AUTOMATED PREFORMING WITH A SMART MOULD APPROACH FOR EFFICIENT LIQUID RESIN INFUSION IN AEROSPACE APPLICATIONS

F. Helber[1*], Z. Deutsch[2], H. Linne[3], T. Sonnemann[3], F. Dungern[3] and P. Middendorf[1]

[1] University of Stuttgart, Institute of Aircraft Design (IFB), Pfaffenwaldring 31, 70569 Stuttgart, helber@ifb.uni-stuttgart.de, www.ifb.uni-stuttgart.de
[2] Israel Aerospace Industries ltd., Ben-Gurion International Airport, 70100 Lod, zvickad@iai.co.il, www.iai.co.il
[3] INVENT GmbH, Christian-Pommer-Str. 47, 38112 Braunschweig, hannah-linne@gmbh.de, www.invent-gmbh.de

Keywords: Composite Materials; Dry Fiber Placement; Binder Materials; Microvibrations; Integrated Heating

ABSTRACT

This paper presents the assessment of non-conventional materials and consumables as well as the development of novel technologies and processing strategies for the manufacturing of thermoset composite materials in order to reduce the ecological footprint of structural components in the aerospace industry. The particular technologies, which are being addressed, involve, novel automated preforming concepts with dry unidirectional fabrics, optimized infusion processes with a sustainable polymer resin and corresponding infusion strategies, a novel smart mould with micro-vibrations for improved fiber wetting and integrated sensor technologies, resulting in a significant reduction of energy consumption during composite manufacture and consequently a minimization of production costs and the environmental footprint of composite manufacturing technologies. Lastly, a stabilizer panel, with slight curvature and integrated stiffener elements was realized using the aforementioned technologies in order to demonstrate the feasibility and ecological benefits. This paper presents the results of the Clean Sky 2 ecoTECH project and highlights its potential and ecological benefits.

1 INTRODUCTION

The European Union's Clean Sky 2 (CS2) joint research programme [1] has been launched in order to push the European competitiveness in cutting edge technologies and environmentally friendly production methods on a new level and to develop a strong and globally competitive aeronautical industry and supply chain within Europe. CS2 is covering all major topics of innovative aviation research, in order to develop cleaner air transport technologies and reduction of CO2, NOX and noise emission compared to state-of-the-art (SoA) aircrafts. The Institute of Aircraft Design (IFB), Israel Aerospace Industries ltd. (IAI) and INVENT GmbH (INVENT) are part of the ecoTECH project within the CS2 sub-branch "AIRFRAME ITD" and are responsible for research on the development of novel and efficient manufacturing technologies for composite materials used in aerospace applications. Main goals within the ecoTECH activities are the decrease of production costs at increased process efficiencies and to provide a lower ecological impact of the resulting composite structure and its manufacturing chain.

Up to today, the manufacturing of large-scale structures, made from fiber reinforced composite materials in various industries is still dominated by a high percentage of manual work. Next to the utilisation of pre-impregnated semi-finished products [2], it is still standard practice to first build a near-net shape preform from pre-cut semi-finished products, layer by layer [3]. The individual reinforcement layers are held together and fixed by an auxiliary binder material [4]. In a subsequent processing step, the finished preform is then impregnated with a low-viscosity resin system. Automated preform manufacture offers the potential of a faster, more cost-effective and more sustainable production of FRP structures [5]. For successful automation, reliable textile handling and wrinkle-free draping of the semi-finished structures in the mould are essential.

This study will present the main achievements and developments of the CS2 project ecoTECH with special focus on novel automated preforming concepts with dry unidirectional fabrics (USTUTT), optimized infusion processes with a sustainable polymer resin and corresponding infusion strategies (IAI) and a novel smart mould with micro-vibrations for improved fiber wetting and integrated sensor technologies (INVENT).

1.1 STATE OF THE ART

In order to achieve high and repeatable quality, while maintaining competitive production rates, automated processing of FRP materials is essential for a resilient, industrial production of composite materials [5]. In the aerospace industry, the Automated Tape Laying (ATL) [6] and the Automated Fiber Placement (AFP) [7] technology can help to achieve a resilient and sustainable value creation. Within robotized AFP technologies, textile semi-finished products are placed onto a substrate material in order to achieve near-net shape preforms [6]. State-of-the-art AFP technologies focus on the layup of pre-impregnated semi-finished products. However, Dry Fiber Placement (DFP) has recently gained increasing interest in various industrial sectors, due to reduced storage and material cost as well as enhanced process- and material flexibility [8, 9]. Within DFP technologies, unimpregnated, pre-bindered textiles are used during fiber deposition. For processing of the dry fiber textiles, an auxiliary tackifying agent, which is located on the textiles surface, needs to be thermally activated during the layup process in order to achieve adequate adhesion between a substrate material and the textile semi-finished product [10,11]. The thermal heat input in AFP technologies can be achieved with common heat transfer principles [12].

ATL and AFP are known to be the key enabling technologies for the application of composite materials in major aerospace structures, such as the Boeing 787 or the Airbus A350. Semi-finished products with high fiber areal weights can be used for Automated Tape Laying in order to quickly layup large amounts of material. However, the ATL process is limited to large-scaled components with little complexity and what the process offers in speed and volume it sacrifices in conformability and flexibility [13]. The AFP process, on the other hand, can be used for automated manufacturing of parts with higher degrees of complexity but is restricted to fabrics with lower fiber areal weights at the same time [14].

To accommodate for parts, that lie within the range of the two aforementioned processes, a novel layup process has been developed: The Advanced Ply Placement (APP) [15].

In order to impregnate the preform with a polymer matrix system, a variety of liquid resin infusion (LRI) processes are available [16]. Resin infusion technology is a process that uses a vacuum to pull a low viscosity liquid resin into the dry preform and is used for manufacture of high-quality composite components. LRI processes cover a variety of applications and are compatible with different types of textile semi-finished products and resin matrices commonly used today. It is suited for the manufacture of large-scale composite parts, in which high strength and light weight are essential. In the resin infusion process, the dry preforms, necessary auxiliaries and potentially core materials as well as inserts are laid up in a mould. This layup is covered by a vacuum bag and sealed to the mould. The entire setup is then put under vacuum, which compacts the preform and the low viscosity polymer resin is introduced into the preform via a resin inlet. The pressure differential between the atmosphere at the resin inlet and the vacuum port is causing the infusion of the resin into the layup [3]. Due to the vacuum compaction, composite structures manufactured with the resin infusion process can achieve fiber volumes of about 55-65% [17]. Autoclave manufacturing is regarded as benchmark for the manufacture of composite structures in the aerospace industry. The autoclave process consolidates the impregnated preform via pressure and thermal heat in order to cure thermoset-based composite structures. Due to the elevated consolidation pressure in the autoclave process, high mechanical properties and a low void content can be achieved [3]. However, high capital invest for acquisition and operational cost are required to enable the autoclave process. Large autoclaves are often used inefficiently for the manufacture of composite parts, where unnecessary energy is utilised for achieving and maintain the consolidation pressure and the heat input. As a result, the use of autoclaves does not allow for sustainable composite manufacture. For that reason, flexible and sustainable out-of-autoclave (OoA) processes are gaining increasing interest within industrial applications in order to speed up manufacturing time and reduce operational cost without sacrificing composite quality [18]. Next to flexible heating blankets [19], self-heated composite toolings [20] are one possibility to achieve a homogeneous heat distribution during the composite cure.

1.2 Scope

This study presents the results of the Clean Sky 2 ecoTECH project, in which a novel approach for the manufacture of aerospace composite structures was developed. Special emphasis was set on the processability of unidirectional (UD), non-crimped fabrics (NCF) within a novel automated preform manufacturing approach and a subsequent one-shot liquid resin infusion (LRI) approach with sustainable polymer resins and corresponding infusion strategies. Therefore, preforms were manufactured, using the Advanced Ply Placement (APP) technology. Furthermore, a novel smart tooling concept is introduced, using micro-vibrations for improved fiber wetting and integrated sensor technologies, in order to achieve data collection and process control during the entre infusion process. Furthermore, the smart mould technology enables integrated heating with reduced energy consumption, when compared to SoA curing concepts.

2 MATERIALS AND METHODS

2.1 Materials

2.1.1 Fabrics

Initial infusion trials were carried out, using an AFP laminate, which was manufactured using ¼" HiTape® [21, 22] from HEXCEL Corporation (Stamford, USA) with a fiber areal weight (FAW) of 126 g/m². For the manufacture of the final demonstrator geometry, the unidirectional carbon fiber plain weave fabric HEXForce G0827 BB1040 [23] was purchased from HEXCEL Composites SASU (Dagneux, France). G0827 has a fiber areal weight of 160 g/m², containing 3k TORAYCA FT300B carbon fibers (198 tex, density: 1.76 g/cm³) in warp direction (97 wt.%) and EC5 5.5 X 2 glass fibers in weft direction (3 wt.%).

2.1.2 Tackifying Agents

Within the ecoTECH project, a comprehensive screening of tackifying agents was carried out [10, 24, 25]. For manufacturing of the preforms, using the APP technology, the self-adhesive veil SAERfix EP [26] was purchased from SAERTEX GmbH (Saerbeck, Germany). SAERfix EP (SAER) is compatible with epoxy resins due to chemical cross-linking in the course of curing. Throughout the various studies, SAER was considered for further application, due its low impact on mechanical and thermal properties as well as minimal impact on overall composite performance, while maintaining good processability in terms of binder application and adhesive properties [27].

2.1.3 Resin System

The initial LRI trials were carried out using the mono-component HexFlow RTM6 [28] from HEXCEL Corporation (Stamford, USA), as an aerospace qualified resin system and benchmark system. For the manufacture of the ecoTECH demonstrator, the resin system Resoltech 1500 with the hardener 1504 from Resoltech Advanced Technology Resins (Rousset, France) [29] were used. This low-viscosity, amine curing epoxy resin is suited for LRI processes. The mixing ratio is stated in the respective technical data sheets (TDS) with 100:30 ± 2 wt.% (resin: hardener). Curing was accomplished within 24 h at room temperature, followed by a resin-specific post-cure cycle at 3 h at 50°C, 3 h at 100°C and 3 h at 150°C, according to the respective TDS, resulting in a glass transition temperature ($T_{g)}$ of 141 °C [29].

2.1.4 Consumables

During the LRI manufacture of the stabilizer panel with the smart mould approach, the following consumables were used. The knitted polyester flow mesh KNITFLOW 105HT [30] from AIRTECH EUROPE SARL (Hanebosch, Luxembourg) was used to support the resin flow throughout the preform during LRI. The polyester weave RELEASE PLY C [31] and RELEASE EASE 234 TFP [32] from AIRTECH EUROPE SARL (Hanebosch, Luxembourg) were applied as peel ply materials. WL5200R [33] from AIRTECH EUROPE SARL (Hanebosch, Luxembourg) was selected as perforated release film. As vacuum bagging, the embossed nylon vacuum film SK2VF200-E1 was purchased from VIK-Composites (Schwäbisch Gmünd, Germany). During LRI processing, the VAP Membrane C2003 [34] from COMPOSYST GmbH (Landberg am Lech, Germany) was utilized to create a vacuum over the entire components surface and to ensure that air and gas pockets are reliably extracted during resin infusion. For manufacture of the inner mold line of the omega shaped stiffeners a customized and thermoformed DAHLAR® RELEASE BAG 500 (RB500) [35] from AIRTECH EUROPE SARL (Hanebosch, Luxembourg) was purchased and used during LRI processing.

2.2 Methods

2.2.1 Preforming

The Advanced Ply Placement technology [15] was developed as a technology for the automated manufacturing of complex, large-scaled carbon fiber reinforced components using unidirectional, pre-impregnated fabrics. Within the APP technology, three coordinated robots are used for placement of NCF materials onto a double-curved mould (Figure 1 a). Two industrial six-axis robots are used for synchronized transportation and handling of the unidirectional fabric, while a third robot is responsible for the layup and consolidation of the pre-cut reinforcement fabrics into the corresponding mould. Segmented gripper elements, allow axial shearing of the UD fabric and therefore compensation of differences in length during layup on complex geometries. Furthermore, the gripper segmentation guarantees a defined and constant ply tension throughout the entire layup process. Furthermore, the shape adaptive compaction roller enables adaption of the layup head to double-curved surfaces and a defined pressure across the entire ply width can be set and enabled during the layup process.

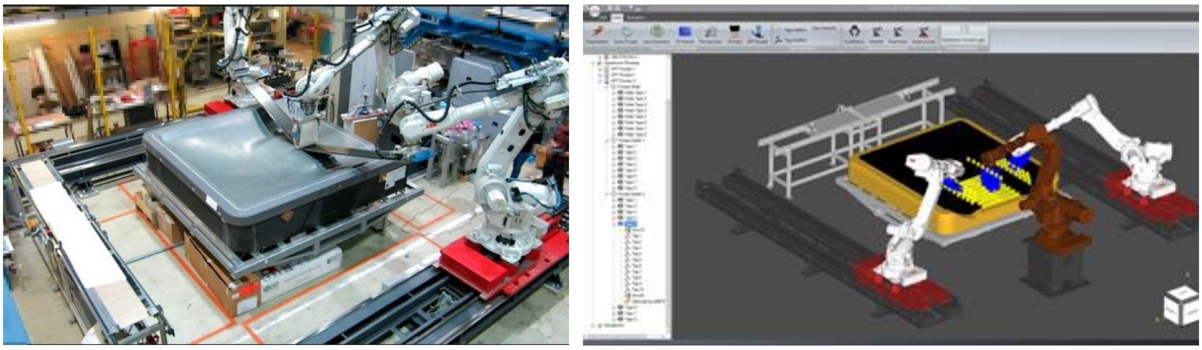

Figure 1: APP a) Ply Placement b) Offline APP Programming

Within the ecoTECH project, a methodology for the offline programming of the multi-robotic APP process was developed, using a kinematic draping approach for analytical calculation of the placement behaviour of the NCF material, visual process simulation and subsequent export of synchronized robotic trajectories to the machine control (Figure 1 b).

After successful process simulation and feasibility studies, APP specific parameters were set for the manufacture of the skin preform (Length: 1800 mm; Width: 750 mm). HEXForce G0827 with a width of 300 mm was determined as NCF material for preform manufacture due to its superior shearability. Prior to layup in the APP preforming cell, the NCF material was equipped with the SAER tackifying agent. Based on a previous numerical simulation of the load cases the stacking sequence was set to [0° / 45° / -45° / 90° / 90° / - 45° / 45° / 0°]. Omega stringers were chosen as stiffener elements and the corresponding preforms were manufactured in a winding process. In order to achieve material compliance HEXForce G0827 with a fabric width of 150 mm was set as reinforcement material for the winding process (unfolded dimensions: Length 1800 mm; Width: 230 mm). [0° / 45° / 0°/ -45° / 0° / 90° / 0° / -45° / 0° / 45° / 0°] was determined as stacking sequence based on the aforementioned numerical simulation.

2.2.3 Smart Mould

One of the main objectives of the ecoTECH project is the reduction of energy consumption in composite manufacture and the minimization of the cure cycle duration by adopting OoA processes with a self-heated composite mould. Therefore, two self-heated composite moulds with integrated sensors and piezo-based actuators were manufactured in order to study the influence of micro vibrations on the impregnation behaviour and the energy input during FRP cure in order to realize sustainable manufacture of composite components. Numerical simulation of the piezoinduced microvibrations and the smart mould periphery was carried out to identify suitable positioning and amount of the piezo-based actuators as well as corresponding frequencies of the microvibrations in order to improve the wetting behaviour.

For analysis of the active impregnation improvement a two-dimensional composite mould (780 mm x 780 mm) was manufactured, which was equipped with piezo-based actuators DuraAct P-876.A15 [36] from PI Ceramic GmbH (Lederhose, Germany), integrated heating as well as temperature and cure sensors (Figure 2 a).

Consequently, a scaled three-dimensional mould (2310 mm x 2020 mm; R: 1303,21 mm) was manufactured based on the outputs and conclusions from the initial 2D composite mould. For active impregnation improvement, piezo-based actuators were integrated and the heating system was adapted to a resistive multi-zone heating concept for improved heat homogeneity. In order the quantify the energy consumption of the scaled smart mould with integrated heating and in order to compare it to a corresponding oven cure, two infusions with the final demonstrator preforms were carried out (Table 1). During the infusion of the demonstrator using the smart mould approach, a minor inhomogeneity in the heat distribution on the upper surface of the aluminum caul plates was noticed. For that reason, an additional fan heater was connected to the smart mould and its energy consumption was recorded and analyzed. The control unit of the moulds allows adjusting and programming of the microvibrations frequencies, the cure cycle as well as extraction and export of the sensor data. The infusions on the smart moulds were carried out according the specifications and settings, as it can be seen in Table 1.

Figure 2: SMART Mould a) 2D Set Up b) 3D Set Up

Table 1: Description of Smart Mould Infusion Campaigns

Label	Mould	Microvibrations	FRP Cure
PRE-INF-01	2D	---	Smart Mould
PRE-INF-02	2D	255 Hz *	Smart Mould
PRE-INF-03	2D	287 Hz *	Smart Mould
DEM-INF-01	3D	4 x 265 Hz; 2 x 180Hz *	Multi-Zone Smart Mould
DEM-INF-02	3D	---	Oven

* acc. to num. Simulation

2.2.2 Liquid Resin Infusion

In the course of the ecoTECH project a comprehensive material screening was carried out with the objective of finding a room temperature infusion resin with corresponding high T_g, improved fiber wetting and adequate mechanical performance. For that reason, 6 resins were down-selected from initial 40 potential resin systems. Testing and preliminary characterization was carried out, analyzing viscosity, Tg, curing profile, mechanical properties (OHC, ILSS, DMA, etc.). Finally, the low viscosity infusion resin Resoltech 1500/1504 was selected.

In order to study the impregnation behavior of a compact AFP preform (HiTape, ¼", 126 g/m²; 600 mm x 600 mm) using the 2D smart mould with piezo induced microvibrations, the aerospace certified, monocomponent RTM6 resin system was used as benchmark resin. Three infusions were carried out (PRE-INF01: No microvibrations; PRE-INF02: Microvibrations; Frequency: 255 Hz; PRE-INF03: Microvibrations; Frequency: 287 Hz). Figure 3 (a) shows the schematic setup for the benchmark infusion campaign.

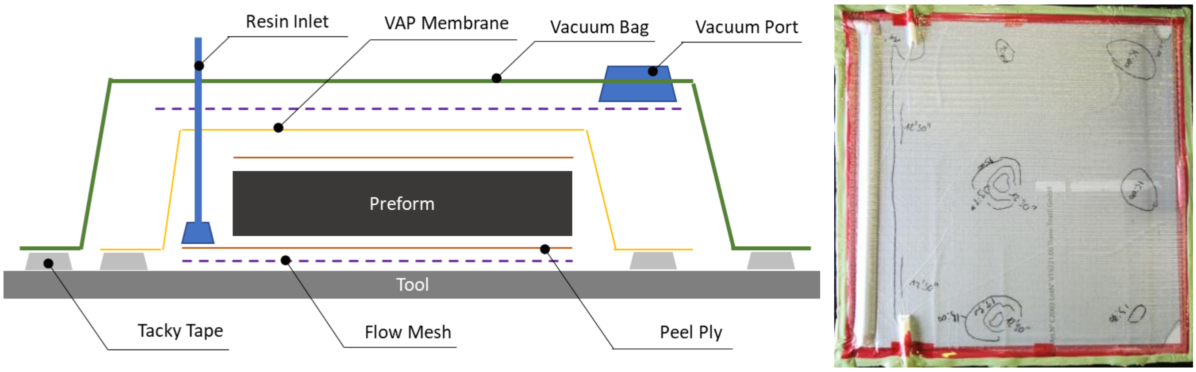

Figure 3: 2D LRI a) Schematic Infusion Strategy b) LRI Setup

For one-shot LRI processing of the stabilizer panel including skin and stiffener preforms, a gravimetric VAP infusion approach was chosen. Therefore, the VAP membrane is applied onto the mould surface and vacuum is being pulled from below the preform (Figure 4 (a)). Two infusions were carried out in order to study the energy consumption during composite cure and the feasibility of the 3D smart mould concept (DEM-INF01: Microvibrations; Cure on self-heated smart mould; DEM-INF02: Microvibrations; Oven Cure).

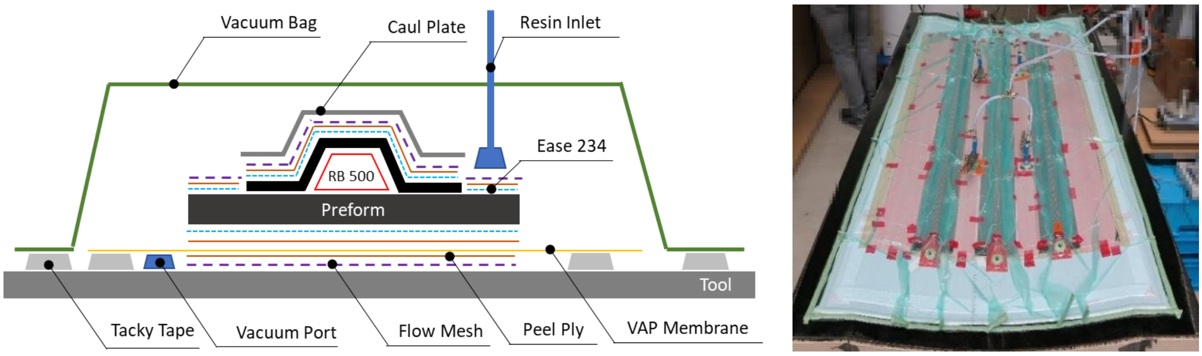

Figure 4: Demonstrator LRI a) Schematic Infusion Strategy b) LRI Setup

3 RESULTS AND DISCUSSION

3.2.1 Preforming

The Advanced Ply Placement robotic cell was used for the manufacture of preforms for subsequent liquid resin infusion and mechanical characterization as well as the production of the final skin preforms for demonstrator manufacture (1800 mm x 750 mm) using [0° / 45° / -45° / 90° / 90° / - 45° / 45° / 0°] as stacking sequence. The SAERfix EP binder veil was able to provide sufficient tack to adhere the individual textile layers of the preform. However, prior to the layup of the binder-equipped NCF material, the backing paper of the tackifying agent has to be removed. It was not possible to automate this process and due to the fragility of the backing paper, it often tore, which led to increased manual effort.

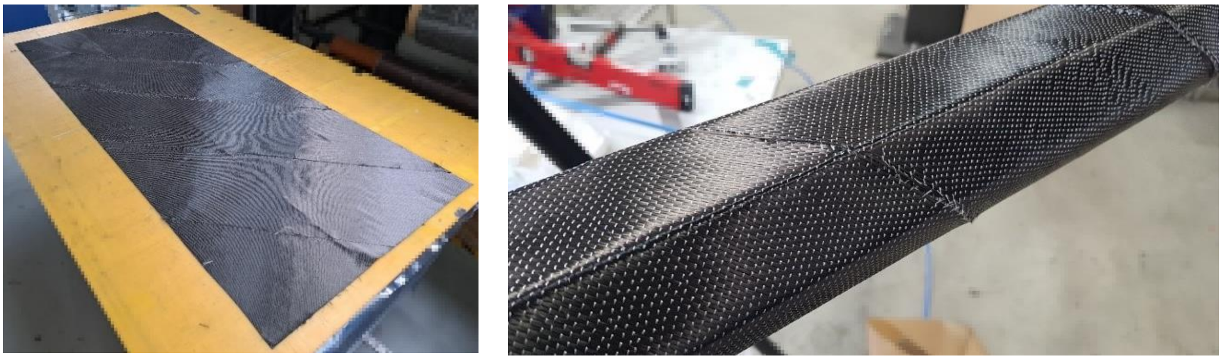

Figure 5: Preform Manufacture a) APP; Skin Preform; -45° Layup b) Stiffener Preform Manufacture

3.2.2 Liquid Resin Infusion

CFRP laminates were produced, using the material combination described in Section 2.1 and the aforementioned infusion strategy. The laminates were mechanically characterized in order to compare with SoA material combinations. A selection of the material properties can be found below:

Table 2: Mechanical Characterization – LVL1 Testing – G0827 / RESOLTECH 1500/1504

Property		Test Standard	Unit	Mean Value[1]
Tensile Strength	f_{11t}	ASTM 3039	MPa	1419.4
Tensile Modulus	E_{11t}	ASTM 3039	GPa	115.31
Poisson Ratio	ν_{12}		-	0.29
Compression Strength	f_{11c}	ASTM 3410	MPa	838.54
Compression Modulus	E_{11c}	ASTM 3410	GPa	107.56
In-Plane Shear Strength	f_{12}	ASTM 3518	MPa	80.58
In-Plane Shear Modulus	G_{12}	ASTM 3518	GPa	5.45
Interlaminar Shear Strength	f_{13}	ASTM 2344	MPa	78.6
Fracture Toughness	G_{1c}	AITM 1.0005	J/m²	315.18
Interlaminar Fracture Toughness	G_{2c}	AITM 1.0006	J/m²	782.44

[1] Average Values were obtained from 5 measurements

The VAP infiltration approach for the demonstrator part, using four resin inlets for impregnation of the preform with Resoltech 1500/1504 resin, in combination with the smart molds' microvibrations for impregnation improvement was successfully demonstrated (Figure 6). Nondestructive testing, using ultrasonic C scanning, did not show any dry spots, indicating successful impregnation of the composite part. Furthermore, micrographs of the demonstrator's cross-section also indicate adequate fiber impregnation (Figure 7).

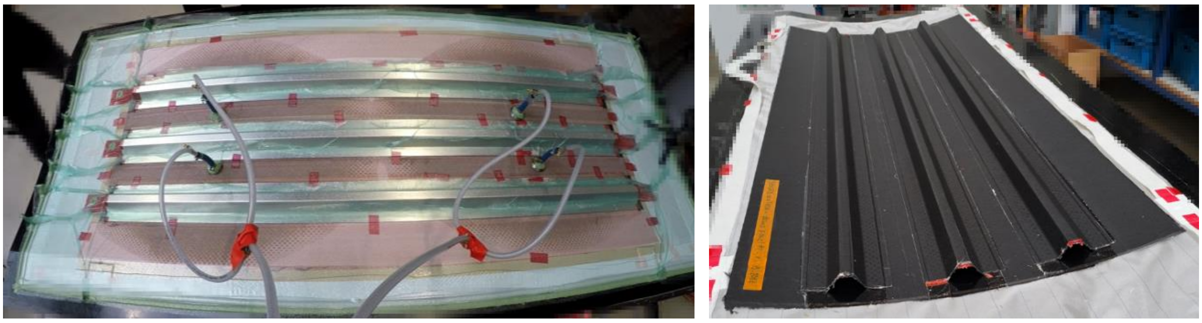

Figure 6: Demonstrator LRI a) Schematic Infusion Strategy b) LRI Setup

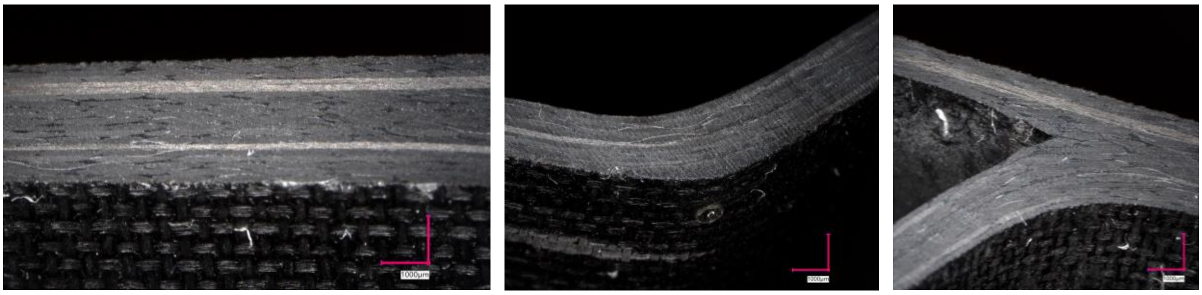

Figure 7: Micrographs a) Stiffener Flange b) IML Omega c) IML Flange Region

3.2.3 Smart Mould

With the utilization of piezo-induced microvibrations on the two-dimensional smart mould it was possible to reduce the impregnation time during the VAP resin infusion, while maintaining the infusion parameters, as it can be seen in Table 3. Furthermore, a more homogeneous flow front propagation was observed. Based on the initial results, it can already be assumed, that due to piezo-induced active impregnation optimization, the energy consumption during composite manufacture can be reduced by the decrease of impregnation time and therefore overall process time, which shall be validated by trials on the scaled tooling.

Table 3: Impregnation Duration on 2D smart Mould

Label	Microvibrations	Impregnation Duration	Reduction
PRE-INF-01	---	23 min 50 sec	---
PRE-INF-02	255 Hz	21 min	12%
PRE-INF-03	287 Hz	17 min	29%

Successful one-shot infusion of the combined skin and stiffener preforms on the scaled smart mould was demonstrated in two infusions. The energy consumption was measured for both scenarios, during smart mould cure and oven cure (Table 4 and Figure 8). Due to additional volume, which inevitably needs to be heated during oven cure an elevated energy consumption of 85.02 kW was measured. Using the smart mould approach an energy consumption of 9.10 kW was measured. Although, an additional fan heater had to be connected during the last ramp up phase to 150 °C, the overall energy consumption with 18.85 kW can be considered low in comparison to SoA curing processes and demonstrates a high potential for sustainable composite manufacture. The energy consumption during manufacturing is reduced because of the self-heating structures and only heats material and the space directly linked to the process.

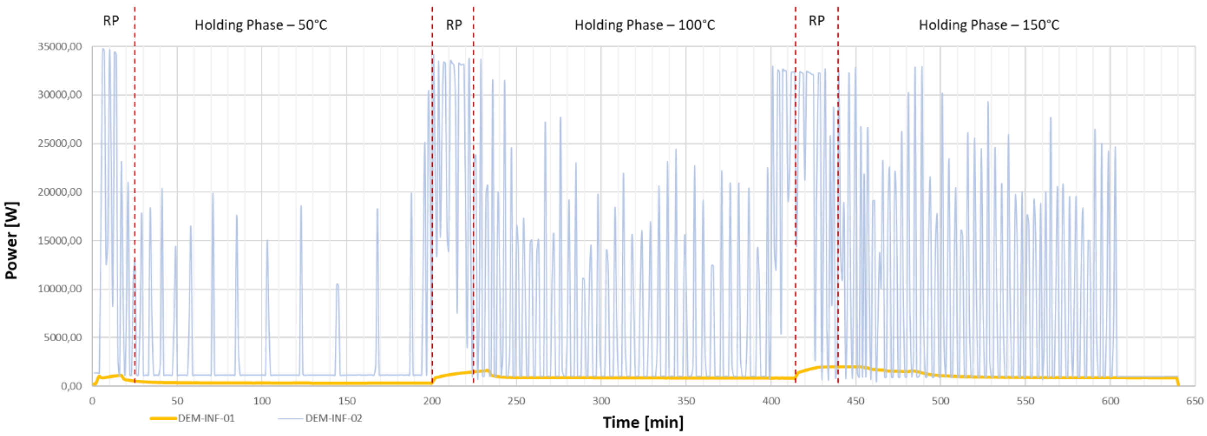

Figure 8: Energy Consumption during Composite Cure

Table 4: Energy Consumption Comparison

Label	**Energy Consumption**			**Overall Energy Consumption**
	Smart Mould	Fan Heater	Oven	
DEM-INF-01	9.10 kW	9.75 kW	---	18.85 kW
DEM-INF-02	---	---	85.02 kW	85.02 kW

4 CONCLUSIONS

This paper presents some results of the CS2 ecoTECH project, focusing on the development of novel manufacturing technologies and processing strategies for the manufacturing of thermoset composite structures. Global objective of the research project is the development of novel processing approaches to reduce the ecological footprint of structural components in the aerospace industry. For that reason, the Advanced Ply Placement process was introduced and a novel material combination for Dry Fiber Deposition (DFD), using a low FAW NCF material equipped with a self-adhesive tackifying agent was analyzed und used for preform manufacture. Next to the development and material screening for DFD processes, a comprehensive material screening was carried out for the selection of a low-viscosity room temperature infusion resin with elevated glass transition temperature. Furthermore, a novel sensor-controlled and self-heated tooling concept was developed in the course of the project. The integration of sensors into the mould enables monitoring of the material state and therefore allows active influence of the process control. The smart mould is also equipped with piezo-based actuators in order to introduce microvibrations into the mould for active impregnation improvement. The research indicates, that with the smart mould approach the impregnation duration can be reduced and furthermore a significant reduction of energy consumption during composite manufacture can be achieved, resulting in a minimization of production costs and the environmental footprint of composite manufacturing technologies. The smart mould concept allows for faster heating and independency from state-of-the-art ovens and autoclave processes. In order to demonstrate the feasibility and the ecological benefits of the ecoTECH developments, a stabilizer panel, with slight curvature and integrated stiffener elements was realized using the aforementioned technologies

ACKNOWLEDGEMENTS

This research was funded by the European research programme Clean Sky 2. The ecoTECH project has received funding from the European Union’s Horizon 2020 Clean Sky 2 Joint Undertaking under the AIR FRAME ITD grant agreement 945521. Furthermore, the authors would like to acknowledge the University of Patras (UPAT) for their support in mechanical characterization of composite laminates, INASCO HELLAS for the supply of the sensor system and the Netherland Aerospace Center (NLR) for manufacture of the AFP laminates.

REFERENCES

[1] Clean Sky 2. Available online: https://www.clean-aviation.eu/clean-sky-2/programme-overview-and-structure (accessed on 19.05.2023)

[2] Lengsfeld, H.; Wolff-Fabris, F.; Krämer, J.; Lacalle, J.; Altstädt, V.. *Faserverbundwerkstoffe*, Carl Hanser Fachbuchverlag, 2020.

[3] C. Cherif. *Textile Werkstoffe für den Leichtbau*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2011.

[4] Schmidt, S.; Mahrholz, T.; Kühn, A.; Wierach, P.. *Powder binders used for the manufacturing of wind turbine rotor blades. Part 1. Characterization of resin-binder interaction and preform properties*, Polymer Composites, 2018, Vol. 39(3), pp. 708–717 (DOI: 10.1002/pc.23988).

[5] A Roadmap to Automated Composites. Available online: https://www.cgtech.com/images/pdf/Roadmap-to-Automated-Composites.pdf (accessed on 15.05.2023)

[6] Lukaszewicz, D. H.-J.; Ward, C.; Potter, K.D.. *The engineering aspects of automated prepreg layup: History, present and future.* Composites Part B: Engineering, 2012, Vol. 43(3), pp. 997–1009 (DOI: 10.1016/j.compositesb.2011.12.003).

[7] Veldenz, L.; Francesco, M.D.; Astwood, S.; Anno, G.D.; Kim, B.C., Potter, K.. *Characteristics and processability of bindered dry fibre material for automated fibre placement*, Munich, Proceedings of the 17th European Conference on Composite Materials 2016, Munich, Germany, June 26th – 30th, 2016.

[8] Grisin, B.; Carosella, S.; Middendorf, P.. *Dry Fibre Placement: The Influence of Process Parameters on Mechanical Laminate Properties and Infusion Behaviour*. Polymers, 2021, Vol. 13 (21), (DOI: 20.3390/polm13213853).

[9] Veldenz, L.; Francesco, M.D.; Giddings, P.; Kim, B.C.; Potter, K.. *Material selection for automated dry fiber placement using the analytical hierarchy process*. Advanced Manufacturing: Polymer & Composites Science, 2018, Vol. 4(4), pp. 83–96 (DOI: 10.1080/20550340.2018.1545377).

[10] Helber, F.; Szcesny, M.; Carosella, S.; Middendorf, P., *Tack and Binder Solubility Investigations on Reactive and Non-Reactive Binder Systems*, Proceedings of the SAMPE Europe Conference 2019, Nantes, France, September 17th – 19th 2019.

[11] Brody, J.C., Gillespie, J.W.. *Reactive and non-reactive binders in glass/vinyl ester composites*. Polymer Composites, 2005, Vol. 26(3), pp. 377–387 (DOI: 10.1002/pc.20068).

[12] Schledjewski, R.; Yadav; N.. *Safe and efficient heating - How to identify the best performing heating method for thermoplastic tape placement*. Proceedings of the SAMPE Europe Conference 2019, Nantes, France, September 17th – 19th 2019.

[13] Grant, C.. *Automated processes for composite aircraft structure*. Industrial Robot: An International Journal, Vol. 33 (2), pp. 117-121 (DOI: 10.1108/01439910610651428)

[14] Zenker, T.. *T-AFP - Thermoplastic Automated Fiber Placement for the manufacturing of structures*, Luftfahrttechnisches Handbuch, Under Review.

[15] Szcesny, M.; Heieck, F.; Carosella, S.; Middendorf, P.; Sehrschön, H.; Schneiderbauer, M.. *The advanced ply placement process – an innovative direct 3D placement technology for plies and tapes*. Advanced Manufacturing: Polymer & Composites Science, 2017, Vol. 3:1, pp. 2-9 (DOI: 10.1080/20550340.2017.1291398).

[16] Oosterom, S.; Allen, T.; Battley, M.; Bickerton, S.; *An objective comparison of common vacuum assisted resin infusion processes*. Composites Part A, 2019, Vol. 125 (DOI: 10.1016/j.compositesa.2019.105528)

[17] Ehrenstein, G.; *Faserverbund-Kunststoffe*; Carl Hanser Fachbuchverlag. 2006.

[18] Meinhardt, T.; Harismendy, I.; Heieck, F.. *LOWFLIP – Tailored Snap-Cure Prepregs for novel Composite Production Processes*, Proceedings of the 17th European Conference on Composite Materials 2016, Munich, Germany, June 26th – 30th, 2016.

[19] msquare. Available online: https://www.msquare.de/heating-blankets/ (accessed on 17.05.2023)

[20] Composites World. Available online: https://www.compositesworld.com/articles/heated-composites (accessed on 17.05.2023)

[21] Composites World. Available online: https://www.compositesworld.com/cdn/cms/SAMPE%20April%202015%20HiTape%20V4%20udpated%202019%20Final.pdf (accessed on 18.05.2023)

[22] Bouquerel, L.; Moulin, N.; Drapier, S.. *A Contribution to the Study of the Forming of Dry Unidirectional HiTape® Reinforcements for Primary Aircraft Structures*. Frontiers in Materials Vol. 7, 2021 (DOI: 10.3389/fmats.2020.571779).

[23] HEXCEL Fibers SASU, Roussillon, France, *Product Data Sheet HexForce G0827 BB1040*, 2018.

[24] Helber, F.; Szcesny, M.; Carosella, S.; Middendorf, P., *Enhancement on Automated Preforming for Composite Structures*. Proceedings of the 22nd International Conference on Composite Materials, Melbourne 2019, Australia, August 11-16,2019.

[25] Helber, F.; Carosella, S.; Middendorf, P.. *Effects of reactive and non-reactive tackifying agents on mechanical neat resin and composite performance for preforming processes and Liquid resin Infusion (LRI) techniques*. Advanced Manufacturing: Polymer & Composites Science, Vol. 9 (1), 2023 (DOI: 10.1080/20550340.2023.2205796).

[26] SAERTEX GmbH & Co. KG, Saerbeck, Germany, *Safety Data Sheet SAERfix® EP*, 2017
[27] Helber, F.; Carosella, S.; Middendorf, P.; *Quantitative Assessment of Reactive and Non-reactive Binder Systems on First Ply Adhesion for Dry Fiber Placement Processes*. Key Engineering Materials, Vol. 926, pp. 1317-1326, 2022 (DOI: 10.4028/p-5j966g).
[28] HEXCEL Corporation, Stamford, USA, *Product Data Sheet HexFlow® RTM6/RTM6-2*, 2022
[29] Resoltech Advanced Technology Resins, Rousset, France, *Safety Data Sheet 1500*, 2020.
[30] AIRTECH Europe SARL, Haneboesch, Luxembourg, *Data Sheet Knitflow 105 HT*, 2022
[31] AIRTECH Europe SARL, Haneboesch, Luxembourg, *Data Sheet Release Ply C*, 2021
[32] AIRTECH Europe SARL, Haneboesch, Luxembourg, *Data Sheet Release Ease® 234 TFP*, 2019
[33] AIRTECH Europe SARL, Haneboesch, Luxembourg, *Data Sheet Wrightlon® 5200*, 2020
[34] COMPOSYST GmbH, Landberg am Lech, Germany, *Technical Data Sheet VAP® Membrance C2003*, 2020
[35] AIRTECH Europe SARL, Haneboesch, Luxembourg, *Data Sheet Knitflow DAHLAR® Release BAG 500*, 2016
[36] PI Ceramic GmbH, Lederhose, Germany, *Data Sheet DuraAct P-876*, 2023