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# TOWARDS THE OPTIMIZATION OF THE INFUSION PROCESS THROUGH NUMERICAL PERMEABILITY ANALYSIS AND SIMULATION

Nihad Siddig<sup>1,\*</sup>, Paris Mulye<sup>2</sup>, Yves Le Guennec<sup>1</sup>, Philippe Le Bot<sup>1</sup>, Damien Lecointe<sup>1</sup>, Yvan Denis<sup>1</sup>, Elena Syerko<sup>2</sup>, Olivier Fouché<sup>1</sup>, Christophe Binetruy<sup>2</sup>

<sup>1</sup> Nantes Université, IRT Jules Verne, F-44000 Nantes, France

nihad.siddig@irt-jules-verne.fr, yves.le-guennec@irt-jules-verne.fr, philippe.le-bot@irt-jules-verne.fr, damien.lecointe@irt-jules-verne.fr, yvan.denis@irt-jules-verne.fr, olivier.fouche@irt-jules-verne.fr

<sup>2</sup> Nantes Université, Ecole Centrale Nantes, CNRS, GeM, UMR 6183, F-44000 Nantes, France  
parismulye@gmail.com, elena.syerko@ec-nantes.fr, christophe.binetruy@ec-nantes.fr

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## Abstract

The liquid resin infusion (LRI) process is continuously used for manufacturing large industrial parts across various sectors, yet it poses challenges due to its inherent variabilities. The MONOCLE research project, led by the Jules Verne French Institute and industrial partners, aims to develop a digital monitoring approach for complex parts during infusion. This initiative seeks to enhance decision-making during the process. Optimizing infusion necessitates simulations to save time and resources. To ensure reliability, numerical methods must be validated, particularly for thick and complex parts. Material characterization, especially permeability, is pivotal for accurate process modeling and defect prediction. This study establishes a physics-based model for thick part infusion, applying a numerical approach for permeability characterization validated by experiments via a monitoring system. Infusion experiments on 25 mm thick components were conducted, monitored by sensors. The software suite called PoroS developed at the GeM research institute was used to numerically predict the permeability of the material using the 3D fabric scans. The permeability tensor obtained using PoroS serves as one of the key inputs for the process simulations using PAM-RTM<sup>®</sup> software, validated against sensor data. The validated model facilitated numerical prediction for diverse scenarios, aiding decision-making for composite part monitoring. This integrated approach promises enhanced efficiency and reliability in LRI processes.

## 1. Introduction

The liquid resin infusion (LRI) process is continuously used to manufacture large-sized industrial parts for a wide range of applications. Although simple, this process yields several variabilities and challenges. Online process monitoring has been used to identify process disturbances allowing the detection of dry spots and reducing the number of parts rejected as scrap [1].

The optimization of the infusion process requires the use of simulations to save the considerable time, effort and cost associated with experiments. To be trustworthy, these numerical methods must be validated to ensure accurate predictions of potential defects, especially in thick and complex parts [2]. Material characterization is required for process modeling and simulation. Permeability characterization is vital for modeling the flow filling patterns and the pressure evolution in fibrous media [3], facilitating the prediction of residual defects. The main challenge lies in the prediction of the flow behavior under variable process conditions.

### 1.1 MONOCLE project

The research project MONOCLE (MONitoring des prOcédés Composites par infusion pour la navaLE) aims to develop a digital approach for monitoring the infusion process for complex parts, and

to provide operators with a real-time decision-making tool. The project is led by Jules Verne French Institute, member of Nantes University, in collaboration with a consortium of key industrial partners (Naval Group, SICOMIN, iQanto -PREDICT, BUREAU VERITAS Marine & Offshore, and PCMI).

### 1.2 Study description and objectives

This work aims to establish a physics-based numerical model for the infusion of thick parts. This is achieved using the following four substeps:

- (1) Applying a numerical approach for permeability characterization
- (2) Performing part filling simulations using the permeability and other process parameters as input
- (3) Validation of the numerical results with experiments through the monitoring system
- (4) Using the model to predict the process behavior and dry spots for a different scenario to assist the decision-making process.

In this study, infusion experiments were carried out on thick components of 25 mm using a test bench equipped with a robust monitoring system. Sensors were placed throughout the part to monitor and control various parameters during the infusion. All preform permeability components are obtained virtually using the image-based permeability software suite PoroS [4], which quantifies the ability of a heterogeneous porous media to transmit fluids at micro- and/or meso-scale by solving single and/or dual-scale flow problems. This software allowed to predict the full permeability tensor based on a 3D segmented image of the thick stack of fabrics obtained from  $\mu$ CT scans. The permeability values were used as input for the process simulations, which were carried out with the commercial software PAM-RTM<sup>®</sup> from ESI group. The results were compared and validated against sensor signals. Subsequently, the validated model provided a basis for the numerical prediction of multiple scenarios with variable material and process parameters. These simulations are used as a decision-making tool for the monitoring of composite parts produced by the infusion process.

### 1.3 A digital twin approach

Figure 1 shows a general approach to the use of real-time digital simulation of a sensor-driven process, to provide information that is impossible to obtain with sensor signals alone.

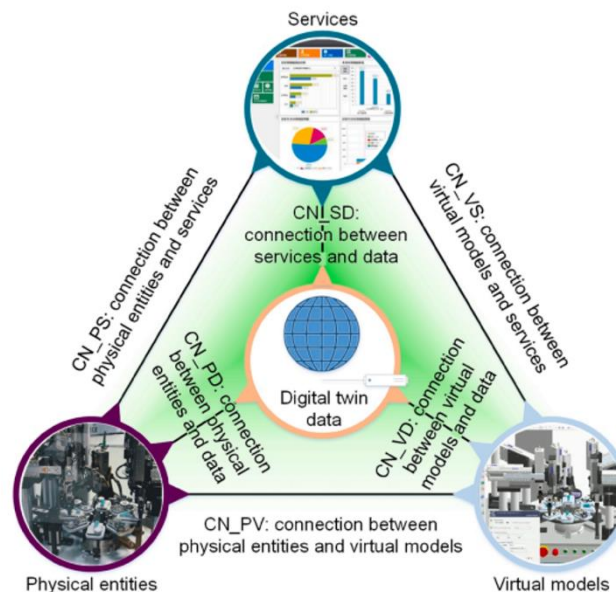


Figure 1: 5D approach of Digital twin data [5]

An efficient communication protocol (fast, accurate and fault-free) must then enable reliable information exchange. The resulting tool is a real-time digital shadow of the process, which can provide a range of services such as optimizing process set-up (parameters, tooling, etc.), predicting

and then eradicating faults, optimizing process times, etc. Reduced order models (ROM) and AI methods can then contribute to rapid response and use at the industrial scale. The architecture is based on a strong assumption: the accuracy of the numerical process simulation tool, and a detailed knowledge of its sensitivity to various parameters such as material properties, environmental parameters and, of course, process parameters.

The paper addresses the off-line high-fidelity simulations that can provide the basis for AI or ROM solutions, allowing real-time process predictions. For the simulations to be accurate, they need to be validated against experiments. Moreover, accurate predictions depend on the quality of the material characterizations. Thus, a numerical method is used to evaluate the preform permeability as input to simulation models.

## 2. Methodology

### 2.1. Materials and methods

The bio-sourced epoxy system SR InfuGreen 810 developed by Sicomin was used and mixed with the hardener SD8823 for the manufacturing of composite parts. The composite panel contains a stack of 41 plies of biaxial glass fabric (LT850) measuring 600 mm in length, 300 mm in width and approximately 25 mm in thickness.

### 2.2 Infusion process

An infusion test bench equipped with a monitoring system is linked to the connected Liquid Resin Infusion machine (Figure 2). Flow rate (Keyence FD-XC20R3) and resin pressure (Balluff BSP00ZK) can be monitored and acquired at the inlet before entering the mold. A glass mold is used allowing to follow the flow front advancement at the upper and lower mold sides with cameras (Basler a2A 1920). HBM QuantumX 1601B and HBM QuantumX 1609 devices allow monitoring of the flow meter and vacuum sensor as well as some thermocouples to ensure the quality of the infusion process.

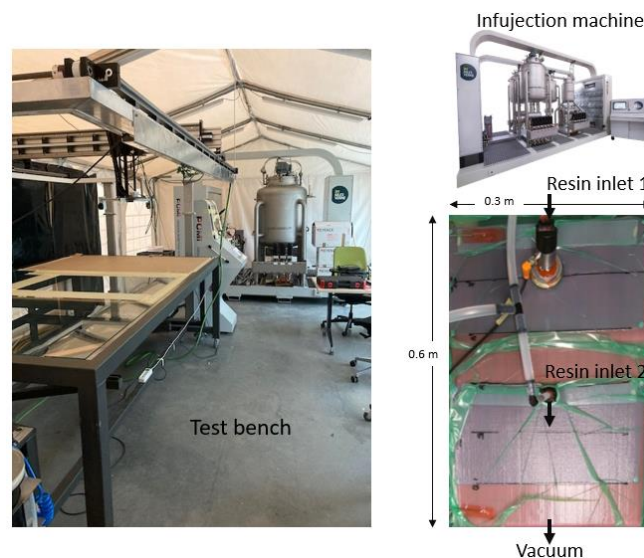


Figure 2: Experimental set-up, test bench and infujection machine

### 2.3 Image-based permeability characterization using PoroS

A software suite named 'PoroS', developed at GeM laboratory at Centrale Nantes consists of a set of new porous media permeability solvers that use a finite element based approach [4]. PoroS has been designed in such a way that it can directly work on the 3D or 2D segmented images of the micro- or meso-structure of the material. Thus, it works on individual textiles as well as on the full-stack of the material. These material images can be obtained either by performing a  $\mu$ CT scan or by building a

voxelized digital twin of the material in TexGen<sup>®</sup> [6,7]. PoroS is specifically designed to address the problems of large size (order of upto billions of degrees of freedom) which can often be the case for the voxelized images obtained using the scan with a high resolution.

The overall workflow of PoroS is shown in Figure 3, where a numerical approach of a body-force driven flow is induced one by one in each of the three independent spatial directions i.e. X/Y/Z and the solution to the stationary Stokes (micro-scale, single-scale flow) or Stokes-Brinkman (meso-scale, dual-scale flow) problem in each of the three directions is obtained. PoroS uses a strategy of 1 voxel = 1 element where each element is a 27 node hexahedral (HEX27) Taylor-Hood type of element [8]. Once, the three flow problems are solved, the velocity fields of the three solutions serve as an input to the permeability evaluation subroutine which uses the approach of full-field homogenization, details of which can be found in [4] and [9]. Finally, the output of the PoroS software are the flow-fields for each of the flow problems X, Y and Z along with the full 3D permeability tensor.

In this work, the full stack of the material was scanned at Centrale Nantes with a resolution of 5.7  $\mu\text{m}/\text{voxel}$  and then the resulting image obtained from the scan was segmented using an assisted machine learning approach. The resulting segmented image contained three phases: yarns in warp direction, in weft direction and the resin which occupies the inter-yarn space. The fluid flow inside the yarns is not explicitly modeled but instead it is modeled using the Brinkman term with effective permeability of the yarns in the Stokes-Brinkman equation. The effective permeability of the yarns was estimated based on the geometry information about the stack and data from the specification sheet of the material. The resulting dual-scale flow problem of the complete material stack consists of about 80 million degrees of freedom, which was solved using the global-matrix free conjugate gradient solver inside the PoroS suite (Figure 4) and the permeability of the material configuration was obtained numerically.

The advantages of using PoroS were threefold: (a) it requires very little material, in this case, it was a sample of size  $7 \times 7 \times 10 \text{ mm}^3$  (b) it requires no experimental set-up and (c) being a numerical tool, it is highly scalable as one can test multiple materials, multiple configurations, multiple fiber volume fractions at the same time by launching multiple simulations at the same time. These advantages are nearly impossible to obtain with the experimental approach.

Even though the input to PoroS that was used in this study did require the  $\mu\text{CT}$  scan of the material; this step in the future can be replaced by the creation of a digital twin of the material in textile modeler software such as TexGen<sup>®</sup>. This would require some statistical measurements in terms of the architecture and configuration of the material which are less expensive to obtain. Therefore, the numerical characterization of permeability using PoroS is even more attractive choice to predict the permeability of the porous materials.

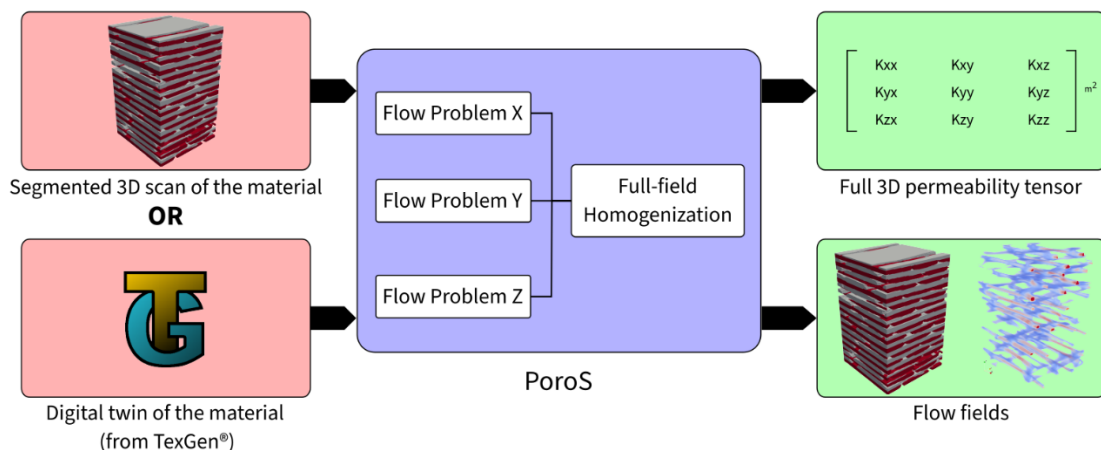


Figure 3: Overview and scope of PoroS: Input to the software is a segmented 3D scan of the material or a digital twin constructed using TexGen<sup>®</sup>. PoroS includes a suite of stationary Stokes and Stokes-Brinkman solvers and a permeability subroutine. The output consists of the flow fields for each of the flow problems and a full 3D permeability tensor

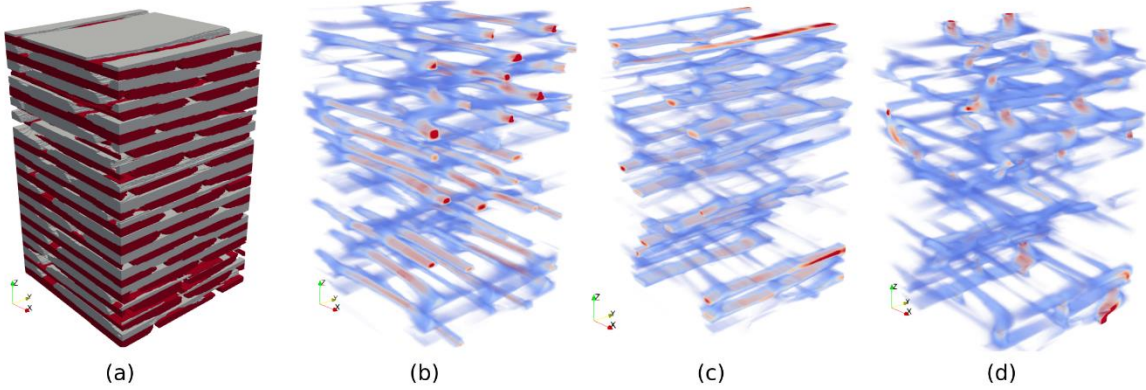


Figure 4: Dual-scale flow simulation using PoroS: (a) Segmented 3D geometry of the stack obtained from the  $\mu$ CT scan (b) The velocity field for flow problem in X direction (c) Velocity field for flow problem in Y direction (d) Velocity field for flow problem in Z direction

## 2.4. Process Design

### 2.4.1 Simulation software

The commercially available simulation software PAM-RTM<sup>®</sup> developed by ESI Group is used to simulate the infusion process. It is a Finite Element (FE) solution for modeling the manufacturing processes of structural and non-structural composites reinforced by continuous fibers. The PAM-RTM<sup>®</sup> software helps engineers and manufacturers simulate the entire liquid composite molding process numerically before actual production begins. This simulation includes modeling the flow of resin through the mold, predicting the impregnation of the fibers, monitoring temperature and pressure variations, and assessing the final part's quality and properties. By using simulation software like PAM-RTM<sup>®</sup>, manufacturers can optimize their processes, reduce material waste, minimize defects, and ensure the production of high-quality composite parts. The software allows coupling of the physical phenomena involved in the infusion process. The flow of the incompressible fluid in the fibrous medium is governed, if the change of thickness is neglected, by the simplified form of the mass balance equation (Eq. 1) [10]:

$$\nabla \cdot (\vec{U}) = 0 \quad (1)$$

Where  $\vec{U}$  is the liquid velocity. Darcy's law describes the flow of Newtonian fluids through porous media (Eq. 2); it relates the liquid velocity to the permeability tensor  $\mathbf{K}$  obtained with PoroS, the resin viscosity  $\mu$  and the pressure gradient  $\nabla P$  [11].

$$\vec{U} = \frac{-\mathbf{K}}{\mu} \nabla P \quad (2)$$

The energy balance equation (Eq. 3) governs the heat transfer problem. The terms of the energy balance equation on the left-hand side are, respectively from left to right: the transient and advection terms. On the right-hand side of the equation, the first part of the equation is the conduction term. The internal heat generation in the system is represented by  $\dot{R}$  [6].

$$\rho c_p \frac{\partial T}{\partial t} + \rho_r c_{p,r} \vec{U} \cdot \nabla T = -\nabla \cdot (\lambda \cdot \nabla T) + \dot{R} \quad (3)$$

Where  $T$  is the temperature,  $\rho$  and  $\rho_r$  are respectively the composite and the resin density.  $c_p$  and  $c_{p,r}$  are the composite and the resin specific heat capacity, respectively. The subscript  $r$  denotes the resin.  $\lambda$  is the thermal conductivity of the composite material. The term  $\dot{R}$  is the volumetric heat generation related to resin polymerization.

Pressure Dirichlet boundary conditions are prescribed at the injection lines with the atmospheric pressure. The vacuum pressure of 0.2 bar is applied at the outlet along the opposite side. The initial temperature was assigned to the part at the mold side. All the other surfaces are subjected to natural convection boundary conditions.

### 3. Results

#### 3.1 Validation with infusion experiments

The flow dynamics predicted by simulation are compared to the experiment during the filling phase. Figure 5 illustrates the flow front positions for the experiment at four different instants at the upper mold side. The comparison has shown good agreement in the transient phase with experimental observations.

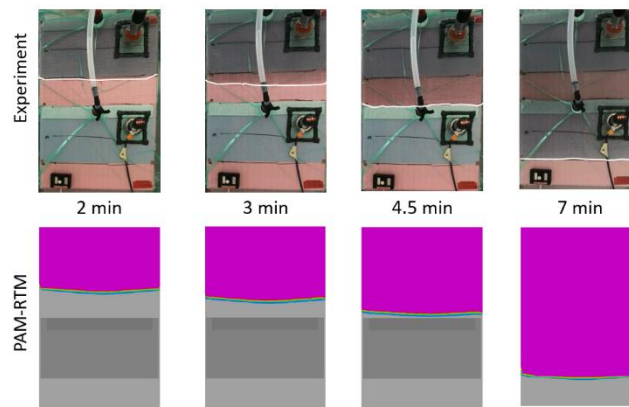


Figure 5: Comparison between experimental and numerical flow front advancement

Figure 6(a) compares the numerical and experimental flow rates. The total flow rate shown in this figure is measured at the first resin inlet by a flowmeter. Both curves show two peaks related to the opening of the resin inlets. The first flow rate peak corresponds to the opening of the first resin inlet, then a gradual decrease is observed, till 5 minutes 48 seconds from the beginning of infusion, where the second inlet is open. This transition in flow behavior is also observed in the resin front advancement with time in Figure 6(b). In this figure, two distinct curves are observed with two phases; a steep advancement and a slower phase that follows the first instants of flow through the distribution medium. Generally speaking, simulations predicted the flow dynamics of this scenario with slight discrepancies. These discrepancies are related to the modeling simplifications, as the software does not consider the dual-scale nature of the flow or the flow-induced thickness variations during the infusion. The infusion process and material variabilities could also contribute to increasing the gap between experimental and numerical results.

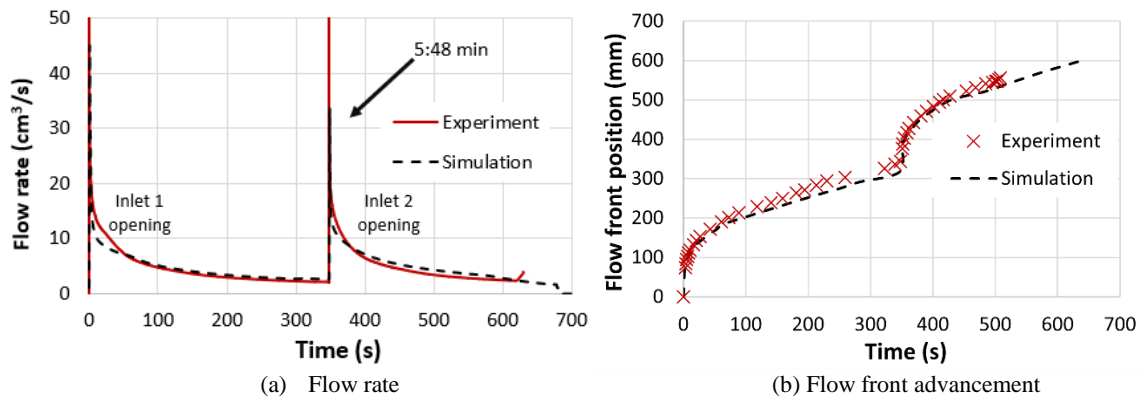


Figure 6: Comparison between experimental and numerical flow dynamics

The infusion strategy presented in this section guaranteed the complete part filling. The comparison in the transient phase has shown a good correlation, which validates the model. In the next section, the model is evaluated with a different scenario to evaluate the model capability of predicting dry spots.

### 3.2. Towards process optimization

Once the model is validated for the nominal scenario, a second one is tested to ensure that it can predict new cases with additional complexities. The second scenario is identical to the nominal scenario, the only difference lies in the second inlet opening time, the two inlets are open at the same time to intentionally create dry zones. The objective is to ensure that these dry zones are predictable by the simulation.

Figure 7 shows the comparison between the model and the experiment. It can be observed from this figure that the scenario resulted in two symmetrically-located dry zones.

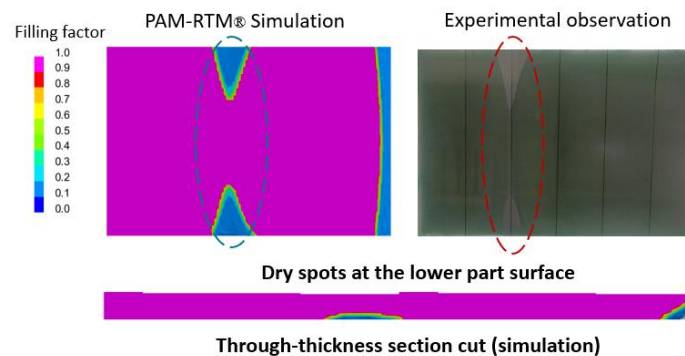


Figure 7: Prediction of dry spots at the end of filling

A filling time of 11 minutes is recorded experimentally versus 10 minutes with the simulation. The results have shown the capability of the model to predict the position and the shape of the dry zones.

## 4. Conclusions and perspectives

In this paper, a new numerical methodology of permeability characterization is applied to a biaxial glass preform. To do so, the 3D image of the material obtained from the micro-CT scan was first segmented and then the software suite called PoroS was used to obtain the full 3D permeability tensor of the material using a dual-scale flow simulation with the Stokes-Brinkman solver of the software. The measured values are implemented in the commercial software PAM-RTM<sup>®</sup> from ESI group. Flow simulations are conducted for two experiments, a nominal defect-free experiment where the second



inlet is open upon the flow front arrival. A second experiment where the two inlets are open simultaneously is realized. The model allowed the dry spot location and approximate size predictions.

The discrepancies observed between the experiment and simulation could be related to the infusion process variabilities, measurement uncertainties or the simplifications in the simulation tool PAM-RTM<sup>®</sup>. The software solves Darcy's equation at the macroscale and doesn't consider the dual-scale nature of flow. Moreover, mechanics of thickness variations due to the preform decompaction during resin infusion are not considered in these calculations. Applying the same methodology, future work will address the prediction of flow dynamics for the infusion industrial parts with large dimensions and more complex geometries, e.g. thicker or including stiffeners.

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