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RIGA TECHNICAL UNIVERSITY

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EFFECTIVENESS AND PRODUCTIVITY IMPROVEMENT OF CONVENTIONAL PULTRUSION PROCESSES

Summary of the Doctoral Thesis

RTU Press
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RIGA TECHNICAL UNIVERSITY
Faculty of Civil and Mechanical Engineering
Institute of High-Performance Materials and Structures

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The results presented in the Thesis are part of the European Regional Development Fund (ERDF) project No. 1.1.1.1/18/A/053, "An effectiveness improvement of conventional pultrusion processes".

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (PhD), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on 31 October 2025, at 14.00 at the Faculty of Civil and Mechanical Engineering of Riga Technical University, Ķīpsalas 6A Street, Room 546.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (PhD) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Endija Namsone-Sīle ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, four chapters, Conclusions, 62 figures, 30 tables, and 10 appendices; the total number of pages is 121, including appendices. The Bibliography contains 82 titles.

CONTENTS

1. REVIEW OF THESIS

1.1. Topicality of the theme

Pultrusion is a continuous process for the production of fibre-reinforced polymer composite profiles with a constant cross-section. It is an automated and cost-effective process with minimal waste of materials and the requirement of labour [1]. The origin and history of the pultrusion process began in the early 1950s with the first published patent in 1951, proposing a continuous manufacturing method of rod composite structures [2]. The conventional pultrusion process and the equipment employed are schematically represented in Fig. 1.1. During this automated process, reinforced fibres are pulled through a heated die, forming them into a fibre-reinforced polymer composite product.

Nowadays, fibre reinforced composites are used widely in different lightweight structures requiring high stiffness-to-weight and strength-to-weight properties and working under high operational loads. The pultruded profiles are replacing a lot of conventional materials used in a wide range of industries – transportation, civil constructions, wind energy, marine and aerospace. At the present time, pultrusion is one of the fastest-growing manufacturing processes within the composites market.

Although the pultrusion sector demonstrates healthy growth, a continuous increase in the cost of electricity could considerably reduce this movement or even stop it. The effectiveness and productivity of conventional pultrusion processes, preserving the quality of pultruded profiles and reducing their cost, could be improved by the process optimisation of the parameters of the pultrusion process or by the application of innovative heating sources instead of electrical resistances with high heat losses. For this reason, a new effective optimisation methodology, taking into account all the required parameters of the industrial pultrusion processes and ambient room temperature, and electromagnetic-thermo-chemical finite element models and algorithms, is developed.

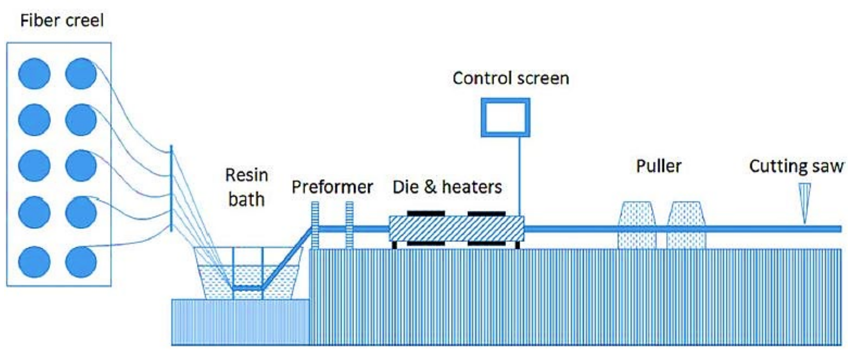


Fig. 1.1. Conventional pultrusion process [1].

1.2. The aim of the Thesis

The main aim of the Thesis is to improve considerably the effectiveness and productivity of conventional pultrusion processes, preserving the quality of pultruded profiles. It can be done by:

- the process optimisation and interactive technological map development;
- an application of innovative heating sources instead of electrical resistances with high heat losses and development of innovative microwave-assisted pultrusion processes.

1.3. Research objectives

- Development of new electromagnetic and coupled electromagnetic-thermo-chemical finite element models and algorithms for the design of advanced pultrusion processes.
- Modification of existing thermo-chemical finite element models and algorithms for a solution of coupled electromagnetic-thermo-chemical problem and optimisation of industrial pultrusion processes.
- Formulation and solution of optimisation problems for an improvement of the effectiveness and productivity of conventional industrial pultrusion processes.
- Development of interactive technological maps to be used in an industrial shop by technologists.
- Development of a new microwave-assisted pultrusion process for the production of rod profiles.
- Estimation of the effectiveness and productivity of the developed advanced pultrusion process.

1.4. Research tools and methods

Research methods of the Thesis include:

- finite element software *ANSYS Mechanical*, *COMSOL Multiphysics*;
- *ANSYS* parametric design language programming;
- methods of response surface technique and experimental design;
- software *EDAOpt* (for optimisation);
- graphical tools of the *Microsoft Excel* program to represent the obtained results;
- solver tool of the *Microsoft Excel* program for the solution of optimisation problems.

1.5. Scientific novelty of the Thesis

In the Thesis, a new effective optimisation methodology, considering all the required parameters of the industrial pultrusion processes and ambient room temperature, is developed, employing the method of experimental design and response surface technique. More accurate and realistic process optimisation is achieved with the temperature control executed by the heater's switch-on and -off strategy.

A new microwave-assisted pultrusion process for the production of rod profiles is developed by solving a coupled electromagnetic-thermo-chemical problem. It is done by using the general-purpose finite element software, which results in considerable savings in development time and costs and makes available various modelling features of the finite element packages. The developed finite element models and algorithms allow to for preserve a dependence of dielectric material properties on temperature as it happens in real pultrusion processes.

1.6. Practical value of the Thesis

The results presented in the Thesis are part of the European Regional Development Fund (ERDF) project No. 1.1.1.1/18/A/053, "An effectiveness improvement of conventional pultrusion processes". The aim of the project is to improve the effectiveness of conventional pultrusion processes, preserving the quality of pultruded profiles and considerably reducing their cost as well as contributing to a healthier environment.

The Thesis has direct practical value since two industrial technological processes have been considerably improved. So, the pull speed of the industrial technological process producing two rod profiles in COMPOR Ltd. has been increased by 50–125 % and the energy consumption has been reduced by 20–33 % per one meter of pultruded profile, depending on the ambient room temperature, by using the developed interactive technological map. Moreover, the effectiveness and productivity of the industrial technological process producing rod profiles used in AIMPLAS have been increased by 3 and 5.5 times, respectively, by applying a microwave heating source instead of electrical resistances with high heat losses in the developed advanced pultrusion process.

1.7. Statements of the Thesis

The effectiveness (energy consumption) and productivity (pull speed) of conventional industrial pultrusion processes can be improved considerably by the application of the developed process optimisation methodology or by the application of innovative heating sources instead of electrical resistances and the development of advanced microwave-assisted pultrusion processes.

1.8. Approbation of the Thesis results and publications

The results of the Thesis have been presented in five international conferences and two seminars within the ERDF project. The results of the Doctoral Thesis have been discussed at a scientific meeting in the Institute of High-Performance Materials and Structures, Riga Technical University. Results of the Thesis have been published in 10 papers in international journals (indexed in *SCOPUS* database) and conference proceedings.

1.8.1. Publications

1. Namsone, E., Namsone, E., Šahmenko, G., Korjakins, A., **Namsone, E.** (2019). Research on Properties of Composites Based on Magnesium Binders. In: Environment Technology. Resources: Proceedings of the 12th International Scientific and Practical Conference, Rezekne, Latvia, pp. 192–197.
2. Barkanov, E., Akishin, P., **Namsone, E.**, Bondarchuk, A., Pantelelis, N. (2019). In-Line Characterization of Pultruded Profiles. In: AIP Conference Proceedings: The 9th International Conference on Structural Analysis of Advanced Materials, Ischia, Italy, pp. 020003-1–020003-4.
3. **Namsone, E.**, Ermakov, D. (2019). Lamina Properties Non-destructive Characterisation of Asymmetric Carbon Fiber Reinforced Laminates. In: IOP Conference Series: Materials Science and Engineering, 4th International Conference on Innovative Materials, Structures and Technologies, Riga, Latvia pp. 1–9.
4. Namsone, E., Šahmenko, G., Namsone, E., **Namsone, E.**, Korjakins, A., Bajāre, D. (2019). Experimental Investigation on Foamed Concrete Produced Using a Planetary Ball Mill. In: Modern Building Materials, Structures and Techniques: Selected Papers of the 13th International Conference, Vilnius, Lithuania, pp. 16–17.
5. **Namsone, E.**, Arshanitsa, A., Morozovs, A. (2020). Analysis of Curing Kinetic Models for Polyester Resin C-L ISO 112 G. Key Engineering Materials, Vol. 850, pp. 70–75.
6. Barkanovs, E., Akishin, P., **Namsone, E.**, Bondarchuk, A., Pantelelis, N. (2020). Определение характеристик пултрузионных процессов с контролем температуры в реальном времени. Механика композитных материалов/Mechanics of Composite Materials, Vol. 56, pp. 203–224.
7. Barkanov, E., Akishin, P., **Namsone, E.**, Auziņš, J., Morozovs, A. (2020). Оптимизация процессов пултрузии для промышленного применения. Механика композитных материалов/Mechanics of Composite Materials, Vol. 56, pp. 1015–1036.

8. Barkanov, E., Akishin, P., **Namsone, E.**, Bondarchuk, A., Pantelelis, N. (2020). Real Time Characterization of Pultrusion Process with a Temperature Control. Mechanics of Composite Materials, Vol. 56, pp. 135–148.
9. **Namsone, E.** (2021). Investigation of Residual Stresses and Deformations of a Pultruded Thin Beam Profile. In: Environment, Technology, Resources: Proceedings of the 13th International Scientific and Practical Conference, Rezekne, Latvia, pp. 232–235.
10. **Namsone, E.**, Arshanitsa, A. (2021). An effectiveness Improvement of the Pultrusion Process for a Production of Thin-Walled Rectangular Profile. Solid State Phenomena, Vol. 320, pp. 161–165.
11. **Namsone, E.**, Ermakov, D. (2021). Characterization of Woven Composite Material Properties by Using an Inverse Technique Based on Vibration Tests. Key Engineering Materials, Vol. 930, pp. 113–118.
12. Barkanov, E., Akishin, P., **Namsone, E.**, Auziņš, J., Morozovs, A. (2021). Optimisation of Pultrusion Process for an Industrial Application. Mechanics of Composite Materials, Vol. 56, pp. 697–712.
13. Barkanov, E., Akishin, P., **Namsone-Sile, E.** (2022): Effectiveness and Productivity Improvement of Conventional Pultrusion Processes. Polymers, Vol. 14, pp. 841–851.
14. Barkanov, E., Akishin, P., **Namsone-Sile, E.**, Emmerich, R., and Graf, M. (2022). Finite Element Solution of Electro-Magnetic-Thermo-Chemical Problem in Microwave Assisted Pultrusion Processes. Finite Elements in Analysis and Design, Vol. 208, pp. 1–8.

1.8.2. Conferences

1. Namsone, E., Namsone, E., Šahmenko, G., Korjakins, A., **Namsone, E.** Research on Properties of Composites Based on Magnesium Binders. 12th International Scientific and Practical Conference: Environment Technology. Rezekne, Latvia, 20–22 June 2019.
2. Barkanov, E., Akishin, P., **Namsone, E.**, Bondarchuk, A., Pantelelis, N. In-Line Characterization of Pultruded Profiles. The 9th International Conference on Structural Analysis of Advanced Materials. Ischia, Italy, 12–15 September 2019.
3. **Namsone, E.**, Ermakov, D. Lamina Properties Non-destructive Characterisation of Asymmetric Carbon Fiber Reinforced Laminates. 4th International Conference on Innovative Materials, Structures and Technologies. Riga, Latvia, 25–27 September 2019.
4. Namsone, E., Šahmenko, G., Namsone, E., **Namsone, E.**, Korjakins, A., Bajāre, D. Experimental Investigation on Foamed Concrete Produced Using a Planetary Ball Mill. The 13th International Conference: Modern Building Materials, Structures and Techniques. Vilnius, Lithuania, 16–17 May 2019.

5. **Namsone, E.**, Arshanitsa, A., Morozovs, A. Analysis of Curing Kinetic Models for Polyester Resin C-L ISO 112 G. 60th International Scientific Conference: Materials Science and Applied Chemistry. Riga, Latvia, 24 October 2020.
6. **Namsone, E.**, Arshanitsa, A. An effectiveness Improvement of the Pultrusion Process for a Production of Thin-Walled Rectangular Profile. The 28th International Baltic Conference: Materials Engineering and Modern Manufacturing. Kaunas, Lithuania, 22-23 October 2020.
7. **Namsone, E.** Investigation of Residual Stresses and Deformations of a Pultruded Thin Beam Profile. The 13th International Scientific and Practical Conference: Environmental Technologies. Resources. Rezekne, Latvia, 17–18 June 2021.

1.8.3. Project seminars

1. Barkanov, E., Akishin, P., Namsone, E., Tatarinov, A. An Effectiveness Improvement of Conventional Pultrusion Processes. Riga, Latvia, 20 October 2020.
2. Barkanov, E., Akishin, P., Namsone-Sile, E., Tatarinov, A., Kovalov, A. An Effectiveness Improvement of Conventional Pultrusion Processes. Riga, Latvia, 22 March 2022.

1.8.4. Approbation of Thesis Results

1. Namsone-Sile, E. Effectiveness and Productivity Improvement of Conventional Pultrusion Processes (Tradicionālu pultrūzijas procesu efektivitātes un produktivitātes uzlabošana). Institute of High-Performance Materials and Structures, Riga Technical University, Riga, 18 June 2024.

2. STRUCTURE OF THE THESIS

The Thesis consists of five chapters.

1. **Chapter 1** is a short summary of scientific literature, describing the pultrusion process, numerical simulations, and optimisation methodologies.
2. **Chapter 2** presents the thermo-chemical, electromagnetic and coupled electromagnetic-thermo-chemical finite element models and algorithms developed for the design of microwave-assisted pultrusion processes.
3. **Chapter 3** formulates optimisation problems and solution methodology based on experimental design and response surface technique.
4. **Chapter 4** presents the design of microwave-assisted pultrusion processes and the evaluation of their effectiveness and productivity.
5. In **Chapter 5,** the obtained results are discussed, and recommendations are given for further research.

2.1. Literature review

This section of the Thesis is a literature review about pultrusion processes. Three main subjects are studied in the literature review: the conventional pultrusion processes, the microwave-assisted pultrusion processes and the optimisation of pultrusion processes. A brief review of numerical simulations of pultrusion processes is also given. However, fewer studies have been conducted on advanced microwave pultrusion processes and their simulations compared to conventional pultrusion processes.

2.2. Modelling of multi-physical problems

The section presents the developed thermo-chemical, electromagnetic and coupled electromagnetic-thermo-chemical finite element models and algorithms for a microwave-assisted pultrusion process.

Electromagnetic problem

An electromagnetic finite element model and algorithm are necessary to determine the electric field distribution and, as a result, to obtain the absorbed energy field in the composite material and ceramic die, which will be used later as a heating source in the subsequent thermo-chemical problem.

The electromagnetic field is described by the well-known Maxwell's equations, which in a differential form can be expressed in terms of electric $\vec{E}$ and magnetic $\vec{H}$ field intensities in the following way:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \ \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}, \ \nabla \cdot \vec{D} = \rho, \ \nabla \cdot \vec{B} = 0, \tag{2.1}$$

where

$\vec{B}$ – the magnetic flux density;

$\vec{D}$ – the flux density;

$\vec{J}$ – the current density;

ρ – the charge density;

t – time.

The corresponding constitutive relations have the following form:

$$\vec{B} = \mu\vec{H},\ \vec{D} = \varepsilon\vec{E},\ \vec{J} = \sigma\vec{E}, \tag{2.2}$$

where

μ – the magnetic permeability;

ε – the electric permittivity;

σ – the electric conductivity.

The magnetron harmonically oscillates the electromagnetic field at the fixed frequencies of 915 MHz or 2.45 GHz recommended by the International Telecommunications Union for Industrial, Scientific and Medical use. Solving numerically these Eqs. (2.1)–(2.2), an intensity of the electric field can be found.

$$\vec{E}(x,y,z,t) = \vec{E}(x,y,z)e^{i2\pi ft}, \tag{2.3}$$

where x, y, z are the components of the location vector, and $f$is the microwave frequency. Its values are used later for the determination of the absorbed energy field necessary for the thermo-chemical analysis.

To describe the dielectric losses, the electric permittivity is examined as a complex value:

$$\varepsilon^* = \varepsilon' - i\varepsilon''. \tag{2.4}$$

consisting of the electric permittivity itself, ε', and the corresponding loss factor ε''. Moreover, in pultrusion processes, this is a complex function of frequency f, temperature T and degree of cure α:

$$\varepsilon^*(f,T,\alpha) = \varepsilon'(f,T,\alpha) - i\cdot\varepsilon''(f,T,\alpha). \tag{2.5}$$

The electro-magnetic power per unit volume dissipated in the composite material and ceramic die due to their dielectric losses can be derived by an integration of the Poynting vector and using Maxwell's equations as in [3]:

$$Q = 2\pi f\varepsilon_0\varepsilon'' E_{rms}^2, \tag{2.6}$$

where ε_0 is the vacuum permittivity, and E_{rms} is the root mean square of the electric field.

Since no physical tests and literature exist which could be used for testing, the finite element model is developed additionally in the *COMSOL Multiphysics* code to verify the results of the simulation to be carried out in *ANSYS*. In this case, the definition of absorbed energy must match in both codes. In *COMSOL,* for a nonmagnetic material, the absorption energy due to dielectric losses is determined automatically in the following form:

$$Q = \frac{1}{2}\mathrm{Re}(J \cdot E^*), \tag{2.7}$$

where * denotes the complex conjugate.

Considering the expression of current density (Eq. (2.2)) and following dependencies

$$\sigma = 2\pi f \varepsilon_0 \varepsilon'', \tag{2.8}$$

$$E\,E^* = E'^2 + E''^2. \tag{2.9}$$

The absorption energy field in both codes, *COMSOL* and *ANSYS*, is determined with the same expression by using the intensity of the electric field:

$$Q = \pi f \varepsilon_0 \varepsilon'' \left(E'^2 + E''^2\right). \tag{2.10}$$

The effectiveness of the microwave heating is estimated later as follows:

$$Q_{\%} = \frac{\sum_{i=1}^{N} Q_i V_i}{P_{MW}} \cdot 100\%, \tag{2.11}$$

where

Q_i – the energy absorbed in the *i*-th finite element;

V_i – the volume of the *i*-th finite element;

P_{MW} – the energy of the microwave heating source;

N_i – the number of finite elements used for the modelling of a ceramic die or a composite.

The simulation procedures are developed in the *COMSOL Multiphysics* and *ANSYS* environments. The cross-section of the products is predetermined, and the first step of the problem is to design the base model of a microwave setup with an analytically known field distribution most suitable for the requested cross-section. In the second step, an electromagnetic field intensity is computed by using universal finite element codes. Then the results are read from the finite element solution, and the absorbed energy field is evaluated by the user-developed program. Later, an initial electromagnetic model is improved numerically towards a homogeneous field distribution and high efficiency of the provided energy. This is performed by adjusting the model dimensions for the specified ceramic die and cured composite materials until the target specifications are reached (Fig. 2.1).

According to the Nyquist-Shannon sampling theorem [6] for the discrete sampling of a wave function, the maximum element size x_{max} of the mesh applied to the geometry has to fulfill $x_{max} < \lambda/2$, where λ is the local wavelength. Local wavelength means that λ might be shortened by dielectric materials or influenced by conductive parts, so that a good value for the maximum mesh element size can be defined as shown in Fig. 2.1.

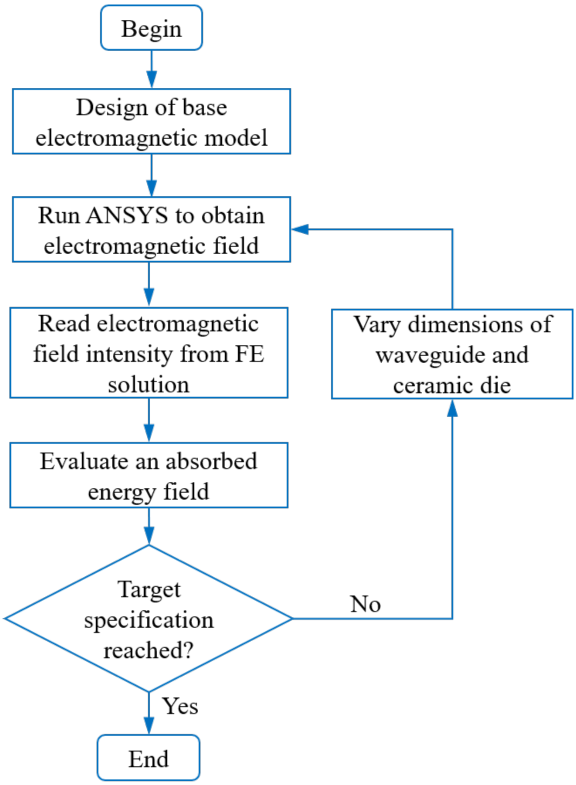


Fig. 2.1. Electromagnetic algorithm for specified ceramic die and cured composite materials.

$$x_{max} < \frac{\lambda_0}{20\sqrt{\varepsilon_r}}, \qquad (2.12)$$

where λ_0 is the wavelength in free space, and $\varepsilon_r = \varepsilon' / \varepsilon_0$ is the relative permittivity.

For the finite element mesh developed, Eqs. (2.1)–(2.2) are solved for the electric field amplitudes with respect to the local material properties from Equation (2.5) 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 are applied by a so-called "port" boundary condition. Then the heating rate Q is calculated using Eq. (2.10) and evaluated regarding homogeneity and efficiency.

To demonstrate the features and benefits of electromagnetic heating, the pultrusion process of rod profiles with a diameter of 16 mm made of polyester resin POLRES 305BV and glass fibres 4800 tex with a fibre volume content of 55 % is studied. The setup scheme for microwave heating is presented in Fig. 2.2. The corresponding finite element model is developed in *ANSYS* by using high-frequency electromagnetic finite elements HF120. To verify the finite element models and algorithm developed for the electro-magnetic analysis in *ANSYS*, the same problems have been solved in *COMSOL Multiphysics* [5]. The results of *COMSOL* after a rigorous convergence study are presented in Fig. 2.3, together with *ANSYS* results, where very good agreement between both results is observed, which indicates their high accuracy and reliability. So, the difference between significant microwave energies calculated by *ANSYS* and *COMSOL* and absorbed in the composite materials lies in the range of 0 – 0.2% for different set-ups, but in the ceramic die, 0.6%.

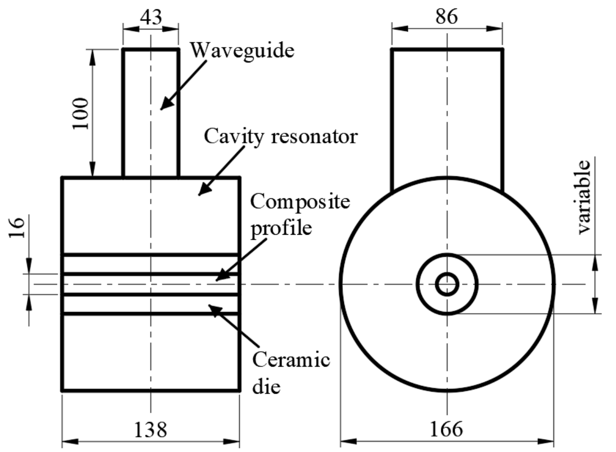
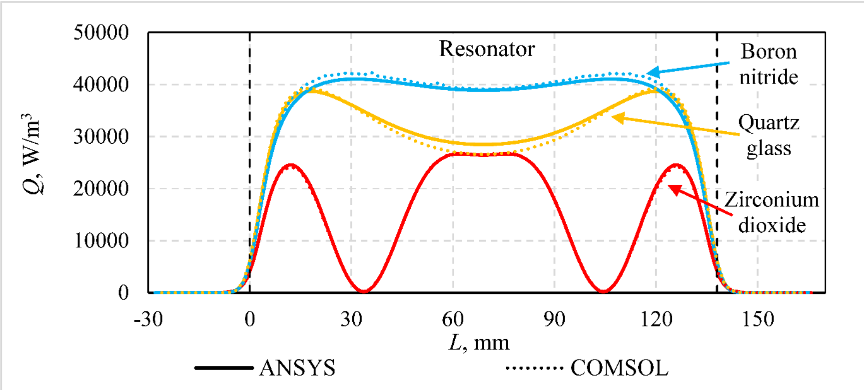
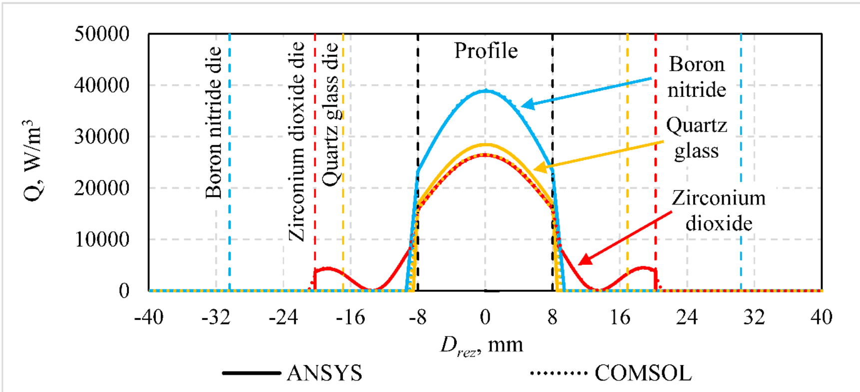


Fig. 2.2. Scheme of the setup for microwave heating.



a



b

Fig. 2.3. Distribution of absorbed energy for ceramic die made of different materials along profile centerline (a) and along profile middle cross-section (b).

The parametric study shows that for the same microwave setup but using different ceramic materials for the pultrusion die, different heat transfer processes should be examined in the consequent thermo-chemical analysis. So, if for the ceramics with low relative loss factor, heat transfer is executed only by the energy absorbed in composite material and starts inside the profile, for ceramic with high internal losses – an ignore of conventional heating (conduction) from the hot ceramic die is impossible since microwave absorption losses are approximatively the same values for the die and composite. Moreover, for the ceramic materials with close permittivity parameters, it was impossible to obtain close diameters of pultrusion dies for an effective and homogeneous absorption field.

Thermo-chemical problem

A thermo-chemical finite element model and algorithm are necessary to determine the temperature and degree of cure field distribution, and as a result, to evaluate the quality of pultruded profiles.

The thermo-chemical problem describing the conventional pultrusion processes consists of three governing equations: the energy equation for the tool, the energy equation for the composite moving in the pull direction, and the species equation (transport equation) for the resin:

$$\begin{cases} \rho\, c_p \dfrac{\partial T}{\partial t} - \dfrac{\partial}{\partial x}\left(k_x \dfrac{\partial T}{\partial x}\right) - \dfrac{\partial}{\partial y}\left(k_y \dfrac{\partial T}{\partial y}\right) - \dfrac{\partial}{\partial z}\left(k_z \dfrac{\partial T}{\partial z}\right) = 0 \\ \overline{\rho}\, \overline{c}_p \left(\dfrac{\partial T}{\partial t} + u\dfrac{\partial T}{\partial x}\right) - \dfrac{\partial}{\partial x}\left(\overline{k}_x \dfrac{\partial T}{\partial x}\right) - \dfrac{\partial}{\partial y}\left(\overline{k}_y \dfrac{\partial T}{\partial y}\right) - \dfrac{\partial}{\partial z}\left(\overline{k}_z \dfrac{\partial T}{\partial z}\right) - q = 0 \\ \left(\dfrac{\partial \alpha}{\partial t} + u\dfrac{\partial \alpha}{\partial x}\right) = R_r \end{cases} \quad (2.13)$$

where

T – the temperature;

ρ and c_p – the density and specific heat of the tooling materials;

k_x, k_y, k_z – the thermal conductivities of the tooling materials in x, y, z directions;

u – the pull speed;

$\overline{\rho}$ and $\overline{C}_p$ – the lumped density and specific heat for the composite material;

$\overline{k}_x$, $\overline{k}_y$, $\overline{k}_z$ – the lumped thermal conductivities of the composite material in x, y, z directions;

q – the generative term related to the internal heat generation due to the exothermic resin reaction;

$\alpha = H(t)/H_{tr}$ – the degree of cure;

$H(t)$ – the amount of heat evolved during the curing up to time t.

Heat transfer in the composite occurs as a result of conduction and from the exothermic chemical reaction initiated by the die temperature. Due to the exothermic resin reaction, the generative term related to the internal heat generation is written as

$$q = V_r \rho_r H_{tr} R_r, \quad (2.14)$$

where

V_r – the resin volume fraction;

ρ_r – the resin density;

R_r – the rate of resin reaction determined as

$$R_r(\alpha,T)=\frac{\partial\alpha}{\partial t}=\frac{1}{H_{tr}}\frac{dH(t)}{dt}=K(T)\cdot f(\alpha)\,, \tag{2.15}$$

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:

$$K(T)=K_0\exp\left(-\frac{E}{RT}\right), \tag{2.16}$$

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 physical values and could be determined by the Kissinger method or ASTM E 698 standard methodology from DSC tests [6]. Coefficients of the selected function $f(\alpha)$ are obtained in a simple way by fitting the experimental heat flow curves by applying the least squares method [7].

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

$$\begin{aligned}
\bar{\rho}&=(1-V_r)\rho_f+V_r\rho_r\\
\bar{c}_p&=\frac{(1-V_r)\rho_f c_{pf}+V_r\rho_r c_{pr}}{\bar{\rho}}\\
\bar{k}&=\frac{k_f k_r\bar{\rho}}{(1-V_r)\rho_f k_r+V_r\rho_r k_f}
\end{aligned} \tag{2.17}$$

where indexes f and r relate to the fibres and resin, respectively.

The present algorithm is developed in the *ANSYS Mechanical* environment and is based on the mixed time integration scheme and nodal control volumes method to solve simultaneously the coupled energy and transport Eqs. (2.13) and (2.18) by using an iteration technique. The nodal control volumes are constructed based on the finite element mesh as presented in Fig. 2.4.

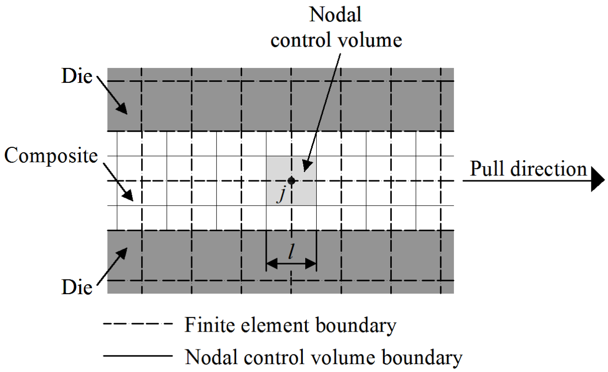


Fig. 2.4. Finite element and nodal control volume meshes.

At the beginning, it is assumed that the degree of cure has the same value α^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 by the user-developed program:

$$\frac{\partial \alpha_j^i}{\partial t} = \left[\frac{\Delta \alpha_j^i}{\Delta t}\right] = K_0 \exp\left(-\frac{E}{RT_j^i}\right) f(\alpha_j^{i-1}). \qquad (2.18)$$

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

$$\alpha_j^i = \alpha_j^{i-1} + \left[\frac{\Delta \alpha_j^i}{\Delta t}\right] \Delta t, \qquad (2.19)$$

where Δt is the time step determined as

$$\Delta t = \frac{1}{p} \cdot \frac{l}{u}, \qquad (2.20)$$

where

l – the length of nodal control volume in the pulling direction;

u – the pulling speed;

p – the number of sub-steps.

If the procedure of sub-stepping is not applied, $p = 1$. The exothermic effects of the cure reaction are evaluated as the equivalent nodal heat power for a nodal control volume or node j by the following relation:

$$q = V_r \rho_r H_{tr} R_r = V_r \rho_r H_{tr} \left[\frac{\Delta \alpha_j^i}{\Delta t} \right]. \qquad (2.21)$$

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 α^0 at any step of iterations. In general, the algorithm can be summarised as a flowchart presented in Fig. 2.5. In the case of simulation of conventional pultrusion processes with temperature control, the temperatures obtained from the transient thermal finite element analysis are also used for the control of the work of electrical heaters. In real conditions, this control is executed by thermocouples located in the corresponding points of the die. The modified thermo-chemical algorithm is presented in Fig. 2.6.

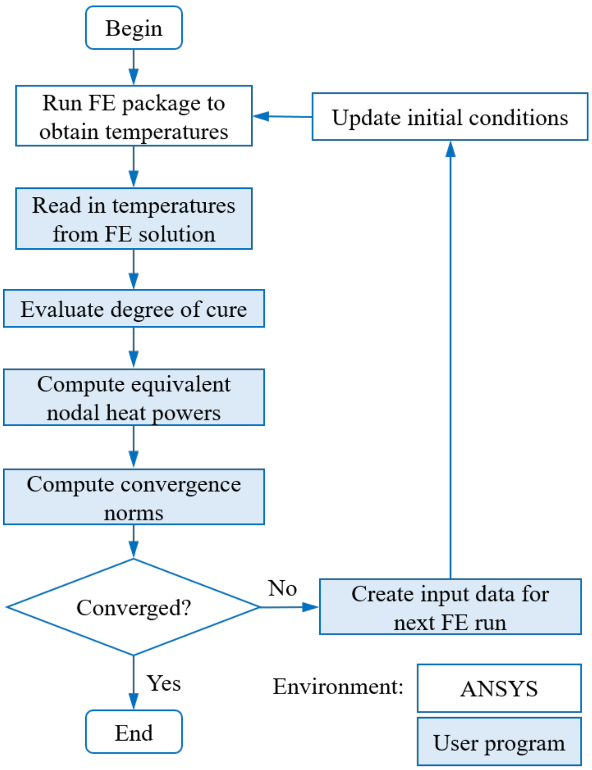


Fig. 2.5. Thermo-chemical algorithm for conventional pultrusion processes.

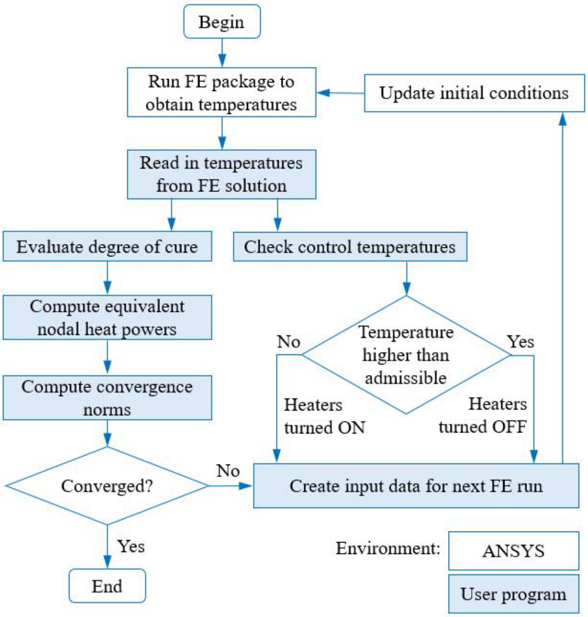


Fig. 2.6. Thermo-chemical algorithm for conventional pultrusion process with temperature control.

The thermo-chemical algorithm [8] based on the mixed time integration scheme and nodal control volumes method has been successfully validated by the analysis of the pultrusion process for different profiles [9], [10]. A greater difference in results has been observed in the first sensor, where the resin was in the gelation stage. Whereas, a very good agreement has been obtained in the areas where the resin was almost fully cured.

Electromagnetic-thermo-chemical problem

For the microwave-assisted pultrusion processes, the system of Eqs. (2.13) describing the thermo-chemical problem should be slightly modified:

$$\begin{cases} \rho\, c_p \dfrac{\partial T}{\partial t} - \dfrac{\partial}{\partial x}\left(k_x \dfrac{\partial T}{\partial x}\right) - \dfrac{\partial}{\partial y}\left(k_y \dfrac{\partial T}{\partial y}\right) - \dfrac{\partial}{\partial z}\left(k_z \dfrac{\partial T}{\partial z}\right) - Q_{cd} = 0 \\ \bar{\rho}\, \bar{c}_p \left(\dfrac{\partial T}{\partial t} + u\dfrac{\partial T}{\partial x}\right) - \dfrac{\partial}{\partial x}\left(\bar{k}_x \dfrac{\partial T}{\partial x}\right) - \dfrac{\partial}{\partial y}\left(\bar{k}_y \dfrac{\partial T}{\partial y}\right) - \dfrac{\partial}{\partial z}\left(\bar{k}_z \dfrac{\partial T}{\partial z}\right) - q - Q_{comp} = 0 \\ \left(\dfrac{\partial \alpha}{\partial t} + u\dfrac{\partial \alpha}{\partial x}\right) = R_r \end{cases} \quad (2.22)$$

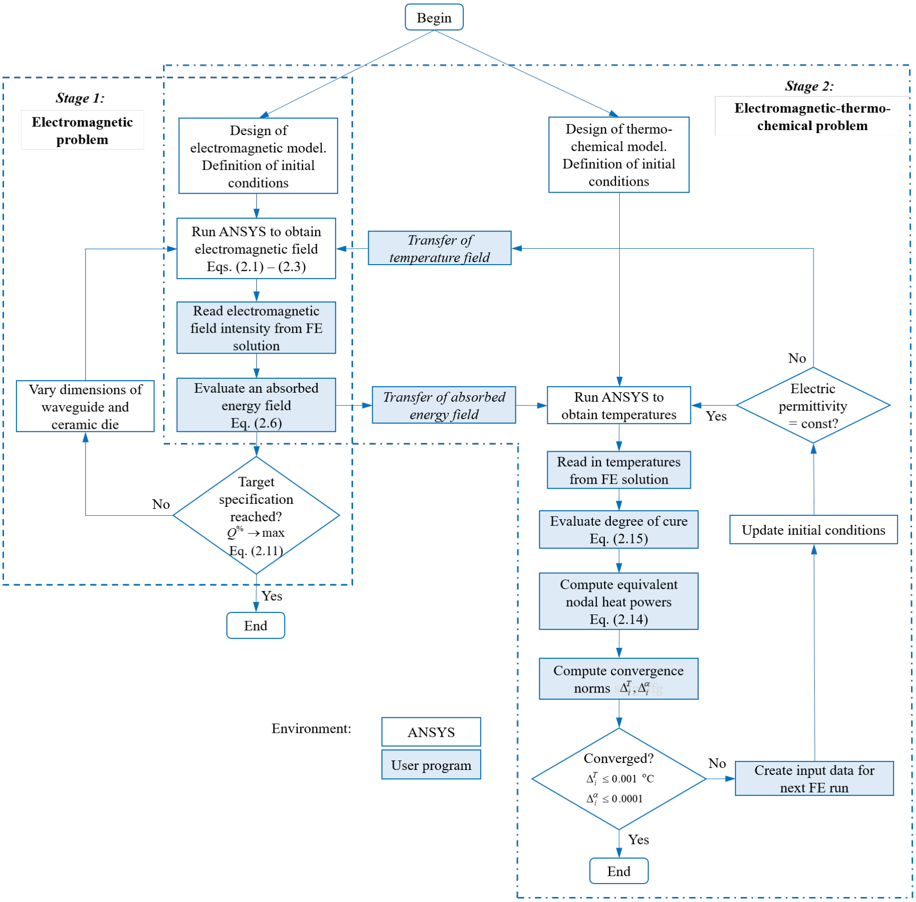


Fig. 2.7. Coupled electromagnetic-thermo-chemical algorithm for a simulation of microwave-assisted pultrusion process.

The second equation is completed with the term $Q_{comp}(f,T,\alpha)$ presenting the absorbed energy field Q_{comp} in composite material, and the first equation – with the term $Q_{cd}(f,T)$ presenting the absorbed energy field in ceramic die, taking into account only for the materials with high dielectric losses where f is the microwave frequency. The first equation is modified only in the case when the dielectric losses of the ceramic material are high and cannot be excluded from the thermo-chemical analysis. The energy and transport equations are coupled since an exothermic heat release term appears in the energy equation of the moving composite, but the electromagnetic and thermo-chemical problems are coupled due to the relative electric permittivity, which is used for a computation of both absorption energy fields and in general case presents complex value dependent on the microwave frequency, temperature, and degree of cure (Eq. (2.5)).

To solve the system of coupled governing Eq. (2.22), an iterative finite element algorithm, preserving an electric permittivity dependence on the microwave frequency, temperature, and degree of cure, has been developed (Fig. 2.7).

For the simulation of the MW-assisted pultrusion process, the resin from the class of polyesters has been chosen since its degradation temperature is quite high – 270 °C, as demonstrated by experiments carried out in *COMPOR* Ltd [11]. The finite element model for a simulation of thermo-chemical behaviour of rod profile (Fig. 2.8) has been created in *ANSYS Mechanical* by using 3-D thermal solid finite elements Solid 70. The element has eight nodes with a single degree of freedom – temperature at each node and the orthotropic material properties. Considering the symmetry of the examined problem, only half of the die and profile is modelled.

The results of the physically justified microwave-assisted pultrusion process operating with the applied microwave energy of 0.6 kW and pull speed of 50 cm/min are presented in Fig. 2.9 for the setup with a ceramic die made of boron nitride, which is more effective from the examined solutions to the largest microwave energy absorbed in the composite material. Figure 2.10 demonstrates that all the constraints on the allowable and desired degree of cure on the profile surface at the die exit and in the final product are now executed.

The corresponding results of thermo-chemical analysis for the modified pultrusion setup are given in Fig. 2.10, demonstrating that all constraints taken for the development of microwave-assisted pultrusion processes are executed now. It is necessary to ensure that the productivity of the modified process has been improved twice by increasing the pull speed till 100 cm/min, but this requires considerably higher microwave energy applied (1.1 kW) than has been used in the previous pultrusion process. Of course, the effectiveness and productivity of the analysed pultrusion process can be improved by its optimisation.

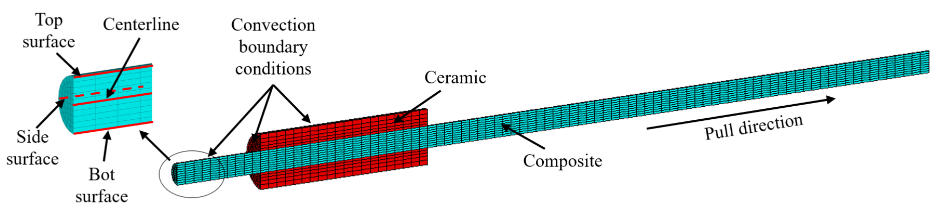


Fig. 2.8. Thermo-chemical finite element model for a simulation of the pultrusion process.

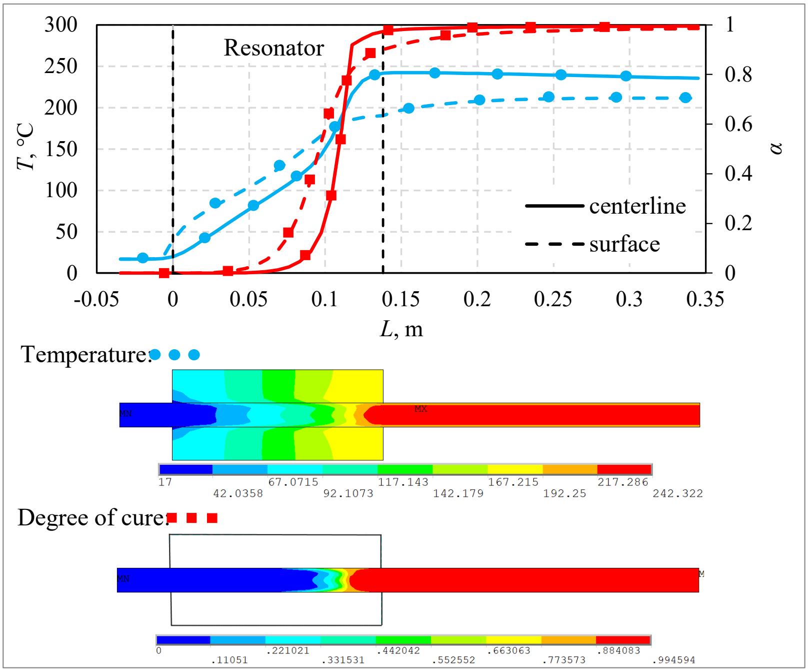


Fig. 2.9. Distribution of temperature and degree of cure along pultruded profile for ceramic die made of boron nitride.

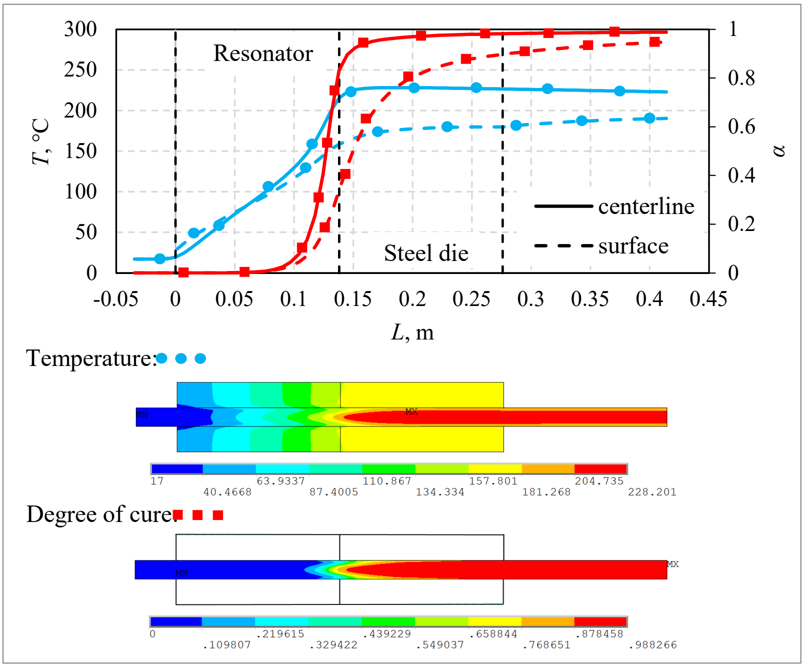


Fig. 2.10. Distribution of temperature and degree of cure along pultruded profile for modified pultrusion die.

2.3. Optimisation of conventional pultrusion processes

A new effective optimisation methodology, taking into account all the required parameters of the industrial pultrusion processes and ambient room temperature, is developed, employing the method of experimental design and response surface technique. More accurate and realistic process optimisation, that have been reached in the previous studies, is achieved with the temperature control executed by the heater's switch-on and -off strategy. Using non-direct optimisation methodology, technological maps, presenting *EXCEL* tools, are developed additionally for the technologists' convenience.

Due to the large dimension of numerical problems to be solved, a non-direct optimisation methodology is developed employing the method of experimental design [12] and the response surface technique [13], presented in Fig. 2.11.

Since in our case a distribution of the design variables in the design space is unknown, the plan of experiments with as regular as possible distribution of the points of experiments in the domain of factors is chosen. To create this plan, the following criterion is used:

$$\Phi = \sum_{i=1}^{n} \sum_{j=i+1}^{n} \frac{1}{l_{ij}^2} \Rightarrow \min, \tag{2.23}$$

where n is the number of experiments, and $l_{ij}$is the distance between the experimental points numbered i and j ($i \neq j$).

The plan of experiments is characterised by the matrix of plan B_{ij}. The domain of factors is determined as $x_j \in [x_j^{\min}, x_j^{\max}]$, and the points of experiments are calculated using the following expression:

$$x_j^{(i)} = x_j^{\min} + \frac{1}{n-1}\left(x_j^{\max} - x_j^{\min}\right)\left(B_{ij} - 1\right), \quad i = 1,2,\ldots,n\,, \quad j = 1,2,\ldots,k\ . \tag{2.24}$$

The minimal number of experimental points in the optimisation problem is determined as $N = 2L$, where $L = (k + 1)(k + 2)/2$ and k is the number of design parameters.

The pultrusion tool for the production of two rod profiles at the same time is presented in Fig. 2.12. Its die has the following dimensions: 500 mm × 150 mm × 110 mm, and the distance between the two profile channels is 40 mm. The die is heated by two electrical heater platens located at the top and bottom sides, and close to the die exit.

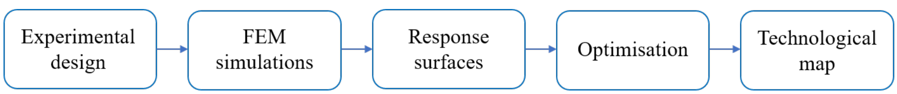


Fig. 2.11. Optimisation methodology.

Fig. 2.12. Pultrusion tool.

Dimensions of the heaters are 300 mm × 150 mm × 15 mm, and their electrical power is 2750 W. The work of the heaters is controlled by the thermocouple located between them. The materials used for the production of the rod profile are glass fibre Tex4800 with the fibre mass fraction of 78 % and polyester resin C-L ISO 112G. The finite element model for a simulation of two rods pultrusion has been created in *ANSYS Mechanical* by using 3-D thermal solid finite elements, Solid 70. Taking into account the symmetry of the examined problem, only a quarter of the die is modelled. An additional length of 300 mm of the rod is arranged at the die exit to extend the thermo-chemical analysis to the post-die region. The heater platens are located at the die exit, as in the real technological process. Since resin curing is expected in the post-die region, the modelling of the profile length after the die exit is extended to 1 m.

The optimisation problem is formulated for two objective functions. The first describes the effectiveness of the pultrusion process and minimises the electrical energy (kWh) necessary for the production of a pultruded profile with a length of 1 m:

$$\frac{n \cdot W_{heater} \cdot k_t}{m \cdot V_{pull}} \rightarrow \min, \tag{2.25}$$

where

n – the number of heaters;

m – the number of simultaneously produced profiles, and in our case $m = 2$;

W_{heate} – the power of the electrical heater in kW,

V_{pull} is the pull speed in m/h;

k_t– the relative time of the heater's work determined by Eq. (3.12).

The second objective function is connected with the productivity of the pultrusion process and maximises the pull speed:

$$V_{pull} \rightarrow \max \quad . \tag{2.26}$$

Table 2.1

Accuracy and Reliability of Approximations after Elimination of Some Points

Symbol, unit	σ_{cross}, %	R^2_{adj}	σ	σ, %	Δ_{max}, % (Point No.)
		1st-order approximation			
α_{surf}	59.8	0.70	0.09	54.4	24.7 (27)
α_{cent}	79.1	0.49	0.13	71.2	46.1 (17)
		2nd-order approximation			
α_{surf}	20.7	0.97	0.03	16.3	3.6 (11)
α_{cent}	52.3	0.86	0.07	37.9	15.6 (17)
		3rd-order approximation			
α_{surf}	22.4	0.99	0.02	9.6	3.2 (27)
α_{cent}	24.8	0.99	0.01	8.1	1.4 (3)

Table 2.2

Optimal Design Parameters

	Min value	Max value	Optimal
Pull speed, cm/min	20	45	45
Room and resin temperature, °C	10	40	40
Control temperature on electrical heaters, °C	115	150	142

Some parameters of the pultrusion process (power and number of electrical heaters) are taken into consideration as constant values in the optimisation problem. Another (pull speed and control temperature on heaters) and room and resin temperature are examined as design variables with the borders describing the design space. Constrains are introduced into the optimisation procedure with the aim of providing a qualitative profile production when the resin is fully cured and not overheated during the pultrusion process. Errors of approximations describing their accuracy and reliability are summarised in Table 2.1. It is seen from Table 2.1 that no improvement of the quality of approximations has been reached, eliminating some points with the low value of the degree of cure for the first- and second-order polynomials.

An optimisation problem with second-order polynomials for two objective functions (Eqs. (2.25)–(2.26)) is solved by the generalised reduced gradient nonlinear algorithm embedded in *Microsoft Excel © Solver*. The same optimal parameters of the developed pultrusion process have been obtained for both objective functions. They are presented in Table 2.2.

Technological map

The technological map based on regression polynomials has been developed in the *EXCEL* environment for an effective design of the two rods pultrusion process. An interface of this *EXCEL* tool is presented in Fig. 2.13, and it consists of two major sections:

• calculation of process conditions (temperatures and degrees of cure in the composite profile, and process energy consumption) for the defined process parameters, and ambient room and resin temperature (fixed pull speed, heaters control temperature and room temperature);

• optimisation of process parameters by minimisation of energy consumption (Eq. (2.25)) or maximisation of pull speed (Eq. (2.26)), taking into account previously defined constraints of the process conditions (Table 2.3). It is necessary to note that some parameters in the optimisation process could be examined as constant values.

To follow industrial shop conditions, the optimisation problem has been solved repeatedly for different ambient room temperatures. The process optimised parameters are presented in Table 3.18 together with the results obtained by the regression using information from the COMPOR technological map.

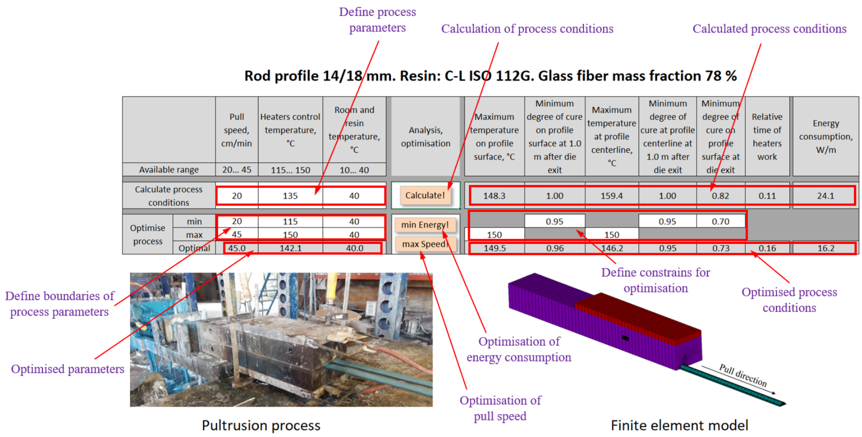


Fig. 2.13. Interface of the developed technological map.

Table 2.3

Comparison of Process Parameters Obtained by COMPOR and Optimised Technological Maps for Different Room Temperatures

	COMPOR technological map				**Optimised technological process**			
Pull speed, cm/min	20				29.9	35.4	39.9	45.0
Control temperature of electrical heaters, °C	135				138	141	142	142
Room and resin temperature, °C	**10**	**20**	**30**	**40**	**10**	**20**	**30**	**40**
Maximal temperature on profile surface, °C	146	146	147	148	147	150	150	150
Minimal degree of cure on the profile surface	1.00	1.00	1.00	1.00	0.97	0.97	0.97	0.96
Maximal temperature on profile centreline, °C	161	161	161	159	150	150	148	146
Minimal degree of cure on the profile centreline	1.00	1.00	1.00	1.00	0.95	0.95	0.95	0.95
Minimal degree of cure on the profile surface at the die exit	0.82	0.82	0.82	0.82	0.77	0.79	0.77	0.73
Energy consumption, W/m	**33.4**	**30.3**	**27.2**	**24.1**	**26.7**	**22.6**	**19.3**	**16.2**

2.4. Development of advanced pultrusion processes

An application of the developed finite element models and algorithms is demonstrated by the development of a real microwave-assisted pultrusion process producing a rod profile with a diameter of 16 mm (Fig. 2.14).

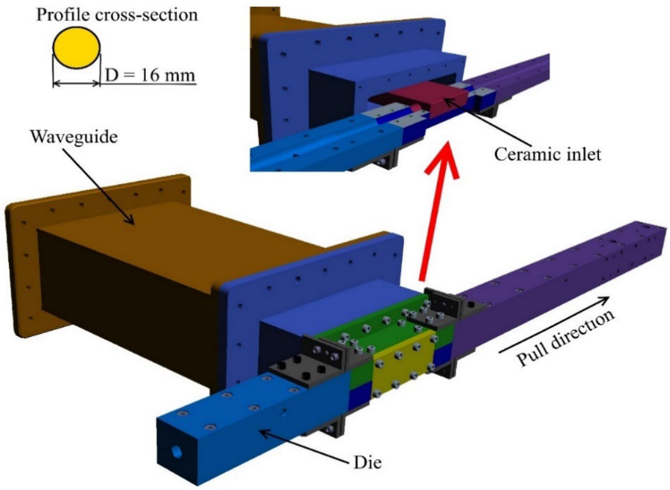


Fig. 2.14. Microwave-assisted pultrusion process.

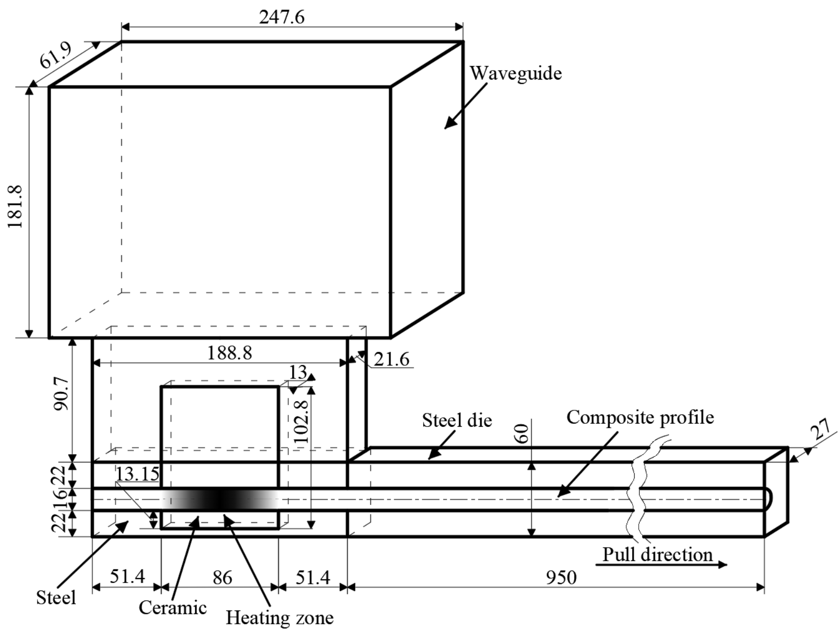


Fig. 2.15. Scheme of microwave-assisted pultrusion process (symmetry used).

The scheme of this innovative process is presented in Fig. 2.15, and it consists of a steel die with a length of 950 mm and cross-section dimensions of 54 mm x 60 mm, and a microwave block attached to the die and consisting of the ceramic inlet (zirconium dioxide) and waveguide.

The electromagnetic finite element model is built in *ANSYS* by using high-frequency electromagnetic finite elements HF120. This is a first-order hexahedral element formulation with one degree of freedom – the tangent component of the electric field (AX) on each edge. A rectangular port with the applied energy of 1 W at the top of the waveguide and TE_{10} mode is used.

A convergence study is carried out by using the finite element model with 5 different meshes. The parameters of finite element models are given in Table 2.4. To verify the results of electromagnetic analysis obtained in *ANSYS*, the finite element model for the same microwave-assisted pultrusion process has been developed and analysed in *COMSOL Multiphysics*. Distribution of the electric and absorbed energy fields along the profile centreline is presented in Figs. 2.16. and 2.17. It is seen that no difference is observed between the results obtained by different finite element software: *ANSYS* and *COMSOL Multiphysics*. This talks about the high reliability of the developed electromagnetic finite element model and algorithm.

Results of thermo-chemical analysis show that the die length can be shortened without any losses for the pultrusion process. This will contribute to a reduction of costs necessary for the pultrusion die production (less material) and high-precision treatment of working surfaces. The length of the steel die is decreased by 5 times (from 950 mm to 190 mm), which leads to the total length reduction of the pultrusion setup by 3 times (from 1138.8 mm to 378.8 mm). To investigate the curing process in profile, leaving the die, its length is not changed. It has been obtained that the die length reduction does not change the distribution of the temperature and degree of cure in the pultruded profile. Moreover, the curing process in the shorter steel die is faster due to the absence of additional thermal losses in a massive die.

The effectiveness of the developed microwave-assisted pultrusion processes has been estimated in comparison with the real conventional pultrusion process [10], which

Table 2.4

Convergence Study

Model	FE length in pull direction, mm	Max dimension of FE in cross-section, mm			Number of FE in pull direction	Number of FE in half of comp. cross-section	Total number of FE	Energy absorbed in comp. profile, %	Energy absorbed in ceramic, %
1	7.25	2.2	4.0	3.3	157	48	99501	7.4	7.7
2	7.25	1.4	3.8	3.3	157	70	104525	7.4	7.8
3	4.63	2.2	4.0	3.3	246	48	141357	7.4	7.6
4	4.63	1.4	3.8	3.3	246	70	149229	7.4	7.8
5	4.63	1.1	2.1	1.7	246	122	524567	7.6	8.0

has been successfully verified experimentally under the ambient room temperature of 17°C. The results demonstrating productivity (dependent on pull speed) and effectiveness (dependent on energy consumption) are presented in Table 2.5 for both technological processes. It is necessary to note that the productivity and effectiveness of the real conventional process have been taken as 100 %. Results in Table 2.5 show that by using a magnetron with a high frequency of 2.45 GHz, it is possible to increase the productivity of the pultrusion process by more than 5.5 times, but the effectiveness by almost 3 times. An application of a magnetron with a lower frequency of 915 MHz has allowed only to improve the productivity by more than 3 times, but the energy consumption has been considerably increased. In this way, to develop an effective microwave-assisted pultrusion process with high productivity, magnetrons with a high frequency of 2.45 GHz should be recommended.

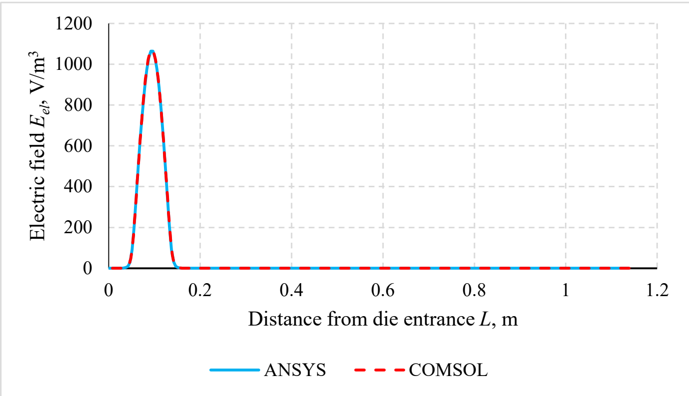


Fig. 2.16. Distribution of electric field along the profile centreline calculated by *ANSYS* and *COMSOL*.

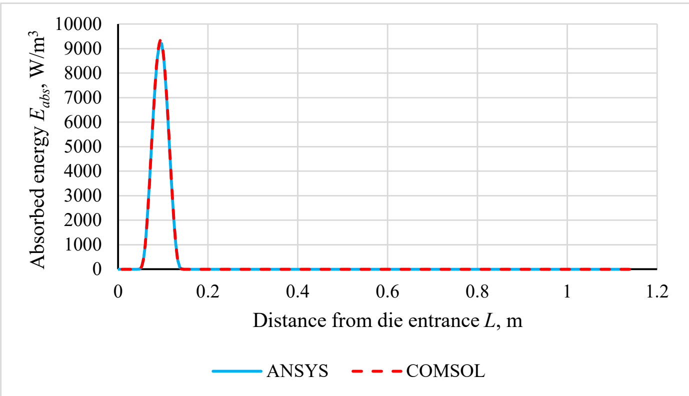
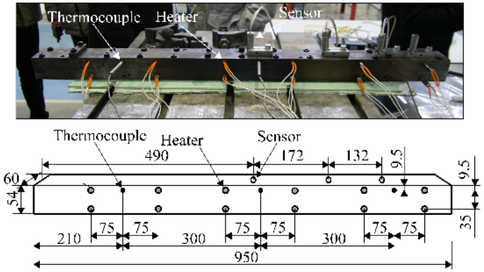
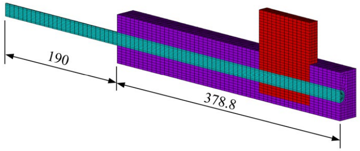
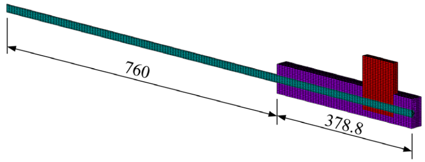


Fig. 2.17. Distribution of absorbed energy field along the profile centreline calculated by *ANSYS* and *COMSOL*.

Table 2.5

The Effectiveness of the Microwave-Assisted Pultrusion Process

Product	Rod with a diameter of 16 mm made of polyester resin POLRES 305BV (v_f = 45%) and glass fibres 4800 tex (v_f = 55 %)					
Pultrusion	Conventional [14]	Microwave-assisted				
Schemes or finite element models						
Dielectric properties of resin taken in the simulation	Constant	Constant	Constant		Temperature dependent	
Heating system	12 electrical heaters, 315 W each	Magnetron: 915 MHz, 5290 W Ceramic block: zirconium dioxide	Magnetron 2.45 GHz Ceramic block: boron nitride			
			1000 W	850 W	850 W	550 W
Heating system operating mode	Controlled by a proportional-integral-derivative controller (automatically switches ON and OFF)	Continuous (always ON)				
Pull speed, cm/min	18	59	100			
Energy consumption of steady-state process, W/m	24.8	149.4	16.7	14.2	14.2	9.2
Productivity, %	100	327.8	555.6			
Effectiveness, %	100	602.4	67.3	57.3	57.3	37.1

CONCLUSIONS

1. New electromagnetic-thermo-chemical finite element models and algorithms have been developed for a holistic simulation of microwave-assisted pultrusion processes, as well as for the pultrusion tooling design and process control. For this purpose, the general-purpose finite element software *ANSYS* has been used, which results in considerable savings in development time and costs, and also makes available various modelling features of the finite element packages. This has allowed us to solve coupled electromagnetic-thermo-chemical problems with temperature-dependent dielectric material properties. The parametric study confirms that microwave-assisted pultrusion processes operate with high speed (fast curing) and their working temperatures are higher than those that occur in the conventional pultrusion processes. For this reason, resins with high dielectric losses and high destruction temperatures are the best choice for this application. Moreover, they should be tested by DSC machines at higher speeds than used previously for conventional pultrusion processes. It is important to note that all the finite element models and algorithms developed in the present study have been successfully validated by the results obtained by the authors in some specialised software (*COMSOL Multiphysics*), experimentally or using open literature.
2. New optimisation problems have been formulated based on the results of the parametric study, taking into account all the required parameters of the industrial pultrusion processes. Non-direct optimisation methodology based on the planning of experiments and response surface techniques has been successfully developed for the design of conventional pultrusion processes. This approach has allowed us to estimate the effectiveness and productivity of industrial pultrusion processes with the temperature control executed by the heater's switch-on and -off strategy. In this way, more realistic values of electrical energy spent for a die heating have been obtained. Allowing resin curing outside the pultrusion die has allowed the development of a more effective pultrusion process. However, in this case, an exothermic chemical reaction is moved to the die exit, and an additional constraint should be introduced into the formulated optimisation problem. This is a minimal degree of cure for the composite profile at the die exit. With this constraint, it is guaranteed that resin at the die exit does not flow, and it is in a solid state.
3. The present optimal solutions have been obtained for the existing pultrusion dies used now in the industrial shop. In this study, no possibility has existed to change the dies' design. However, the highest effectiveness of the technological process could be obtained for a joint optimal design of the die and process itself, and for the resin chosen in the initial stage. In this case, it is possible to

additionally save an expensive steel material used for the production of the pultrusion die and to reduce the high costs of its treatment.

4. A new interactive technological map using non-direct optimisation methodology has been developed for the examined technological process. It not only allows defining the process conditions (temperature and degree of cure in composite profile) for the fixed process parameters and ambient room temperature, but also minimises the energy consumption or maximises the pull speed for an actual ambient temperature in industrial shops. An application of the developed technological map has demonstrated a considerable improvement in the process effectiveness and productivity in comparison with the existing technological map currently used in the industrial shop. To increase the operating speed of the developed technological map, the generalised reduced gradient nonlinear algorithm has been applied for the solution of formulated optimisation problems. This is done with the purpose of using these technological tools on all possible computers, even with slow CPU speed. However, it is necessary to remember that in this case, the optimal solutions in some problems could be highly dependent on the initial conditions, and the obtained solution may not be optimised globally.
5. Evaluation of the developed microwave-assisted pultrusion process in comparison with the real conventional pultrusion process, verified experimentally, has demonstrated its considerable productivity (more than 5.5 times) and effectiveness (almost 3 times), preserving the high quality of pultruded profiles.

For future investigations, in order to preserve the quality of pultruded profiles and evaluate the structural behaviour and geometrical precision, the thermo-mechanical finite element model and algorithm should be developed to calculate the process stresses and deformations.

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