

## NUMERICAL SIMULATION OF ADVANCED PULTRUSION PROCESSES WITH MICROWAVE HEATING

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**Keywords:** Pultrusion, Microwave Heating, Finite Element Method, Electromagnetic Model, Thermo-Chemical Model, Cylindrical Rod.

**Abstract.** *Pultrusion is a continuous and cost-effective process for a production of composite structural components with a constant cross-sectional area. This technological process could be made more effective applying instead of conventional heaters a high frequency electromagnetic energy source characterized by the fast, instantaneous, non-contact and volumetric heating. To provide better understanding of the microwave assisted pultrusion process, to support the pultrusion tooling design and process control, new simulation methodology consisting of two sub-models has been developed. Each of them is constructed by using the general-purpose FE software that results in considerable savings in development time and costs, and also makes available various modeling features of the FE package. In the first step the electromagnetic sub-model is used to evaluate the electric field distribution by solving the Maxwell's equations with the COMSOL Multiphysics. It is necessary to note that in this sub-model the transport phenomena is neglected since an influence of the pull speed of the processing material on the electric field distribution is negligible. The objective of simulations is to find the microwave field as homogeneous as possible inside the cured composite profile in the ceramic inlet. In the second step an absorption energy field in the composite material determined with the electromagnetic sub-model is used as a heating source in the pultrusion process modeled with the thermo-chemical sub-model. This simulation procedure is developed in ANSYS Mechanical environment and based on the mixed time integration scheme and nodal control volumes method to decouple the coupled energy and species equations. To demonstrate an application of the developed methodology for the design of technological process, the microwave assisted pultrusion of the cylindrical rod made of glass fibers Unifilo 4800 tex and polyester resin POLRES 305BV has been investigated.*

## 1 INTRODUCTION

Pultrusion is a continuous and cost-effective process for a production of composite structural components with a constant cross-sectional profile (Fig. 1). During pultrusion the fiber reinforcements are saturated with the resin in a resin tank and then continuously pulled through a heated die by a puller. Inside the die the resin gradually cures and solidifies to form a composite part with the same cross-section profile as in the die. At the final stage a traveling cut-off saw cuts the composite profile into desired lengths.

This technological process could be made more effective applying instead of conventional heaters a high frequency electromagnetic energy source characterized by the fast, instantaneous, non-contact and volumetric heating. It is necessary to note that at present time microwave heating [1] is successfully and widely used in different industrial curing processes [2, 3]. Due to the complexity of the multiphysical problem to be solved for a microwave assisted pultrusion process, initially these processes have been analyzed experimentally [4, 5]. A brief review of the potential for microwave heating in the pultrusion manufacturing processes of fiber reinforced composites is presented in paper [6]. Recently, due to the rapid development of the finite element software for a solution of multiphysical problems, a computational modeling of the microwave assisted pultrusion processes has started. In paper [7] the finite element model and corresponding analysis have been developed for the microwave assisted pultrusion process of a fiberglass-epoxy cylindrical profile with the diameter of 5 mm. Several die external radius and two different sets of material die properties have been investigated to obtain an effective manufacturing process.

To provide better understanding of the microwave assisted pultrusion process, to support the pultrusion tooling design and process control, new simulation methodology consisting of two sub-models are developed. Each of them is constructed by using the general-purpose FE software that results in considerable savings in development time and costs, and also makes available various modeling features of the FE package. In the first step the electromagnetic sub-model is used to evaluate the electric field distribution by using the COMSOL Multiphysics software. In the second step an absorption energy field obtained in the composite material is applied as a heating source in the thermo-chemical sub-model developed in ANSYS Mechanical environment to determine temperature and degree of cure fields in the pultruded composite. To demonstrate an application of the developed methodology for the design of technological process, the microwave assisted pultrusion of the cylindrical rod is investigated. Conditions of the advanced pultrusion process, and the temperature and degree of cure fields in the composite material, are determined for the design of modular pultrusion die consisting of microwave block with the ceramic inlet located at the entrance of the steel mould. To obtain desired characteristics of the investigated pultrusion process, an influence of the capacity of the absorption energy field, thermal insulation, preheating of steel mould, heating of resin bath and reduction of the steel mold length on the parameters of pultrusion process are studied.

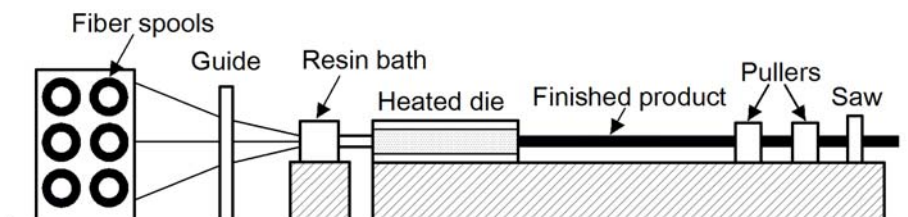


Figure 1: Pultrusion process.

## 2 STATEMENT OF THE PROBLEM

For a numerical simulation of the microwave assisted pultrusion process it is necessary to solve two coupled multiphysical problems - electromagnetic and thermo-chemical. The electromagnetic problem is solved with the purpose to determine the electric field distribution and as the result to obtain the absorbed energy field in the composite material which will be used later as a heating source in the subsequent thermo-chemical problem. Solving the last problem, the temperature and degree of cure fields in the pultruded composite could be estimated.

Using the common approach of a harmonic oscillating electric field  $\vec{E}$

$$\vec{E}(\vec{r}, t) = \vec{E}(\vec{r}) \cdot e^{2\pi i f t} \quad (1)$$

where  $\vec{r}$  is the location vector,  $t$  is a time and  $f$  is the microwave frequency, Maxwell's equations could be written as following

$$\nabla \times \nabla \times \vec{E}(\vec{r}) - \varepsilon_0 \mu_0 (2\pi f)^2 \varepsilon_r \vec{E}(\vec{r}) = \vec{0} \quad (2)$$

where  $\varepsilon_0$  is the vacuum permittivity and  $\mu_0$  is the magnetic constant. This complex valued equation is solved numerically for the amplitudes of the electric field  $\vec{E}(\vec{r})$  with respect to the relative permittivity  $\varepsilon_r$ , which for loss dielectric materials like mixtures of glass fibers and polyester resin is a complex function of frequency  $f$ , temperature  $T$  and degree of cure  $\alpha$

$$\varepsilon_r(f, T, \alpha) = \varepsilon'(f, T, \alpha) - i \cdot \varepsilon''(f, T, \alpha) \quad (3)$$

It can be obtained by the cavity perturbation method [8] at fixed frequencies or Corbino probe measurements [9, 10] with variable frequency. After numerical solution of Equation (2), the absorbed microwave energy generated by dielectric losses could be obtained like in paper [11]:

$$Q(\vec{r}) = 2\pi f \varepsilon_0 \varepsilon'' |\vec{E}(\vec{r})|^2 \quad (4)$$

Knowing the absorbed energy field  $Q$  in the composite material, the following thermo-chemical problem consisting of three governing equations should be solved in the second step:

$$\left\{ \begin{array}{l} \rho c_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) - \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) - q_b = 0 \\ \bar{\rho} \bar{c}_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial x} \left( \bar{k}_x \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial y} \left( \bar{k}_y \frac{\partial T}{\partial y} \right) - \frac{\partial}{\partial z} \left( \bar{k}_z \frac{\partial T}{\partial z} \right) - q - Q = 0 \\ \left( \frac{\partial \alpha}{\partial t} + u \frac{\partial \alpha}{\partial x} \right) = R_r \end{array} \right. \quad (5)$$

where  $T$  is the temperature,  $\rho$  and  $c_p$  are the density and specific heat of the tooling material,  $k_x$ ,  $k_y$ ,  $k_z$  are the thermal conductivities in  $x$ ,  $y$ ,  $z$  directions,  $q_b$  is the rate of energy exchange at the boundary,  $u$  is the pull speed,  $\bar{\rho}$  and  $\bar{c}_p$  are the lumped density and specific heat for the composite material,  $\bar{k}_x$ ,  $\bar{k}_y$ ,  $\bar{k}_z$  are the lumped thermal conductivities in  $x$ ,  $y$ ,  $z$  directions,  $q$  is the generative term related to the internal heat generation due to the exo-

thermic resin reaction,  $\alpha = H(t)/H_r$  is the degree of cure and  $H(t)$  is the amount of heat evolved during the curing up to time  $t$ . It is necessary to note that the first equation in the system (5) presents the energy equation for the tool, second – the energy equation for the composite moving in the pull direction and third – the species equation (transport equation) for the resin.

Heat transfer in the composite occurs as a result of the conversion of electromagnetic energy into heat, according to specific loss mechanisms, conduction and the generation of heat resulting from the exothermic chemical reaction initiated by the microwave heating. The generative term related to the internal heat generation due to the exothermic resin reaction could be written as:

$$q = V_r \rho_r H_r R_r \quad (6)$$

where  $V_r$  is the resin volume fraction,  $\rho_r$  is the resin density,  $H_r$  is the total heat of reaction and  $R_r$  is the rate of resin reaction determined as:

$$R_r(\alpha, T) = \frac{\partial \alpha}{\partial t} = \frac{1}{H_r} \frac{dH(t)}{dt} = K(T) \cdot f(\alpha) \quad (7)$$

where  $f(\alpha)$  depends on the resin properties and varies with the applied resin reaction model, and  $K(T)$  is defined by the Arrhenius relationship:

$$K(T) = K_0 \exp\left(-\frac{E}{RT}\right) \quad (8)$$

where  $R = 8.314$  J/mol·K is the universal gas constant. It is necessary to note that coefficients of the Arrhenius relationship: activation energy  $E$  and frequency factor  $K_0$  are the physical values and are determined by the Kissinger method or ASTM E 698 standard methodology from the DSC tests. Coefficients of the selected function  $f(\alpha)$  could be obtained in a simple way by a fitting of the experimental heat flow curves applying the least squares method.

The reinforcement is saturated with the resin before entering the heated die in pultrusion process. Therefore, it is reasonable to assume that the resin does not flow. In most cases the continuous model with lumped material properties are used for a simulation of the pultrusion processes. These properties are evaluated by the rule of mixture:

$$\begin{aligned} \bar{\rho} &= (1 - V_r) \rho_f + V_r \rho_r \\ \bar{c}_p &= \frac{(1 - V_r) \rho_f c_{pf} + V_r \rho_r c_{pr}}{\bar{\rho}} \end{aligned} \quad (9)$$

$$\bar{k} = \frac{k_f k_r \bar{\rho}}{(1 - V_r) \rho_f k_r + V_r \rho_r k_f}$$

where indexes  $f$  and  $r$  relates to the fibers and resin, respectively.

The above system (5) of three governing equations could be solved by using the prescribed initial and boundary conditions. It is assumed that at time  $t = 0$ , for a curing composite the temperature is  $T = T^0$  and the degree of cure is  $\alpha = \alpha^0$ , where index “0” denotes the initial values. The temperature of the composite at the die entrance and everywhere in the composite

at the first step of numerical algorithm is prescribed as the pre-heat resin temperature. The value of the degree of cure at the die entrance and everywhere in the composite at the first step of numerical algorithm is taken as zero or very small value depending on the resin curing kinetic model. In some pultrusion processes this value could be much higher in relation to the ambient room temperature which is used also as the boundary conditions for a die to describe the convection effect. It is important to note that the power flux at the entrance and exit of the composite in the die is specified as zero. The insulated boundary conditions could be applied also to reduce unnecessary heat losses and conserve energy in pultrusion processes.

### 3 NUMERICAL SIMULATION PROCEDURES

The developed algorithms simulate the phenomenon of microwave assisted pultrusion by solving the set of coupled electromagnetic, energy and species equations.

#### 3.1 Electromagnetic sub-model

The targeted application of an industrial microwave pultrusion process comes along with two major requirements: the usage of a cost-effective microwave source with a power output in the range of some kW and the capability to generate a homogeneous microwave field distribution for the complete products cross section. As magnetrons provide sufficient power output at fixed frequencies very economically it is obvious to use a magnetron as microwave source working at one of the ISM-frequency-bands (Industrial Scientific and Medical use).

The cross-section of the products is predetermined and the first step of the problem is to design the base model of a microwave set-up with an analytically known field distribution most suitable for the requested cross-section. In a second step, the model is improved numerically towards a homogeneous field distribution and high efficiency of the provided energy. This is performed adjusting the models dimensions and variation of some material properties until the target specifications are reached (Fig. 2). For the electromagnetic sub-model the FEM software package COMSOL Multiphysics is used with the optional radiofrequency (RF) module.

Against standard design drawings, for the simulation of microwave phenomena it is necessary to generate a design defining a closed (e.g. metallic) structure from electric point of view and allocate material properties in every region inside – especially the “air” typically left out as logical region in design drawings – is almost important for wave propagation. On the other hand, the thickness of solid metallic machinery parts is rarely important, because their surfaces usually are treated as perfect electric conductor. The microwave field is reflected at the surface and does not penetrate into the metallic regions – so they can be left out in the drawing.

According to the Nyquist-Shannon sampling theorem [12] for the discrete sampling of a wave function, the maximum element size  $x_{\max}$  of the mesh applied to the geometry has to fulfill  $x_{\max} < \lambda/2$  with  $\lambda$  - local wavelength. Local wavelength means that  $\lambda$  might be shortened by dielectric materials or influenced by conductive parts so that a good value for the maximum mesh element size is given by  $x_{\max} < \lambda_0/20\sqrt{\varepsilon_r}$  with  $\lambda_0$  - the wavelength in free space and  $\varepsilon_r$  - the relative permittivity.

For this mesh Equation (2) can be solved for the amplitude of the electric field  $\vec{E}(\vec{r})$  with respect to the local material properties from Equation (3) by iterative or direct solvers in the frequency domain with the fixed frequency  $f$  of the magnetron. The wave excitation and thereby the power input is applied by a so called “port” boundary condition provided by the

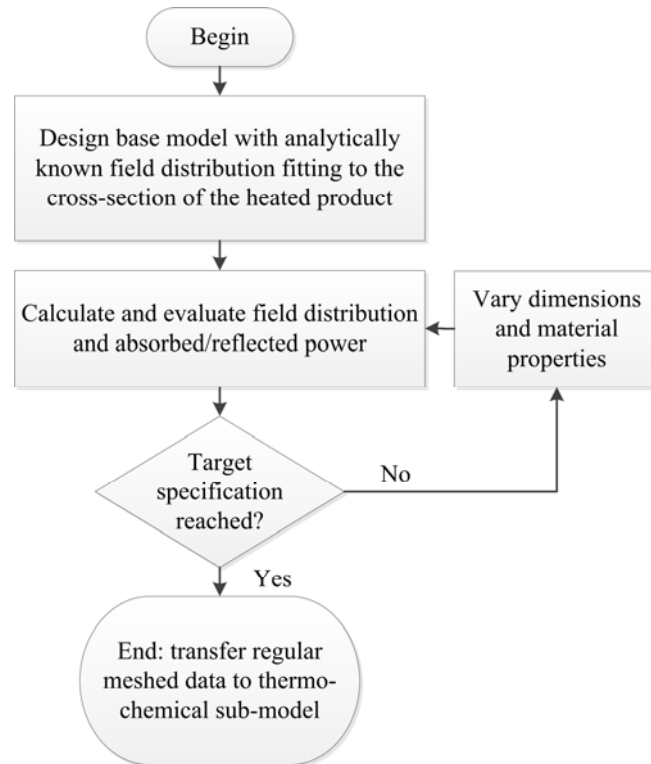


Figure 2: Flowchart of the numerical procedure based on COMSOL Multiphysics.

RF – module. Then the heating rate  $Q$  can be calculated using Equation (4) and evaluated regarding homogeneity and efficiency.

### 3.2 Thermo-chemical sub-model

This simulation procedure is developed in ANSYS Mechanical environment and is based on the mixed time integration scheme and nodal control volumes method to solve simultaneously the coupled temperature state and degree of cure by using an iteration technique. A uniform finite element discretization is applied in the pull direction. The nodal control volumes are constructed based on the finite element mesh as presented in Figure 3. Centers of the control volumes coincide with the nodal points of the finite element. In the control volume the distribution of a field variable is assumed constant and its value is defined by the field variable calculated at the representative finite element node.

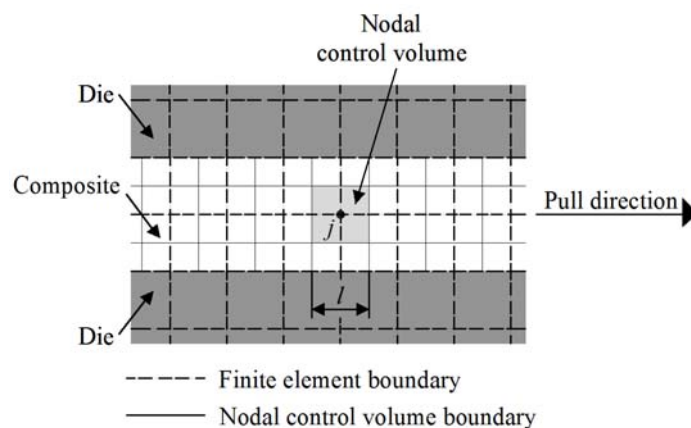


Figure 3: Finite element and nodal control volume meshes.

At the beginning it is assumed that the degree of cure has the same value  $\alpha^0$  in each nodal control volume of the composite. In most cases it equals zero. Then the transient thermal finite element analysis is performed to obtain an initial state of temperatures for each element. From the temperature field, the rate of cure for the nodal control volume  $j$  at any time step  $i$  is calculated outside the finite element software:

$$\frac{\partial \alpha_j^i}{\partial t} = \left[ \frac{\Delta \alpha_j^i}{\Delta t} \right] = K_0 \exp\left(-\frac{E}{RT_j^i}\right) f(\alpha_j^{i-1}) \quad (10)$$

For  $t > 0$ , the degree of cure can be obtained continuously by using the following relation:

$$\alpha_j^i = \alpha_j^{i-1} + \left[ \frac{\Delta \alpha_j^i}{\Delta t} \right] \Delta t \quad (11)$$

where  $\Delta t$  is the time step determined as:

$$\Delta t = \frac{1}{p} \cdot \frac{l}{u} \quad (12)$$

where  $l$  is the length of nodal control volume in the pulling direction,  $u$  is the pulling speed and  $p$  is the number of sub-steps. If the procedure of sub-stepping is not applied,  $p = 1$ . The exothermic effects of cure reaction are evaluated as the equivalent nodal heat power for a nodal control volume or node  $j$  by the following relation:

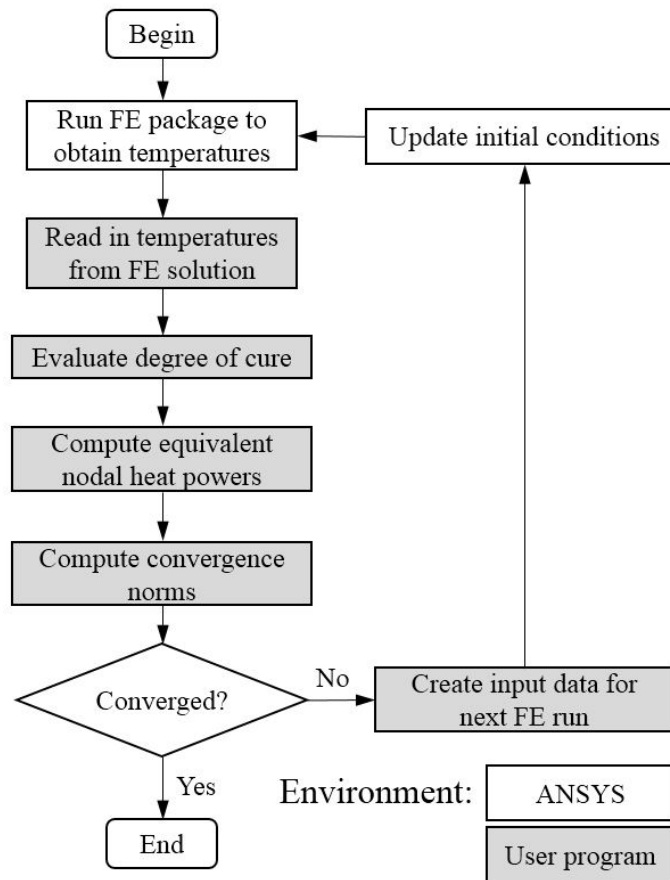


Figure 4: Flowchart of the numerical procedure based on ANSYS Mechanical.

$$q = V_r \rho_r H_{tr} R_r = V_r \rho_r H_{tr} \left[ \frac{\Delta \alpha_j^i}{\Delta t} \right] \quad (13)$$

These values will be applied to calculate the temperature field for a new step of iteration. Thereby, a movement of the resin-saturated composite is simulated by shifting the temperature and degree of cure fields after each calculation step. It is necessary to note that at the entrance of the die, the degree of cure remains unchanged and equals to  $\alpha^0$  at any step of iterations. In general, the algorithm can be summarized as a flowchart presented in Figure 4.

#### 4 MICROWAVE ASSISTED PULTRUSION OF CYLINDRICAL ROD

To demonstrate an application of the developed methodology for the design of technological process, the microwave assisted pultrusion of the cylindrical rod with the diameter of 16 mm and made of glass fibers Unifilo 4800 tex and polyester resin POLRES 305BV has been investigated.

##### 4.1 Analysis with electromagnetic sub-model

In the present case, the base model has to provide a symmetric cylindrical field distribution with an extended maximum of electrical field covering the products diameter. As starting point, an electric maximum of a standing wave pattern in a shorted rectangular waveguide section is used. To minimize reflection losses the waveguide has been tapered to the dimensions of the pultrusion die. The centerpiece of the microwave system consists out of a ceramic part ( $ZrO_2$ ) with a 16 mm hole, which has been inserted as a section into the metal pultrusion die. The objective was that the microwave field inside the hole and therefore inside the rod running through that hole is as homogenous as possible. The Zirconium oxide has a very high real part of the permittivity  $\epsilon'$ , which shortens the wave length of the microwaves. Therefore a magnetron of frequency 915 MHz and a waveguide WR 975 have been chosen.

Figure 5 shows the scheme of the electromagnetic sub-model for microwave pultrusion with the ceramic insert and coupling of the microwave to the ceramic part with a waveguide. The different color has indicated the different parts and the materials. Dark blue indicates steel (pultrusion die), light blue - air (waveguide), red - ceramic (insert) and green - product (rod). The dielectric properties  $\epsilon_r$  of the glass fiber/polyester resin composition have been measured before with a cavity perturbation method versus temperature and mean values taken at a temperature of  $T=60$  °C have been used for the calculation of the electric field distribution.

Running through the optimization loop is shown in Figure 2 several times, the shape of the ceramic inlay has been adjusted to achieve a homogeneous field distribution inside the rod and a minimized power reflection. The materials and properties applied to the domains are specified in Table 1 and the boundaries - in Table 2.

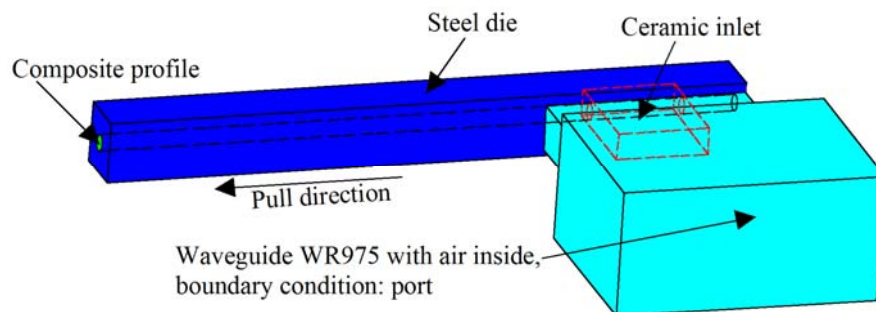


Figure 5: Scheme of the microwave model.



Property	Symbol	POLRES 305BV + Unifilo 4800 tex	Zirconia ceramic	Steel 40Cr	Air (volume in waveguide)
Dielectric constant	$\varepsilon'$	5.7	29	Perfect electric conductor	1
Dielectric loss	$\varepsilon''$	0.32	0.2		0

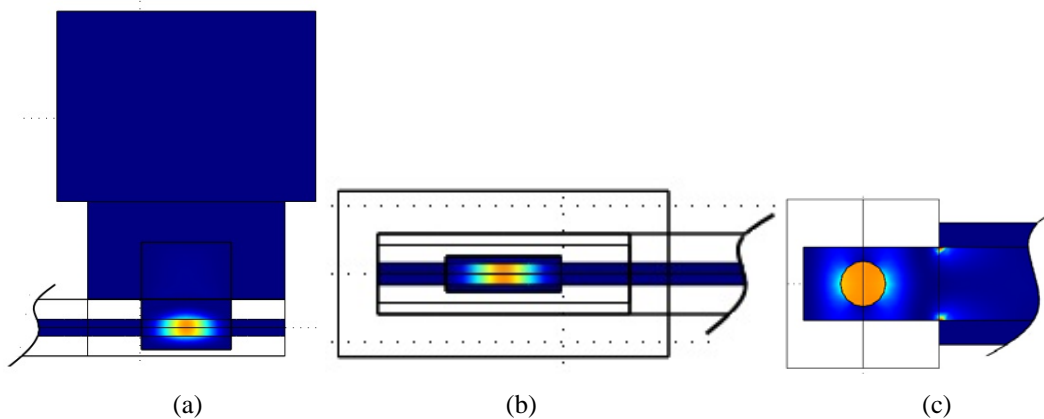
Table 1: Parameters of the electromagnetic sub-model.

Boundary	Material	Property
Port	Air	TE <sub>10</sub> mode for rectangular waveguide power $P = 1$ W (scalable)
Surrounding areas (die, waveguide)	Steel 40Cr	perfect electric conductor
Rod	POLRES 305BV + Unifilo 4800 tex	open circular ports

Table 2: Boundaries for the electromagnetic sub-model.

Figure 6 shows the distribution of the resulting heating rate  $Q$  in different 3D- and cross-sectional views for the optimized geometry of the ceramic inlay. In Figures 3a and 3b it is obviously, that only the rod inside - the ceramic insert is heated. The microwave coupling and the pultrusion die are not heated by the microwave. Outside of the ceramic insert the microwave field is close to zero. Figure 3c shows the cross-section of the heating rate in the die and the waveguide. The heating rate is homogeneously concentrated in the rod. Additionally a small heating effect inside the ceramic material itself gets visible.

In detail the power density in the cross-section of the rod is about  $7000 \text{ W/m}^3$  inside the ceramic insert but outside the rod it is between  $200$  and  $800 \text{ W/m}^3$  (Fig. 7). The deviation of the power density is low, therefore the heating is homogenous. The power density is concentrated to the cross-section of the rod. Figure 7 shows the power density in the cross-section of the ceramic pultrusion die. The power is concentrated to about  $1.6 \text{ cm}$  along the rod with a variation of about  $7\%$ .


 Figure 6: Distribution of the heating rate  $Q$ : a) top-view, b) side-view, c) cross-section.

## 4.2 Analysis with thermo-chemical sub-model

The thermo-chemical analysis means determination of the temperature and degree of cure fields in the composite material travelling in the pultrusion die. In our case the absorption energy field in the composite material determined with COMSOL Multiphysics is used as a heating source in the pultrusion process modeled with ANSYS Mechanical.

The advanced pultrusion die consists of microwave block with the ceramic inlet located at the entrance of the steel die (Fig. 8). The thermal properties of steel material used for an advanced die production is given in Table 3. Table 4 includes the thermal properties of ceramic material.

Heating of the composite profile is realized by using an absorption energy field obtained by COMSOL Multiphysics. It is simulated only in the composite material within boundaries of the ceramic inlet. Distribution of the absorption energy in the cross-section of the profile is constant (Fig. 7) but in the longitudinal direction varies accordingly to the law demonstrated in Figure 9. Integrating the curve presented in Figure 9 and taking into account area of the profile cross-section, it is possible to obtain the total absorption energy which is equal to 100.2 W. The simulated absorption energy field with the total value of 95.8 W is shown in Figure 10. It is necessary to note that temperature control is not applied in this case, and energy source is working continuously. Conditions of the pultrusion process are presented in Table 5.

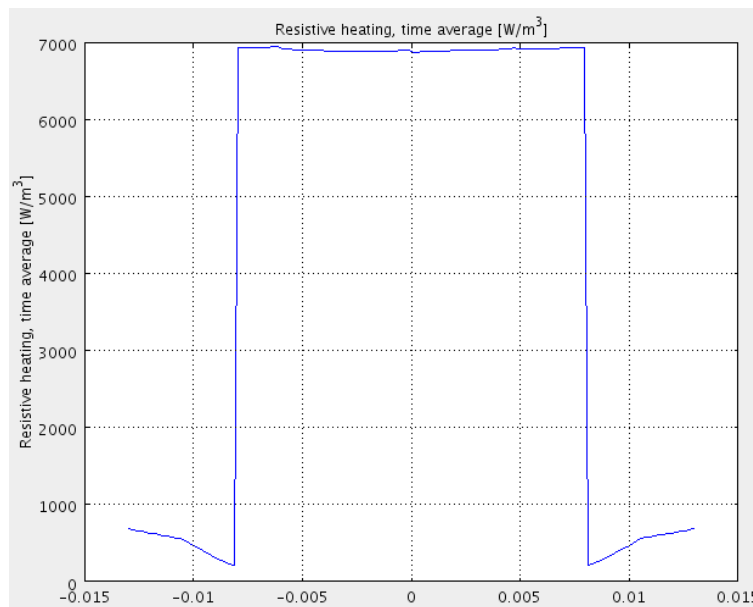


Figure 7: Power density in the cross-section of the ceramic pultrusion die.

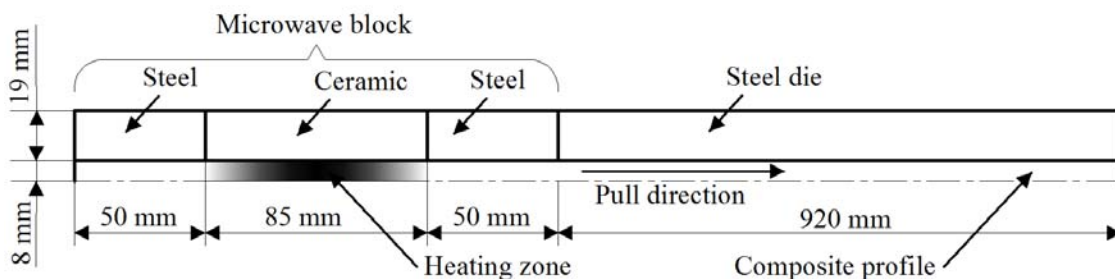


Figure 8: Scheme of the advanced pultrusion die.

The materials used for a production of the cylindrical rod are glass fibers Unifilo 4800 tex and polyester resin POLRES 305BV. The resin volume content in the pultruded material is 40% (resin mass fraction 22.6%). The thermal properties of the applied materials are given in Table 6. The rate of resin reaction is described by using the Kamal-Sourour curing kinetic model:

$$\frac{\partial \alpha}{\partial t} = \left( K_1 \exp\left(-\frac{E_1}{RT}\right) + K_2 \exp\left(-\frac{E_2}{RT}\right) \cdot \alpha^m \right) \cdot (1 - \alpha)^n \quad (14)$$

with the parameters presented in Table 7.

Property	Symbol (unit)	Steel 40Cr
Density	$\rho$ (kg/m <sup>3</sup> )	7820
Specific heat	$C$ (J/(kg·K))	460
Thermal conductivity	$k_x$ (W/(m·K))	66.6

Table 3: Thermal properties of die material.

Property	Symbol (unit)	Circonia ceramic
Density	$\rho$ (kg/m <sup>3</sup> )	6000
Specific heat	$C$ (J/(kg·K))	418
Thermal conductivities	$k_x$ (W/(m·K))	2

Table 4: Thermal properties of ceramic inlet.

Name	Value	Unit
Room and resin temperature in the bath	17 or 27 or 37	<sup>0</sup> C
Pulling speed	0.18 or 0.12 or 0.06	m/min

Table 5: Conditions of pultrusion process.

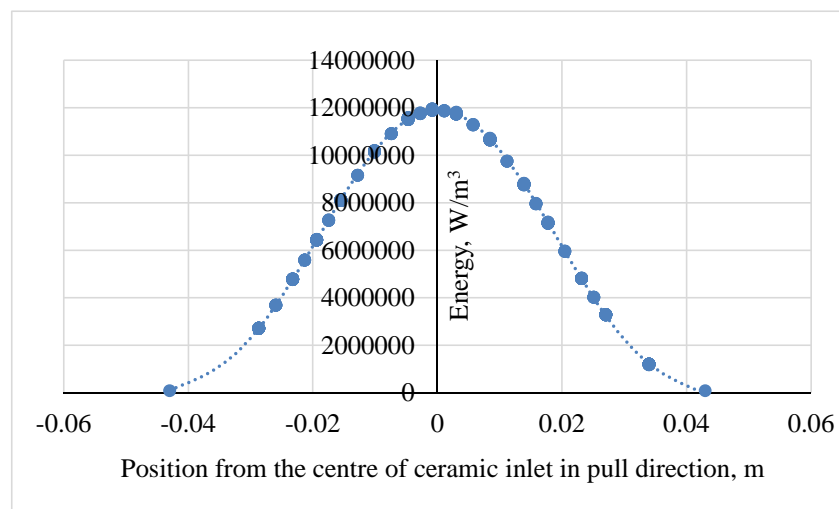


Figure 9: Distribution of the absorption energy in the longitudinal direction of the pultruded profile.

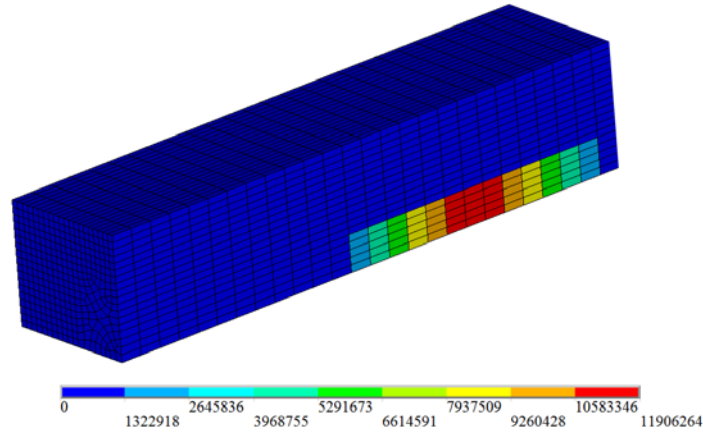


Figure 10: Simulation of the absorption energy in the pultruded profile.

The finite element model for a simulation of the cylindrical rod pultrusion has been created in ANSYS Mechanical by using 3-D thermal solid finite elements Solid 70. Using symmetry of the simulated domain, only a quarter of advanced pultrusion die is modeled. A fragment of the finite element model is presented in Figure 11. The finite element mesh is regular in pull direction and has 221 elements along the profile. The total number of finite elements is 74258 (3978 for the composite, 58512 for the die, 9728 for the steel part of microwave block and 2040 for the ceramic part). The time step of the solution depends on the pull speed. It is equal to 1.67 s for the speed of 18 cm/min, 2.5 s for the speed of 12 cm/min and 5 s for the speed of 6 cm/min. During this time the composite travels in the pull direction on the distance equals to the dimension of one finite element (5 mm). It is necessary to note that iterations (sub-steps) are not performed in the finite element analysis. Initial conditions are applied at time  $t=0$  when all nodal points of the composite have the room temperature and degree of cure equals to  $\alpha = 10^{-10}$ .

Property	Symbol (unit)	Unifilo 4800 tex	POLRES 305BV
Density	$\rho$ (kg/m <sup>3</sup> )	2500	1100
Specific heat	$C$ (J/(kg·K))	1235	1360
Thermal conductivity	$k_x$ (W/(m·K))	11	0.209
Thermal conductivity	$k_y$ (W/(m·K))	1	

Table 6: Thermal properties of pultruded material.

Parameter	Symbol (unit)	POLRES 305BV
Heat reaction	$H_{tr}$ (J/kg)	323074
Frequency factor	$K_1$ (s <sup>-1</sup> )	14289310986
Frequency factor	$K_2$ (s <sup>-1</sup> )	285.870
Activation energy	$E_1$ (J/mol)	85573
Activation energy	$E_2$ (J/mol)	33141
Order of the reaction	$n$	2.342
Order of the reaction	$m$	0.519

Table 7: Parameters of curing kinetic model.

Results of simulation, temperature and degree of cure obtained in the composite at the die exit in dependence on time, are presented in Figure 12 for room temperature 27°C and pull speed 12 cm/min. It is necessary to note that process is not steady-state after 55 min from the beginning of the numerical experiment in all tests for the degree of cure at the profile surface.

Results of simulation, temperature and degree of cure at the profile centerline and surface, are given for the time 50 min from starting of the pultrusion process in Figure 13 for room temperature 27°C and pull speed 12 cm/min. It is seen that, as opposed to conventional pultrusion process, now the curing comes considerably faster in the profile centerline than on the surface. So high degree of cure in the profile centerline is reached at the beginning of steel die already for the pultrusion process with pull speed equals to 18 cm/min and room temperature equals to 37°C. Moreover, full curing in the profile centerline happens already in the ceramic inlet for the pultrusion processes with pull speed equals to 6 cm/min and all examined room temperatures while the degree of cure at the profile surface has not reached high values.

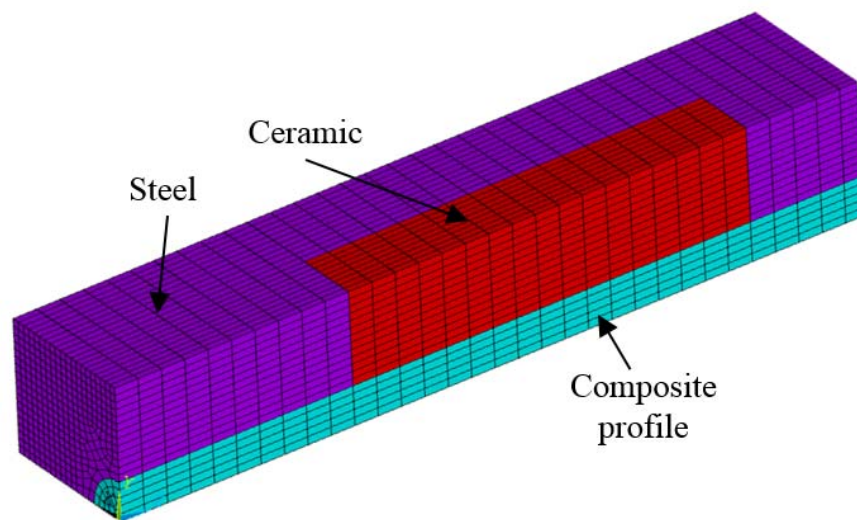


Figure 11: Fragment of the finite element model.

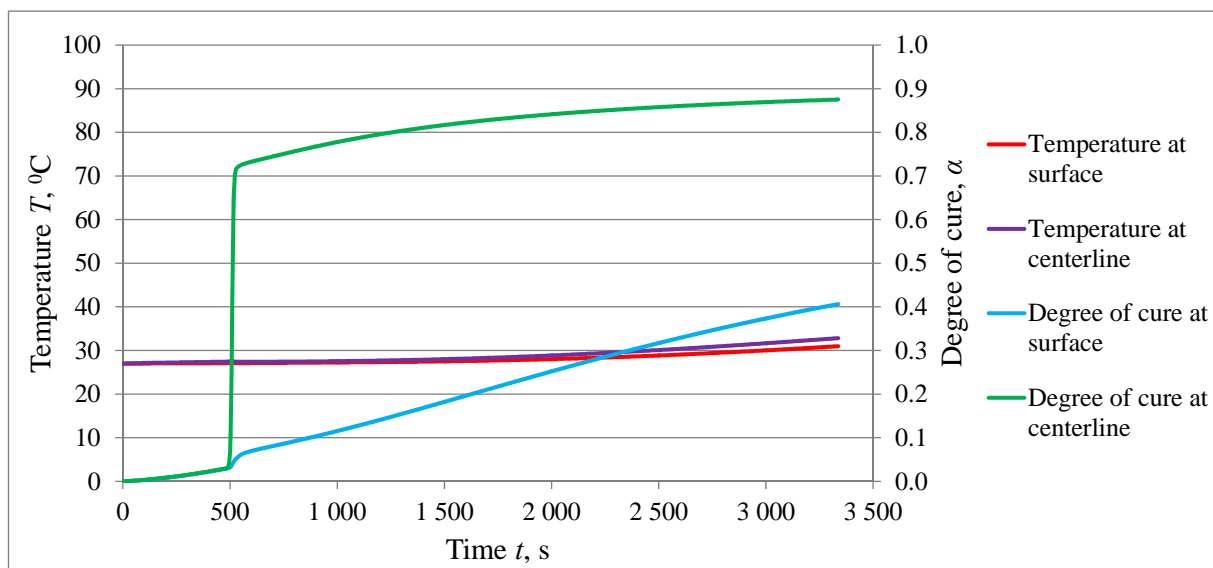


Figure 12: Dependence of temperature and degree of cure in the composite at the die exit on time for room temperature 27°C and pull speed 12 cm/min.

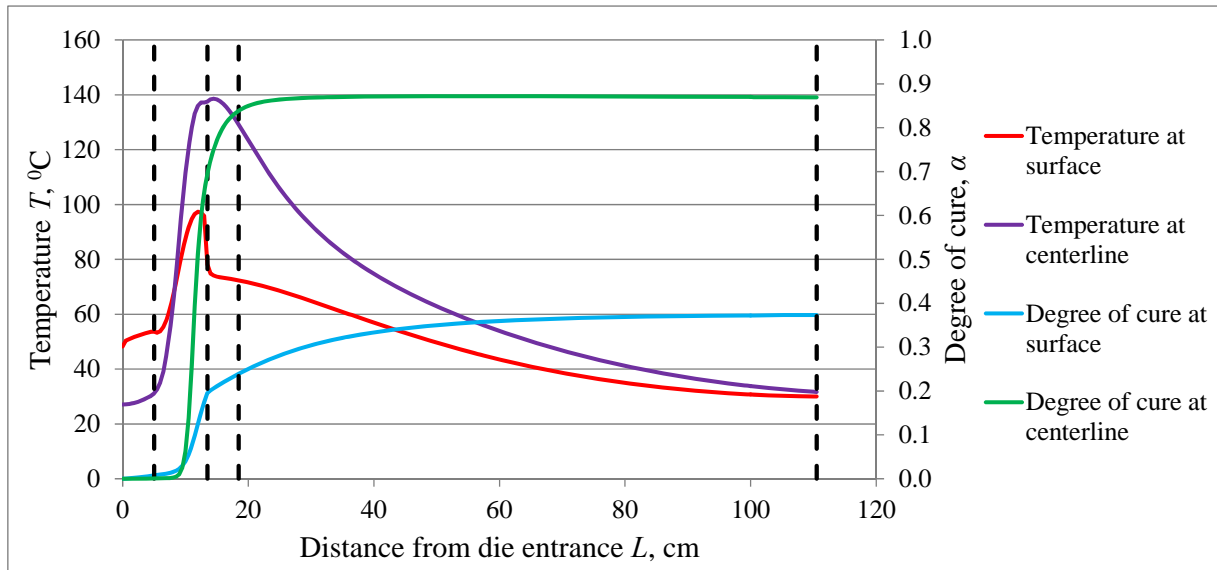


Figure 13: Temperature and degree of cure at the profile centerline and surface for room temperature 27°C and pull speed 12 cm/min.

To obtain the high value of the degree of cure at the profile surface in the advanced pultrusion die and to increase the pull speed of the process, improving by this way effectiveness of the pultrusion process, an influence of the following parameters of pultrusion process has been investigated:

- reduction in twice of steel die length,
- application of thermal insulation at all external surfaces of advanced pultrusion die (both steel die and microwave block),
- preheating of steel die, excluding microwave block, with the uniform temperature of 60°C before the beginning of pultrusion process,
- heating of resin bath (composite) with the temperature of 50°C for the full duration of pultrusion process.

An influence of the examined factors has been studied for the pultrusion process with the room temperature of 27°C and pulling speed of 12 cm/min. Simulation results are presented in Figures 14-17.

Figure 14 shows that reduction of steel die length has no effect on the degree of cure at the profile surface. However, any reduction of all important parameters has not been observed too. This fact could be used in the design of advanced pultrusion die for a saving of expensive die material. Figure 15 demonstrates that an application of thermal insulation at all external surfaces of advanced pultrusion die has increased considerably by 36% the value of the degree of cure at the profile surface. Figure 16 shows that only by preheating of steel die with the temperature of 60°C before the beginning of pultrusion process, it is possible to increase considerably by 29% the value of the degree of cure at the profile surface. These effects could be effectively used in the design of advanced pultrusion die. Figure 17 demonstrates that heating of resin bath has increased considerably by 44% the value of the degree of cure at the profile surface that could be used also in the design of advanced pultrusion die. However, it is necessary to note that an effectiveness of the pultrusion process could be not so high since the heating of resin bath is realized for the full duration of pultrusion process.

Joint influence of two factors having large effect on the degree of cure at the profile surface and on the process effectiveness, namely an application of thermal insulation and preheating of steel die, has been investigated additionally. Figure 18 shows that by preheating of

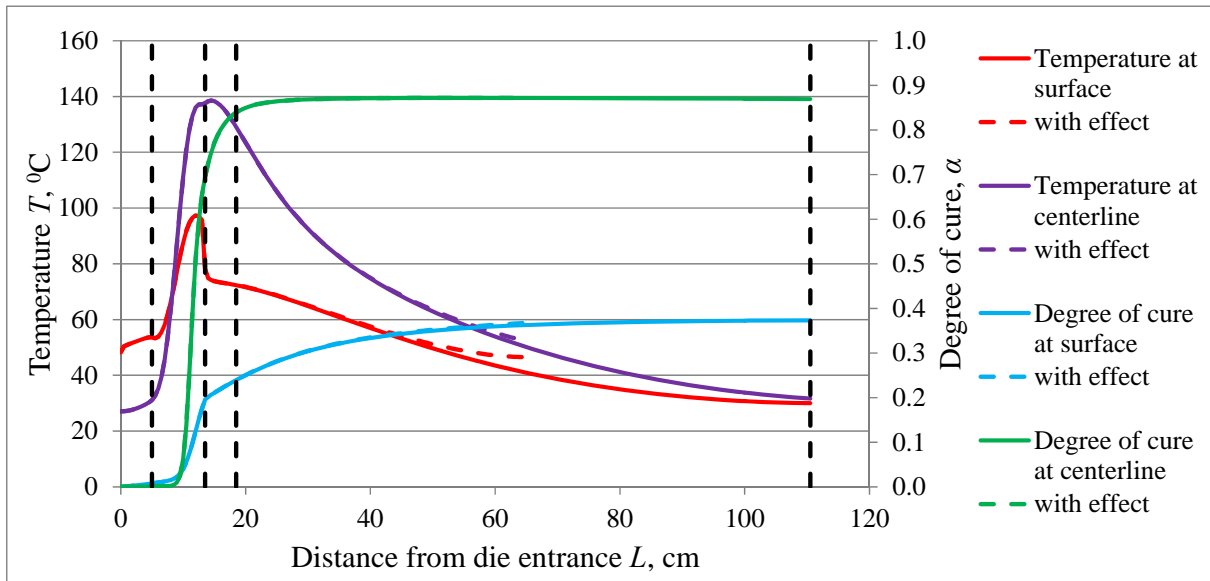


Figure 14: Temperature and degree of cure at the profile centerline and surface taking into account the effect of reduction of steel die length.

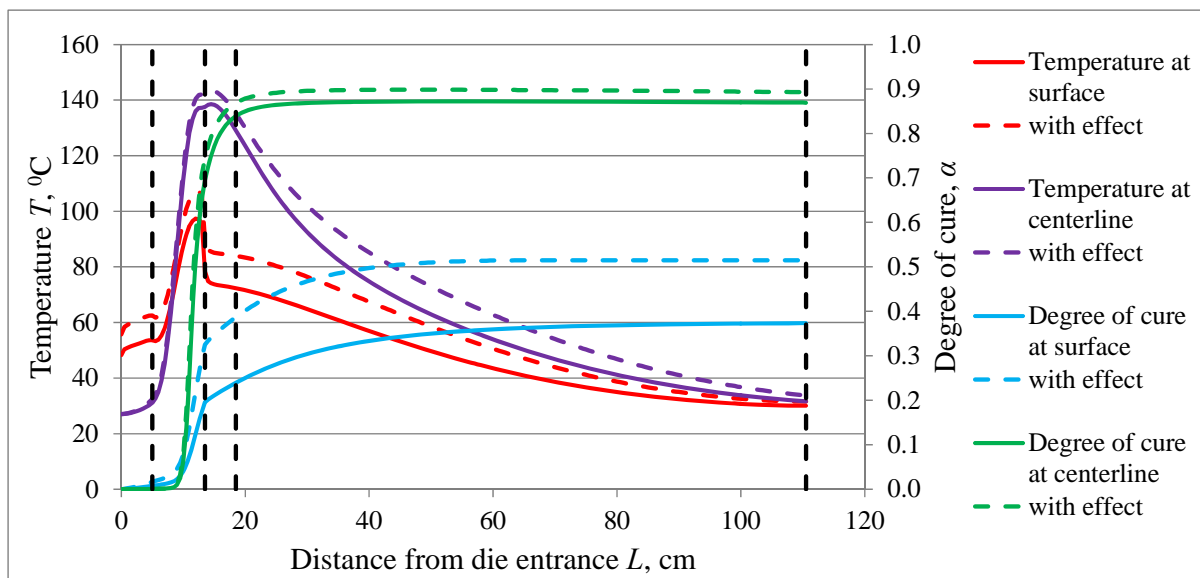


Figure 15: Temperature and degree of cure at the profile centerline and surface taking into account the effect of thermal insulation.

steel die with the temperature of  $60^{\circ}\text{C}$  before the beginning of pultrusion process and applying the thermal insulation, it is possible to increase considerably by 79% the value of the degree of cure at the profile surface. It is necessary to note that joint influence of two examined factors (79%) is higher than their separate influence summarized together (65%).

To obtain highest values of the degree of cure at the profile surface in the advanced pultrusion die, an influence of the capacity of the absorption energy field on the parameters of pultrusion process has been investigated. It is necessary to note that a distribution of the absorbed energy in the composite profile is not changed while its intensity has been increased proportionally with the coefficients: 1.5, 2.0 and 2.5. Figure 19 shows that the high value of the degree of cure at the profile surface could be reached already in the ceramic inlet of the microwave block. However, it is necessary to note that the material temperature in this case

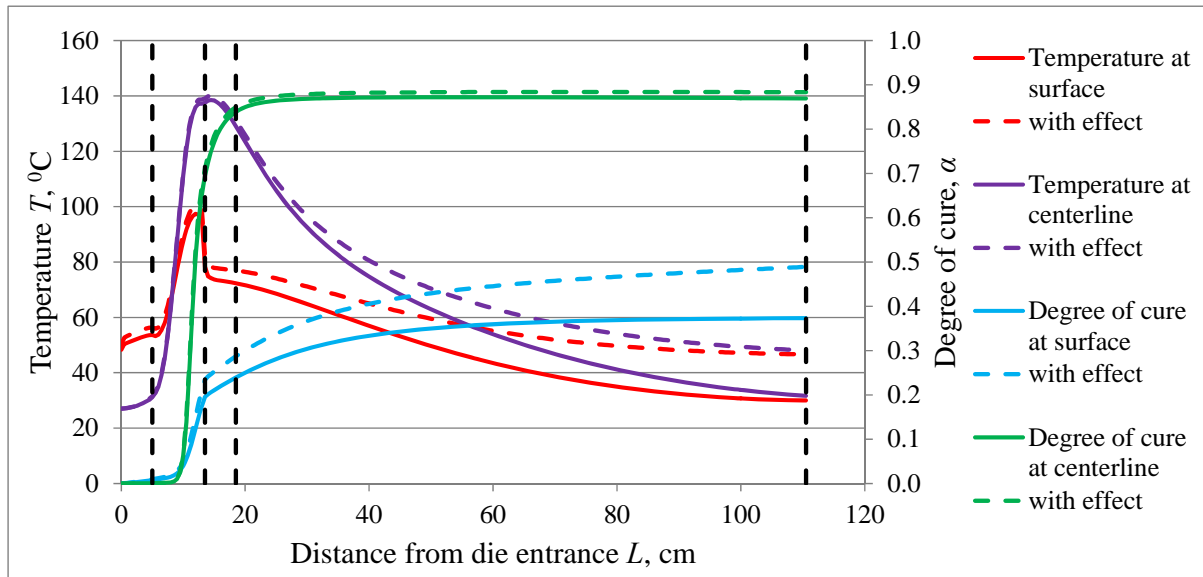


Figure 16: Temperature and degree of cure at the profile centerline and surface taking into account the effect of preheating of steel die.

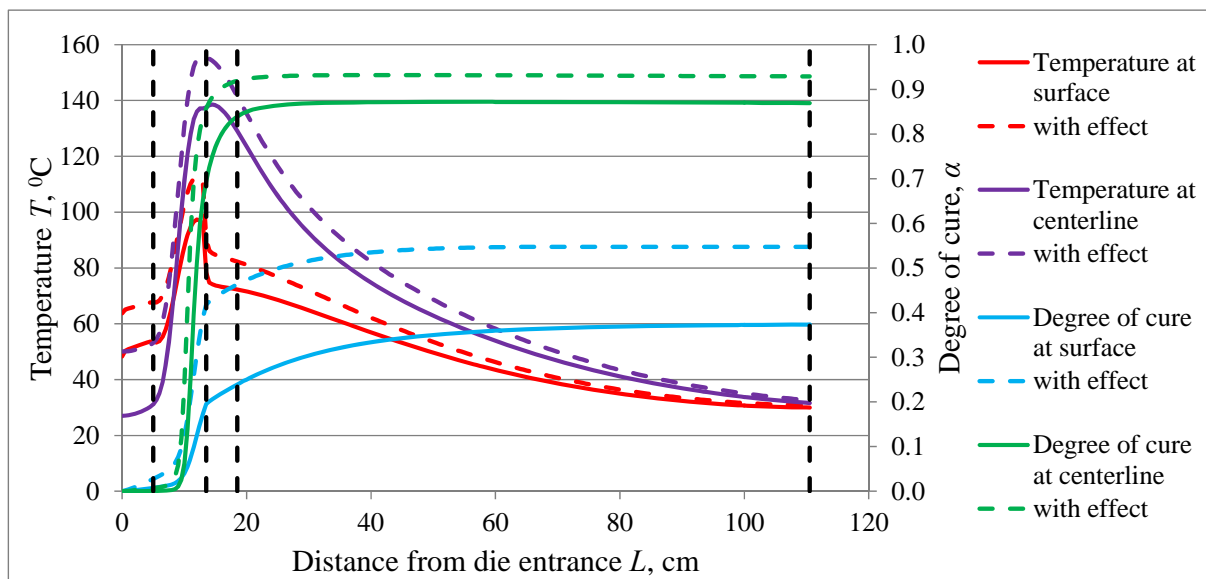


Figure 17: Temperature and degree of cure at the profile centerline and surface taking into account the effect of heating of resin bath.

could be higher than allowable resin temperature. To avoid overheating of the resin, the pulling speed should be increased in the same time that will contribute to the considerable increase of an effectiveness of the microwave assisted pultrusion process.

## 5 CONCLUSIONS

To understand the microwave assisted pultrusion process, to support the pultrusion tooling design and process control, new simulation methodology based on COMSOL Multiphysics and ANSYS Mechanical has been developed. This approach has been constructed by using the general-purpose FE software that results in considerable savings in development time and costs, and also makes available various modeling features of the FE packages.



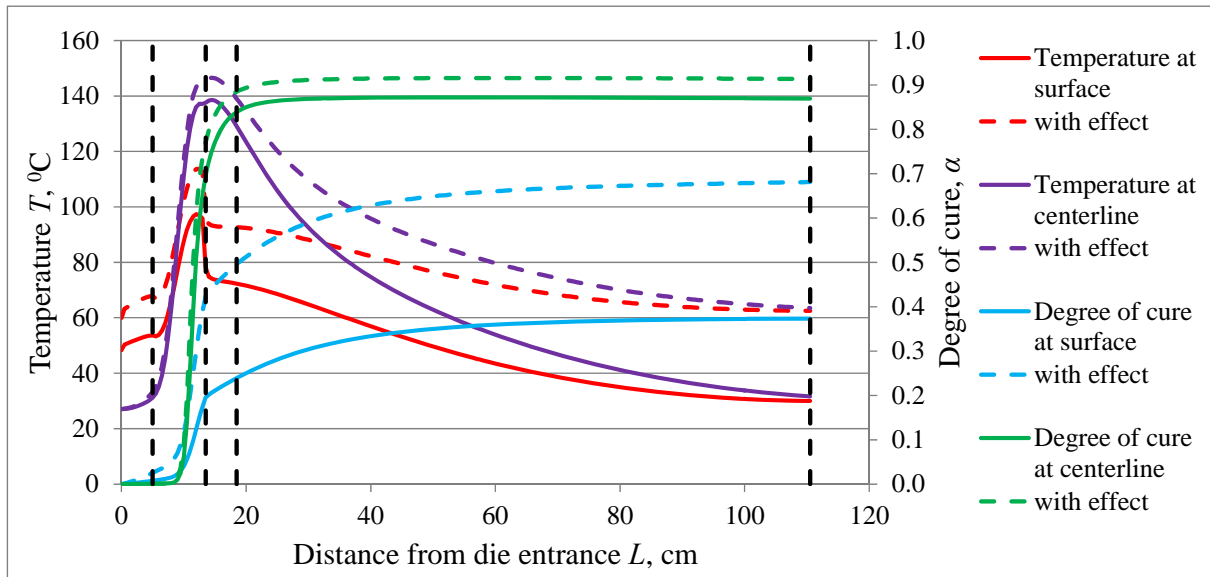


Figure 18: Temperature and degree of cure at the profile centerline and surface taking into account the effects of thermal insulation and preheating of steel die.

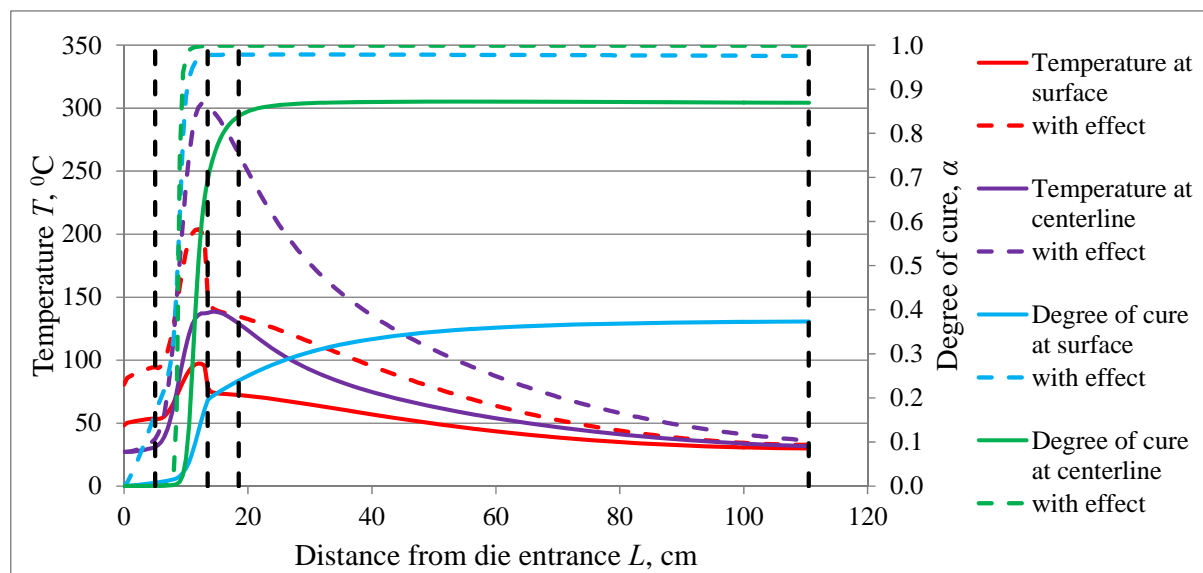


Figure 19: Temperature and degree of cure at the profile centerline and surface with the intensity coefficient of the absorption energy field equals to 2.5 (pull speed: 12 cm/min).

Conditions of the microwave assisted pultrusion process, and the temperature and degree of cure fields in the composite material, have been determined for the design of advanced pultrusion die. Simulation results show that the developed technology gives the possibility to ensure a homogeneous curing of the composite profile and to obtain high values of the degree of cure in the cured composite.

To improve an effectiveness of the microwave assisted pultrusion process, an influence of different process parameters has been additionally investigated. Based on the obtained results, the following recommendations could be done for technologists designing advanced pultrusion dies:

- More effectively is to apply the thermal insulation at all external surfaces of advanced pultrusion die or to preheat the steel die before the beginning of pultrusion process if the highest value of the degree of cure at the profile surface is required.

- To obtain largest effect on the degree of cure at the profile surface and on the process effectiveness, the joint application of both factors, namely an application of thermal insulation and preheating of steel die, should be realized.
- The heating of resin bath could be used also to obtain the highest values of the degree of cure at the profile surface. However, an effectiveness of the pultrusion process in this case is not so high since the heating of resin bath should be organized for the full duration of pultrusion process.
- The reduction of steel die length has no effect on the degree of cure at the profile surface. However, this effect could be used in the design of advanced pultrusion die for a saving of expensive die material.

## ACKNOWLEDGEMENTS

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