OPTIMIZATION FOR QUALITY THERMOSETTING COMPOSITES PULTRUDATE THROUGH DIE HEATER LAYOUT AND POWER CONTROL

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Abstract

In the present investigation, pultrusion of an uneven composite C-section with 915mm long die assembly with 4as well as 6 heater pads was studied. Different optimization case studies such as die heating with different heater sizes along with and independent of pull speed, and die heating through heating power control were carried out. The goal was to achieve desired value of mean degree of cure ($\alpha_{desired}$) with maximum uniformity of cure within the cross-section. The simulation was performed using the specially developed, three-dimensional finite element/ nodal control volume (FE/NCV) computational scheme.

Major achievement of this work was the optimization of heating power control for a pultrusion die by using the concept of "heater switch-on and -off" upon receiving feedback from a thermocouple mounted on the heater pads. By adopting this idea and approach, a more accurate and realistic process simulation was achieved.

1 Introduction

Composites are broadly known as reinforced plastics and are a combination of reinforcing fibers in a polymer matrix. Composites materials have been proven to be effective in reducing cost and improving performance. There are several manufacturing processes used to make composites. Each is suited to different combinations of products, markets and raw materials.

Pultrusion is a continuous process for manufacturing composites. Since the first patent in 1951, pultrusion has developed into a widely used method of manufacturing straight sections of fiber-reinforced plastics having constant cross sections.

The process consists of pulling reinforcing fibres through a resin impregnation bath and into a shaping die where the resin is subsequently cured [1]. Heating to both gel and cure the resin is mostly accomplished within the die length, which is about 0.7-1.0 m long. In some versions of the process, preheating of the resin-wet reinforcement is accomplished prior to entry into the die, or post-curing is continued after the exit from the die.

The continuous nature of the process lays constraints on the quality control system utilized in a pultrusion operation. Although pultrusion appears relatively simple to control, the numerous inter-dependencies of the control variables make optimization of the process difficult. One effective method to optimize pultrusion process is by simulation.

To achieve uniform and high enough degree of cure across the section of thermosetting polymer composites is important for the product quality. The objective of this investigation is to enhance the degree and uniformity of cure through appropriate combination of the various processing parameters. Many die heater parameters such as heater temperatures, pre-heating temperature, post-curing temperature, die-cooler temperature, die heater mounting, die heater size, heater power control etc., influence the process. Among these, the effect of die heater size and die cooler temperature was assessed. Emphasize was laid on an uneven shape that generally experience non-uniform curing. The present case studies focus on optimizing the curing profiles for uneven C-section made of glass fibre reinforcement and Shell EPON 9420/9470/537 epoxy resin system.

2 FE Model and Other Details

The adopted heater layout for the C-section with 4 heater pads is shown in Fig. 1. The die dimensions were 72mm (width) x 72mm (height) x 915mm (length). The front top and bottom (FTH & FBH) die heater dimensions were 72mm (width) x 375mm (length) and the rear top and bottom (RTH & RBH) die heater dimensions were 72mm (width) x 390mm (length). The same case was analyzed with six heating pads [2]. The total surface area of the heaters was the same in both cases. Except for the number, size, and location of the heating pads, the rest of the heater and the FE model parameters were also the same. In both cases, only one half of the die assembly was modeled because of the symmetry. LUSAS (a general-purpose FE software) Modeler was used to generate the FE model. A total of 3294, 8-noded, solid field elements were used to describe the composites part and the die. The size of all the finite elements in the pull direction was 15mm.

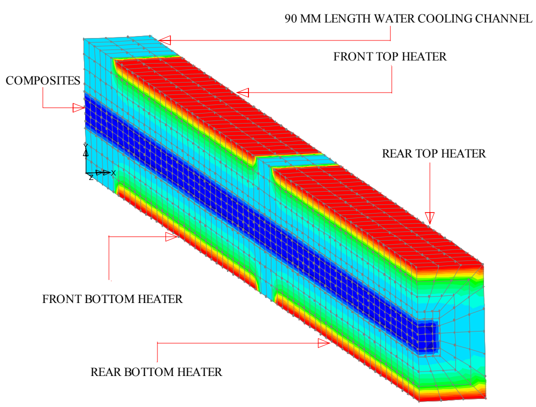
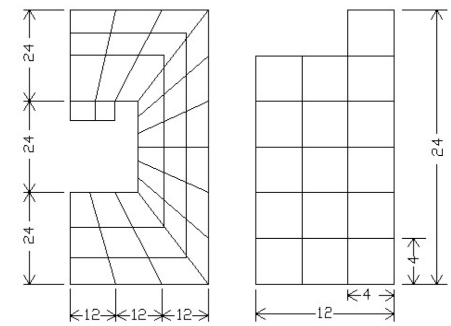


Fig. 1. LUSAS model for the C-section.

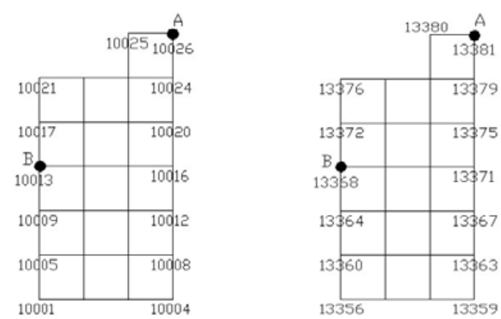
The initial temperature for all heaters was set at 177ºC, which is the curing temperature of the resin system. Along the first 90mm length of the die-entrance area, there were water-cooled channels whose temperature was maintained at 50ºC to prevent premature resin gelation. The surrounding air was assumed to be at 30ºC. The pull speed for the C-section was maintained at 5mm/sec. During one optimization iteration, the heaters' temperature was modified within a range δT = ±5ºC. The convergence limit of δ = 0.005 was used during optimization where $\alpha_{desired}$ was chosen as 0.9. The simulation was performed using the specially developed, three-dimensional finite element/ nodal control volume (FE/NCV) computational scheme [2-4].

The cross sectional views of the FE models of the die and composites C-section with some FE nodes are shown in Figures 2 and 3 respectively.



(a) Die section (b) ¼ th of C-section

Fig. 2. Cross sectional views of FE model of the die and composites C-section.



(a) Die inlet (b) Die exit

Fig. 3. Cross sectional views of C-section composites with FE nodes shown.

2.1 Material Properties

In both cases, chrome steel was used as the die material. The composite section was made of glass fibers and Shell EPON 9420/9470/537 epoxy resin system. The properties of the materials are given in Table 1. The cure kinetic parameters for the epoxy system are listed in Table 2.

Table 1. Properties of the materials used [2]

Material	Density (g/cm^3)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)
Glass Fibers	2.56	670	$k_{fx} = k_{fy} = 1.04$ $k_{fz} = 11.4$
EPON 9420/9470/537 Epoxy Resin	1.26	1255	0.2

Table 2. Cure kinetic parameters for Shell EPON 9420/9470/537 epoxy resin system [2]

Parameter	Symbol	Value
Pre exponential constant	K_1	$19.14x10^4[s^{-1}]$
Activation energy	ΔE_1	$60.5x10^3[J/mol]$
Heat reaction	H_t	$323.7[J/g]$
Order of reaction	n	1.69

3 Case Studies with No Power Control

3.1 Effect of Die Cooler Temperature

The purpose was to compare the effect of die cooler temperatures 50ºC and 65ºC for the same type of 4-heater arrangement. The study with 50ºC show that with the optimized die-heater temperatures, the target value of $\alpha_{desired}$ = 0.9 was almost achieved; however, the maximum temperature in composites exceeded its constraint value of 240ºC. For the 65ºC case, $\alpha_{desired}$ was successfully achieved upon optimization without exceeding the limiting temperatures. The results in Figures 4-6 confirm that a better product quality can be achieved by choosing appropriate die-cooler temperature.

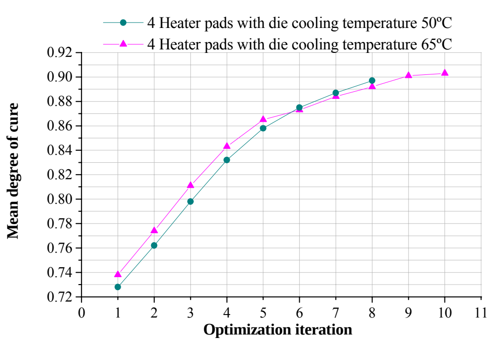


Fig. 4. Mean degree of cure for C section at die exit for two different die cooling temperatures.

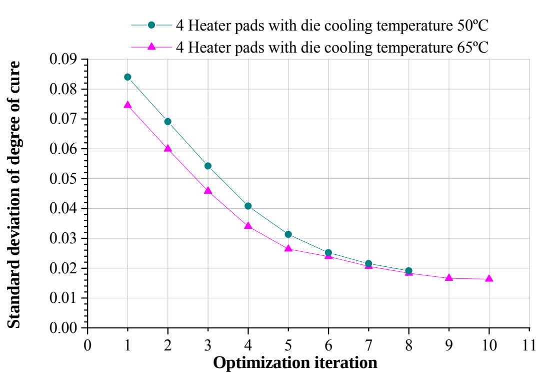


Fig. 5. Standard deviation of degree of cure for C section for two different die cooling temperatures.

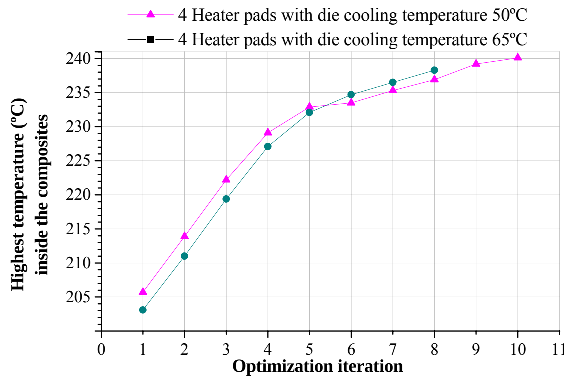


Fig. 6. Highest temperature in C-composites as a function of optimization iterations.

3.2 Effect of Number of Heater Zones and Their Sizes

The results of optimization for 4 and 6 heater cases (same total heater surface area) with die-cooler temperature of 65ºC are compared in Figures 7-9.

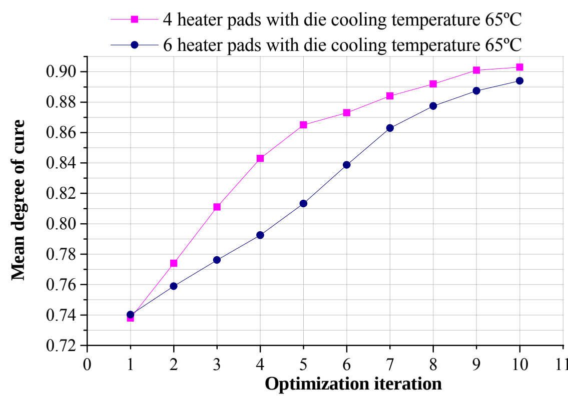


Fig. 7. Comparison of mean degree of cure for C section at the die exit based on heater arrangement.

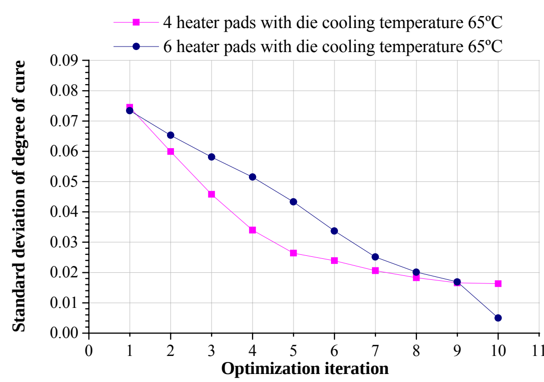


Fig. 8. Comparison of Standard deviation of mean degree of cure for C section at the die exit based on heater arrangement.

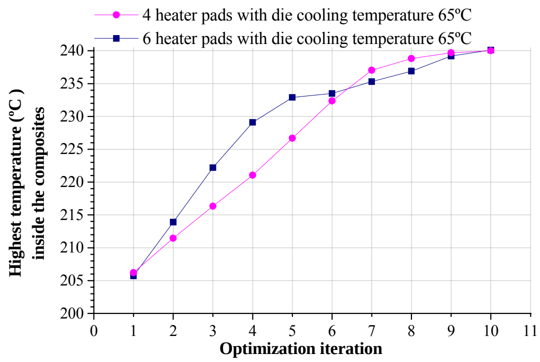


Fig. 9. Highest temperature in C-composites for two different heater arrangements.

For the case of 6 heating zones, the highest temperature for the composites reached 240ºC after 10th optimization iterations. The optimization was terminated even though $\alpha_{desired}$ was 0.894 as against the expected value of 0.9. The results for 4-heaters case show that the highest temperature in the composites reached 239.2ºC after 9th optimization iterations and was less than the earlier case. Also, $\alpha_{desired}$ was almost achieved within the 9 optimization iterations. This was possible only when the larger heaters were used.

This confirms that the location and the size of the die heaters play a role in deciding the curing performance in pultrusion.

3.3 Influence of Variations in Pull Speed

The temperatures for all 4 heaters were maintained at 195ºC throughout. The 195ºC temperature is the average of the minimum (175ºC) and the maximum (205ºC) heater temperature settings used so far. Preheating temperature for the composites at the die inlet was set to 45 ºC. Die-cooler temperature was 50ºC. Different pull speed from 2 to 10mm/sec was used during simulation.

Simulations with 16 different variations in pull speed were carried out. The results in Figure 10 indicate that pull speed has an impact on the quality of the final product. Graphs show that the mean degree of cure decreased as pull speed increased. To have tolerable temperature within composites with an excellent mean degree of cure (~0.925), a minimum pull speed of 2mm/sec shall be chosen.

Figures 11 and 12 show 3D degree of cure and temperature profiles in composites at two different pull speeds; the variations in these two parameters are less with 2 mm/sec pull speed.

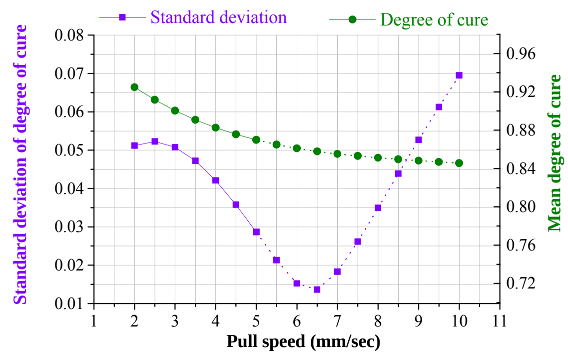


Fig. 10. Mean and standard deviation of degree of cure for C-section at die exit as a function of pull speed.

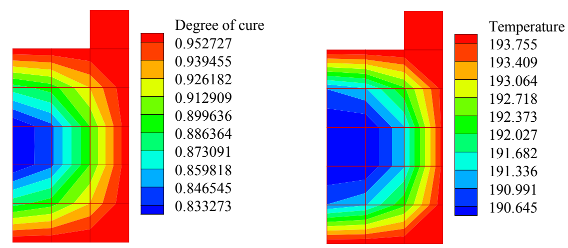


Fig. 11. Degree of cure and temperature profiles at pull speed 2mm/sec.

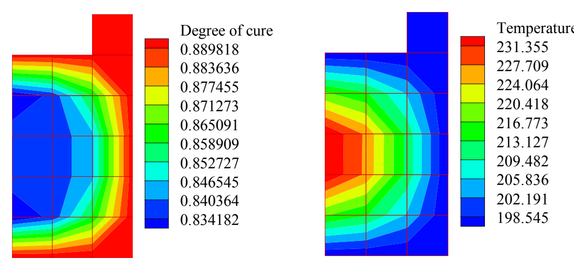


Fig. 12. Degree of cure and temperature profiles at pull speed 5mm/sec.

4 Case Studies with Heater Power Control

This exercise was carried out to demonstrate the numerical technique for controlling heater power supply as in real situation and how this affects the quality of pultruded component.

As seen in Figure 13, When CR (Control range) is set to 0ºC, power supply to heaters will switch off the moment actual temperature (AT) exceeds ST (Set temperature). It will switch on only when AT < ST. For the case with CR = 1, (i.e. temperature tolerance = ±1ºC), for ST = 177ºC, the power supply to heaters will switch off the moment AT exceeds 178ºC. It will switch on, when AT falls below 176ºC. The optimization process performs this "heater switch-on and off" activity based on the feedback from a thermocouple point marked on the heater pad. This is more realistic and close to the actual operation.

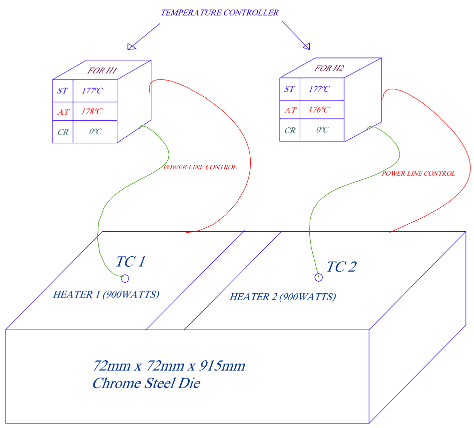


Fig. 13. Schematic showing concept of controlling die-heater temperature through power supply to die heaters.

4.1 Influence of Heater Power Control

In this case the heater power control was set to achieve the temperature tolerance of ±1ºC. The optimization of temperatures of the 4 heating pads with the die cooler temperature 65ºC was carried out. After 15 optimization iterations, the product temperature exceeded the allowable temperature of 240ºC. Figures 14 and 15 are presented to show how the control of the heating power was achieved in a numerical way. Figure 14 shows the heater zones and total power-on and -off time in seconds at the end of 1st optimization iteration. As compared to the previous similar cases (without power control), this case took more time (600sec as against 420 sec) to reach the stabilized state. From this figure, it is clear that power-off time is more than power-on time. Heater zones 1, 2, 3, 4 refer to FBH, FTH, RBH and RTH respectively. The front heaters required power-on for more time than the bottom heaters. It could be because of the composites geometry.

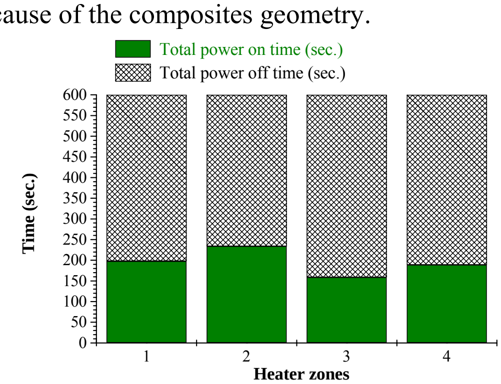


Fig. 14. Heater zones and total power-on and -off time seconds at the end of 1st optimization iteration.

As seen in Figure 15, two bottom heaters started the power off state at 114th seconds as their temperature exceeded 178ºC. Two top heaters exceeded 178ºC and started the power-off state at about 159th seconds. After that, periodically power-on and -off states changed during the optimization.

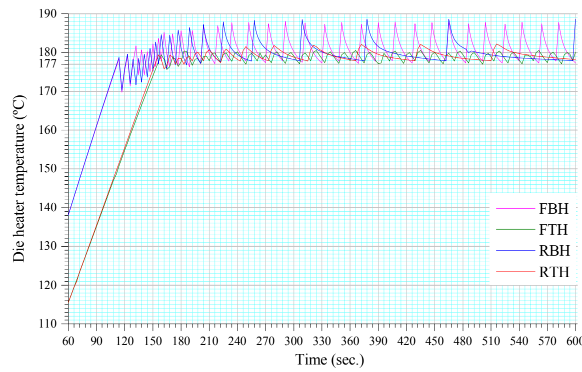


Fig. 15. Fluctuations in die heater temperature due to 'switch-on & off' power control.

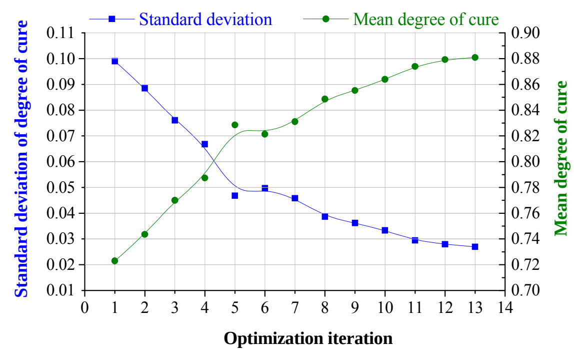


Fig. 16. Mean degree of cure and standard deviation of degree of cure for C section at die exit.

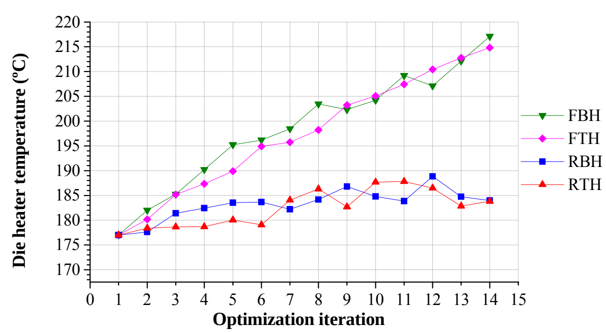
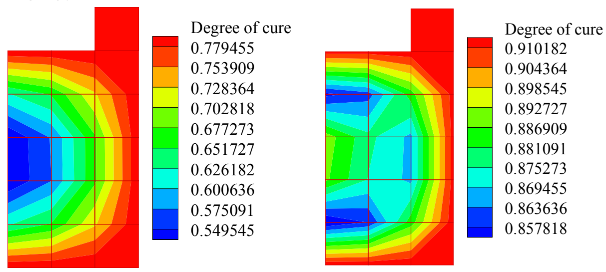


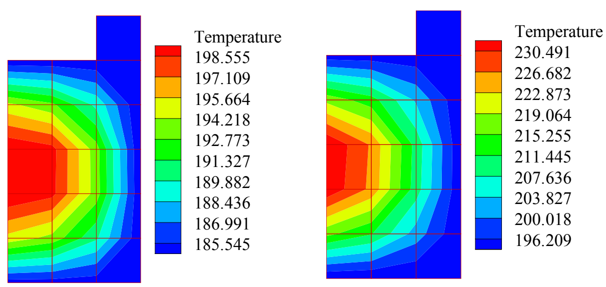
Fig. 17. Die heater temperatures for every optimization iteration.

Figure 16 shows that the standard deviation of degree of cure reduced to 0.0234 and mean degree of cure reached 0.895 (the highest temperature in the composites was 238.4ºC). During optimization, 76.36% improvement in the standard deviation and 23.79% in the mean degree of cure was achieved. Figure 17 shows the temperature variations for die heaters as a function of optimization iterations. The results show that the optimized temperatures of the front pairs of the die heaters (i.e. FBH, FTH) were considerably higher than the rear heaters. It means that composites had to receive most of the heat energy required for curing while it was in the front zone.



(a) Before optimization (b) After optimization

Fig. 18. Degree of cure profiles in C-section.



(a) Before optimization (b) After optimization

Fig. 19. Temperature profiles in C-section.

Figures 18 and 19 depict the respective cure and temperature profiles in the C-section at die exit before and after the optimization.

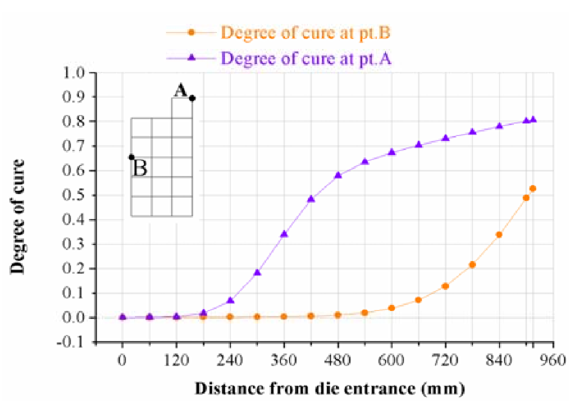


Fig. 20(a). Degree of cure before optimization.

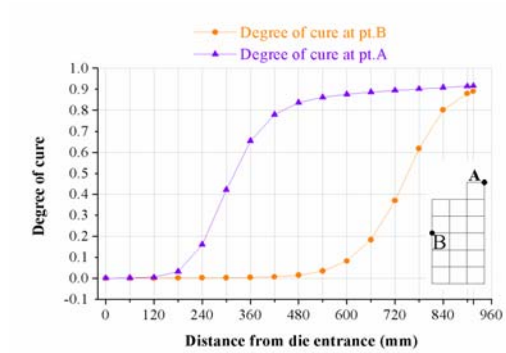


Fig. 20(b). Degree of cure after optimization.

These along with the plots of degree of cure at points A and B shown in Figure 20 confirm that the optimization helped in achieving better and uniform curing.

4.2 Influence of Variations in Heating Power

The purpose of this exercise was to understand influence of the heating power (Watts) for heaters on the mean value and the uniformity of degree of cure and, the highest temperature in the composite pultrudate given that the die-heating environment is kept constant.

Table 3. Optimization results for heater power variation

Iteration no.	Power (Watts)	Highest temp.(ºC)	Mean degree of cure	Standard deviation
1	1000	237.7	0.885	0.0258
2	1100	238.1	0.886	0.0247
3	1200	237.9	0.886	0.0248
4	1300	237.7	0.886	0.0253
5	1400	239.0	0.891	0.0232
6	1500	238.1	0.888	0.0241
7	1600	239.2	0.890	0.0233
8	1700	238.3	0.890	0.0238
9	1800	238.7	0.891	0.0233
10	1900	238.9	0.892	0.0241
11	2000	239.3	0.894	0.0228
12	2100	241.3	0.900	0.0214

A 6 hear-pad case was used for the simulation. The heater temperatures were maintained at 195ºC. The die-cooler temperature was 65ºC. The pull speed was maintained at 5 mm/sec. Different heating power from 1000 to 2000Watts was used during simulation with a temperature tolerance of ±1ºC. Simulations for 12 different variations in heater power were carried out; the results are presented in Table 3.

The degree of cure and temperature profiles in the C-section composites at die exit for 1000Watts and 2000Watts are presented in Figures 21 and 22 respectively.

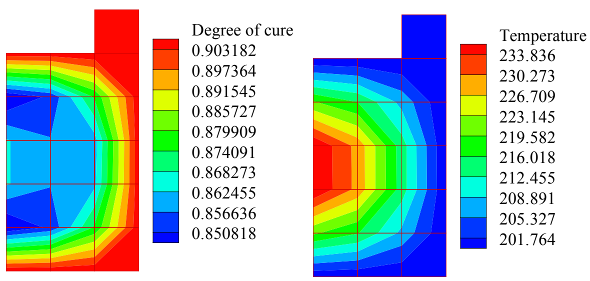


Fig. 21. Contours in C-section at the die exit after optimization at 1000 Watts heater power.

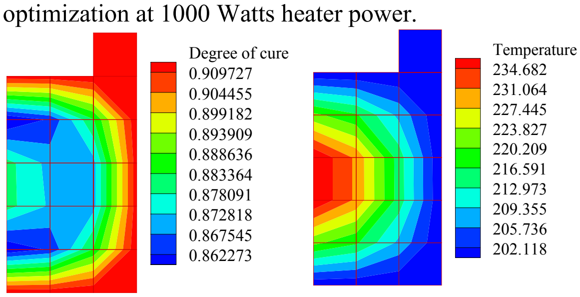


Fig. 22. Contours in C-section at the die exit after optimization at 2000 Watts heater power.

It may be seen that the case with 2000Watts of heating power helped to achieve mean degree of cure of 0.9 with minimum standard deviation without violating the constraint on the temperature in the composites.

5. Conclusions

In this work, different case studies on optimization of die heater parameters for pultrusion of polymer composites were performed using the FE/NCV procedure.

In the simulation of pultrusion with 4 heater pads, the uniformity of degree of cure was about 14% higher than that of the case with 6 heater pads with the same total surface area. It was observed that the degree and uniformity of cure achieved by optimization for 4 heater pads with die-cooler temperature of 65ºC approached the desired values steadily.

It was also observed that the mean degree of cure decreased as pull speed increased. However, when the pull speed exceeded 5mm/sec, the highest temperature inside the composites also exceeded 240ºC. Thus, the pull speed of 5mm/sec proved to be reasonable pull speed for this particular product.

To investigate the effect of heating power control for heaters, optimization with heater switch-on and -off strategy was performed. The optimization of die heating with the heater power control was more accurate and realistic. When this case was compared with the results of optimization without heater power control, initial die-heater temperature was significantly lower. It was found that the degree and uniformity of cure with heater power control approached the desired values more steadily, which is a good news for actual process. Initially, it was observed that 900Watts of heating power with the power control for 6 heater pads was not enough to achieve 90% cure. However, by increasing the power to 2000Watts, the desired improvement could be achieved. This was the indication that the heater power plays an important role in obtaining a quality product.

The results of all cases presented show that the development and implementation of the FE/NCV optimization scheme for pultrusion of polymer composites was successfully accomplished. The developed procedure could be utilized in real production scenario to save process time and cost.

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