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SOLUTION OF ELECTROMAGNETIC PROBLEM FOR AN APPLICATION IN ADVANCED PULTRUSION PROCESSES

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Abstract. To demonstrate features and benefits of electromagnetic energy source, the heating of rod profile made of polyester resin POLRES 305BV and glass fibres 4800 tex in cylindrical cavity resonator was studied. Materials with different dielectric properties: zirconium dioxide, boron nitride and quartz glass for a microwave transparent die were selected and analysed. The optimal diameter of ceramic die providing an effective and uniform electric field in the composite profile was found for each material.

1 INTRODUCTION

Pultrusion is a technological process for the fast and effective production of composite profiles with constant cross-sections. During pultrusion fibers are saturated with the resin and then pulled through a heated die, where the resin cures and solidifies to the form of die's channel [1]. Effectiveness of this technological process, preserving the quality of pultruded profiles, could be improved by an application of new effective heating sources instead of using traditional electric heaters with high heat losses. Among all possible heating methods, a high frequency electromagnetic energy source [2], successfully used in different industrial curing processes [3, 4] could be examined as the best choice for the pultrusion applications. A very limited number of studies in the experimental [5, 6, 7] and simulation [8, 9] aspects of microwave assisted pultrusion processes slows down their development as well as pultrusion tooling design. For this reason, new effective electro-magnetic-thermo-chemical finite element models and algorithms were developed [10, 11, 12] by using the general-purpose finite element software ANSYS Mechanical.

Electro-magnetic model described in this paper was used to find the optimal diameter of ceramic die made of materials with different dielectric properties providing an effective and uniform electric field in the pultruded composite profile.

2 ELECTROMAGNETIC PROBLEM AND ITS NUMERICAL IMPLEMENTATION

The electromagnetic field is described by Maxwell's equations:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \; \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}, \; \nabla \cdot \vec{D} = \rho, \; \nabla \cdot \vec{B} = 0 \tag{1}$$

where $\vec{E}$ is electric field intensity, $\vec{H}$ is magnetic field intensity, $\vec{B}$ is magnetic flux density, $\vec{D}$ is electric flux density, $\vec{J}$ is current density, ρ is charge density and t is time.

The corresponding constitutive relations have the following form

$$\vec{B} = \mu \vec{H}, \; \vec{D} = \varepsilon \vec{E}, \; \vec{J} = \sigma \vec{E} \tag{2}$$

where μ is magnetic permeability, ε is electric permittivity and σ is electric conductivity.

An intensity of electric field can be found solving numerically equations (1-2):

$$\vec{E}(x,y,z,t) = \vec{E}(x,y,z)e^{i2\pi ft} \tag{3}$$

where x, y, z are the components of location vector and f is microwave frequency.

The absorption energy field can be determined using an intensity of electric field [2]:

$$Q = \pi f \varepsilon_0 \varepsilon'' \left(E'^2 + E''^2\right) \tag{4}$$

where E' and E'' are real and imaginary parts of electric field, f is the microwave frequency, ε_0 is the vacuum permittivity and ε'' is loss factor of the material.

Effectiveness of the heating was evaluated by the ratio of the applied energy to the absorbed in composite and ceramic materials:

$$Q(\%) = \frac{\sum_{i=1}^{n} Q_i \cdot V_i}{P_{MW}} \cdot 100\% \tag{5}$$

where Q_i is energy, absorbed in ***i***-th FE of composite or ceramic, V_i is volume of ***i***-th FE, ***n*** is number of FE used for modelling of composite profile or ceramic die, P_{MW} is applied energy.

3 HEATING DEVICE AND FINITE ELEMENT MODEL

To demonstrate features and benefits of electromagnetic energy source, the heating of rod profile made of polyester resin POLRES 305BV and glass fibres 4800 tex in cylindrical cavity resonator was studied. Diameter of rod profile was 16 mm, and fibre volume content was 55 %. Scheme of the microwave heating device designed for industrial microwave frequency of 2.45 GHz [8] is presented in Fig. 1. The model was improved towards a homogeneous field distribution and high efficiency of the provided energy. This is performed adjusting the diameter of ceramic die until the target specifications were reached (Fig. 2).

Materials with different dielectric properties: zirconium dioxide, boron nitride and quartz glass for a microwave transparent die were selected and analysed. Their properties are presented in Table 1. Dielectric properties of boron nitride and quartz glass are similar, but zirconium dioxide has greater real and imaginary parts of permittivity. It is slightly microwave absorbing, therefore conductive heating of composite material by heated die also is expected.

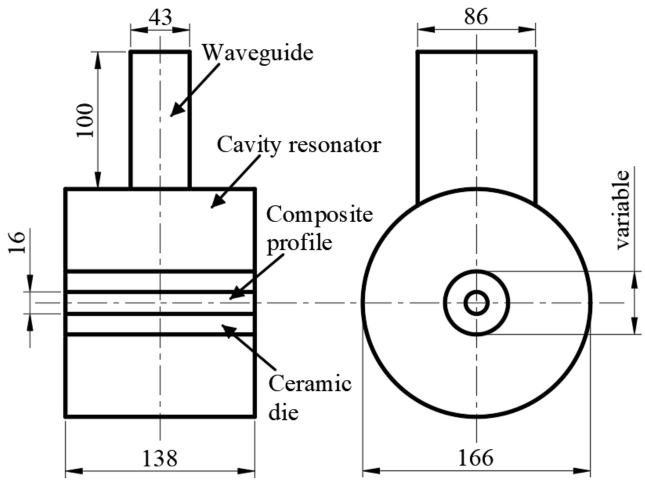


Figure 1: Scheme of microwave heating device

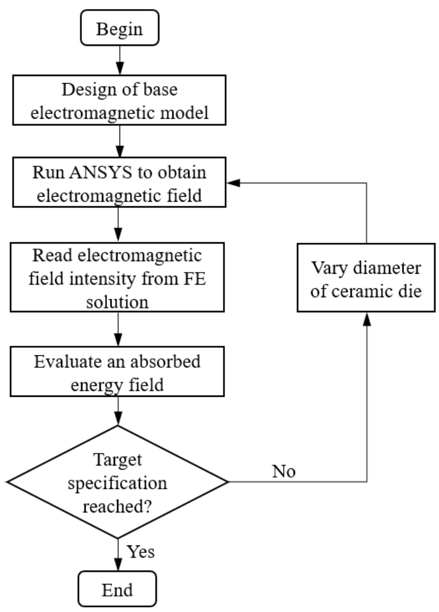


Figure 2: Electromagnetic algorithm for specified ceramic die

Table 1: Dielectric material properties

Property	Symbol (unit)	Composite	Air	Zirconium dioxide	Quartz glass	Boron nitride
Relative permeability	μ_r (-)	1	1	1	1	1
Relative permittivity	ε'_r (-)	5.7	1	29	3.5	3.0
Relative loss factor	ε''_r (-)	0.32	0	0.2	0.0001	0.0001
Resistivity	R (Ω)	-	∞	-	-	-

3.2 Finite element model

FE model was built according to scheme presented in Fig. 1 in ANSYS software using high frequency electromagnetic finite element HF120. A first-order hexahedral element formulation with one degree of freedom on each edge was used. Profile was brought out the cavity to small distance of 27.6 mm to obtain correct distribution and loss of electric field in composite profile on model boundaries. Perfect electric conductor (electric wall) boundary conditions were applied to all external surfaces of the FE model except the composite profile, because the waveguide and cavity were made of steel. TE_{10} mode for rectangular port with applied energy of 1 W was defined at the entrance of the waveguide. Due to symmetry of the examined problem, one half of the domain presented in Fig. 1 was modelled, and perfect magnetic conductor (magnetic wall) boundary conditions were applied to the symmetry plane. FE model is presented in Fig. 3.

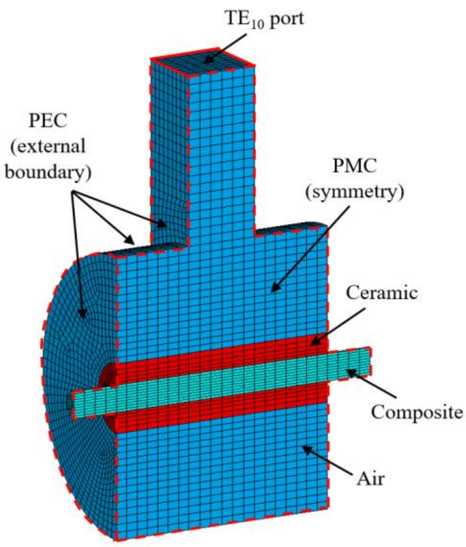


Figure 3: FE model with applied materials and boundary conditions

4 RESULTS AND DISCUSSIONS

Parametric study of ceramic die diameter influence on electric field in composite profile was formulated and executed for 3 materials with different dielectric properties.

4.1 Zirconium dioxide

Wide range of the diameter of ceramic die (D_{cer} = 24… 64 mm) was analysed. Amount of the energy, absorbed in the composite profile and ceramic die, is presented graphically in Fig. 4. It is seen that the maximum absorbed energy could be obtained by ceramic die diameter of 40.8 mm, but slight asymmetry of absorbed energy field (Table 2) is observed in this case. Therefore, ceramic die with diameter of 40.9 mm is selected as the optimal.

4.2 Quartz glass

For the die made of quartz glass the optimal diameter in considered range is D_{cer} = 33.8 mm. As it is shown in Table 2, in this case distribution of electric field is symmetric and maximally homogeneous, but energy absorption in composite – the maximal. 77.2 % of applied energy is absorbed in composite, but energy absorption in ceramic is negligible due to very small loss factor of the material.

4.3 Boron nitride

Calculation showed that in considered range of ceramic die diameter it is possible to obtain symmetric electric field by D_{cer} = 29.6 mm and D_{cer} = 60.8 mm. Smaller diameter gave electric field, concentrated in cavity centre, but bigger provides field, almost homogeneous along the profile (Table 2). Energy absorption in composite reached 83.7 % in the second case.

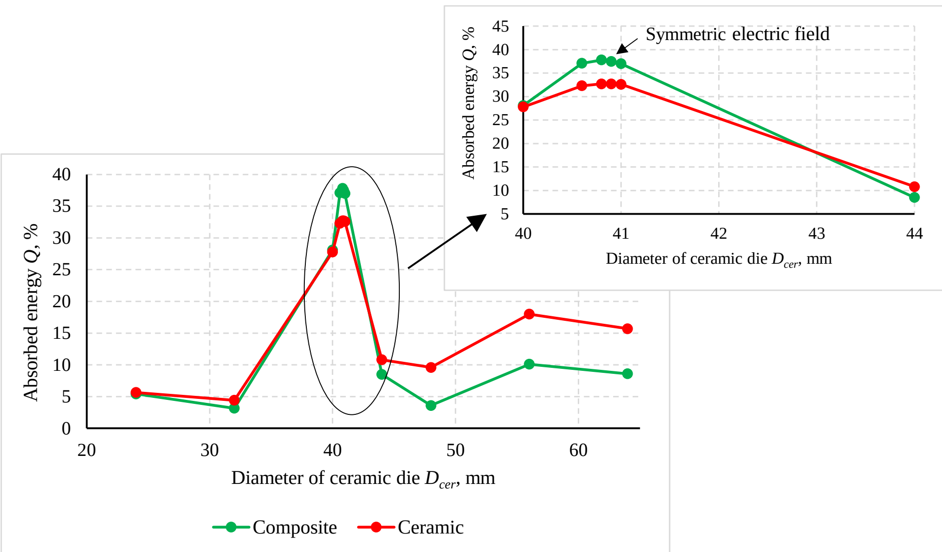
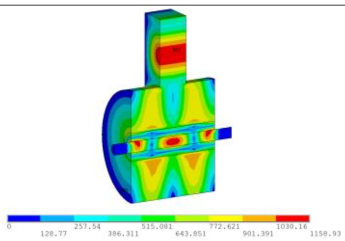
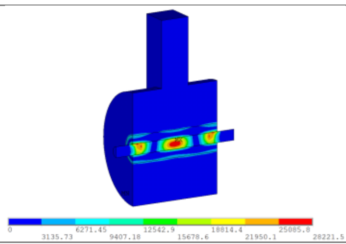
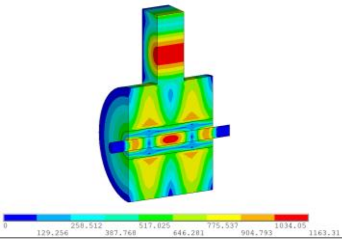
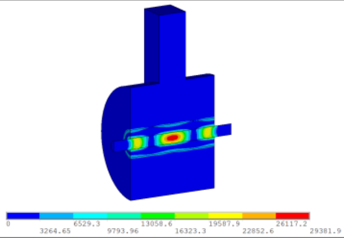
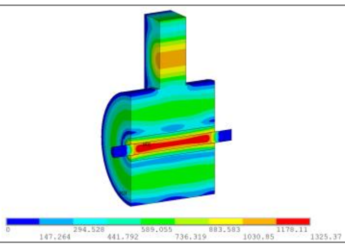
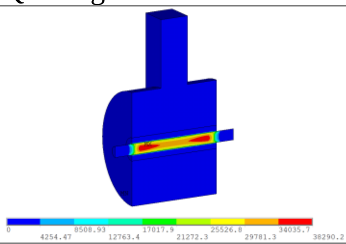
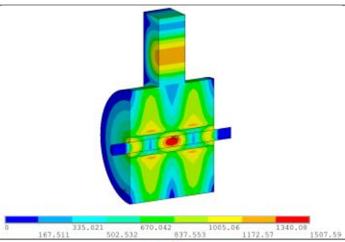
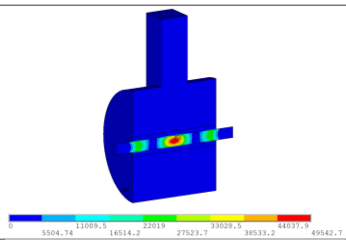
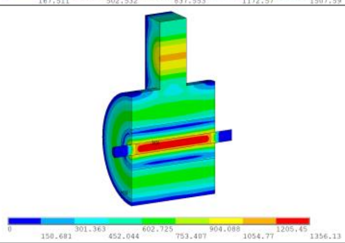
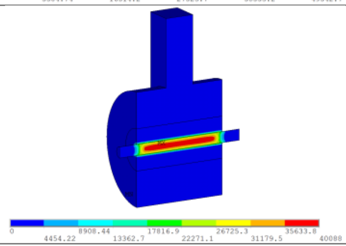


Figure 4: Dependences of absorbed energy on diameter of zirconium dioxide die

Table 2: Electric and absorbed energy fields

Diameter of ceramic die D_{cer}, mm	Electric field E, V/m	Absorbed energy field Q, W/m^3	Energy, absorbed in composite, %	Energy, absorbed in die, %
		Zirconium dioxide		
40.8			37.8	32.7
40.9			37.5	32.7
		Quartz glass		
33.8			77.2	0.03
		Boron nitride		
29.6			51.8	0.03
60.8			83.7	0.04

5 CONCLUSIONS

Influence of microwave transparent ceramic die diameter on electric field distribution in cylindrical cavity resonator was analysed using FEM. As a result of this parametric study the optimal diameter of the die providing an effective and uniform electric field in the composite profile was found for 3 ceramic materials having different dielectric properties.

- For zirconium dioxide characterized by relative big loss factor the optimal diameter is 40.9 mm. 37.5 % of applied energy is absorbed in composite material and 32.7 % - in ceramic die in this case.
- For quartz glass the optimal diameter is 33.8 mm. 77.2 % of applied energy is absorbed in the composite, energy absorption in die is negligible due to very small loss factor of the material.
- For boron nitride the optimal diameter is 60.8 mm. 83.7 % of applied energy is absorbed in the composite, energy absorption in die is also negligible.

The die made of boron nitride looks potentially better for application in microwave assisted pultrusion since this die provides the uniformest distribution of absorption energy field and the highest total energy absorption in pultruded profile.

Die made of zirconium dioxide also could be considered since it absorbs microwave energy, heats up and, therefore, provides conductive heating of the composite profile.

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