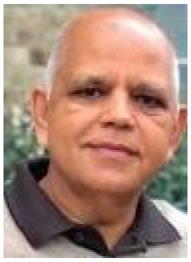
TECHNOLOGY

Optimising the pultrusion process with I-Rheo

10 min · ASJAD SHAFI,, Senior Fellow, Intugent



Through I-Rheo, Intugent applies physics-based simulation to the pultrusion process, turning complex curing dynamics into actionable insight. Temperature, viscosity and reaction kinetics can be simulated and analysed with high precision, helping engineers anticipate process deviations, improve consistency, and move faster from lab validation to production.

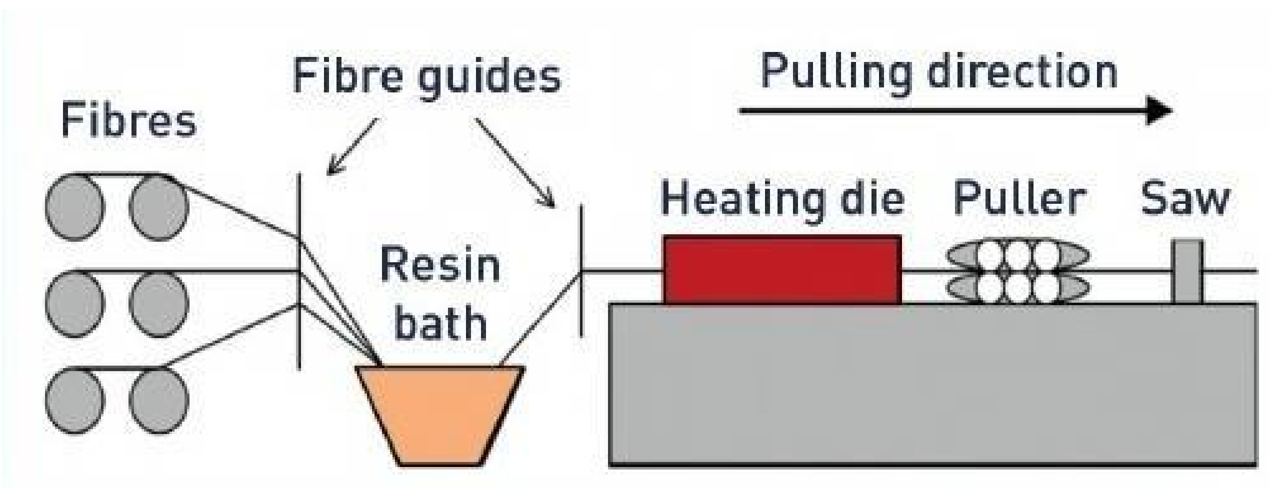


Fig. 1: A schematic of typical pultrusion process [2]

Behind every pultruded profile lies a delicate balance between chemistry, heat and tension. Even for a mature process, keeping viscosity, temperature and cure under control remains a constant challenge, especially when new resin systems or production speeds are introduced. Understanding how these parameters interact is key to achieving consistent quality, higher throughput and reduced waste. This is where Intugent's I-Rheo comes in, providing engineers with a fast and intuitive way to visualise these interactions and optimise process settings before they reach the production line. Engineers do not need any background in finite element analysis or math modelling.

Pultrusion: balancing parameters for quality

Pultrusion is a continuous – and the most economical process – for manufacturing straight profiles of any length **[1]**. Fibre rovings or mats are impregnated with resin, either through a bath or an injection chamber, then shaped in a preformer and pulled through a heated die shaped according to the final profile of the part (Figure 1). Inside the die, the resin temperature rises and polymerisation begins, transforming the liquid mixture into a solid composite. While thermoplastic variants exist, thermoset systems dominate due to their processing stability and predictable curing behaviour.

During curing, irreversible cross-linking reactions create a threedimensional network through condensation or chain polymerisation. As temperature increases, the resin first becomes less viscous — favouring fibre wet-out — then its viscosity rises sharply as polymerisation accelerates, and gelation occurs. The temperature profile, minimum viscosity and gel point are the key factors governing process stability and part quality.

By the time the part exits the die, the material is fully cured and continuously pulled by automated clamps before being cut to length by a flying cut-off. Designing a new pultrusion process or optimising an existing process requires engineers to balance design material formulation and process parameters: fibre type, architecture and layup, resin chemistry, initial viscosity, die temperature and pulling speed. The resin's reactivity can often be tuned to fit process constraints while preserving final thermal and mechanical performance. If not properly balanced, these parameters can lead to defects that affect part quality and process stability — such as resin backflow, poor surface finish, dry spots, voids, cracking or high pulling forces.

Simulation tools have become essential to predict these complex interactions. Pultrusion math models include constitutive equations for reaction kinetics, rheological relationships with the degree of cure, and heat transport equations. These coupled equations are typically solved using finite control volume methods, requiring high performance

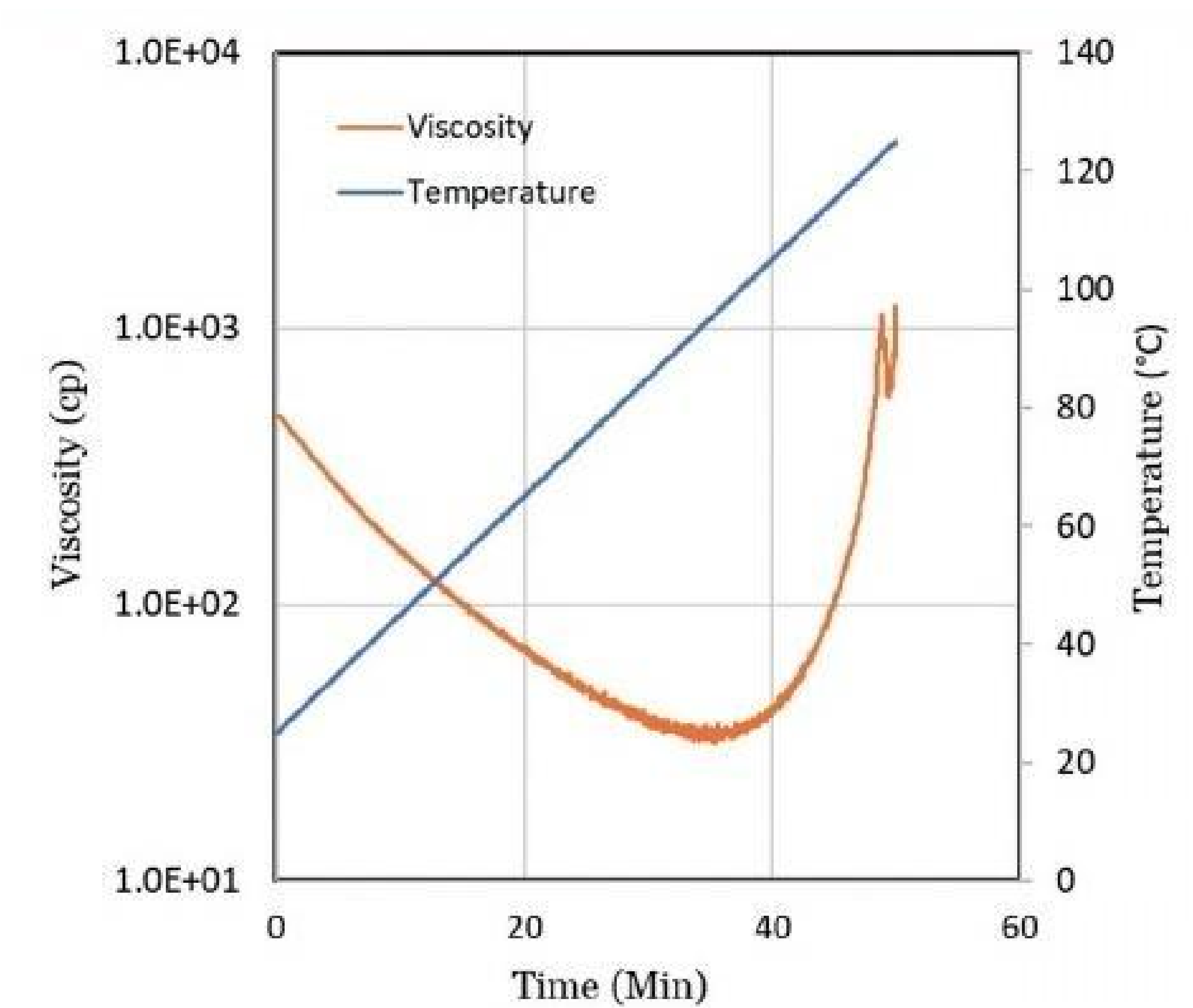


Fig. 2: A temperature scan of viscosity of a typical thermoset epoxy resin 2°C/min ramp

computation (HPC) machines and trained professionals, as they are heavy to run and complex to use on the shop floor [2-3].

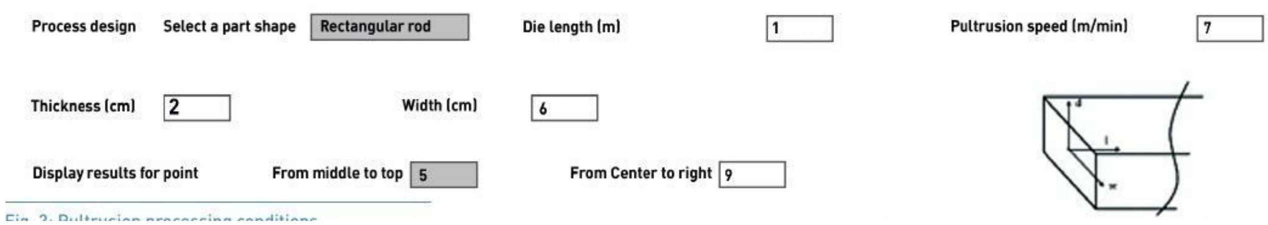


Fig. 3: Pultrusion processing conditions

A digital process model built for engineers

Intugent introduces I-Rheo — a digital transformation software designed for composite engineers who may not have backgrounds in finite element analysis or mathematical modelling. Predesigned shapes with variable dimensions are available in the I-Rheo library. Professionals simply need to have a basic understanding of thermoset resin curing. Engineers specify the part dimensions, choose the resin system from the library, and click “Run Pultrusion Simulation”. With its proprietary algorithms, I-Rheo solves the combined kinetic, rheology, and finite control volume heat transfer equations in just a few seconds. The graphical display makes it easier for engineers to draw their conclusions.A pultrusion simulation using a rectangular die and precharacterised resin systems from the I-Rheo library to illustrate how temperature, viscosity and curing evolve through the die and influence overall process performance.

Pultrusion simulation for rectangular parts

To illustrate the thermo-mechanical behaviour of a resin system and its impact on process and part quality, a typical pultrusion simulation was performed using a rectangular die (Figure 3),, which was 2 cm thick and 6 cm wide. The die was 1 m in length with three heating sections (set at 140, 150, 140 °C) and a pulling speed of 0.7 m/min. The simulation used a typical vinyl ester resin (PULL 1) with 55% glass fibre content, previously characterised for its kinetic and rheological properties and stored in the I-Rheo library. After pressing the “Run Pultrusion Simulation” button, I-

Rheo generates results almost instantly. For the material point shown as red dot in Figure 4(e), the software displays the evolution of temperature, degree of cure, viscosity and glass transition temperature through the die (Figures 4ad). The user can also inspect any other point across the cross-section before or after the simulation. The results are reviewed below.

Max temperature: As shown in Figure 4(a), the temperature gradually rises as the material travels through the die, driven by heat transfer from the tooling and the exothermic curing reaction. Once the resin reaches its activation range, the temperature increases rapidly until curing is nearly complete and a maximum is reached. This peak at the middle of the point must occur before the part exits the die to prevent thermal stresses that can cause cracking. If heating continues after exit, stresses due to thermal expansion may cause the adhesive bonds between the fibre and resin to break resulting in formation of cracks.

Initial Viscosity: Viscosity profile has a strong effect on the pultrusion process and quality of the final product. It must be carefully controlled for optimum performance. If the initial viscosity, also referred to as resin bath viscosity, of the material is too low, it may not carry the needed amount of resin into the die and the part will have dry spots and poor wetting. On the other hand, if initial viscosity is too high, fibres will carry more than needed amount of resin into the die which may cause backflow from the die entrance into the resin bath. The backflow will result in higher bath temperature and higher viscosity due to curing reactions. In the simulation with PULL 1 resin, the initial viscosity is approximately 1200 cp at the bath temperature. During most of the pultrusion process, the resin bath viscosity is usually in the 1000-1500 cp range.

Minimum viscosity: As the resin enters the die, its temperature begins to rise. Viscosity initially increases slightly due to the low heating rate, then drops rapidly as the material warms. Viscosity continues to drop until the resin approaches the gel state, where polymerisation dominates and viscosity rises sharply toward solidification. The combined effect of temperature and curing rate defines the viscosity profile along the die, as illustrated in Figure 4c for the reference point shown in Figure 4e. The resin bath viscosity is primarily designed for carrying right amount of resin into the die. However, it is not low enough to ensure full penetration between individual filaments. As the viscosity of resin decreases inside the die, surface tension also drops allowing the resin to wet all the fibre filaments. Achieving the right minimum viscosity is therefore essential for complete impregnation and consistent product quality.

Gel point and viscosity profile: The ideal viscosity profile inside the pultrusion die is achieved when the increase in viscosity due to curing reactions is balanced by the decrease in viscosity due increase in temperature until the resin is ready to gel. This ensures that the resin fully impregnates the fibre reinforcement before it gels (Figure 4(C)). If the resin viscosity starts increasing immediately after entering the die, wetting may be poor. At gelation, thermoset materials shrink resulting in a small gap between the part and the die surface. If gelation takes place too far into the die, the pull force will be high, and the surface quality will be poor. In general, gelation should take place within 30-40% of the die length.

Glass transition temperature: As curing progresses, the resin's glass transition temperature (Tg) rises. If Tg increases above the process temperature, curing effectively stops. The resin temperature must be significantly higher than the Tg to ensure completion of curing reactions. However, if the part exits the die while the material temperature is very high compared to its Tg, the resin will be in a rubbery state and the part may deform due to stress relaxations.

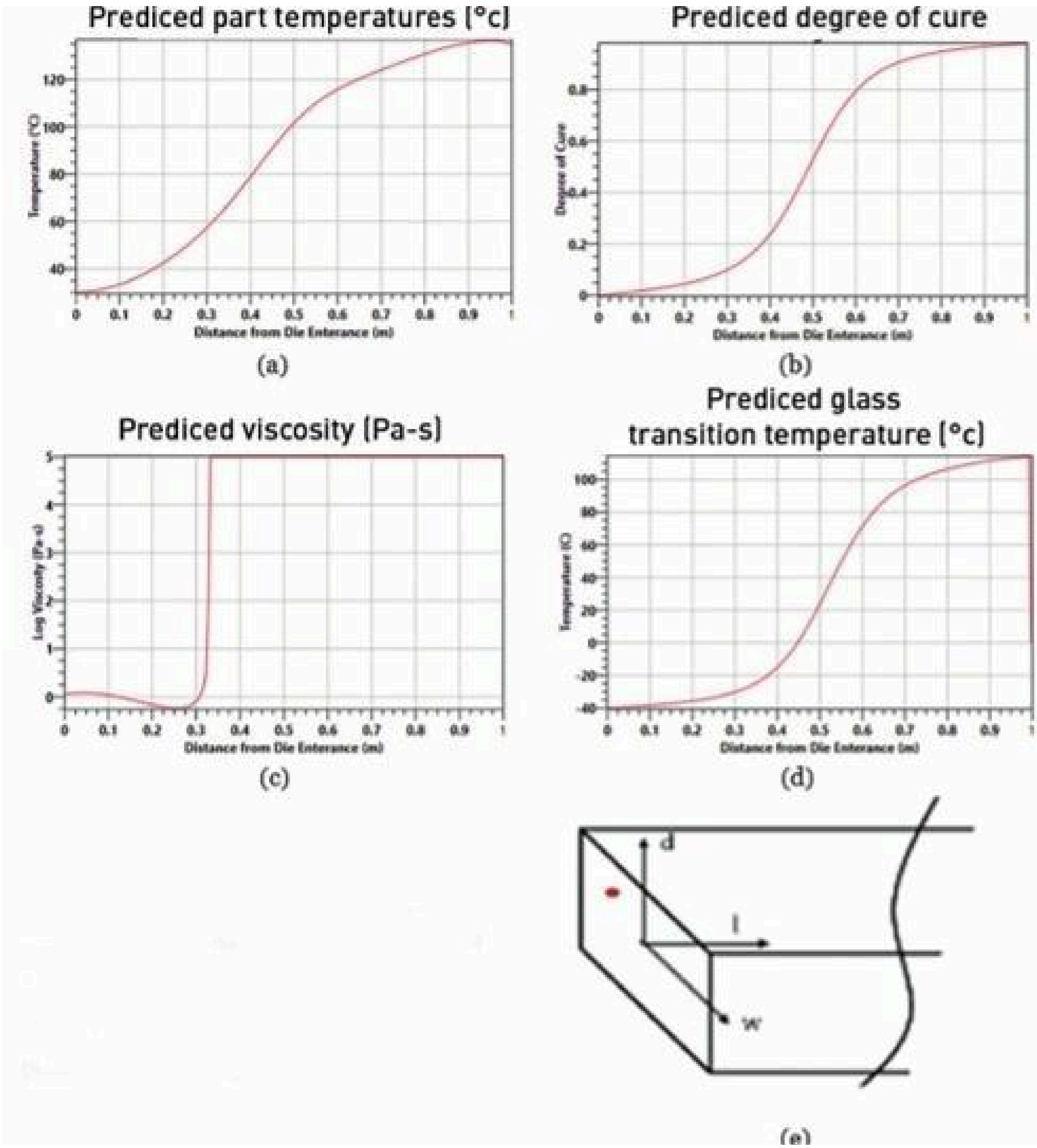


Fig. 4: Simulation results showing temperature (a), degree of cure (b), log of viscosity (c), and glass transition temperature of the material point shown as the red dot in Figure (e) as the material point travels through the die.

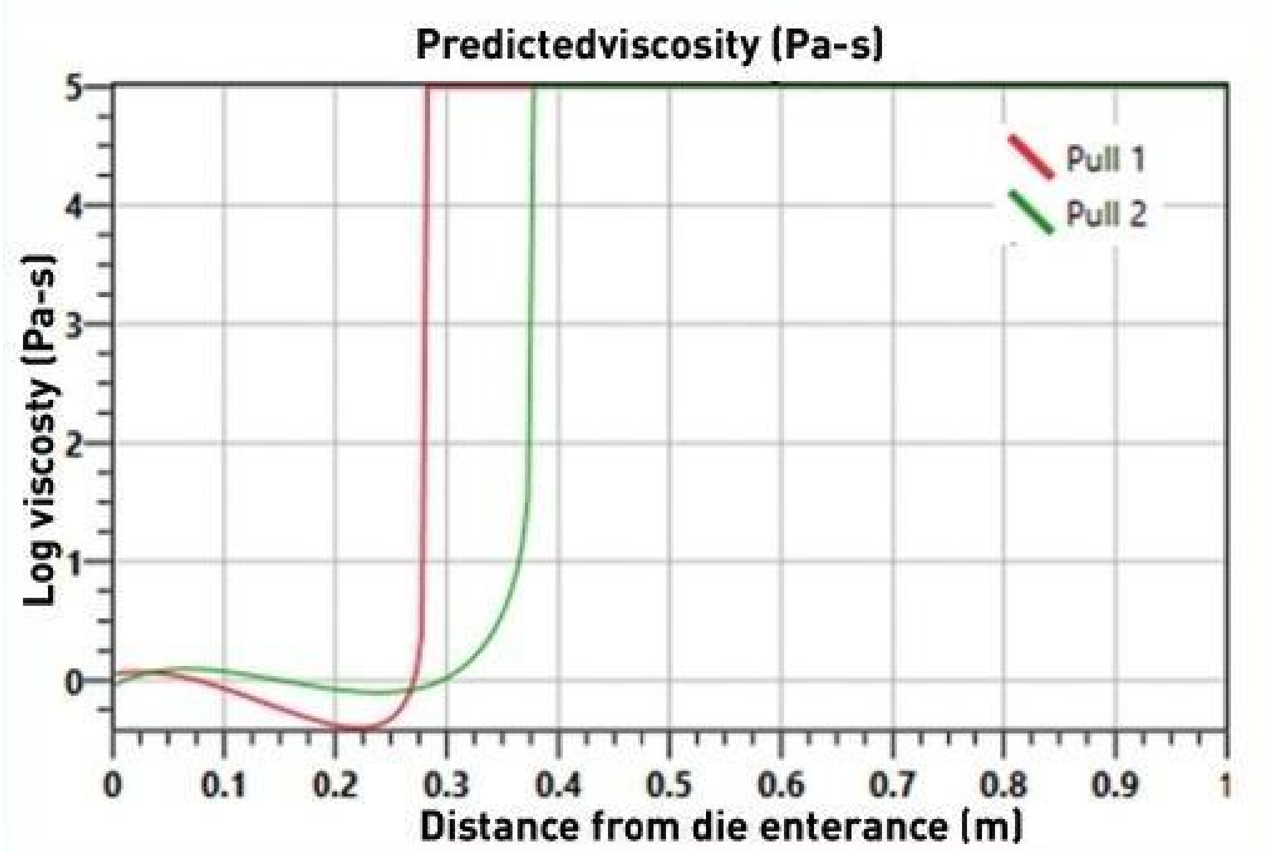


Fig. 5: Viscosity profile at the point shown as red dot in Figure 3(C)

Comparing different resins

I-Rheo enables direct comparison of resin formulations under identical process conditions. Figure 5 illustrates the viscosity evolution along the die for two systems, Pull 1 and Pull 2. Even though Pull 2 has lower resin bath viscosity, its minimum viscosity inside the die is significantly higher, with gelation occurring further into the die than Pull 1. As a result, Pull 2 may have more wetting issues as well as surface quality issues. Pull 2 resin will also require a higher pull force. Under equivalent conditions, Pull 1 therefore offers better process stability and part quality.

Figure 6 shows the temperature profile along the die for two resin systems, Pull 3, being more reactive than Pull 1, reaches a higher temperature peak and cures faster. To avoid thermal stresses, this maximum should remain within the die. Although highly reactive resins such as Pull 3 tend to increase viscosity and reduce wet-out, these effects can be offset by raising the line speed by about 10–20%, while keeping curing confined inside the die.

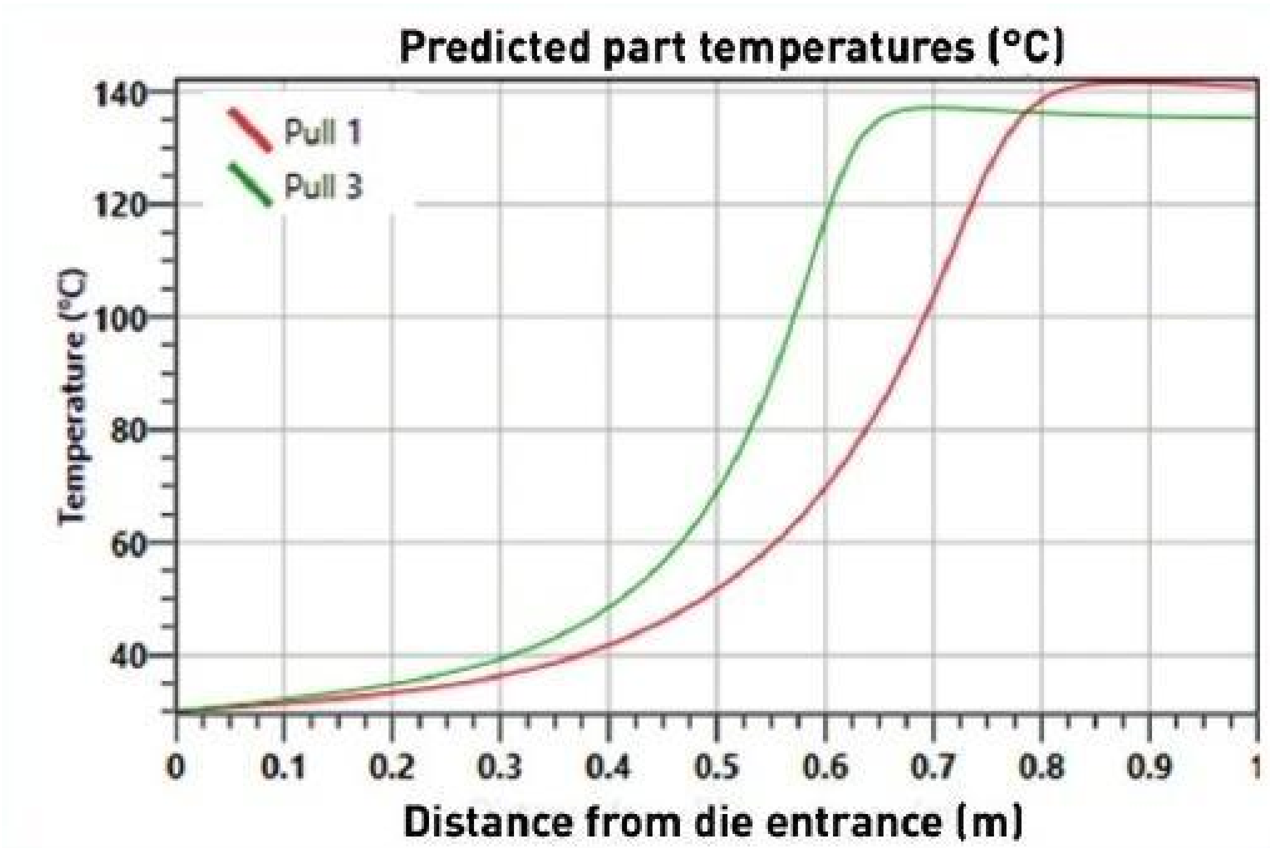


Fig. 6: Temperature profile through the die for the material point in the middle of the part.

Rheokinetic models for new resins

During the pultrusion process simulation, I-Rheo solves coupled kinetic and rheology equations, referred to as rheokinetic models, together with finite element/control volume heat transfer equations. While computational chemistry continues to progress with the availability of high performancecomputing (HPC) machines, these techniques are not advanced enough for predicting the kinetics of curing reactions. The I-Rheo models were developed by extracting information from collected laboratory data obtained through dynamic scanning calorimeters (DSC) and rheometry. While I-Rheo intelligently draws the baselines for the DSC scans and determines the end point of the rheology scan, users can modify these graphically as well. Any user with minimal or no training in math modelling can develop these models and save them in the database for use in process simulations.

By translating physical models into an accessible digital environment, Intugent's I-Rheo brings simulation-driven process design within reach of any composite manufacturer. It turns pultrusion's intricate mix of heat, chemistry and mechanics into a predictable, optimisable workflow — thereby helping engineers reduce trial time, improve quality, and push composite manufacturing toward greater consistency and efficiency.

More information: www.intugent.com

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