SIMULATION OF INJECTION OVER-MOLDING FOR HIGH-RATE COMPOSITES PROCESSING

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Abstract

A manufacturing process simulation for injection over-molding using commercial simulation tools will be presented. The major fabrication steps of preforming, mold filling, packing, cooling and warping are simulated using CATIA, LS-DYNA and Moldex3D. The preform shearing, development of knit-lines, flow-induced fiber orientations and resulting effective properties, part warpage and residual stresses are predicted. The direct implications of the prediction of temperatures at the interface between the preform and the over-molding material on the resulting bond strength are discussed. Applications of the process simulation to tool design and process design are and implications of the process simulation on performance of the as-manufactured part are discussed.

Injection Over-Molding

Injection over-molding is the preforming of a continuous fiber fabric prepreg, to form a structural backbone, followed by injection of discontinuous-fiber reinforced polymer, to form complex three-dimensional geometry. Often termed “hybrid molding”, injection over-molding offers both structural performance and geometric complexity in a high-rate manufacturing process [1]. The process involves the physical phenomenon of fabric draping or preforming [2], viscous suspension flow, discontinuous fiber flow orientation [3]–[9], polymer phase change, solidification kinetics, thermal contraction, and residual stresses and deformations [10]–[12]. Each of these are captured in commercial simulation tools as illustrated in Figure 2. In this case, CATIA is used to define the model geometry, LS-DYNA to simulate the preforming of the fabric preforming, Moldex3D to simulate the injection filling, packing and cooling and warping, and LS-DYNA to simulate the impact performance.

The paper will describe:

- Issues in injection over-molding and show how simulation addresses these issues;
- Processing simulation, including processing parameters for process design;
- Details of the information flow and connections in terms of the inputs and outputs between the models implemented in the commercial simulation tools;
- Implications of process simulation on tool design;
- Influence of manufacturing simulation on performance simulation, specifically by means of the fiber orientations, effective properties, and residual stresses predicted from the preforming and flow simulations.

Issues in Injection Over-Molding

Three main issues in injection over-molding are:

1. Multi-material mold filling
2. Dimensional stability of hybrid structures
3. Performance of hybrid structures

The first issue is the ability to predict the mold filling under conditions with a preform in the mold cavity. This is particularly challenging if the preform exhibits significant flexibility or deforms upon contact with the high-pressure injection melt. Typical issues to be considered in mold filling are complete fill of the mold, the development of weld lines and air traps, and fiber orientation. Some of the issues more unique to over-molding include interaction of the flow front with the fabric preform, lofting or thickness increase of the fabric preform at melt temperature, and the bonding between the preform and injection compound. We will see the ability of the simulation to begin addressing aspects of bonding.

Second, dimensional stability is a challenge because the part contains two different materials with dissimilar contraction properties. In the case of the fabric preform, extensional shape change is almost negligible. The injection compound, on the other hand, exhibits significant shape change from both thermal and solidification effects. This makes dimensional stability a challenge in two ways. First, the as-manufactured part geometry will exhibit deviations from the design or mold geometry owing to thermal contraction, internal stresses, and solidification. This affects the shape of the part immediately upon cooling. The second effect is the tendency of the internal stresses in the part to relax over time, due to viscoelasticity, causing the shape of the part to change over a period of time - on the order of days. Thus while the as-produced part may have been acceptable, by the time the part is received and ready to be assembled, its geometry is no longer within tolerance.

The last challenge is the ability to predict the mechanical performance of the as-manufactured part. The heterogeneity not only of the individual materials themselves, but also the difference between the preform material and the injection material causes additional complexity. The bonding between the preform and the injection also influences the mechanical performance.

While each of these issues are a challenge, they can be addressed with manufacturing process simulation.

Process Simulation

Overview of Integrated Process Simulation

Let us first examine and overview of the integrated process simulation, shown in Figure 1. The major process steps of defining the geometry, simulating the fabric preforming, simulating the injection over-molding and simulating performance are shown. The commercial simulation tools associated with each step are indicated next to the process step. Arrows indicate the transfer of information from one step to another.

The workflow begins with geometry creation using a CAD software, CATIA in this case, to develop the part geometry, ply geometry, preform tool geometry and injection tool geometry. These geometries are passed to the appropriate stages of the manufacturing process simulation as indicated in the flow diagram.

The fabric preforming is simulated in LS-DYNA and receives the ply geometry and preform tool geometry from CATIA. The preforming simulation predicts the fabric deformation, including the shearing of the fabric yarns.

The fabric deformation information is passed together with the injection tool geometry to Moldex3D, which simulations the injection over-molding process. Moldex3D captures the physical processes of injection, packing, cooling, and warping which enable prediction of the as-manufactured part geometry and properties.

The as-manufactured part geometry and properties may then be passed to LS-DYNA or any other finite element software for performance simulation. “Manufacturing-Informed Performance” refers to such a simulation of the performance of the as-manufactured part with the as-manufactured properties.

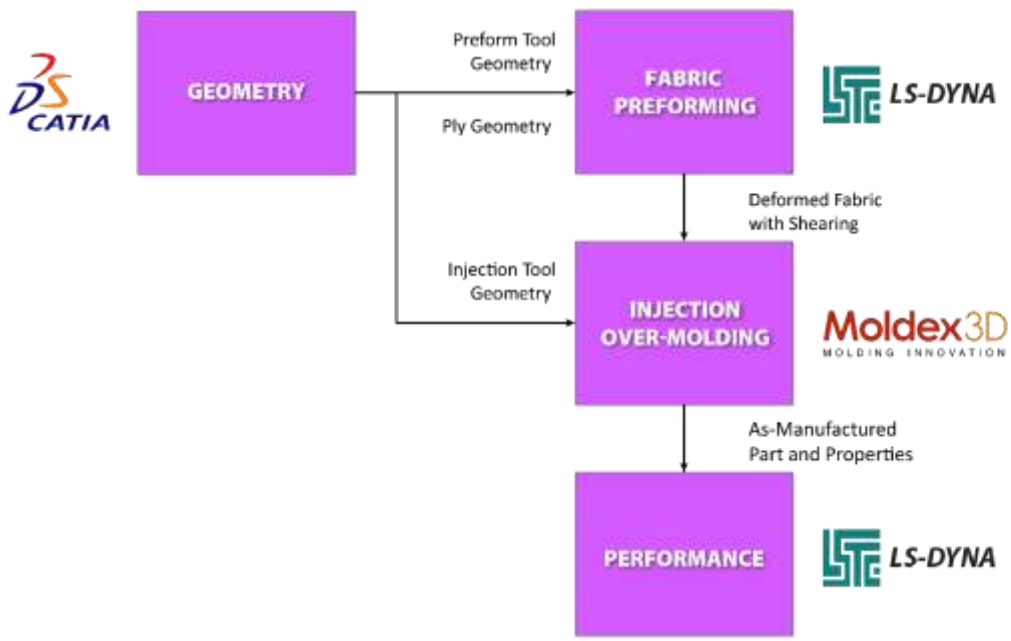

Figure 1: Process simulation workflow for injection over-molding

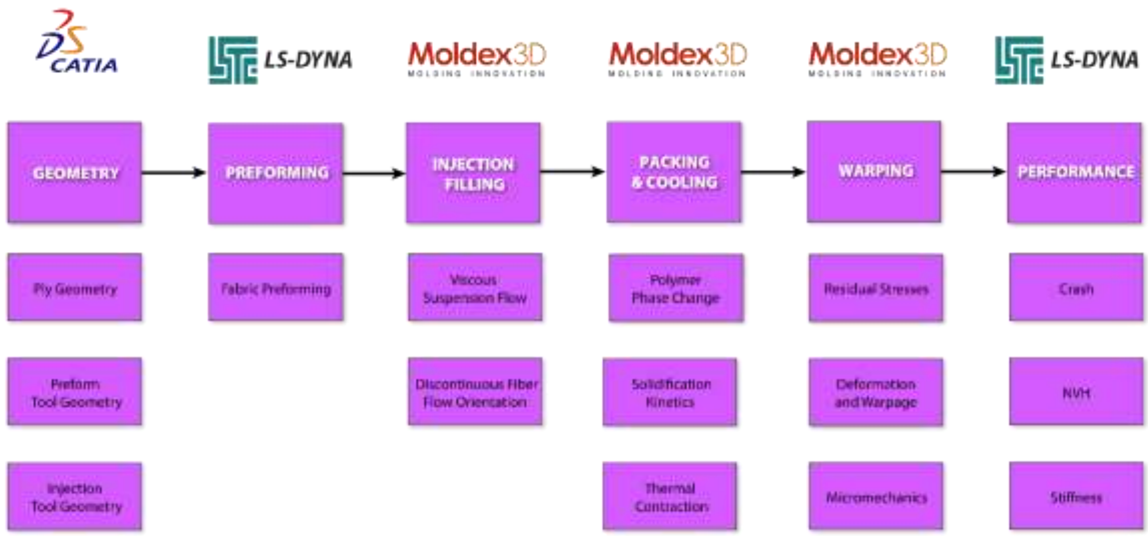

Figure 2: Injection over-molding physical phenomenon and process simulation

A more detailed view of the physics captured in each process step is shown in Figure 2. Here we are examining the physical phenomena captured in each of the major steps in the process workflow: geometry creation, fabric preforming, injection filling, packing and cooling, warpage, and performance. It is by capturing the relevant physics that the manufacturing process can be simulated. Again, the simulation tools that simulate these steps are shown above the boxes.

The geometry creation step consists of defining the part geometry, the flat ply geometry, and the geometry for the preforming tool and for the injection tool.

During preforming, the fabric sheet is shaped to the curvilinear geometry of the forming tool. This preforming step, performed in LS-DYNA, captures the physics of fabric preforming arising from shear deformation.

Following preforming, polymer melt is injected inside the injection tool to form the complex 3-dimensional features, including ribs, supports and attachment points. The injection step, modeled in Moldex3D, consists of the phenomenon of viscous fiber-suspension flow and flow orientation of the discontinuous fibers in the suspension. While the fiber suspension flow is characterized by significant anisotropy – that is the flow characteristics are strongly dependent on direction owing to the orientation of the fibers within the fluid – the current models invoke the simplifying assumption of isotropy. The injection step ends when the mold cavity is filled.

Upon entry into the mold cavity, the polymer melt immediately begins cooling. Because the polymer contracts and shrinks in volume as it cools, it is common practice to apply significant injection pressure to the molding during the initial stages of cooling until the gate or injection location freezes or solidifies. During this packing stage, additional volume of material may be forced into the mold to compensate for the volumetric shrinkage of the material and prevent void formation. During packing and cooling, which involve significant heat transfer, the polymer phase changes from liquid to solid, and in the case of semi-crystalline polymers, crystallization occurs. Cooling, solidification, and crystallization are all accompanied by volumetric contraction.

After cooling to below melt temperature, the part is ejected from the mold. As the part continues to cool, it develops internal stresses, which are particularly significant in the case of injection over-molding because of the multiple material forms involved. Some fraction of these internal stresses are relieved by shape change resulting in deformation and warpage as well as formation of voids and cracks. The remaining internal stresses are then classified as residual stresses and may continue to cause deformation over time through viscoelastic effects, or may serve to induce premature failure under application of additional structural loading. The warping produces an as-manufactured part geometry. In addition, the fiber orientations resulting from injection process and the fiber yarn orientations in the fabric due to the preforming process have a significant influence of the effective properties of the part. The polymer crystallinity also has some influence. The field of micromechanics is used to determine the effective engineering performance properties of the as-manufactured part based on the fiber orientations and polymer state.

Finally, the performance of the as-manufactured part may be predicted from these as-manufactured properties. Performance in this case refers to crash, NVH, stiffness or other performance metrics of interest in the design process.

Geometry and Materials

With an understanding of the issues in injection over-molding and an overview of the process simulation, a detailed example of the injection over-molding process simulation for an example part will be presented.

A generic beam structure with geometric complexity in the form of stiffening ribs was selected as shown in Figure 3. For scale, the beam is approximately 1 meter in length and will be fabricated from glass-reinforced polypropylene. For the fabric, the continuous glass content is 60% weight. The injection compound is 40% discontinuous long-fiber glass by weight.

The choice of the materials was based on materials available in the Moldex3D database. The Moldex database has thousands of materials available and contains a host of information about the mechanical, thermal, and phase properties of the materials.

The fabric sheet was chosen to be a pre-consolidated fabric with comingled glass and polypropylene woven in a 2x2 twill pattern. The mechanical properties of the fabric are modeled as seen in Table I. Because the sheet is preheated prior to preforming, the shear modulus in the preforming simulation is reduced by an order of magnitude.

Figure 3: Complex generic beam geometry

Table I: Preform material properties

E_1	14 GPa
E_2	13 GPa
G_{12}	1.7 GPa
n_{12}	0.1

Preforming Simulation

The first step in the process simulation is the fabric preforming. The focus is simulating the deformation of the fabric preform. These results allow for responses to the following question, "Is the design manufacturable or will wrinkling and/or fabric tearing necessitate a design change in the tooling or part geometry?" If the design is manufacturable, then the information about the as-manufactured design, namely the shearing deformation of the fabric preform is passed to the next step of the analysis, the over-molding simulation.

The ply geometry and tool geometry are brought into LS-DYNA for the preforming simulation. The ply is positioned atop the upper surface of the lower convex tool. An upper tool is then positioned atop the ply and the lower surface of the upper tool acts as the upper concave tool face.

The tools are modeled as rigid surfaces and the ply as an orthotropic elastic solid, with negligible shear rigidity owing to preforming at elevated temperature. The contact constraints between the tool and preform and the tool velocity are defined.

The output of the preforming simulation is the deformation of the preform fabric. Because the fibers are essentially inextensible, the deformation mechanism is entirely through shear, or angle change.

Whenever a fabric is required to conform to curvature in more than one plane, it will do so through shearing deformation or angle change. In addition to affecting the effective properties, excessive shearing is manifest through wrinkling, or, with sufficient constrain, through tearing of the ply. Therefore, the prediction of shearing deformation is a key output of the preforming simulation and affects both the manufacturing and performance design.

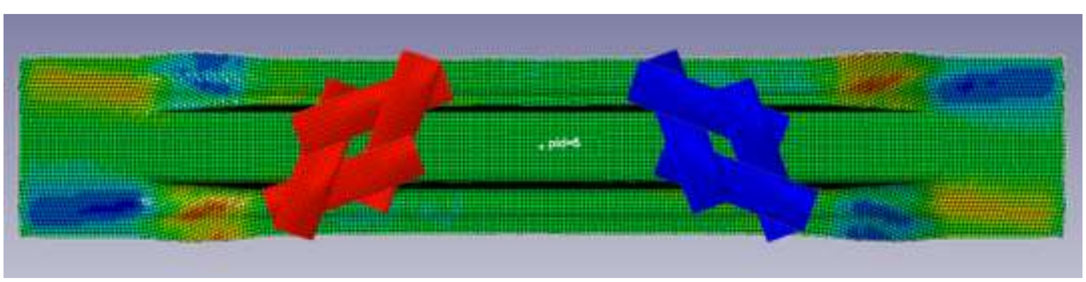

Figure 4: Top-view of simulation prediction for shearing of the as-manufactured preform. The red indicates positive shearing strain and the blue, negative shearing strain.

The results of the preforming simulation are shown in Figure 4 where the contours indicate local shearing strain. Regions of red indicate positive shearing strain while regions of blue indicate negative shearing strain. The final shape of the preform after the simulation has antisymmetry in the shearing strain. The regions of maximum shearing strain are those regions most likely to exhibit wrinkling or fabric tearing. Wrinkling arises when the fabric shear-locking angle is exceeded and the fabric can deform no further in the plane. Tearing arises from excessive tension in the fabric. The fabric deformation simulation can answer the main question, “Can the design geometry be formed?”

If the answer is no, options are to modify the tool geometry, to change the fabric weave pattern to a more open weave – such as from a plain weave to a twill or satin weave – or to change the initial fabric orientation. The process simulation can anticipate which changes will be effective and how they will impact the manufacturability later in the process and the performance at the end of the day.

If the design is manufacturable - neither the limits for fabric wrinkling or for preform tearing were exceeded – then the deformed fabric geometry and shearing deformation are passed along to the injection molding simulation.

Molding Simulation

Following the preforming simulation, the injection over-molding process is simulated in Moldex3D. Just as the preform is placed in the injection mold for over-molding, the preheated preform is included in the molding simulation for the thermal and warping analyses. Fiber orientation results from the preforming process simulation in LS-Dyna are included in the Moldex3D model which will be used to predict the anisotropic mechanical properties.

The region of the molding cavity which will be filled by the injection compound is modeled using Moldex3D’s boundary layer mesh. Additionally, the moldbase, cooling channels, and runner system are included in the model. The material models of the injection compound’s PVT, viscosity, crystallization kinetics, thermal conductivity, heat capacity, and mechanical properties are taken from the Moldex3D database.

Critical processing parameters are given as inputs to the simulation. Some of these include fill rate, packing pressure profile, melt temperature, mold temperature, initial preform temperature, and cycle times. Computational parameters may also be modified to specify parameters for the desired fiber orientation models.

The first step of the over-molding process is the part filling for which Moldex3D predicts the melt front progression as shown in Figure 5. The flow rate controlled filling process switches to pressure control near the end of fill which models the packing phase of the molding process which helps compensate for shrinkage of the injection compound. The filling simulation additionally predicts flow induced orientations of the chopped fibers. The fiber orientation results are expressed as a fiber orientation tensor. The axial component of the fiber orientations resulting from the flow simulation are shown in Figure 6.

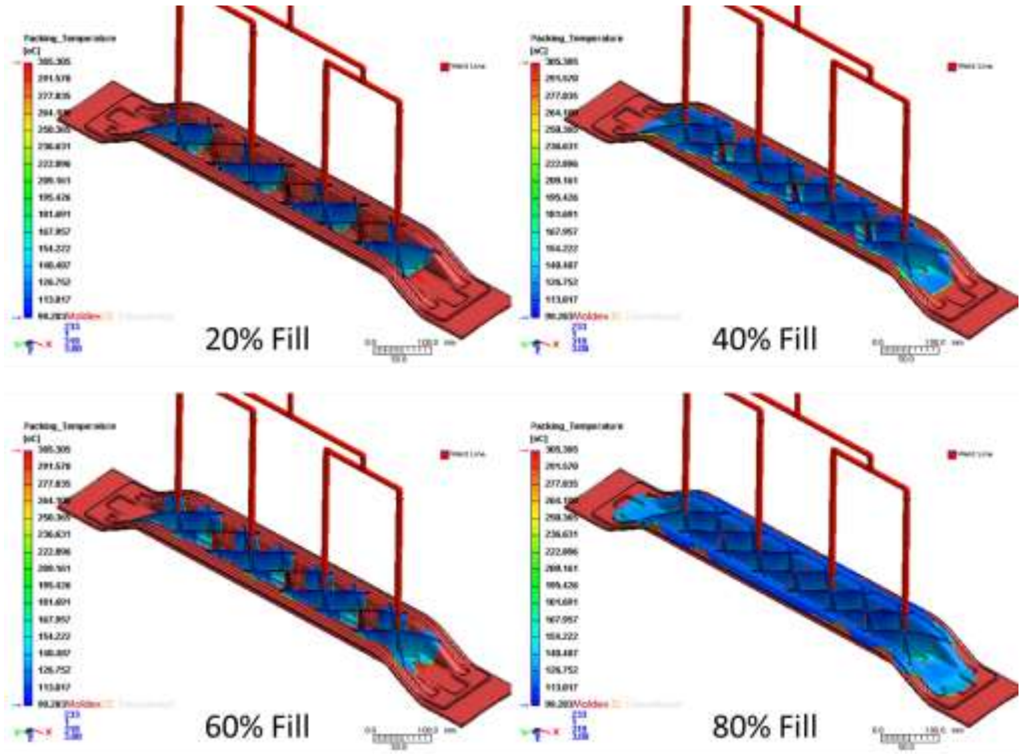

Figure 5: Fill simulation melt front progression with melt temperature shown. The preform is shown in dark red

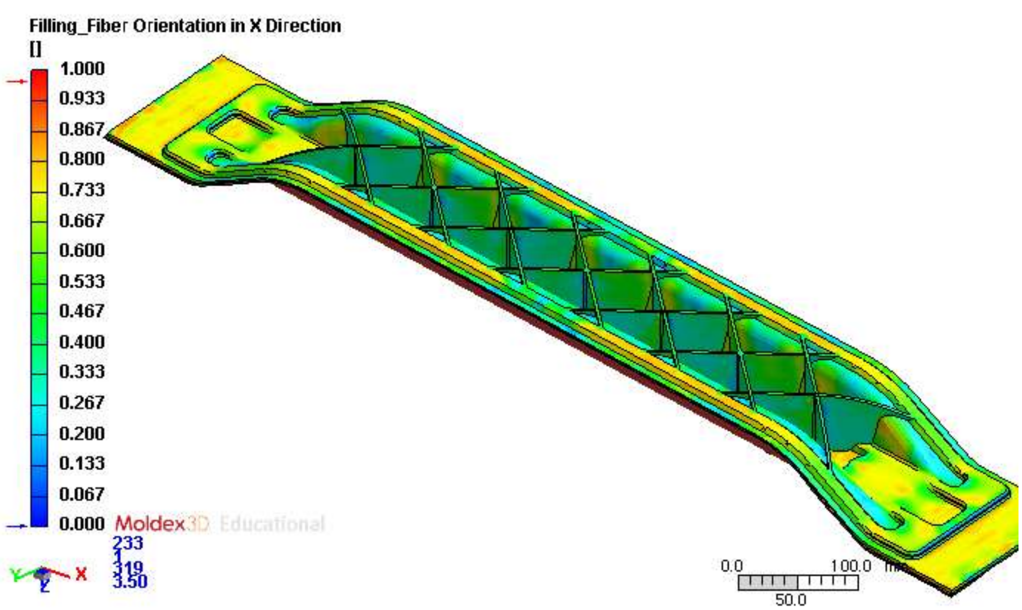

Figure 6: Axial fiber orientations resulting from the mold filling simulation

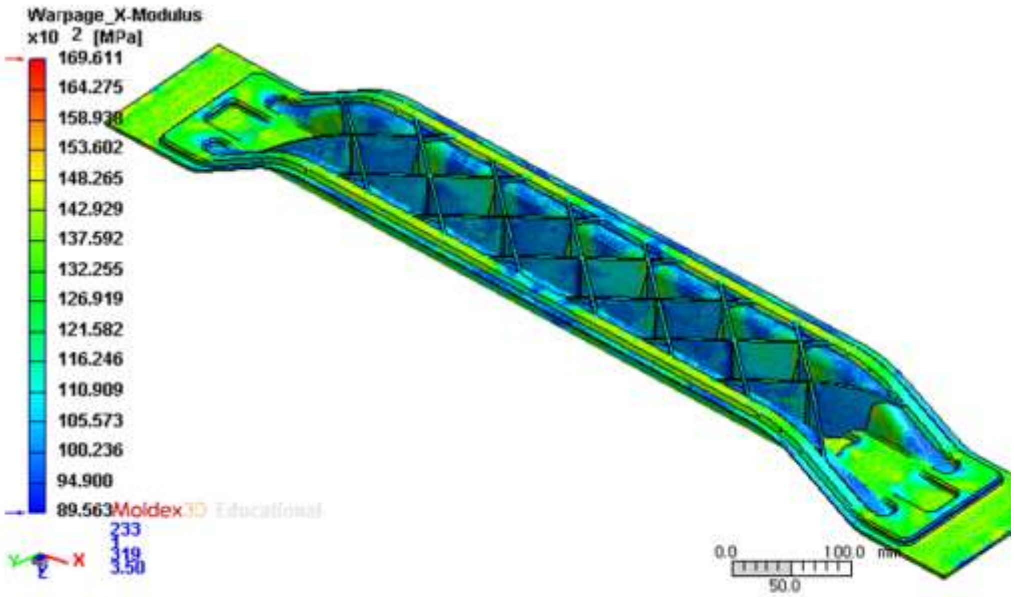

Figure 7: Effective Young's modulus in X (axial) direction computed from the flow induced fiber orientation results

A cooling analysis is also performed by Moldex3D, which evaluates the thermal history of the part throughout the over-molding process. This thermal history includes the heat transfer to the preform, to the moldbase and within the over-molded injection compound. This thermal history may be used to inform bonding between the preform and the injection compound. This bonding is critical to the performance of the hybrid molded composite part. Figure 8 below shows the temperatures of the surface of the preform which have reached a threshold value indicating potential for re-melting.

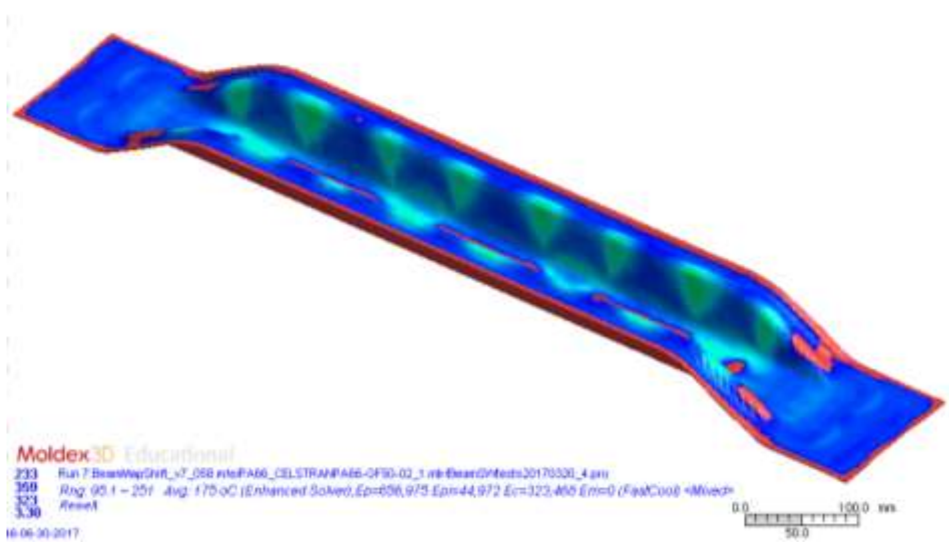

Figure 8: Region of preform which are heated to melting temperature by the injection melt at the end of fill

Of particular relevance to the quality of the bonding between the preform and the molding compound is the interface temperature. Recent work in hybrid processing of thermoplastic-based multi-materials has shown a significant influence of interface temperature on interfacial bond strength [13]. As Chandran's work was primarily experimental, there is significant potential for informing the experiments of the interface temperature predicted from the molding simulation and providing further insight into the experimental results. In addition, incorporating the experimental characterization of the effect of processing on bond strength into the Moldex3D model would be a step towards performance prediction of hybrid-molded structures.

In the warp simulation performed in Moldex3D, the thermal and pressure history of the polymer are used with the PVT and crystallization models to compute polymer shrinkage during the over-molding process. Additional shrinkage due to the part cooling to room temperature after ejection uses the mechanical coefficients of thermal expansion. These CTE's are anisotropic material properties informed by the fiber orientations for the preform and injection compound. The differential shrinkage between the injection compound and the preform manifests in out of plane deformation or warpage shown magnified by three times in Figure 9. This results in a part shape that is different from the design shape. The simulation tool can be used to predict whether this deformation will be within tolerance and can be used to explore compensation strategies such as tool and process modifications.

Conclusions

In summary, we have presented a process for simulating the injection over-molding or hybrid molding process. The simulation process integrates the commercial simulation tools of CATIA, LS-DYNA and Moldex3D and provides predictions of the preform shearing and deformation, the mold filling, the resulting fiber orientations, the effective properties of the part and the final shape and residual stresses within the part. Of particular interest in injection over-molding is the ability to predict the temperature at the interface between the preform and injection compound. These predictions address the challenges of multi-material mold filling and dimensional stability and provide elements necessary to treat the larger challenge of performance of multi-material structures.

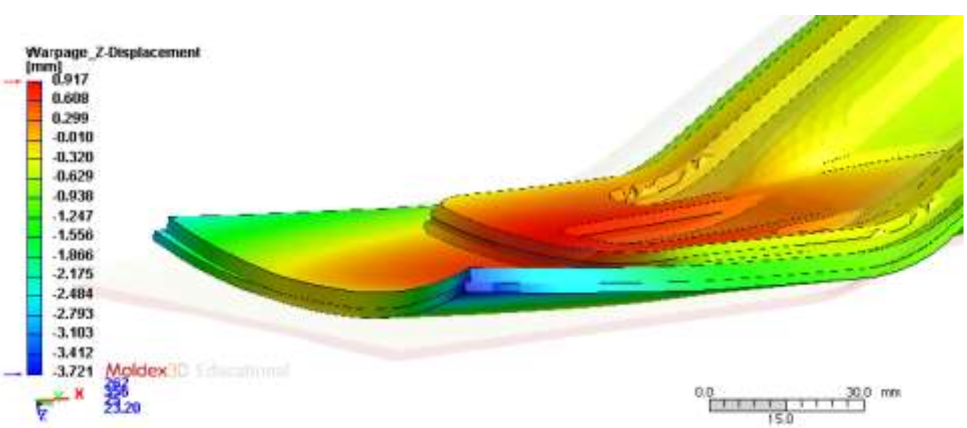

Figure 9: 3X magnification of part warpage

Acknowledgements

The authors would like to acknowledge the Institute for Advanced Composites Manufacturing Innovation (IACMI) for funding this work.

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