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Publication date
2019

Document Version
Final published version

Published in
SAMPE Europe Conference 2019 Nantes France

Citation (APA)
Nardi, D., & Sinke, J. (2019). Optimization of multistep forming process for thermoplastic composite parts: Process parameters and simulation. In J. Faber, C. Frommel, & R. Rogg (Eds.), *SAMPE Europe Conference 2019 Nantes France*

SAMPE Europe Conference 2019 Nantes - France

OPTIMIZATION OF MULTISTEP FORMING PROCESS FOR THERMOPLASTIC COMPOSITE PARTS - PROCESS PARAMETERS AND SIMULATION

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ABSTRACT

Press forming of Fibre Reinforced Thermoplastics (FRTP) is a widely used manufacturing process. However, in order to boost innovation in FRTP production, new manufacturing strategies have to be implemented. In this context, the multistep forming process represents a promising concept for achieving a higher level of performances by means of customized fibre orientations, fibre types, fibre architecture, and thicknesses, but also higher product functionalities through the combination of different polymers in the same product. In order to improve the functional efficiency of FRTP components, this paper investigates the optimization of a multistep forming process of glass fibre fabric combined with polyetherimide (GF/PEI). The deformation mechanisms encompassing the multistep forming process is here analysed, along with the understanding of the effects of process parameters (e.g. temperature and pressure) over part quality. In particular, the feasibility of the reduction of the cycle time of the process is evaluated by means of active cooling. In addition, in order to foster future industrial application of multistep forming processes, robust and reliable process simulations are presented aiming at reducing development times and improving the overall cost-effectiveness.

1. INTRODUCTION

Thermoforming is a long-established process for FRTP composites manufacturing. It allows rapid transformation of semi-finished raw material into the required design shape by the combined action of heat and pressure.

The process can be generally divided into three main steps, in which (1) the pre-consolidated laminate is heated to a temperature above the melt temperature (if semi-crystalline) or above the glass-transition temperature (if amorphous) of the polymer matrix; (2) the material blank is positioned into a forming station and consolidated into the desired shape under the combined action of pressure and temperature; (3) the formed part is removed from the forming station once a safe temperature is reached by free surface convection [1].

Woven textile structures are widely used as reinforcement in composite materials due to their ease of handling, low fabrication cost, good stability, and excellent formability. A number of deformation mechanisms during forming can be identified, such as intra-ply shear, intra-ply tensile loading, ply/tool or ply/ply shear, ply bending, and compaction/consolidation [2].

Due to their medium to high processing and temperature-dependent properties, along with the complex deformation mechanisms that occur in the laminate during the forming, challenges are generated in the production of the parts [3].

Composite forming simulations provide a tool to prevent or reduce these iterations and the appearance of the corresponding defects. Robust and reliable process simulations can save costs during the design phase to prevent tool and part design modification in the following product development step [4]. Nonetheless, several aspects of finite element modelling must be addressed such as large strains and deformations, non-linear material behaviour, incompressibility, contact between the laminate and the mould/punch, and time-dependent material and thermal effects [5].

To improve the performances of the thermoformed composite to higher levels, new manufacturing concepts have to be investigated.

Among the available technology, the Tailor Made Blank (TMB) concept is commonly used in the automotive industry in the production of sheet metal parts.

The potential application of the TMB for thermoplastic applications can be significant. The main features regarding fibre orientations, fibre types, fibre architecture, thicknesses, etc., can result in composite materials with improved performance levels and selective functionalities. To do so, the different laminate layers should be properly deformed and deposited on the mould, with adequate temperature, pressure, and time values to get a good consolidation between the different layers [6].

A schematic representation of the production sequence is shown in Figure 1.

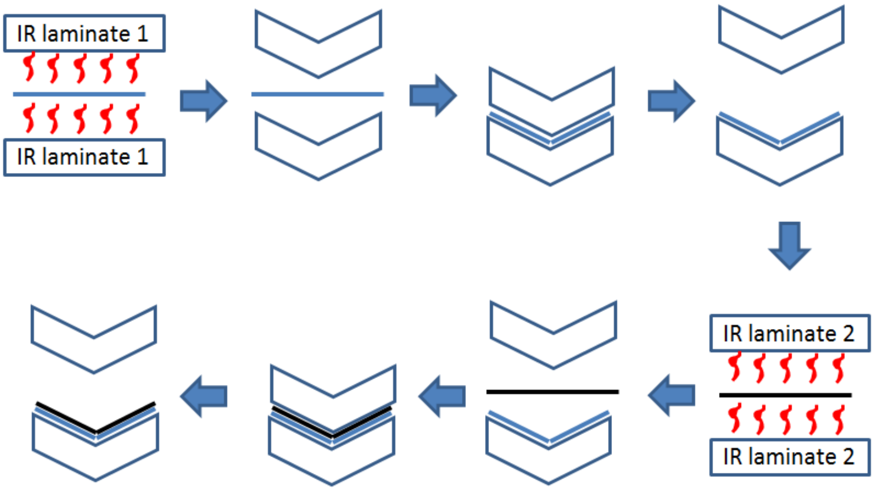


Figure 1. Multistep forming process.

Although few issues need to be addressed, it is possible to create an analogous thermoforming process for thermoplastic composites, such as the selection of the proper process parameters window (temperature, pressure, time) for process optimization.

The main objective of this paper is to evaluate the feasibility of a multistep forming process for thermoplastic glass fibre reinforced polyetherimide woven composite (GF/PEI 8HS). In order to do so, the paper addresses:

- the required approach for robust and reliable finite element simulations aiming at process optimization,
- the manufacturing of GF/PEI 8HS laminates via multistep forming,
- the deformation mechanisms occurring in the multistep forming process,
- the process parameters that affect the laminate quality.

First, the essential features to consider for performing the finite element simulation of the multistep forming process are outlined. Then, an experimental investigation of the process is presented, which will be considered for future simulation validation.

2. PROCESS SIMULATION

Multistep forming process optimization focuses mainly on the preheating stage, the stamping speed, the time to transfer the material to the forming setup, the consolidation pressure, and the cooling time. To do so, finite element simulations have to represent the complex anisotropic behaviour of the woven reinforcement composite.

Two main mechanisms occur in the three-dimensional forming of woven composites. These are intra-ply shearing of the individual plies and inter-ply shearing between plies [3].

Among the different analysis scale, this paper focus on the macro-scale analysis, in which each layer is considered as a whole (no interaction between warp and weft modelled). Figure 2 shows the modelled parts based on the rubber mould on top, the blank, and the metallic mould at the bottom, according to the experimental setup.

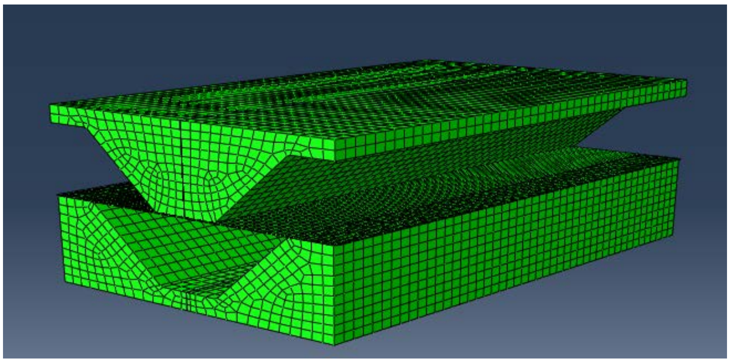


Figure 2. Finite element representation of the experimental setup for the multistep forming process.

The methodology adopted to model the multistep forming process is presented in terms of the simulation key parameters. Simulations are currently under development following the outlined approach.

2.1 Solving Methodology

The explicit (nonlinear) solving method is mainly adopted since it is able to capture the dynamic and highly nonlinear response of the material. The implicit method can be however more suitable for slower forming situations.

2.2 Constitutive Models

Constitutive models must represent the complex behaviour due to the different deformation mechanisms (see Section 1) produced by the deformed yarn directions and strain along these directions. Nonlinear elastic behaviour, damaged elastic behaviour, or elasto-plastic behaviour for permanent deformation upon complete unloading are the constitutive features that have to be represented.

Previous research for woven composites has been conducted describing the material model as a bi-phase model in which the elastic fibre and viscous matrix components are treated separately [3,7].

Based on the type of woven composite the ability that the material has to adapt to a 3D shape is different. An experimental test campaign has to be conducted to properly characterize the material behaviour.

These tests are based on

- Tensile testing to extract the material in-plane extension deformation mechanism (stress vs strain). The common tests are the Uniaxial Tensile Testing (warp/weft/shear) and the Biaxial Tensile Testing [2], where the load is applied to both principal directions simultaneously;
- Shear testing to capture the intra- and inter- ply shear mechanism. Since the intra-ply shear is the most dominant deformation mechanism in woven composite forming, the testing is based on the Picture Frame Test [8] and the Bias Extension Test [9]. Such tests have to characterise the intra-ply shear responses as a function of temperature and deformation rate in terms of viscoelastic properties.

2.3 Finite Element Formulation

Finite element formulation has to capture the main deformation mechanisms. de Luca et al. [3] proposed an approach in which each ply of the laminate is modelled separately with shell elements and appropriate material laws for intra- and inter-ply shearing are adopted. In particular, viscous-friction laws between shells are employed to represent inter-ply shearing. Haanappel et al. [10] employed triangular shell elements as a combination of a membrane element and a Discrete Kirchhoff Triangle (DKT) element in which an orthotropic elastic model is used to model the bending behaviour of the plies.

2.4 Multiphysics: Heat Transfer and (co) Consolidation

The modelling must include the heat transfer mechanism, represented by conduction and convection. Conduction occurs within the plies, and between the hot plies and colder tools and is prevalently a one-dimensional flow (through-the-thickness). Convection takes place mostly via heat dissipation to the ambient.

In addition, pressure is applied to prevent potential weak bonds between co-consolidated and formed laminates.

2.5 Tool and plies contact

The interactions between the parts (blank, rubber mould, mould) have to be considered and their properties, both mechanical and thermal, have to be included considering the coefficient of friction of sliding surfaces and thermal interface conductance.

McEntee and O’ Bradaigh [11] modelled the interplay region using special contact finite elements which connect the individual plies. Hence, the inter-ply slip mechanism is treated as a contact-friction phenomenon. The contact kinematic condition imply that individual plies must not penetrate each other, nor should they separate. Tool contact is also modelled via contact finite elements, allowing the separation from the woven work piece.

Friction laws are material dependent and are function of temperature, contact pressure, and fibre orientations and sliding velocity between different plies [12].

2.6 Cooling

Cooling mechanism plays a significant role during the blank transfer for the infra-red panels to the forming station but also in terms of the total process time. In the first case, the drop in the blank temperature at the moment of forming can bring the laminate below the T_g of the polymer matrix, thus decreasing material formability and hindering the co-consolidation in a following forming step. This can be prevented by decreasing the transferring time of the laminate from the oven to the press or by using a different tooling material with lower ability to absorb heat. In the second case, due to the inability to actively cool the metal mould, the natural convection mechanism can yield to a relatively low cooling rate. As a result, active cooling mechanisms should be implemented so that cycle time can be reduced.

2.7 Defect Indicators

The proper description of the most relevant phenomena in multistep forming is required to predict the occurrence of defects. The occurrence of these defects depends on features such as tool radii, blank holders force, blank shape, forming velocity, friction.

3. EXPERIMENTAL TESTS

3.1 Setup and Parameters

An experimental setup has been built to evaluate the TMB concept [13]. It consists of a pneumatic press able to quickly displace and close a set of dies (< 1-2 seconds), a set of matching dies, namely an aluminium mould and a silicone rubber mould, and a heating plate, as shown in Figure 3.

Figure 3. Thermoforming experimental setup.

Laminates with a $[0/90]_S$ stacking sequence were produced by cutting, laying up and consolidating stacks of pre-preg in a hot press. Laminates 335x210 mm and 335x110 mm were cut from a larger blank previously consolidated. The warp and weft directions coincided with the width (210 mm) and length (335 mm) directions of the laminate, respectively.

A two multistep forming process was investigated. For each test run the laminate is heated up to approximately 320°C by infrared heaters and then transferred to the press to be formed and consolidated by means of sliding rails. During the test, the laminate is fixed at the edges in a frame by means of springs.

Three forming experiments were performed varying the values of the mould temperature and the consolidation time. In all the tests, the mould temperature was set to be higher than the glass transition temperature of the PEI matrix (210°C). The rubber mould temperature was set to 50°C. Mould temperature of 220°C and 240°C were selected since they are above 210°C, the PEI matrix T_g (glass transition temperature) at which the co-consolidation and bond of the laminates are possible. The temperature of 240°C also represents the limit temperature that the current setup can provide. A constant pressure of 40 bar was set for all the tests to prevent the weak bond between co-consolidated and formed laminates. A co-consolidation time of 15 minutes was applied to ensure a good co-consolidated bond. Cooling of the material under pressure started after the co-consolidation time in the second forming step was reached. The pressure was removed when the mould temperature reached 170°C, 40°C below the PEI T_g. Formed laminates were then removed from the mould and cooled down via free surface convection.

Table 1 summarizes the details of the experiments. Two laminates were formed in the multistep forming process, i.e. Step 1 and Step 2. Laminate dimensions were varied between the 1st and the 2nd forming step to produce a variable thickness profile.

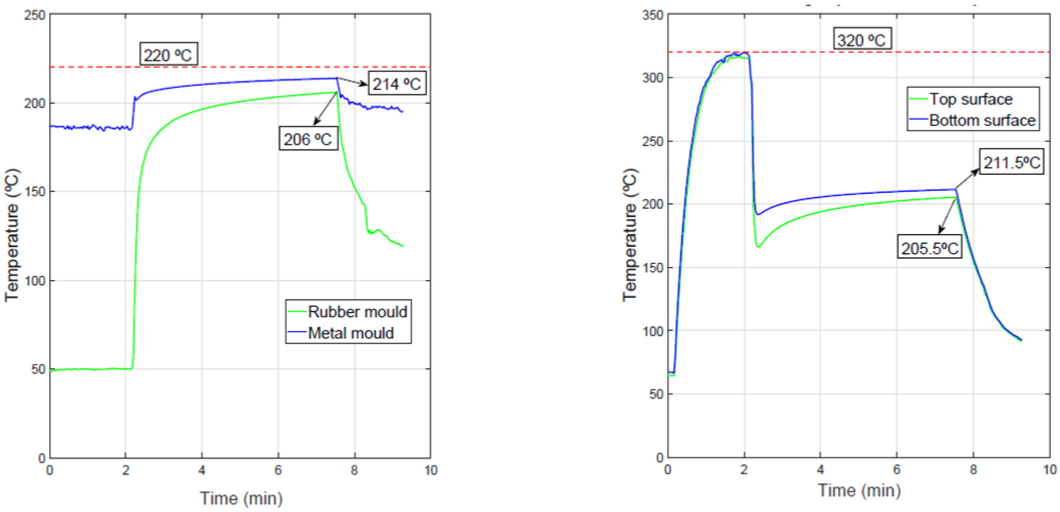
Table 1. Parameters used in the forming experiments.

Test	**Laminate temperature [°C]**		**Rubber mould temperature [°C]**		**Metal mould temperature [°C]**	**Pressure [Pa]**	**(Co) Consolidation time [min]**		**Laminate dimension [mm]**	
	Step 1	**Step 2**	**Step 1**	**Step 2**			**Step 1**	**Step 2**	**Step 1**	**Step 2**
1	320		50		220	40	5	5	335x210	335x110
2					240			15		335x110
3					240			45		335x110

Temperatures were recorded every 2 seconds by means of thermocouples from the moment when the laminate was moved to the IR oven and until the consolidation pressure was removed. The metal and the rubber moulds temperature were recorded in both forming steps. Laminate's top and bottom surfaces temperatures were measured in the first step, while during the second step one thermocouple was placed on the top surface of the laminate formed in the first step and the second one placed at the bottom surface of the laminate about to be formed.

3.2 Results

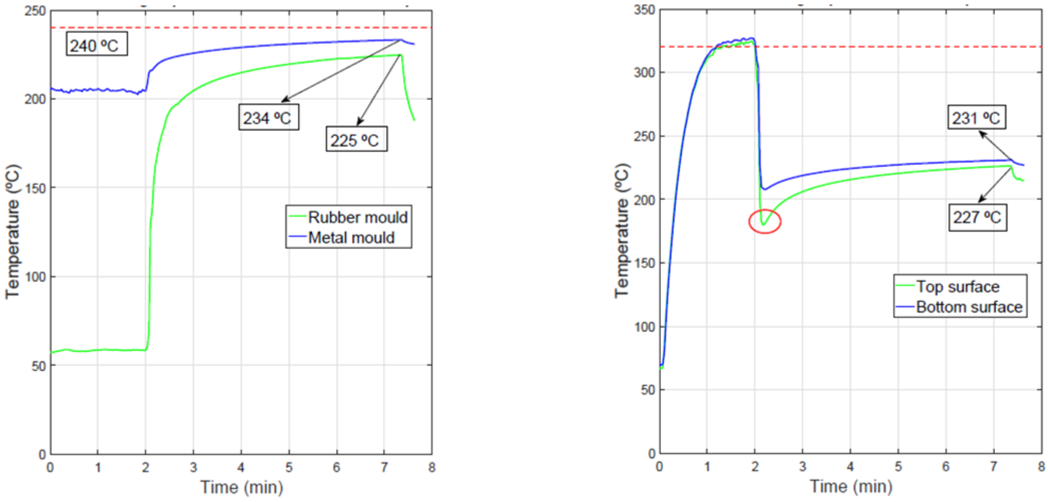
The temperature curves from the first test are shown in Figure 4. It can be seen (Figure 4a) that at the moment the laminate is formed, both the metal mould and the rubber mould temperatures increase from their initial value and they keep increasing with the application of the pressure. However, the 220°C temperature is not achieved since the rubber mould temperature still remains low due to its poor heat absorption capability. Thus, the rubber cools down also the laminate, which is not able to reach 220°C during the consolidation stage (Figure 4b). This drop in temperature is enough to bring the laminate temperature below the T_g of the PEI matrix, resulting in a reduction of the material formability. Hence, a subsequent co-consolidation with another laminate is not possible since after the pressure removal the laminate was affected by sever spring-back.



(a) (b)

Figure 4. Temperature profiles obtained in the first test. Rubber and metal moulds (a), top and bottom laminate surfaces (b).

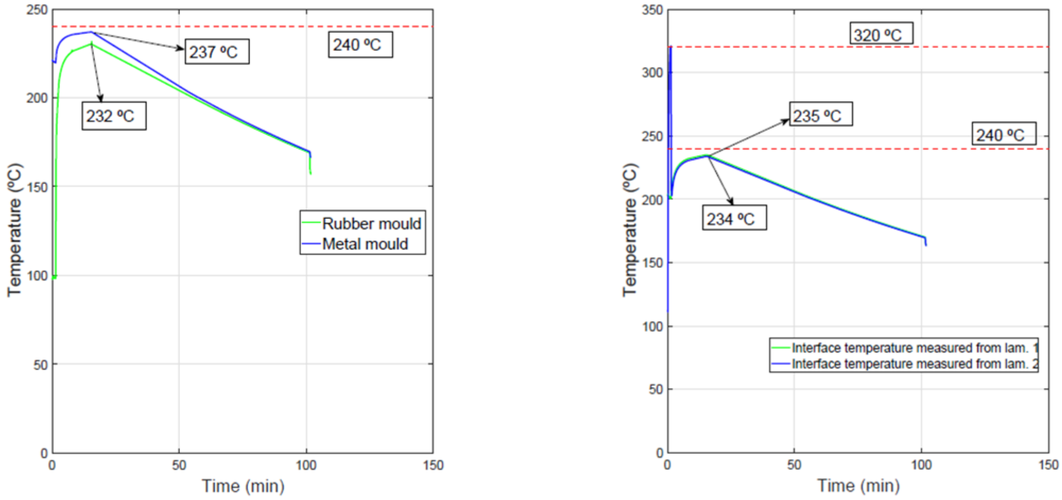
Figure 5 shows the temperature curves obtained from the second test. Temperature values of the mould and of the rubber mould are now above the T_g (Figure 5a) after consolidations. Hence, the formed laminate was able to follow the mould shape after the pressure removal and a second forming step was possible. Nonetheless, the laminate top surface temperature resulted to be below the T_g (Figure 5b), which is in undesirable for the optimal process quality.



(a) (b)

Figure 5. Temperature profiles obtained in the second test. Rubber and metal moulds (a), top and bottom laminate surfaces (b).

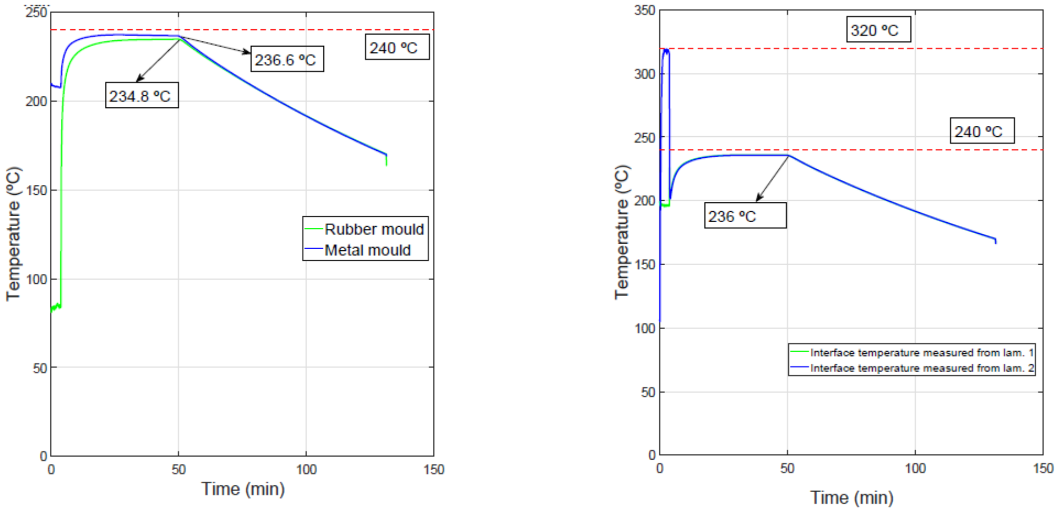
The second laminate was formed over the first one, and potential sticking issues were prevented using spring-clamp holder mechanism. In the second forming step, due to a longer consolidation time (15 min) the maximum temperatures of the rubber and of the mould were higher with respect to the first forming step, as shown in Figure 6a. Before stamping, the interface temperature measured from the first laminate was lower than the temperature of the mould (see Figure 6b). This may be due to a lack of proper contact between the thermocouple with the tools. Anyhow, at the end of the consolidation stage interface temperatures of 235°C and 234°C were recorded. Lastly, it results evident that the cooling rate was relatively low (about 0.85°C/min). Active cooling mechanisms should be further considered to reduce the processing time.



(a) (b)

Figure 6. Temperature profiles obtained for the second forming in the second test. Rubber and metal moulds (a), interfaces from the first and the second laminate (b).

The temperature curves from the third tests show comparable results with the trend observed in the second test. Only the temperature profiles of the second forming step are reported (see Figure 7). Due to the longer consolidation time, slightly higher interface temperatures of the laminates were achieved.



(a) (b)

Figure 7. Temperature profiles obtained for the second forming in the third test. Rubber and metal moulds (a), interfaces from the first and the second laminate (b).

However, the bond between the two formed and co-consolidated laminates resulted to be very weak and easily peeled off by hand. Therefore, a 240°C co-consolidation temperature is not high enough to generate a strong bond. Higher temperatures are required to increase molecular movement and inter-diffusion mechanisms across the interface.

3.3 Discussion

The performed work showed that laminates can be formed in multiple steps into three-dimensional shapes without visual forming defects. However, a good bond quality between formed and co-consolidated laminates cannot be achieved for the considered temperature range.

Among the various deformation mechanisms that are present in the forming process of woven fabric composite materials, some become more relevant in the performed multistep forming. Ply to ply shear between the two laminates is of great importance since now the geometry of the second laminate has to adapt to the geometry of the first consolidated laminate. Variables like thickness reduction due to compaction/consolidation, friction coefficient, temperature difference at the interfaces, and fibre orientation can potentially affect the bonding strength and the defects formation.

The main issue for the GF/PEI laminate was related to the required processing temperature, which was greatly limited by the maximum aluminium die temperature. The overall process cycle was also quite long (about 2 hours). Hence, active cooling represents a necessary step that has to be implemented for manufacturing time reduction of this kind of composite material. This can be obtained through a mechanical heat sink, which absorbs the heat from the mould or by means of a cooling oil running in the tools [14].

4. CONCLUSIONS

The key parameters to consider for a multistep thermoforming finite element simulation have been presented. The optimization of the process can be achieved by means of the proper selection of the solving methodology, the constitutive model, the finite element formulation, the coupling of the temperature and displacement fields, and the contact between the plies and the tools.

The representation of the main deformation mechanisms should be incorporated in the simulation in order to evaluate the influence of the process parameters in terms of defects formation and to improve the overall cost-effectiveness.

The feasibility of a multistep forming process for thermoplastic woven composite has been experimentally investigated with emphasis on the deformation mechanisms occurring in the forming process, the process parameters that affect the laminate quality, and the required approach for robust and reliable finite element simulations aiming at process optimization.

The process window as tested in this investigation depends significantly upon temperature and time.

Co-consolidation of a second laminate is in fact not possible if the first laminate is not properly formed into the mould shape, which is caused by a forming temperature not enough above the polymer matrix T_g .

When the forming temperature resulted to be higher than the T_g no defects were visible from the co-consolidated laminates. However, the bond strength resulted to be very low. Hence, a higher forming temperature is required.

The laminate surface in contact with the rubber mould has a lower temperature than the surface in contact with the metal mould, thus causing a temperature gradient through the thickness.
Faster laminates transferring is crucial to prevent temperature drop before the forming step.
Maximum consolidation temperatures increase with longer consolidation time.
Active cooling mechanisms should be incorporated in order to reduce the processing time.

5. ACKNOWLEDGMENT

The authors thank Francisco Saraiva for the experimental tests performed to obtain the degree of Master of Science at the Delft University of Technology.

6. REFERENCES

[1] R. McCool, J. Materials: Des. and App. (2011) 226.

[2] R. Akkerman, S.P. Haanappel, in: A.C. Long (Eds), Composite forming technologies, Woodhead Publishing Limited, Cambridge (England), 2007, pp. 111-129.

[3] P. de Luca, P. Lefebure, A.K. Pickett, Compos. Part A 29A (1997) 97.

[4] R. Akkerman, B. Rietman, S. Haanappel, U. Sachs, ITHEC (2012).

[5] B.L. Koziey, M.O. Ghafur, in: D. Bhattacharyya (Eds), Composite Sheet Forming, Elsevier, Amsterdam, 1997, pp. 75-89.

[6] J. Sinke, ESAFORM (2018).

[7] R.H.W. ten Thije, R. Akkerman, Int. J. Mater. Form. 3 (2010).

[8] S.V. Lomov, A. Willems, I. Verpoest, et al., Text. Res. Journ. 76 (2006) 3.

[9] P. Boisse, N. Hamila, E. Guzman-Maldonando, A. Madeo, G. Hivet, F. dell’Isola, Int. Journ. Mat. Form. 10 (2017) 4.

[10] S.P. Haanappel, U. Sachs, R.H.W. ten Thije, et al., Key. Eng. Mat. 504-506 (2012).

[11] S.P. McEntee, C.M. O’ Bradaigh, Compos. Part A 29A (1998).

[12] A.M. Murtagh, J.J. Lennon, P.J. Mallon, Compos. Manuf. 6 (1995).

[13] F. Saraiva, MSc Delft University of Technology (2017).

[14] D. Tatsuno, T. Yoneyama, K. Kawamoto, M. Okamoto, Journ. Compos. Mater. 51 (2017) 30.