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MODEL FOR THE COMPARISON OF CONVECTIVE AND CONTACT PREHEATING IN A THERMOPLASTIC PULTRUSION PROCESS

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SUMMARY: In this work, after modelling of the preheating process of commingled glass fibre/polypropylene yarn, the preheating of a thermoplastic pultrusion line to produce profiles with unidirectional reinforcement in axial direction was modified by adding contact heating pins. Compared to the convective heating used before, profiles with higher qualities could be produced at three times higher processing speeds. First trials of a combined braiding and pultrusion test, also with contact preheating, led to promising results.

KEYWORDS: Thermoplastic Pultrusion, Contact Heating, Glass Fibre/Poylpropylene, Commingled yarn, Braiding

INTRODUCTION

Composites with thermoplastic matrices compared with thermosetting composites possess e.g. higher toughness and damage tolerance, they are recyclable and post-formable and can be joined by welding [1]. Furthermore, their considerable energy absorption quantity enables their application as crash elements for automotive applications [2]. Recent developments of impregnation technology for thermoplastic matrices have generated considerable interest in the possibility of thermoplastic pultrusion [3-4]. Successful works have however only been performed for simple cross-sections, and at pultrusion speeds not dramatically exceeding those known for commercial thermoset pultrusion (0.6 - 1.2 m/min). Major reasons for these deficits are the inherent difficulties associated with the thermoplastic matrices, such as high processing temperatures and high melt viscosities. An additional obstacle may be a lack of both fundamental understanding of the governing process mechanisms and adequate mathematical models for predicting the relationships between the various processing variables and the resulting structural/mechanical properties of the thermoplastic pultruded products [5].

By special methods, the speed in thermoplastic composites processing could be dramatically increased [6-8]. Here, the heating process by convection of hot air is compared to contact preheating by heated copper pins. A technical solution was found how to realise the contact preheating in combination with a braiding process.

PULTRUSION PROCESS

For the experiments, as prepreg, the commingled yarn Twintex^{TM} from Vetrotex was used. It consists of glass fibres (GF) and polypropylene (PP) fibres. In every case, a GF volume content of 35% was used. A scheme of the used pultrusion line is shown in Figure 1. Fiber bundles are preheated in a 600 mm long hot air preheating zone before entering the heated die used for shaping the profile geometry. The heated die is followed by a water cooled cooling die. The beam is pulled by a pulling mechanism, which can realize speeds between 0.01 and 30 m/min. The temperature T_{PH} of the fiber bundles directly before entering the heated die and the temperature T_{HD} of the heated die are varied between 170°C and 300°C. Speeds up to 1.5 m/min are realized. The final cross section of the beams is 3.5 x 10 mm^2, i.e. it is sufficient for the manufacturing of specimens for mechanical testing.

Furthermore, a combined braiding and pultrusion line was used. With this line, 12 mm diameter GF/PP pipes were produced.

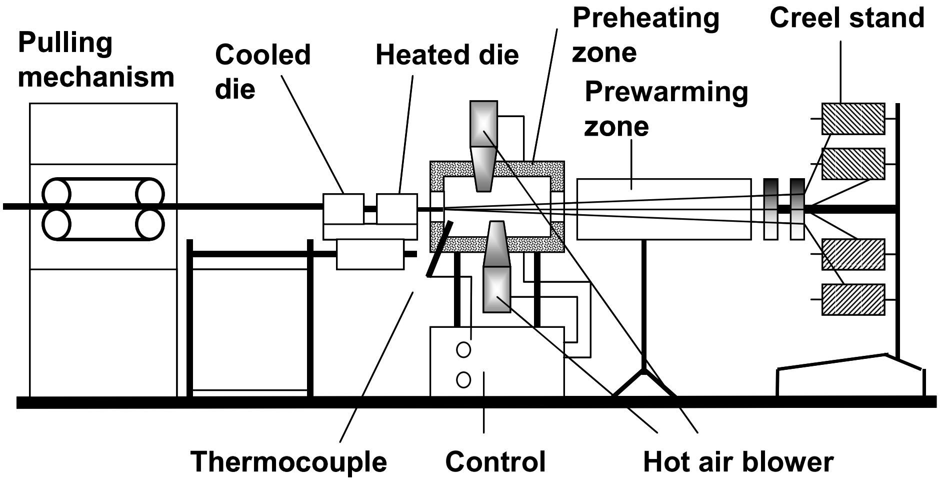

Fig.1 Scheme of thermoplastic pultrusion line

NECESSARY TIME TO HEAT THE PREPREG ROPE BY CONVECTION

About 65 – 70 ropes of 800 tex commingled yarn are necessary to fill the heated die cross section. The clustered ropes can be simplified to a homogeneous massive cross section, having the material properties of the present mixture of glass, Polypropylene and air. The diameter is fixed to 30 mm, estimated from observations during the experiments (Figure 2). This leads to a cross section area of 706.9 mm^2. Out of this, 10 mm x 3.5 mm (the final profile's cross section) belong to the commingled yarn. From the commingled yarn itself, 35 area percent belong to the glass fibres and the rest to PP. The mean density can therefore be calculated by the linear rule of mixture to $\rho_H = 74{,}66 kg / m^3$, using the density of air: $\rho_L = 1.2\ kg/m^3$, of GF: $\rho_{GF} = 2560\ kg/m^3$, and of PP: $\rho_{PP} = 906\ kg/m^3$ respectively.

In the following, the necessary time to increase the temperature in the centre of the bundle from 18°C to 170°C by convective heating is calculated. The temperature profile in the bundle, depending on time and location, is drawn in Figure 3. The mean temperature of the surrounding air in the preheating zone is estimated to be 200°C.

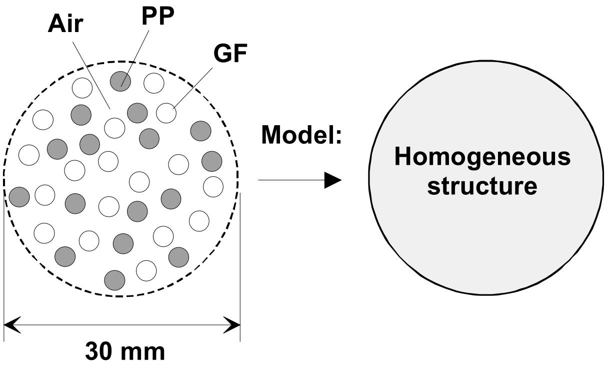

Fig.2 Simplified prepreg rope

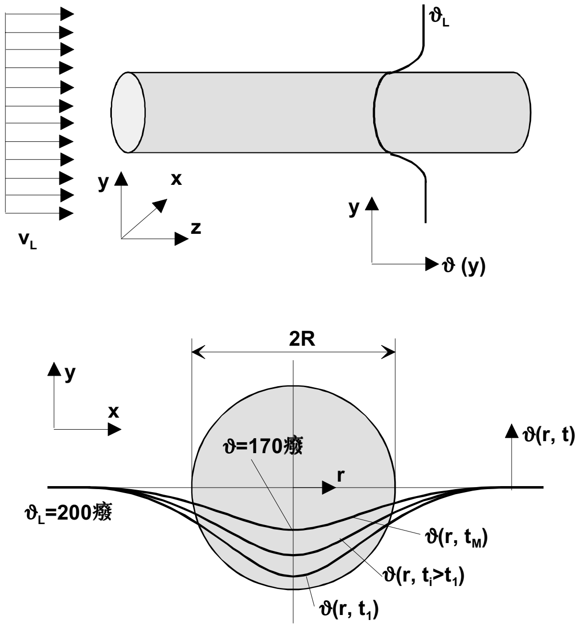

Fig.3 Temperature distribution in convective heated prepreg rope

In order to simplify the calculation, the bundle is simplified to a rod with an infinite length and a diameter equal 2R. For this problem, solutions of the Fourier heat transfer equation exist. The formulation in case of source and sink free transient behaviour, one dimensional in cylinder co-ordinates, is

$$\frac{\partial \vartheta}{\partial t} = a\left(\frac{\partial^2 \vartheta}{\partial r^2} + \frac{1}{r}\frac{\partial \vartheta}{\partial r}\right) \tag{1}$$

a: Temperature conduction coefficient [m^2/s]
t: Time [s]
r: Radius [m]
ϑ: Temperature [K]

The initial and boundary conditions can be formulated as follows:

$$\alpha_L \left(\vartheta(r=R,t)-\vartheta_L\right) = -\lambda_H \left.\frac{\partial\vartheta}{\partial r}\right|_{r=R} \tag{2}$$

$$\vartheta(r,t=0)=\vartheta_A \tag{3}$$

α_L: Heat transfer factor air - prepreg [W/m^{2}K]
R: Half diameter of prepreg [m]
ϑ_L: Air temperature of hot air blower [°C]
λ_H: Heat conductivity number of prepreg [W/mK]
ϑ_U: Ambient temperature = 18°C

The dimensionless form of the differential equation can be solved by the product approach [9]. With

$$\Theta_M = \frac{\vartheta_M - \vartheta_L}{\vartheta_U - \vartheta_L} \tag{4}$$

$$Fo = \frac{at}{R^2} \tag{5}$$

Θ_M: Dimensionless temperature [1]
Fo: Fourier number [1]

yields the solution from (7):

$$\Theta(\frac{r}{R},Fo) = \sum_{i=1}^{\infty} 2\frac{J_1(\mu_i)}{\mu_i(J_0^2(\mu_i)+J_1^2(\mu_i))} J_0(\mu_i \frac{r}{R}) exp(-\mu_i^2 Fo) \tag{6}$$

with

$$\mu_i = Bi\frac{J_0(\mu_i)}{J_1(\mu_i)} \tag{7}$$

$$Bi = \frac{\alpha R}{\lambda} \tag{8}$$

J_0, J_1, μ_i: Bessel function coefficients [1]
Bi: Biot number [1]

For Fourier numbers $Fo > 0.21$, the error of equation 6 is below 1%, if the calculation is stopped after the first term of the summation [9]. Later it will be shown that this is allowed in the present case. Therefore, for the core of the rod result

$$\Theta(Fo) = 2\frac{J_1(\mu_1)}{\mu_1(J_0^2(\mu_1)+J_1^2(\mu_1))} J_0(0) exp(-\mu_1^2 Fo) \tag{6a}$$

Rearranged result for $t = t_M$:

$$t_M = -\frac{R^2}{\mu_1^2 a} ln\left(\Theta_M \frac{\mu_1\left(J_0^2(\mu_1)+J_1^2(\mu_1)\right)}{2J_1(\mu_1)} \right) \tag{6b}$$

t_M: Necessary time to obtain ϑ_M in the centre of the rod [s]

For determination of the Biot number, it is necessary to calculate the heat transfer factor α at the cylinder with an infinite length. This can be realised with the equation

$$\alpha = \frac{Nu\ \lambda}{L} \tag{9}$$

Nu : Nußelt number [1]

λ : Heat conductivity [W/mK]

L : Characteristic length [m]

As characteristic length, the length of the preheating zone of 0.6 m is used. To determine the Nußelt number, the flow is taken as a turbulent flow over a plane plate, because the cylinder (the prepreg bundle) is streamed along lengthwise (the air flows in axial direction over the prepreg rope). The necessary equation is

$$Nu = \frac{0{,}037\, Re^{0,8}\ Pr}{1 + 2{,}443\, Re^{-0,1}(Pr^{2/3} - 1)} \tag{10}$$

with

$$Re = \frac{vL}{\nu} \tag{11}$$

Re: Reynolds number [1]

The speed of the heating air still has to be determined:

$$v_L A_L = \dot{V}_L \tag{12}$$

v_L: Speed of heating air [m/s]

A_L: Cross section area of preheating zone [m^2]

The cross section area results from the geometry (width x height of the preheating zone). $v_L = 1{,}365\ m/s$ and therefore $Re = 52230$ result. Although the critical Reynolds number of 10^5 is not exceeded, the flow was calculated as turbulent, because the heat transfer is much better as in the laminar case. This leads to a conservative comparison of the necessary heating time compared to the contact heating. Furthermore result $Nu = 187.6$, $\alpha = 7.504\ W/m^2K$, $Bi = 4.69$, $\Theta_M = 0.1648$.

To determine the thermal conductivity a, the heat transfer coefficient of the prepreg must be calculated by the linear rule of mixture. The results are $\lambda_H = 0{,}052\ W/mK$ and

$$a = \frac{\lambda_H}{\rho_H c_H} = 5.568 \cdot 10^{-7}\ m^2/s \tag{13}$$

The Bessel coefficients are still missing. They are determined by the aid of the Biot number (equation 8) listed in tables. Intermediate values are determined by linear interpolation. The method is described in [9]. The results are: $J_0 = 0.260$ and $J_1 = 0.600$. This lead to $t_M = 207.4\ s$, corresponding to a pulling speed of 0.16 m/min at the given preheating zone length.

From the above mentioned, it can be summarised, that 207.4 s are necessary to exceed the temperature of 170°C in the centre of the prepreg rope. However, the melting enthalpy of the prepreg is not taken into account. This would slow down the heating process. Nevertheless, the result enables a comparison with the effectivity of a contact preheating process.

CONTACT HEATING

The contact heating process is simulated by two half infinite rigid bodies contacting on one surface, see Figure 4. The initial temperatures differ. The contact of the copper heating device is set to 200°C, the prepreg initial temperature corresponds to 18°C. This enables a conservative estimation of the time necessary to increase the temperature of the prepreg in a depth corresponding to its real thickness to 170°C. Here too, the procedure is started by drawing the expected qualitative temperature distributions in time and location (Figure 4). In this case, the differential equation is

$$\rho c \frac{\partial \vartheta}{\partial t} = \lambda \left(\frac{\partial^2 \vartheta}{\partial x^2} \right) \tag{14}$$

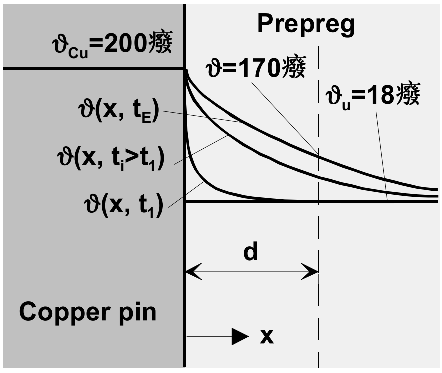

Fig.4 Temperature distribution in contact heated prepreg rope

After introduction of the dimensionless temperature (Equation 4), following [9], the solution for equation 14 is

$$\Theta = erf\left(\frac{d}{2\sqrt{a t_E}} \right) \tag{15}$$

t_E: Time necessary to increase the prepreg temperature to 170°C in depth *d* [s]

For equation 15, solutions can be found in specific tables. The argument in the error function must be 0.09546. The thermal conductivity *a* has to be determined once more by equation 13, because here, the geometry differs to the one of the thick prepreg rope in the conductive preheating above: the copper pins cause a strong widening of the prepreg rope, leading to a considerable reduction of its thickness. As air content, the value for the cubic densest packing, 0.215, is taken. For the prepreg, 78.5 % remain, from which 35 % consist of glass fibres and the rest of PP. With the linear rule of mixtures, the following results are obtained: $\lambda_H = 0.475\ W/mK$, $\rho_H = 1166\ kg/m^3$, $c_H = 1280\ J/KgK$ and $a = 3.183 \cdot 10^{-7}\ m^2/s$.

The thickness of the prepreg rod d is calculated as follows. At the pins, the rope is widened to 10 cm (this corresponds to a factor of 10, related to the final width of 10 mm). After passing the heated die, the height will be 3.5 mm (resulting from the die's cross section). The fraction of the prepreg on the whole thickness is 78.5 % (the rest consisting of air), therefore it follows: $d = 10 \cdot 3.5mm / 0.785 = 0.446mm$. This result in a time t_E = 17.14s.

The necessary heating time in reality is certainly considerably shorter, as the prepreg will not be heated starting from ambient temperature, but is already partly heated by the hot air heating. Also, here, the melting of the PP was not taken into account. However, it is obvious, that the relative time necessary in both models is similar. Therefore, it can be generally stated that the contact heating reduces the heating time by at least a factor of 10.

PRACTICAL REALISATION AND EXPERIMENTAL RESULTS

In order to verify the analytical results and to improve the pulling speed, a contact heating device with three controlled heated copper pins was constructed, see Figure 5. This device was inserted in the preheating zone. It works as follows: the commingled yarn is lead over the first, beneath the second and then again over the third pin, before entering the heated die. Between the pins, due to the friction, a certain pulling force develops. Therefore, the rope is widened a lot, enabling short heat flow paths and a rapid heating [10].

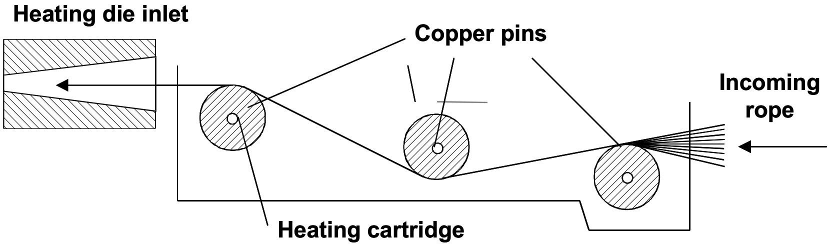

Fig.5 Realisation of contact heating on UD pultrusion

On Figures 6 and 7, the results of shear strengths determined without and with application of the contact heating pins are compared. Already at a first glance it can be seen that the pulling speed could nearly be increased three times without any problems. Furthermore, the shear strength of the contact heated specimens does not vary significantly at the realised processing parameters. Its mean value is about 50 % higher as the shear strength of the other specimens (35 vol. % GF) produced without the pins. This is a hint for a good impregnation quality.

Furthermore, the contact heating principle was applied to a combined pultrusion and braiding process [11]. In this process, using a Muratec Braiding machine, type J32, Murata, Kyoto, Japan, pipes with 12 mm outer diameter, a wall thickness of 1 mm and ±45° reinforcement could be produced out of 64 GF/PP commingled yarn tows, each with 800 tex. With the convective heating process, pulling speeds of 0.1 m/min could be realised. The maximum compression modulus was about 2.8 GPa, the void contents were around 4 %.

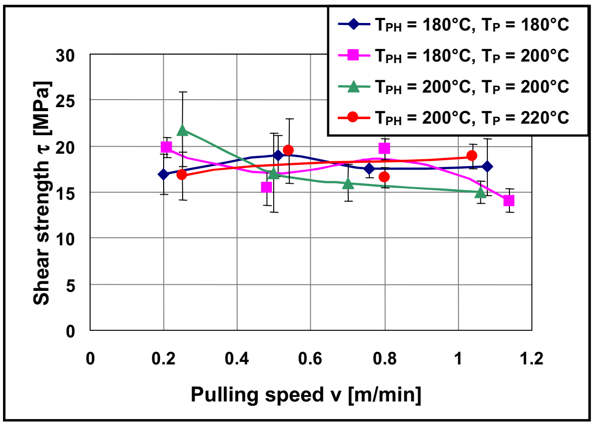

Fig.6 Shear strength of profiles produced with contact heating (T_P: pin temperature, T_{HD}: constant 200°C)

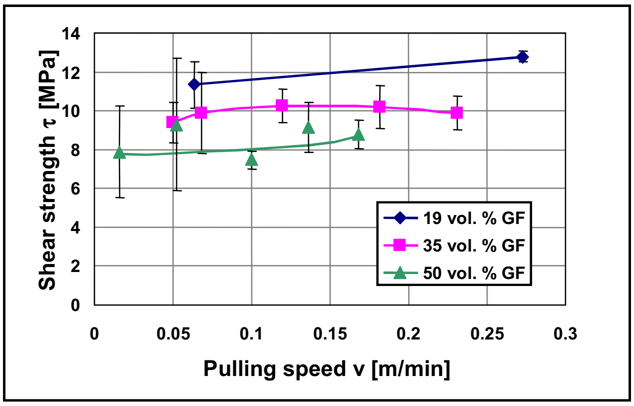

Fig.7 Shear strength of profiles produced with convective heating, T_{PH}=163°C, T_{HD}=235°C

The pultrusion line was modified as shown in Figure 8. The contact heating was realised by three heated rings, heating the yarn rapidly over its melting temperature. A list of parameter combinations and resulting compression moduli is shown in Table 1. Figure 9 shows the good quality of impregnation.

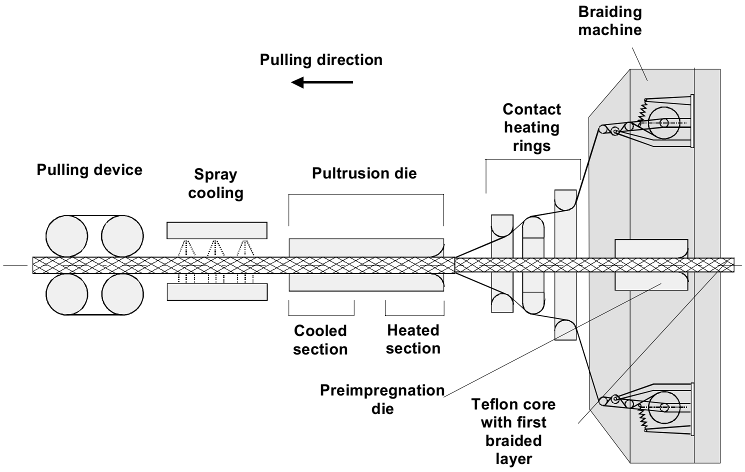

Fig.8 Pullbraiding line with contact preheating

Table 1. Parameters used at pullbraiding experiments with the contact preheating device

Temperature of female rings [°C]	**Temperature of male ring [°C]**	**Temperature at die inlet [°C]**	**Temperature at die outlet [°C]**
80	165	215, 230 or 240	80

Temperature at die inlet [°C]	**Compression modulus E_D [GPa]**	**Standard deviation E_D [GPa]**
215	3.87	2.13
230	5.17	1.09
240	2.95	0.88

CONCLUSIONS

The modelling of the preheating zone of a thermoplastic pultrusion process was done analytically by simplified models of the intermediate material by using heat balances and the heat conduction equation. The melting enthalpy of the polypropylene was neglected, however, its maximum influence on the heat balance was estimated. By a contact heating, the necessary preheating time is reduced by a factor of 10 compared to the convective hot air heating.

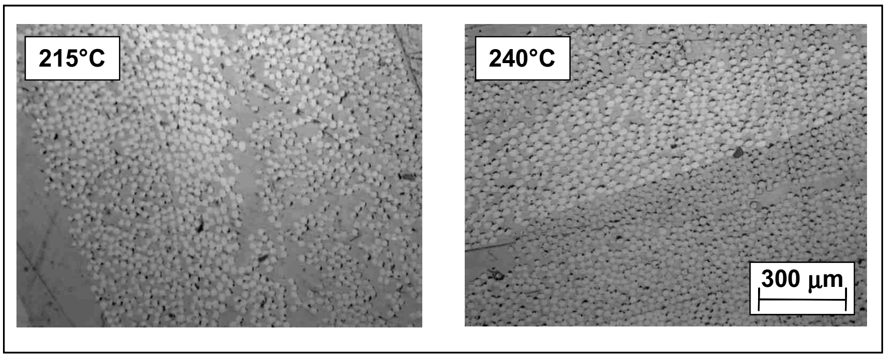

Fig.9 Cross sections of pullbraided profiles at two different die inlet temperatures

For the characterisation of the pultrudate's quality, after experiments, mechanical and morphological testing was conducted, and co-relations to process parameters were made. It was shown that a contact preheating leads to increased mechanical and morphological properties. The shear strength could be increased by 50 % compared to pultrudates conductively heated by hot air. In first trial experiments with a combined braiding and pultrusion line, also an improvement of the mechanical properties could be obtained.

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