

# Finite Element Analysis (FEA) Applied to Heat Transfer Optimization Process of Pultrusion Die Systems

F.J.G. Silva, F. Ferreira, C. Costa, A.C. Meira Castro, J.P. Meixedo, M.R. Castro, R.P.C. Santos, M.C.S. Ribeiro, A. Fiúza and M.L. Dinis

**Abstract**—The aim of this study is to optimize the heat flow through the pultrusion die assembly system on the manufacturing process of a specific GFRP (Glass-Fiber Reinforced Polymer) pultrusion profile. The control of heat flow and its distribution through whole die assembly system is of vital importance in optimizing the actual GFRP pultrusion process. Through mathematical modeling of heating-die process, by means of Finite Element Analysis (FEA) program, an optimum heater selection, die position and temperature control was achieved. The thermal environment within the die was critically modeled relative not only to the applied heat sources, but also to the conductive and convective losses, as well as the thermal contribution arising from the exothermic reaction of resin matrix as it cures or polymerizes from the liquid to solid condition. Numerical simulation was validated with basis on thermographic measurements carried out on key points along the die during pultrusion process.

**Keywords**—Finite element analysis, GFRP pultrusion process, Heating-die, Optimization.

## I. INTRODUCTION

PULTRUSION is worldwide used to obtain bars, tubes and other profiles with constant cross section [1]-[4], commonly useful in structural applications where light weight, high specific mechanical strength and good chemical resistance are required [3]. Some of these properties are shown in Fig. 1, in comparative graphics with other materials usually applied in mechanical construction. Furthermore, they offer great electrical, thermal and magnetic insulation, dimensional stability which corresponds to low thermal expansion coefficient, high resistance to heat and severe cold [5]. These bars are, on average, about 4 times lighter than steel and 2/3 than aluminum, and one of the great advantages of using this material is the high strength/weight ratio that can be achieved

F.J.G. Silva, F. Ferreira, C. Costa, A.C. Meira Castro, J.P. Meixedo and M.R. Castro are with ISEP – School of Engineering, Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 431, 4200-072, Porto, Portugal (phone: +351228340500; fax: +351228321159; e-mails: fgs@isep.ipp.pt; fmf@isep.ipp.pt; carloscosta@eu.ipp.pt; ana.meira.castro@eu.ipp.pt; jme@isep.ipp.pt; mário.alvim@alto.com.pt).

R.P.C. Santos is with ALTO-Perfis Pultrudidos, Lda., Rua Raimundo Durães Magalhães, Lote 20, 4470-000 4475-189 Maia, Portugal (e-mail: tome.santos@alto.com.pt).

M.C.S. Ribeiro, A. Fiúza and M.L. Dinis are with FEUP – Faculty of Engineering of University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal (e-mails: cribeiro@inegi.up.pt; afuza@fe.up.pt; mldimis@fe.up.pt).

[6]. These products turn easy its transportation and assembly (by screws, rivets and adhesives, among others) and can be applied in places where corrosion problems subsist, reducing recurrent maintenance operations usually needed in steel structures. These products are commonly classified as glass fibers reinforced plastic (GFRP) composites due to its composition: thermosetting or thermoplastic resin as matrix and glass fibers as reinforcement [7].

Pultruded products are based on long glass fibers impregnated in a thermosetting resin matrix, cured when they are molded by a tool die, which provides the heat necessary to promote the set cure. Tool die is usually divided in two parts, exhibiting inside the external shape required for the product. When the pultruded products have a tubular shape, mandrels are used addressing the internal form [7].

Concerning the pultrusion process, one of the major advantages of this manufacturing technique is its simplicity of tooling and low labor requirements. Pultrusion process starts with racks where fiberglass rolls are held. The raw fiber is pulled off the racks and guided through a resin bath contained in an appropriate vat. Simultaneously, unidirectional roving type is introduced in the process, joining to the wet fibers.

Depending on the end application, the manufacturer must decide on the appropriate set of materials and parameters that should be used, as unidirectional, woven or stitched bar manufacturing, weight grade and number of fiber sets that should be applied. The decision to use continuous strand matting and surfacing veils must be taken into account as well [8]. The matrix is constituted by a thermosetting resin which is sometimes combined with fillers, catalysts and pigments. The fiber reinforcement becomes fully impregnated with resin such that all the fiber filaments are completely saturated with the resin mixture [7].

Epoxy resins tend to stick to the die much more than polyesters and vinyl esters. This feature is more pronounced because epoxy systems are both better adhesives and less prone to shrink than polyesters and vinyl ester resins, therefore tend to remain in intimate contact with the die whereas the polyesters and vinyl esters shrink away. Nevertheless, epoxies are suitable for pultrusion when high corrosion resistance, elevated thermal resistance or special mechanical properties are required.

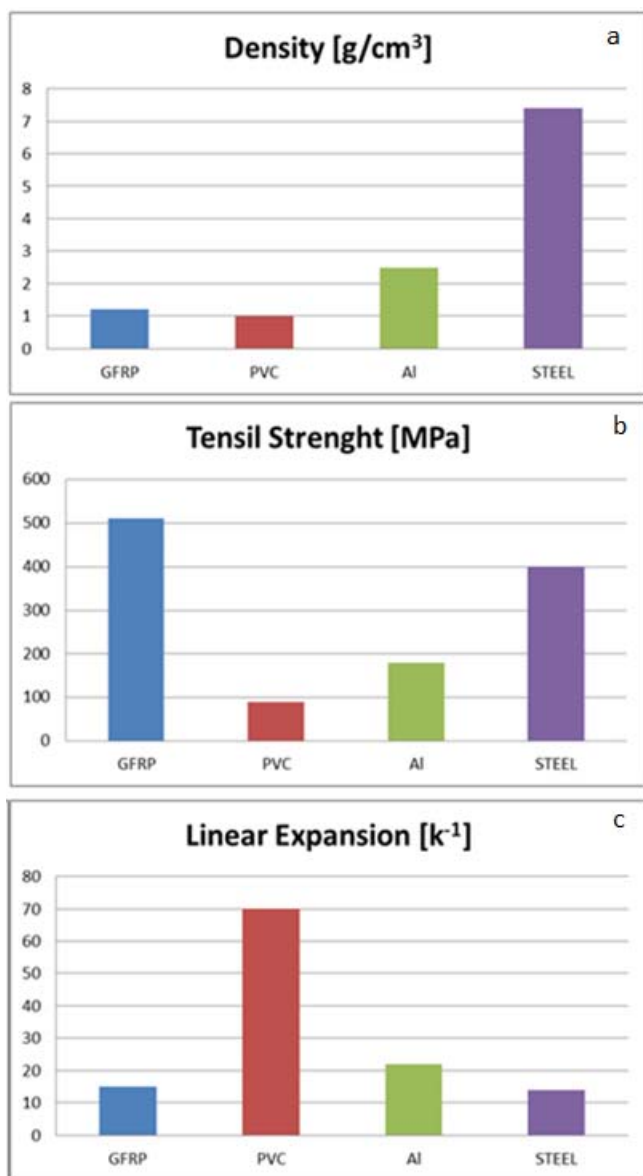


Fig. 1 a), b) and c) - Comparative properties of the GFRP with other materials intensively used in structural applications.

Resins are not applied without other important additives: fillers, pigments, and other additives such as fire retardants need to be mixed in desirable proportions. Viscosity of the resin is an important goal in order to ensure proper wet-out of the reinforcement, which affects the pultrusion speed.

When the wet fiber exits the resin impregnation system, the uncured composite material is guided through a series of tools. These tools help to guide and organize the fibers into the correct shape, while excess resin is squeezed out, also known as “debulking.” This tooling system is known as a “pre-former.” Often, continuous strand mat and surface veils are added in this step to increase structure and surface finish. Now, the composite will pass through a heated steel die.

The pultrusion die must be manufactured with special requirements. Tool steel bar (C45 steel) is milling in order to obtain the shape and measures specified in the design. Then,

machined tool is ground and mirror-polished. After this, tool is subjected to a surface hardening treatment of electroplated hard chromium leading to friction reduction. Further operations of grinding and polishing will be required in order to minimize the surface roughness. These manufacturing tasks take place only on the internal surfaces of the die. In designing the die, one must decide on the length which affects the time that the composite will be exposed to the heat. It will also affect the inside surface area, friction, and production line speed. The die is heated by electrical resistances connected to a power controller, providing different temperatures from the entrance to the outside, which cure the thermosetting resin in different stages. Die temperature is an extremely important parameter in the process because, if it is too low, the composite does not fully cure and, if it is too high, the composite could blister, crack, or worse, get stuck in the die [8]. For each kind of profile there are an ideal temperature, ply schedule, resin matrix, line speed and die length [8]. Properties of the resin need to be taken into account as well because each one has different exothermic reactions. Often, pultrusion manufacturers take detailed notes during every run in order to achieve accurate parameters for each product. At the end of the pultrusion die, bars are cured and can be considered as a pultruded GFRP composite. This GFRP bar is pinched and pulled by a “gripper” system. Caterpillar tracks clamps are used to pull the composite through the pultrusion die on a continuous basis [7].

The speed of the gripper system must take into account the bar thickness, die length, die temperature, and resin formulation. Once again, experience is the key to line speed optimization with quality in the pultrusion process. At the end of the process, the cutting unit cuts the pultruded composite in the required length dimensions [1]-[3].

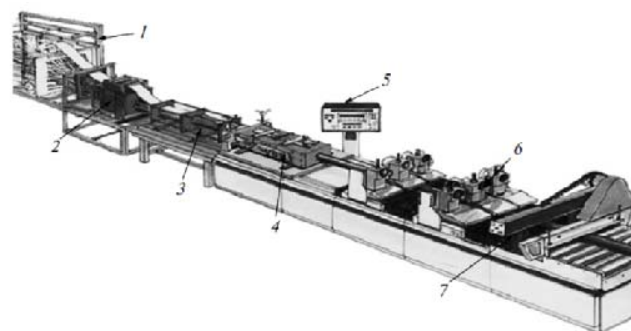


Fig. 2 - Pultrusion layout (Adapted from [7]) where it can be observed the (1) fibers and roving rack, (2) impregnator, (3) folder, (4) die, (5) control board, (6) withdrawal roll facility and (7) cutting device.

Usually, pultrusion manufacturers do not pay any special attention to heating systems applied to heat the die. A lot of energy is expended by electrical resistances without advantages for the process. Heaters are commonly applied externally to the die [10], leading to a significant loss of heat into their surroundings.

In this work, aiming to optimize the die heating system of a specific pultrusion profile production process, initial studies were previously conducted in order to analyze the accuracy of the thermal measurement system and simulation software required to pursue with the intend study. Then, thermographic temperature measurements were carried out in order to quantify the heat evolved from the electrical resistances to the die, considering the traditional die heating system using blocks of resistances. Some studies, carried out by other research teams, have simulated the temperature profile along the pultrusion dies using finite element analysis (FEA) [4], [9]-[11], and this approach was also applied in the present study.

Simulation process was calibrated based on temperature profile computed from the thermographic measurements and, within the purpose of this work, a new heating system was designed using embedded cylindrical heaters, as previously referred by J. Sumerak [12]. New temperature measurements were conducted on the new die, in order to validate the previous simulation results.

## II. EXPERIMENTAL

The pultrusion system used in this work makes use of four electrical resistances placed under and over the die. The die had one meter length as commonly used by other authors [9]. This set is tight against the work table by screw clamps leading a better contact among them. An electronic device controls the connection of the resistances to the power supply in two different groups: the small and the big sets of resistances.

In order to know the initial stage of the heating system and plot the corresponding temperature profile, thermographic measurements were carried out along a selected die used to produce an U-shape pultrusion profile. Sensitivity and geometric resolution were considered as important factors in the characterization of the thermography system.

Sensitivity represents the smallest temperature difference that can be measured or detected, being specified by NETD (Noise Equivalent Temperature Difference) and MDT (Minimum Detectable Temperature) values.

The geometrical resolution shows the size of the smallest object that the system is able to recognize, as specified by SRF (Slit Response Function) and MRTD (Minimum Resolvable Temperature Difference).

Factors that influence the temperature measurement can be classified as external and internal. The external parameters defined by the object are inserted in the user's equipment namely emissivity, distance, room temperature, relative humidity and room temperature.

Concerning to internal factors, the main source of error corresponds to radiation emitted by the system itself, which can be due to optical reasons or intrinsic properties of the internal elements. Some elements present in the "light path", as lenses and mirrors, causing some attenuation of the radiation emitted by the body whose temperature can be measured.

Despite of this, the infra-red thermography has some not negligible advantages, which highlight: temperature

measurement is carried out without contact, does not interfere with the process, fast response time allowing the study of transient regimes, enables the study of spatial thermal distributions, collects large amount of data in a short time, allow for temperature measurement in hazardous atmospheres or conditions and permit accurate measurements. These are the main reasons because this technique was used in this work.

Thermographic measurements were performed using Flir® i40 equipment with the following characteristics:

- Spectral band: large wave (7.5 - 13  $\mu\text{m}$ );
- Detector Type: Focal Plane Array (FPA) microbolometer 120x120 pixels;
- Frame rate: 9 Hz;
- Accuracy:  $\pm 2\text{ }^\circ\text{C}$  or  $\pm 2\%$  of reading;
- Thermal Sensitivity:  $<0.20\text{ }^\circ\text{C}$  to  $+25\text{ }^\circ\text{C}$ ;
- Range of object temperatures:  $-10$  to  $+350\text{ }^\circ\text{C}$ ;
- Display: 89 mm color LCD, 18 bit color;
- Interpolation: imaging detector interpolated to 240x240 pixels.

These measurement procedures were conducted following the equipment supplier specifications, respecting 1m distance between gun and die and keeping the camera aligned with the die. Some material characteristics were introduced in the thermography equipment leading to accurate results.

Attending simulation operations, the initial set of die and heating system was firstly design on 3D cad software (Solidworks®) in order to allow the application of the modeling procedure. Fig. 3 let to understand how initial heaters are assembled in the die. The electrical resistances were initially positioned in order to allowing it to adjust and fixing to the work table of the pultrusion equipment. As can be observed, a large surface of the resistances was in contact with the atmosphere, leading to huge heat lost.

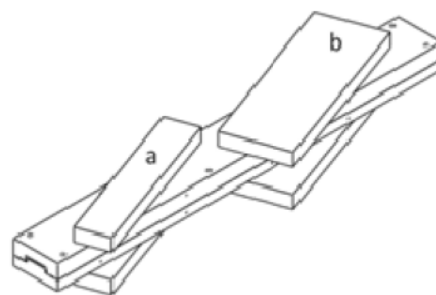
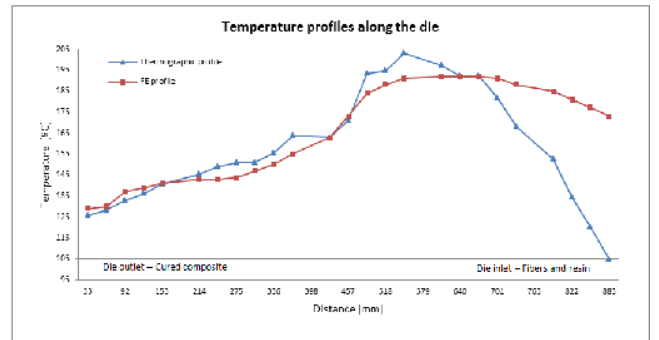
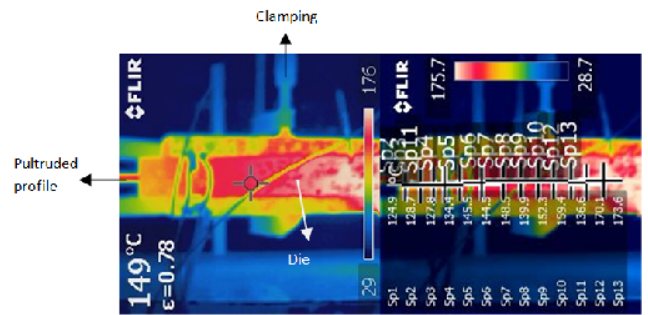
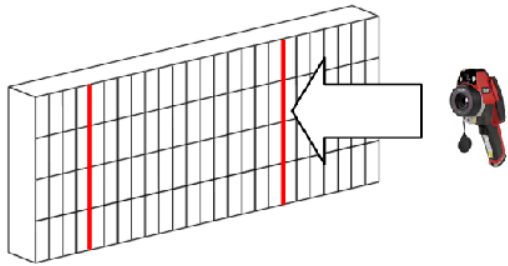
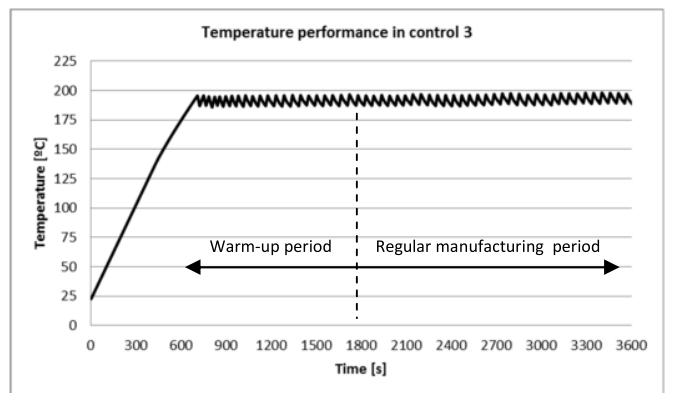
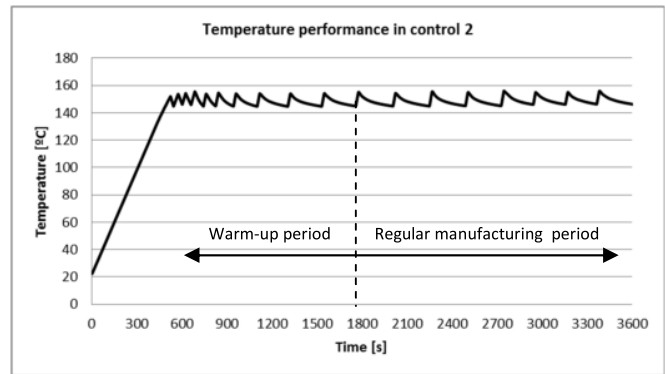
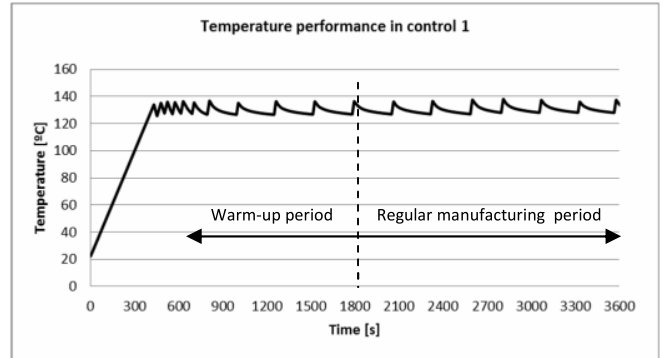
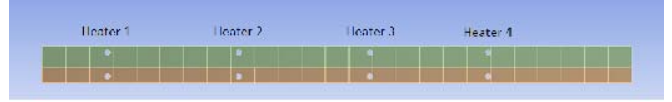
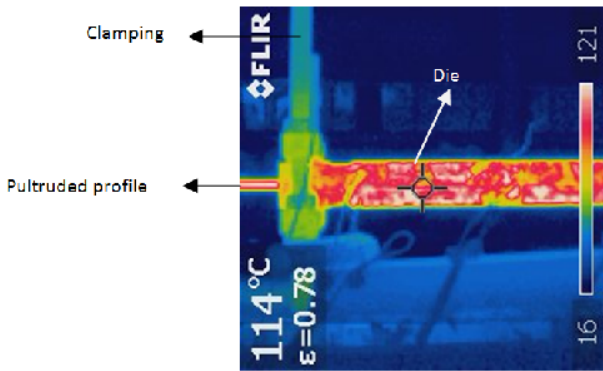
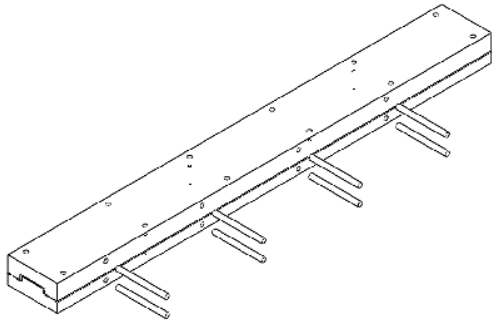
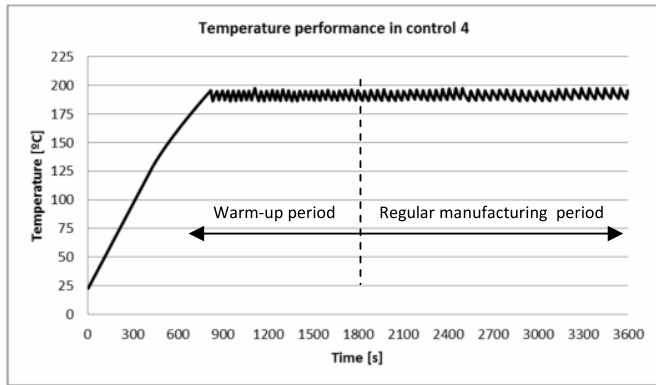


Fig. 3 Initial set-up die with 800W plane heaters: (a) small and (b) large electrical resistance.

Thermograph images were analyzed using the program provided by the equipment supplier (Flir quick report). Each image was divided in 100 different points corresponding to a matrix of 4 lines in height and 25 in width, considering the lateral surface of the die, as represented in Fig. 4. Two captions were taken in similar conditions, increasing the measurements accuracy and leading to better results. These measurements allow to understand how the heat is distributed along the die, attending that the process runs without







Heater	Warm up (1h) [kWh]	Manufacturing (7h) [kWh]	Subtotal working time (8h) [kWh]
Small heaters	0,660	0,192	2,004
Large heaters	1,412	0,948	8,044
<b>Total [kWh]</b>			10,048
<b>Month total (22 days) [kWh]</b>			221,066

Initial System total working time [kWh]	10,05
New System total working time [kWh]	4,35
Reduction [%]	-56,7%

Heater 1	
Warm Up [h]	0,5
Total time of work in 30 min. [min]	9,65
Total time of work in 1h [h]	0,322
Heat Power [W]	800
Power usage [kWh]	0,258
<b>Manufacturing time [h]</b>	<b>7,5</b>
Total time of work in 30 min. [min]	1,40
Total time of work in 1h [h]	0,047
Heat Power [W]	800
Power usage [kWh]	0,038

Heater 2	
Warm Up [h]	0,5
Total time of work in 30 min. [min]	11,70
Total time of work in 1h [h]	0,390
Heat Power [W]	800
Power usage [kWh]	0,312
<b>Manufacturing time [h]</b>	<b>7,5</b>
Total time of work in 30 min. [min]	2,05
Total time of work in 1h [h]	0,068
Heat Power [W]	800
Power usage [kWh]	0,054

Heater 3	
Warm Up [h]	0,5
Total time of work in 30 min. [min]	16,62
Total time of work in 1h [h]	0,554
Heat Power [W]	800
Power usage [kWh]	0,443
<b>Manufacturing time [h]</b>	<b>7,5</b>
Total time of work in 30 min. [min]	6,72
Total time of work in 1h [h]	0,224
Heat Power [W]	800
Power usage [kWh]	0,179

Heater	
Warm Up [h]	0,5
Total time of work in 30 min. [min]	20,18
Total time of work in 1h [h]	0,673
Heat Power [W]	800
Power usage [kWh]	0,538
<b>Manufacturing time [h]</b>	<b>7,5</b>
Total time of work in 30 min. [min]	7,72
Total time of work in 1h [h]	0,257
Heat Power [W]	800
Power usage [kWh]	0,206

Heater	Warm up (0,5h) [kWh]	Manufacturing (7,5h) [kWh]	Subtotal working time (8h) [kWh]
H1 & H2	0,569	0,092	0,975
H3 & H4	0,981	0,385	3,377
<b>Total [kWh]</b>			4,352
<b>Month total (22 days) [kWh]</b>			95,744

- Reinforced Composite, Polymer composites, February 2002, Vol. 23, No. 1.
- [2] S. M. Moschiar, M. M. Reboledo, H. Larrondo, and A. Vazquez, Pultrusion of Epoxy Matrix Composites: Pulling Force Model and Thermal Stress Analysis, Polymer Composites, December 1996, Vol. 17, No. 6.
- [3] Sunil C. Joshi, Y.C. Lam, Kyaw Zaw, "Optimization for quality thermosetting composites pultrudate through die heater layout and power control", ICCM 16th International Conference on Composite Materials, Kyoto-Japan, 08-13 July 2007.
- [4] Y. C. Lam, Jianhua LI, and Sunil C. Joshi, "Simultaneous Optimization of Die-Heating and Pull-Speed in Pultrusion of Thermosetting Composites", POLYMER COMPOSITES, FEBRUARY 2003, Vol. 24, Nr. 1.
- [5] Goldsworthy, B., *Pultrusion* - International Encyclopedia of Composites, Vol. 6, Lee, S.M. (Eds), Wiley-VCH, 1991.
- [6] J. Zhu, K. Chandrashekhara, V. Flanigan and S. Kapila, Manufacturing and mechanical properties of soy-based composites using pultrusion, Composites: Part A 35 (2004) 95–101.
- [7] A. A. Safonov and Yu. V. Suvorova, "Optimization of the Pultrusion Process for a Rod with a Large Diameter", Journal of Machinery Manufacture and Reliability, 2009, Vol. 38, Nr. 6, pp. 572–578.
- [8] S. M. Moschiar, M. M. Reboledo, J. M. Kenny, and A. Vazquez, "Analysis of Pultrusion Processing of Composites of Unsaturated Polyester Resin With Glass Fibers", Polymer Composites, June 1996, Vol. 17, Nr. 3.
- [9] X.-L. Liu, "Numerical modeling on pultrusion of composite I beam", Composites Part A: Applied Science and Manufacturing, Volume 32, Issue 5, 1 May 2001, Pages 663-681.
- [10] G. Viola, T. Portwood, P. Ubrich, and H. R. DeGroot, "Numerical optimization of pultrusion line operating parameters", 35th International SAMPE Symposium, Anaheim, CA, USA, 2 April 1990, pp. 1968-1975.
- [11] D. Santiago, G. Lombera, S. Urquiza, S. M. Moschiar, "Modelado Numérico del Proceso de Pultrusión en Materiales Compuestos", Materials Research, Vol. 6, No. 4, 583-589, 2003.
- [12] Sumerak., J.E Pultrusion Die Design Optimization Opportunities Using Thermal Finite Element Analysis Techniques, 49th Annual Conference, The Society of the Plastics Industry, February 1994.
- [13] Bathe K.J. *Finite Element Procedures*, Prentice-Hall Internacional Editions, 2007.
- [14] J. Mackerle, "Finite elements analyses and simulation of manufacturing processes of composites and their mechanical properties: a bibliography (1985-2003)", Computational Materials Science, Volume 31, November 2004, 187-219.