

Role of Predictive Engineering in the Design Evolution of a Thermoplastic Fender for a Compact SUV

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ABSTRACT

Automotive fenders is one such example where specialized thermoplastic material Noryl GTX* (blend of Polyphenyleneoxide (PPO) + Polyamide (PA)) has successfully replaced metal by meeting functional requirements. The evolution of a fender design to fulfill these requirements is often obtained through a combination of unique material properties and predictive engineering backed design process that accounts for fender behavior during the various phases of its lifecycle. This paper gives an overview of the collaborative design process between Mitsubishi Motors Corporation and SABIC Innovative Plastics and the role of predictive engineering in the evolution of a thermoplastic fender design of Mitsubishi Motors Corporation's compact SUV RVR fender launched recently. While significant predictive work was done on manufacturing and use stage design aspects, the focus of this paper is the design work related to identifying support configuration during the paint bake cycle. In this paper, simulation results of several real life design changes that were evaluated for their efficacy in reducing deformation during paint bake are presented followed by qualitative comparison between experimental and simulation data.

1. INTRODUCTION

Automotive fenders represent one of the many automotive applications where specialized thermoplastics have successfully replaced metals while meeting regulatory as well as Original Equipment Manufacturer (OEM) specifications. Usage of thermoplastics in fenders facilitates complex shapes and styling that may not be readily possible with metals. In addition they offer advantage of part integration, weight reduction and dent resistance for low speed impact. Depending on the number of vehicles made, they also offer cost reduction opportunities. The evolution of thermoplastic fender design to fulfill OEM requirements is often obtained through a combination of unique material properties and predictive engineering-backed design process that accounts for fender behavior during the various phases of its lifecycle. In this paper we present the role of predictive engineering in the design and validation process of thermoplastic fender with the example of Mitsubishi Motors Corporation's compact SUV RVR fender development (Referred henceforth as RVR in this paper). This fender development involved collaborative work between Mitsubishi Motors Corporation (MMC) and SABIC Innovative Plastics (SIP) spanning a period of 2 years. During this phase significant simulation work was performed to address various design aspects, related to molding, paint bake and operations during use phase. However we focus on the work of identifying an optimum support configuration to control fender displacement within OEM specified limits during the paint

bake cycle. Emphasis on design for paint bake has been given, as it is the most evolved procedure among the various simulation activities and occupied major chunk of the design work.

The organization of the paper is as follows. Section 2 provides the functional requirements imposed on fender material, as well as design, during the various phases of its lifecycle. Section 3 describes the scope of the structural design optimization required to ensure satisfactory fender performance during paint bake. Section 4 shares the process map of the collaborative predictive engineering backed design work between Mitsubishi Motors Corporation and SABIC Innovative Plastics right from the initial concept to final production part evaluation. The details of the numerical modeling approach used are presented in Section 5 followed by results and conclusions in Section 6 and 7 respectively.

2. FUNCTIONAL REQUIREMENTS

A typical thermoplastic fender is designed considering the functional requirements that arise from three major phases in its lifecycle.

1. Manufacturing by Injection molding.
2. Performances during paint bake cycle.
3. Production or actual use performance.

2.1. MANUFACTURING BY INJECTION MOLDING

Injection molding is the most common manufacturing process for thermoplastic fenders. Thus fender design needs to be amenable to the injection molding process by ensuring, that part design and thickness distribution is such so as to allow for balanced filling at reasonable pressure and fill time. It is also essential to identify gate design, process parameters and mold temperature that helps minimize the warpage and residual stresses in part, post the molding operation. Another priority is to avoid weld lines, sink marks or at least take them away from the exterior surface of the fender.

2.2. PAINT CYCLE PERFORMANCE

A typical car has at least 2-3 paint layers. The first among them is the e-coat paint layer followed by a filler or base/clear coat. Every paint cycle is followed by a curing process in an oven before it goes to the next stage in paint line. There are several types of painting process, however we restrict the discussion to the online painting as it poses the maximum demands on material. For an overview of the automotive paint process and types of painting, other than online painting, interested readers may refer [1][2]. In an online painting, the thermoplastic fender is assembled on to the Body in White (BIW) before the e-coat bath and stays on the BIW right through the paint process and hence all the curing cycles. During online paint cycle the fender material needs to

undergo at least 2 or 3 thermal cycles in successive curing ovens after each paint stage. In general, the peak oven temperature during the e-coat paint curing is in the range of 180°C to 210°C.

During the painting process, the thermoplastic fender is subjected to transient temperature cycle whose temperature peaks (180°C to 210°C) and time duration varies with each OEM. The deformations that arise during the paint curing process are an outcome of interactions of several factors namely,

1. Relative thermal expansion due to difference in coefficient of thermal expansion (CTE) between fender material and steel BIW.
2. Increase in deformation at constant self-weight due to reduction of modulus at higher temperatures.
3. Viscoelastic creep of the thermoplastic material at elevated temperature during its residence in paint oven during curing.
4. Paint line shrinkage that occurs during the curing cycle at elevated temperatures. (Please note that the paint line shrinkage is different from the post molding shrinkage.)

Given the location of a fender, its edges are in close proximity of other car sub-assemblies such as headlamp, bumper, hood and hence maintaining deformation within tolerances during paint curing is critical. Typically, for a given fender - tolerances on in plane and out of plane deformation are subscribed by the OEM and are commonly referred to as gap and flush respectively. [Figure 1](#) gives the definition of gap and flush for typical fender edges.

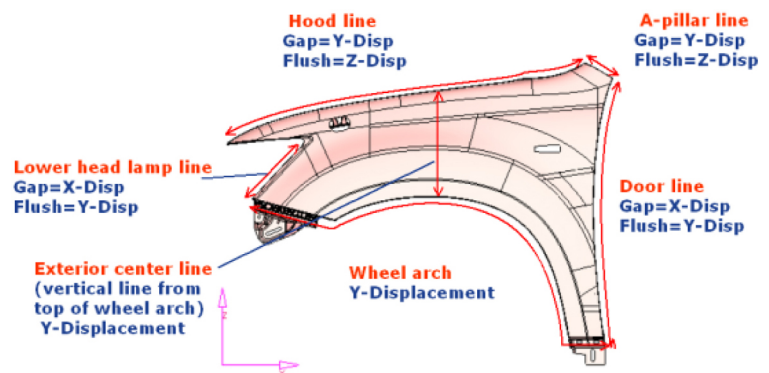


Figure-1. Definition of gap and flush for fender edges

2.3. PRODUCTION OR ACTUAL USE PHASE

Fender, being an external surface of the car it requires adequate surface rigidity to withstand minor abuse loadings like hand push, stone impacts, low velocity impact etc that may arise during the life of a car. The assembled fender

should also be designed to account for temperature fluctuations associated with seasonal variations. Based on the geographic location, it may also need to meet pedestrian safety and or insurance related requirements. Thus fender design has to ensure sufficient surface rigidity, tolerance to thermal environmental variations and low speed impact management within permissible deformation.

3.0. DESIGN STRATEGY

The functional requirements of fenders have been covered in detail in previous section. These requirements are typically met by a combination of utilizing appropriate thermoplastic materials and a structural design that accounts for the material behavior during the operations. In next subsection we briefly cover the material blend developed for paint-line applications.

3.1. MATERIAL PORTFOLIO

Automotive fenders is one such example where specialized thermoplastic material Noryl GTX* (blend of Polyphenyleneoxide (PPO) + Polyamide (PA)) has successfully replaced metal. In Noryl GTX* blend, Polyphenyleneoxide (PPO) an amorphous polymer is a suspended phase in a matrix of semi-crystalline polyamide (PA). PPO with a glass transition temperature (T_g) of 215°C, contributes towards heat resistance, dimensional stability and low density to the blend. Polyamide (PA) semi-crystalline material contributes towards good chemical resistance, processability and paintability. One of the best advantages of thermoplastic blends like Noryl GTX* is that the properties can be tailored for different customer requirements.

3.2. STRUCTURAL DESIGN CONSIDERATION

A fender made of Noryl GTX* when assembled on steel BIW and subjected to a transient thermal cycle, the co-efficient of thermal expansion (CTE) difference induces thermal expansion and thermal stresses. Another point to be considered is that peak temperatures may reach close to 210°C. The structure and its support configuration should sustain its own weight during its residence time during soaking, where the material stiffness reduces, due to high temperature before it gets restored to normal value at room temperature.

It should also be pointed out that unlike metals, thermoplastics in response to temperature, can exhibit elastic, viscoelastic or even hyper-elastic behavior depending on the (T_g) of the thermoplastic [3]. Temperature close to the T_g evokes a viscoelastic response. The PPO+PA blend system has three different glass transition temperatures (T_g), one of which is close to 200° C and hence design has to account for viscoelastic relaxation during e-coat paint bake cycle.

To account for some of the stated effects, sliding joints are used to absorb the thermal expansion and contraction during the paint cycle. Figure 2, represents the schematic of a sliding joint and typical locations along the hood-line and door-line. Some of these may subsequently get fixed during the final assembly while some of them may retain some sliding degree of freedom to account for environmental temperature fluctuations or sun-load during actual use stage.

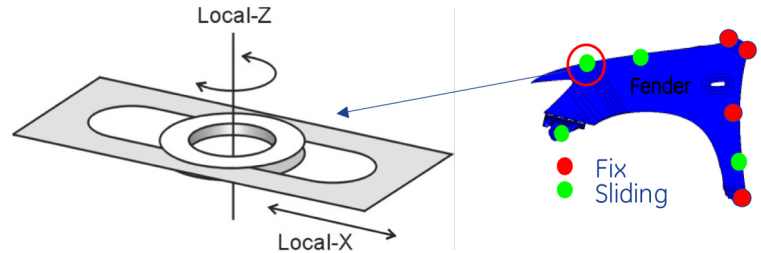


Figure 2. Typical locations of joints on hood-line and door-line with a schematic of sliding joint.

A typical fender has about 9-13 support locations and the gap and flush tolerances that need to be minimized are usually specified for at least 6-7 edges of the fender as shown in Figure 1. Thus the scope of the structural design problem is to identify a combination of constraints that minimize the gap and flush of all the edges of interest or at least most of them and maintain them within OEM specified limits during the paint cycle as well as the actual use phase. Arriving at such a constraint configuration requires identification of

- Precise location of each support on fender.
- Type of restraint on the joint i.e. sliding or fixed.
- Orientation of the slot in which sliding occurs i.e., horizontal vs. vertical vs. inclined.

Case studies in the subsequent results sections will highlight the effect of above stated factors on fender edge deformations. Given the multitude of variables involved - use of numerical tools becomes increasingly essential to virtually ascertain various constraint combinations and shortlist a few that show promising trends for further consideration.

Numerical modeling of fender under a variety of real life scenarios like passage through e-coat bake, pedestrian head impact etc requires the presence of appropriate material model that would mimic the materials response. For example the e-coat bake simulation requires a thermo-viscoelastic model as shown in N.A Hardikar et al, [1]. A pedestrian head impact simulation would require an elastic-plastic strain rate dependent model [4]. In some cases, even “User defined material models” UMAT¹ have been developed to model the effect of painting on the impact performance. Such material model in turn requires extensive characterization of thermoplastics to get the material constants required for the

numerical models. Material suppliers often have the characterization and numerical modeling expertise for their materials.

Auto OEM's on the other hand have significant expertise of part styling, product knowledge and intimate knowledge of components adjacent to the part being designed. For example, fender design and the position of its supports have to take into account interaction with other sub-assemblies like door, hood, reflectors, bumpers etc. Hence collaborative design & development between the OEM and material suppliers is beneficial to expedite the design and development cycle.

4.0. COLLABORATIVE DESIGN & DEVELOPMENT BETWEEN MMC AND SIP.

In this section we provide an overview of the comprehensive collaborative development work which was performed between Mitsubishi Motors Corporation and SABIC Innovative Plastics on the design and optimization of the Noryl GTX* 979 fender on the recently launched RVR version for global market. This vehicle was first launched in Japan as “RVR” on February 17, 2010 and then released as “OUTLANDER SPORT” in the U.S. and “Mitsubishi ASX” in the other regions globally. (Referred as “RVR” in this paper.)

During the design process, the scope of the predictive work in each design iteration was namely

- Suggest and evaluate different support configurations and identify the most promising among them for paint bake as well as environmental thermal variation performance. (Referred in this paper as sunload)
- Identify gate location, thickness variation, process parameters for optimum manufacturing of fender through injection molding process.

The collaborative design process followed between Mitsubishi Motors Corporation and SABIC Innovative Plastics in all the iteration from M0-M4 is shown in [Figure 4](#).

Predictive results from iteration M0-M2 helped in determination of appropriate thickness distribution and identification of areas that required local reinforcements to achieve sufficient stiffness at high temperature and maintain deformations within tolerances. For example, e-coat bake simulation identified that the initial design was too weak at the lower front-end structure and predicted wide gap at the hood line. This data was useful in the design of the prototype versions, which had a major improvement in hood line gap due to reinforcement of the weak points.

Major focus of design iterations M3-M4 was to understand the influence of various support configurations and fine-tune design as well as the constraint locations to enhance paint bake performance. During each design iteration, predictive engineering results were generated on the various aspects of the fender design namely paint cycle, sunload performance, molding operation and the following output generated for Mitsubishi Motors Corporation's designers.

1. Gap and flush prediction during e-coat bake for all 6 fender edges for various constraint combinations
2. Gap and flush in assembly condition due to sunload
3. Molding related parameters like balanced filling, pressures, warpage etc.

For both e-coat bake and sunload procedures ABAQUS™ Standard 6.7 [5] was utilized. For the simulation of injection molding process Moldflow™ Plastic insight 6.2 was utilized.

Among the different types of predictive procedures performed, the e-coat-bake simulation is the most evolved procedure among the various activities and represents the major chunk of the work done. Hence we present the modeling procedure and results on the paint bake performance and the optimization of support achieved in the next 2 sections respectively.

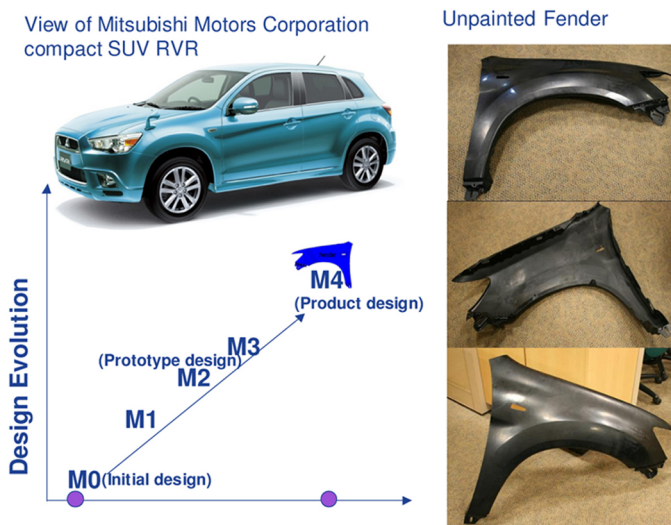


Figure 3. Design evolution of RVR thermoplastic fender from concept to production

During the design evolution phase as shown in [Figure 3](#), extensive predictive work was performed on the design configurations that evolved from the initial design M0, to product design stage M4. [Figure 3](#) depicts the unpainted images of the product design and view of the compact SUV RVR with the Noryl GTX* 979 fender.

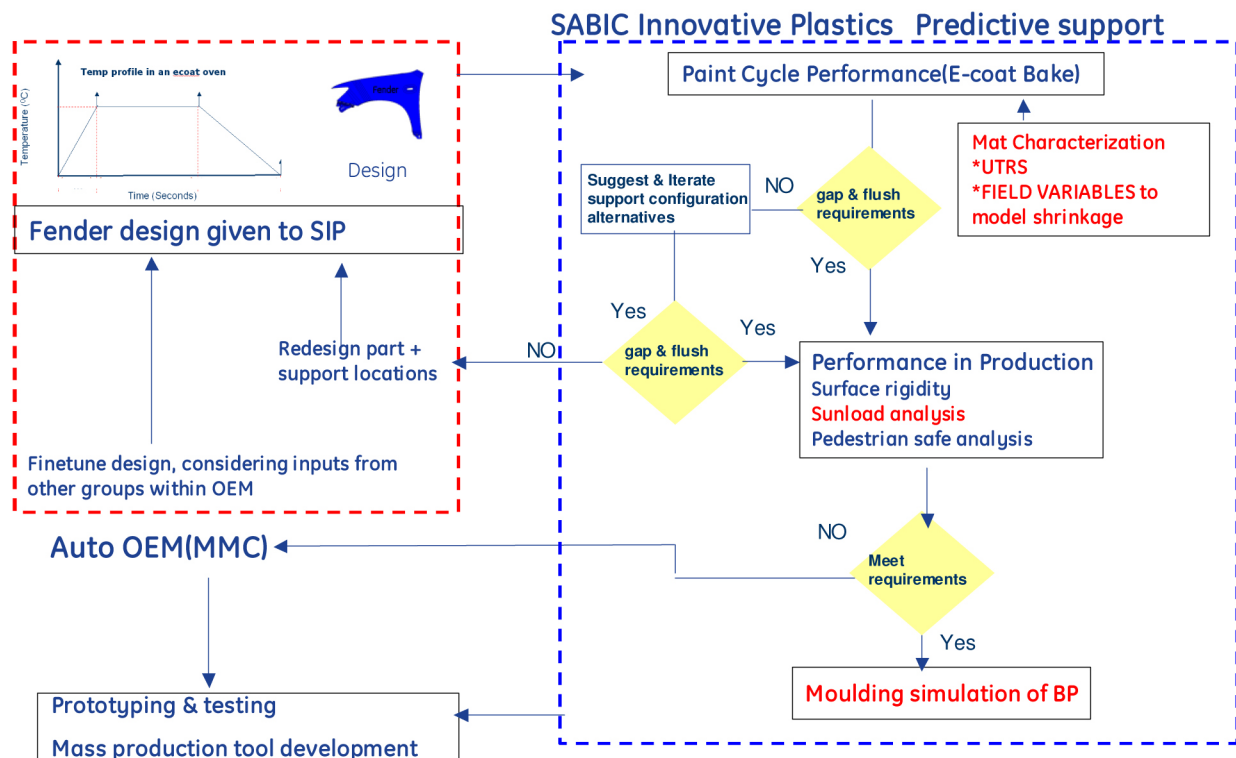


Figure 4. Process map of Collaborative design and development of thermoplastic fender.

5.0. NUMERICAL MODELING OF THE E-COAT BAKE PROCESS

In this section we present the details and various considerations in the numerical modeling of the e-coat paint bake process.

5.1. THERMO-VISCOELASTIC STRESS ANALYSIS

Given the high temperatures and the typical residence time in the e-coat bake oven, modeling the deformation of a thermoplastic fender during the paint cycle involves solution of a thermo-viscoelastic stress analysis problem [1]. To mimic the response of the material it is essential to capture viscoelastic relaxation, the effect of temperature on that relaxation and the paint line shrinkage.

The viscoelastic relaxation is modeled using the generalized Maxwell model available in ABAQUS™. The model can be represented by a linear spring in parallel with an array of Maxwell elements. The linear spring in the model represents the instantaneous response, which can be temperature dependent. The relaxation response is modeled by using Prony series coefficients, obtained by fitting the relaxation experimental data at a reference temperature. The effect of temperature on the viscoelastic relaxation behavior and its inclusion in the viscoelastic stress analysis is obtained by the use of horizontal shift factor function and reduced time

concept first introduced by Leaderman [6]. Since the horizontal shift factors do not follow the William Landel Ferry (WLF) equation [7], a user thermorheologically simple (UTRS¹) function was developed to account for the influence of temperature variation in the viscoelastic stress analysis. For further details of the viscoelastic model, the need for horizontal shift factors, the concept of reduced time and the role of *UTRS interested readers may refer [1]. An isotropic representation of the paint line shrinkage has been incorporated in the stress analysis by utilizing extensive in house experimental shrinkage data [8] coupled with the innovative use of the FIELD¹ variables concept in ABAQUS™.

5.2. MATERIAL CHARACTERIZATION SUMMARY

In the e-coat modeling, temperature dependent material (wherever applicable) data was utilized for simulation. Co-efficient of thermal expansion, density, Young's modulus, viscoelastic relaxation data in Prony series format horizontal shift factor variation (aT) programmed into UTRS¹, shrinkage data used for FIELD¹ variables was used in the simulation. Figure 5 shows the schematic of the characterization process used for obtaining viscoelastic data. For further details of material characterization and the underlying assumptions and procedures interested readers may refer to [1][5][9].