Windshield Heating and Bending Simulations for Predicting Surface Contour

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Abstract

Automobile original equipment manufacturers (OEMs) need windshield surface data based upon supplier production capability for use in vehicle design, optical evaluations, and wiper system design early in the design process. To meet OEMs requests for this information, windshield surface simulation capability based upon production process data was developed. Windshield heating simulation capability was developed using a computational fluid dynamics (CFD) code with a model that includes two glass plies, production tooling in a furnace cavity, banded absorption of radiation by glass, radiation data from actual process control settings, and variations in thermal conductivity produced by ply separation during heating. The time based glass thermal history from the CFD simulation serves as input for a finite element simulation to calculate glass bending using temperature dependent creep. Measured and simulated bent windshield surface contours agree well, as do glass temperature levels in the glass bending temperature regime. This windshield heating and bending simulation capability can be utilized to define windshield bending process capability with production equipment for new OEM parts during the new vehicle design process and to refine production glass heating control settings to increase the process operating window for meeting windshield surface control specifications.

Introduction

With a focus on designing windshield surfaces that will exhibit excellent optics when produced as designed and that will have no issues with the operation of new wiper systems, OEMs have requested that manufacturers provide predictive capability for producing OEM specified windshield surfaces from production equipment. In order to meet these requests, windshield surface simulation capability based upon production process data was developed.

The challenge for developing the windshield surface simulation capability begins with defining the radiant field present in a windshield bending lehr based upon process control settings that do not include the heating coil surface temperature levels. In addition, windshield glass heating must be addressed by including the physics of radiation absorption in two plies of semi-transparent material, one of which may be a ply with an infrared reflective coating, such as PPG's **SUNGATE**® coating, and also, the thermal conduction of heat between plies when variation in separation occurs based upon thermally induced mechanical movement of the plies relative to each other during the heating process.

From a simulation perspective, the use of a CFD code for glass heating in addition to a finite element code for glass bending is necessary to properly handle the physics of glass heating, where radiation absorption by wavelength bands is required to account for the absorption of radiation within both plies of the windshield, depending on the wavelength of the radiation. In addition, radiation absorption by wavelength bands is essential for correctly handling radiation absorption for windshields with an infrared reflecting coated ply, such as a PPG **SUNGATE** coating.

Production Process Radiant Field Temperature Levels

Typical process control systems for commercially available windshield bending lehrs utilize heater power output percentages to maintain an ambient temperature level in a heating zone, which indirectly sets the heater temperature level and distribution, rather than directly controlling the heater temperature level. From a simulation perspective this control methodology does not provide radiant field temperature levels for use in glass heating calculations.

Therefore, in order to determine the effective radiant field temperature from the heater surface area to the glass for input into a CFD heating simulation, an effective radiant field temperature level must be determined from the heater temperature level based upon the process control settings, the heater coil geometry and spacing, and the distance from the heating coil to the glass.

The effective radiant field temperature for use in the CFD heating simulation was calculated using process heater temperature measurements. Heater temperature level measurements were made under production process operating conditions by measuring the actual heating coil wire temperature at percent power levels of from 0 to 100 percent at varying zone ambient temperature levels that correspond to levels measured in the production lehr. Then, based upon the heater temperature level and the radiation view factor from the heating coils to the glass, the effective radiant flux was calculated using the Stefan-Boltzman law and the radiation view factor from the heating coil to the glass [1]. From the effective radiant flux, a corresponding heater temperature level was determined that would produce the same flux. This temperature level would then represent the effective radiant field temperature for the heater surface area for use as input for the CFD simulation.

For use in the CFD heating simulation, input of the effective radiant field temperature for the heater surface area into the simulation was automated. This was accomplished by loading the actual process control settings from the bending lehr into software that produces a text file for input into the CFD code, which contains the effective radiant field temperature for the heater surface area level for each coil in the lehr.

Thermal Conduction Heating Between Windshield Glass Plies

Since the actual windshield contains two glass plies, conduction of heat between plies occurs, and must be accounted for by conduction of heat through the air in the space between the plies in the simulation. The air space between plies varies in thickness due to thermal gradients that are produced by process heating conditions. In order to include variation of conduction by ply separation in the simulation, three separate conditions that occur during the windshield heating process must be included.

First, there is an initial separation of plies that occurs from the action of gravity when the glass is supported on the windshield bending mold prior to entering the heating lehr. This separation can be measured cold, and used in the simulation as the initial condition for calculating the effective thermal conduction of the air gap based upon ply separation and variation in the thermal conductivity of the air with temperature during the heating cycle.

The second condition affecting ply separation occurs once glass heating begins in the preheat zones of the lehr, and is caused by thermal gradients through the plies that produce mechanical movement of the glass. To account for the variation in thermal conductivity that the separation causes, an iterative process was used that matched measured ply temperature levels to simulated temperature levels calculated by varying the thermal conduction between plies by varying the thickness of the air gap between the plies. For the heating simulation the air gap thickness was adjusted in this manner for each lehr preheat zone.

For inclusion in the glass heating simulations, calculated air gap thickness adjustments were made for each lehr preheat zone during the heating cycle, with the adjustments varying from 0.005 to 0.233 inches. These adjustments were calculated by matching measured thermal gradients from top to bottom surfaces with results from heating simulations by varying gap thickness to match measured thermal gradients in the preheat zones of the lehr, where thermal mechanical separation is present. The calculated variation in ply separation as the windshield progresses through the preheat zones of the lehr is shown in the following plot, Figure 1.

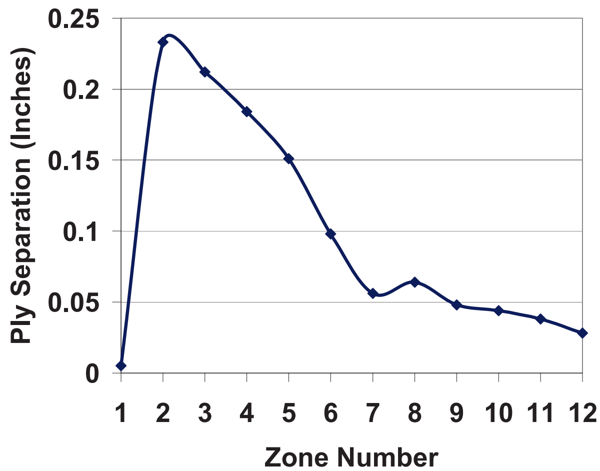

Figure 1 Windshield ply separation in each lehr preheat zone.

The third condition affecting ply separation occurs in the bending zones of the lehr, where the glass temperature level is high enough for viscoelastic behavior to influence movement of the plies relative to the applied thermal gradient. The physical manifestation of this phenomenon is that separation of the glass plies caused by thermally induced mechanical stresses decreases toward zero as the glass temperature increases in the glass viscoelastic temperature regime. This decrease in ply separation follows the decrease in glass stiffness as permanent deformation begins to occur. The corresponding increase in thermal conductivity between the plies that the glass viscoelastic movement produces can be measured as a significant decrease in the thermal gradient between the top and bottom surface temperature levels of the plies. Measured thermal gradient reduction caused by the collapse of the thermal mechanical ply separation can be seen in the glass surface temperature profiles with time shown in the following Figure 2.

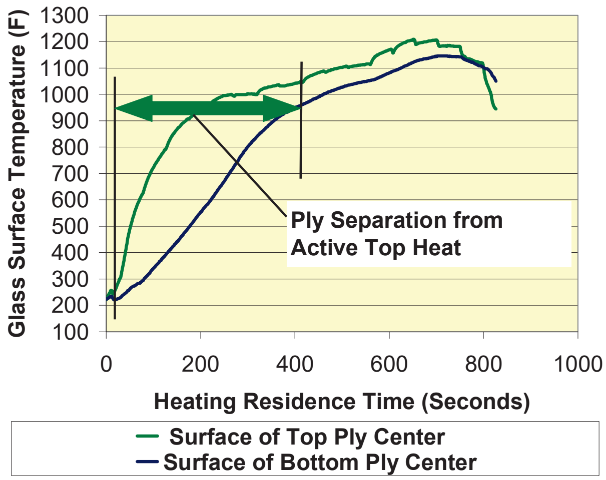

Figure 2 Measured windshield surface temperature levels with time.

Windshield Heating Model and Simulation Results

The CFD windshield heating simulation consists of two models run in series, one for the preheat zones of the lehr, and another for the bending zones of the lehr, which are required due to differences in lehr construction and heating coil layout between the two sections.

The windshield cross section used in this simulation consists of two plies of 0.084 inch thick clear float glass separated by an airspace with a PPG **SUNGATE** infrared reflective coating present on the second glass surface as measured from the outside of the vehicle. This cross section is shown in the following sketch, Figure 3.

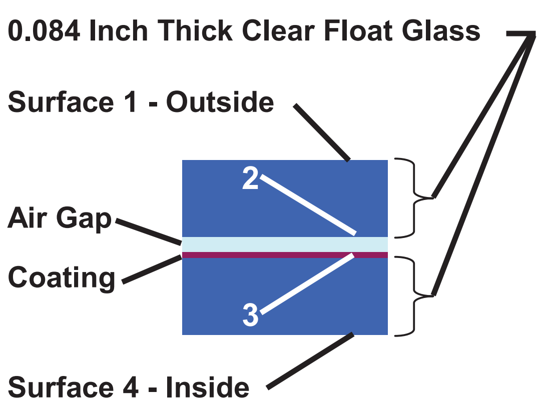

Figure 3 Windshield cross section used in the simulation with surface #1 the outer surface of the vehicle, and surface #4 the inner surface of the vehicle.

Simulated results from CFD analysis showing windshield temperature levels at the end of the preheat section of the lehr overlaid with the heating coil locations are shown in the following thermal image, Figure 4.

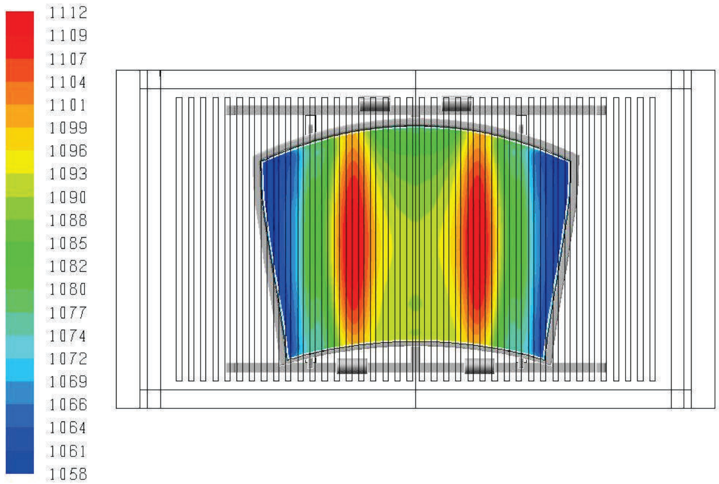

Figure 4 Top view of the windshield and heating coils at the end of the preheat section with temperature levels shown in degrees Fahrenheit.

As can be seen from the windshield thermal image shown in Figure 4, thermal gradients are present side to side in the windshield at the end of the preheat zones. Top to bottom thermal gradients are limited due to the mechanical layout of the heating coils in the lehr, that is, each heating coil is the length of the zone, as can be seen from the heating coil overlay shown in Figure 4.

Simulated CFD results showing windshield temperature levels at the end of the bending section of the lehr overlaid with the heating coil locations are shown in the following thermal image, Figure 5.

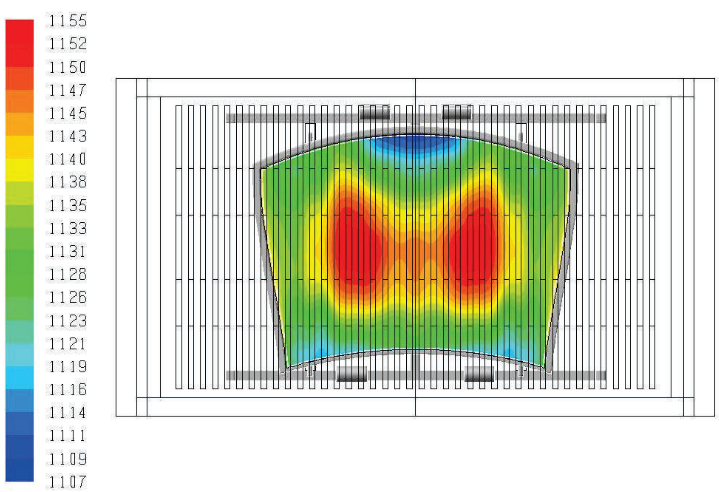

Figure 5 Top view of the windshield and heating coils at the end of bending section of the lehr with temperature levels shown in degrees Fahrenheit.

As can be seen from the windshield thermal image shown in Figure 5, thermal gradients are present top to bottom and side to side in the windshield at the end of the bending zones. The top to bottom thermal gradients that are present in the center of the windshield produce a progressive surface profile in the windshield. This glass heating profile is possible due to the mechanical layout of the heating coils in the lehr, that is, there are five heating coils top to bottom covering the length of the zone that can be utilized to impart a thermal gradient to the glass. The heating coil mechanical layout relative to the windshield thermal profile can be noted from the heating coil overlay shown in Figure 5.

The windshield heating profile with lehr residence time was measured for comparison with the simulated profile in the center of the top and bottom surfaces of the windshield. In the zones of the lehr where the glass bottom surface temperature level is at or greater than 1060 °F, where bending occurs, the measured and simulated bottom center glass temperature levels are within 20 °F of each other. Since the stiffness of the bottom ply, which depends on the glass viscosity at temperature, controls the bending process, close agreement between the measured and simulated bottom center glass temperature levels in the zones where bending occurs is critical to insure accurate bending simulation results. The agreement between measured and simulated bottom surface temperature levels in the glass bending temperature regime can be noted in the following comparison plot, Figure 6.

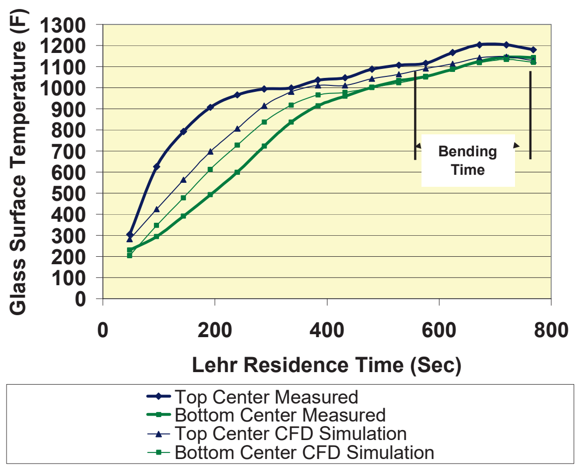

Figure 6 Windshield heating profile comparison between measured and simulated results.

Windshield Bending Model and Simulation Results

For the windshield bending simulation a finite element (FE) model was constructed that contained the articulated bending tooling used for bending the windshield and two glass plies, as in the heating simulation. Shell elements were used in the simulation for the glass plies, and sliding friction was allowed between glass plies and between the bottom glass ply and the windshield bending tooling.

For the bending simulation the CFD calculated glass temperature distribution and level with time was imported as input for the FE model to calculate the windshield surface profile with time in the bending zones. In addition, the articulated bending tooling temperature level with time was also imported from the CFD thermal simulation.

In the bending simulation, glass ply surface deformation was calculated using creep with varying glass temperature. Since permanent glass deformation begins when the glass reaches 1060 °F, the bending simulation was initiated when the glass temperature level reached that point in time within the CFD simulated glass temperature results.

The FE model of the glass located on the articulated bending tooling under gravity loading at the beginning of the bending simulation is shown in the following Figure 7.

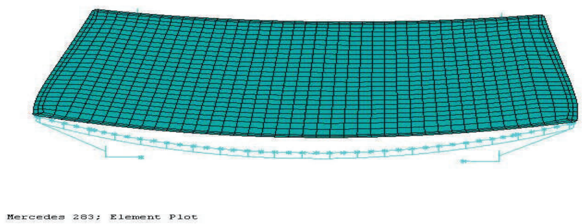

Figure 7 Plot of finite elements for the windshield plies and the bending tooling.

Based upon comparisons between simulated and measured windshield centerline profiles, which were made during the simulation development process, both the shape of the profile as well as the maximum depth of the bend are significantly affected by the glass temperature level at the top and bottom edges of the windshield. For example, a 50 °F variation of the glass temperature level in the top and bottom edges of the windshield changes the maximum depth of bend by 65 percent. This sensitivity of the windshield bend to the glass temperature level in the top and bottom edges of the windshield dictates the use of specialized tooling and process temperature control techniques to control the glass temperature to the required level to produce a specified curvature and depth of bend.

In order to evaluate the results from the FE analysis, the calculated windshield centerline surface contour from top to bottom of the windshield was selected for comparison to measured data for the windshield. For the windshield bending simulation under discussion, the centerline bending comparison between simulated and measured data is shown in the following Figure 8. In this comparison the temperature levels of the top and bottom edges of the windshield were adjusted symmetrically such that the simulated and measured maximum depths of sag were the same. In this case, the maximum deviation between the simulated and measured surface contour is 2.7 mm. The simulated, measured, and design centerline surface profiles are plotted for comparison in the following plot, Figure 8.

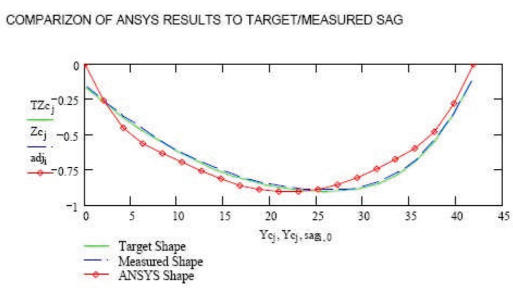

Figure 8 Comparison between simulated, measured, and design windshield centerline surface profiles for the exterior surface of the vehicle.

Conclusions

1. Accurate furnace coil temperature data is essential for predicting glass temperature levels and profiles for use as input in glass bending simulations for predicting windshield surface contour.
2. Radiation absorption by wavelength bands and the effects of ply separation on glass heating must be included in windshield heating simulations to accurately represent the physics involved with glass heating in a windshield bending lehr.
3. Glass temperature gradients near the periphery of the windshield control the depth of bend and surface profile of a windshield.

4. Windshield centerline surface profiles can be predicted to within 2.7 mm by using actual process thermal and timing data as input for windshield heating and bending simulations, which is sufficient to determine process capability for producing surface profiles requested by automotive OEMs

Summary

Windshield heating and bending simulation capability can be utilized as a predictive tool to define windshield bending process capability with production equipment, to refine production glass heating control settings to increase the process operating window for meeting windshield surface control specifications, and to predict if the production surface will meet surface curvature specifications for windshield wiper operation.

Reference

[1] F. Kreith, M. Bohn, Principles of Heat Transfer, Fourth Addition, Harper Collins, 1986.