A numerical methodology for improving the thermoforming process of complex thermoplastic composite components

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Abstract. In recent years, there has been an increasing demand for lightweight composite structures. Thermoplastic composite materials appear to be a very promising solution to this direction considering their unique aspects and their capability to be heated and stamped. Nevertheless, the cost of the development of the dies that are necessary to fulfill the requirements of the process was based, until recently, on trial-and-error tests. In the present work, an automotive component is considered, and the corresponding dies are developed using a fast and efficient process simulation software. The process parameters as well as the characteristics of the cavity are defined aiming to minimize the process induced defects.

Introduction

Since the introduction of new mobility sollutions based on partially or fully electric vehicles, overall vehicle weight reduction is essential for augmenting their efficiency. Needless to mention that the overall structural performance should remain at least the same or even ameliorated. To this end, thermoplastic composite materials are considered as an appealing solution that could bring many advantages such as superior mechanical performance with lower weight, long term conservation without requirements and the ease to produce and among them a combination of superior mechanical performance and weight saving. For the aeronautical industry, both the non-payload and the payload are factors that influence the fuel consumption [1-2] as well as for the automotive industry in which is widely accepted that a weight saving of 100 kg could potentially reduce the vehicle consumption significantly [3].

Among the existing variety of composite materials in terms of both fibre and matrix systems, the thermoplastic-based materials are very appealing, especially to the automotive industry, due to their unique features such as their recyclability and their low requirements of energy spent for both storage and production [4]. Most of these components are fabricated using the traditional injection molding process [4-5] where also short fiber composites may be used. Whenever the quality and structural performance of the produced parts is important, continuous fibers are implemented, usually in the form of textiles (woven or braided). Among the existing techniques to this direction is the thermoforming process [6] that is based on the hot stamping of a semi-finished composite product (plate) by also applying temperature cycle that brings the composite plate to its melting point or even above it. After the stamping and the cooling down of the component, the final product may be extracted.

Even though significant research has been performed in the field of the formability of composite materials, there is a significant number of parameters that have a strong effect on the output. Firstly, the material type in terms of textile type reinforcement and the polymeric matrix system that defines the temperature window in which the composite plate can be thermoformed [5-7]. Secondly the relative crosshead speed between the stamping and mold tools. Nevertheless, one important parameter is the geometry of the component that needs to be produced that defines the cavity of the dies. In research level, the majority of works are referring to simple geometries such as hemispheres [8-11] or double-dome geometries [12-13] that are considered as the benchmark ones.

Among the most important aspects is the development of the dies, especially considering the increasing costs of both the materials and the energy required. Therefore, a lot of attention is paid on reducing the design to production time, an important part of which is the accurate design of the molds for hosting the composite semi-finished product. Most of this part was, until recently, conducted applying a trial-and-error experimental procedure where the defects (wrinkles, textile shearing, polymer mitigation, undesired thickness variation) and product quality was observed and adjustments were made to the molds design to minimize them. However, in the recent years there have been observed FE thermoforming process simulations of hemispheres [8-9,11] or double domes [13] and more recently case studies of significantly more complex geometries such as battery trays [14] or other automotive components [15]. It should be noted that when it comes to the study of more complex, non-symmetric components production, there is no protocol to follow and, therefore, the procedure is based mostly on empirical observations.

In the present work, a non-symmetric triangular profile automotive component (corner bracket) is considered. Numerical analyses of the thermoforming process using beyond stat-of-the-art FE models are conducted, based on the outcome of an experimental campaign for characterizing the visco-elastic behaviour of the composite material. Several adjustments are imposed in the geometry of the dies for assessing their effect on the formation of wrinkles, textile shearing and residual stresses. The results were analysed using indicators for understanding the provenance with respect to the material forming behaviour. This way, a methodology is proposed that inter-connects the dies geometry design with the production of the component.

Methodology Outline

As previously mentioned, the component of interest is a 3-way corner bracket that is used as the basis for welding the laminates of the rear part of the cabin of a commercial vehicle. The methodology followed is depicted in Fig.1. It starts with the definition of the input, in terms of the component to produce, and the composite material forming behavior.

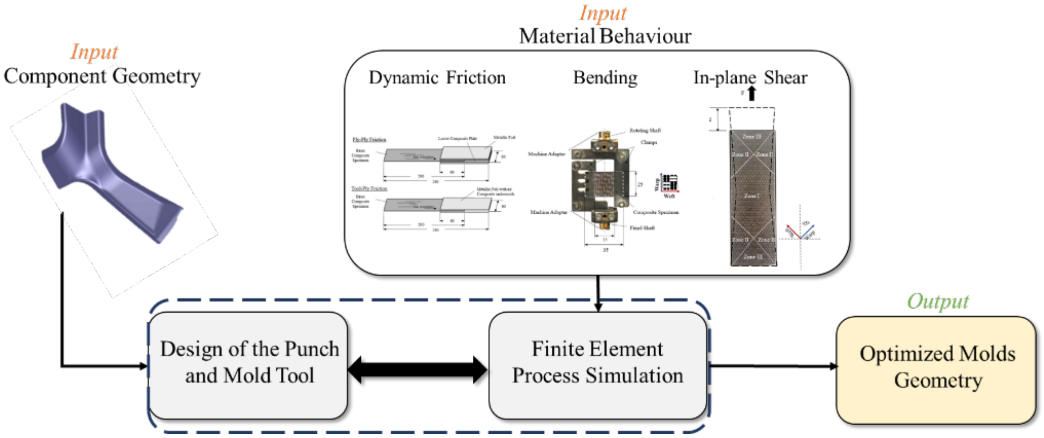


Fig. 1: Outline of the numerical methodology adopted by the present work.

Since the geometry is very complex, a first step is the definition of an initial design of the molds (punch and mold tool) that complies with the characteristics regarding the alignment of the component and the principal directions of the reinforcement. Subsequently, a first finite element simulation of the thermoforming process takes place for identifying the critical zones of high probability for wrinkles and the residual stresses as well as the fiber shearing (the in-plane deformation of the textile fabric). The ideal conditions in terms of stamping speed and material temperature are defined. Considering the fact that the component is highly non-symmetric, the cavity characteristics in terms of orientation and inclination insider the molds assessed as a method for relieving the final product from residual stresses and for eliminating the wrinkles. Therefore, after having conducted a limited number of finite element simulations, the optimized molds may be obtained, saving a lot of time and reducing the cost of a potential trial-and-error experimental investigation.

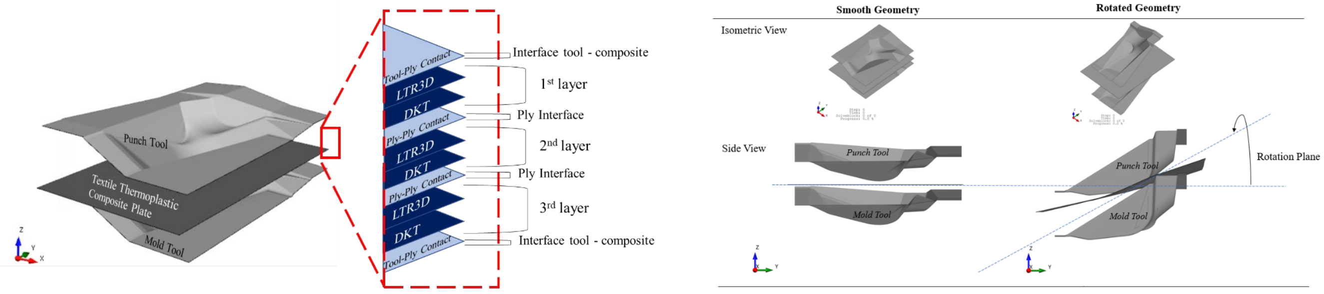
Materials

The composite material utilized is the TEPEX 104 RG600(x)/47% (Bond Laminates GmbH, Brilon, Germany). It consists of a polypropylene matrix system reinforced by 47% with an E-glass 2-2 twill weave fabric. The fabric is balanced (50/50) having equal number of fibers in the warp and weft directions. Its nominal ply thickness is roughly 0.5 mm. This composite semi-finished plate is produced in the European Union using a continuous press process where 2 films of polypropylene and the textile are pressed under a well-defined pressure and temperature cycle to achieve a complete impregnation. According to past works [14], the composite material’s melting point is roughly 164 ºC while the solidification one at 121 ºC. A very interesting part is the temperature opening windows that define the onset of both processes. For the melting process, the onset temperature is 127 ºC while the extrapolated end is 172 ºC. For the crystallization onset, the temperature is at 130 ºC while the material crystallization ends at 110 ºC. To this end, the temperatures 160 ºC and 190 ºC are considered, since at 140 ºC the material is fully (when heated up) or partially (when firstly melted and then cooled down) solidified. The data regarding its forming behaviour in the 2 temperatures of interest and in various stamping speeds were adopted from past research [14].

Thermoforming Simulation

Starting with the necessary assumptions, the component studied in the present work should be made of 3 layers of the TEPEX 104 RG600(x)/47% composite material. In addition, the fabrication process should be horizontal and not vertical for mainly two reasons; the first one is related to the gravity which can cause a shaggy deformation of the heated composite plate while the second one is related to the absence of auxiliary equipment such as tensioners/springs. Therefore, responding to the industrial requirements, no additional supporting fixture is foreseen. Furthermore, the crosshead speed of the stamping tools, and thus the relative closing speed of the dies, should be 5 mm/s, as required by the manufacturer of the component. Finally, the composite plate imposed has dimensions of 688 mm length and 434 mm width.

The assumptions of the second category are related to the restrictions of the simulation strategy and the FE package used. In the present work, Aniform^{TM} FE code [14,16] is utilized which assumes an isothermal process. Thus, during the process, it is assumed a constant material temperature without any thermal interaction between the stamping tools and the composite plate. Moreover, the cool-down phase of the thermoforming is not taken into consideration in the analysis. Finally, it is assumed that the punch and mold tools are closing completely, leaving a cavity of a thickness equal to the laminate nominal thickness. The most interesting fact of this software package though, as seen in previous works [13], is the ability of utilizing a novel and sophisticated approach to derive accurate predictions with a relatively lower time consumption compared to traditional FE approaches. The Aniform^{TM} software incorporates the innovative LTR3D membrane elements alongside with a DKT (Direct Kirchhoff Triangle) shell elements that enclose the in-plane shear behaviour of the material and the bending behaviour. The dynamic friction behaviour is assigned to the contact elements. To this end, there can be placed contact elements incorporating the dynamic friction between the dies and the composite plate while, for adding information regarding the interlayer behaviour, contact elements incorporating the results of the experimental campaign for the identification of these properties are inserted. To this end, the 3-layer configuration used in the present work is schematically described in Fig.2(a).



(a) (b)

Fig. 2: The stacking sequence of the elements of the FE model (a) and the characteristics of the smoothed and inclined geometrical configurations (b).

Consequently, the following simulations are performed in the Initial geometry design and the Smoothed one as seen in Table 1 for capturing the optimal design and process parameters. The Initial geometry refers to the first design of the stamps and the component. After the execution of the first loop of simulations, the critical zones are identified, and the stamps are smoothed, eliminating potential zones of geometrical instability.

Table 1: The process parameters imposed for performing the thermoforming of the composite component.

Geometry	Stamping Speed [mm/min]	Stamping Temperature [ºC]	Additional Rotation [degrees]	Simulations
Initial	50, 100, 200	160, 190	-	6
Smoothed	50,100, 200	160, 190	-	6
Rotated	100	190	42	1

In addition to that, FE simulation is conducted introducing an out-of-plane rotation of the cavity formatted by the dies for assessing a potential amelioration in terms of reduction of the defects introduced by the process. In the Rotated geometry configuration, the dies (punch and mold tool) are aligned in a way that a major part of the component to produce is fully aligned to the y-axis (xy plane) as seen in Fig.2(b). This way, to the heated composite plate different stresses are developed locally during the application of pressure by the punch tool and different stress states and deformations are expected.

Results and Discussion

The Effect of Stamping Speed and Material Temperature

In almost symmetrical, box shaped geometries, the synergistic effect between the stamping speed and the material temperature has been well addressed [14]. The FE software output can either be the ply or the laminate characteristics in terms of textile deformation, normal or shear stresses and the distribution of the thickness as seen in Fig.3 in the case of the Initial configuration, 160 ºC material temperature and 50 mm/min stamping speed.

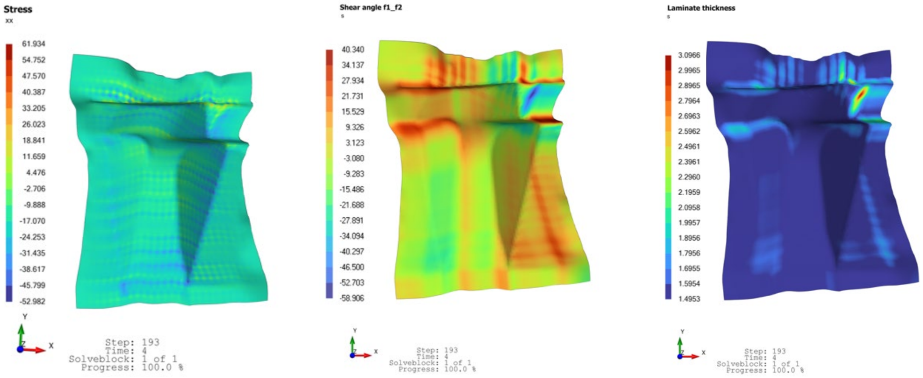
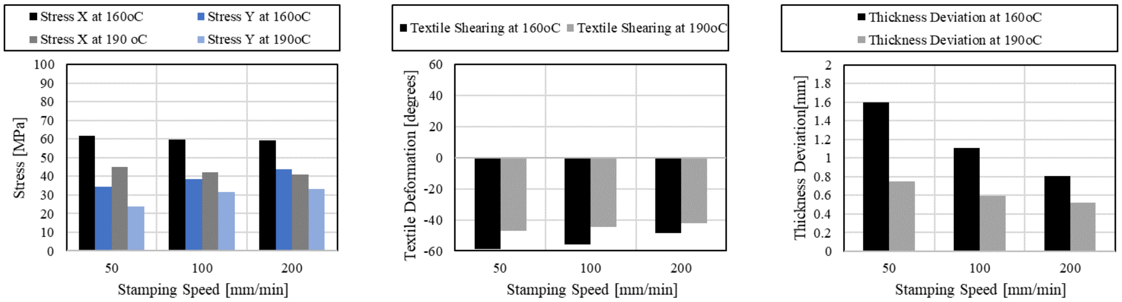


Fig. 3: The normal stress x, the shear angle (textile shearing) deformation and the laminate thickness distribution of the Initial configuration.

It is obvious a significant increase of the laminate thickness in a particular zone inside the product form where a wrinkle is expected. The laminate thickness prior to the hot stamping was 1.5 mm and, at some points, the final thickness values were up to roughly 3 mm which is a strong indication of the presence of folds/wrinkles. On the other hand, there can be noticed a severe deformation of the textile (Textile Shear Deformation) that is attributed to the complex form of the component and the aggressive angles of the cavity. The intense residual stresses in the x-axis are also attributed to the cavity geometrical characteristics. After having captured the maximum values of each of the abovementioned characteristics of the same product in different stamping speeds and material temperatures, the synergistic effect of these two manufacturing parameters are addressed in the comparative histograms of the maximum values of Fig.4. The maximum normal stresses x and y were tensile. Moreover, increased compressive stresses were observed that are a pre-requisite for the formation of wrinkles. In addition, the textile shear angular deformation was negative that practically indicates that the warp and weft bundles angle was reduced. Finally, by increasing the material temperature, a stress relief was observed with less textile shearing and lower deviation between the final and the nominal laminate thickness.



(a) (b) (c)

Fig. 4: Results regarding the maximum residual stresses in x and y direction (a), the textile shearing (b) and the thickness deviation (c) from the nominal value for the Initial geometry configuration.

Amelioration Through Edge Smoothening

As previously mentioned, a trial-and-error procedure was adopted for ameliorating the characteristics of the cavity for relieving the final product from defects. The procedure was explained in section 4. A comparison between the values of stresses, laminate thickness and textile shearing is presented in Fig.5. There can be noticed a net reduction of the residual stresses at both 160 ºC and 190 ºC in all the stamping speeds of interest. In fact, by introducing smoother stamping tools, the maximum stress x became compressive with significantly lower value compared to the

Initial configuration for the case of 160 ºC. At 190 ºC and stamping speeds between 50 and 100 mm/min the maximum normal stress is not compressive but tensile, a fact explained by the increased formability of the composite material in higher temperatures. In addition, the textile shearing became positive, therefore the textile angle tends to open which is another indication of less folding and, therefore, less possibility of the development of wrinkles. The increase of both the stamping speed and the material temperature introduced a significant decrease of the textile deformation and the thickness deviation from the nominal value. However, there should be noticed a tendency for the residual stresses to increase. Especially in the case of the stresses towards the y axis with a stamping speed of 200 mm/min, a fact that may introduce a negative effect on the structural performance of the component.

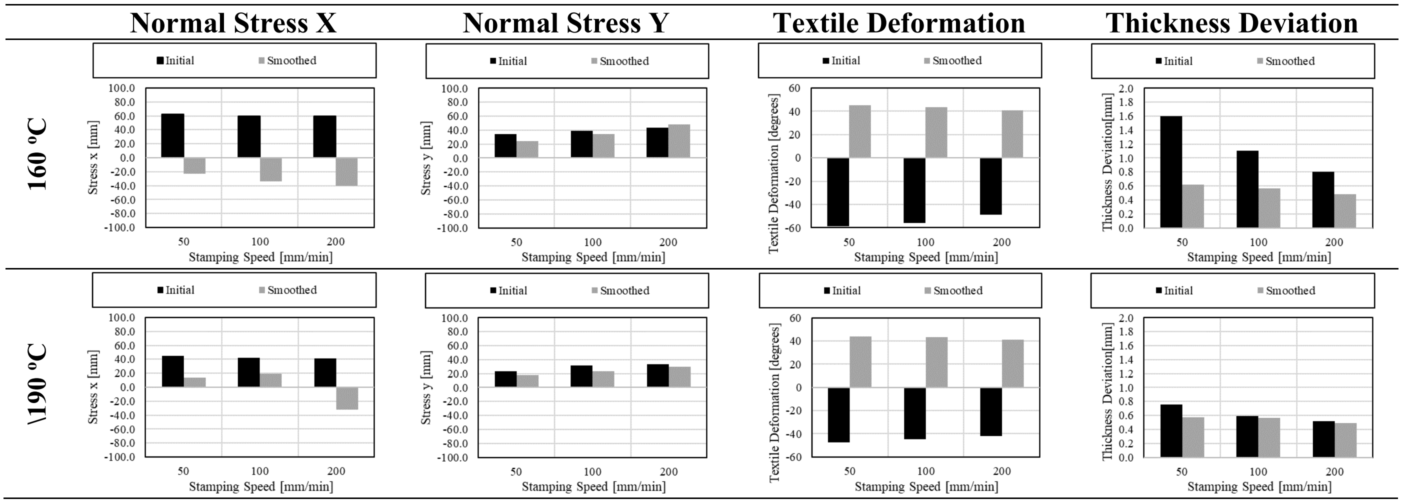


Fig. 5: The output of the simulations for the 2 geometries at the 2 temperatures and various stamping speeds.

Experimental Validation

After completing the tasks of the proposed methodology, the stamping tools developed using the iterative procedure explained in the previous sections were produced and placed in a 4-axis universal industrial press as seen in Fig.6, at the premises of the Crossfire srl (Faenza, Italy). The validation of the methodology was conducted by replicating the exact conditions of the FE simulation in which the material is heated up to 160 ºC and stamped imposing a speed of 50 mm/min using the same composite material. In the same figure, presented is a comparison between the output of the FE analysis and the actual production of the composite component. The Aniform software incorporates an AI add-on that calculates the probability of the introduction of some defects, based on the information gained regarding the residual stresses, thickness variation and textile shearing, delivering values from 0 (absence) to 1 (certain) in the zones of the thermoformed composite plate. From this comparison, it is evident the accuracy of the simulation regarding the critical zones (highlighted within the red circles and formed out of the form of the component) and the good quality of the thermoformed component. In fact, by observing the thermoformed composite laminate, the useful zone of the component is free of defects such as wrinkles (folding) while the textile deformation was found to be in accordance with the predictions of the FE analysis.

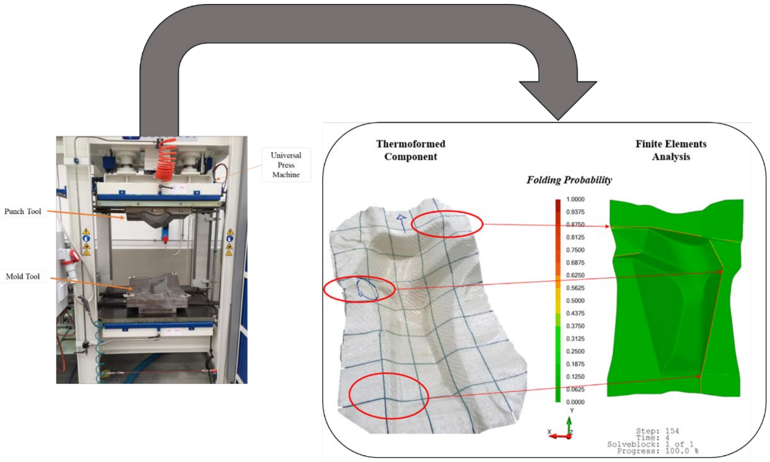


Fig. 6:Comparison between the results of the conducted experimental and numerical analyses.

The Effect of the Stamping Plane Rotation

The results in terms of total laminate thickness, textile shearing angle and stresses x are presented in the following Fig.7. Starting from the laminate thickness, the inclination of the cavity inside the dies appears to derive a bracket uniform enough with values near the nominal thickness while the critical zones of folding appeared to be reduced. However, the maximum value obtained was found to be 22% higher compared to the normal Smoothed configuration. What is worse though, is the prevision about the shearing angle that appears to be distributed not uniformly, introducing an unbalanced textile deformation. This deformation of the fibers direction (textile shearing) is the cause of the unbalanced distribution of the residual stresses. In fact, the deformation of the textile introduced an in-plane waviness that increases the residual stresses locally, leading to a net worsening of the component from both the quality and structural point of view.

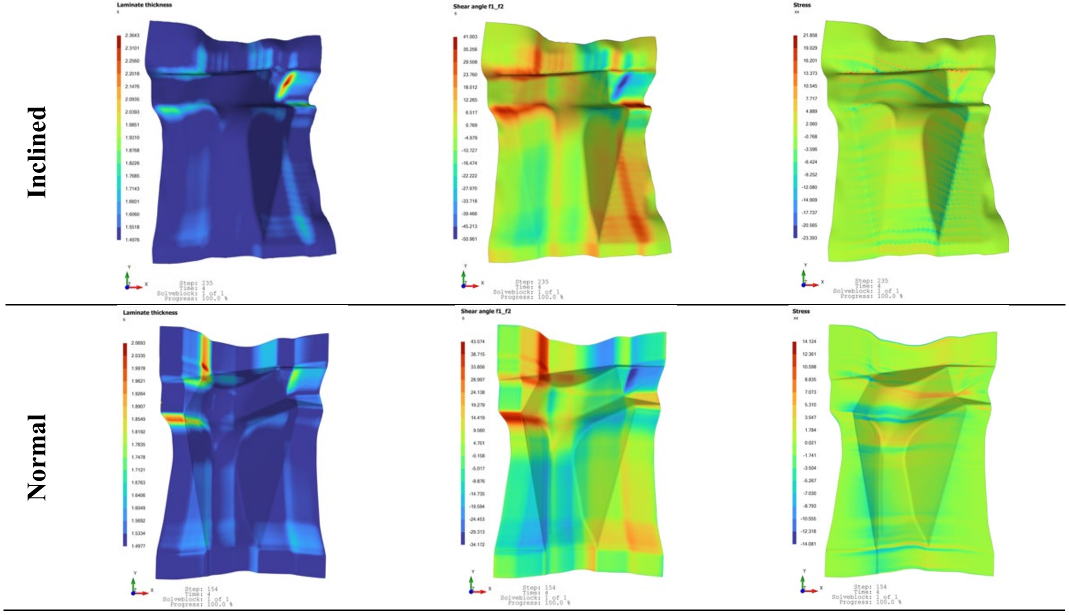


Fig. 7: Comparison between the Normal and the Inclined smoothened molds geometry effect on various outputs of the final component

Conclusions

In the present work, there was presented a numerical methodology for ameliorating the thermoforming process applied to thermoplastic textile composites. The increase of the material temperature in general appears to have a positive effect on some of the characteristics while the increase of the stamping speed appears to ameliorate the uniformity of the thickness and, as a result of the increased formability, the decrease of the deformation of the textile. However, at stamping speeds of 200 mm/min there was observed the introduction of more residual stresses to the component. By the implementation of the artificial intelligence module of the software the critical zones of the initial and the smoothed geometry were identified, leading to the conclusion about the effectiveness of the edges smoothening strategy that potentially contributes to the stresses redistribution during the stamping procedure. The inclination of the stamping plane though, even if it contributes to the uniformity of the overall product thickness, appears to introduce a severe textile shearing and more residual stresses with an unbalanced stress field. Finally, this procedure appears to be an effective solution for developing the dies of processes such as the present one, since it contributes to the virtualization of the process and the reduction of the process development time and cost. It should be noted that similar approaches are considered as pillars of the transition to the modern industry 4.0 years and to more competitive process lines, also considering the cost of the dies for producing components of high geometrical complexity such as the one treated in the present paper.

References

[1] Turgut E.T: An Analysis of the Effect of the Non-Payload Weight on Fuel Consumption for a Wide-Bodied Aircraft. Anadolu University Journal of Science and Technology 18(1), 59-68 (2017). https://doi.org/10.18038/aubtda.300429

[2] Lathasree P, Sheethal RM.: Estimation of aircraft fuel consumption for a mission profile using neural networks. In: Proceedings of the International Conference on Aerospace Science and Technology INCAST 2008, 26 - 28 June 2008, Bangalore, India.

[3] Patel M., Pardhi B., Chopara S., Pal M.: Lightweight Composite Materials for Automotive - A Review. International Research Journal of Engineering and Technology 5 (11), 41-47 (2018).

[4] Campbell F.C.: Manufacturing processes for advanced composites". Elsevier Science, ISBN 9781856174152, (2004).

[5] Stamopoulos A.G., Gazza F., Neirotti G. Assessment of the compressive mechanical behavior of injection molded E-glass/polypropylene by mechanical testing and X-ray computed tomography. The International Journal of Advanced Manufacturing Technology, 1-15 (2023). https://doi.org/10.21203/rs.3.rs-2298336/v1

[6] Ashter S.A.: Thermoforming of single and multilayer laminates. William Andrew Publishing, ISBN 9781455731725, (2014).

[7] De Luca P., Lefebvre P., Pickett A.K.: Numerical and experimental investigation of some press forming parameters of two fibre reinforced thermoplastics: APC2-AS4 and PEI-CETEX. Composites Part A: Applied Science and Manufacturing 29A: 101-110, (1998). https://doi.org/10.1016/S1359-835X(97)00060-2

[8] Guzman-Maldonado E., Hamila N., Boisse P., Bikard J.: Thermomechanical analysis, modelling and simulation of the forming of pre-impregnated thermoplastic composites. Composites Part A: Applied Science and Manufacturing 78: 211-222, (2015). https://doi.org/10.1016/j.compositesa.2015.08.017

[9] Haanappel S.N., Ten Thije R.H.W., Sachs U., Rietman B., Akkerman R.: Formability analyses of uni-directional and textile reinforced thermoplastics. Composites: Part A 56: 80-92, (2014). https://doi.org/10.1016/j.compositesa.2013.09.009

[10] Haanappel S.P., Sachs U., ten Thije R.H.W., Rietman B., Akkerman R.: Forming of Thermoplastic Composites. Key Engineering Materials 504 (506), 237-242 (2012). https://doi.org/10.4028/www.scientific.net/KEM.504-506.237

[11] D'Emilia G., Gaspari A., Natale E., Stamopoulos A.G., Di Ilio A. Experimental and numerical analysis of the defects induced by the thermoforming process on woven textile thermoplastic composites. Engineering Failure Analysis 135, 106093 (2022). https://doi.org/10.1016/j.engfailanal.2022.106093

[12] Harisson P., Gomes R., Curado-Correia N. Press forming a 0/90 cross-ply advanced thermoplastic composite using the double-dome benchmark geometry. Composites Part A: Applied Science and Manufacturing 54, 56-69 (2013). https://doi.org/10.1016/j.compositesa.2013.06.014

[13] Sargent J., Chen J., Sherwood J., Cao J., Boisse P., Willem A., Vanclooster K., Lomov S.V., Khan M., Fetfatsidis K., Jauffres D. Benchmark study of Finite Element Models for simulating the thermostamping of woven-fabric reinforced composites. International Journal of Material Forming 3, 683-686 (2010). https://doi.org/10.1007/s12289-010-0862-5

[14] Stamopoulos A.G., Di Genova L.G., Di Ilio A. Simulation of the thermoforming process of glass-fiber reinforced polymeric components: investigation of the combined effect of the crosshead speed and the material temperature. The International Journal of Advanced Manufacturing Technology 117, 2987-3009 (2021). https://doi.org/10.1007/s00170-021-07845-2

[15] Guzman-Maldonado E., Hamila N., Naouar N., Moulin G., Boisse P. Simulation of thermoplastic prepreg thermoforming based on a visco-hyperelastic model and a thermal homogenization. Materials and Design 93, 431-442 (2016). https://doi.org/10.1016/j.matdes.2015.12.166

[16] Haanappel S.N., Ten Thije R.H.W., Sachs U., Rietman B., Akkerman R.: Formability analyses of uni-directional and textile reinforced thermoplastics. Composites: Part A 56: 80-92, (2014). https://doi.org/10.1016/j.compositesa.2013.09.009