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Investigation on the Shape Distortions of Pultruded Profiles at Different Pulling Speed

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Abstract

Pultrusion is a continuous technique for manufacturing of polymer composites which combines automation and versatility. The main factors behind the wide application of the process are the enhanced productivity and the remarkable mechanical properties achievable. Nevertheless, the quality of pultruded products dramatically depends on the choice of the process parameters. As a matter of fact, pultrusion presents numerous tunable parameters, such as the temperature of the heating plates or the pulling speed, because most of the polymerization reaction of the resin occurs within the curing-forming die in a short time. Resin shrinkage, thermal contraction and residual internal stresses change the geometry of the profiles after their production. Process related stresses typically result in distortions evolving for months after the process, which can lead to out of geometrical tolerances. The present paper discusses an experimental/numerical investigation of the shape distortions of L-shaped profiles made of epoxy-based resin reinforced with E-glass rovings and unidirectional glass fabrics. The samples were pultruded at three different pulling speeds, namely 200, 400 and 600 mm/min. For each of them, the spring-in angle was periodically measured for the 90 days following production. The results show the dependence of the shape distortions on pulling speed and on time.

Keywords: Pultrusion; shape distortions; spring-in; residual stresses

1. Introduction

The topic of manufacturing induced shape distortions is a significant issue for the scientific and industrial communities [1-7]. Much effort has been spent in relation to different composite technologies [8-13]. Prominent research regarding the manufacturing induced shape distortions in pultrusion process is conducted in [14-16]. However, many gaps still exist.

The last century has been marked as the beginning of composite materials wide adoption around the world [17]. Within the different markets, an enormous number of applications can be found. Thanks to their advantages over traditional materials, composites are utilized in many industries such as: civil engineering, bridge construction, transportation, aerospace, energy system, etc. [18-25]. Moreover, new applications emerge every year. There are many different available techniques for the production of composite materials. One of them is called pultrusion. This word comes from terms “pull” and “extrusion”. The advantages of pultruded profiles are apparent. They exhibit high strength and low weight, enhanced corrosion and fatigue resistance, ease of installation and maintenance, cost-effectiveness for medium-large batch, and low labor effort. The main idea of this technological process is that fiber reinforcement (e.g. glass, carbon, basalt) is pulled through a bath filled with the polymer matrix [26]. Afterward, the excess of the resin is removed and the impregnated reinforcement is guided to the die, heated by the heating plates. The polymerization process occurs inside the die. With the help of the pullers, the system manufactured profile is then guided forward. The last step of the process is the

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cutting of the profiles to the desired length by the saw. Although the pultrusion process may look to be relatively simple from the first view, this is not the case [27-28]. Many factors related to the technological process itself (pulling speed, temperature regime, chemical agents, type of the reinforcement, etc.) affect the process outcome. In addition to the mentioned parameters, the mechanical properties of constituent materials influence the final result as well. According to previous studies, there are three key mechanisms affecting the value of manufacturing-induced defects. Namely, they are a mismatch between the coefficients of thermal expansion (CTE) of the matrix and the reinforcement (matrix has higher CTE than the reinforcement), chemical shrinkage of the matrix, interaction between the pultruding composite and the die (composite-die contact). These aspects provoke so-called "spring-in" distortions. In addition, the following imperfections can appear as well: warpage, delamination, and matrix cracking. The presence of any manufacturing-induced defects decreases mechanical properties of the final profile at both stages: production and assembly. Moreover, spring-in grows over time, thus, demonstrating time-dependent behavior. As a result, some of the manufactured parts do not fall into the range of geometrical tolerances even immediately after the process; some of them can fail to fulfill these requirements after a few months of storage. Therefore, to optimize the process and increase productivity, an analysis must be performed [29-30]. This paper aims to explore the relation between pultrusion pulling speed and value of time-dependent spring-in deformation of the L-shaped structural profile.

2. Materials and methods

To study the influence of the pulling speed on the value of time-dependent spring-in deformation, three production speeds were used, namely, 0.2, 0.4, and 0.6 m/min. L-shaped pultruded profiles were cut to the desired length of 1.5 m. The cross-section profile and the dimensions are depicted in Fig. 1. The pultrusion machine employed for the production was a Pultrex Px500-6T. The die had a length of 600 mm. The temperature on the heating plates was set to 145 °C. To provide strength in the longitudinal direction of the profiles, 104 glass-fiber rovings of PS 2100 9600 TEX were applied. While for the enhancement of transversal strength two layers of LT 0600/S 300/06 H 01/125 GUS fabric were placed on both sides of the profile. Epoxyvinyl-based "Atlac 430" was used as a resin. "Triganox C" and "Perkadox 16" were used for hardening agents. "BYK-A555" component was added to reduce the amount of air trapped in the composite. Zinc Stearate additive was used as a lubricant. Components of the resin mixture are listed in Table 1.

Table 1. Components of resin mixture.

Name of the component	Units	Amount
Resin Atlac 430	kg	25.07
BYK-A555	kg	0.09
Triganox C	kg	0.38
Perkadox 16	kg	0.13
Zinc Stearate	kg	1

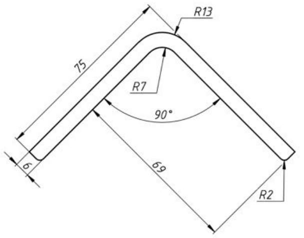

Fig. 1. Cross section of L-shaped profile.

An analog calibrated tool and set of thin metallic plates of different thicknesses were applied to measure the value of spring-in. The accuracy of the mentioned method was ± 0,09°. Spring-in was measured along the profiles at 15-cm increments along the length. Measurement technique is shown on Fig. 2. The value of the metallic plate thickness (t_s) was converted to the spring-in angle (α_s) by a formula that is depicted in the Eq. 1, where L_w is the corresponding size of the web of the profile. The measurement procedure was repeated every 2-3 days. The experiment lasted for 90 days.

To control the temperatures, three thermocouples were embedded within the profiles during the manufacturing process. Thermocouples had the following placement: TC_surface – on the surface of the profile, TC_middle – in the middle of the profile, TC_fabric – under the fabric. After the production pultruded elements were cut and the final locations of thermocouples were determined. Their respective placements are depicted on the half of the cross-section in the Fig. 3-6 according to the corresponding colors.

$$\alpha_s = arctan(t_s/L_w) \tag{1}$$

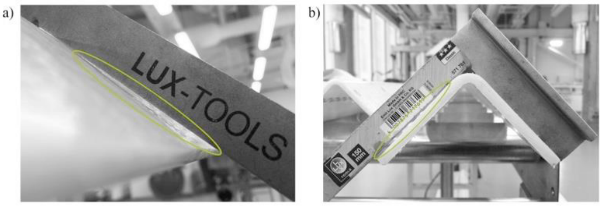

Fig. 2. Spring-in measurement technique.

3. Results and discussions

The temperature evolution obtained from the thermocouples placed within the profiles that were pultruded with the pulling speed of 0.2 and 0.4 m/min is shown on Figs. 3 and 4 (die phase only) and Figs. 5 and 6 (5.5 m starting from the beginning of the die), respectively. In addition to the temperature profiles, a horizontal line representing a set value of the temperature on the heating plate (THP) have been plotted.

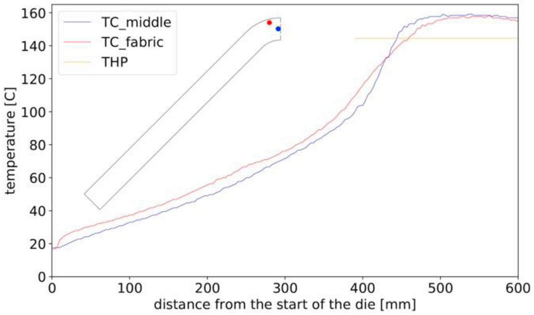

Fig. 3. Temperature evolution within the pultruded profile at a pulling speed of 0.2 m/min (inside the die). Placement of thermocouples.

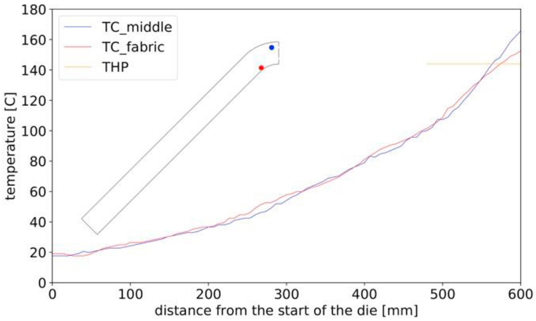

Fig. 4. Temperature evolution within the pultruded profile at a pulling speed of 0.4 m/min (inside the die). Placement of thermocouples.

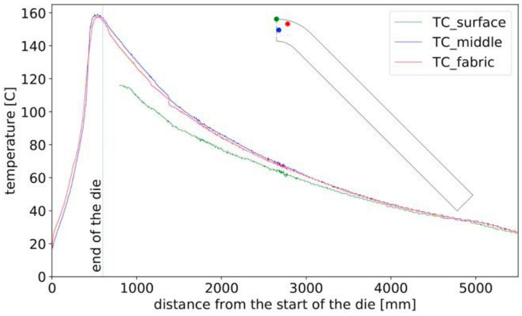

Fig. 5. Temperature evolution within the pultruded profile at a pulling speed of 0.2 m/min. Placement of thermocouples.

It can be seen from Figs. 3 and 4, that at the beginning of the process the temperature in the middle of the profile is lower than the temperature under the fabric because heating occurs from the outer to the inner part of the profile. After some point from the beginning of the die, these lines cross each other, and then the temperature in the middle is higher than the temperature under the fabric. This result is due to heat released during the thermochemical reaction of the resin. The core of this reaction is located in the middle of the profile, and it propagates from the inner to the outer part. At the end of the die overshoot of the heating-plate temperature is a result of the exothermic reaction.

When the profile exited the die, the third thermocouple was fixed on the surface of the cured profile. Temperature profiles, collected on all the locations and including the post-die region, are plotted in Figs. 5 and 6. After the exit from the die, the temperature of the profile starts decreasing due to the convection with the surrounding air. Graphs in Figs. 3 and 4 demonstrate the fact that the increase in pulling speed pushes the peak of polymerization reaction further along the axis of the pultrusion process. This pushing results in an extended period of composite gel zone. In fact, this condition is the reason for increased spring-in deformation as the pulling rate increases.

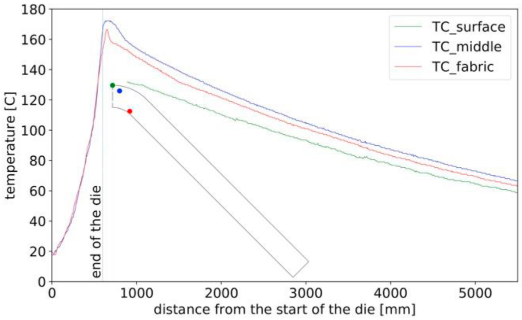

Fig. 6. Temperature evolution within the pultruded profile at a pulling speed of 0.4 m/min. Placement of thermocouples.

Graphs, demonstrating the evolution of the spring-in angle as the function of the time starting from the day of manufacturing, are presented on Figs. 7, 8, and 9 for all the pulling speeds. It is evident that the initial spring-in is nonzero. As already mentioned, many mechanisms explain this phenomenon. However, two of the most significant are the mismatch between the coefficients of thermal expansion of resin and reinforcement and the chemical shrinkage of the polymer matrix. In addition, the value of the spring-in angle directly depends on the pulling speed of pultrusion: higher speeds induce a higher value of the deformation. The analysed datasets show similar behavior in a qualitative point of view.

The spring-in remarkably increases in the first 10-15 days after the fabrication of the profiles. After this initial period, the spring-in keeps growing at a slower rate, up to a maximum value, reached in every case at about 50 days from the date of production. Finally, the spring-in distortion gradually reaches a plateau.

The observed time evolution of the shape distortion evidences two different behaviors acting on two different time-scales. On a short-time horizon, a slow (compared to the pultrusion process time) evolution of the residual cure reaction provokes further shrinkage and, therefore, a progressive increase in spring-in. On the other hand, the relaxation of the process-induced internal stress allows the L-shaped profile to recover the distortion gradually. It is worth noting that the faster the process is, the lower the degree of cure is at the end of the process, due to the shorter curing cycle. Therefore, in the fast case, the residual cure is expected to be higher than in slower cases. This difference induces a two times greater initial increase of the spring-in in the profile produced at 0.6 m/min (about 0.20°) when compared to the one pultruded at 0.2 m/min (about 0.10°).

The final comparison of the spring-in angles evolution is shown in Fig. 10. In particular, increasing the pulling speed from the 0.2 to 0.4 m/min contributes to the difference in the initial spring-in of 22%, while increasing the pulling speed from the 0.2 to 0.6 m/min gives the difference of the initial spring-in by 48%. Comparison of the spring-in angle values 90 days after the manufacturing date shows that it is higher by 30% (between 0.2 and 0.4 m/min) and 53% respectively (between 0.2 and 0.6 m/min).

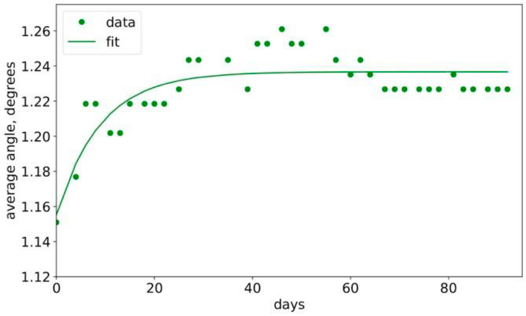

Fig. 7. Spring-in evolution as a function of the time measured from the production day. Profile pultruded at pulling speed of 0.2 m/min.

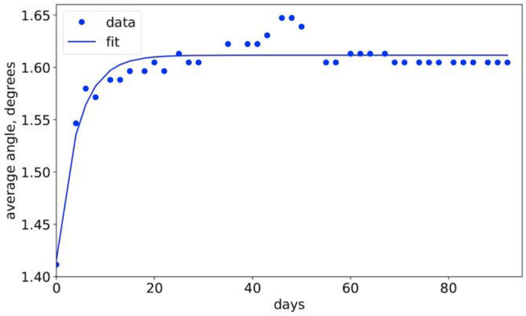

Fig. 8. Spring-in evolution as a function of the time measured from the production day. Profile pultruded at pulling speed of 0.4 m/min.

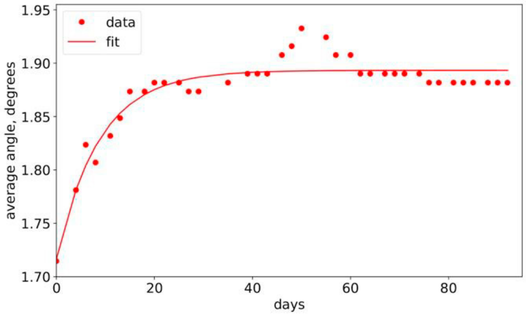

Fig. 9. Spring-in evolution as a function of the time measured from the production day. Profile pultruded at pulling speed of 0.6 m/min.

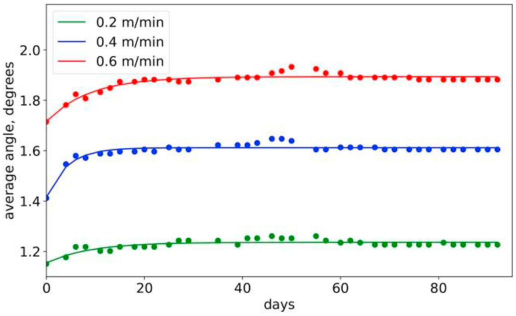

Fig. 10. Spring-in evolution for different pulling speeds 0.2, 0.4, 0.6 m/min.

4. Conclusions

This paper summarized a 90-day analysis aiming to assess the influence of pulling speed on the initial value as well as on the time-dependent behavior of spring-in deformation of pultruded L-shaped structural profiles. It was proved that the spring-in angle is growing with increasing pulling speed. The presence of initial spring-in was registered immediately after pultrusion. Growth of the absolute value has been registered through the first 40-60 days starting from the day of production. This spring-in was followed by a plateau. Moreover, the initial difference between the spring-in values of the profiles produced at different rates is increasing in time.

Application of thermocouples embedded in the profiles allowed to register the position of thermal peaks of the exothermic reaction. An increase in the pulling speed pushes coordinate of these maximum temperatures towards the end of the process, thus, explaining lower or higher values of registered initial spring-in.

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References

[1] Zhang G, Wang J, Ni A, Hu H, Ding A, Li S. Process-induced deformation of L-shaped variable-stiffness composite structures during cure. Compos Struct 2019;230.

[2] Wisnom MR, Gigliotti M, Ersoy N, Campbell M, Potter KD. Mechanisms generating residual stresses and distortion during manufacture of polymer-matrix composite structures. Compos Part A Appl Sci Manuf 2006;37:522–9.

[3] Fernlund G, Rahman N, Courdji R, Bresslauer M, Poursartip A, Willden K, et al. Experimental and numerical study of the effect of cure cycle, tool surface, geometry, and lay-up on the dimensional fidelity of autoclave-processed composite parts. Compos - Part A Appl Sci Manuf 2002;33:341–51.

[4] Ersoy N, Garstka T, Potter K, Wisnom MR, Porter D, Stringer G. Modelling of the spring-in phenomenon in curved parts made of a thermosetting composite. Compos Part A Appl Sci Manuf 2010;41:410–8.

[5] Bapanapalli SK, Smith L V. A linear finite element model to

predict processing-induced distortion in FRP laminates. Compos Part A Appl Sci Manuf 2005;36:1666–74.

[6] Sorrentino L, Bellini C. Compaction influence on spring-in of thin composite parts: Experimental and numerical results. J Compos Mater 2015;49:2149–58.

[7] Safonov A, Gusev M, Saratov A, Konstantinov A, Sergeichev I, Konev S, et al. Modeling of cracking during pultrusion of large-size profiles. Compos Struct 2019:111801.

[8] Albert C, Fernlund G. Spring-in and warpage of angled composite laminates. Compos Sci Technol 2002;62:1895–912.

[9] Ersoy N, Potter K, Wisnom MR, Clegg MJ. An experimental method to study the frictional processes during composites manufacturing. Compos Part A Appl Sci Manuf 2005;36:1536–44.

[10] Svanberg JM, Holmberg JA. An experimental investigation on mechanisms for manufacturing induced shape distortions in homogeneous and balanced laminates. Compos - Part A Appl Sci Manuf 2001;32:827–38.

[11] Kappel E, Stefaniak D, Hühne C. Process distortions in prepreg manufacturing - An experimental study on CFRP L-profiles. Compos Struct 2013;106:615–25.

[12] Ersoy N, Potter K, Wisnom MR, Clegg MJ. Development of spring-in angle during cure of a thermosetting composite. Compos Part A Appl Sci Manuf 2005;36:1700–6.

[13] Hsiao K-T, Gangireddy S. Investigation on the spring-in phenomenon of carbon nanofiber-glass fiber/polyester composites manufactured with vacuum assisted resin transfer molding. Compos Part A Appl Sci Manuf 2008;39:834–42.

[14] Baran I, Akkerman R, Hattel JH. Modelling the pultrusion process of an industrial L-shaped composite profile. Compos Struct 2014;118:37–48.

[15] Baran I, Hattel JH, Akkerman R. Investigation of process induced warpage for pultrusion of a rectangular hollow profile. Compos Part B Eng 2015;68:365–74.

[16] Baran I, Tutum CC, Nielsen MW, Hattel JH. Process induced residual stresses and distortions in pultrusion. Compos Part B Eng 2013;51:148–61.

[17] Safonov AA, Carlone P, Akhatov I. Mathematical simulation of pultrusion processes: A review. Compos Struct 2018;184.

[18] Starr TF. Pultrusion for engineers. 2000.

[19] Fiorina M, Seman A, Castanie B, Ali KM, Schwob C, Mezeix L. Spring-in prediction for carbon/epoxy aerospace composite structure. Compos Struct 2017;168:739–45.

[20] Fedulov BN, Safonov AA, Sergeichev I V., Ushakov AE, Klenin YG, Makarenko I V. Strength Analysis and Process Simulation of Subway Contact Rail Support Bracket of Composite Materials. Appl Compos Mater 2016;23:999–1013.

[21] Ushakov AE, Safonov AA, Sergeichev I V., Fedulov BN, Kornienko EI, Timofeev MA, et al. Design and optimization of a vacuum infusion technological process for hopper car fabrication using polymeric composite materials. J Mach Manuf Reliab 2015;44:276–82.

[22] Sorina TG, Safonov AA, Khairetdinov AK. Pecularities of using carbon glass-reinforced plastic in pultrusion composite profiles for bridge engineering. J Mach Manuf Reliab 2010;39:47–51.

[23] Abouhamzeh M, Sinke J, Jansen KMB, Benedictus R. Closed form expression for residual stresses and warpage during cure of composite laminates. Compos Struct 2015;133:902–10.

[24] Safonov AA. Mathematical modeling for impregnation of reinforcing filler of fiberglasses during vacuum infusion. J Mach Manuf Reliab 2010;39:568–74.

[25] Tucci F, Bezerra R, Rubino F, Carlone P. Multiphase flow simulation in injection pultrusion with variable properties. Mater Manuf Process 2020.

[26] Safonov AA, Suvorova YV. Optimization of the pultrusion process for a rod with a large diameter. J Mach Manuf Reliab 2009;38:572–8.

[27] Baran I, Straumit I, Shishkina O, Lomov S V. X-ray computed tomography characterization of manufacturing induced defects in a glass/polyester pultruded profile. Compos Struct 2018;195:74–82.

[28] Safonov AA. Mathematical description of the technological process of injection pultrusion. J Mach Manuf Reliab 2011;40:68–73.

[29] Yuan Z, Wang Y, Yang G, Tang A, Yang Z, Li S, et al. Evolution of curing residual stresses in composite using multi-scale method. Compos Part B Eng 2018;155:49–61.

[30] Hörberg E, Nyman T, Åkermo M, Hallström S. Thickness effect on spring-in of prepreg composite L-profiles – An experimental study. Compos Struct 2019;209:499–507.