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«СКОЛКОВСКИЙ ИНСТИТУТ НАУКИ И ТЕХНОЛОГИЙ»

На правах рукописи

Минченков Кирилл Олегович

Исследование механических свойств пултрузионных термопластичных композиционных материалов

Специальность: 1.1.8. Механика деформируемого твердого тела

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Study of the mechanical properties of pultruded thermoplastic composite materials

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General description of work

Fiber-reinforced polymer (FRP) are used in aerospace, civil engineering, energy systems and marine applications due to their high specific strength and stiffness, increased durability, and high fatigue and corrosion resistance. One of the most productive methods of manufacturing composites is pultrusion. In the pultrusion process, a fiber with polymer passes through a heated die. Inside the die, the fiber is impregnated with polymer and the composite material takes the desired shape. At the exit of the die, a glass fiber with a constant cross section is obtained. Today, most pultrusion profiles are made of thermoset polymers that do not melt when heated. The use of thermoplastic polymers in pultrusion composites will increase the impact strength of the material, make it easier to process and create welded structures due to the ability of thermoplastics to melt during the heating.

The **relevance** of the dissertation lies in the fact that it addresses the existing thermoplastic pultrusion challenges related to the high viscosity of the melt thermoplastics, which increases the porosity of the manufactured profiles and reduces the mechanical properties.

Extent of research topic development. Currently, profiles of complex shapes such as boxes, L-shape, I-beam, U-shape are produced by thermoset pultrusion. Thermoset composite polymer structures have found their application in pedestrian bridges, fences, pool covers, etc. Unfortunately, thermoplastic large profiles and structures based on them are not presented in scientific literature and engineering practice. Thermoplastic pultrusion used for prototype production of rods up to 20 mm in diameter for intended application in insulation of overhead power lines and thermoplastic strip profiles up to width of 30 mm and thickness up to 3.5 mm.

Three-dimensional mathematical models have been developed to study the process of thermoset pultrusion. These models allow to analyze resin flow and impregnation, curing and crystallization, heat transfer, pulling force, residual stresses, and shape distortion. However, in the field of thermoplastic pultrusion, only two-dimensional models of fiber impregnation, heat transfer, pulling force, and crystallization kinetics have been presented.

Thermoplastic composite materials are considered to have inferior mechanical properties compared to thermoset materials. This is due to the challenge of impregnating the fiber with high viscosity thermoplastic polymer, which makes it difficult to achieve a high volume fraction of fiber and low porosity in the final product. To address this issue, prepregs are utilized, which involve impregnating the fiber with polymer to reduce porosity of thermoplastic profiles. However, there are few scientific studies that examine the influence of prepreg properties on the mechanical properties of pultruded thermoplastic composite materials.

The **aim** of the dissertation is to improve the mechanical properties of thermoplastic pultruded composite materials. To accomplish this aim, the following **objectives** have been solved:

- Effects of prepreg manufacturing methods on the mechanical properties of pultruded profiles are studied.
- Effects of raw materials quality (fiber volume fraction, porosity) on the mechanical properties of pultruded materials are studied.
- Mathematical model of heat transfer to analyze the influence of heated die temperature and pulling speed on mechanical properties of pultruded profiles is developed.

The scientific **novelty** of this thesis is summarized as follows:

- The technology for manufacturing thermoplastic tapes from commingled yarns with a fiber volume fraction of 50% for use in pultrusion has been developed. Pultruded glass fiber/polypropylene profiles made of these tapes have flexural modulus at least 37 GPa.
- New structural composite channel (31 mm × 25 mm), tube (20 mm × 30 mm), and strip profiles (75 mm × 3.5 mm) were manufactured by thermoplastic pultrusion.
- New design of windows structure with reinforcing cores made of thermoplastic pultruded composites instead of steel ones was presented.
- A three-dimensional mathematical model was developed and validated to analyze

and predict the heat transfer inside the composite material at different pulling speeds and heating temperatures.

The **theoretical significance** of this thesis lies in the determination of the temperature distribution inside the thermoplastic composite material during pultrusion, which effects on mechanical properties. The study also determined the effects of raw material quality on the mechanical properties of the manufactured material. The **practical significance** of the thesis lies in the ability to predict the optimal pultrusion process parameters for manufacturing high-quality profiles. Additionally, the study demonstrated the practical application of thermoplastic pultrusion profiles in window structures, which improved strength and thermal resistance.

Research methodology and methods. The heat transfer equations within the die and material were solved using the finite element method (FEM). The melting temperatures of polymers were obtained by the differential scanning calorimetry (DSC) method. The cross section of the profiles was examined by optical and electron microscopy. Density estimation was carried out by gravimetric method. The mechanical properties of the fabricated materials were determined experimentally on testing machines according to ASTM, ISO standards.

There are following **statement to be defended:**

- Composite profiles made of glass fiber and polypropylene with a flexural modulus of 37 GPa have been produced by pultrusion from tapes made in the laboratory.
- Increase in pulling speed results in a reduction in flexural, tensile, and compressive strength and modulus. This reduction in mechanical properties is attributed to inadequate heating of the pultruded material, which increases the porosity.
- Three-dimensional mathematical model of heat transfer of thermoplastic pultrusion is developed for prediction of pulling speed and heating temperature to manufacture composite material with high mechanical properties.
- The developed heat transfer model was used to predict pultrusion parameters for the production of structural profiles, which were used in the window structure as

reinforcing core.

The **validity and reliability of the results** are ensured using a mathematical model is based on physics equations that are solved using finite element method. Model allows to predict pultrusion process parameters such as pulling speed, heating temperature based on the profile shape. The results of this work are in agreement with experimental data obtained during the manufacturing of various pultrusion products. The reliability of the work is confirmed by the accuracy of mathematical formulations and the validity of the numerical methods and programs used. All mechanical tests were conducted in accordance to ISO, ASTM, GOST standards.

The results of the thesis were obtained by the applicant through a series of personal and direct **contributions**. The applicant conducted a comprehensive literature search and analysis related to the research topic, performed mechanical tests, prepared samples, and performed microscopy. The mathematical model of heat transfer was developed by the applicant under the supervision of Associate Professor A. Safonov. The production of tapes and pultrusion composite material was conducted by the applicant under the guidance of Senior Engineer S. Gusev in the Laboratory of Composite Materials and Structures at the Skolkovo Institute of Science and Technology. The fabrication of materials for the window structure was conducted by the research group of the Materials Technology Center of the Skolkovo Institute of Science and Technology. The analysis of the obtained data regarding the window structure was carried out by the applicant as a chapter part of this thesis.

The **dissertation structure** includes an abstract, six chapters, conclusions, list of figures, list of tables, list of abbreviations, bibliography of 174 references and acknowledgements. The full volume of the dissertation is 123 pages, including 58 figures and 18 tables.

The dissertation content

Flowchart of the study is shown in Figure 1.

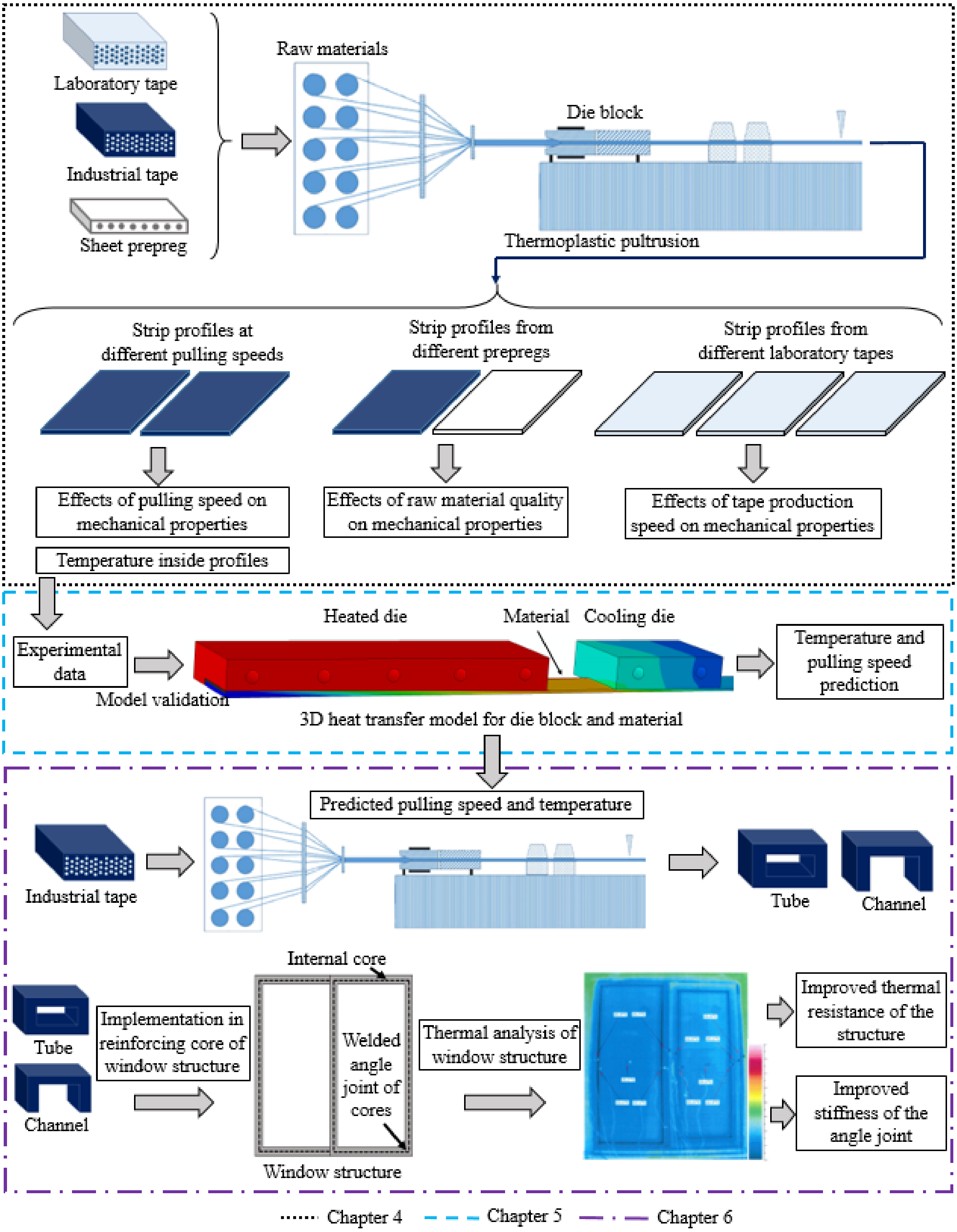


Figure 1. Flowchart of the study.

The 1st **chapter** “Introduction” covers the relevance of the work, the aim, and objectives, presents the objects of research, scientific novelty, theoretical and practical significance of the work, approbation of the results, personal contribution of the author, and thesis structure.

In the 2nd **chapter** “The state of the art” the literature review, forecasts, and trends of thermoplastic pultrusion are overviewed. Process parameters such as preheater temperature, temperature and geometry of the heated die, temperature of the cooling die, pulling speed, pulling force, and pressure are discussed. Raw materials and their structure in thermoplastic pultrusion are presented. Process modeling of impregnation, heat transfer, pressure and pulling force are observed.

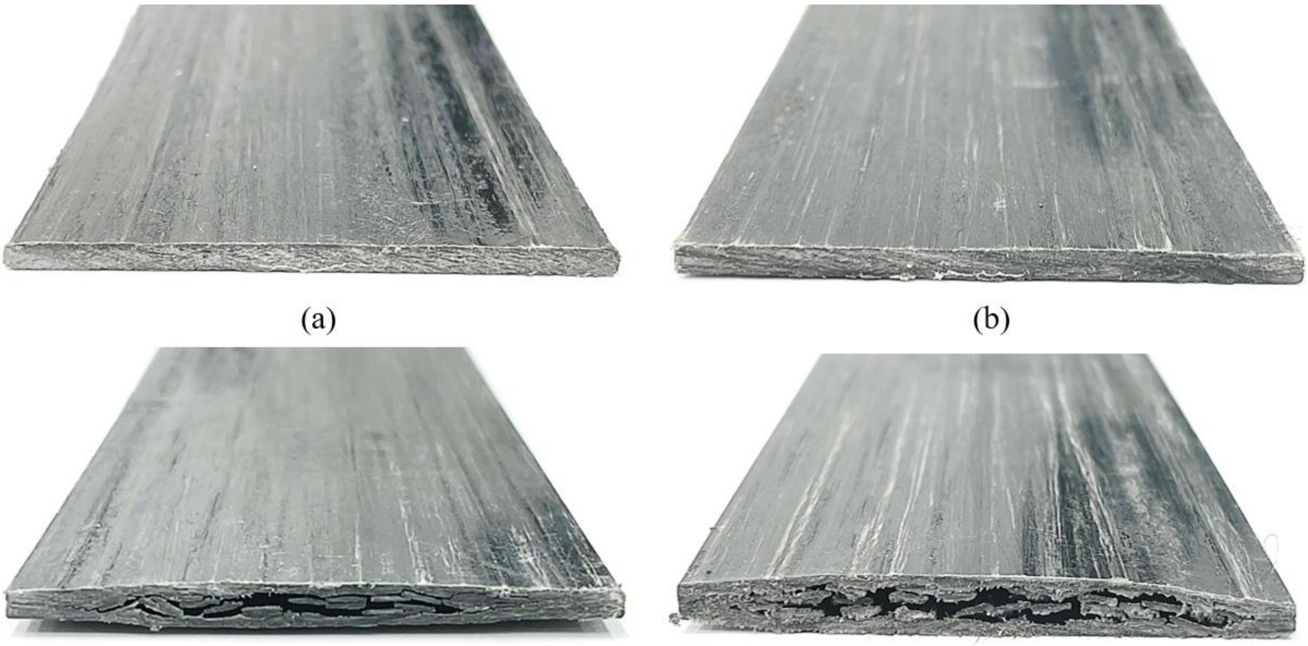
Chapter 3 is entitled “Materials and methods” are described used prepregs for thermoplastic pultrusion. This chapter includes pultrusion setup for production of strip profile 75 mm × 3.5 mm, rectangular tube 20 mm × 30 mm with wall thickness of 3.5 mm, and channel profile with dimensions of 25 mm × 31.5 mm and a wall thickness of 3.5 mm. In this chapter tape production method from commingled yarns on extrusion machine is described. The process is as follows: commingled yarns are taken from the spools and fed through the guiding system into the heated die block. Then the formed strip exiting the heated die block passes through the puller into the accumulator located at a distance of 6 m from the die block. After the accumulator, the tape is wound onto the spools. Mechanical test standards and procedure of microscopic observation, thermal analysis and surface roughness measurement are described.

Chapter 4 is entitled “Effects of raw materials on thermoplastic pultruded profiles”. This chapter explores how the quality, structure of raw materials and pultrusion process parameters affect the mechanical properties of thermoplastic profiles. To ensure brevity and clarity, the code SP-PT-PSNN to denote the profiles was used. The first two letters “SP” represent the abbreviation from strip profile, the second two letters “PT” represent the prepreg type, the next two letters 'PS' represent the pulling speed, and the last two digits “NN” represent the value of pulling speed in meters per minute.

Figure 2 shows raw materials used for this study. To produce the first batch of composite strip profile 75 mm × 3.5 mm, 110 industrial tapes were used. Heated die temperature was set 200 ± 10 °C, while that of the cooling die was 60 ± 10 °C. Thermoplastic profiles were pultruded at four pulling speeds (0.2, 0.4, 0.6, and 0.8 m/min) to investigate effects of pulling speed on mechanical properties. Figure 3 shows manufactured profiles.

(a) (b) (c)

Figure 2. Raw materials: (a) industrial tape, (b) sheet prepreg, (c) laboratory tapes



(a) (b)

(c) (d)

Figure 3. Pultruded thermoplastic profiles produced at different pulling speeds:
(a) SP-IT-PS02, (b) SP-IT-PS04, (c) SP-IT-PS06, (d) SP-IT-PS08.

The second batch of thermoplastic strip profile 75 mm × 3.5 mm was produced from laboratory-made tapes. Three types of tapes were used. The first type was manufactured at production of 2 m/min and named T2. The second tape type was manufactured at production speed 5 m/min and named T5. The third tape type was produced at pulling speed 8 m/min and named T8. Each profile was produced from 76 tapes of a single type at the pulling speed of 0.2 m/min. Pultruded profiles are marked SP-T2-PS02 (strip profile – tape T2 – pulling speed 0.2 m/min), SP-T5-PS02, and SP-T8-PS02. Heated die temperature was set 200 ± 10 °C, while that of the cooling die was 60 ± 10 °C. All three types of profiles are visually indistinguishable from each other and are similar to SP-IT-PS02 (Figure 4 (a)).

The third batch of thermoplastic strip profile 75 mm × 3.5 mm was produced from sheet prepreg. 11 sheets with width of 75 mm were used. Proper sheet consolidation was achieved at a heated die temperature of 210 ± 10°C, cooling die temperature of 60 ± 10°C, and pulling speed of 0.1 m/min. Profiles were marked as SP-SP-PS01 (strip profile – sheet prepreg – pulling speed 0.1 m/min). Pultrusion process parameters of all manufactured profiles are summarized in Table 1.

Table 1. Pultrusion process parameters of GF/PP manufactured strip profiles

Manufactured GF/PP profile	Pulling speed, m/min	Heated die temperature, °C	Colling die temperature, °C	Type of prepreg	Number of prepreg elements
SP-IT-PS02	0.2	200 ± 10	60 ± 10	Industrial tape	110
SP-IT-PS04	0.4	200 ± 10	60 ± 10	Industrial tape	110
SP-IT-PS06	0.6	200 ± 10	60 ± 10	Industrial tape	110
SP-IT-PS08	0.8	200 ± 10	60 ± 10	Industrial tape	110
SP-T2-PS02	0.2	200 ± 10	60 ± 10	Laboratory-made tape T2	76
SP-T5-PS02	0.2	200 ± 10	60 ± 10	Laboratory-made tape T5	76
SP-T8-PS02	0.2	200 ± 10	60 ± 10	Laboratory-made tape T8	76
SP-SP-PS01	0.1	210 ± 10	60 ± 10	Sheet prepreg	11

To investigate effects of raw material quality on mechanical properties comparison between SP-SP-PS01 and SP-IT-PS02 materials are prepared in Table 2. Strip profile made of sheet prepreg (SP-SP-PS01) demonstrated higher flexural, tensile, and compressive strengths, by as much as 19.8%, 27.3%, and 27.1%, respectively in comparison to profile made of industrial tape (SP-IT-PS02). This difference in mechanical properties is attributed to the presence of the defect (matrix cracks and debonding) in industrial tape, which is lacking in sheet prepreg. Although the source raw material had an equal reinforcement volume fraction (38%), the SP-SP-PS01 outperformed SP-IT-PS02 in most cases in terms of mechanical performance.

To investigate effects of tape production speed on mechanical properties of pultruded profiles comparison between SP-T2-PS02, SP-T5-PS02 and SP-T8-PS02 materials are prepared in Table 2. The fiber volume fraction of these profiles constituted 50%, with porosity of 1%. Increase in tapes production speed results in increased strength of pultruded profiles based on those tapes. The profile based on T8 tapes has higher flexural strength than T5- and T2-based profiles, by 4% and 13.5%, respectively. With increase in tapes production speed, the tape surface becomes curved. Tapes with curved surface have larger perimeter and the greater area of contact between tapes. Greater contact area allows better consolidation of tapes in the profile, resulting in higher strength of material.

To investigate effects of pulling speed on mechanical properties comparison between profiles made of industrial tapes is prepared in Table 2. Mechanical tests were conducted only on specimens SP-IT-PS02 and SP-IT-PS04 because it was impossible to cut testing specimens from SP-IT-PS06 and SP-IT-PS08 due to the presence of a large amount of unconsolidated tape. A comparison of SP-IT-PS02 and SP-IT-PS04 test results showed that an increase in pulling speed resulted in a slight reduction in flexural, tensile, and compression moduli by as much as 4%, 11%, and 5%, respectively. In addition, the reductions in flexural, tensile, and compressive strengths were 43%, 15%, and 23%, respectively. Further, specimen SP-IT-PS04 exhibited a higher standard deviation. Thus, the presence of unconsolidated tape, caused by insufficient heating of the material at high pulling speeds, degrades the mechanical performance of the produced composite.

Table 2. Mechanical properties of GF/PP pultruded profiles

Pultruded GF/PP materials	Fiber volume fraction [-]	Flexural strength [MPa]	Flexural modulus [GPa]	Tensile strength [MPa]	Tensile modulus [GPa]	Compression strength [MPa]	Compression modulus [GPa]
SP-SP-PS01	0.38	492.2 ± 44.4	20.4 ± 0.1	839.8 ± 48.1	30.3 ± 0.5	257.9 ± 37.3	26.6 ± 1.6
SP-IT-PS02	0.38	411.0 ± 27.9	26.8 ± 0.5	659.8 ± 28.4	28.7 ± 0.3	202.9 ± 7.9	27.2 ± 2.5
SP-IT-PS04	-	235.0 ± 91.2	25.7 ± 2.9	561.0 ± 34.9	25.2 ± 0.7	154.8 ± 25.0	25.9 ± 3.7
SP-T2-PS02	0.51	488.2 ± 29.5	37.2 ± 2.0	-	-	-	-
SP-T5-PS02	0.50	532.8 ± 28.1	38.7 ± 0.9	-	-	-	-
SP-T8-PS02	0.50	554.8 ± 45.6	39.4 ± 1.4	-	-	-	-

Chapter 5 is entitled “Numerical analysis of the thermoplastic pultrusion”. A 3D simulation was performed to analyze the temperature distribution over the die blocks and inside the composite material during pultrusion under various heating conditions and pulling speeds. Temperature distribution data were used to predict the consolidation of tapes inside the composite material and determine the maximum allowable pulling speed. A numerical simulation of the heat transfer was performed based on the equations of heat transfer with convection, which, in the case of thermoplastic pultrusion, can be expressed as follows:

$$\rho_c Cp_c u \frac{\partial T}{\partial x} = k_{x,c} \frac{\partial^2 T}{\partial x^2} + k_{y,c} \frac{\partial^2 T}{\partial y^2} + k_{z,c} \frac{\partial^2 T}{\partial z^2}, \tag{1}$$

$$0 = k_{x,d} \frac{\partial^2 T}{\partial x^2} + k_{y,d} \frac{\partial^2 T}{\partial y^2} + k_{z,d} \frac{\partial^2 T}{\partial z^2}, \tag{2}$$

where T is the temperature, t is the time, u is the pulling speed, ρ is the density, Cp is the specific heat, k_x, k_y, and k_z are the thermal conductivities along x, y, and z directions, respectively (x coincides with pulling direction, y and z coincide with the transverse directions). Subscripts c and d correspond to the composite and die, respectively.

Thermoplastic pultrusion was considered as a steady-state process; therefore, the time derivative is neglected. The temperature inside the heater slots was approximated as constant. The temperature was assumed to be constant at the entrance of the heated die block. The temperatures of the heated and cooling slots and composite material at the entrance to the heated die are given by Equation 3 for a constant surface temperature as follows:

$$T|\Omega \ = T_{surf}(x), \tag{3}$$

where T_{surf} is the surface temperature, Ω is the surface with a constant temperature. Because the contact between the moving composite material and die block is imperfect, thermal contact resistance exists. Considering the thermal contact resistance, the boundary condition between the composite and die block was modeled through the convective boundary condition using Equation 4:

$$k\frac{\partial\, T}{\partial\, n}\bigg|\,\Omega \ = -h_{die}(x)\cdot\big(T - T_{die}(x)\big), \tag{4}$$

where T is the temperature, k is the conductivity, Ω is the heat transfer area, h_{die} is the coefficient of heat transfer between the die block and composite material, T_{die} is the temperature of the die block cavity. The heat transfer between the ambient air and die block, as well as between the ambient air and composite material, is given by the Equation 5 of convective boundary conditions, as follows:

$$k\frac{\partial\, T}{\partial\, n}\bigg|\,\Omega \ = -h_{air}\cdot(T - T_{air}), \tag{5}$$

where h_{air} is the coefficient of convective heat transfer between the ambient air and die surface, as well as between the ambient air and surface of the composite material, T_{air} is the temperature of the ambient air.

The Abaqus FEA suite is used to solve the 3D heat transfer problem. The movement of the composite material was expressed in terms of the mass flow rate. The mass flow rate values in the x-, y-, and z-directions were set at each node of the composite material mesh. Figure 4 shows the finite element model of the die block. Owing to the symmetry, only a quarter of the die block was modeled for the computations

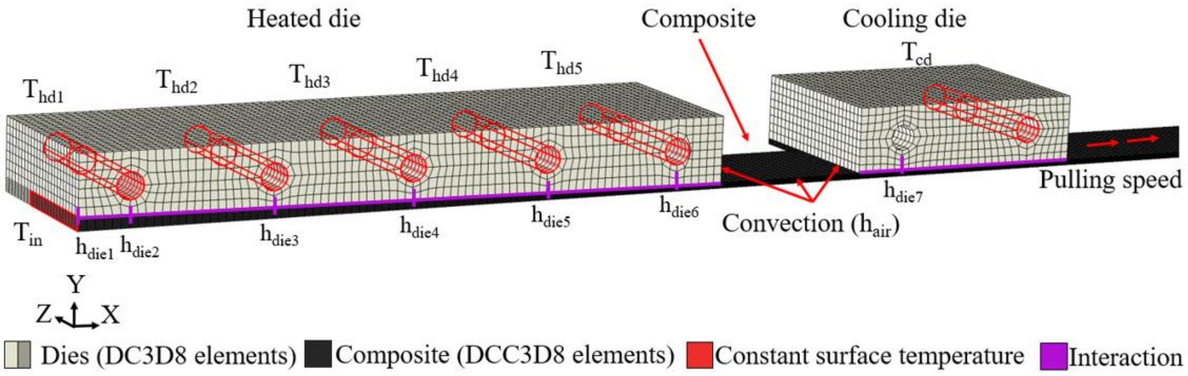


Figure 4. Finite element model of the die block and composite material.

The 3D finite element model of the heat transfer was experimentally validated at pulling speeds of 0.2, 0.4, and 0.6 m/min. Temperature inside profiles was measured by bare thermocouples during pultrusion of SP-IT-PS02, SP-IT-PS04, SP-IT-PS06. Figure 5 shows the temperature evolution observed in the simulations and experiments as a function of the position coordinates. The simulation results are indicated by the colored dashed lines. Values obtained with bare-wire thermocouples are indicated by the colored dotted lines. The position of the thermocouple in the cross-section of the profile is shown in the bottom-right corner of the plot. The temperature values obtained by the simulation were taken from points located along the path of the movement of the thermocouples during the experiment. The red horizontal dashed lines indicate a melting temperature of 150 °C and a Vicat softening temperature (A50) of 130°C. The black vertical dashed lines indicate the boundaries between the heated and cooled dies.

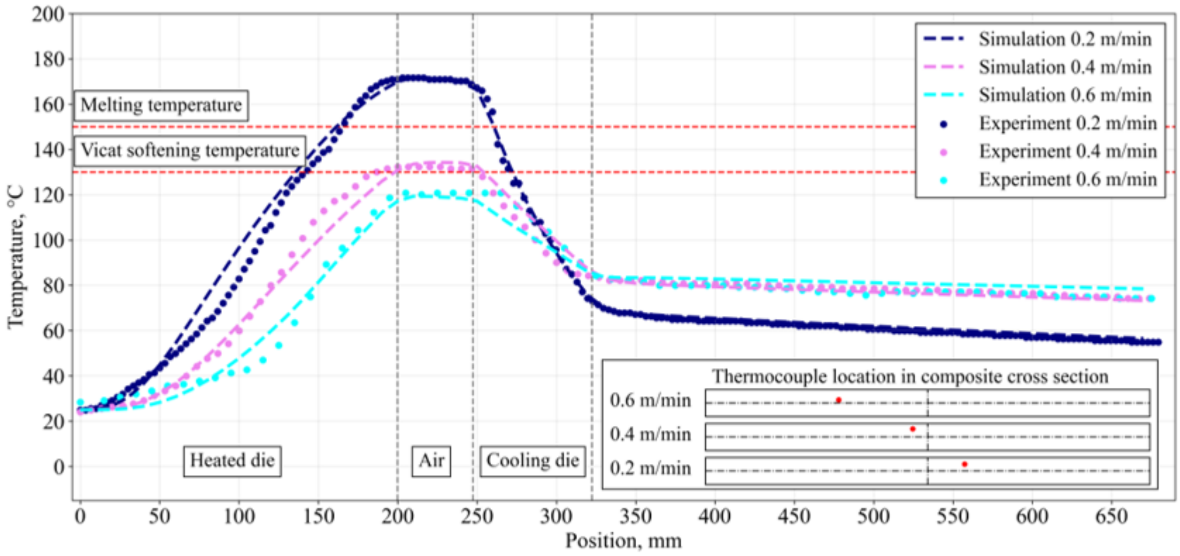


Figure 5. The temperature of the profile as the function of its position in the die block.

The experimental data are in good agreement with the simulation results at all pulling speeds. The validated model was used to determine the highest temperature in the profile and temperature distribution over the profile during pultrusion. Figure 6 shows the temperature distribution over the cross-section of the profile in the region with the highest profile temperature. The black line shows the isosurface corresponding to the melting temperature and the white line shows the isosurface corresponding to the Vicat softening temperature (VST).

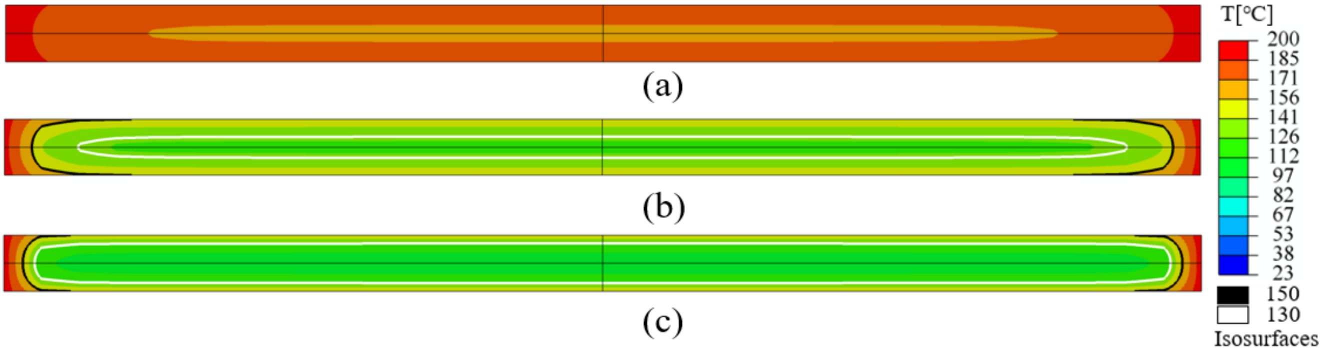


Figure 6. Temperature of material in the region of the maximum heat: (a) SP-IT-PS02, (b) SP-IT-PS04, (c) SP-IT-PS06.

Only the SP-IT-PS02 specimen was heated to the melting temperature over the entire cross-section. The SP-IT-PS04 specimen reached the melting temperature only at the profile surface; the material in the internal part of the profile did not reach the VST. The temperature of the SP-IT-PS06 specimen reached the melting point, and the VST was reached only at the surface of the profile. The relationship between the microstructures of the specimens and the simulation results was established. The SP-IT-PS02 profile could reach the melting temperature, which resulted in full consolidation of the tapes in the profile. In the SP-IT-PS04 profile, the melting temperature was near the profile surface. The VST was reached at a depth equal to the thickness of the two tapes from the profile surface, and the tapes in this region were consolidated. The core of the SP-IT-PS04 profile did not reach the VST, and the tape remained unconsolidated. Thus, the tapes consolidated above the VST.

Chapter 6 entitled “Pultruded profile for window frame structure”. This chapter presents a study of a window structure with a reinforcing core made of GF/PP pultruded profiles. Figure 7 shows the cross-sectional diagrams of the sash and outer frame assembly and the reinforcing steel profiles.

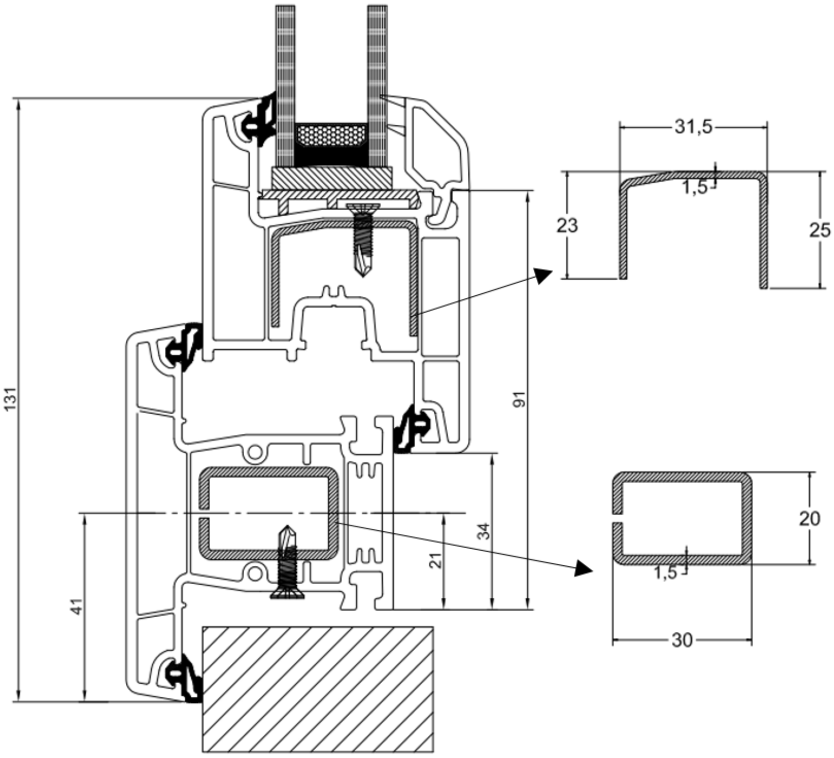
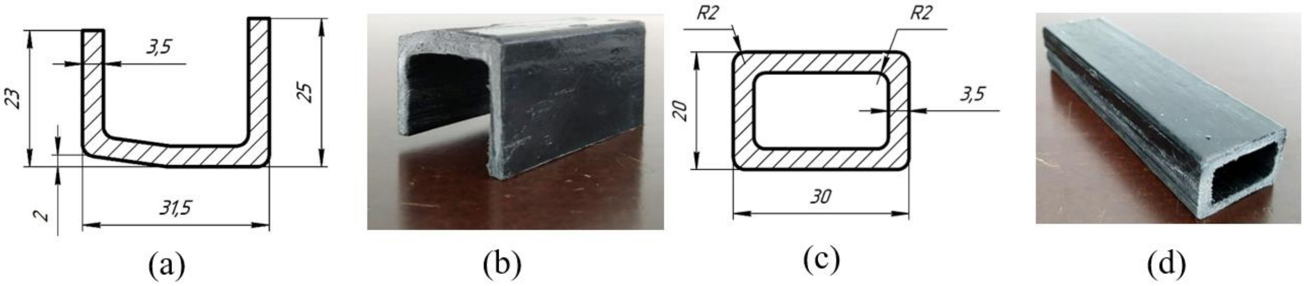


Figure 7. Cross-section sketch of window frame structure with reinforced cores.

Developed heat transfer model was adopted and used for heating temperature and pulling speed prediction of tube and channel pultrusion. According to the simulation results, thermoplastic tube profile was manufactured at a temperature of 190°C and a pulling speed of 0.15 m/min. Thermoplastic channel profile was manufactured at a temperature of 210°C and a pulling speed of 0.10 m/min based on simulation results. Figure 8 shows the sketches and manufactured channel and tube profiles.



(a) (b) (c) (d)

Figure 8. Cross-sectional sketches and pultruded profiles: (a) sketch of the channel (b) pultruded channel, (c) sketch of the tube, (d) pultruded tube.

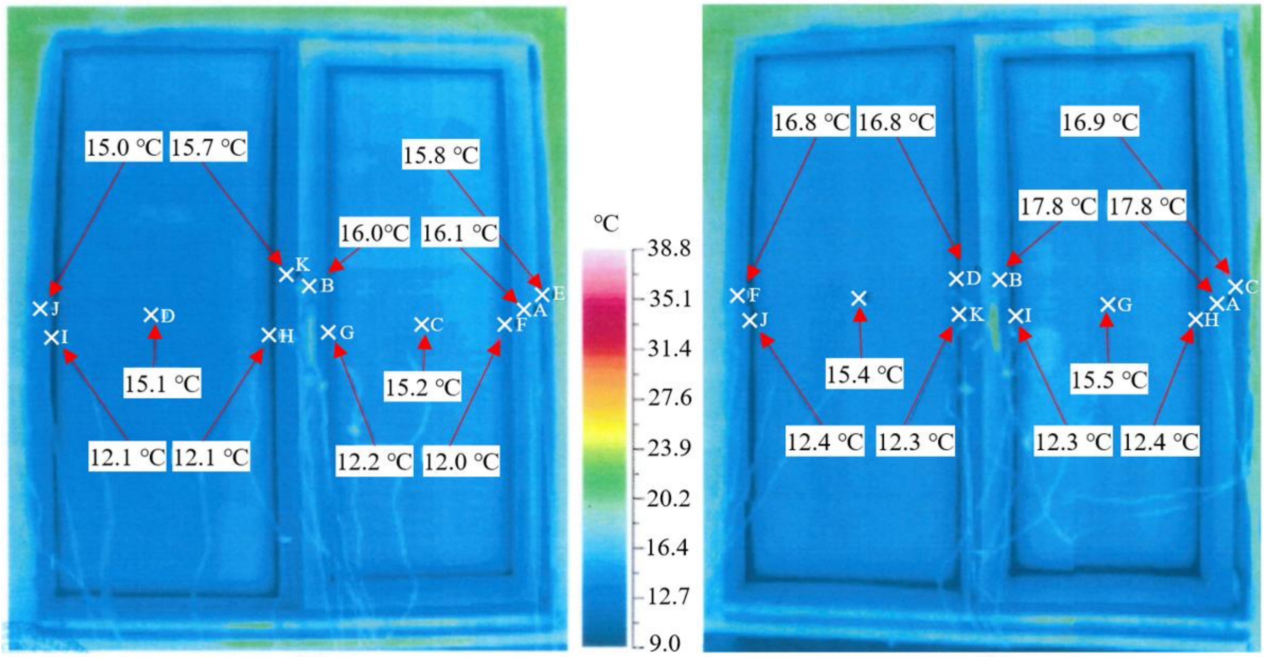
The polyvinylchloride (PVC) frames and composite thermoplastic cores were welded simultaneously in a single technological stage using butt-welding machines. The corner joint of 250 mm × 250 mm was tested according to scheme A of GOST 30674-99. Table 3 shows mechanical test results of angle joint. The mechanical test results of the corner joint of the window structure show that the window with a composite core can withstand twice as much load as the window with a steel core.

Table 3. Test results of angle joint

Sash height, [mm]	Minimum required load for sash height, [N]	Maximum load (steel core), [N]	Maximum load (composite core), [N]
Less than 1300	750	705	1426
1300 – 1500	800		
1500 – 1800	900		
For glass area of windows 2.1-2.3, [m^2]	1000		

Heat resistance tests were conducted following GOST 26602.1-99 in the climatic chamber. Figure 9 shows thermal infrared maps of window structures. The reduced heat transfer resistance of the window structure ($R_{\mathrm{o}}^{\mathrm{pr}}$, $m^2 \cdot °C/W$, see GOST 30674-99) was calculated based on the obtained data and shown in Table 4.

In accordance with the standard GOST 23166-99, window structures are subdivided into classes based on obtained value of reduced resistance to heat transfer. The window structure with steel core has class C1, and the window structure with steel core has class B2. The windows of class B2 have a higher thermal resistance and can be used in northern territories. Thus, the use of thermoplastic composite core instead of steel core will allow to expand the geography of application of window construction without changing PVC profile.



(a) (b)

Figure 9. Thermal infrared map of window structure with reinforcement core made of: (a) steel, (b) GF/PP.

Table 4. Reduced resistance to heat transfer of window structures.

Reinforcement core material	Reduced resistance to heat transfer of window structure, R_o^{pr}, (m^2·°C/W)
Steel	0.647
GF/PP	0.681

Conclusions

1. Material made of laboratory-made tapes exhibit superior mechanical properties compared to material made of industrial tapes. This can be attributed to the enhanced impregnation of glass fiber reinforcement in laboratory-made tapes. An increase in the production rate of laboratory tapes, from 2 m/min to 8 m/min, has been observed to result in a 13% enhancement of flexural strength of pultruded material. Profiles made of laboratory tapes have a fiber volume fraction of 50% and exhibit a flexural modulus of at least 37 GPa.
2. Despite the equal reinforcement volume fraction, the mechanical characteristics of the strip profile made of sheet prepreg were superior to those of the industrial tape-based

profile. This was attributed to the presence of small matrix cracks and debondings in the industrial tapes.

3. The results of the mechanical tests of strip profile indicate that an increase in pulling speed from 0.2 m/min to 0.4 m/min results in a reduction in flexural, tensile, and compression moduli by up to 4%, 12%, and 5%, respectively, and in a reduction in flexural, tensile, and compression strengths by up to 43%, 15%, and 23%, respectively. This reduction can be attributed to inadequate heating and the presence of voids between unconsolidated tapes.
4. The micrographs and heat transfer model results indicate that consolidation of the GF/PP tapes is feasible at temperatures above the Vicat softening temperature. The tape that was heated below the VST remained unconsolidated within the profile. During pultrusion, heating the material to its melting point reduces the number of pores in the tape and the porosity of the profile. Presence of unconsolidated tapes and pores within the composite material reduce the mechanical properties.
5. The developed 3D heat transfer model was used for analysis of pultrusion process parameters for manufacturing of tube and channel profiles. The new thermoplastic profiles were produced based on the predicted pulling speed and heating temperature obtained from the model. In the window structure, rectangular tube and channel profiles made of glass fiber and polypropylene were utilized as a reinforcing core instead of steel. This choice made it possible to reinforce the corner joint of the window structure by welding the cores simultaneously with PVC profiles welding. The welding of reinforcing cores allows for the improvement of the strength of the angle joint by a factor of two. Thermal analysis of window structure according to GOST 26602.1-99 shows that window structures with pultruded GF/PP reinforcement core has higher thermal resistant compared to window with steel core and could be used in northern territories.

Author’s publications on the dissertation topic

Journal articles:

1. Thermoplastic pultrusion: A review / **K. Minchenkov**, A. Vedernikov, A. Safonov, I. Akhatov // Polymers. – 2021. – Vol. 13. – № 2. – P. 1-36.
2. Pultrusion of thermoplastic composites with mechanical properties comparable to industrial thermoset profiles / **K. Minchenkov**, S. Gusev, A. Rogozheva [et al.] // Composites Communications. – 2023. – Vol. 44. – № October. – P. 101766.
3. Effects of the quality of pre-consolidated materials on the mechanical properties and morphology of thermoplastic pultruded flat laminates / K**. Minchenkov**, A. Vedernikov, Y. Kuzminova [et al.] // Composites Communications. – 2022. – Vol. 35. – № February. – P. 101281.
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2. Thermoplastic pultrusion of rods with various reinforcement content / **K. Minchenkov**, S. Gusev, Y. Yavorsky [et al.] // International conference of young scientists and student’s topical problems of mechanical engineering. – Moscow, 2023. – P. 59-66