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Optimized Set-Up of Internal Controlled Electrical Cartridges for Efficient Heating in Pultrusion Processes

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Abstract

An optimized system of internal controlled electrical cartridges is developed for an efficient heating in pultrusion processes. This is done with non-direct optimization methodology based on the planning of experiments and response surface technique. The temperature control strategy executed by the heaters switch-on and -off operations is simulated by the finite element modelling (FEM) approach based on the mixed time integration scheme and nodal control volumes method and using the continuous model with lumped material properties for a cured composite. The thermal efficiency of the pultrusion process is achieved by improving the thermal distribution of the die body, optimized pull speed in relation to the ambient room temperature. An effectiveness of the developed pultrusion process producing simultaneously two rod profiles with ears is estimated and compared with the effectiveness of optimized technology utilizing external platen heaters and physical process in industrial shop.

Keywords: pultrusion, internal cartridges, temperature control, FEM, optimization, process effectiveness

1 Introduction

Pultrusion is a technological process for the fast and effective production of composite profiles with constant cross-sections where external platen resistances are used widely for a die heating. However, they often suffer from large heat losses to the environment and limited control of the temperature gradient inside the die. The process could be made more effective with reduced set-up and warm-up times, applying instead of flat platen electrical resistances located on the die surfaces, internal cartridge heaters as it is demonstrated in [1].

Since the finite element models, describing the coupled thermo-chemical problem, have large dimensions and time-consuming iterative process is required for its solution, a limited number of optimization studies could be found in the open literature. So, a heating arrangement with internal cartridges inside the die body has been optimized in [2] with the parametric study and analysis of duty cycles for U-profile production. The stochastic (particle swarm optimization) algorithm [3] and the quadratic programming algorithm [4] have been used to improve heat distribution and to reduce energy consumption in technological processes producing I-beam and C-section profiles, respectively, where for the pultrusion modelling the Computational Fluid Dynamics (CFD) algorithm has been applied. However, it is necessary to note that optimal distribution of die temperatures have been obtained there with the constant pull speed and without the temperature control of heating elements widely used now in industrial pultrusion processes.

In the present study new effective optimization methodology is developed for the design of industrial pultrusion processes with internal controlled cartridge heaters, using the method of experimental design and response surface technique. Optimization problem is formulated as a minimal energy applied to produce one-meter pultruded profile with the constrains on resin degradation temperature and minimum degree of cure in the composite and on the profile surface at die exit to avoid the resin flow from the die exit. As the design variables: pull speed, control temperature on heaters, room and resin temperature, and set-up of internal heaters describing their number and positioning are examined. An effectiveness of the developed pultrusion process producing simultaneously two rod profiles with ears is compared with the effectiveness of corresponding optimized technology utilizing external platen heaters and real manufacturing process.

2 Formulation of Optimization Problem

The present optimization problem is formulated for the improvement of real manufacturing process producing two rod profiles with ears in one time. The pultrusion die with dimensions of 500x150x110 mm and the distance between two profile channels of 40 mm is heated by two electrical platen resistances located at the top and bottom sides of the die. In the present study the existing heating system is replaced by a set of internal cartridge heaters with a length of 130 mm and diameter of 8 mm. The scheme of pultrusion process with the profile cross-section and its

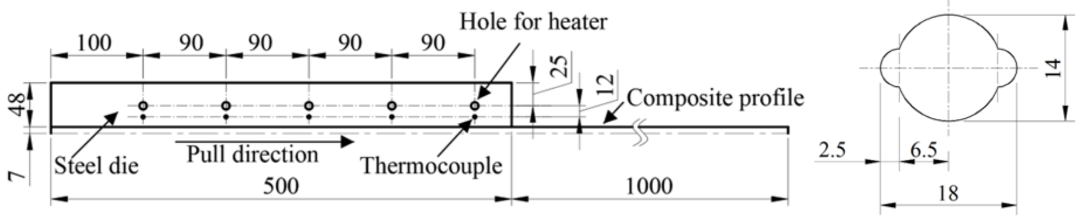

Figure 1: Scheme of pultrusion process.

Property	Symbol [unit]	Die	Heater
Density	ρ [kg/m^3]	7720	2700
Specific heat	C [J/(kg·K)]	470	896
Thermal conductivity	k_x [W/(m·K)]	43	180

Table 1: Thermal properties of die and heater materials.

Property	Symbol [unit]	tex 4800	C-L ISO 112G	Lumped
Density	ρ [kg/m^3]	2500	1100	1953
Specific heat	C [J/(kg·K)]	1235	1360	1263
Thermal conductivity	k_x [W/(m·K)]	11	0.209	0.890
Thermal conductivity	k_y [W/(m·K)]	1		0.546

Table 2: Thermal properties of composite material.

Parameter	Symbol [unit]	C-L ISO 112G
Heat reaction	H_{tr}, [J/kg]	223385
Frequency factor	K_1 [s^{-1}]	$2.6 \cdot 10^{13}$
Frequency factor	K_2 [s^{-1}]	$1.2 \cdot 10^{12}$
Activation energy	E_1 [J/mol]	116769
Activation energy	E_2 [J/mol]	200000
Order of the reaction	n	1.27
Order of the reaction	m	0.0011

Table 3: Kinetic parameters of resin.

dimensions in mm is presented in Figure 1. In the case of application of internal cartridge resistances, no, one or two pairs can be absent in all possible combinations in the heating set-up describing by this way their number and positioning. Heaters are located symmetrically above and below the profiles along the die and pairwise grouped. Work of each group is controlled by the thermocouple located between the heaters. The thermal properties of electrical heaters and die materials are given in Table 1.

The materials used to produce the rod profile with ears are glass fibre tex4800 with the fibre mass fraction of 78% and polyester resin C-L ISO 112G. Their thermal properties are given in Table 2. The rate of resin reaction is described by using the Kamal-Sourour curing kinetic model:

$$\frac{\partial \alpha}{\partial t} = \left(K_1\, exp\left(-\frac{E_1}{RT}\right) + K_2\, exp\left(-\frac{E_2}{RT}\right) \cdot \alpha^m\right) \cdot (1-\alpha)^n \qquad (1)$$

with the kinetic parameters presented in Table 3.

The objective function in the optimization problem requires minimization of the pultrusion process energy consumption necessary for a production of 1 m profile:

$$\frac{n \cdot W_{heater} \cdot k_{t\,\Sigma}}{m \cdot V_{pull}} \rightarrow min \qquad (2)$$

where $n = 2$ is the number of heaters in a group, $m = 2$ is the number of simultaneously produced profiles, $W_{heater} = 400$ W is the power of electrical cartridge heater, V_{pull} is the pull speed, $k_{t\,\Sigma} = \sum k_{t\,i}$ is the sum of the relative times of heaters groups work determined as

$$k_{t\,i} = \frac{t_{work\,i}}{t_{sim}} \tag{3}$$

where $t_{work\,i}$ is the time of heaters group work and t_{sim} is a simulation time of the pultrusion process without the preheating time.

As the design variables: pull speed, control temperature on heaters, room and resin temperature are examined. They change in the following boarders:

$$20 \le V_{pull} \le 45 \text{ cm/min},\ 115 \le T_{cont} \le 150 \text{ °C},\ 10 \le T_{room} \le 40 \text{ °C} \tag{4}$$

Additional design variable H, which is integer value, is an absence of cartridge pair in the die holes (Table 4). In this case no, one or two pairs are absent in all possible combinations in the heating set-up and optimization problem is replenished with zero, one or two design variables. Information about cartridges location is given in Table 4, where “+” corresponds to the heater installed in the hole and “-” corresponds to the empty hole.

The constraints are introduced into optimization problem to provide a qualitative profile production, when the resin is fully cured and not overheated during the

Number of combination	Hole number					Number of cartridge pairs	Design parameters
	1	2	3	4	5		
1	+	+	+	+	+	5	-
2	-	+	+	+	+	4	$1 \le H_i \le 5$
3	+	-	+	+	+		
4	+	+	-	+	+		
5	+	+	+	-	+		
6	+	+	+	+	-		
7	-	-	+	+	+	3	$1 \le H_i \le 5$ $1 \le H_j \le 5$ $i \ne j$
8	-	+	-	+	+		
9	-	+	+	-	+		
10	-	+	+	+	-		
11	+	-	-	+	+		
12	+	-	+	-	+		
13	+	-	+	+	-		
14	+	+	-	-	+		
15	+	+	-	+	-		
16	+	+	+	-	-		

Table 4: Combinations of heater pairs location.

pultrusion process. To satisfy quality requirement, the minimal value of the degree of cure in the profile cross-section located on the distance of 1 m from the die exit is limited as $\alpha \geq 0.95$. To prevent overheating, the maximal temperature is constrained as $T \leq 160°\text{C}$. It is necessary to note that for the rod profile it is enough to check degree of cure and temperature only on the profile surface and centerline. Since curing is allowed in the profile outside die, additional constraint on the degree of cure at die exit is examined to avoid the resin flow from the die exit. It can be written for the profile surface: $\alpha_{surf}^{exit} \geq 0.7$ or for the entire cross-section: $\alpha^{exit} \geq 0.7$ or $\alpha^{exit} \geq 0.95$. It is necessary to note that to avoid the resin flow from the die exit, an execution of the first condition is enough. However, in most present pultrusion processes, the last condition is applied widely.

3 Non-Direct Optimization Methodology

The present non-direct optimization methodology (Figure 2) is developed to improve the effectiveness of pultrusion process with an application of internal controlled cartridge heaters. Since solution of coupled thermo-chemical problem requires utilization of iterative algorithm operating with large dimension matrices, present optimization is based on the planning of experiments [5] and response surface technique [6]. In this case the finite element solution is executed only in the points of the plan of experiments that contributes to considerable saving of required optimization time.

It is known [7] that, if an optimization problem contains the discrete and continuous design variables and is planned to use the second order polynomial functions for global approximations, the Combined Latin Hypercube D-Optimal experimental design is the most suitable. The minimal number of experiments in this case is determined as

$$n = \frac{(k+1)(k+2)}{2} \tag{5}$$

where k is the number of design parameters. The Combined Latin Hypercube D-Optimal plan of experiments is generated by using EDAOpt software [8].

Then the finite element analysis is carried out in each point of the developed plan of experiments. Algorithm for coupled thermo-chemical problem is developed in ANSYS Mechanical environment by application the mixed time integration scheme and nodal control volumes method, where ANSYS is used only for the solution of transient thermal problem, but calculation of the resin degree of cure, simulation of composite movement and process control is realized by the user developed program. Movement of the composite is simulated by shifting the temperature and degree of cure fields after each calculation step [9]. Process control is realized by turning-on

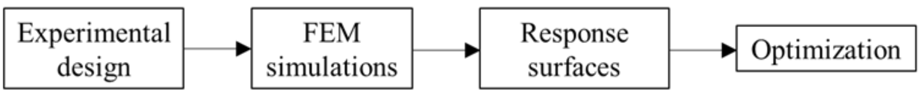

Figure 2: Optimization procedure.

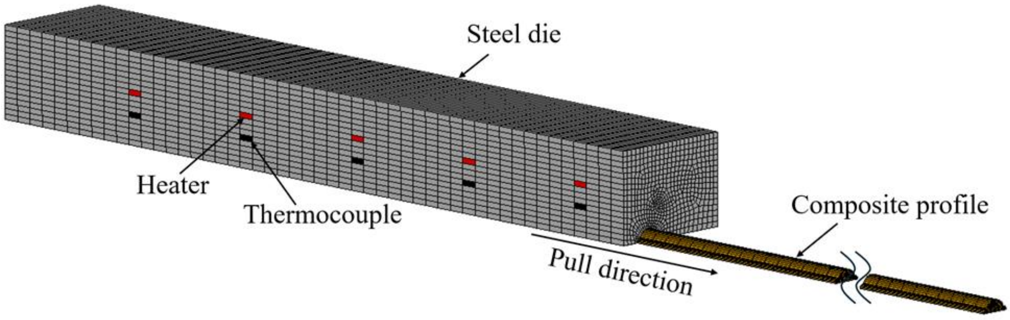

Figure 3: Finite element model.

and -off the heaters, when the temperatures reach corresponding threshold values [10]. This approach of manufacturing process modelling most accurately simulates the real work of the heating system that allows not only to calculate the process conditions (temperatures and degrees of cure), but also to evaluate accurately the energy consumption. The finite element algorithm has been validated successfully by using the developed cure sensors measuring electrical resistivity and temperature on the profile surface in [11]. The corresponding finite element model has been created by using 3-D thermal solid finite element Solid 70. The element has eight nodes with a single degree of freedom - temperature at each node and the orthotropic material properties. Considering symmetry of the examined problem, only a quarter of the die is modelled. It is necessary to note that the finite element mesh is regular in pull direction, and it is presented in Figure 3.

In the present study a conventional un-weighted least square estimation with an elimination of some points in the case of necessity [8] is applied to obtain second order polynomial approximations of the process conditions:

$$y = a_0 + \sum_{i=1}^{k} a_i x_i + \sum_{i=1}^{k} \sum_{j=i}^{k} a_{ij} x_i x_j \quad (6)$$

where a_0, a_i, a_{ij} are unknown coefficients. Accuracy, quality and adequacy of the approximations are evaluated by using the following criteria: the maximal relative error in the bad point (Δ_{max}), the root mean squared error (σ) and its relative value determined relatively to a diapason of the approximating function in the domain of interest (σ_r), the relative cross-validation estimate (σ_{cross}) and the adjusted coefficient of determination (R^2_{adj}). The detailed description of these estimates could be found in [12].

Later the developed response surfaces are used in the following optimization problem:

$$y\, min \;\; F(x);\; H_i(x) \geq 0;\; G_j(x) = 0$$
$$i = 1,2,\ldots,I;\; j = 1,2,\ldots,J \quad (7)$$

where I and J are the numbers of inequality H and equality G constraints. This problem is replaced with an unconstrained minimization problem, where constraints are considered with the penalty functions. The formulated optimization problem is solved by using random search method described in [13] and two algorithms embedded in Microsoft Excel © Solver: the generalised reduced gradient (GRG) nonlinear algorithm and evolutionary algorithm.

4 Results of Optimization

At the beginning the optimization problem has been solved for all possible combinations presented in Table 4. However, the response surfaces for all behaviour functions have been obtained with low accuracy. For this reason, separate optimization problems have been formulated and solved for 5, 4 and 3 cartridge pairs used for a die heating and more effective pultrusion process has been defined. In this case the plans of experiments have been built for 3, 4 and 5 design variables and 15, 21 and 57 experimental points respectively.

Then the finite element analysis has been carried out in each point of the experimental design. The second order approximations have been built for all the constraints and the sum of the relative times of heaters groups work, which is only one regression function directly entering into the objective function. The estimates describing accuracy and reliability of the response surfaces obtained are presented in Tables 5-7. Finally, all minimization algorithms have been applied for a solution of the formulated optimization problems to increase the reliability of the optimization results. Since practically the same values have been obtained for the objective function, design variables and constraints by different solvers, optimal results

Symbol [unit]	Second order approximations				
	σ_{cross} [%]	R^2_{adj}	σ	σ [%]	Δ_{max} [%] (point Nr.)
T_{surf} [°C]	34.6	0.96	2.2	19.0	2.0 (14)
T_{cent} [°C]	19.1	0.99	1.9	9.3	1.5 (5)
α_{surf}	27.8	0.98	0.03	15.0	10.8 (13)
α_{cent}	54.8	0.92	0.08	28.2	26.4 (5)
α_{surf}^{exit}	26.1	0.98	0.04	14.6	12.5 (5)
$k_{t\Sigma}$	5.7	1.00	0.01	3.21	0.6 (2)

Table 5: Accuracy and reliability of the response surfaces (5 pairs of heaters).

Symbol [unit]	Second order approximations				
	σ_{cross} [%]	R^2_{adj}	σ	σ [%]	Δ_{max} [%] (point Nr.)
T_{surf} [°C]	33.5	0.97	2.1	17.5	2.1 (14)
T_{cent}, [°C]	39.1	0.97	3.6	18.2	4.0 (14)
α_{surf}	51.6	0.95	0.05	22.9	10.6 (6)
α_{cent}	65.3	0.92	0.08	29.0	36.4 (6)
α_{surf}^{exit}	43.3	0.95	0.06	22.4	14.0 (6)
$k_{t\Sigma}$	34.4	0.97	0.03	17.0	4.2 (1)

Table 6: Accuracy and reliability of the response surfaces (4 pairs of heaters).

Symbol [unit]	Second order approximations				
	σ_{cross} [%]	R^2_{adj}	σ	σ [%]	Δ_{max} [%] (point Nr.)
T_{surf} [°C]	14.3	0.99	1.2	11.0	1.9 (16)
T_{cent}, [°C]	23.4	0.97	3.7	17.1	6.1 (11)
α_{surf}	26.4	0.97	0.05	18.6	77.6 (11)
α_{cent}	41.1	0.91	0.10	29.4	200 (11)
α^{exit}_{surf}	16.4	0.99	0.03	10.6	77.4 (11)
$k_{t\,\Sigma}$	32.8	0.93	0.06	26.0	15.6 (34)

Table 7: Accuracy and reliability of the response surfaces (3 pairs of heaters).

presented in Table 8 relate to those determined with the faster tool, namely the GRG nonlinear algorithm. It is seen that more effective pultrusion processes have been obtained with utilization of the full set of internal controlled electrical cartridges and especially with an application of the constraint prohibited resin flow from the die exit on the profile surface, namely $\alpha^{exit}_{surf} \geq 0.7$. An increase of allowed degrees of cure till the values used in industrial shops now, increase the energy consumption by 43% and, if this constraint requires the degree of cure higher 0.7 for entire profile cross-section, by 27%. At the same time, it also decreases the process productivity, since the pull speed reduced considerably. Applying set-up consisting of 4 cartridge pairs, an effective die heating appears, when cartridges are absent in second after first or second to last holes in the die, but applying set-up consisting of 3 cartridge pairs – in the first and last die holes. It is necessary to note that optimal process parameters, as well as higher process effectiveness, has been obtained for higher surrounding temperatures in the workshop.

Parameters	Min value	Max value	$\alpha^{exit}_{surf} \geq 0.7$			$\alpha^{exit} \geq 0.7$			$\alpha^{exit} \geq 0.95$		
			5 pairs	4 pairs	3 pairs	5 pairs	4 pairs	3 pairs	5 pairs	4 pairs	3 pairs
Design variables											
V_{pull} [cm/min]	20	45	**45.0**	40.7	45.0	25.5	23.4	26.6	20.3	20.1	24.8
T_{cont} [°C]	115	150	**139**	140	146	143	136	142	138	140	145
T_{room} [°C]	10	40	**40**	40	40	40	39	40	35	40	40
H_1	-,1,2,3,4,5		**-**	4	1	-	4	1	-	2	1
H_2	-,1,2,3,4,5		**-**	-	5	-	-	5	-	-	5
Behaviour functions											
T_{surf} [°C]		160	**139**	140	144	147	140	145	143	148	149
T_{cent} [°C]		160	**150**	149	147	159	148	153	155	157	160
α_{surf}	0.95		**0.95**	0.95	0.95	0.96	0.95	0.97	0.98	1.00	0.99
α_{cent}	0.95		**1.00**	0.99	0.96	0.95	0.95	0.95	0.95	0.95	0.96
α^{exit}_{surf}	0.70		**0.81**	0.76	0.73	0.97	0.82	0.84	0.95	0.95	0.95
Objective function											
Energy [W/m]			**15.0**	16.5	17.0	19.1	20.1	19.8	21.5	24.5	21.4

Table 8: Optimization results.

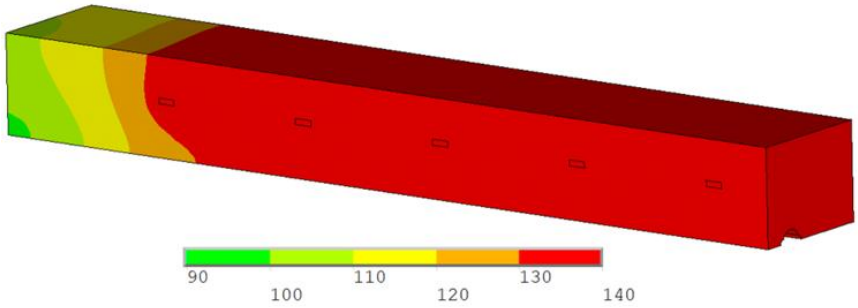

Figure 4: Temperature distribution in the die for an optimal solution.

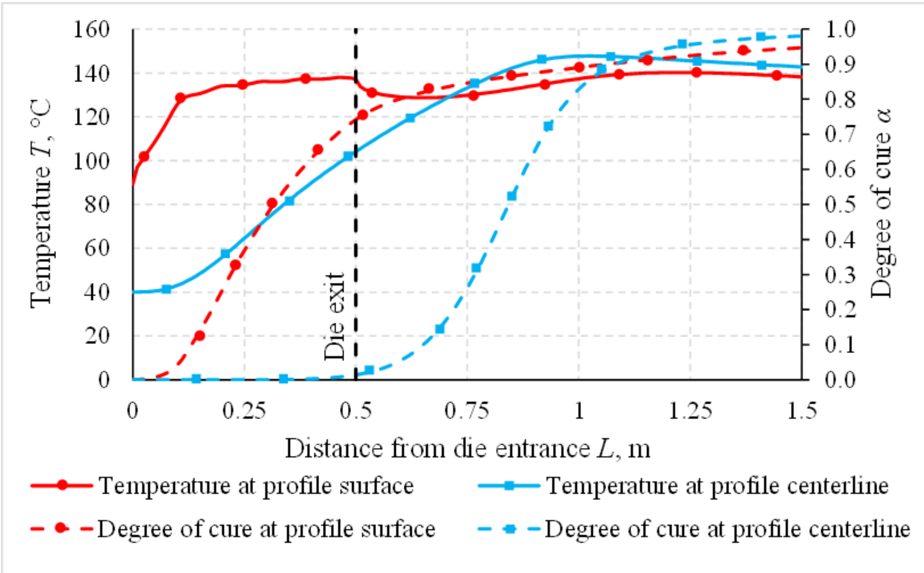

Figure 5: Temperature and degree of cure distribution on profile surface and centreline for an optimal solution.

Figure 4 shows the temperature field in the die for the optimal solution, where a very uniform distribution is observed. Temperature and degree of cure distribution on the profile surface and centreline for an optimal solution are presented in Figure 5. Since non-direct optimization methodology has been applied, the optimal solution has been verified by an additional finite element analysis in the optimal point. Table 9 demonstrates a slight difference between optimized and numerical solutions indicating high accuracy of optimization procedure.

An effectiveness of the developed pultrusion process with energy consumption of 15.0 W/m is estimated by its comparison with the effectiveness of physical process in industrial shop (24.1 W/m) [14] and optimized technology utilizing external platen heaters (16.2 W/m) [15]. In this case the present technology requires by 61% less electrical energy than are used for qualitative production of 1m profile in the physical process and by 8% less electrical energy than are used in optimized pultrusion process with external platen heaters.

5 pairs of heaters			
Parameters	Optimization	FE analysis	Difference [%]
Design variables			
V_{pull} [cm/min]	45.0		
T_{cont} [°C]	139		
T_{room} [°C]	40		
Behaviour functions			
T_{surf} [°C]	139	140	0.7
T_{cent} [°C]	150	148	1.4
α_{surf}	0.95	0.95	0.0
α_{cent}	1.0	0.98	2.0
α_{surf}^{exit}	0.81	0.74	9.5
$k_{t\Sigma}$	1.01	1.02	1.0
Objective function			
Energy [W/m]	15.0	15.1	0.7

Table 9: Validation of optimal results.

5 Conclusions

Non-direct optimization methodology based on the planning of experiments and response surface technique has been developed and successfully applied for the design of effective pultrusion process with a temperature control of internal heating cartridges. To optimize the present manufacturing process for all possible combinations of heater pair's location, three separate optimization problems have been formulated and solved for 5, 4 and 3 cartridge pairs used for a die heating. The high reliability of the optimization results has been confirmed by using three different optimisation solvers which gave the same parameters of optimised process. The lower energy consumption has been achieved with utilization of the full set of internal controlled electrical cartridges and for higher temperature in industrial shop.

The comparison of effectiveness between the developed pultrusion process, physical process in industrial shop and optimized technology utilizing external platen heaters has demonstrated that applying the internal cartridge heaters is possible to reduce considerably the energy consumption of the physical process and slightly of the optimized process with external platen heaters.

Acknowledgements

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