Multiphysics Modelling of an Intermittent Microwave Pultrusion Process

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Pultrusion is one of the most important manufacturing processes for the production of fiber reinforced plastics. In pultrusion the reinforcing fibers are impregnated with a thermoset matrix material and then pulled through a heated forming die. The thermoset cures while moving through the die and solidifies with the cross section imposed by the tool [1]. As this is a continuous process it is suited very well to large scale production and therefore very economical compared to other production processes for fiber reinforced composites [2]. However, the process is limited to the production of profiles with constant cross section which are straight or of constant radius [3]. Microwave assisted pultrusion offers large potential for improvement of the process as the selective heating properties of microwaves can be used to only heat the pultrusion profile in an otherwise cold tool. Turning the microwave on and off during the process allows alternate application to cured and uncured sections. The uncured sections can then be reshaped in a following processing step e.g. by folding them into a more complex space frame structure [4].

In this work a microwave assisted intermittent pultrusion process using carbon fibers as reinforcement is investigated via finite element modelling in COMSOL Multiphysics. The microwave pultrusion tool is designed to keep the heating zone as short as possible which will also lead to sharp transitions between the cured and uncured profile sections. This was achieved by using a coaxial microwave applicator which is shown in Figure 1, where the profile is pulled through the center conductor. The center conductor is then interrupted by a ceramic window and the conducting carbon fibers will act as the center conductor from this point on. Due to the low conductivity of carbon fibers they will be effectively heated as soon as they exit the previous tool section. The ceramic window is kept short to minimize the heat loss of the pultrusion profile to the tool. The last section of the tool consists of a microwave filter to prevent leakage of radiation. The microwave is fed using a T intersection and three tuning stubs are included between the T and the window to achieve optimal heating of the profile. The profile is an elliptical cross section with a minor axis of 1.8 mm and a major axis of 5.8 mm.

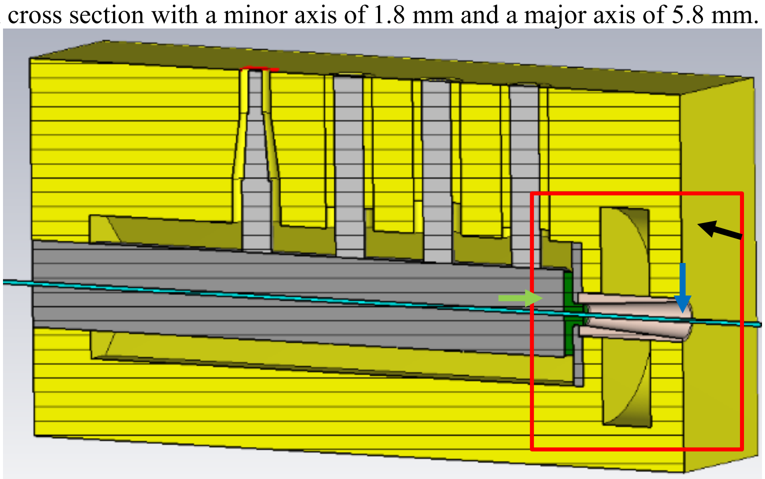

Fig. 1. 3D Model of the coaxial microwave applicator. The red box shows the parts of the tool which are used for the Multiphysics simulation. The arrows mark the points which are used for temperature measurements.

To simulate the curing of the resin, the profile needs to be modeled with a moving mesh, however the moving mesh in COMSOL is not supported by the electromagnetic wave solver. The simulation must therefore be split into two steps. First the electromagnetic model is solved by itself. The resulting power loss distribution can then be used as a heat source for the thermal model. This approach is valid, as the microwave behavior of the profile is dominated by the carbon fibers which do not change during the curing. The contribution of the resin can be neglected. To keep the solving duration of the thermal model within a reasonable time frame the model needs to be built as efficiently as possible. As the interaction of the microwave with the profile occurs only after the profile leaves the center conductor, only the tool area marked in red in Figure 1 needs to be considered for the simulation. While the exclusion of the matching elements and the T intersection might change the simulated efficiency the general interactions of the process will not be affected. Another measure to reduce the model size is to exploit the two axes of symmetry of the model reducing the model to a quarter of its original size. For the thermal model symmetry boundary conditions need to be applied to the cut surfaces, whereas the electromagnetic model requires the use of perfect magnetic conducting boundaries to allow the existence of the coaxial mode. The biggest contribution for increasing the simulation performance is by reducing the length of the profile as much as possible. Due to the small size of the profile cross section compared with the tool the mesh resolution of the profile needs to be very fine. The length of the profile is determined by the pultrusion speed and the process duration. To achieve results close to the steady state, several on-off cycles of microwave power should be included in this duration. Instead of simulating this duration entirely it is beneficial to only simulate a single on-off cycle. After this cycle the profile can be moved back to its original position and the temperature distribution of the last timestep can be used as the initial values for the next simulation cycle. This way the length of the simulated profile is kept as short as possible.

With this model the influence of several process parameters such as microwave power, pultrusion speed or tool temperature on the curing of the profiles and especially on the transitions between cured and uncured profile segments has been investigated. For the simulations a microwave power of 50 W and a pultrusion speed of 16 cm/min was used. The profile was modeled with an effective conductivity of 40 kS/m and the reaction kinetics of the fast-curing polyurethane resin system described in [5].

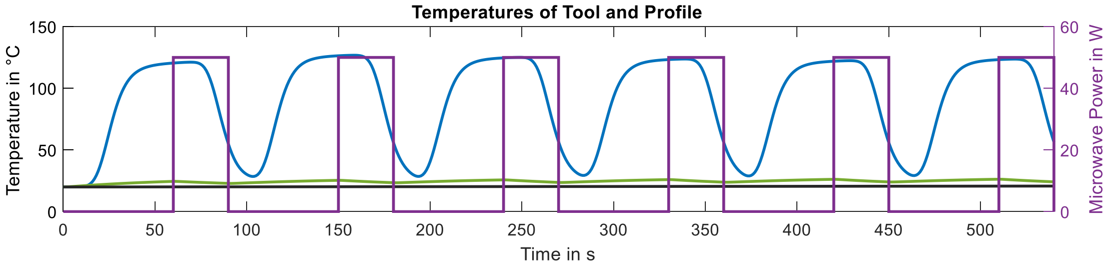

Fig. 2. Simulated temperatures at the profile surface directly after exiting the tool (blue), at the ceramic window(green) and on the tools outside wall (black, according to the arrows in Figure 1 and microwave power at the port (purple)

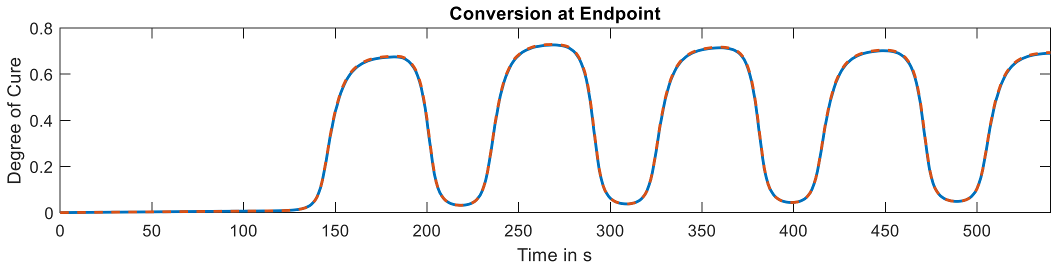

Fig. 3. Achieved degree of conversion after reaction has stopped at the center of the profile (blue, solid) and at the surface (red, dashed).

Figures 2 and 3 show the temperature and conversion at specific points over the course of six on-off cycles with 60 s on time and 30 s off time. It can be seen that the short contact region in the ceramic window serves its purpose and does not take too much heat out of the profile, as the second on cycle already achieves the maximum temperature and conversion. From Figure 3 the average transition lengths can be found. The average transition lengths from 20 % to 60 % degree of cure are 3 cm when turning the power on and 2.1 cm for turning the power off. This is a result of the profile transferring some of its thermal energy to the tool. Overall, this energy loss is still small as the ceramic disk only shows minimal heating and the outside wall of the tool does not show any temperature change. The homogeneity of the microwave heating is also sufficient, as no difference in cure can be observed between the profile center and profile surface in Figure 3.

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