

Design and Fabrication of Thermoplastic Moulds for Manufacturing CFRP Composite Impeller Blades

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Abstract. *The main objective of this study was to investigate thermoplastic materials design and fabrication processes for manufacturing composite impeller blades. Polyurethane (Necuron) and ABS (3D printed) thermoplastics were chosen due to their good mechanical properties, tooling applications, easy manufacturing and lifetime. For both thermoplastics, workability and hardness tests were performed, as well as microstructural and mechanical characterization evaluating their physical and mechanical properties. A 1:2.5 scale mould was designed and milled from Necuron N651 and N1001 and used for manufacturing of 1:2.5 scale composite impeller blades. Also, 1:1 scale ABS mould components were 3D printed and used to manufacture full scale composite impeller blades. All composite impeller presented good surface quality and tolerances with respect to CAD design, thus answering to requirements related to composite processing*

Keywords: *polyurethane material, composite materials, impeller blade, centrifugal rotor*

1. Introduction

It has been proven that technology breakthroughs happened due to significant material progress and researches. This class of composite materials is characterized by the marriage of quite diverse individual components that work together to produce capabilities exceeds those of their separate elements and their unique properties make them the materials for major technological advances. fibre reinforced polymeric matrix composite (CFRP) have enormous potential in the construction, transport, aerospace and energy sectors because of their durability, light weight and ability to be manufactured in complex shapes. Initial applications of composite materials to aircraft structures were in secondary structures such as fairings, small doors and control surfaces. As the technology matured, the use of composite materials for primary structures such as wings and fuselages has increased. Their applications in industries like aerospace are not only related to high thrust-to-weight ratio, but also to their corrosion and fatigue resistance. Moreover, these material present high stiffness to weight ratio optimization, thermal and environment resistance for high performances and fuel efficiency [1]. These composite materials are usually used in the form of prepregs, for ease of manufacturing, labour cost and time. Prepregs can be manufactured according to beneficiary requirements, varying in resin and fibre type and volume. Figure 1, presents a summary of prepreg technology and its main advantages.

Most of the major types of renewable energy cycles require a piece of turbomachinery. The concept of continuous fibre woven impeller initially originated for development of an axial compressor that utilized these novel impellers for compressing water vapour as a refrigerant. Research aims to expand their application across other sectors of energy as shown in figure 2 [2]. Manufacturing a composite impeller blade is a complex task, offering several advantages. Starting from the design and

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geometry optimisation (aero-elastic studies) with respect to the manufacturing process represents the first step in the development cycle.

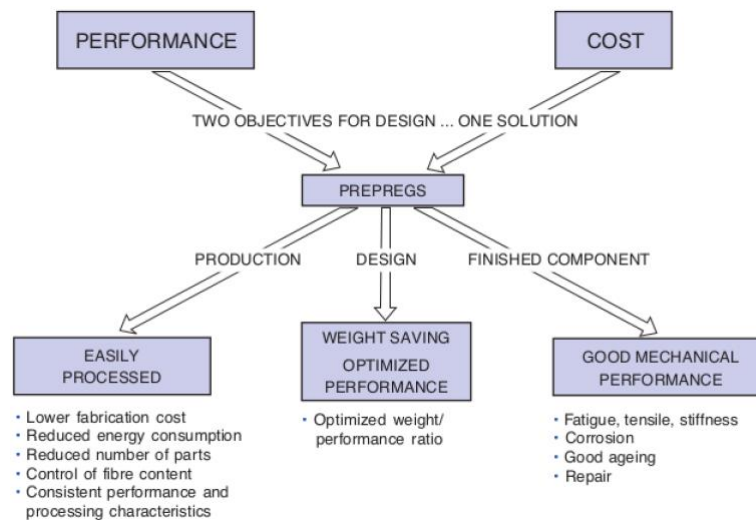


Figure 1. Polymer composite materials properties

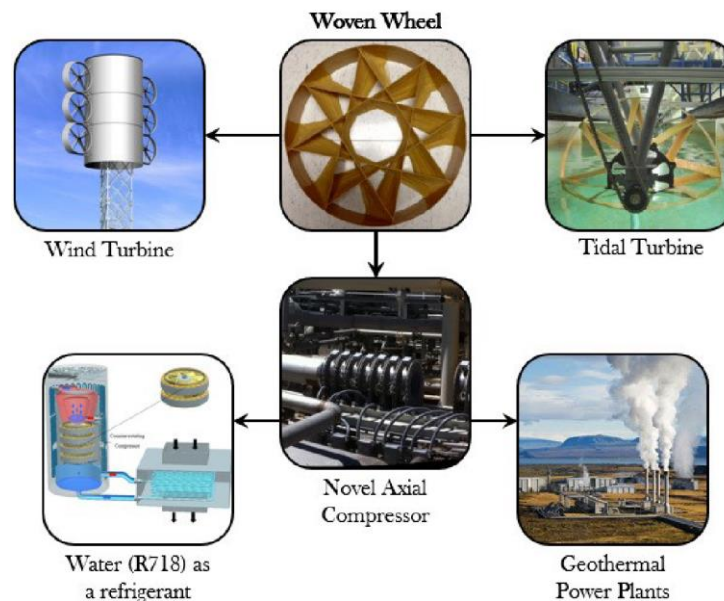


Figure 2. Woven impeller application areas [2]

In the recent years metallic classic materials has been replaced by polymeric materials when modelling, tooling applications, fixtures and jigs are targeted, due to their good mechanical properties, easy manufacturing and lifetime. Polymeric materials like polyurethanes can be both thermoplastic and thermoset, reinforced or not, and can be manufactured through traditional manufacturing methods including extrusion, injection, thermoforming (for thermoplastics) and lay-up, compression moulding and casting (for thermosets). A great application of these reinforced polyurethanes is in moulding tools. Necuron materials [3] are typically thermoplastics made from filled polyurethane and they exhibit very high dimensional stability, low density, high compression strength, good machining, high stiffness, wear resistance making it suitable for different applications: insulators, copy models, rollers, housing parts, clock-gearing, plain bearings, gear wheels, moulding tools, [4, 5]. The mechanical properties are remarkably aligned to the requirements which guarantee constant quality. Researchers have expressed an ongoing interest regarding the mechanical behaviour of different types of polymers through some important studies that use various loading conditions, tensile, compression or more

complex tests [6, 7], bending tests of polyurethane foams [6]. With the increasing applications of these materials, a good knowledge of their workability, chemical, structural, physical and mechanical behaviour is important, mostly because many data sheets lack information about material properties.

2. Materials and methods

Starting from the metallic reference rotor design presented in Figure 3, a new and optimised geometry has been made (Figure 4) that will generate at least 50% weight reduction of the rotary assembly and better performances related to fuel consumption and pollutant emission reductions.

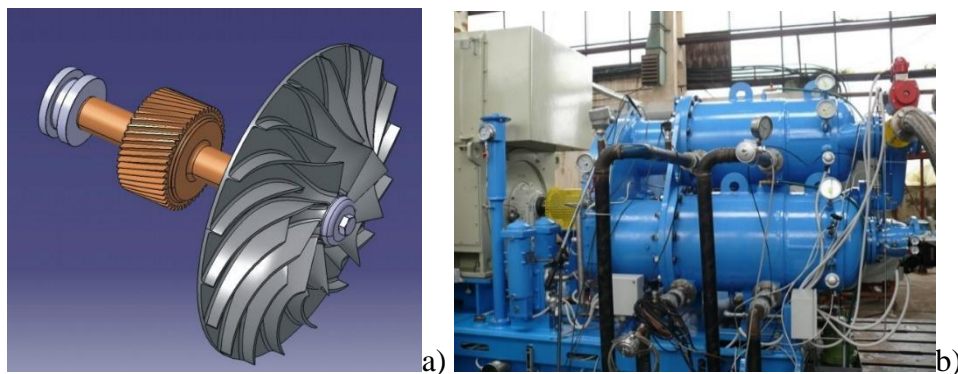


Figure 3. a) Metallic rotor reference as part of
 b) Centrifugal air compressor assembly

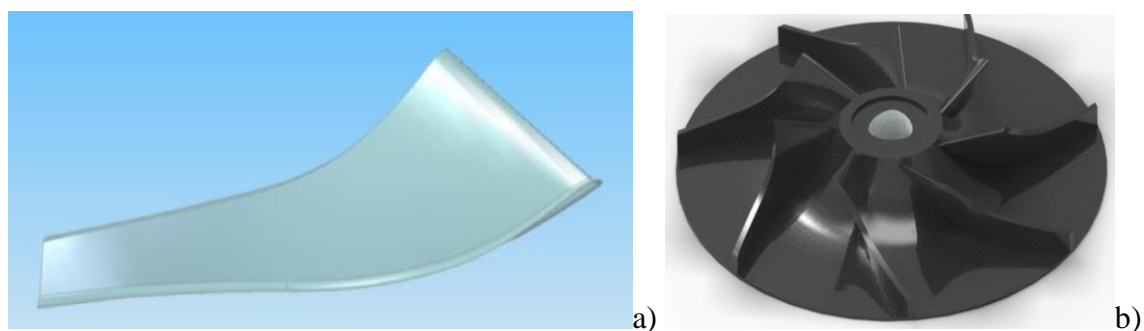


Figure 4. CAD model of a) optimised compressor rotor impeller blade and b) CFRP compressor rotor

The equation 1 and 2 sets the base formula for the centrifugal forces calculations, in the present case a first iteration of calculus takes into account a volume element (i.e. ΔV is $2 \times 10^4 \text{ mm}^3$, ρ is taken for the woven High Strength Carbon Epoxy composite as 1.47 g/cm^3 , the acceleration ω is taken at $17 \times 10^3 \text{ rot/min}$. and the radius R is $121,48 \text{ mm}$), the centrifugal forces acting on the composite materials structure taken into account within the first iteration is around $11,3 \text{ kN}$.

$$F_c = R \times \omega^2 \times \rho \times \Delta V, (N) \quad (1)$$

$$\omega = 2 \times \pi \times n, (\text{rad/sec}) \quad (2)$$

2.1. Materials, sample preparation and testing methodology

The experimental program on three commercial polymer materials Necuron 651, 702, and 1001 [8, 9, 10], consisted in investigating their workability, finding the optimum milling regime, performing roughness measurements, hardness, mechanical tests and structural investigations using scanning electron microscopy SEM equipped with EDAX system. Selection of materials for the 1:2.5 scaled mould of a centrifugal rotor impeller was done based on a set of requirements imposed by the centrifugal compressor rotor/impellers advance composites materials processing and cure stages. The

mould material has to answer to following requests: low CTE (coefficient of thermal expansion) in order to avoid thermal stress concentrations do to CTE mismatch between mould and processed composite materials, good machining, quality surface, good dimensional stability up to high temperatures (i.e. 140°C) used during composite materials processing.

2.2. Workability

Different mechanical processes were used like milling, drilling and polishing. The milling of the mould was realized using a DMU Deckel Maho CNC machine testing several regimes. Following milling and polishing operations, roughness was measured using an electronic roughness tester, Marsurf PS1.

2.3. Hardness tests

Hardness of plastics is difficult to establish and compare because when using indenters there is an elastic recovery effect. Rockwell and Shore hardness are typical for plastic materials. Shore hardness tests exclude any elastic recovery effect. Within the present study ShoreD, Rockwell hardness tests were performed on the three materials under study. Shore hardness tests were performed according to ASTM D2240 to determine the relative hardness of materials under study (being used for soft materials, usually plastic or rubber) by penetration with a spring loaded needle-like indenter. Shore D scale was used with loading force of 4536 g. Rockwell hardness tests were performed on EMCO Test M4C025G3M harness equipment according to ASTM D 785, the indentors for the Rockwell test included a diamond cone penetrator having an included angle of 120° with a spherical tip having a radius of 0.2 mm. The specimen was loaded by a minor load, followed by a major load applied for 15 seconds and then again by same minor load, and then the hardness was read off the dial. Rockwell HR-M and HR-45N scales were used, being commonly used with plastics.

2.4. Microstructural Analysis

SEM investigations were conducted on all three Necuron samples. The samples subjected to SEM were first cut into smaller size (10 x 10 x 10 mm) with MetaCut M250 Manual Cutoff Machine. After sizing the samples to an appropriate size in order to fit the microscope chamber and coated with gold 100 Å film thickness to be electrically conductive using a cladding machine Emitech SC7620 mini sputter coater. This was realized to prevent the charge-up on the specimen surface and to increase secondary electron emission. SEM investigations at 30kV voltage, using a spot of 3.5 in both secondary and backscattered electrons, were conducted on a FEI Inspect F50 SEM having a 1 nm resolution, equipped with Energy Dispersive X-ray system

2.5. Mechanical characterization

A short mechanical test campaign was performed for both flexural and compressive strength determination. A number of 5 specimens were tested for each material. All tests were carried out using and 250 kN Instron 8802 hydraulic testing machine, at room temperature in accordance with ISO 178:2010 “Determination of Flexural Properties” and respectively ASTM D695 “Standard Test Method for Compressive Properties of Rigid Plastics”.

2.6. Design and manufacturing of 1:2.5 scale impeller blade mould


The components of the 1:2.5 scale impeller blade mould were first realized by CAD modelling using SolidEdge 2019 software. Following design assessment, N 651 and 1001 were used in manufacturing of a mould for an impeller blade mould scale 1:2.5. Different mechanical processes were used like milling, drilling and polishing. The milling of the mould was realized using a DMU Deckel Maho CNC milling machine.

3. Results and discussions

3.1. Workability: optimum milling regime and roughness measurement

Several milling regimes were tested on N 651 block on four regions (grooves of 8mm wide and 0.2mm depth). The milling regimes and a picture of grooves are presented in Table 1 below. Following milling and polishing operations on four groove, roughness of the N 651 was measured. In Table 1 are presented the roughness of each groove. The optimum roughness was obtained after milling with 4000 rpm speed and 0.01 lead.

Table 1. Milling regimes and roughness on N651

Groove	a	b	c	d
	 <p>Milled hole and grooves on N651</p>			
Speed (rpm)	5000	4000	4000	4000
Feed	0.025	0.05	0.01	0.005
Roughness (µm)	2.9	3.3	2.46	2.57

3.2. Hardness tests

Before starting the harness test campaign a Brinell test was performed using a steel ball of 5 mm applying a force of 62.5 kgf. Measuring the diameters of the prints using a microscope it was observed that N651 presents the highest diameter of 4.3 mm (mean of five measurements), N702 3.5 mm and N1001 2.5 mm. The first indication is that the harder material seems to be N1001.

Table 2. Hardness values of Necuron tested materials

Macro Hardness			
Material: Necuron	Rockwell HR-4N Minor Load: 3 kgf Major Load: 45 kgf	Rockwell HR-M Minor Load: 10 kgf Major Load: 100 kgf	Shore D 4536 g.
	ASTM D 785		
N651	56.1	49	68
N702	60.8	57	74
N1001	67.8	60	83

The hardness tests results are summarized in Table 2 above. The values obtained for harness confirmed the first observations performed using Brinell ball indentations, N1001 exhibits the highest hardness from all three analyzed Necuron materials. Nevertheless, the harnesses measured were scattered and the reported values from Table 3 are means of five measurements for each sample material and each testing condition. The reason these scattered measurements is related to pore inhomogeneous distribution in all materials, along with parameters related to casting conditions process with respect to curing effectiveness, depth of cure. The results obtained were correlated with materials morphology showing a clear correlation between the hardness and the porous internal microstructure of materials processed through casting. The inhomogeneous distribution of pores and their size which varies from one material to another led to different results in local hardness. The highest hardness of N1001 is explained by the pore lower size and closer distribution as shown by SEM analysis, when compared with N651 and 702 materials. Likewise, the density which is 0.66g/cm³ for N651 compared to 702 (0.78 g/cm³) and respectively 1001 (1.19 g/cm³).

3.3. Microstructural analysis

SEM microstructural analyses were performed at different magnifications, using both secondary and the electron backscatter diffraction (EBSD) technique. A first observation was their high porosity, as the SEM images at magnification 1000x shows (Figure 5). All materials exhibit an average size of the pores from 40-50 on N1001 and 40 to 80 μm on both N651 and N702, and the resin morphology grains presents a typical amorphous structure with sharp edges. Energy Dispersive X-ray analysis results of resin on three materials are typical for polyurethane and polyurethane epoxy blends (figure 6).

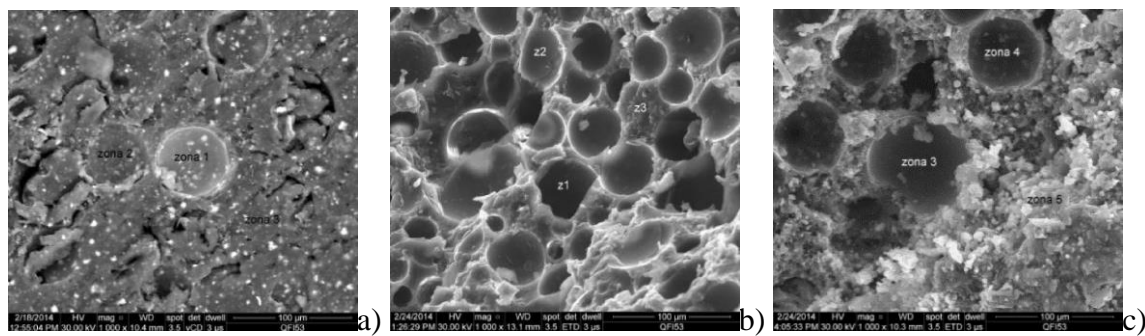


Figure 5. Resin morphology on three analyses materials and areas for EDAX analysis a) N651, b) N702 and c) N1001

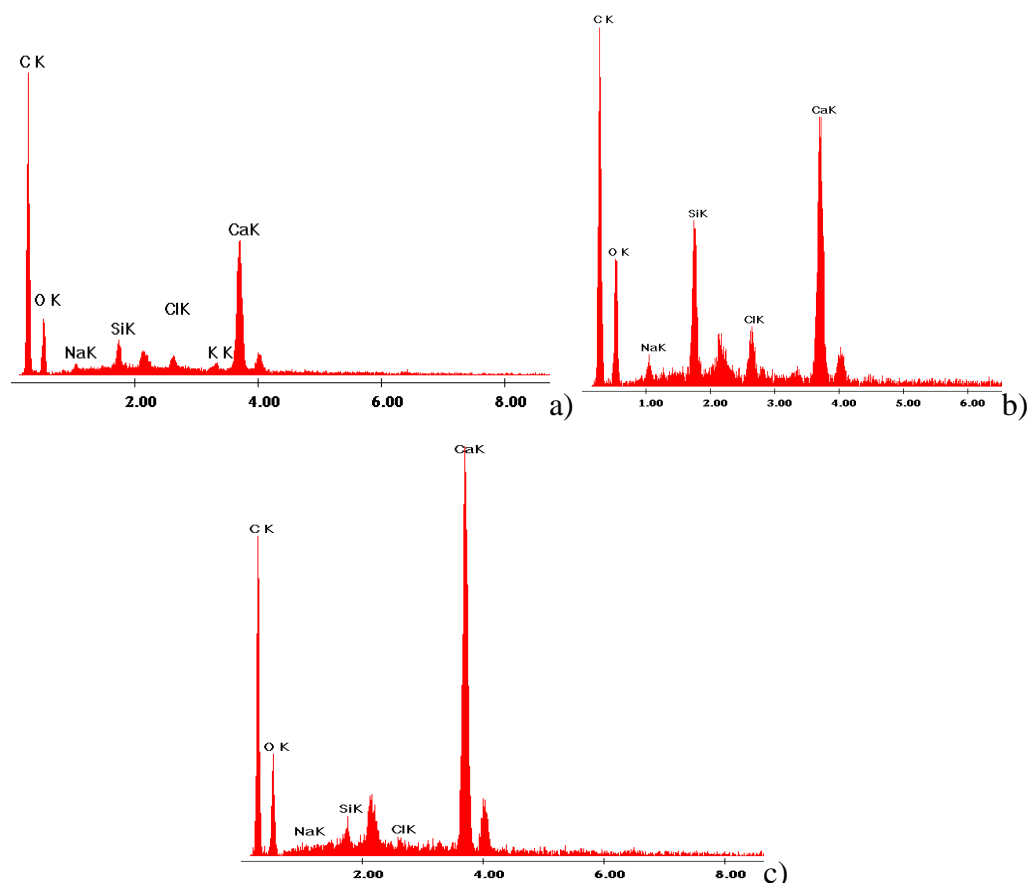


Figure 6. SEM-EDX spectra of a) N651 b) N702; c) N1001

3.4. Mechanical characterization

Five samples of each Necuron material were tested in three-point bending and compression regimes and the results are presented as a mean value in table 3. The N1001 presents the highest values, whereas the N702 presents satisfying performances. Nevertheless, when manufacturing a 1:1

scale mould the best balance must be found between materials properties: CTE, thermal resistance, dimensional stability, mechanical strength, lifetime (reuse, number of manufacturing cycles) and price.

Table 3. Results of mechanical tests

Necuron Type	Mechanical Properties	
	Flexural Strength [N/mm ²]	Compressive strength [N/mm ²]
651	30	26
702	28	32
1001	75	70

3.5. Design and manufacturing of 1:2.5 scale impeller blade mould

For the technological mould scale 1:2.5, N651 and 1001 materials were chosen, assuring a CTE of around $50 \times 10^{-6} \text{ K}^{-1}$ and a thermal resistance of 70°C. Prior to manufacturing the mould, an impeller blade mould (scale 1:2.5) was designed and manufactured. Dimensions of the two blocks were 100 x 97.5 x 50 mm for N 651 and 100 x 110 x 50 mm for N 1001. Due to the small scale and geometry complexity, the mould has been made out of three individual components (figure 7). The black coloured face represents the part where the composite material will be placed, forming after polymerization, the composite impeller.

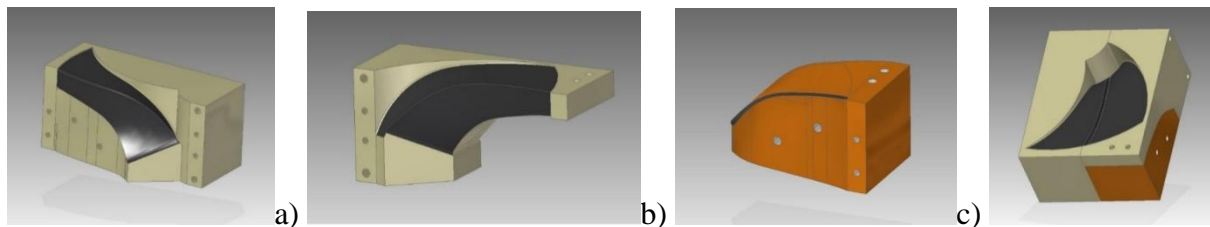


Figure 7. Mould components for the blade a) pressure side, b) suction side, c) blade flow path and d) Mould Assembly (Brown–N 651; Light brown–N 1001)

Starting from CAD design, components were manufactured using a milling machine. To keep the components in place, 8 pins (\varnothing 3.2mm and 9mm length) were manufactured out of aluminium. The mechanical processing of Necuron and the final mould is shown below (fig. 8). Milling regimes are presented in table 4. After mould manufacturing finishing operations were conducted and roughness was measured using the same equipment as in previous measurements. N651 presented a 4.9 μm roughness while N1010 3.2 μm .



Figure 8. Machining of a) N1001; b) N651; c) final Necuron mould (scale 1:2.5)

Table 4. Milling regimes for 1:2.5 scale Necuron mould manufacturing

Cotter milling		Planar milling	
Speed [rpm]	4000	Speed	1200
Mill [mm]	2.5	Cutter	80
Feed rate [mm/min]	200-300	Feed rate [mm/min]	200-300

3.6. Manufacturing of 1:2.5 scale impeller blade

Necuron V7 was applied to the Necuron mould to create a glossy surface and to lower the mould roughness. The gelcoat was applied several times according to the data sheet to obtain the desired characteristics. HexPly M49/42%/200T2X2/CHS prepreg was used to manufacture the scaled impeller blade. Six plies of M49 were placed on the mould to obtain the final blade wall thickness of 1.5 mm. The mould assembly was vacuum bagged and introduced in an oven at 100°C for 2 hours to cure the composite. Figure 9 presents the manufactured composite impeller blades.



Figure 9. Composite impeller blades, 1:2.5 scale

In addition, thermoplastic ABS parts were 3D printed using Dimension Elite printer to fabricate a 1:1 scale mould, presented in figure 10. Due to printed technique, each part has a very rough surface. Thus, each ABS part was polished using grinding paper until the surface was smooth. Mould parts were degreased to ease the removal of composite part after curing. The same M49 prepreg material has been used for manufacturing the 1:1 scale composite impeller blade, the difference being in the curing temperature. As the ABS material has a maximum use temperature of 87°C, the curing temperature was set to 82°C, for a period of 5 hours. The manufactured composite impeller blades present smooth surfaces on the side in contact with the mould. Images of full scale composite impeller blades are presented in figure 11.

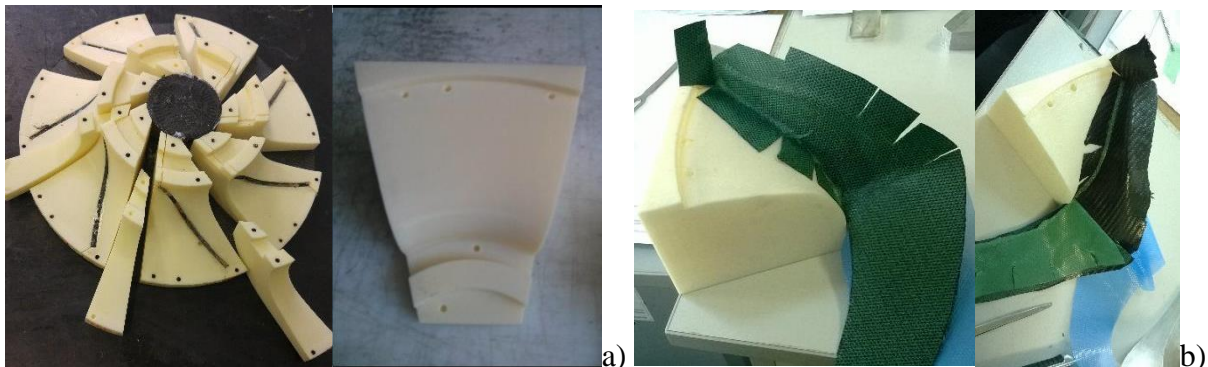


Figure 10. a) 3D printed ABS mould parts for mould assembly;
b) manufacturing stage of a composite impeller blade

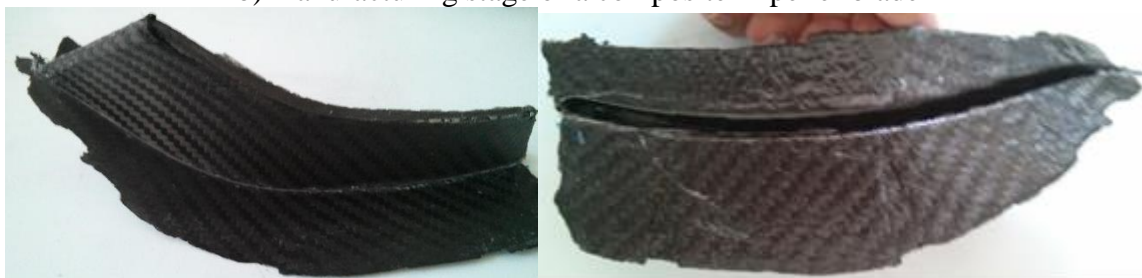


Figure 11. Final composite blade manufactured using 3D printed thermoplastic material



4. Conclusions

Three thermoplastic materials were investigated for the manufacturing process of a composite rotor impeller blade, as they exhibit very high dimensional stability, high compression strength, high stiffness and good machining, perfect qualities for mould fabrication. Different milling operations have been performed on all three thermoplastic materials to select the best machining regimes. The results showed that microstructure and morphology have a critical influence on materials performances. N1001 exhibits the higher performances in terms of mechanical strength, hardness, workability, surface quality but a lower working temperature while N702 has acceptable mechanical strength, hardness but high thermal resistance up to 140°C. The scaled impeller blades presented good tolerances with respect to CAD model and high quality surface. Moreover, several thermoplastic components were 3D printed for a 1:1 scale mould to manufacture full scale composite impeller blades. This technology was also validated as moulding capability for fabrication of composite parts with high geometry complexities.

Acknowledgements

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