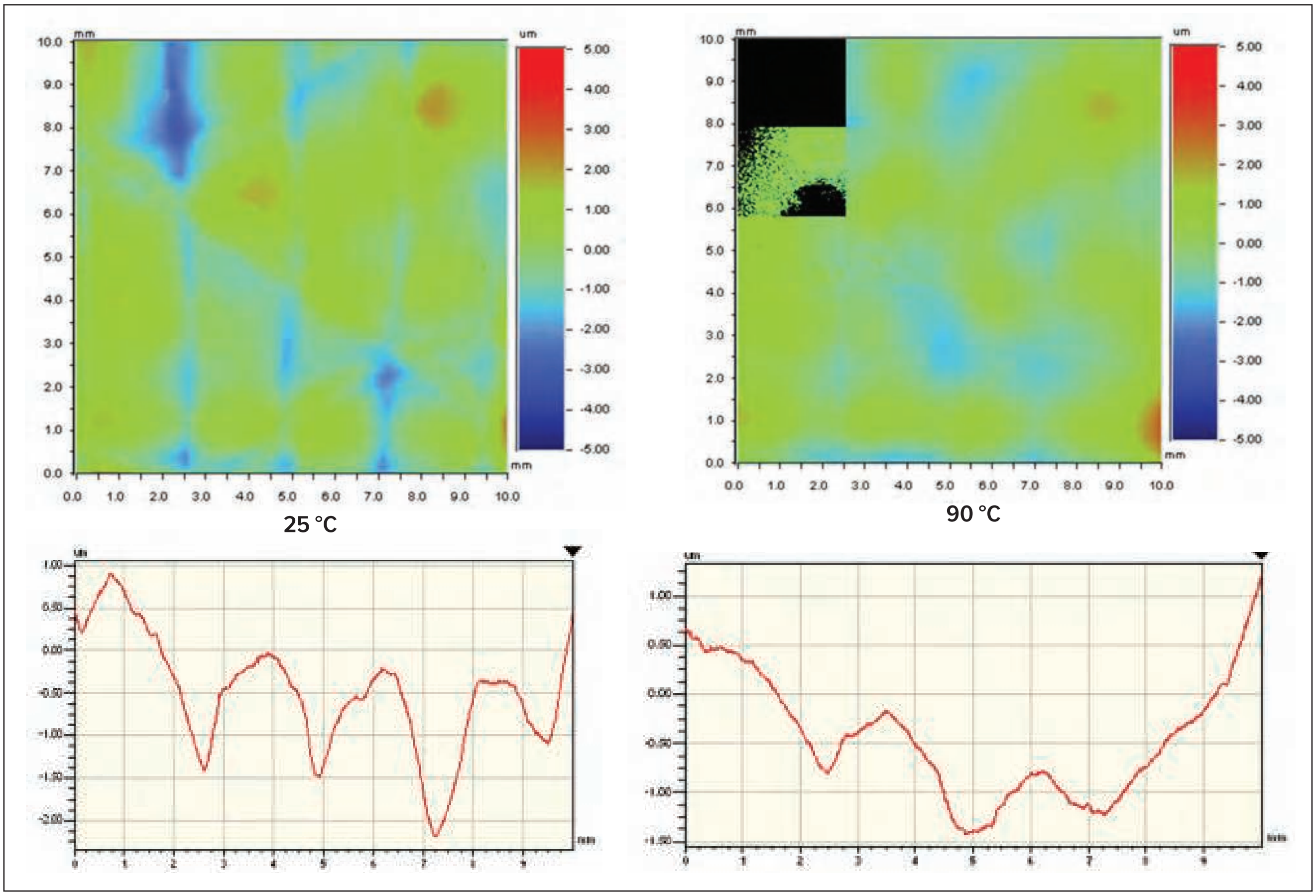


FIGURE 3—Topography of Topcoated RTM Substrate at 25 °C and 90 °C



MECHANISM OF FIBER INFLUENCE ON APPEARANCE

To demonstrate the mechanism of the fiber influence on the appearance, we will first report work that was done over RTM substrate. Here, the carbon-fiber weave provides a substrate where the fiber distribution is readily observed so that its effect can be more easily determined. The distribution of the fiber can be seen in *Figure 2* where the cross section shows large fiber-rich domains as well as a resin-rich domain outlined in red. Although it is not readily detected, there is a 5-micron depression that is located directly above the resin-rich area of the substrate.

This substrate was primed with several different polyester-melamine thermoset primer types. Each panel was sanded smooth on one half of the panel after priming. Topcoating was done with a black polyurethane-melamine water-based basecoat and a two-component acrylic polyol-polyisocyanate clearcoat. After topcoating, the sanded area looked slightly better than the un-sanded area, but the fiber mapping was still visible even in the sanded area. When these panels were reheated to the baking temperature (100 °C) and observed while still hot, the surface was smooth in both the sanded and the un-sanded areas. The depressions reappeared after cooling.

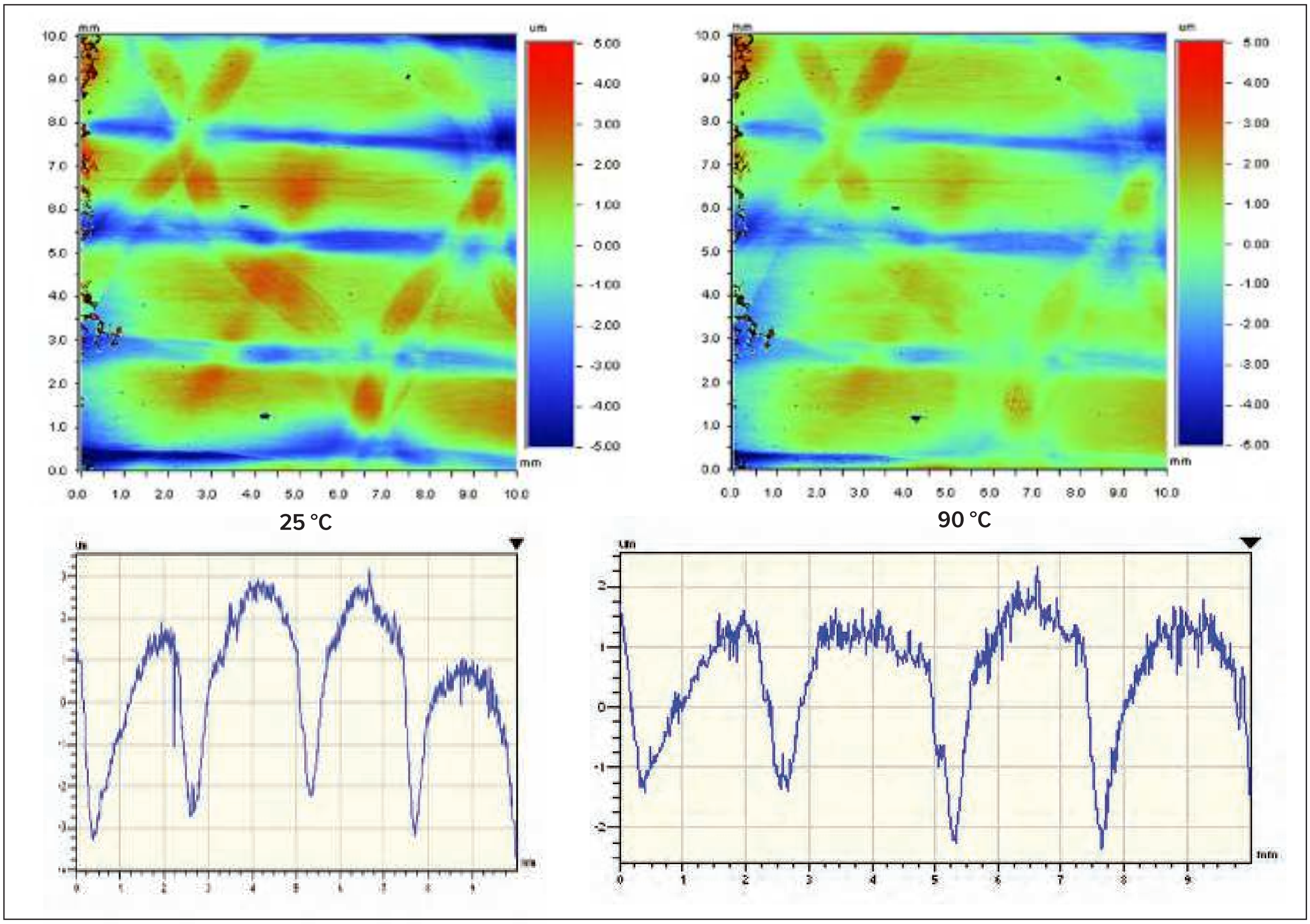
Changes in surface topography at different temperatures were then studied with a laser profilometer for both the substrate and for the topcoated system. The topcoated system is shown at 25 °C and at 90 °C in *Figure 3*. The bare substrate is in *Figure 4*. The deep, vertical-depression lines in *Figure 3* and the horizontal lines in *Figure 4* are located directly above the resin-rich areas that are seen in the cross section of *Figure 2*.

Although the heated stage for this work was set at the topcoat baking temperature of 100 °C, at the end of the runs, it was determined that the panel surface only achieved 90 °C and the leveling was not quite complete in *Figure 3* at high temperature. Nonetheless, the figures show that the substrate itself undergoes

TABLE 1—Changes of Topography with Temperature

PEAK-TO-VALLEY DEPTH	SUBSTRATE-ONLY PANEL	TOPCOATED PANEL
Depth at 25 °C	4-5 microns	2-3 microns
Depth at 90 °C	2-3 microns	0-1 micron
Difference in depth	2 microns	2 microns

FIGURE 4—Topography of Uncoated RTM Substrate at 25 °C and 90 °C



changes in topography that are comparable to those seen in the topcoated surface. These changes are summarized in *Table 1*. For example, on the uncoated substrate, the depressions are 4-5 microns deep at 25 °C, but only 2-3 microns deep while at 90 °C.

Likewise for the primed and topcoated substrate, the depressions are 2-3 microns deep at 25 °C and 0-1 microns deep at 90 °C. In both cases, the depth increases by 2 microns when the panel is cooled. This is consistent with the 0.8% thermal expansion measured for the resin between 25 °C and 100 °C in *Figure 5* and the 250-micron depth of the resin-rich domain in *Figure 2*. Combining these yields 2 microns of change assuming near-zero coefficient of thermal expansion (CTE) for the carbon-fiber domains.

Thus, we see that the clearcoat has leveled completely over the substrate at the bake temperature of 100 °C. It is the change in the substrate between 100 °C and 25 °C that distorts the clearcoat. But because the clearcoat has already solidified due to crosslinking, it can no longer flow to accommodate this distortion. To be clear, the 5-micron depression in the panel is not the problem. It is the 2-micron change that occurs upon cooling. Likewise, the sanded area of the panel has no depression, but it still raises 2 microns with heating and then shrinks back 2 microns with cooling. Similar effects have been reported by Neitzel et al. in glass-fiber composites[3]. These were also attributed to non-uniformity of the fiber distribution and different coefficients of thermal expansion.

Recent work has been extended to chopped-fiber-reinforced polyamide substrates in an injection-molding process. Here, we also see a dramatic change in appearance as the panels are cooled from the bake temperature to room temperature in *Figure 6*. Both the longwave and the shortwave values increase fourfold as the panels are cooled from the baking temperature to room temperature for the fiber composites. This effect is seen for both the carbon fiber and the glass-fiber composite. The longwave and shortwave values of the PA6 substrate without fiber are unchanged by the cooling of the panel.

Like the case of the RTM substrate, the same temperature dependence seen in the topcoated panels is also observed in the substrate surface as shown in *Figure 7a* and *7b*. Again, this same change in substrate texture is not observed in the PA6 substrate that does not contain the carbon fiber.

In the case of the RTM substrate, the relationship with the fiber distribution was obvious in the laser profilometry profile of the topcoated substrate. To determine the uniformity of the fiber distribution in these substrates, X-ray imaging of the substrate was performed. This image is shown in *Figure 8* along with the average wavelength scales of the wave packets reported by the BYK Wavescan. Indeed, a random non-uniformity of the fiber density is observed within the substrate in the same plane as the coated surface. The wavelength of this non-uniformity is on the length scale of the Wb-Wc values.

FIGURE 5—RTM Plaque: Resin-Only Area CTE

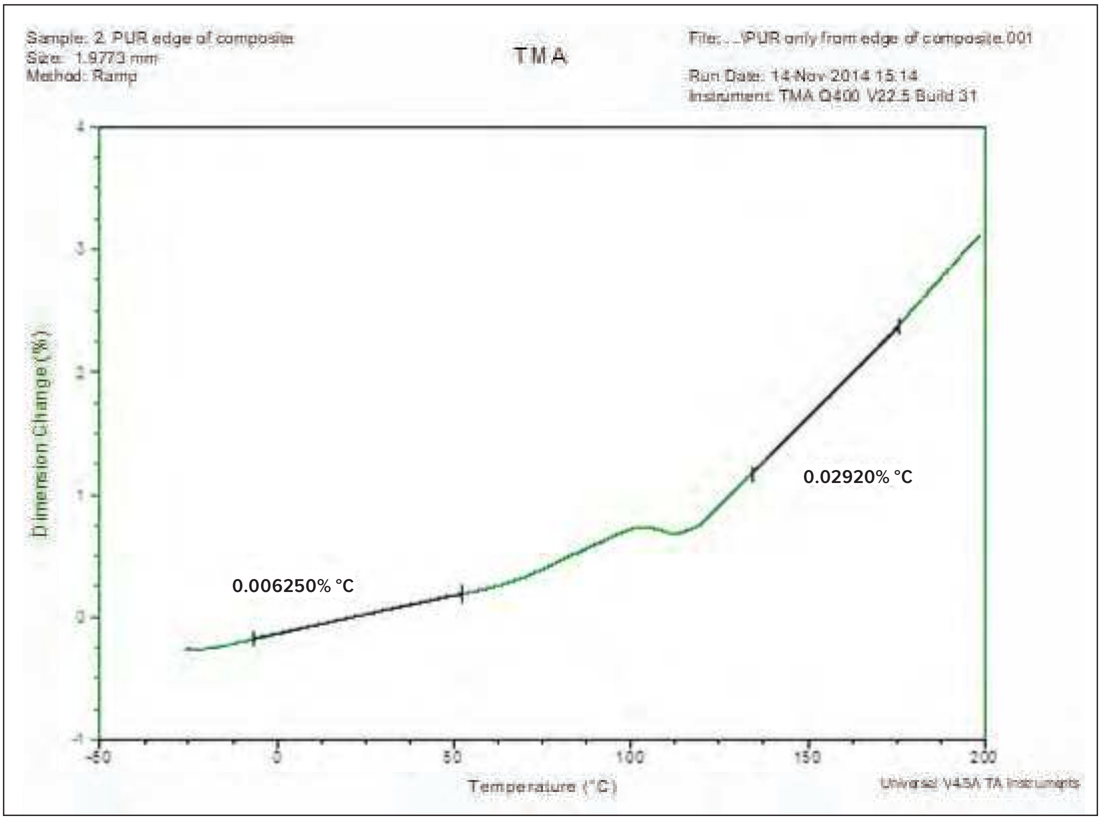
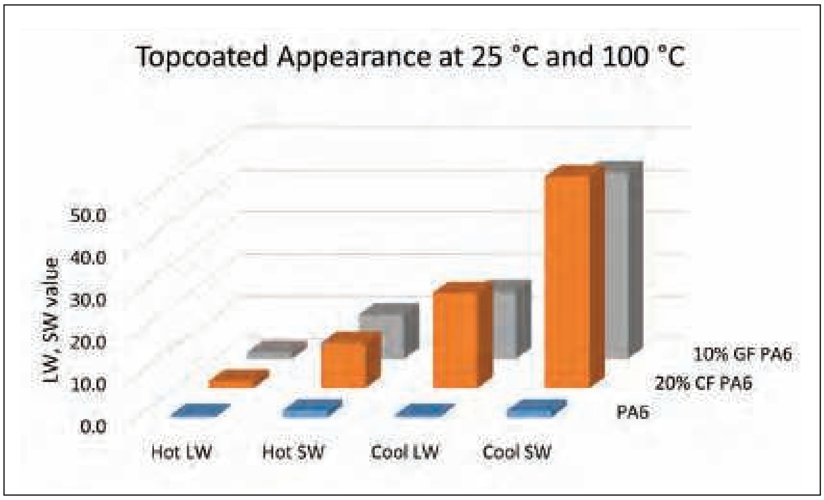
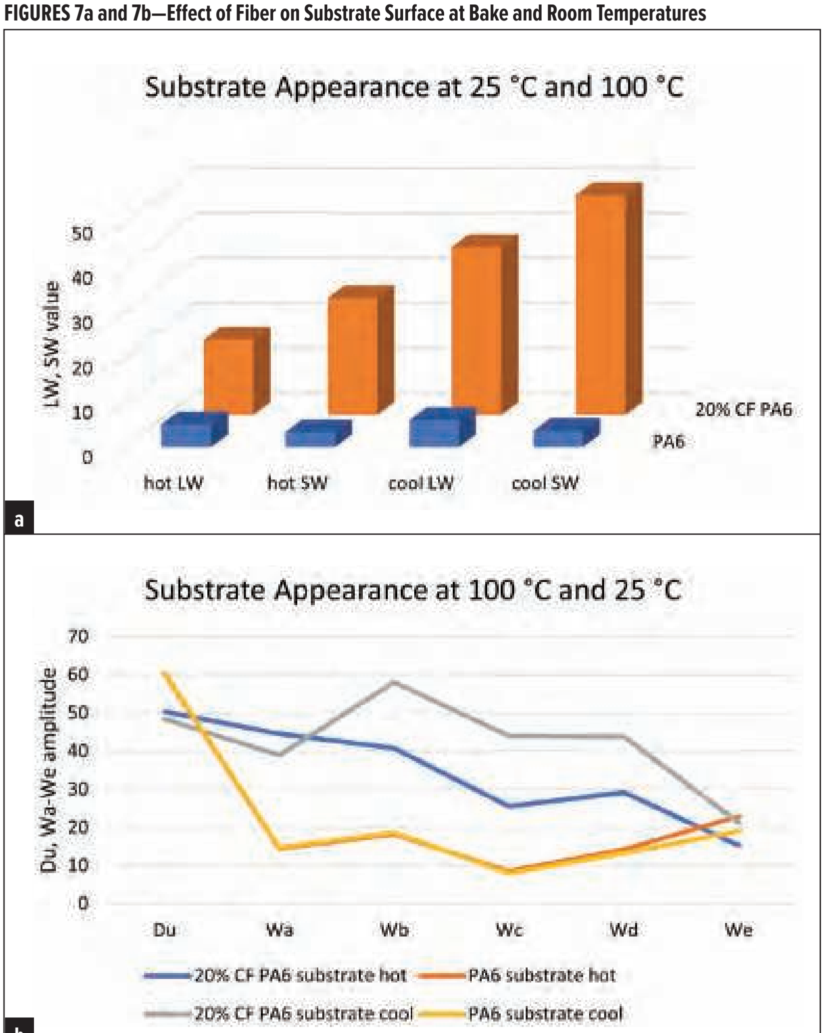


FIGURE 6—Effect of Fiber on Topcoated Appearance at Bake and Room Temperatures



FIGURES 7a and 7b—Effect of Fiber on Substrate Surface at Bake and Room Temperatures



POTENTIAL SOLUTIONS

There are currently several potential solutions to this problem that involve various methods of applying 100-250 microns of fiber-free resin to the Class A surface of the part. In cases where the composite is laid into the mold, such as autoclave or compression molding, it is possible to lay down a resinous veil onto the Class A side before closing the mold, as described by Noordegraaf et al.[4] However, in cases where this surface has complex features this layer can be distorted and penetrated during compression.

Furthermore, such a technique cannot be applied to injection-molded parts such as is used with thermoplastic polymers or in RTM. Others have applied this layer after molding of the part by backfill molding applications as described by Beyl[5]. If the panel is flat, then the mold face can be backed away 200 microns and a second resin of the same or different type can be injected and cured. However, if the panel has complex features, then a second mold is required that is 200 microns larger in all dimensions to achieve a uniform thickness. This second mold increases the capital costs as well as the footprint of the molding operation. Alternatively, thick laminate films can be applied after molding is complete as described by Warta[6].

FIGURE 8—Fiber Distribution by X-Ray Analysis

Wrinkling of the film can occur during application and the film must be trimmed at the edges adding yet another step and adding waste to the process. Current coating processes for unimproved fiber-composite substrates involve multiple primer coats. In many cases, sanding is performed between coats. However, with successive coats, a sufficient layer thickness can be achieved.

All these methods function on the same principle of adding a thick resinous layer to the Class A surface of the composite part. To study the effect of the thickness of this surface layer on the appearance, we applied a two-component primer layer at 50-micron increments up to 200 microns before topcoating the panels (20% CF PA6). The Wavescan results for this evaluation are shown in *Figure 9*. We have added the average defect wavelength for each of the wave packets to the legend.

From this data, we saw that the shorter wavelength defects (Wa, Wb) were reduced more by the thick primer than the longer wavelength defects (Wc, Wd, We). To better understand this effect, we first calculated the percent defect coverage from the ratio of each Wavescan value at the different primer thicknesses (50-200 microns) divided by the Wavescan value with no primer. This was then plotted against the log of the dimensionless ratio of the primer thickness to the average defect wavelength. This plot is shown in *Figure 10*. It demonstrates that the defect is covered when the log of the length ratio is zero, or when the primer thickness is equal to the defect wavelength.

We felt that this relationship was consistent with the effect of Poisson's ratio (ν) in the stress tensor for the linear elastic model defined by *Equation 1*. Here, the 11 direction is perpendicular to the substrate and the 22 and 33 directions are parallel to the substrate. A stress (σ_{11}) in the 11 direction produces a strain (ε_{11}) in this same direction that is proportional to the coating modulus (E). For example, a downward stress towards the substrate will cause a downward strain or deflection of the coating that leads to the coating surface deformation.

EQUATION 1—Linear Elastic Model for Isotropic Materials

$$\begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\end{bmatrix} = \frac{1}{E}\begin{bmatrix}1 & -\nu & -\nu\\ -\nu & 1 & -\nu\\ -\nu & -\nu & 1\end{bmatrix}\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\end{bmatrix}$$

However, for linear elastic materials, the constant volume requirement (ν = 0.5) in the tensor leads σ_{11} to cause strains in the 22 and 33 direction (ε_{22} and ε_{33}) proportional to Poissons ratio ($-\nu$) for the material. Thus, a depression that is formed on the substrate surface during cooling is dissipated by pulling material inward from areas adjacent to the depression as the strain propagates through the primer layer. (This effect is best known as the reason that a rubber band becomes thinner when it is stretched).

This has been modeled using computer-aided engineering and finite element analysis. In this work, we varied the surface-layer thickness, the deformation wavelength and Poisson's ratio of the surface layer.

In this model, a film (primer) was placed over a plate (PA6 substrate). The modulus of the plate was set to 8000 MPa and the film to 800 MPa. The film was assumed to be bonded to the plate, and a 5-micron-square wave was induced at the interface of a plate-film

FIGURE 9—Wavescan® Values for Varied Primer Thicknesses

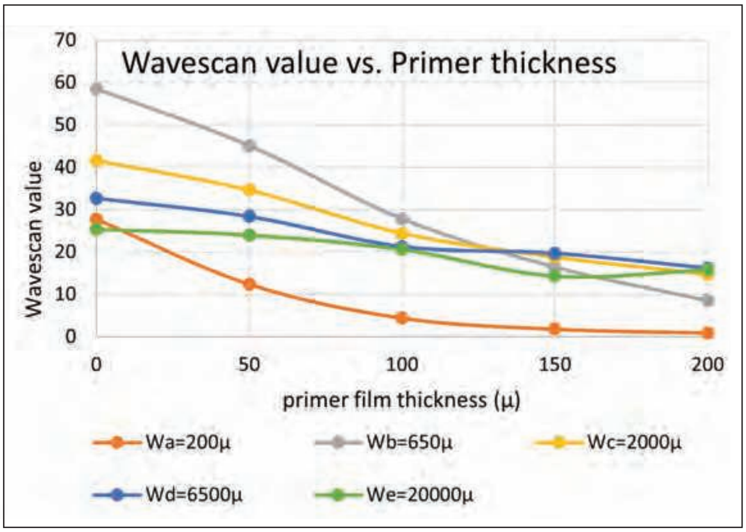
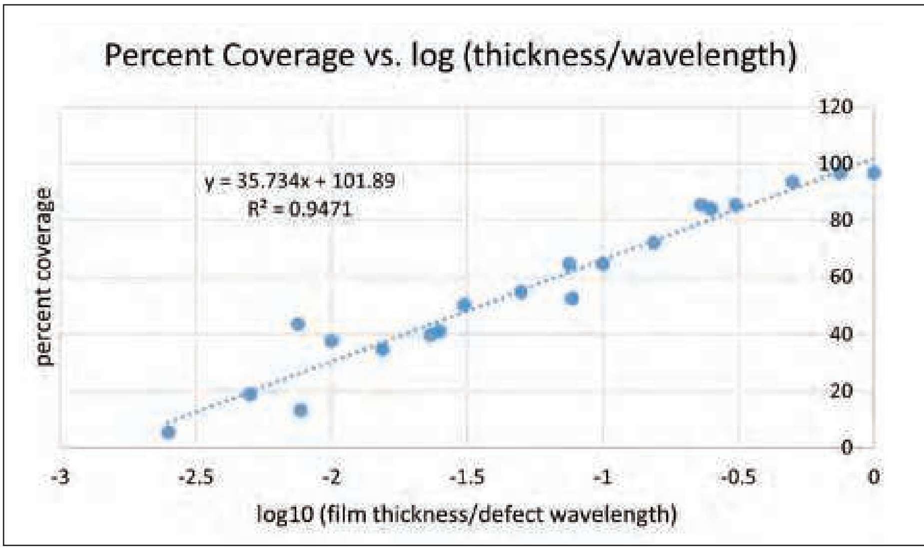


FIGURE 10—Relationship of Primer Thickness to Defect Wavelength Ratio to Defect Coverage



system by enforcing displacement boundary conditions. The waviness at the surface of the film was then observed and measured as shown in *Figure 11*.

The analysis above represents the baseline at a Poisson's ratio of 0.495. The other conditions that were modeled are summarized in *Table 2* below.

This CAE modeling supports the interpretation of the experimental results by demonstrating the effects of Poisson's ratio in the primer and the modeling confirms the elimination of waviness when the primer film thickness exceeds the wavelength of the defect. Thus, the thickness of the film, or primer layer, in the 11 direction must be equal to the defect wavelength, or fiber non-uniformity, in the 22 and 33 directions.

ONGOING PROJECTS IN THIS AREA

Based on the understanding yielded above, two processes have been developed for achieving Class A appearance carbon-fiber-filled thermoplastic substrates. Both polyamide and polypropylene substrates have been evaluated. The results of these are compared to the conventional

FIGURE 11—Finite Element Analysis of Defect Propagation through Primer

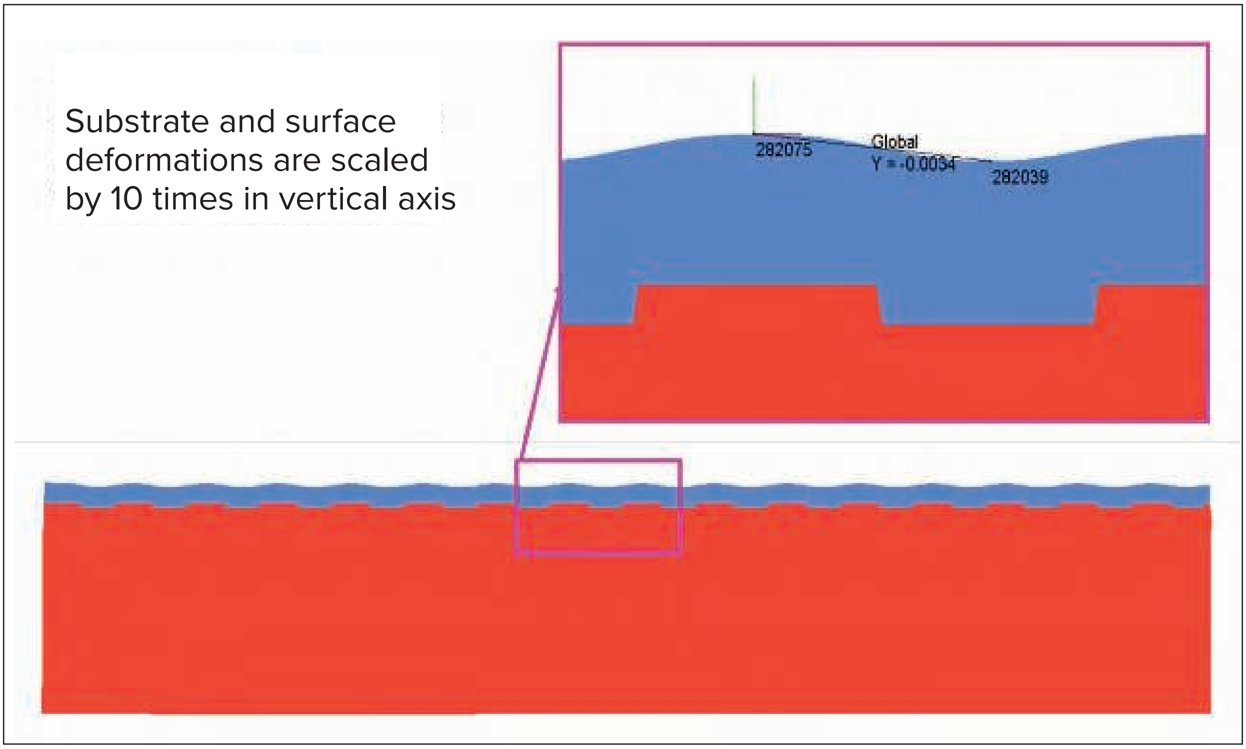
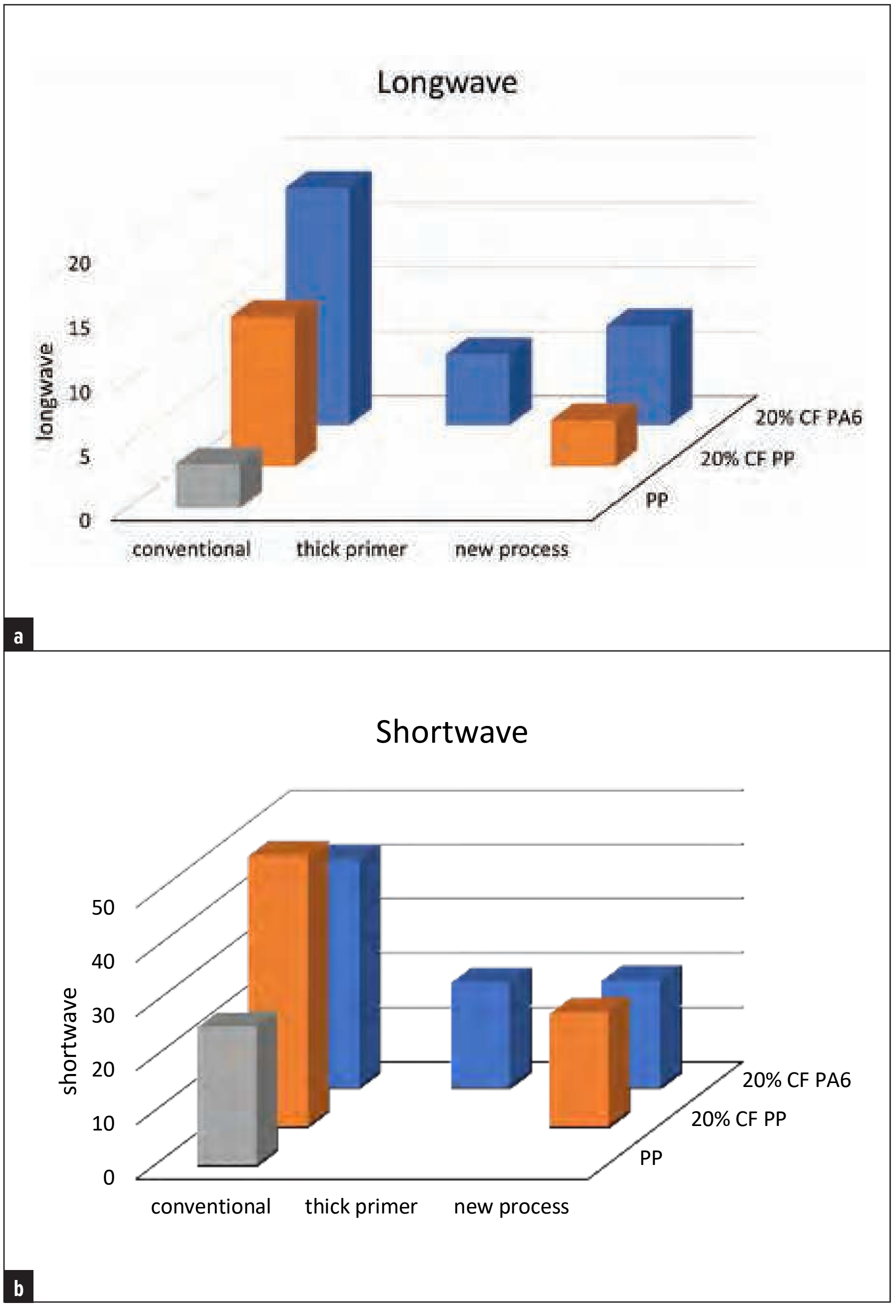


TABLE 2—Finite Element Analysis of Varied Primer Thickness, Wavelength, and Poisson's Ratio

DESIGN	POISSON'S RATIO OF FILM	FILM THICKNESS (MICRONS)	WAVELENGTH (MICRONS)	SURFACE WAVINESS, PEAK TO THROUGH (MICRONS)	COMMENTS
Baseline	0.495	200	700	3.4	Wave pattern observed on surface
Baseline	0.15	200	700	3.9	Lower Poisson's ratio of film increases waviness
Iteration 1	0.495	400	700	1.2	Higher the film thickness, lower the waviness
Iteration 2	0.495	2000	700	0	Waviness disappears
Iteration 3	0.495	200	340	1.1	Lower the wavelength, lower the waviness
Iteration 4	0.495	200	100	0	Waviness disappears

FIGURES 12a and 12b—Appearance Values for Topcoat Processes on Carbon-Fiber-Filled Polyamide and Polypropylene



topcoat process in *Figures 12a* and *12b*. In the case of polypropylene, the new process over 20% CF yields similar appearance values as the conventional process over unfilled polypropylene substrate.

In summary, fiber mapping in the topcoating of fiber-reinforced composite substrates is related to the non-uniformity of the fiber distribution and resulting CTE of the substrate. These variations in CTE on the microscale result in microscale deformations of the substrate surface during cooling that are mapped through to the topcoat surface. We have also shown that both the coating thickness and the length scale of fiber non-uniformity in all directions within the substrate are critical to achieving a Class A surface appearance. This demands that both fiber uniformity, as well as the required coating process, be considered early in the design of these new lightweight substrates for Class A automotive body panels. ❊

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