CHARACTERISTICS AND PROCESSABILITY OF BINDERED DRY FIBRE MATERIAL FOR AUTOMATED FIBRE PLACEMENT

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Abstract

Automated Fibre Placement (AFP) of bindered dry fibre material has emerged as a potential manufacturing process for advanced composites. The technology is in its early stages of development and material suppliers are entering the market with a range of different materials. This paper addresses the current knowledge gaps by assessing the fundamental differences between five of the available materials. The differences between the as supplied raw materials were characterised in terms of their geometrical tolerances (width, thickness and areal weight) and their manufacturability was assessed in terms of the number of faults during automated fibre placement lay-up, the fibre volume fraction of the preform and the infusion time. The procurement challenges (lead time, risk and customer support) were also taken into account. The results were compiled in a decision matrix using the Analytical Hierarchy Process (AHP) to define a suitability index for each material. Two materials were identified as viable options.

1. Introduction

Automated fibre placement (AFP) is an additive manufacturing process for composite material originally developed for the lay-up of slit prepreg tapes. The automated fibre placement processes commonly utilise 3.2 mm, 6.35 mm or 12.7 mm wide tapes and a heat source to promote adhesion between the incoming material and the substrate [1, 2].

Recent developments of the dry fibre technology have allowed the lay-up of dry carbon fibre material containing between 5 and 10% by weight of binder and resulting in dry, yet coherent preforms to be impregnated with resin in a subsequent step, by resin transfer moulding or vacuum infusion [3]. Such a sequential manufacturing process is potentially more cost effective than automated fibre placement with prepreg material, as the material can be processed out-of-autoclave and the raw material has the potential to be cheaper [4,5].

Preliminary work conducted at the National Composites Centre (NCC) identified the following challenges to the deployment of the dry fibre automated fibre placement process specifically for applications in the aerospace industry:

1. Identification of raw materials availability and their physical characterisation.

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2. Limited knowledge regarding the definition, prediction and optimisation of the parameters governing the deposition process of bindered materials with automated fibre placement.
3. Lack of detailed process understanding for the definition, prediction and optimisation of the resin impregnation process.
4. Limited understanding of the correlation between the automated fibre placement set-up and the quality of the cured laminate.

The work presented in this paper addresses point 1 by assessing a set of available dry fibre materials and investigating their differences in processabiltiy in the context of the automated fibre placement process. The assessment has been carried out in order to determine the suitability of the investigated materials to manufacture a technology demonstrator, representing a typical, thin, mildly curved aerospace component (see Figure 1).

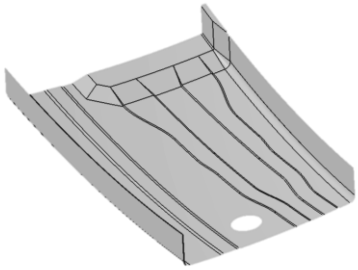

Figure 1. Preliminary design of the technology demonstrator (~1.5 x 1 m).

2. Dry Fibre Material

The scope of this project was limited specifically to commercially available products. There is currently no dominant design on the market, and therefore different suppliers may provide substantially different products, as summarized in Table 1.

Table 1. Overview of different available dry fibre materials.

				Material		
	Definition	*A*	*B*	*C*	*D*	*E*
Carbon Fibre						
Fibre type		HS*	HT*	HT*	IM*	HS*
Nominal areal weight [g/m^2]		196	126	126	210	262
Tape type	Tow		✓	✓	✓	✓
	Slit tape	✓				
Binder						
Chemical composition	Epoxy based	✓	✓			
	Thermoplastic based			✓	✓	✓
Binder application	Veil	✓**			✓	
	Powder/spray	✓	✓	✓		✓

*HS = high strength; HT = high tenacity; IM = intermediate modulus
** carbon fibre veil including binder

In Figure 2, the different surface topographies of the chosen materials are illustrated, exhibiting different surface characteristics due to different binder application methods.
Most materials have the same finish on both sides, except material A that has distinct features on either side of the tape. Material A has a carbon veil on the top side and epoxy based binder spots on the bottom side (indicated by grey spots). Material B, C and E have binder spots evenly distributed on both sides, where B exhibits a lower density of spots than C and E. Material D has a thermoplastic based veil on both sides. A perforation due to the manufacturing process can be seen on the surface, possibly in order to enhance the through thickness adhesion or to improve the through thickness

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permeability (shown as ellipses).

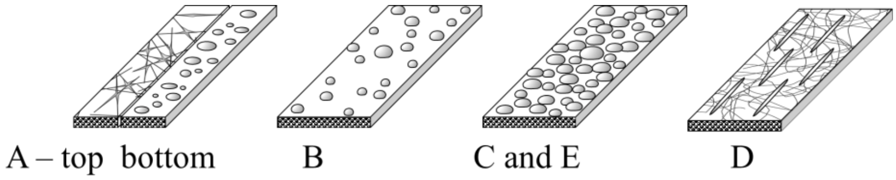

Figure 2. Sketches of Dry Fibre Materials (A-E).

3. Methodology

3.1. Experimental set-up - Automated Fibre Placement

In this study, an automated fibre placement machine from Coriolis Composites S.A.S (Queven, France) was used. The machine processes eight tapes of 6.35 mm width. The bobbins of dry fibre material are mounted in an environment controlled creel, then guided through individual channels to the deposition head. When the material leaves the deposition head, it is heated up by a heat source and the binder is activated. Subsequently, the material is compacted under the roller, where pressure promotes adhesion of the material to the substrate. Approximately 200-300°C are required to activate the binder, therefore a 3 kW diode laser with a wavelength of 1025 ± 10 nm and a laser optic spot size of 8 x 57 mm is used as a heat source (see Figure 3).

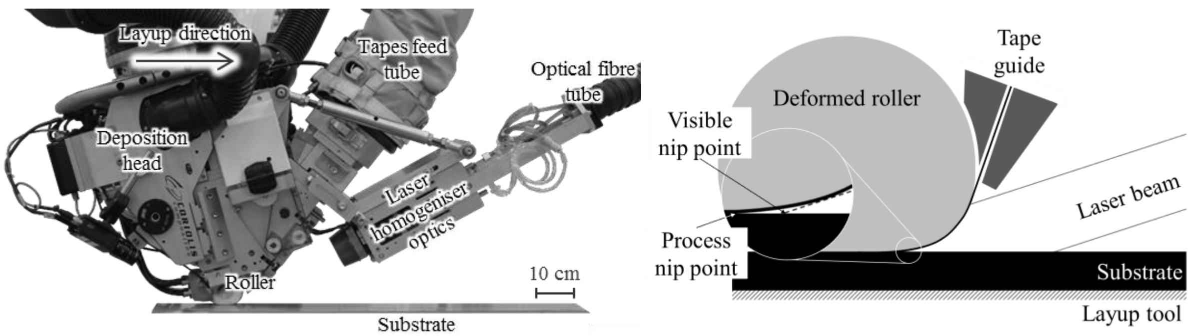

Figure 3. Automated Fibre Placement (left: image of deposition head; right: schematic of the nip point area).

3.2. Material characterisation methods

For the width measurements, ten samples of 200 mm length per sample were taken from each bobbin (eight bobbins per material). These samples were taken over a length of about 500 m of material. A high resolution scanner (2400 dpi, 0.01 mm per pixel) and a subsequent image analysis (Matlab, US) was used to assess the width of each sample. The areal weight of the material was assessed using the same scanned images and the weight measurement from a high precision scale (XSE105, Mettler Toledo, US). The thickness of the raw material was characterised using a surface roughness measurement device (InfiniteFocus, Alicona, Austria). The binder quantity (wt. %) was investigated using thermogravimetric analysis following ASTM E1131 [6] on one sample per bobbin (eight samples per material).

3.3. Methods for assessment of processability

All materials were processed on the automated fibre placement machine at constant speed (400 mm/s), 446 ± 23 N (95% confidence interval) compaction force and at variable power unique to the materials (see Table 2). Processing temperature was measured at the visible nip point.

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Table 2. Manufacturing details of the different materials A-E.

Material	*A*	*B*	*C*	*D*	*E*
Processing temperature [°C] (95% confidence interval)	215 ± 3	197 ± 4	319 ± 8	252 ± 2	357 ± 5
Input laser power [W]	627	609	738	549	668
Number of plies (strips)	10	16	16	10	8
As laid fibre volume fraction [%] (95% confidence interval)	50 ± 0.3	58 ± 0.3	42 ± 0.8	40 ± 0.6	45 ± 0.9
Number of plies (panels)	15	23	23	14	11

Strips (comprising eight tapes) with were laid up to a nominal thickness of 2 mm on which the measurement of the thickness was performed. Additionally, a panel (600 x 600 mm) for each material was produced at the same speed and compaction force. A symmetric bi-directional lay-up was chosen with different numbers of plies in order to generate the same nominal preform thickness (3 mm).

Nine different fault types were identified during the manufacturing trials. The number of faults was taken into account without accounting for severity. In order to assess the processability, the occurring faults were monitored by a trained operator at each ply (Table 3).

Table 3. List of different fault types observed during automated fibre placement.

Observed fault types		
fibre fluff	loose fibres on surface	shearing
binder residue inclusion	twisted tow	overlap
gap (>2 mm)	fibre folding	foreign inclusion

The thickness of the manufactured preform was measured contactlessly using an articulated arm with an integrated laser line scanner (ModelMaker MMDx100 digital laser scanner and MCAx35+ Manual Coordinate measuring Arm, Nikon, Japan). The system has an accuracy of 76 μm (2 σ) according to the manufacturer.

A panel for each material was infused in a closed mould with a cavity (500 x 500 x 3 mm). The epoxy resin was Epikote RM135/H137 (Hexcel, US) and the preform was infused under vacuum pressure only, the tool temperature was kept at 30 °C. A glass top allowed monitoring of the flow front, see set-up in Figure 4. As a baseline, a preform of ten plies of bindered unidirectional woven material (HexForce® 48330 QB1200, Hexcel, US) was used.

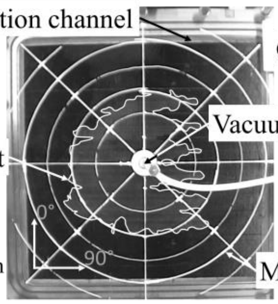

Figure 4. Top view of ongoing infusion of preform through the glass top plate (material A) at 35 min.

3.4. Analytical Hierarchy Process approach

“[…] even when numbers are obtained from a standard scale and they are considered objective, their interpretation is always […] subjective.” [7]. This supports that engineering judgement is required to make the decision of the most suitable material for the purpose of manufacturing the described demonstrator, especially given limited understanding on the effect of material characteristics and

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process variables on the lay-up quality. In order to put this judgement into a framework which makes use of both objective data and qualitative judgements, the analytical hierarchy process (AHP) was used, which is a widely applied tool from the field multi-criteria decision-making [7].

A prerequisite for the decision making process is that all of the alternatives must be generally suitable for the intended use. In this instance, this means that:

1. The price of the dry material has to be below the price of the equivalent prepreg version.
2. The down time during machine operation has to be comparable to the prepreg manufacturing route.
3. The preform has to wet out completely in the infusion trial.

The procedure of the analytical hierarchy process is shown in Figure 5. First the alternatives are identified, in this instance material A - E, then the criteria and sub-criteria for the decision are identified (a detailed list of sub-criteria can be found in Table 4). A weight factor is assigned to all criteria, based on a series of pairwise comparisons by experts that are then checked for consistency, if no weight factor can be established, equal weighing is used. Finally the alternatives (A - E) are assessed by pairwise comparison with regards to their suitability for one criterion at a time or, if data is available, a ranking is established. This means, that the highest and lowest ranking alternatives set the scale. By multiplying the result of the pairwise comparison of the alternatives with the previously determined priority, a final ranking is derived [7].

Figure 5. Analytical Hierarchy Process in brief.

A table of all criteria that play a role in determining the suitability of a material for a specific purpose was produced (Table 4). The data that is available at this point (underlined) will be taken into account for a preliminary decision.

Table 4. Criteria and their respective sub-criteria used in the analytical hierarchy process (perceived importance taken into account in %).

Procurement (4%)	*Raw material characteristics (16%)*	*Manufacturability AFP (41%)*	*Resin infusion processabiltiy (39%)*	*Laminate characteristics*
Lead time (15%) Risk (20%) Customer service (9%) Technical support (5%) Material cost (3%) Procurement conditions (48%)	Width tolerance (19%) Width deviation from nominal (50%) Thickness tolerance (18%) Material complexity (3%) Binder quantity deviation (9%)	Fault occurrence (37%) Fibre volume fraction (34%) Ply areal weight Steering capability (9%) Preform coherence (15%)	Permeability (100%) Flow front characteristic Resin compatibility	Void content Fibre volume fraction Geometrical tolerance Ply thickness Mechanical performance

4. Results

4.1. Material characterisation

Table 5 reports the results of the various measurements in regards to material variability. As a baseline for the acceptability of width variation, a prepreg slit tape was used. As the data was available for a

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3.2 mm tape [1, pg. 479], the relative standard deviation is given for comparability. The binder quantity across materials varies from 4 to 7 wt. %, where material A has the lowest variability (± 0.8 wt. %). The areal weight was calculated using the linear density measured and compared against the nominal value. Fibre content in the raw material is calculated based on the tape thickness, the areal weight, fibre density and binder content.

Table 5. Overview of characterisation results of materials A - E and a prepreg slit tape as baseline.

	Baseline *Slit prepreg*	*A*	*B*	*C*	*D*	*E*
Width [mm]	3.20	6.55	6.77	6.38	6.86	6.68
Standard deviation	0.13	0.12	0.41	0.08	0.21	0.22
Relative standard deviation	4%	2%	6%	1%	3%	3%
Binder quantity [wt.%] (Confidence 95%)	n/a	4.5 ± 0.8	5.9 ± 2.6	6.9 ± 2.2	3.8 ± 1.2	not measured
Areal weight w/o binder [g/m²] (Confidence 95%)	n/a	202 ± 14	120 ± 17	130 ± 25	195 ± 13	250 ± 23*
Nominal areal weight [g/m²]	n/a	196	126	126	210	262
Fibre content by volume as supplied [%]	n/a	45.4	25.4	27.1	25.2	23.5

*assuming the same binder quantity as material C (same supplier)

4.2. Processabiltiy of dry fibre material

The results for the assessment of processabiltiy can be found in Table 6. The fault count reveals a range of 16 to 179 total faults per 100 meters. The fibre content of the processed preform is shown, and it is always higher than the as supplied fibre content.
The result of the infusion trial is the duration of the infusion. The preforms manufactured with automated fibre placement always have a longer infusion time, the shortest infusion time of an AFP preform is four times as long as the benchmark (material A). Material B did not infuse fully with the chosen setup.

Table 6. Overview of processabiltiy of materials A – E and UD fabric as baseline.

	Baseline *UD fabric*	*A*	*B*	*C*	*D*	*E*
Fault per 100 m	n/a	23	179	132	32	16
V_f after AFP processing [%]	n/a	49.9 ± 0.3	57.5 ± 0.3	42.2 ± 0.8	39.8 ± 1.8	44.5 ± 1.2
Duration of infusion [min]	15	60	125*	not tested	145	120

*not fully infused

4.3. Material choice

Taking into account all data from the completed work, the result is that the best choice for the described purpose is material A (see Figure 6). However, if the prerequisites; material cost, machine down time and wet out during infusion (defined in section 3.4) for the choice process are applied, only material D and E are viable options (solid columns), as only these two materials pass the prerequisite of being generally suitable. Material E is judged to be more suitable than material D, as it is outperforming material D in the categories 'AFP process' and 'resin impregnation process', which are also the criteria with the highest importance.

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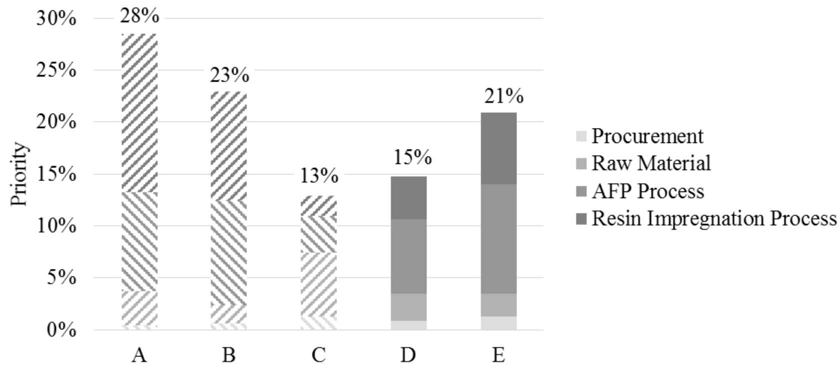

Figure 6. Result of the analytical hierarchy process

5. Discussion

The fibre content of the as-supplied material shows, that only material A has an as-supplied fibre content (45%) close to the target nominal fibre volume fraction (55%) whereas all other materials have a lower fibre content (23.5 - 27.1%) which needs to be increased by compaction during the automated fibre placement process. Therefore the automated fibre placement process has a lower impact on material A than the other materials. Only the fibre volume fraction of material B is increased significantly during the AFP process. Material B has a lower binder quantity on the surface but a similar binder content (wt. %) to material C – E, which suggests that it contains binder distributed within the tape, facilitating the compaction of the preform during the automated fibre placement process.

The fault occurrences count shows two clusters, high fault count (132 and 179) and low fault count (16 - 32). The cluster with the high fault count corresponds to the two materials with relatively low areal weight (B and C). The impact of the tape's fibre areal weight on its processability should be investigated further. An investigation of the mechanical properties (bending and torsion) of the as-supplied material can possibly give an indication of processabiltiy.

The duration of the infusion gives a first indication of the impregnation behaviour of the preforms manufactured with automated fibre placement against the broad good preform. Material A shows a significantly faster infusion time when compared to the other materials, which can potentially be attributed to the carbon veil on its surface which creates a high permeability layer between the plies. Material B can possibly be infused with a different setting, which has not been taken into account, but its high fibre density in the preform suggests low permeability.

The analytical hierarchy process compiles all captured data to make a decision based on the requirements of a specific case. That means, the process accounts for different requirements in different scenarios but it is highly dependent on the experts' opinion. However, the chosen experts are experienced AFP researchers, additionally the logical consistency of the answers is verified. The process will continuously be reviewed. Adding data or better judgements due to an increase of understanding can have an impact on the outcome of the AHP process.

All criteria are captured by the quality of the final laminate, as the laminate is a consequence of the raw material and prior processes. In theory, the assessment of the laminate should give enough indication whether the material should be chosen or not. However, the generation of data suitable for it as well as the knowledge about the interrelations of material and processes that lead to the final laminate are often unknown or too costly to generate. In addition, a practical aspect is that the assessment of each step of the process allows defining and redefining the variables according to the individual requirements of the materials.

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6. Concluding remarks

The following conclusions were drawn from the study of the characteristics and processabiltiy of bindered dry fibre for automated fibre placement:

- A wide variety of dry fibre materials is available, they show different behaviours in terms of their manufacturability.
- All but one (material B) of the materials assessed satisfy the width tolerance when benchmarked against prepreg material.
- All but one (material A) need to be compacted significantly during the AFP process to achieve the target fibre volume fraction.
- Materials with low areal weight exhibit a higher number of fault occurrences during the manufacturing process than materials with a high areal weight.
- The use of the analytical hierarchy process enables a structured and purpose specific material selection.

7. Further work

All materials have exhibited a width higher than nominal (6.35 mm), varying from + 0.03 mm to + 0.42 mm which ensures that there are no gaps between the tapes. However, Graupner has shown that the permeability varies greatly with the variation of gap width and frequency [8]. In order to enhance the generally very slow infusion time of all preforms (compared to the baseline), the introduction of flow channels by using tapes narrower than nominal can potentially enhance the flow. The implications on the mechanical properties will have to be investigated.
The assessment of steering capability will be developed, as it is a major advantage of dry fibre over prepreg material. The current assessment method for prepreg material is visual, e.g. counting of defects in a steered path. This is reliant on the operator and it is also unsuitable for steering with dry fibres, as defects cannot be identified individually.

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