Microwave-assisted pultrusion process (MAP)

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Abstract. Pultrusion is a continuous and cost-effective process for the production of composite structural components with a constant cross-sectional area. This technological process could be made more effective by replacing conventional heaters by a high-frequency electromagnetic energy source characterized by fast, instantaneous, non-contact and volumetric heating. The state of the art in MAP processing is to replace the metal die at least partly by a microwave-transparent die or insert mostly made of ceramic, which is the main drawback and the main barrier to industrial uptake. This study presents a microwave module for accelerating the pultrusion process for (in principle) all tube geometries and shapes, without any use of microwave-transparent elements or inserts in the die. The module can be integrated into the pultrusion machine without any major modification of the die. It is also possible to retrofit existing pultrusion dies.

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INTRODUCTION

Pultrusion is a continuous and cost-effective process for the 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-sectional profile as in the die. At the final stage a traveling cut-off saw cuts the composite profile to the desired length.

The curing time of the resin limits the pultrusion speed, which significantly influences the cost of product. High-frequency electromagnetic energy sources characterized by fast, instantaneous, non-contact and volumetric heating reduce the curing time of the resins and enable higher pultrusion speeds and shorter pultrusion dies. It should be noted that microwave heating [1] is currently successfully and widely used in various industrial curing processes [2, 3].

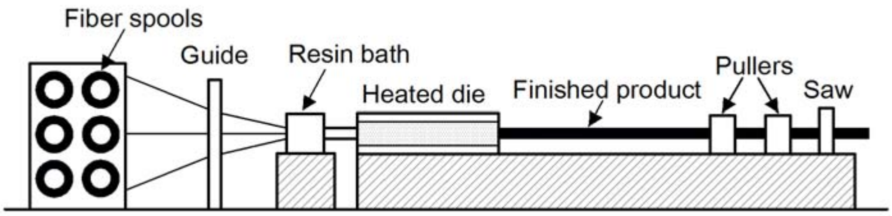

FIGURE 1. Pultrusion process

Microwaves are electromagnetic waves in the frequency range between 300 MHz and 300 GHz. Depending on the material, the applied microwaves are absorbed, transmitted or reflected. Metals in general have high electrical conductivity and consequently the microwaves are reflected. Microwaves heat material very fast, because they deposit contactless energy inside the material, independently of its thermal conductivity. Microwaves can be instantaneously controlled. For industrial application microwaves with a frequency of 915 MHz, 2.45 GHz or 5.8 GHz are used with a wave length of about 32 cm, 12 cm or 5.5 cm respectively.

Metheven et al. [4] described a MAP process in which the metal die was replaced by a microwave-transparent die and heating was applied in a so-called resonant or single mode cavities applicator. This approach has two principle drawbacks: the partial replacement of the metal die with ceramic and the limited possible diameters due to the cavity concept.

MICROWAVE MODULE

The objective was to develop a microwave module for a pultrusion die for tubes of any geometry and shape, for example circular, square or rectangular. The die for tube pultrusion consists of a hollow metal mold containing a metal core. The resin flows between the inner side of the metal mold and the core to fix the shape and geometry of the tube. The new approach is to use the die geometry for transmitting the microwave inside [5]. The microwave energy is directed from the beginning or end of the module into the core. The microwave travels along the core and is distributed inside along the metal mold. The resin there absorbs the microwave energy and is heated. The metal pultrusion die is completely retained and there is no need for any ceramic insert in the mold.

Figure 2 shows a sketch of the microwave module mounted at the end of the pultrusion die. The different colors indicate the different parts and the materials. The microwave module consists of a wave guide (grey) which is connected to the microwave generating part and a transfer module (brown). The length of the core of the die (green) is extended so that it continues into the transfer module, leaving a gap for the tube (blue). The metal mold (purple) ends on the outer side of the wave guide. The pultruded tube is already solid at the end of the pultrusion die and is guided through the transfer module.

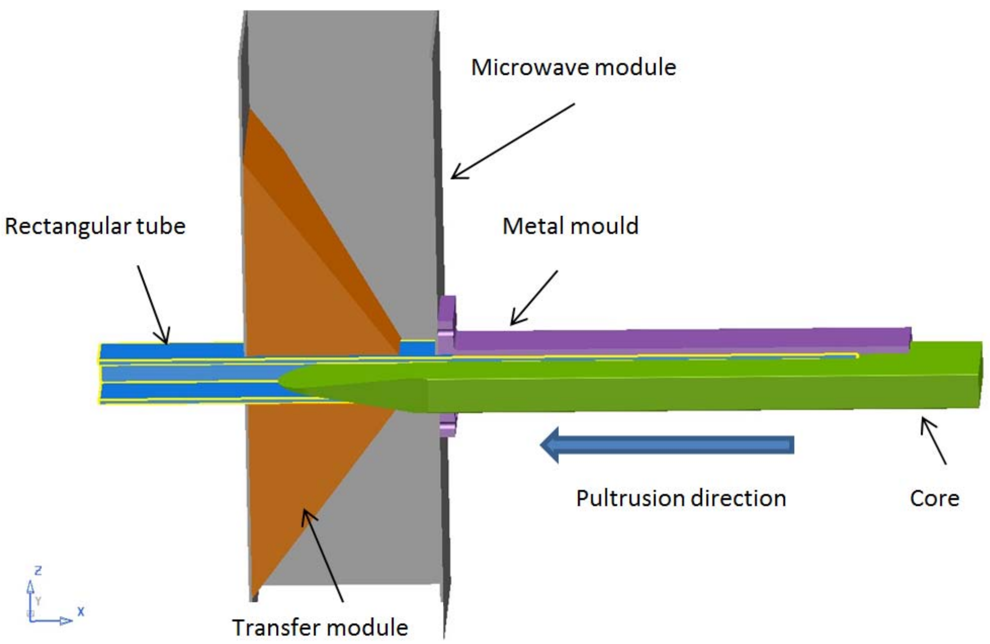

FIGURE 2. Schematic diagram of the electromagnetic model

To design the microwave module the microwave field in the module and in the resin-filled die is simulated with the FEM software package COMSOL Multiphysics. We decided to design the microwave module for a rectangular polyester glass fiber (POLRES 305BV + Unifilo 4800 tex) reinforced tube with the dimensions 80 mm length, 30 mm height and 3 mm wall thickness.

The simulation calculates the spatial electric field distribution, and consequently the dimensions and geometries for the design. Using the common approach of a harmonic oscillating electric field

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

Maxwell’s equations could be written as following:

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

This complex valued equation is solved numerically for the amplitudes of the electric field with respect to the relative permittivity, which for loss dielectric materials like mixtures of glass fibers and polyester resin is a complex function of frequency, temperature and degree of curing.

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

$\vec{E}(\vec{r},t)$	harmonic oscillating electric field
t	time
$\vec{r}$	location vector
f	microwave frequency
ε_0	vacuum permittivity
μ_0	magnetic constant
ε_r	relative permittivity

The dielectric properties of the glass fiber/polyester resin composition were measured before with a cavity perturbation method [6] versus temperature, and mean values taken at a temperature of T=60 °C were used for the calculation of the electric field distribution.

Running through the optimization loop the geometry of the microwave module was adjusted to achieve a symmetric field distribution inside the die, and a minimized power reflection.

Figure 3 shows the microwave field distribution in top view in the die and the microwave module for the optimized geometry. Along the tube a standing wave pattern is generated, with symmetrically distributed high (red) and low (blue) microwave energy spots. While being pulled through the die the tube passes spots of high and low energy, resulting in a homogenous heating as an average. The field distribution on the side of the tube has the same spatial distribution.

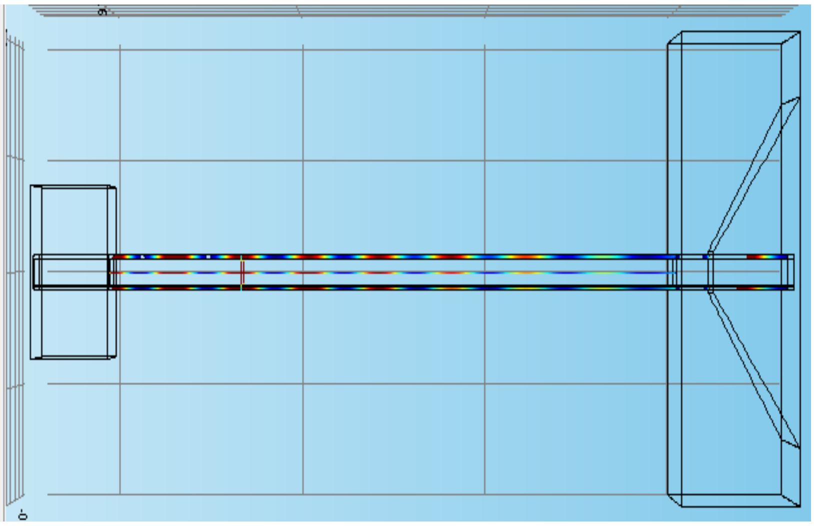

FIGURE 3. Field distribution top-view

DESIGN AND FIRST TEST OF THE MICROWAVE MODULE

On the basis of the numerical simulation results the microwave module was designed and built up. The module is mounted at the end of the pultrusion die (Fig. 4) and initial pultrusion tests are carried out. The tests show that the concept of the microwave module works. The microwave is radiated into the pultrusion die. The resin absorbs the radiation and cures considerably faster. This fast curing of the resin allows an increase of the pultrusion speed without any visible reduction in the quality of the pultruded tubes.

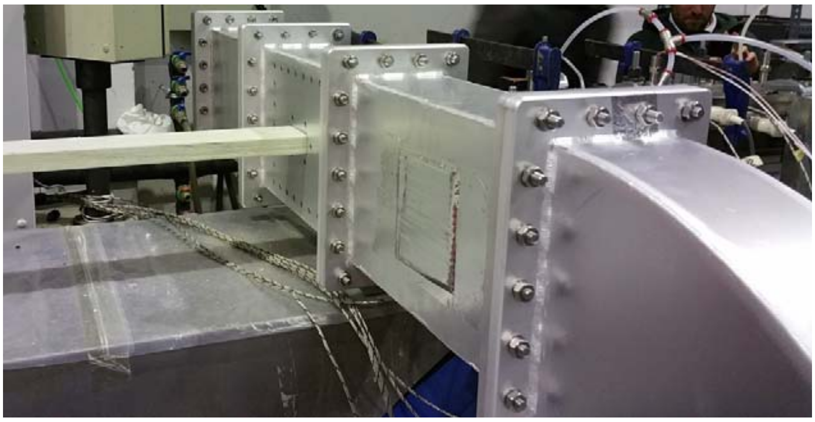

FIGURE 4. Mounted microwave module

CONCLUSION

With the developed microwave module, tubes can be pultruded more efficiently because of the higher possible pultrusion speed. The main feature of the concept is the microwave heating in the metal die without any major modifcations (e.g. no need for ceramic inserts). Further tests will be necessary to fully exploit the potential of the microwave module concept. In particular, it is necessary to determine the resins or polymers for which the microwave module will be most favourable.

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