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THERMOMECHANICAL MODELING AND ANALYSIS OF A REDESIGNED PULTRUSION CAVITY DIE USING EXPERIMENTAL AND FINITE ELEMENT METHODS

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ABSTRACT

Pultrusion enjoys one of the most cost-effective composite materials manufacturing methods. Pultrusion dies (or moulds) play a central role in creating the condition for thermomechanical transformation of the incoming fibers (mostly glass or carbon) impregnated in polymer matrix and obtain the solidified products of desired geometries. In the process, the die cavity surface undergoes wear/erosion due to sustained temperature, pressure, and friction primarily at the contact point between the fiber rovings and the die cavity surface, and secondarily from the residue left from previous runs. As a result, it is a common practice in industry to perform routine inspection tasks which consist of opening the die compartments (made up of multi-sections assembled die) and perform a painstaking cleaning procedure which causes manufacturing downtime and process inefficiency.

The proposed project is a novel idea of incorporating a hard chromed P20 steel tubing inside the standard rectangular two-section cavity die made of Al6061 alloy that will allow for a rapid interchange of the worn tube and resume the pultrusion process in shorter time and less labour-intensive process. Furthermore, it is anticipated that the prototype die will exhibit a better thermal performance complimented by the highly conductive Al6061 alloy medium, which requires further verification. Hence, a large portion of work for this proposed project is to verify the prototype's thermal activities such as heat flux, thermal conductivity and thermal diffusivity between two dissimilar steels of the prototype die through experiment and heat transfer finite element simulation methods. Concurrently, the project aims to work with a thermoplastic polymer, thus replacing the traditional thermoset resin in pultrusion manufacturing, with the goal to design and develop a greener, environmentally sustainable pultruded rod in the redesigned pultrusion machinery available in the University of New Brunswick's Nanocomposites and Mechanics Laboratory (NCM Lab).

To achieve this dual objective, this research employed a combined experimental/numerical research methodology that used a suite of tools and techniques, including a bi-material design philosophy, die thermomechanical profile modeling using ABAQUS/Explicit® finite element method, material machining and surface finish, pultrusion design of experiments (DoE), material testing/characterization, and statistical analysis.

1 INTRODUCTION

Pultrusion is a continuous manufacturing process that uses a pultrusion die to manufacture various material combinations of fiber-reinforced polymer (FRP) composite profiles of constant cross-section [1], [2]. Figure 1 shows a schematic of the pultrusion process used in this research. The reciprocating pullers pull fibers held in a creel rack through the resin bath and impregnate them with a polymer matrix, at a constant speed. The matrix-impregnated fibers then pass through a heated die to get polymerized, forming the final pultruded profile, and eventually reach a cut-off saw and cut into desired length. Consequently, the final quality of the pultruded profile depends overwhelmingly on a) the quality of the pultrusion die, and b) the pultrusion processing parameters. These include pultrusion pulling speed and heat supply by the external heaters located on top and bottom of the pultrusion die [3]. In other words, if the pulling speed was too fast, the matrix would not have sufficient time for fiber impregnation, negatively impacting the part's structural integrity (flexural, tensile, and compression moduli) [3]. On the contrary, residual thermal stress might occur in the core of the pultrusion die if the pulling speed was too low, increasing the probability of crack occurrence [4].

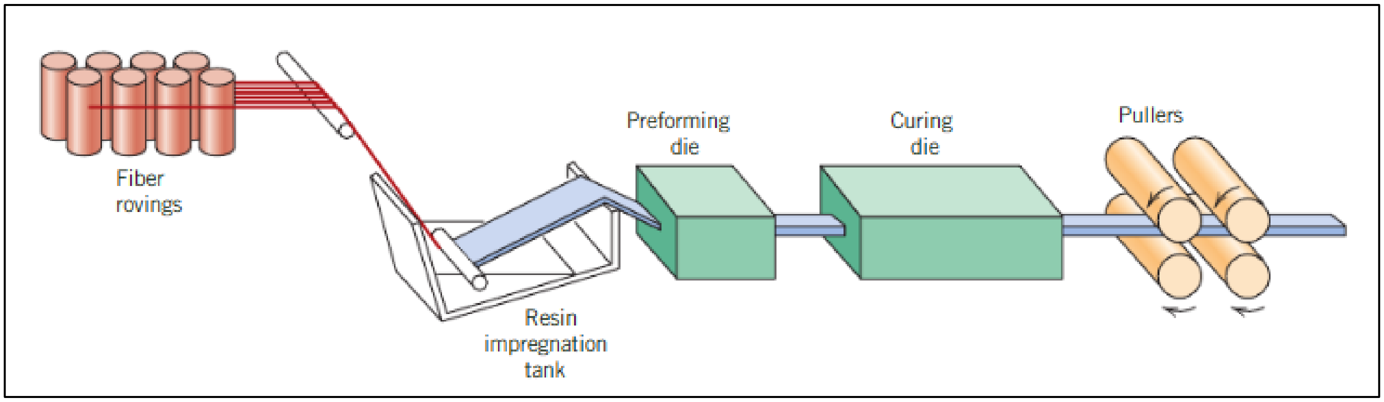

Figure 1. Schematic of a pultrusion process [5].

The abrasive fibrous reinforcement normally abrades away the chrome-plated layer after long production cycles. This requires the manufacturer to send the die to a specialized machine shop to regain the damaged surfaces, as shown in Figure 2.

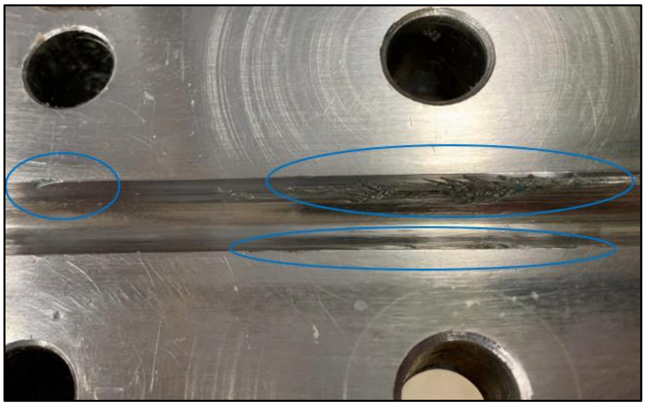

Figure 2. Damaged pultrusion die chrome plated layer.

The primary concern of the existing die is the potential underutilization of heat amount in manufacturing. It is reported that inefficient heating may have an inadvertent impact on the quality of the final product, affected by the incomplete polymerization process of the underlying polymer and additives [4]. Figure 3 shows the real-time temperature difference between the P20 steel pultrusion die surface and composite exothermic temperature at the core. The three single dots represent the die surface temperature, while the 'black' line represents the composite exothermic temperature. The highest temperature difference recorded was 44 °C, the die surface temperature was 145 °C, while the core temperature was 189 °C. This temperature gradient is a source for residual thermal stress buildup in pultruded profile as a result of lower thermal homogeneity inside the die, which can be catastrophic in field application caused by polymer degradation and internal crack formation in the profile [4], [6].

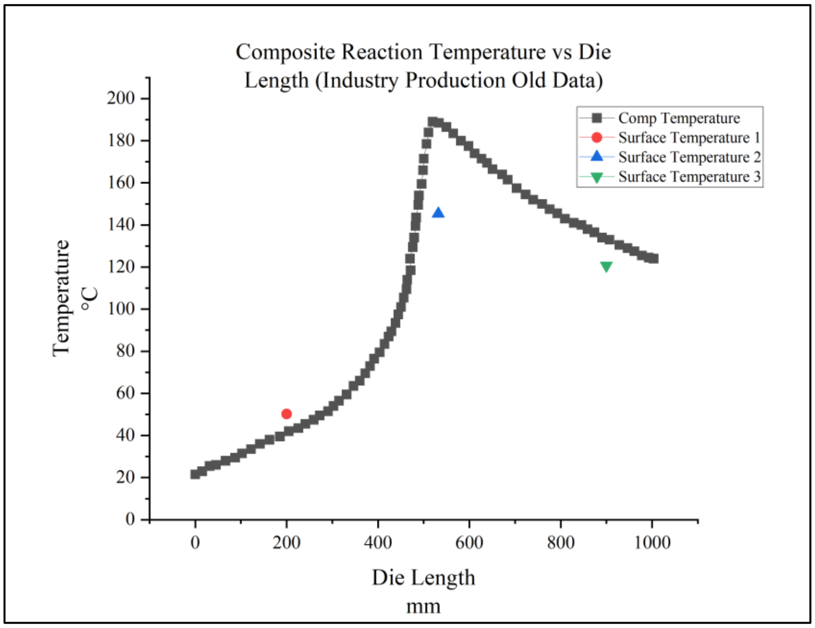

Figure 3. The surface and composite reaction temperatures as a function of die length made of P20 steel.

Hence, the process and product deficiencies related to pultrusion manufacturing of composite profiles were addressed by redesigning a pultrusion die to better accommodate the heat and material transport phenomena, giving rise to a mechanically-superior and environmentally-sustainable pultruded profile. The concept design is shown in Figure 4.

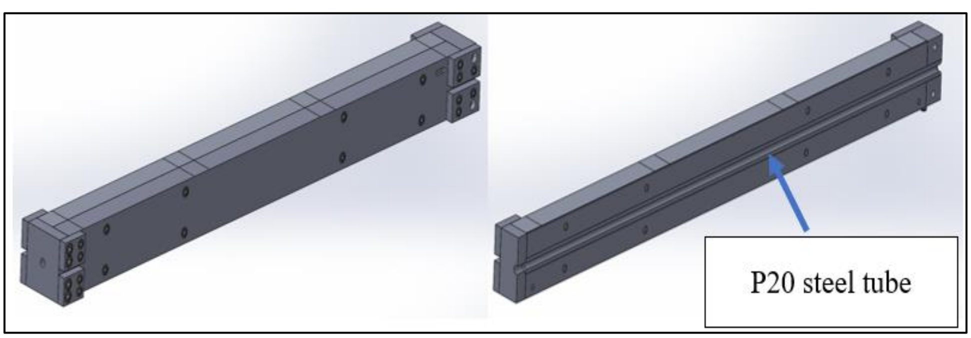

Figure 4. Prototype concept illustration (left) and cut section view of P20 tube (right).

2 Literature Review

Two different steel conduction heat transfer efficiencies discovered by Liu et al. claimed that the interfacial heat transfer coefficient (IHTC) for heat flux transfer from Al6061 alloy to H13 steel is significantly higher than that of the opposite scenario under two different temperature conditions [7]. For instance, the 'red' solid line with 'red' dot markers in Figure 5 shows the IHTC between Al6061 alloy and H13 steel is between 675 W/m^2 °C and 650 W/m^2 °C when Al6061 alloy is at 500 °C whereas H13 steel is at 22.5 °C. On the other hand, the 'red' solid line with 'white' dot markers in Figure 5 shows the IHTC between Al6061 alloy and H13 steel is between 525 W/m^2 °C and 450 W/m^2 °C when H13 steel is at 500 °C whereas Al6061 alloy is at 22.5 °C.

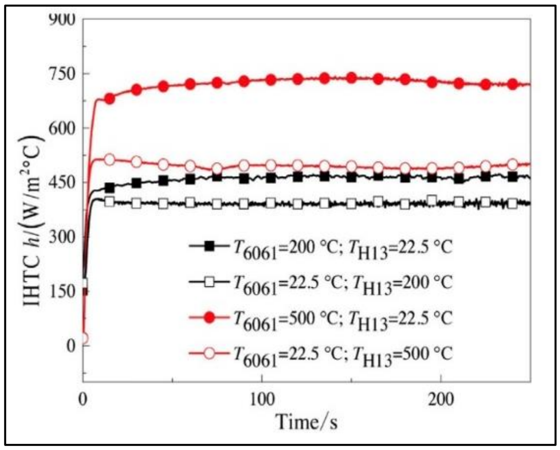

Figure 5. Effect of heat flux direction on the interfacial heat flux coefficient [10].

On the other hand, there was a researcher has started to use different manufacturing techniques, such as one-piece pultrusion die, and pultrusion die with a one-piece replaceable cavity core, which could solve the issue and provide the flexibility of pultruding the same profile with various dimensions [2], [8]. For instance, Ferreira et al. successfully pultruded a thermoplastic profile using a 0.425-m × 0.085-m × 0.085-m pultrusion die with a 2.2-mm diameter one-piece die cavity core in a laboratory setup [8], as shown in Figure 6.

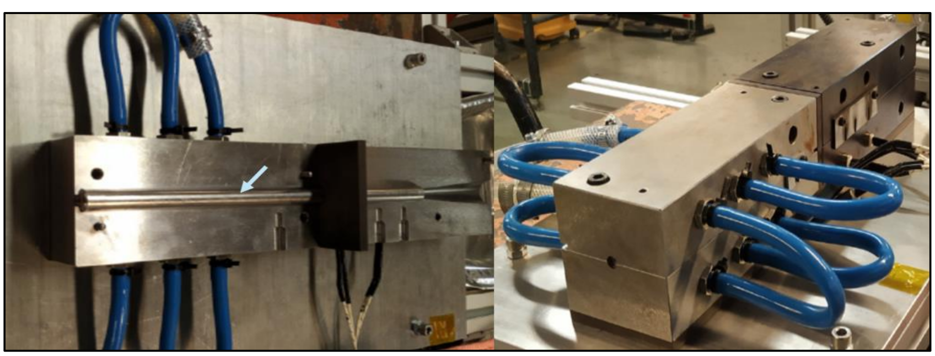

Figure 6. Pultrusion die with a one-piece replaceable cavity core: (Left) middle section view of the die with replaceable core ('blue' arrowhead); (Right) full view of the die [8].

Despite all the mentioned issues, there is a lack of empirical evidence for using a pultrusion die with a one-piece replaceable cavity core developed based on sound engineering principles and methods.

3 Methodology

This project used two sets of pultrusion dies (prototype and conventional) with the dimension of 1.000-m × 0.072-m × 0.078-m to produce the 9.5-mm diameter glass fiber-reinforced polymer (GFRP) rod for quality comparison. The prototype pultrusion die shown in Figure 4 was designed and fabricated using design software and manufacturing machines: computer-aided design (CAD), computer-aided manufacturing (CAM), and a 3-axis computer numerical control (CNC) mill. The pultrusion die prototype design and material heat transfer properties were optimized using ABAQUS/Explicit® FEA heat transfer simulation module. The finite element heat transfer analysis (FEHTA) data served as a reference for analyzing the temperature profile and heat flux activity of the prototype pultrusion die. Each pultrusion die produced a 12-m long 9.5-mm diameter GFRP rod, which was cut into 33 samples at 0.35-m each. Meanwhile, 5 out of the 33 samples were randomly selected for 3-point bending tests to determine the flexural strength of the GFRP rod produced from each die. On the other hand, 3 GFRP rod samples from each pultrusion die production were selected for microstructural analysis to determine the cross-section porosity percentage using scanning electron microscopy at 200× magnification. During the production of the GFRP rods, the pultrusion die surface temperatures were monitored using a temperature logger with seven thermocouples from the die entrance to the die exit. Meanwhile, the matrix reaction temperature in the core of the die was monitored by feeding a thermocouple wire into the core three times at the interval spanned throughout the production.

4 Results

Figure 7 illustrates the FEHTA steady-state temperature profiles along the longitudinal length of P20 and prototype pultrusion dies, encompassed the core and surface temperature data. The x-axis of the plot denoted the die length, which at 0-m represented the entrance of the die, and 1-m, represented the end of the die. In contrast, the y-axis of the plot represented the corresponding longitudinal steady-state temperature. Notably, the steady-state temperature profiles for both the core and surface (blue and green curves) of the prototype pultrusion die demonstrated a high degree of homogeneity. Meanwhile, the P20 pultrusion die core and surface steady-state temperature profiles (red and black) demonstrated slight variability.

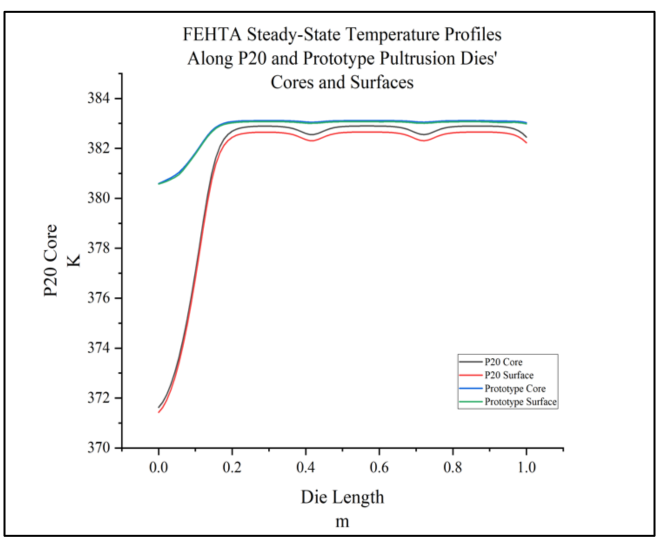

Figure 7. FEHTA steady-state temperature profiles along the P20 and prototype pultrusion dies' cores and surfaces.

This prototype pultrusion die was meticulously engineered in target to enhance the rod quality. It was engineered so that the prototype pultrusion could provide a stable heating environment that remained consistently proximate to the temperature setpoint with minimal deviation. In this case, the heater temperature setpoint (assumed as the die steady-state temperature) was 383.15 K, whereas the highest exothermic peak temperature exhibited by the prototype pultrusion die's composite temperature was 398.15 K. In comparison, the highest composite exothermic peak temperature demonstrated by the prototype pultrusion die was 8.85 K lower than the P20 pultrusion die. Furthermore, the prototype pultrusion die's composite polymerization temperature profiles did not exhibit any aggressive trend of temperature increment, which can eliminate any potential of uneven polymerization of the composite's matrix by slowing down the polymerization rate [4].

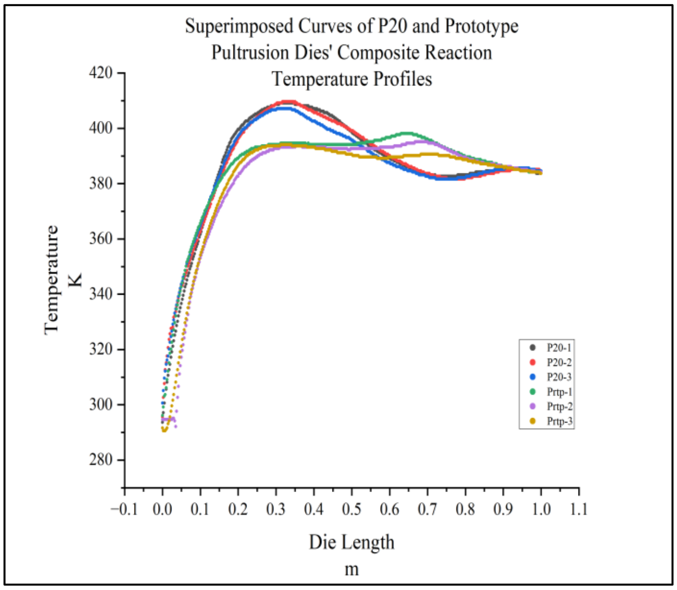

Figure 2. The composite polymerization temperature profiles from both the P20 and prototype pultrusion dies.

Notably, due to a more homogenous heating and less aggressive polymerization, the average flexural strength (FS) for the rod manufactured by the prototype pultrusion die was 789.69 MPa, while the average FS for the rod manufactured by the P20 pultrusion die was 731.74 MPa. In comparison, the average FS for the rod manufactured using the prototype pultrusion die was 7.34 % higher than the rods manufactured using the P20 pultrusion die.

5 Conclusions

The research work presented in this paper serves as a benchmark for utilizing the heat transfer properties of different steels to enhance the polymerization and thermal profile of the pultrusion die section. The current phase of this research work has demonstrated promising results in terms of the polymerization rate. 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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