THERMODYNAMIC PROFILE CHARACTERIZATION OF MOLD GEOMETRY IN COMPOSITE PULTRUSION MANUFACTURING

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ABSTRACT

Manufacturing effects in composite materials such as parting line, fibre waviness, porosity, and radial crack are common issues in composite structures. Although these manufacturing effects are common in the composite structure, they are not considered defects because these effects cannot be avoided entirely. Hence, the industry must find a solution to minimize and prevent these effects at best. This collaborative research proposes to present research results pertaining to the pultrusion die thermal profile when it comes to the fibre-matrix curing process in the die.

Depending on the application, there are different die-setting configurations. For example, the most common pultrusion die are single cavity, multiple cavity and single cavity die mounted in parallel to each other. The selection criteria depend on the size, complexity, dimensional tolerance, and surface quality of the pultruded product. The die design process is both a time- and cost-consuming process. During the preparation of the die, an intense amount of labor involves manual polishing and chroming. Hence, if a die design is not optimal in the manufacturing context, it will impact the manufacturing output. Meanwhile, a good heating or thermal profile is important in maintaining control over resin gelation, curing and cooling of pultruded section within the die. Cracks appear in most of the pultruded parts when the process parameters are not optimized. This can be due to poor die design, process parameter or 'recipe' imperfections, and thermal stress miscalculation. Thermal stress is the governing factor contributing to internal or radial crack in the pultruded profile (or structure). This happens when the heating rate is not suitable for the specific type of pultrusion operations. This paper presents a solution to tackle defects such as parting lines and poor pultruded part quality. Meanwhile, the integration of numerical/simulation data concerning the die's thermodynamic profile provides the die designer with important information and input during the composite materials design stage.

1 INTRODUCTION

Fibre-reinforced polymer (FRP) composite materials have wide applications in various industries after considerable research and innovation studies have been conducted over the last 70 years [4]. The popularity of composite materials stems from their properties, such as high specific strength and stiffness, improved durability, high fatigue, chemical and corrosion resistance, and ease of transportation and assembly of composite structures [4]. Composite materials can be produced in many ways, such as pultrusion, compression moulding, resin transfer moulding, and filament winding [4].

Figure 1 shows the pultrusion process layout where a pack of rovings and continuous strand mat impregnated by resin are pulled through a heated die block where the polymerization process takes place. This method allows the fabrication of products having a constant cross-section [4]. The advantages of pultrusion over other composite manufacturing processes are its high production rate of up to 5 m/min [4], higher efficiency [4], and low costs [4] of production, as well as the ability to produce profiles of virtually indefinite length [4].

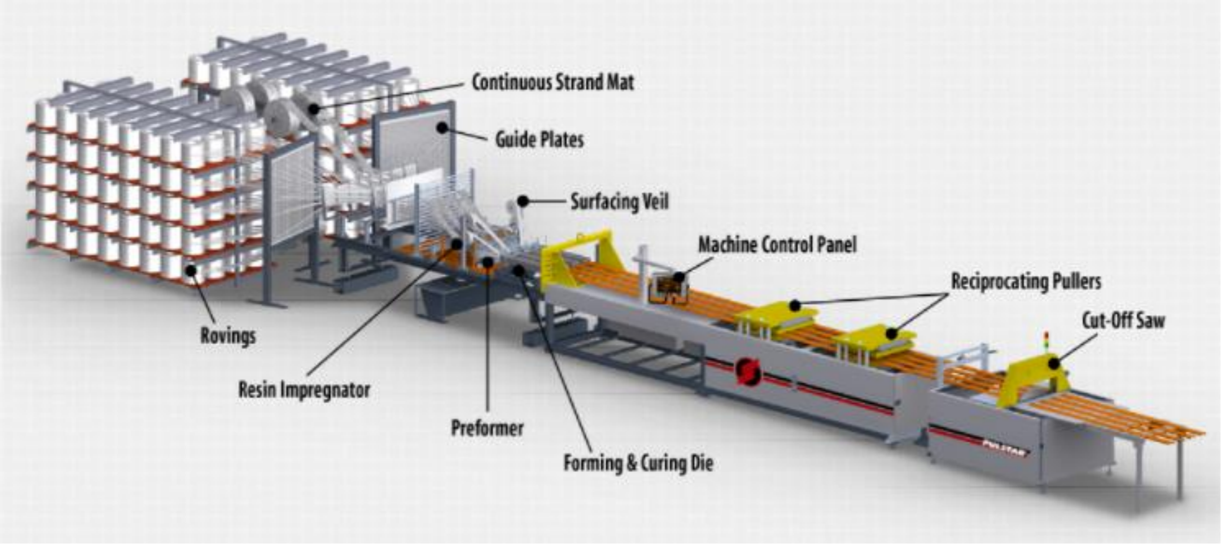


Figure 1. Pultrusion System [5].

In the pultrusion system, the preformers and the die design are two of the most challenging parts for the design and machining department in Thermopak Ltd. The design of the preformers is challenging due to the continuous strand mat conforming issues. At the same time, the die design is due to problems such as product parting line, exposure fibre, heat control in the die, and chromed surface wear-off in the die cavity.

The die design process is time-consuming and cost-consuming. During the die preparation, intense labor is involved for manual polishing and chroming to achieve a good surface finish and tight mould fitting. Hence, if a die design is not optimal in the manufacturing context, it will impact the production schedule significantly. As a result, the manufacturer would need to remove the chromed surface first to fix the damaged area in the die cavity. The time for the die cavity's surface to be repaired varies depending on the severity of the damages. After that, the die would have to go through the chroming process for another time. Furthermore, there are not many chroming companies located in the Maritimes, and some of them are not equipped with a chrome cleaning tank that is large enough for a pultrusion die that is generally up to 1 m in length, let alone chromium being listed as a carcinogenic substance by many countries.

The objective is to develop a novel solution to overcome problems such as the long die fabrication process and substitute the chromed cavity with tube profiles available in the market, which will provide the same quality outcome as the chromed cavity.

2 INDUSTRIAL PROBLEMS

Figure 2 shows the poorly designed pultrusion die where the cavity fitting is not tight. The resin flowed out of the die cavity into the tiny edge gaps, which might be due to the damages done by the abrasive reinforced materials or sub-quality machining of the die cavity.

Figure 2. Resin Flow Out of The Die Cavity.

To avoid cavity damages or loose die fitting, as shown in Figure 2, pultrusion dies require recurring maintenance after certain production hours. Repairing a pultrusion die cavity involves a long and tedious process. Because the product quality will not be accepted as the fibre rovings might be exposed to the product surface and cause harm to the consumers. According to one of the InnovComposites 12.7 mm (0.5 in) diameter rod die, the parting line on the product surface is rough and exposes fine fibres on the product surface, as shown in Figure 3 and Figure 4.

Figure 3. Pultruded Rod's Parting Line.

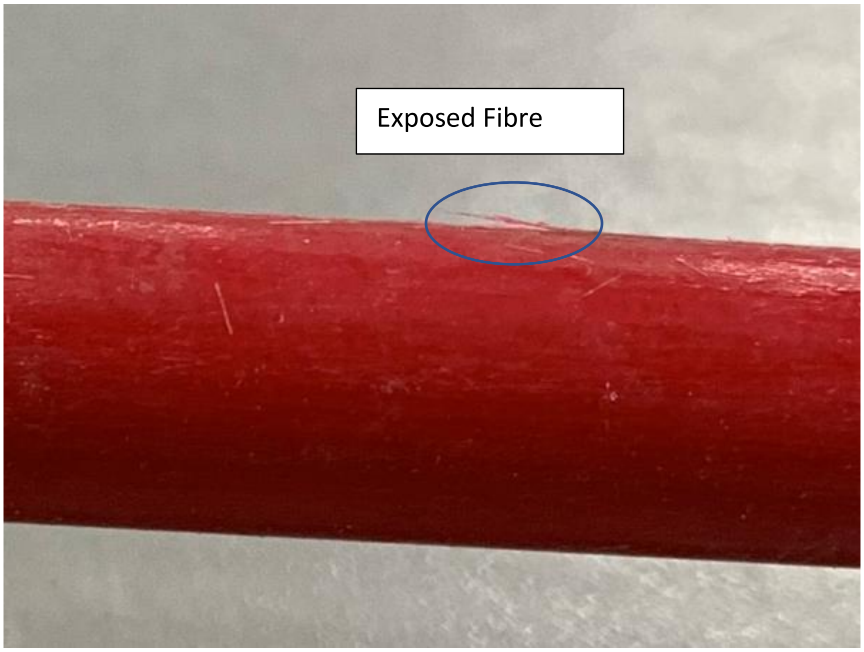
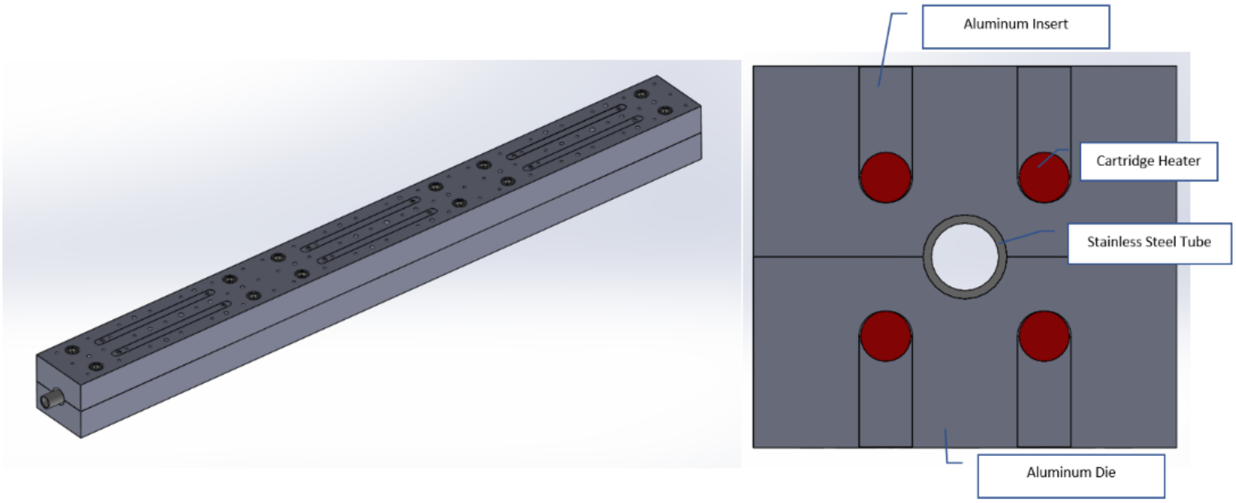


Figure 4. Fine Exposed Fibres on Product's Surface.

3 PULTRUSION DIE DESIGN

The die is designed to achieve thermal homogeneity with a low-cost tooling technique. The term low-cost in this context refers to the man-hour required to fabricate the die. Conventionally, a pultrusion die requires multiple processes to complete the fabrication of the die. The design of this die is shown in Figure 5.



A. Pultrusion Die Assembly

B. Cross Section View

Figure 5. Pultrusion Die Assembly and the Cross-sectional View.

The stainless-steel tube plays a role in providing the matrix's profile to polymerize. At the same time, it must sustain the pressure and abrasion from the reinforced materials, such as fibre rovings and fibre mats. The specifications of the stainless-steel tube are provided in Figure 6.

Figure 6. Specifications of the Stainless-Steel Tube [6,7].

Hardness	Rockwell C60
Material	440C Stainless Steel
Tensile Strength	760-1970 MPa
Yield Strength (@0.2% Strain)	450-1900 MPa
Mechanical Finish	Precision Ground
Surface Roughness	6.3-0.025 µm

The blocks for the aluminum die are fabricated using a 3-axis CNC mill. The cavity sides and the mating side of two symmetrical parts are milled with an endmill with 0.127 mm of material on the stock. Furthermore, the travel parameter on the horizontal axis is set to optimal for achieving a surface finishing of 0.8 µm [7].

4 NUMERICAL SIMULATION

The finite element (FE) models used in this research were implemented in ABAQUS. To ease the computational cost, three-dimensional computation has been developed just on one-half of the geometry, imposing thermal and mechanical symmetry conditions on the cut surfaces. The die was made of Aluminum 6061, and the tube was made of Tight-Tolerance Hardened 440C Stainless Steel. The properties of these materials are presented in Figure 7.

Figure 7. Material Properties of the Die and the Stainless-Steel Tube [8,9].

Material	Thermal Conductivity (K) W/mK	Density (ρ) Kg/m^3	Heat Capacity (C_p) J/kgK
Aluminum 6061	152	2700	897
440C Stainless Steel	24.2	7650	460

Both conduction and convection phenomena exist in this numerical model. The convection boundary condition is applied to the outer surfaces of the die exposed to the atmosphere. The convective heat transfer coefficient and the sink temperature were taken at 10 W/m^2K and 25℃ respectively [10]. Temperature boundary conditions were applied to the heaters. The first two heaters were assigned to 90℃, and the last four heaters were set to 120℃. A standard surface-to-surface interaction was considered for the interaction between the die and the stainless-steel tube surface.

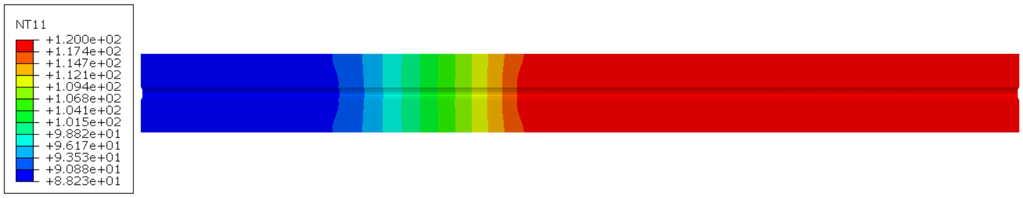


Figure 8. Cross-Sectional View of the Middle of the Die. NT11 Represents the Temperature in Degrees Celsius, °C.

The individual components in the die assembly were meshed by using 3-D brick elements. DC3D8, 8-node linear heat transfer elements were chosen to mesh the individual components. The size of the elements utilized in the finite element model has improved the model's accuracy with minimal computational effort. The temperature profile obtained using a finite element model with elements of sizes 0.01, 0.005, and 0.002 mm was compared for this purpose. Reducing the element size beyond 0.005 does not result in substantial changes in the recorded temperature value, as illustrated in Figure 9. As a result, the finite element analysis employed in this work used an element size of 0.005.

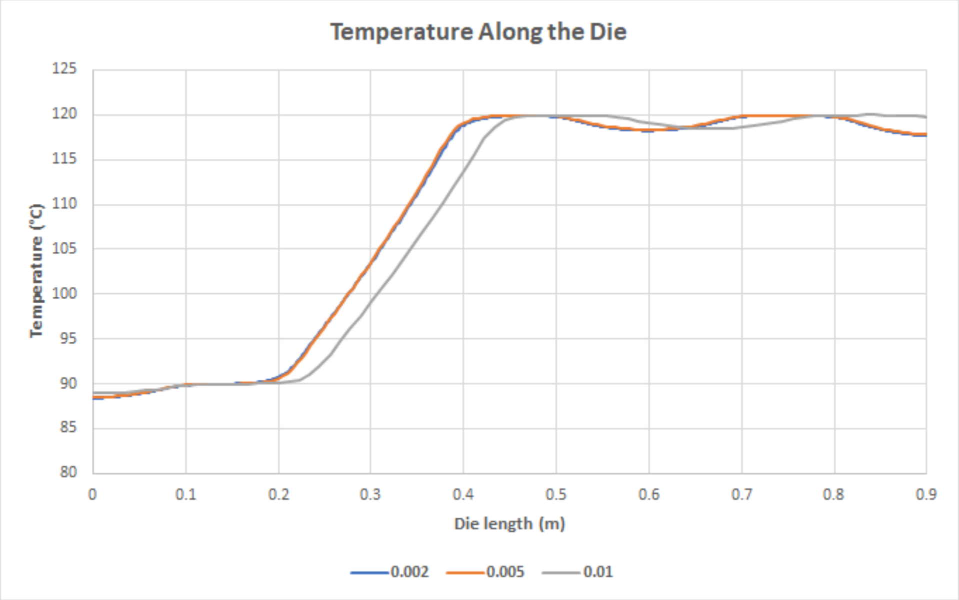


Figure 9. Temperature Distribution Along with the Die at Different Element Sizes.

5 CONCLUSION

The research work presented in this paper is an initial outcome of modelling the thermodynamic load profile when manufacturing FRP composite materials (rods) in the pultrusion manufacturing process. Given dedicated experimental research (underway) by the partnering companies (InnovComposites, and Thermopak Ltd.) and UNB Nanocomposites and Mechanics Laboratory (NCM Lab), the overall objective is to demonstrate that a superior die design along with optimized pultrusion recipe development can create an edge in industrial composite profiles manufacturing of industrial need.

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