The use of right-sized simulation to aid in better decision making for complex composite materials manufacturing systems

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Introduction

Composite materials offer many advantages for the manufacture of advanced structures in fields such as aerospace, transportation, marine and commodity products. As such a tailorable material, with respect to properties and performance, composites are quite attractive to right-size products for their specific application [1]. Likewise, being able to shape a material at the same time as developing its material properties poses many cost and time advantages, by reducing the total number of manufacturing steps required. However, this can have drawbacks too. By taking so many actions at once, it is also possible to more easily make one wrong decision and end up with n suboptimal composites structure. For example, an industrial partner is working in the field of transportation infrastructure, looking to manufacture continuously hot-rolled thermoplastic and fiberglass composite guardrails for automobiles. Figure 1 below illustrates the geometry of the guardrail system being considered.

Figure 1: Illustration of roadway guardrails; the standard, stainless steel variant (top-right, after being subjected to three-point bend testing) and the fiberglass-PP variant (bottom-left)

Linked with the aforementioned issues of composites manufacturing, the fiberglass and polypropylene (PP) composite guardrail poses similar issues. Guardrails have important dimensional tolerances, so that they can effectively be assembled into a reliable and repeatable structural system, without the aid of shimming or other fitting methods that may compromise structural performance. Similarly, the structural performance itself is highly critical, as the energy absorption of the guardrail structure is what ultimately dampens the kinetic energy of an uncontrolled vehicle, to ideally bring it to a steady and controlled stop and prevent the injury of the vehicle's occupants, or other people in the area. A schematic of the manufacturing process is briefly shown below, demonstrating how the spools of continuous comingled material are unwound into convection ovens and progressively rolled into shape.

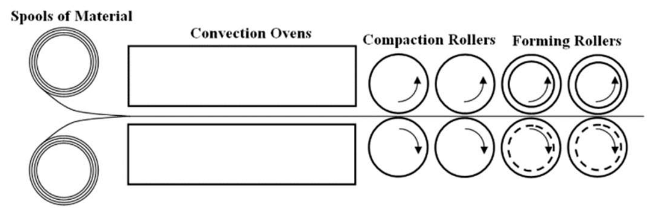

Figure 2: Schematic of the continuous roll-forming process for thermoplastic composites [2]

Designing the process, such that the woven composite material has specific temperatures are specific points in the rolling process, is critical. By deviating from these requirements, the product may have residual stresses formed with it, as well as associated geometrical defects, which can present itself as severely as experiencing cracking and failure during the manufacturing process. It is desirable for the materials to be formed at the right time; not too soon after exiting the oven that it will remain soft and deform, nor should it be too long after exiting the oven when it is hard and unable to properly form.

Analysis

With composites, it is as important to design the manufacturing process as it is to design the structure itself. This means characterizing the materials being used and understanding how the material properties develop under temperature over time. For the materials being used in the guardrail, as a thermoplastic, understanding the material relative crystallinity (RC) is the major factor of importance in a cooling-based process such as continuous roll-forming [2, 3]. As such, it is important to capture how the material RC develops when being rolled through the manufacturing system, where it is desirable for the final shape to be obtained at a specific point in the RC development curve. By characterizing the thermal properties of the PP matrix material, the dataset can be fit to models that predict the RC for the material under the boundary conditions of the manufacturing process. This can be used to determine the process window that is allowable for the desirable outcomes that are sought. Figure 2 shows the response curves for the relative crystallinity of a PEEK polymer subjected to different cooling rates from its high temperature, amorphous state.

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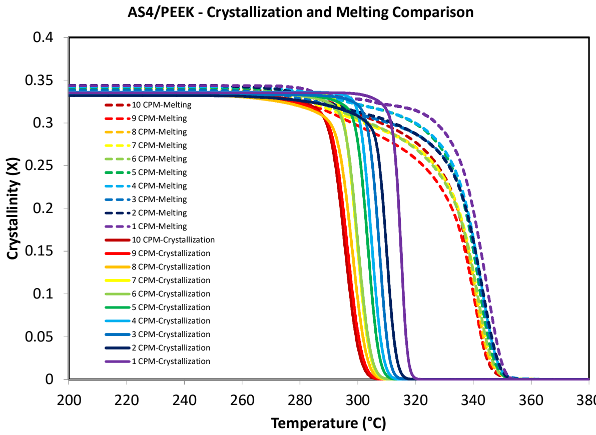

Figure 3: Process map of PEEK relative crystallinity when subjected to different cooling rates (courtesy of Composites Research Network at University of British Columbia, 2016)

However, characterizing these materials is only the first step needed to solve this industrial problem. These process charts do not account for the physics of the manufacturing system, which is composed of various boundary conditions and other properties. For example, the thickness of the composite laminated used is critical, as the thicker the part, the greater the thermal mass and given the low thermal diffusivity of composites, the cooling rate is not only slowed, but a significant gradient is also developed through the thickness of the part. Software that uses the finite element (FE) method can model this type of system, incorporating size-scaling features, such as part thickness, making the problem more mathematically complex. Convergent Manufacturing Technologies (CMT) based in Vancouver B.C. is a company that specializes in this field and has produced a simulation package called RAVEN, tailored to composites. For example, setting up a simulation profile for a 1mm thick PEEK composite part, with an external boundary condition of temperature starting at 300°C and cooling at 10°C/min, yields the plot shown in Figure 4. This plot represents the RC for the centre of this part. These boundary conditions, part configurations, material properties and other features, can be parametrically changed and recorded, to thoroughly and quickly explore the design space.

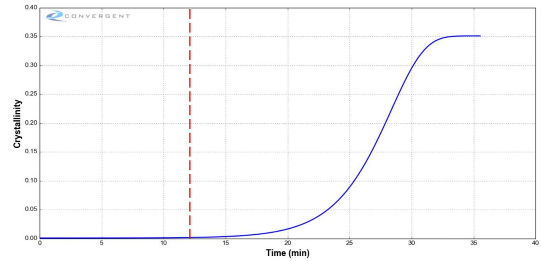

Figure 4: RC curve for a PEEK part 1mm thick cooled at 10°C/min, with the 12-minute mark noted

The curve reaches a plateau after approximately 35 minutes. The roll forming process may be designed, such that the final rolling action is applied at 12 minutes after cooling begins. This figure shows that at 12 minutes, the RC is close to zero, meaning that the RC will develop further well after all rolling has finished, which may result in a range of post-manufacture issues, such as residual stresses and deformation. Figure 5 shows the same RC profile for the PEEK material, but at a cooling rate of 30°C/min. It can be seen that at a time of 12 minutes, the plateau has been reached and the material is safer to consolidate at this time.

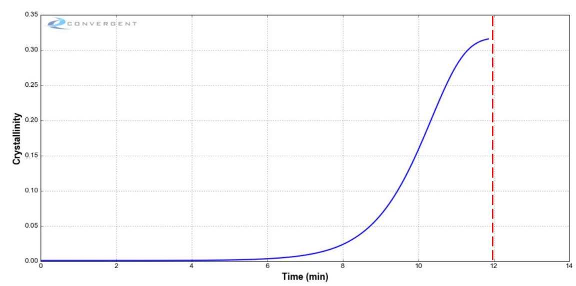

Figure 4: RC curve for a PEEK part 1mm thick cooled at 30°C/min, with the 12-minute mark noted

This type of approach is illustrative of a "right-sized" approach to manufacturing engineering, where simulation and other tools are used early on in the process to make critical decisions. In this example, the company has used right-sized simulation to help design their product to be manufacturable.

Results and Conclusions

It has been shown how the right-sized simulation approach can be used to better support decision making in the field of composites manufacturing engineering. This is an important part of building a complex and multi-physics system, which also aims to reduce risk.

References

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